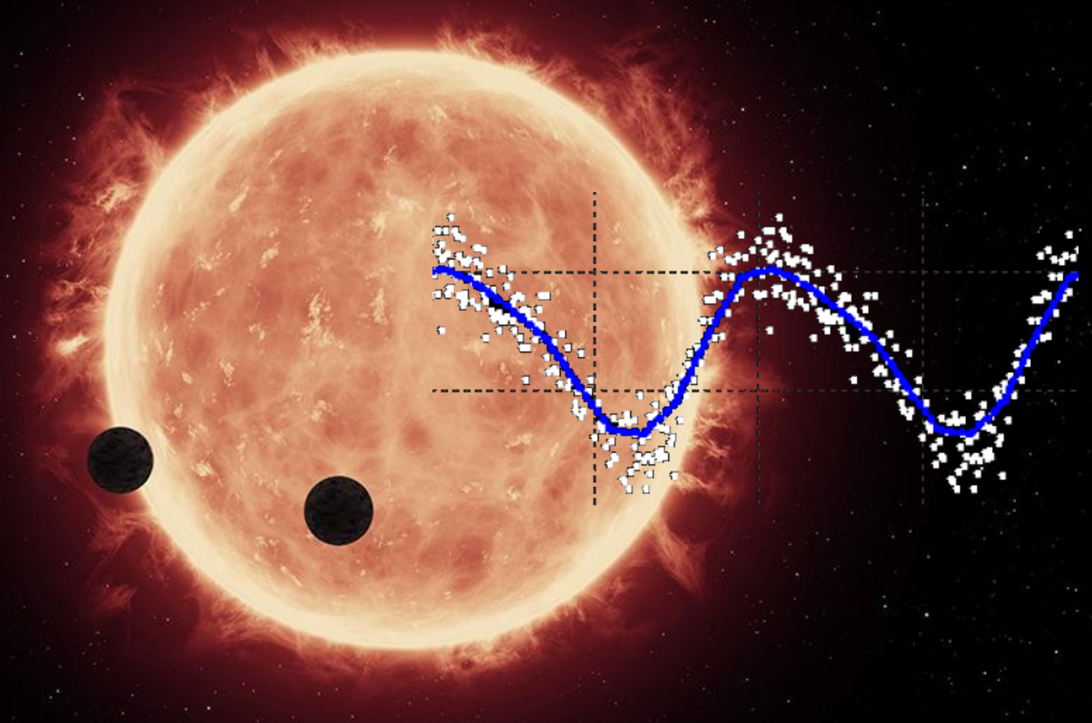
Determinación de períodos de rotación en estrellas enanas de tipo espectral M y búsqueda y caracterización de sistemas planetarios con técnicas fotométricas



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Determinación de períodos de rotación en estrellas enanas de tipo espectral M y búsqueda y caracterización de sistemas planetarios con técnicas fotométricas

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DECLARACIÓN DE AUTORÍA Y ORIGINALIDAD DE LA TESIS PRESENTADA PARA OBTENER EL TÍTULO DE DOCTOR

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Determinación de periodos de rotación en estrellas enanas de tipo espectral M y búsqueda y caracterización de sistemas planetarios con técnicas fotométricas

y dirigida por: el Prof. David Montes Gutiérrez y el Prof. Francisco Javier de Cos Juez

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Resumen

Contexto

En la búsqueda y estudio de planetas tipo Tierra, las estrellas enanas M son objetivos primarios. Esto es así ya que suman el 70 % de las estrellas de la Galaxia, y los planetas tipo Tierra tienden a ser más abundantes según la masa de las estrellas decrece. Además, la detección de planetas en estas estrellas presenta ventajas; las señales en velocidad radial inducidas son más fuertes, y en el caso de que los planetas transiten, las disminuciones de brillo son también más profundas. Al ser estas estrellas menos luminosas, sus zonas de habitabilidad se encuentran próximas, de manera que los planetas que las orbiten en zona de habitabilidad (susceptibles de mantener agua líquida, condición necesaria para la aparición de la vida tal y como la entendemos en la Tierra), tendrán períodos orbitales cortos, lo que favorece su detección. Estos planetas son además objetivos ideales para la caracterización de atmósferas potencialmente habitables mediante espectroscopía de transmisión.

El bajo brillo de estas estrellas en el visible ha sido un inconveniente para su estudio en velocidad radial con anteriores espectrógrafos. Ahora bien, gracias a instrumentos como CARMENES, específicamente diseñado para la detección de planetas en este tipo de estrellas combinando los canales visible e infrarrojo, o MEarth, que observa enanas M para detectar planetas mediante tránsitos, el número de enanas M incluidas en los surveys de búsqueda de exoplanetas ha ido en aumento.

Determinar el período de rotación de las enanas M en las que se buscan exoplanetas con el método de la velocidad radial es crucial, ya que la actividad magnética induce señales semejantes a las inducidas por exoplanetas. Afortunadamente, la variabilidad fotométrica que provocan las regiones de actividad en este tipo de estrellas al rotar, nos permite determinar sus períodos de rotación, ya sea recopilando curvas de luz de cierta extensión temporal en surveys públicos, o realizando un seguimiento fotométrico del que obtener las curvas. Además, en las curvas de luz extraidas de surveys diseñados para detectar exoplanetas mediante tránsitos (como K2, MEarth o SuperWASP), podremos investigar la presencia de los mismos, y por lo tanto detectar candidatos a exoplanetas.

Objetivos y metodología

En el primer artículo, investigamos la fotometría de 337 estrellas monitorizadas en velocidad radial por CARMENES, recopilando curvas de luz en surveys públicos y realizando observaciones propias para 20 estrellas. El objetivo era determinar los períodos de rotación fotométricos de las mismas para identificar las señales en velocidad radial inducidas por la actividad estelar y para entender cómo la rotación se relaciona con parámetros físicos de estas estrellas. De todas las curvas de luz se obtuvo su periodograma Lomb – Scargle para identificar señales que asociamos a la rotación estelar.

En el segundo, tercer y cuarto artículo, presentamos los resultados de investigar las curvas de luz de las enanas M de las temporadas 13, 14 y 15 del Telescopio Espacial Képler en su misión K2, con el fin de detectar, confirmar y caracterizar planetas de interés en estas estrellas (planetas tipo Tierra, sistemas con varios planetas, planetas en zona de habitabilidad), susceptibles de un seguimiento posterior en velocidad radial con instrumentos específicos (como CARMENES) para la determinación de sus masas, o con otros (como el James Webb Telescope) para su caracterización atmosférica. Las curvas de luz fueron analizadas con el método Box Least Squares para identificar posibles tránsitos. Los falsos positivos se descartaron obteniendo imágenes de alta resolución, investigando imágenes de archivo y mediante técnicas de validación estadística. Identificados los candidatos y descartados los falsos positivos, se procedió a la caracterización de las estrellas mediante la obtención de espectros y su comparación con modelos teóricos, así como a partir de relaciones empíricas. Por último, los parámetros de los planetas se obtuvieron ajustando modelos teóricos de tránsitos planetarios mediante cadenas de Markov y métodos de Montecarlo.

Resultados

En el primer artículo se presentan 622 curvas de luz para un total de 334 estrellas, identificando 142 períodos de rotación, 73 de los cuales no se conocían previamente en la literatura, mientras que los 69 restantes coinciden con los períodos de rotación previamente publicados. Además, se encontraron 10 señales identificadas como ciclos de larga actividad, 6 de los cuales son nuevas determinaciones.

Se investigó además la relación entre período de rotación y ciclo de actividad, no encontrando correlación entre ambos. No se encontró el gap en la distribución de los períodos de rotación citado en literatura previa en $\sim$30 d. Se investigó la relación entre el período de rotación e indicadores de actividad, encontrando una fuerte relación entre ambos, y se investigó la relación de la amplitud de la variabilidad fotométrica con el período de rotación e indicadores de actividad, no encontrando relación entre ellos. También se indentificaron tres estrellas muy activas con períodos de rotación determinados por vez primera.

En el segundo y tercer artículo se presenta la detección, confirmación y caracterización de tres sistemas planetarios en las estrellas K2-155, K2-239 y K2-240; K2-155 cuenta con tres super-Tierras, orbitando K2-155 d próximo al límite interior de la zona de habitabilidad. K2-239 cuenta con un sistema de tres planetas tipo Tierra en una configuración compacta y resonancia 2:3:4, mientras que K2-240 cuenta con un sistema de dos super-Tierras.

En el cuarto artículo se presenta la detección, confirmación y caracterización de una super-Tierra orbitando la región interna de la zona de habitabilidad de la estrella K2-286. Establecemos que la estrella presenta menos actividad que otras estrellas similares, por lo que K2-286 b podría experimentar un ambiente más benigno que otros planetas en zona de habitabilidad de enanas M. A partir de espectros adquiridos, ponemos una cota superior a la masa del planeta, excluyendo que se trate de un gigante gaseoso. Comparamos además este planeta con otros planetas similares en estrellas M, encontrando que es más frío que la mayoría de los exoplanetas con radio y masa bien determinados. También discutimos la importancia que este planeta puede tener para entener el gap de Fulton en la distribución de radios.

Abstract

Context

In the search and study of Earth-like planets, M dwarfs are primary targets. These stars account for the 70 % of the population in the Galaxy, and the frequency of terrestrial planets increase as the mass of the stars decreases. In addition, the detection of planets in these low mass stars presents advantages; the induced radial velocity signals are stronger, and in the case of transits, the dimmings are deeper. Due to the low luminosities, their habitability zones are closer, so planets orbiting within the habitable zone (and susceptible to support liquid water, a necessary condition for the appearance of Earth-like life) will have short orbital periods, favoring their detection. These planets are also suitable targets for the characterization of potentially habitable atmospheres by transmission spectroscopy.

For these reasons, the number of M dwarfs included in exoplanet-search surveys, has increased. Nowadays, instruments such as CARMENES, are specifically designed for the detection of planets in this type of stars by radial velocity searches, or MEarth, which observes M dwarfs to detect planets by the transit method.

Knowledge of the rotation period of the M dwarfs in these surveys is necessary (specially in radial velocity surveys such as CARMENES), since signals induced by the magnetic activity are similar to those induced by exoplanets. Fortunately, the photometric variability due to activity regions of M dwarfs and stellar rotation, allows us to determine their rotation period, either collecting light curves from public surveys (such as K2, MEarth or ASAS), or carrying out photometric monitoring to extract the curves. In addition, in light curves obtained from surveys designed to detect exoplanets by the transit method (such as K2, MEarth or SuperWASP), we can search for transit signatures, and therefore detect exoplanet candidates.

Aims and Methodology

In the first publication, we investigated photometric time series of 337 stars monitored by CARMENES, compiling light curves from public surveys and performing observations for 20 stars. The goal was to determine the photometric rotation periods of these stars to identify the radial velocity signals induced by stellar activity, and to improove our understanding of the relation of the rotation period with other stellar parameters. We obtained Lomb-Scargle periodograms for all the light curves to identify signals associated with stellar rotation.

In the second, third and fourth publication, we present the results of analyzing the light curves of the M dwarfs from campaigns 13, 14 and 15 from the Kepler Space Telescope in its second mission (K2), in order to detect, confirm and characterize exoplanets of interest in these stars (Earth-like planets, systems with several planets, planets in habitable zone), for their atmospheric characterization and a continuous follow-up with spectrographs such as CARMENES for their mass characterization.

The light curves were analyzed with the Box Least Squares method to identify possible transits. False positives were discarded obtaining high resolution images, investigating archival images and using statistical validation techniques. After that, we characterized the stars comparing acquired spectra with theoretical models, and using empirical relationships. Finally, the planetary parameters were obtained fitting theoretical models applying Markov chains and Monte Carlo methods (MCMC).

Results

Regarding the first publication, a total of 622 light curves were obtained for 334 stars, finding 142 rotation periods, 73 of which are reported for the first time in the literature, while the remaining 69 periods are in agreement with the previously published values. In addition, we found 10 signals that we identified as long activity cycles, 6 of which are reported for the first time.

The relation between rotation period and activity cycle was also investigated, finding no correlation. The gap at $\sim$30 d in the distribution of the rotation periods was not observed. The relationship between the rotation period and activity indicators was investigated, finding a strong correlation. Also, the relation of the amplitude of the photometric variability with the rotation period and activity indicators was investigated, finding no correlation. Three very active stars were also identified, with rotation periods reported for the first time.

In the second and third articles we report on the detection, confirmation and characterization of three planetary systems in the stars K2-155, K2-239 and K2-240; the K2-155 system consists of three super-Earths, with K2-155 d close to the inner edge of the habitable zone. In the K2-239 system, three Earth-like planets transit the star in a compact configuration, showing 2: 3: 4 resonance. The K2-240 system is composed of two super-Earths.

The fourth publication reports on the detection, confirmation and characterization of a super-Earth in the inner region of the habitable zone of the star K2-286. We establish that K2-286 has lower activity than other similar M dwarfs, so K2-286 b may experience a more benign environment than other planets in the habitable zone of M dwarf stars. From radial velocity measurements, we stablished an upper limit to the mass of the planet, excluding that K2-286 b is a gas giant. We also compared the planet with other similar planets in M dwarf stars, finding that K2-286 b is cooler than most of the exoplanets with well-determined mass and radius, and discussed the importance of this planet in the understanding of the Fulton gap in the distribution of exoplanet radii.

Índice general

Capítulo 1

Introducción

1.1. Planetas extrasolares

1.1.1. Principales hitos

En los últimos 25 años y con $\sim$ 4000 planetas confirmados (junio de 2019), nuestra visión de los planetas extrasolares ha pasado de los primeros planetas de tipo *Júpiter caliente*, a la gran abundacia de planetas *pequeños* ($R < R_{\oplus}$) en torno a estrellas frías, pasando por planetas orbitando sistemas binarios o planetas *vagabundos* no asociados a estrellas.

A continuación se citan algunos de los hitos más destacados que han tenido lugar en estos últimos 25 años en el campo de los planetas extrasolares (en la sección 1.3.2 se hace un repaso específico al campo en estrellas enanas M).

En el año 1991 se publica la detección de dos planetas rocosos orbitando el púlsar PSR B1257+12 (Wolszczan y D. A., 1992). Ahora bien, en 1995 se detecta el primer exoplaneta orbitando una estrella de la secuencia principal de tipo solar (Mayor y D., 1995). 51 Pegasi b fue descubierto mediante el método de velocidad radial, tiene una masa de $\sim 0.5\ M_J$, un período orbital de $\sim$ 4.2 d y orbita a una estrella (51 Pegasi) de tipo espectral G. Pertenece a la tipología conocida como *Júpiter caliente*. A esta clase pertenecen la gran mayoría de exoplanetas descubiertos en los años siguientes ya que los principales métodos de detección (velocidad radial y tránsitos), focalizados en estrellas de tipo solar, son especialmente sensibles a este tipo de planetas.

En 1999 se descubre el primer planeta transitando a su estrella, HD 209458 b, de forma independiente por parte de Henry y col. (2000) y Charbonneau y col. (2000). También en 1999 se publica la detección del primer sistema planetario en torno a una estrella (Upsilon Andromedae, F8 V) por parte de Butler y col. (1999).

En el año 2001 se anuncia el primer planeta en la zona de habitabilidad de su estrella, HD 28185 b, un gigante gaseoso con $\sim$6 veces la masa del planeta Júpiter orbitando una estrella de tipo solar (Santos y col., 2001). Ese mismo año tiene lugar la primera detección de la atmósfera de un exoplaneta (HD 209458 b, Charbonneau y col., 2002).

En el año 2004 se publica la detección de la emisión infrarroja procedente de un gigante gaseoso acompañando a la enana marrón 2MASSWJ 1207334-393254 (Chauvin y col., 2004). En 2005 se publican las primeras detecciones de la emisión infrarroja de los exoplanetas HD 209458 b, (Deming y col., 2005) y TrES-1 (Charbonneau y col., 2005), realizadas mediante el Telescopio Espacial Spitzer, con el que en 2007 también se obtendrían los primeros espectros de exoplanetas (HD 209458 b por Richardson y col., 2007 y HD 189733 b por Grillmair y col., 2007). Al año siguiente, 2008, se obtiene con el Telescopio Espacial Hubble la imagen visual directa del exoplaneta Fomalhaut b (Kalas y col., 2008).

En aquel momento, el único planeta con tránsitos detectados y $R < 4R_{\oplus}$ era CoRoT 7 b ($R = 1.68 \pm 0.09\ R_{\oplus}$, Léger y col., 2009), una super-Tierra orbitando una estrella enana de tipo espectral G. CoRoT 7b fue el primer planeta en ser confirmado como rocoso, al medirse también su masa ($M = 4.8 \pm 0.8\ M_{\oplus}$) mediante velocidad radial (Queloz y col., 2009).

En 2014 se anuncia el descubrimiento de Kepler-186f, el primer exoplaneta rocoso detectado en zona de habitabilidad (Quintana y col., 2014), y en 2015 se publica el descubrimiento de Kepler-452b Jenkins y col. (2015), la primera *super-Tierra* ($R \sim 1.6$ $R_{\oplus}$) orbitando una estrella de tipo solar en la zona de habitabilidad.

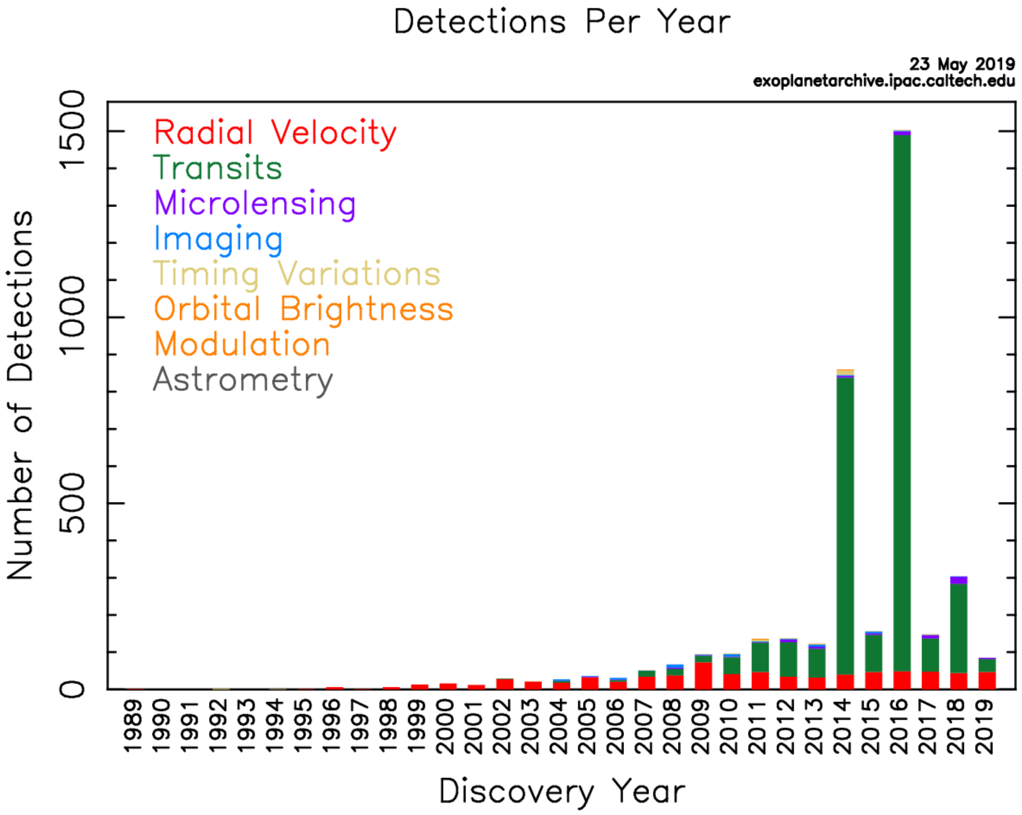

FIGURA 1.1: Número de planetas confirmados por año según diferentes métodos de detección. Tomado de https://exoplanetarchive.ipac.caltech.edu/

En la Figura 1.1 queda patente el aumento exponencial de planetas confirmados desde los primeros descubrimientos. Por otra parte, la Figura 1.2 pone de manifiesto el gran número de planetas pequeños y amplio rango de períodos orbitales detectados gracias al Telescopio Espacial Képler, mientras que la figura 1.3 pone de manifiesto la sensibilidad en el espacio $M - P_{orb}$ de los diferentes métodos de detección.

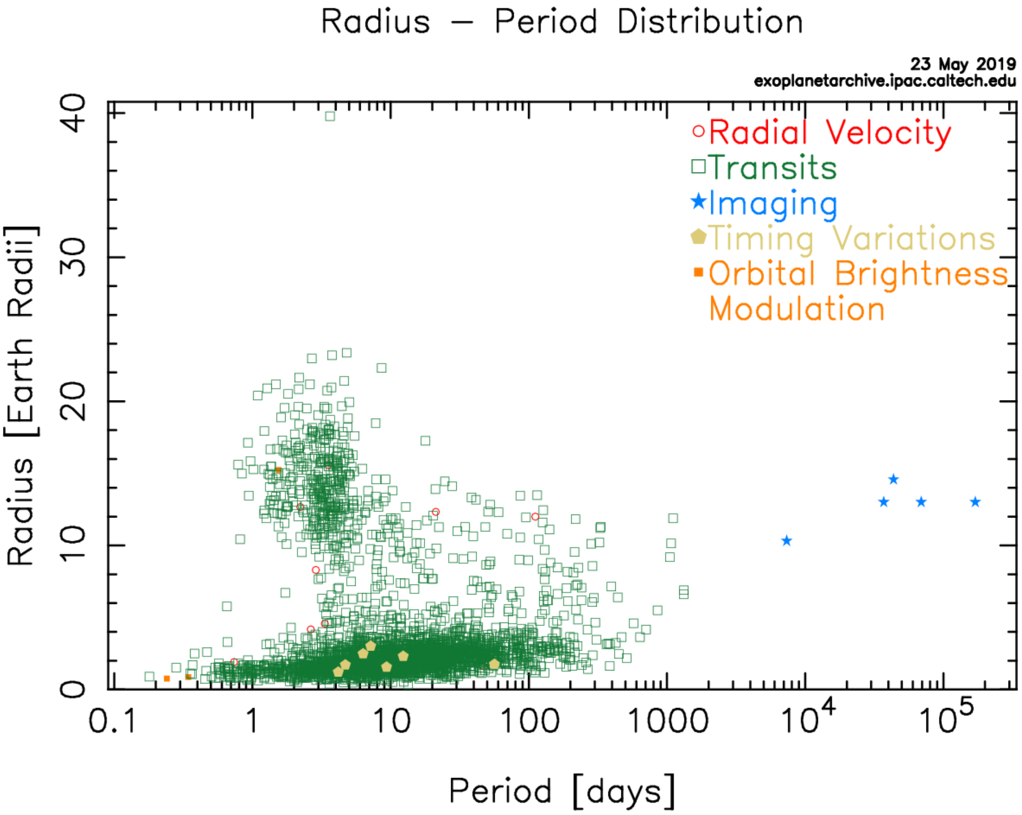

FIGURA 1.2: Radio de planetas confirmados [$R_\oplus$] frente período orbital [d] según diferentes métodos de detección. Tomado de https://exoplanetarchive.ipac.caltech.edu/

1.1.2. Métodos de detección

Múltiples métodos han sido desarrollados para detectar la presencia de planetas extrasolares. Los dos más exitosos son el método de la *velocidad radial*, consistente en la detección de variaciones en la velocidad radial de la estrella debidas a la presencia de uno o varios planetas, y el de *tránsitos*, basado en la detección de disminuciones períodicas de brillo originadas por tránsitos planetarios por delante del disco estelar. Este último se revisará en la sección y 1.6.3.

El método de *velocidad radial* se basa en que, si una estrella se encuentra acompañada por un planeta, esta se moverá en torno al centro de masas del sistema, provocando un desplazamiento Doppler periódico en las líneas espectrales del que se puede inferir la presencia del planeta.

La máxima amplitud K de las líneas espectrales viene dada por:

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \cdot \frac{M_p \sin i}{(M_* + M_p)^{2/3}} \cdot \frac{1}{(1-e^2)^{1/2}} \tag{1.1}$$

donde P es el período orbital del planeta, M_p y M_* son las masas del planeta y de la estrella, i es la inclinación de la órbita con respecto a la línea de visión y e su excentricidad.

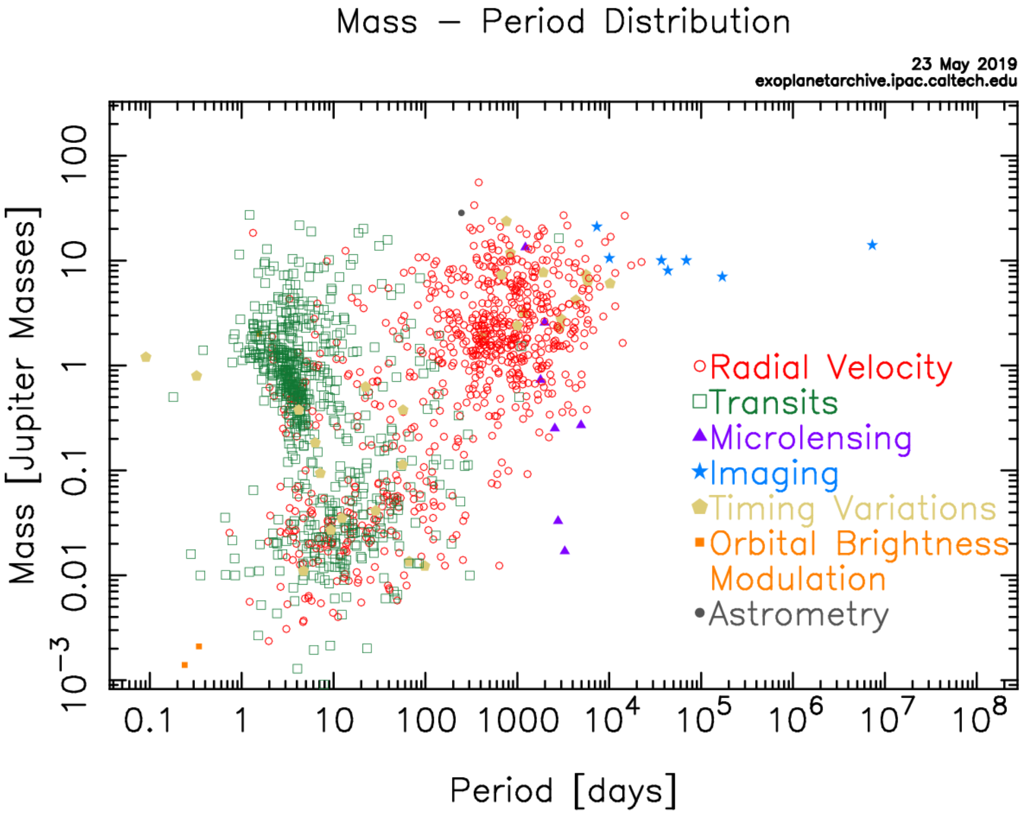

FIGURA 1.3: Masa de planetas confirmados [M_J] frente período orbital [d] según diferentes métodos de detección. Tomado de https://exoplanetarchive.ipac.caltech.edu/

El método, del que puede inferirse una cota mínima para la masa del planeta ($M_p \cdot \sin i$), es especialmente sensible hacia planetas masivos que orbiten próximos a su estrella. Ahora bien, el hecho de que las estrellas menos masivas experimenten mayor desplazamiento y la mayor precisión de los modernos espectrógrafos ($\sim$ 1 m $\cdot s^{-1}$), ha ocasionado que las estrellas enanas M cobren protagonismo en las actuales búsquedas planetarias en velocidad radial.

Por otro lado, factores como la actividad estelar inducen señales en velocidad radial, provocando que el método vea reducida (o comprometida) su efectividad.

El método de *microlente gravitatoria* se basa en la amplificación gravitacional que experimenta la luz que recibimos de una fuente compacta cuando esta se alinea con otra fuente también compacta más próxima. Si la fuente más próxima (amplificadora) es orbitada por un planeta, puede ocurrir que este amplifique también la luz de la fuente lejana, ocasionando una asimetría en la curva de amplificación de la que se puede inferir la presencia del planeta. Incluso planetas *vagabundos*, no asociados a estrellas, pueden ser detectados. A mediados de 2019, al menos una veintena de candidatos han sido detectados y publicados mediante este método, el primero de los cuales fue OGLE-2003-BLG-235/MOA-2003-BLG-53Lb (Bond y col., 2004).

El método *astrométrico* consiste en detectar oscilaciones en el movimiento propio de las estrellas causadas por la presencia de un planeta. Este método, más eficiente con planetas masivos y en órbitas amplias (períodos orbitales $\sim$ años), requiere observaciones de gran estabilidad y precisión durante largos períodos de tiempo.

Con él se han presentado candidatos (Pravdo y S.B., 2009), pero sin duda sufrirá un revulsivo gracias a la misión Gaia (Gaia Collaboration y col., 2018).

El método *cronométrico (Timing)* se aplica a estrellas o remanentes estelares que experimentan variaciones fotométricas periódicas como binarias eclipsantes, estrellas pulsantes, enanas blancas pulsantes o púlsares. La presencia de planetas puede inferirse a partir de oscilaciones observadas en dichos procesos periódicos. Este método es el responsable de la detección de los primeros exoplanetas en torno al púlsar PSR1257+ 12 (Wolszczan y D. A., 1992), y cuando se aplica al adelanto o retraso de los tiempos esperados de tránsito en estrellas con exoplanetas confirmados, se denomina método de *variaciones de tiempos de tránsitos (TTVs, Transit Timing Variations)* (Steffen y E., 2005; Ford y col., 2012).

El método de *imagen directa* consiste en la detección de la emisión procedente del planeta, ya sea la reflejada de su estrella o la térmica del propio planeta. Si bien la emisión del planeta es muy tenue, realmente el mayor reto reside en la detección de esa emisión en las próximidades de una estrella, mucho más brillante. A mediados de 2019 son una veintena los candidatos detectados mediante imagen directa, siendo el sistema de HR 8799 un ejemplo espectacular; un sistema de cuatro planetas con masas comprendidas entre 3 y 7 veces la masa del planeta Júpiter orbitando una estrella joven F0 V (Marois y col., 2008).

1.2. Estrellas enanas de tipo espectral M

Las estrellas de tipo espectral M constituyen el 70 % de las estrellas de nuestra Galaxia (Bochanski y col., 2010). Se trata de las estrellas más pequeñas ($0.1\ R_\odot < R < 0.6\ R_\odot$) y frías ($2300\ \mathrm{K} < T < 3800\ \mathrm{K}$) y suponen la transición entre los objetos estelares y subestelares (objetos con $M < 0.07\ M_\odot$ que no alcanzan la suficiente temperatura para sostener la fusión del Hidrógeno y se engloban en la categoría de las *enanas marrones*).

Para estrellas M en la secuencia principal y edades superiores a 10^9 años, su masa está comprendida entre 0.6 y 0.075 $M_\odot$. Para metalicidad solar, la masa crítica que define el límite subestelar es 0.075 $M_\odot$, lo que corresponde a tipos espectrales M tardíos o L dependiendo de la edad, por lo que las M más tardías pueden ser objetos estelares con fusión de Hidrógeno en su interior si son viejas, o enanas marrones fusionando solo deuterio cuando son mucho más jóvenes (Burrows y col., 1993; Baraffe y col., 1998; Chabrier y col., 2000; Baraffe y col., 2015).

La presencia de fuertes bandas de absorción de óxido de titanio (TiO) en el rango 4500 - 5700 Å caracteriza el tipo espectral M (Morgan, P. C. y E., 1943). Pero además, estas estrellas son lo suficientemente frías como para presentar múltiples bandas moleculares correspondientes a H_2, H_2O, CaH, MgH, FeH o VO, que llegan a oscurecer el contínuo del espectro (ver Figura 1.4). Las bandas de TiO, cuya intensidad aumenta desde los tipos tempranos hacia los tardíos, se emplean para la clasificación de estrellas enanas hasta el tipo M6 V. Para tipos más tardíos, la saturación de dichas bandas hace que la clasificación se base en la intensidad de bandas como CaH, MgH y FeH (Boeshaar, 1976; Kirkpatrick, T. J. y D. W., 1991; Alonso-Floriano y col., 2015).

Las características de los espectros estelares nos informan sobre los procesos que tienen lugar en las capas internas y externas, y de parámetros fundamentales como la masa, la luminosidad, el radio y la gravedad superficial. Ahora bien, la complejidad de los espectros de las estrellas de baja masa y la dificultad que supone una correcta estimación de su metalicidad, hace que la determinación de sus parámetros fundamentales a partir de sus espectros sea una tarea más complicada que para estrellas más masivas, y se realicen esfuerzos para determinar sus parámetros fundamentales basándose en los cocientes de los flujos correspondientes a diferentes regiones del espectro, en la anchura equivalente de ciertos rasgos espectrales (e.g. Casagrande, C. y M., 2008; Mann y col., 2013; Mann y col., 2015; Newton y col., 2014; Newton y col., 2015), o extrapolando las metalicidades de compañeras más masivas en sistemas binarios para poder calibrar las metalicidades de las estrellas enanas M a partir de características espectrales o fotométricas (Mann y col., 2013; Mann y col., 2014; Montes y col., 2018).

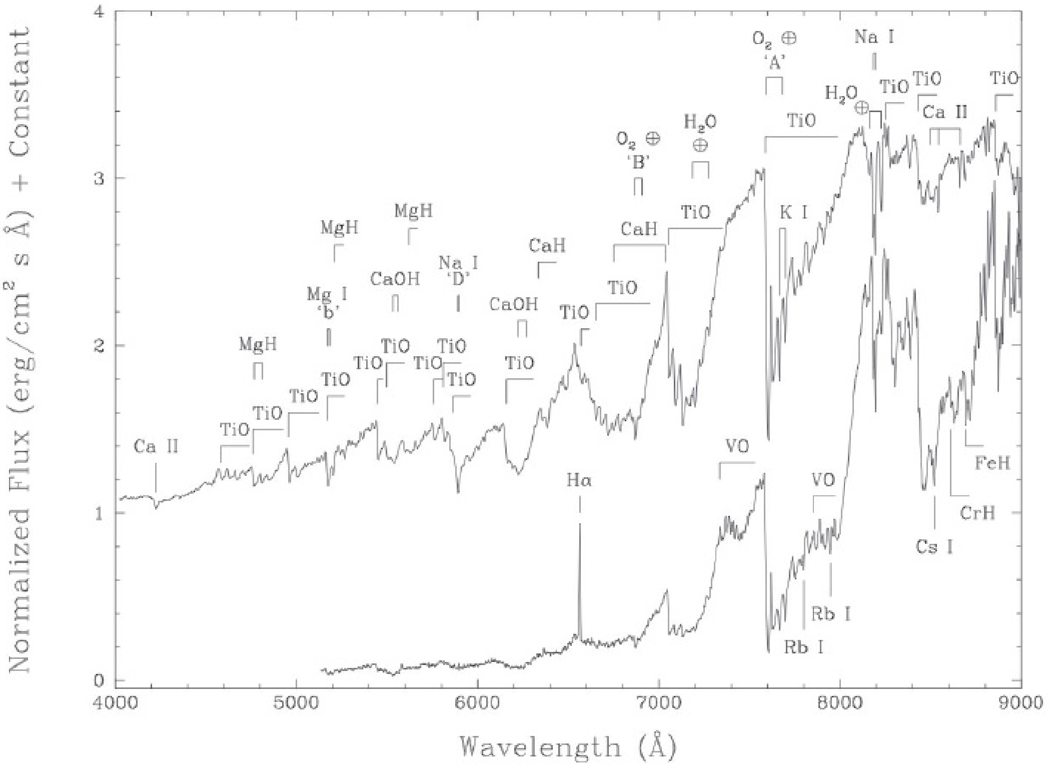

FIGURA 1.4: Arriba: espectro óptico de la estrella M4.5 V AndB (Lowrance, J. D. y C. A, 2002). Abajo: espectro óptico de la M9 V LHS 2065 (Kirkpatrick, C. A. y M. F., 1997). En el espectro superior se indican las principales características espectrales de las enanas M, junto con líneas de absorción telúricas (no sustraídas). En el espectro inferior se indican bandas adicionales relevantes en los tipos más tardíos. Los flujos están normalizados en 7400 Å y el espectro superior se ha desplazado verticalmente una unidad. Figura tomada de Gray y J. (2009).

Como las estrellas más masivas, la formación de estrellas poco masivas tiene lugar por fragmentación en nubes moleculares gigantes. Ahora bien, los mecanismos son discutidos. La acreción de masa podría detenerse a causa de interacciones con otros fragmentos de la nube o protoestrellas próximas (Reipurth y C., 2001; Bate, 2012), inestabilidades en un disco circumestelar en torno a una estrella masiva podrían originar una estrella compañera poco masiva (Goodwin y A., 2007; Stamatellos y A. P., 2009), o la erosión producida por la radiación emitida por estrellas masivas cercanas también podría resultar en estrellas de poca masa u objetos subestelares (Whitworth y H., 2004).

El período de rotación (en adelante P_{rot}) de las estrellas depende tanto de su edad como de su masa. En las primeras etapas, la contracción y la acreción hacen que las estrellas sean rotadoras rápidas (Hartmann y J. R., 1989; Matt y R. E., 2005), mientras que una vez alcanzada la secuencia principal, tiene lugar un frenado a causa de los vientos estelares (Barnes, 2003). Se ha encontrado que para una masa estelar dada existe una relación directa entre el P_{rot} y la edad de la estrella; por lo tanto, a partir del P_{rot} podemos inferir la edad estelar (*girocronología*: Stauffer y L. W., 1987; Barnes, 2007; Mamajek y L. A., 2008). Las estrellas M por encima del límite convectivo de 0.35 $M_{\odot}$ presentan un frenado coherente en su P_{rot} (McQuillan, S. y T., 2013; McQuillan, T. y S., 2014), pero por debajo de dicho límite aparecen dos poblaciones, rotadoras rápidas y lentas, apuntando a un frenado rápido (Irwin y col., 2011; Newton y col., 2016). Típicamente las estrellas M alcanzan $P_{rot} \sim 100$ d transcurridos $5 \cdot 10^9$ años (Newton y col., 2016).

Ahora bien, esta evolución de la rotación estelar puede alterarse por la presencia de planetas cercanos. Las interacciones de marea entre la estrella y los planetas pueden transferir momento angular orbital de los planetas a la rotación estelar, acelerándola. Estas interacciones causarían migraciones planetarias, que en casos extremos podrían terminar con su caída a la estrella, originando un mayor cambio en su momento angular y un incremento en las abundancias de ciertos elementos (Bolmont y col., 2012; Zhang y K., 2014; Privitera y col., 2016; Rao y col., 2018; Gallet y col., 2018; Gallet y P., 2019). Estas interacciones pueden estudiarse a partir de la observación de planetas de tipo Júpiter caliente orbitando estrellas de tipos F, G y K, y podrían extrapolarse a las interacciones entre estrellas enanas M y planetas de baja masa (Rao y col., 2018).

La transición entre estrellas parcial y totalmente convectivas se sitúa en $M \sim 0.35\ M_{\odot}$ (Chabrier e I., 1997; Reiners y G., 2009). Estrellas en el rango M0 V – M4 V tienen interior radiativo y envoltura convectiva. Esta última pasa a dominar a partir de los tipos intermedios ($\sim$ M4 V) siendo totalmente convectivas las estrellas M más tardías. Este interior convectivo de las estrellas de baja masa permite fusionar la totalidad de sus reservas, de manera que una estrella de masa $\sim 0.1\ M_{\odot}$ tendrá una vida $\sim 10^3$ veces más lonjeva que el Sol (Laughlin, P. y F. C., 1997).

La existencia de esta zona convectiva provoca una dinamo que origina actividad magnética, trazada por indicadores como emisión en las líneas H_{α}, *H&K* de CaII, o rayos X. La fase más activa oscila entre 10^9 años para enanas de tipo M0 y $8 \cdot 10^9$ años para enanas M8 (West y col., 2006). Las estrellas M más tempranas muestran la misma relación entre rotación y actividad magnética que las de tipo solar (Pizzolato y col., 2003; Reiners, 2007), implicando rotación más rápida una mayor actividad (ver Figura 1.5). Esta relación puede explicarse mediante una dinamo $\alpha\ \Omega$ (rotación – convección) que puede estar operando solo en presencia de un interior radiativo. De todos modos, las estrellas más tardías muestran una relación rotación – actividad que ha de explicarse en base a otros modelos de dinamo, como α^2 (Chabrier y M., 2006).

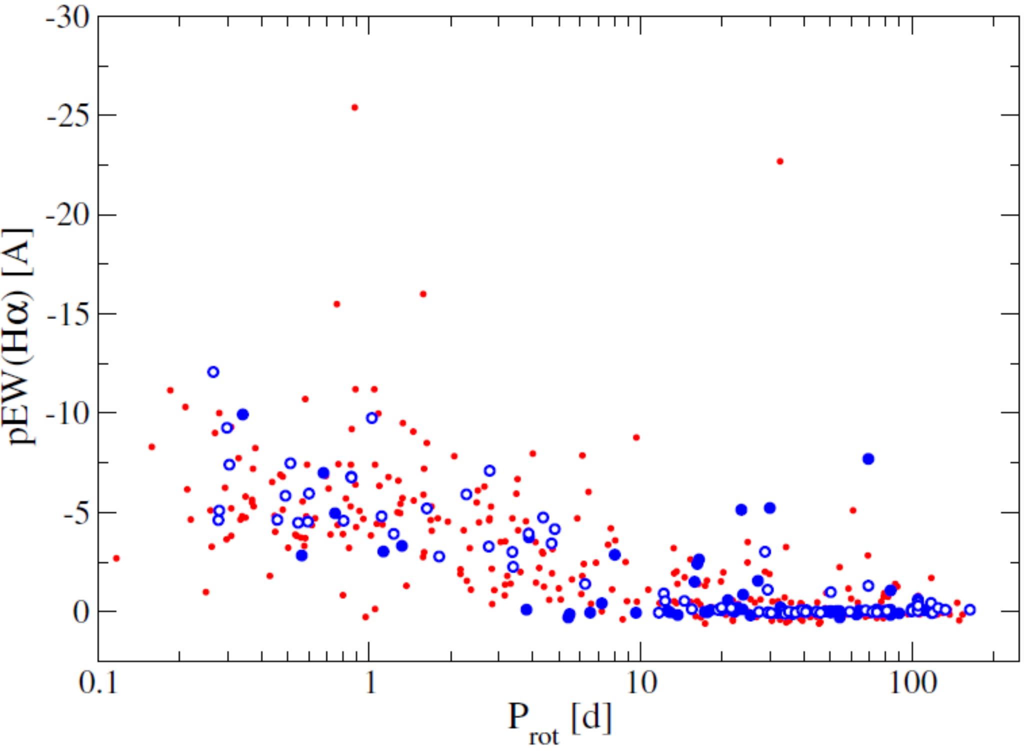

FIGURA 1.5: Pseudo anchura equivalente de la línea Hα, pEW(Hα), [Å] frente P_{rot} [d] para una muestra de estrellas enanas M *(Carmencita)*. Tomado de Díez Alonso y col. (2019b). Consultar el Capítulo 2 para los detalles de la leyenda.

En etapas tempranas la actividad magnética puede inducir inestabilidades en un disco protoplanetario en torno a la estrella, que resultarían en una transferencia de momento angular en el disco y un transporte de masa hacia regiones interiores del mismo, y posiblemente favorecer las condiciones adecuadas para la formación de cuerpos de tamaño 10 – 100 km (Carballido, S. y J., 2006).

En etapas posteriores también pueden producirse interacciones magnéticas entre la estrella y planetas próximos. Estas pueden observarse como una intensificación de la actividad estelar modulada por el período orbital del planeta. Estas interacciones magnéticas, al igual que las de marea, pueden afectar la irradiación del planeta, causar migraciones y modificar la evolución de la rotación (Shkolnik y col., 2005; Cohen y col., 2011; Strugarek y col., 2014).

Con la rotación, las inhomogeneidades relacionadas con el campo magnético estelar como manchas o playas, las pulsaciones, la granulación o inhomogeneidades en la convección, afectan a los perfiles de las líneas espectrales, y por lo tanto a la ubicación de sus centroides (ver Figura 1.6). De este modo se originan señales en velocidad radial de $\sim$ m·s^{-1}, que los modernos espectrógrafos como CARMENES (Quirrenbach y col., 2018), ESPRESSO (Pepe y col., 2014), HARPS (Mayor y col., 2003), HARPS-N (Cosentino y col., 2012) o SPIRou (Artigau y col., 2014), con precisiones de $\sim$ m·s^{-1} o incluso $\sim$ cm·s^{-1}, son capaces de detectar (Quirrenbach y col., 2018).

Las señales ocasionadas por estructuras como manchas y playas, presentan periodicidades con escalas temporales similares al período de rotación estelar. Por otra

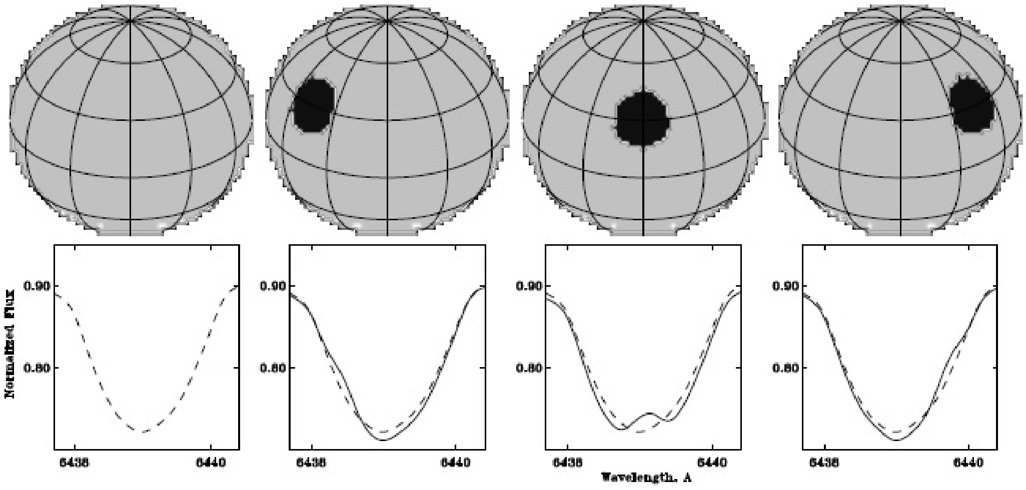

FIGURA 1.6: Perfiles de una línea espectral para una estrella rotadora rápida sin manchas (líneas punteadas) y con una mancha moviéndose por el disco estelar según la estrella rota (líneas sólidas). Tomado de Berdyugina (2005).

parte, oscilaciones en el nivel global de actividad (ciclos de larga actividad similares al ciclo solar de once años), provocan señales con escalas temporales de años. Es crucial entender estos procesos para distinguir las señales inducidas por exoplanetas de aquellas originadas por la actividad de estelar (Saar y R. A., 1997; Queloz y col., 2001; Boisse y col., 2011), especialmente cuando el objetivo es detectar planetas de tipo terrestre en estrellas de baja masa (Dumusque y col., 2012; Anglada-Escudé y col., 2016).

Para diferenciar las señales en velocidad radial provocadas por la actividad magnética se estudia la emisión de líneas como H_α o *H&K* de CaII, indicadoras de la actividad estelar. Su modulación con la rotación estelar (Pallavicini y col., 1981; Drake, T. y J. L., 1989; Suárez Mascareño y col., 2015; Jeffers y col., 2018) y con los ciclos de larga actividad (Baliunas y A. H., 1985; Robertson y col., 2013) nos servirá para identificar estas señales. Otros métodos, como el estudio de la función de correlación cruzada, también permiten identificar la actividad estelar en las medidas de velocidad radial (Queloz y col., 2001; Huélamo y col., 2008; Figueira y col., 2010).

Por otro lado, las regiones activas como manchas y playas modulan el brillo de las estrellas con la rotación, de manera que un seguimiento fotométrico continuado permite inferir sus períodos de rotación (Kron, 1947; Bouvier y col., 1993; Messina y E. F., 2002) y ciclos de larga actividad (Baliunas y A. H., 1985; Berdyugina y S. P., 2005). Estas modulaciones son aun más notables para las estrellas M (Irwin y col., 2011; Kiraga, 2012; Suárez Mascareño, Rebolo y González Hernández, 2016), debido a las extensas regiones de actividad presentes en su superficie (Delfosse y col., 1998a; Mullan y J., 2001). Encontramos así otro método para identificar las señales en velocidad radial estelares.

1.3. Planetas en estrellas enanas M

1.3.1. Motivación

En las estrellas enanas M, encontramos 3.5 veces más planetas pequeños (1.0 $R_\oplus < R < 2.8~R_\oplus$) que en estrellas F, G y K de secuencia principal (Mulders, I. y D., 2015). Además, las enanas M presentan múltiples ventajas para la detección y caracterización de exoplanetas, especialmente los de tipo terrestre. Por una parte, el ser poco masivas hace que las señales en velocidad radial inducidas por los planetas sean más altas. Por otra, su menor radio hace que en el caso de transitar planetas, estos provoquen disminuciones más profundas en su brillo. Por lo tanto la detección de exoplanetas mediante estos métodos es más sencilla en las enanas M. Además la amplitud de las señales en espectroscopía de transmisión es mayor cuanto menor sea el radio de la estrella (Charbonneau y col., 2002), por lo que los planetas que orbiten enanas de tipo M brillantes son excelentes candidatos para su caracterización atmosférica (Batalha y col., 2018).

Dada la baja luminosidad de estas estrellas, su zona de habitabilidad o región en la que un planeta con las condiciones adecuadas podría sustentar agua líquida en su superficie (Kasting, D. P. y R. T., 1993; Joshi, R. M. y R. T., 1997; Kopparapu y col., 2013), está muy próxima, por lo que los planetas que las orbiten en zona de habitabilidad tendrán períodos orbitales más cortos, lo que también favorece su detección.

Por todas estas razones, la inclusión de enanas de tipo M ha ido en aumento desde los primeros proyectos de búsqueda de exoplanetas, tanto en velocidad radial (Butler y col., 2004; Bonfils y col., 2005; Johnson y col., 2007; Bonfils y col., 2013; Quirrenbach y col., 2018; González Hernández y col., 2018) como por tránsitos (Berta, J. y D., 2013; Bonfils y col., 2015; Gillon y col., 2017; Wheatley y col., 2018; Burdanov y col., 2018).

1.3.2. Planetas en estrellas enanas M: revisión

El primer descubrimiento de un exoplaneta en una estrella enana M tuvo lugar en 1998 (Delfosse y col., 1998b; Marcy y col., 1998). GJ 876 b, un gigante gaseoso ($M = 2.28 \pm 0.01~M_J$, $P_{orb} = 61.12 \pm 0.01$ d) descubierto mediante el método de velocidad radial. Ahora bien, debido a la escasez de gigantes gaseosos en torno a enanas M [1], y antes de revelarse como las estrellas con mayor número de planetas *pequeños* ($R < 4~R_\oplus$), comparativamente se las consideraba como estrellas *pobres* en planetas. Fue precisamente en esta misma enana M donde se descubrió la primera super-Tierra, GJ 876d (Rivera y col., 2005), mediante velocidad radial.

La abundante población de planetas pequeños en torno a enanas M (en lo que al método de velocidad radial se refiere), se pone de manifiesto gracias al empleo de telescopios de mayor abertura (Butler y col., 2004; Bonfils y col., 2005), la espectroscopía infrarroja Bean y col., 2010 y escalas temporales de observación más extensas (Anglada-Escudé y col., 2016; Ribas y col., 2018, para las dos estrellas M más cercanas respectivamente, Próxima y estrella de Barnard).

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[1] A fecha 31/12/18, el único Júpiter caliente conocido en una enana M es KOI-254b (Johnson y col., 2012).

En lo que al método de tránsitos se refiere, hasta el año 2009 el único planeta conocido que transitara una estrella enana de tipo M era GJ 436b ($R = 4.3 \pm 0.2\ R_{\oplus}$, $M = 22.2 \pm 1.0\ M_{\oplus}$), descubierto por velocidad radial (Butler y col., 2004) y posteriormente detectados sus tránsitos (Gillon y col., 2007).

El proyecto MEarth (Nutzman y D., 2008) fue diseñado para detectar desde tierra tránsitos de planetas con $R \geq 2\ R_{\oplus}$, monitorizando específicamente estrellas enanas M. Así en 2009 se descubre GJ 1214 b (Charbonneau y col., 2009), una super-Tierra con $R = 2.7 \pm 0.1\ R_{\oplus}$, $M = 6.6 \pm 1.0\ M_{\oplus}$ y $P_{orb} = 1.580 \pm 0.001$ d. GJ 1214 b se convirtió en la primera super-Tierra descubierta por el método de tránsitos desde tierra y orbitando alrededor de una estrella enana M.

La misiónn Képler (Borucki y col., 2010) fue lanzada en 2009 con el fin de detectar exoplanetas a través del método de tránsitos, monitorizando un mismo campo durante cuatro años. El objetivo general era estudiar la estructura y diversidad de los sistemas planetarios con objetivos específicos como determinar el porcentaje de planetas de tamaño mayor o igual al terrestre que orbitan en (o próximos a) la zona de habitabilidad de una amplia variedad de estrellas, determinar las propiedades de sus órbitas u obtener estadística sobre la ocurrencia de planetas en sistemas estelares múltiples. Por ello, de las $\sim$ 150.000 estrellas de catálogo de entrada de Képler (Brown y col., 2011), $\sim$ 90.000 son de tipo solar y tan solo $\sim$ 3.000 son enanas M. Képler no solo confirmó que las estrellas enanas M albergan muchos menos planetas gigantes, sino que también demostró que una enana M típica alberga 2.0 ± 0.5 exoplanetas dentro de un radio de 1 UA (Morton y J., 2014). Se encuentran 3.5 veces más planetas pequeños ($1.0\ R_{\oplus} < R < 2.8\ R_{\oplus}$) en enanas M que en estrellas de tipo F, G y K, pero la ocurrencia de planetas tipo Neptuno ($R > 2.8\ R_{\oplus}$) y mayores es dos veces menor (Mulders, I. y D., 2015).

El proyecto TRAPPIST (Jehin y col., 2011) fue diseñado para monitorizar desde tierra estrellas ultrafrías (enanas M6 ó más tardías). Cabe destacar la detección del sistema TRAPPIST-1 (Gillon y col., 2017), con siete planetas rocosos en una configuración compacta, orbitando una enana M8 a 12 parsecs del Sistema Solar.

El satélite Képler en su misión extendida (K2) (Howell y col., 2014), continuó observando diferentes regiones del plano eclíptico por períodos de $\sim$ 80 días, detectando numerosos candidatos en estrellas frías (e.g. Crossfield y col., 2015; Hirano y col., 2018a; Díez Alonso y col., 2018a; Díez Alonso y col., 2018b). Precisamente en esta tesis se presenta la detección, confirmación y caracterización de nueve exoplanetas en estrellas frías; los sistemas K2-155 (con tres super-Tierras), K2-239 (con tres planetas tipo terrestre), K2-240 (con dos super-Tierras) y K2-286 (con una super-Tierra en zona de habitabilidad).

El número de exoplanetas que se espera detectar en torno a enanas M a corto plazo irá en aumento; el satélite TESS (Ricker y col., 2015), lanzado en abril de 2018, monitorizará durante dos años prácticamente toda la bóveda celeste con el objetivo de detectar exoplanetas transitando estrellas brillantes, susceptibles de caracterización atmosférica (Luque y col., 2019). Se espera que el 75 % de los exoplanetas con radio $R < 2R_{\oplus}$ detectados por TESS se encuentren en enanas M (Sullivan y col., 2015). La misión CHEOPS (Broeg y col., 2013) monitorizará enanas M próximas en búsqueda de exoplanetas que transiten, y PLATO (Rauer y col., 2014) será capaz de detectar en enanas M tránsitos de exoplanetas que se encuentren más allá de la línea de hielo. SPECULOOS (Gillon y col., 2013) monitorizará enanas ultrafrías buscando tránsitos planetarios. ExTrA (Bonfils y col., 2015) buscará planetas de tipo terrestre que transiten estrellas enanas M brillantes, combinando espectroscopía y fotometría.

En cuanto a búsquedas de exoplanetas en velocidad radial dedicada a enanas M, cabe destacar el propio CARMENES (Quirrenbach y col., 2018), centrado en investigar ~330 estrellas enanas M de la vecindad solar, SPIRou (Artigau y col., 2014), espectropolarímetro instalado en el telescopio franco-canadiense de 3.6 m (Hawaii), HPF (Mahadevan y col., 2014), instalado en el telescopio Hobby-Eberly de 10 m (McDonald Observatory, Texas), HARPS (Bonfils y col., 2013), instalado en el telescopio de 3.6 m de La Silla (Chile), o ESPRESSO (González Hernández y col., 2018) instalado en el VLT (La Silla, Chile).

De los ~ 200 exoplanetas descubiertos hasta la fecha orbitando ~ 100 estrellas enanas M, solo 11 han sido detectados mediante tránsitos y velocidad radial. El estudio aplicando los dos métodos es de crucial importancia ya que permite estimar la densidad media del planeta y sus propiedades globales.

Es de obligada mención la aportación del satélite Gaia (Gaia Collaboration y col., 2018), refinando notablemente los parámetros físicos de las estrellas, y por extensión, los de sus planetas. Gracias a su precisión astrométrica, Gaia además es capaz de detectar planetas de tipo Saturno orbitando enanas M a distancias de entre 1 y 4 UAs (Sozzetti y col., 2014).

1.4. CARMENES

CARMENES[2] *(Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs)* (Quirrenbach y col., 2018) es un instrumento instalado en el telescopio de 3.5 metros del Observatorio de Calar Alto (Almería). Está compuesto por dos espectrógrafos que observan en el óptico y el infrarrojo cercano, con una resolución espectral de R = 94.600 para el canal visible y R = 80.400 para el canal infrarrojo, y una precisión en velocidad radial de ~ 1 m·s^{-1}. Su principal objetivo científico es la detección de exoplanetas de baja masa en la zona de habitabilidad de estrellas enanas rojas, monitorizando la velocidad radial de una muestra de ~330 estrellas de este tipo de la vecindad solar. El 01/01/2016 el instrumento inició sus observaciones en Tiempo de Observación Garanzatizado (GTO), que le llevarán a completar el muestreo durante un total de 600 noches de observación.

CARMENES es también el consorcio hispano - alemán encargado del diseño, construcción y explotación científica del instrumento, integrado por once instituciones. Estas son: Max-Planck-Institut für Astronomie (MPIA), Instituto de Astrofísica de Andalucía (IAA), Landessternwarte Königstuhl (LSW), Institut de Ciències de l'Espai (ICE), Insitut für Astrophysik Göttingen (IAG), Universidad Complutense de Madrid (UCM), Thüringer Landessternwarte Tautenburg (TLS), Instituto de Astrofísica de Canarias (IAC), Hamburger Sternwarte (HS), Centro de Astrobiología (CAB) y Centro Astronómico Hispano-Alemán (CAHA).

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[2] http://carmenes.caha.es/

1.4.1. Objetivos científicos

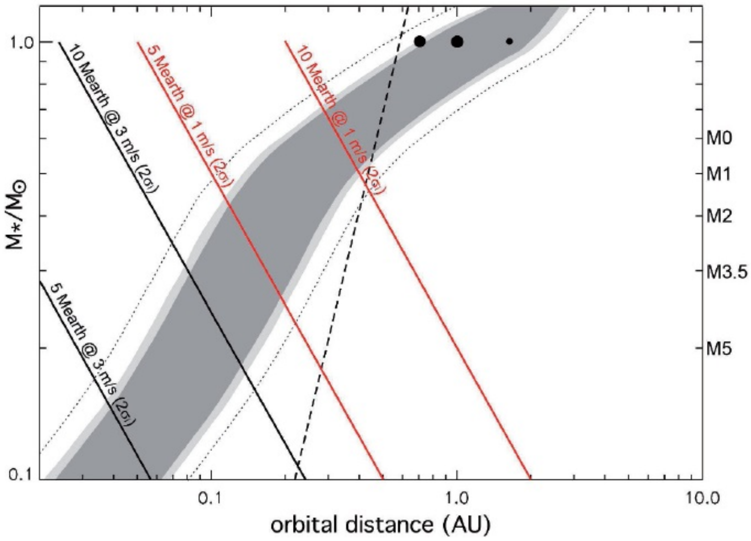

FIGURA 1.7: La región sombreada representa la zona de habitabilidad para enanas rojas como función de la masa estelar y la distancia a la estrella. Las líneas sólidas representan los límites para la detección de super-Tierras de 5 y 10 $M_\oplus$, con precisiones de 1 y 3 m·s^{-1}, y con una significancia de 2σ. La línea discontinua representa la distancia a la que se produce acoplamiento de marea. Tomado de Quirrenbach y col. (2010).

El objetivo principal de CARMENES es detectar planetas de baja masa en la zona de habitabilidad en una muestra de ~330 enanas rojas más tardías que el tipo M4 V. La precisión en velocidad radial de CARMENES es de $\sim$ 1 m·s^{-1}, capaz de detectar un planeta de $M \sim 2\ M_\oplus$ en la zona de habitabilidad de una estrella M5 V. Con esta precisión, CARMENES detectará planetas con $M \sim 5\ M_\oplus$ dentro de los límites de la zona de habitabilidad de estrellas M4 V y más tardías (ver Figura 1.7), aportando información valiosa sobre la ocurrencia y tipología de sistemas planetarios en torno a estrellas enanas M.

Además, con los espectros de alta resolución (en visible e infrarrojo cercano), podrán realizarse estudios de astrosismología, actividad magnética en estrellas ultrafrías, actividad magnética inducida por exoplanetas, determinación precisa de parámetros estelares ($T_{\rm eff}$, velocidad rotacional, gravedad superficial, abundacias), detección de bandas moleculares en atmósferas de exoplanetas, o seguimiento de candidatos detectados por misiones como TESS.

1.4.2. El instrumento

CARMENES está compuesto por dos espectrógrafos que observan simultaneamente en el óptico e infrarrojo cercano (0.55 - 1.05 y 0.95 - 1.7 μm, respectivamente). Dado que la actividad estelar induce señales en velocidad radial de amplitud 2 ó 3 veces superior en el visible que en el infrarrojo (Quirrenbach y col., 2010; Tal-Or y col., 2018), las observaciones simultáneas en ambos canales permiten distinguir la actividad estelar de las señales inducidas por exoplanetas.

El instrumento está acoplado al foco del telescopio de 3.5 m, donde se alimentan las fibras ópticas que van a los dos espectrógrafos. Ambos espectrógrafos, de tipo

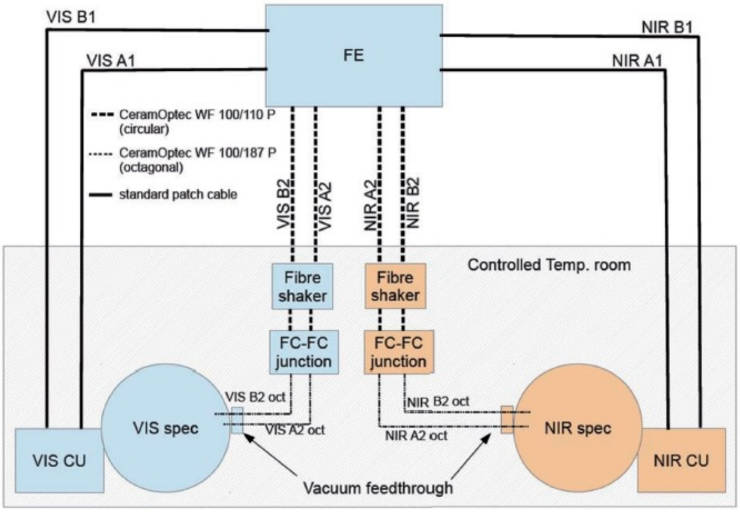

FIGURA 1.8: Representación esquemática del instrumento. Tomado de Amado y CARMENES Consortium (2015).

Echelle, tienen una resolución R = 100000 - 80000 en el rango 0.55 - 1.7 μm y se encuentran dentro de tanques de vacío. El detector visible es un CCD iluminado por detrás de 4112 x 4096 pixeles, mientras que el infrarrojo es un mosaico de dos detectores HAWAii-2RG de 2048 x 2048 pixeles. El canal visible se mantiene enfriado con nitrógeno líquido, mientras que el canal NIR se enfría con un flujo contínuo de nitrógeno gaseoso, encontrándose ambos instrumentos en estancias con temperatura estabilizada. En ambos canales, la calibración se realiza mediante lámparas de Th-Ne y U-Ne e interferómetros Fabry-Pérot.

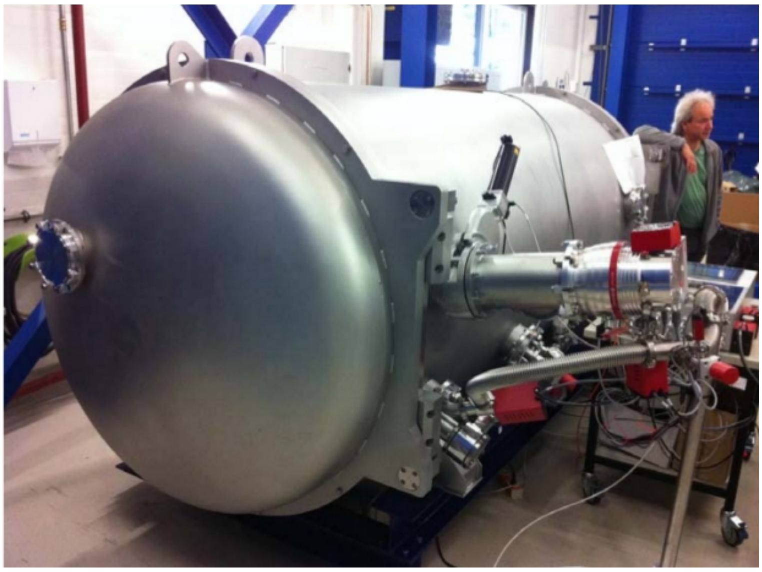

FIGURA 1.9: Tanque de vacío del espectrógrafo visible de CARMENES. Tomado de Quirrenbach y col. (2014).

1.4.3. CARMENCITA

CARMENCITA (CARMENES Cool dwarf Information and daTa Archive), es el nombre del catálogo de estrellas enanas rojas entre las que se encuentran las ∼330 estrellas monitorizadas por el instrumento (Alonso-Floriano y col., 2015; Caballero y col., 2016). Contiene $\sim$ 2200 estrellas cuyos parámetros han sido recopilados tras búsquedas exhaustivas en la literatura, o han sido obtenidos por el consorcio (tipo espectral, astrometría y cinemática, fotometría, multiplicidad, indicadores de actividad, índices espectrales, velocidad rotacional, período de rotación, etc).

El catálogo recopila enanas rojas con declinación >-23º (observables desde Calar Alto con una distancia cenital < +60º), cuyo tipo espectral (en el rango M0.0 V - M9.5 V) ha sido determinado cuidadosamente mediante espectroscopía. Además solo se han incluído las estrellas más brillantes dentro de su tipo espectral, poniendo el límite en J_{mag}=11.5.

1.5. Objetivos de la tesis

Esta tesis tiene como objetivo fundamental aportar información que ayude a extraer conclusiones acerca de la frecuencia de planetas y sistemas planetarios en estrellas enanas de tipo M, así como sobre los parámetros físicos de dichos planetas. Para ayudar a responder esa pregunta se plantean dos objetivos particulares:

En primer lugar obtener los períodos de rotación de las estrellas GTO monitorizadas por CARMENES, para poder distinguir las señales en velocidad radial inducidas por actividad magnética (rotación) de las inducidas por exoplanetas, y para estudiar la relación de los períodos de rotación con la física de dichas estrellas (actividad, estructura interna, edad).

En segundo lugar detectar, confirmar y caracterizar planetas de interés (en zona de habitabilidad, con más de un planeta, en estrellas brillantes), susceptibles de seguimiento posterior en velocidad radial para determinar su masa con instrumentos como CARMENES, o con posibilidad de caracterización atmosférica con instrumentos como el Telescopio Espacial James Webb. La detección y caracterización completa de planetas en el límite rocoso - gaseoso será de especial interés en la comprensión de las teorías de formación y migración planetaria.

1.6. Períodos de rotación de estrellas GTO de CARMENES

1.6.1. Motivación

Como se explica en el punto 1.1.2, la actividad magnética, íntimamente ligada a la rotación, induce señales en velocidad radial semejantes (o que pueden enmascarar) a las inducidas por planetas. Por ello es necesario determinar los períodos de rotación de las estrellas que estudia CARMENES. Además, la determinación de los períodos de rotación de estrellas frías es de especial interés para estudiar su relación con la actividad estelar, la estructura interna y su edad.

Para determinar los períodos de rotación aprovechamos la modulación que las extensas regiones activas (manchas, fulguraciones, playas) presentes en las enanas M, inducen en el brillo de las estrellas al rotar.

TABLA 1.1: Número de curvas de luz y parámetros básicos de los surveys de los que se han obtenido P_{rot}.

Survey	# Curvas de luz	# Estrellas con datos	# P_{rot}	Cadencia de visitas [d]	$\overline{\delta m}$
MEarth	184	95	38	$\sim$0.01	0.004
ASAS	174	174	33	$\sim$2	0.02
SuperWASP	89	89	32	$\sim$0.03	0.02
NSVS	86	86	6	$\sim$1	0.02
ASAS-SN	14	14	4	$\sim$2	0.01
K2	13	13	8	$\sim$0.02	0.0003
HATNet	5	5	2	$\sim$0.002	0.005

1.6.2. Surveys fotométricos

La amplitud de la modulación fotométrica inducida por la rotación estelar está relacionada con la actividad. Las estrellas más activas, con regiones de actividad extensas, pueden alcanzar amplitudes de $\sim$0.05 mag. Esta amplitud es notablemente inferior ($\leq$ 0.01 mag) para las estrellas de más baja actividad (Messina y col., 2003; Kiraga, 2012; Suárez Mascareño, Rebolo y González Hernández, 2016).

Para obtener las curvas de luz en las que investigamos si hay modulación fotométrica atribuible a la rotación estelar, se hizo uso de surveys fotométricos públicos. Se encontraron períodos fotométricos con curvas de luz de los surveys ASAS (Pojmanski, 1997), SuperWASP (Pollacco y col., 2006), MEarth (Nutzman y D., 2008), NSVS (Woźniak y col., 2004), K2 (Howell y col., 2014), ASAS-SN (Kochanek y col., 2017) y HATNet (Bakos y col., 2004). En la Tabla 1.1 se indica, para cada uno de estos surveys, el número de curvas de luz recopiladas, número de estrellas con datos, número de P_{rot} obtenidos, cadencia de visitas y el valor medio del error.

También se extrajeron curvas de luz (aunque sin períodos de rotación resultantes) del survey Catalina (Drake y col., 2009), y se investigaron otros surveys (sin que se encontraran datos de estrellas de nuestra muestra) como TrES (Alonso y col., 2007), CoRoT (Auvergne y col., 2009), LINEAR (Stokes y col., 2000), XO (McCullough y col., 2005) ó KELT (Pepper y col., 2007).

1.6.3. Observaciones propias

La amplitud de la modulación fotométrica debida a la rotación estelar, del orden de centésimas de magnitud, está al alcance de detección de los equipos con los que cuentan ciertos astrónomos aficionados avanzados. Por ello, para 16 estrellas carentes de datos en los surveys investigados (o de calidad insuficiente) se realizó un seguimiento fotométrico en colaboración con observatorios amateurs, sumando $\sim$ 100 horas de observaciones. Los observatorios colaboradores fueron: *Carda*[3] (Asturias, MPC Z76), *Moncabrer*[4] (Barcelona, MPC 213), *AstroLAB IRIS*[5] (Ypres, Bélgica) y *la Vara*[6] (Asturias, MPC J38). También se emplearon cien horas de observación con el telescopio de 0.8 m *Joan Oró* del *Observatori Astronomic del Montsec (OAdM)*[7] (Barcelona, MPC C65) para realizar seguimiento fotométrico de otras 4 estrellas GTO.

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[3] http://www.auladeastronomia.es

[4] http://cometas.sytes.net

[5] http://astrolab.be

[6] http://www.elobservatoriu.com/observatorio

[7] http://www.oadm.cat

TABLA 1.2: Número de curvas de luz y parámetros básicos de las observaciones realizadas en colaboración con observatorios amateurs y profesionales.

Observatorio	# Curvas de luz	# Estrellas con datos	# P_{rot}	Cadencia de visitas [d]	$\overline{\delta m}$
AstroLab Iris	7	7	3	∼2	0.01
Montcabrer	6	6	2	∼0.003	0.005
Montsec	4	4	1	∼0.5	0.005
Carda	3	3	0	∼0.003	0.005

En la Tabla 1.2 se indica, para cada observatorio colaborador, el número de curvas de luz recopiladas, número de estrellas con datos, número de P_{rot} obtenidos, cadencia de visitas y el valor medio del error.

1.6.4. Análisis de datos

Los surveys públicos ofrecen extraída la fotometría de las estrellas a estudiar. Típicamente las curvas de luz constan de tres columnas: fecha, magnitud y error en la magnitud.

Para obtener las curvas a partir de observaciones propias, se realizó por completo el proceso de reducción de las imágenes y obtención de la fotometría. Las imágenes se redujeron de manera estándar mediante darks, flats y bias, empleando paquetes comerciales como *MaxIm*[8].

La magnitud de la estrella en cada imagen se obtiene mediante la técnica de *fotometría diferencial*, es decir, comparando el brillo de la estrella a estudiar con el de otras estrellas presentes en el campo similares en color, con suficiente relación señal/ruido, que no sean variables y de magnitud conocida. Fueron elaboradas cartas de observación para cada estrella a observar como la presentada en la Figura 1.10.

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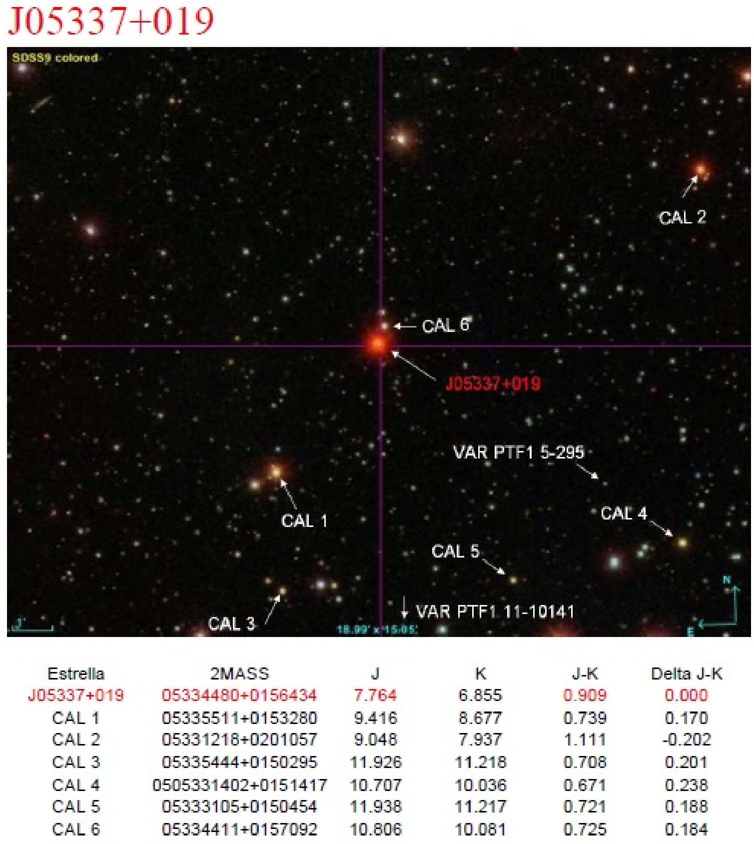
[8] http://diffractionlimited.com/product/maxim-dl/



Estrella	2MASS	J	K	J-K	Delta J-K
J05337+019	05334480+0156434	7.764	6.855	0.909	0.000
CAL 1	05335511+0153280	9.416	8.677	0.739	0.170
CAL 2	05331218+0201057	9.048	7.937	1.111	-0.202
CAL 3	05335444+0150295	11.926	11.218	0.708	0.201
CAL 4	0505331402+0151417	10.707	10.036	0.671	0.238
CAL 5	05333105+0150454	11.938	11.217	0.721	0.188
CAL 6	05334411+0157092	10.806	10.081	0.725	0.184

FIGURA 1.10: Carta de observación de la estrella J05337+019 (V371 Ori) (M3.0 V). Se indica la posición de la estrella así como de estrellas para comparación, con sus magnitudes J & K y su índice de color J-K.

La fotometría diferencial (de apertura) se realizó con los paquetes *FotoDif*[9], *AstroImageJ*[10] y *LesvePhotometry*[11].

Una vez obtenida la fotometría, y con el fin de limpiar de las curvas aquellos datos de baja calidad originados por la debilidad de las estrellas, malas condiciones atmosféricas o posibles fulguraciones, se realizó una limpieza 2.5 σ siguiendo los procedimientos presentados en Suárez Mascareño, Rebolo y González Hernández (2016).

Para obtener las señales más significativas, se obtuvo el periodograma *Lomb-Scargle* (Scargle, 1982) de cada curva de luz. Para ello se usó el software *Peranso* (Paunzen y T., 2016). Además se evaluó la significancia de las señales obteniendo una probabilidad de falsa alarma mediante la modificación de Cumming (2004) de la expresión de Horne y S. L. (1986). Las curvas de luz de ciertas estrellas *criticas* (dobles espectroscopicas, con datos de K2, $P_{rot} < 1$ d, o con diferencias entre el P_{rot} encontrado y el reportado previamente en la literatura superiores al 10 %) fueron tambien analizadas mediante periodograma *GLS (Generalized Lomb – Scargle)* (Zechmeister y M., 2009) y metodos Gaussianos de regresion (Rasmussen y C.K.I., 2006).

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[9] http://www.astrosurf.com/orodeno/fotodif/

[10] https://www.astro.louisville.edu/software/astroimagej/

[11] http://www.dppobservatory.net/AstroPrograms/Software4VSObservers.php

Para la obtención de los periodogramas, la frecuencia mínima de búsqueda se fijó en correspondencia con la mitad de la extensión temporal de las observaciones (típicamente $\sim$0.005 d^{-1}), mientras que la frecuencia máxima se fijó a la frecuencia de Nyquist. Sólo se consideraron aquellas señales con una probabilidad de falsa alarma $<$ 2 % y para las que la extensión de la ventana temporal de las observaciones fuera, como mínimo, el doble que el período correspondiente a la señal. Además se realizó una inspección visual de todas las señales (ver Figura 1.11).

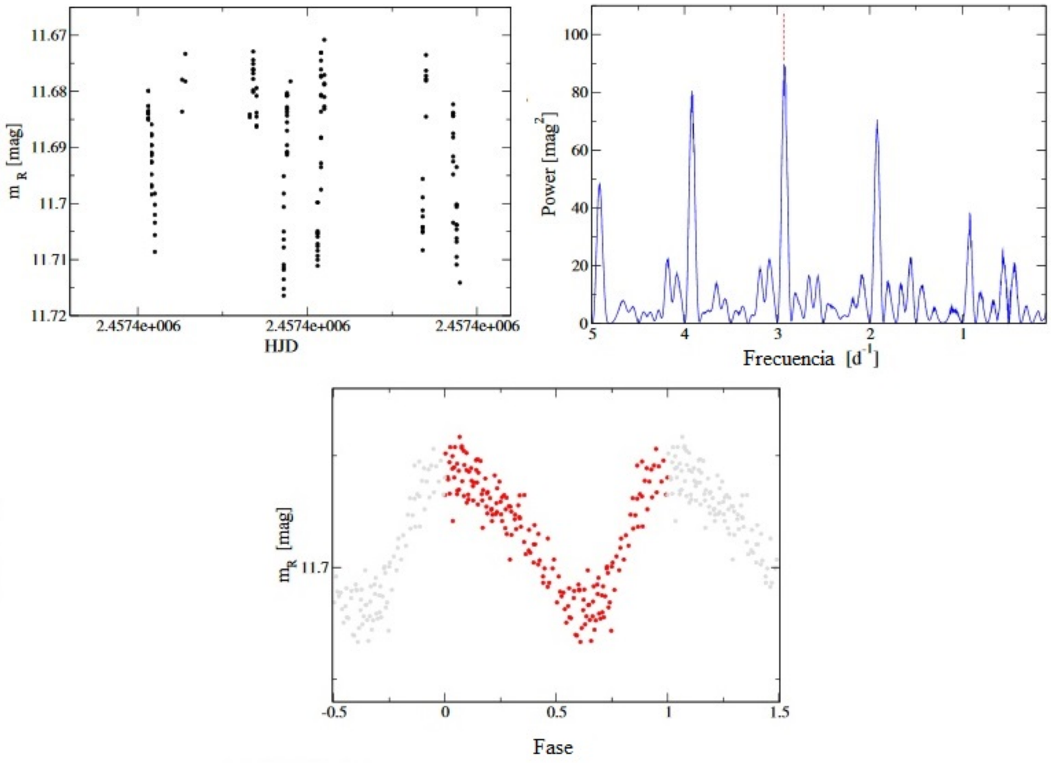

FIGURA 1.11: Curva de luz en banda *R* (panel superior izquierdo), periodograma Lomb-Scargle (panel superior derecho) y curva de rotación (panel inferior) de la estrella J04772+206 (M5.0 V). Observaciones realizadas desde el observatorio Moncabrer. Tomado de Díez Alonso y col. (2019b).

1.6.5. Resultados

El objetivo principal de este trabajo era el de obtener los períodos de rotación para discriminar entre las señales en velocidad radial inducidas por exoplanetas y las originadas por la actividad estelar. En lo relativo a este punto, se buscaron períodos para un total de 337 estrellas M del catalogo de CARMENES, recopilando 622 curvas de luz de 334 estrellas, y realizando observaciones propias para 20. Se encontraron 142 señales que interpretamos como causadas por la rotación estelar, de las cuales 73 se citan por vez primera en la literatura, mientras que las 69 restantes reproducen los períodos reportados previamente.

En el apéndice A se presentan las tablas con los datos de las 622 curvas de luz recopiladas, y de los 142 períodos de rotación obtenidos. Al final del mismo se presenta un ejemplo de curva de luz, periodograma Lomb-Scargle y curva de rotación para cada survey u observatorio. En el apéndice B se recopila, para las 142 estrellas con P_{rot} determinado, la curva de luz del survey utilizado para obtener el P_{rot} (panel superior), su periodograma Lomb-Scargle (panel central) y la curva de rotación correspondiente (panel inferior).

Además, con datos del survey ASAS (con una extensión temporal típica de ∼10 años), se identificaron 10 señales que interpretamos como ciclos de larga actividad (ver Figura 1.12). De ellas, 6 son reportadas por primera vez. Las estrellas de nuestra muestra para las que se ha encontrado tanto P_{rot} como P_{ciclo}, han sido añadidas a otra muestra de 47 enanas M con P_{rot} y P_{ciclo} publicados, con la finalidad de estudiar la relación entre ambos. El resultado ha sido que no se encuentra correlación para estrellas enanas M, en acuerdo con estudios anteriores (Savanov, 2012; Suárez Mascareño, Rebolo y González Hernández, 2016).

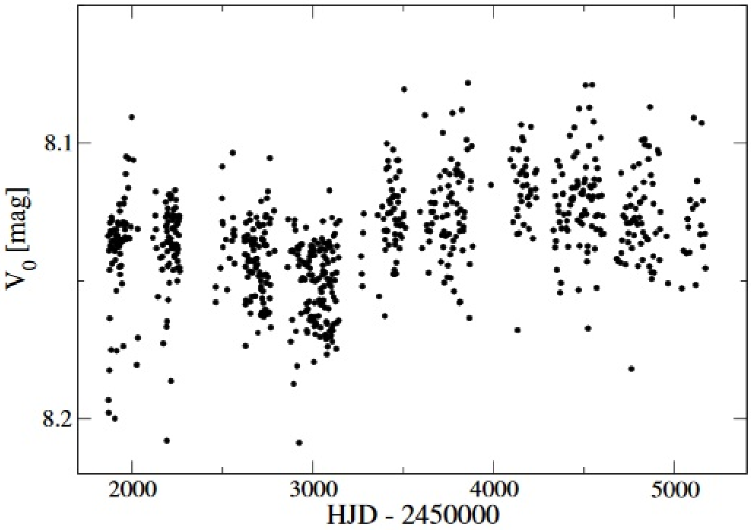

FIGURA 1.12: Curva de luz del survey ASAS de la estrella M0.5 V J06105-218 (banda V). Se aprecia una modulación en ∼8 años relacionada con un ciclo de actividad. Tomado de Díez Alonso y col. (2019b)

.

Tampoco detectamos el *gap* en ∼30 d en el histograma del número de estrellas frente al período de rotación (ver Figura 3 del artículo de Díez Alonso y col. (2019b), capítulo 2) reportado por Newton y col. (2016), sino que encontramos más abundancia de períodos $>$ 30 d y una distribución plana para períodos $<$ 30 d. Atribuímos este hecho a que los surveys que usamos (exceptuando SuperWASP y MEarth) tienen frecuencias de visita ∼1 semana, y por lo tanto son más eficaces en la detección de períodos de rotación largos.

Determinamos por primera vez el período de rotación de tres estrellas que se encuentran entre la lista de 31 estrellas muy activas presentadas por Tal-Or y col. (2018). Además confirmamos la relacion entre período de rotación y actividad, especialmente con la velocidad rotacional $vsini$, y $pEW(H_{\alpha})$. También reportamos la no correlación entre la amplitud de la variabilidad fotométrica con P_{rot}, $vsini$ y $pEW(H_{\alpha})$.

1.7. Exoplanetas con la misión K2

1.7.1. Motivación

Las enanas M presentan una mayor abundancia de planetas rocosos que otros tipos espectrales. Además dada su baja luminosidad la zona de habitabilidad se encuentra más próxima, por lo que es más fácil detectar y estudiar planetas en esta zona. Por lo tanto, la detección de candidatos planetarios que transiten en estrellas enanas M, cuya caracterización pueda ser completada con observaciones en velocidad radial realizadas por instrumentos como CARMENES, es de especial interés para el estudio de planetas tipo terrestre en zona de habitabilidad, de las interacciones que puedan tener lugar con sus estrellas y para mejorar el entendimiento de los procesos de formación y migración planetaria.

Entre los surveys investigados para determinar los períodos de rotación de las estrellas observadas por CARMENES, se encuentran las diferentes campañas de observación de la misión extendida del telescopio espacial Képler (en adelante *K2*), con trece estrellas GTO observadas por K2 hasta la campaña 15, finalizada el 14 de mayo de 2018 (última campaña concluída antes del envío de la publicación de Díez Alonso y col., 2019b). La cadencia de observación de 29.5 minutos y la precisión fotométrica de $\sim$ 0.4 mmag para una sola exposición de 29.5 minutos y de $\sim$ 0.1 mmag para escalas temporales de 6 horas (Howell y col., 2014), lo convierten en el mejor survey (solo limitado por por la extensión temporal de las campañas de $\sim$ 80 d) para encontrar no solo períodos de rotación fotométricos, si no también señales de posibles planetas que transiten, susceptibles de un seguimiento posterior con instrumentos como CARMENES.

1.7.2. El telescopio espacial Képler y su misión extendida (K2)

El telescopio espacial Képler (Borucki y col., 2010) fue lanzado en marzo de 2009 con el objetivo de observar de manera continuada un mismo campo situado en el plano galáctico (a caballo entre las constelaciones Cygnus, Lyra y Draco), monitorizando con una cadencia de dos minutos (observaciones posteriormente agrupadas cada 30 minutos para la gran mayoría de estrellas) el brillo de $\sim$ 150.000 estrellas para detectar candidatos a exoplanetas mediante el método de tránsitos. Entre los diferentes objetivos científicos de la misión estaba el de obtener estadística precisa sobre el número de planetas que se encuentran en la zona de habitabilidad de estrellas de diferentes tipos espectrales.

El satélite albergaba un telescopio Schmidt de 0.95 m de apertura y un sensor CCD consistente en 21 módulos (junto con otros cuatro módulos destinados a guiado) de 2200x2048 pixeles cada uno, con sensibilidad entre 400 y 850 nm. Cada módulo cubría un área de 5^o cuadrados, cubriendo un total de 105^o cuadrados.

Con un período orbital de 372.5 d, el satélite Képler orbitaba alrededor del Sol siguiendo a la Tierra y alejándose de nuestro planeta a razón de 16 millones de km por año. Esta órbita fue elegida por permitir que el satélite apuntara al campo original sin apenas verse perturbado por nuestro planeta.

La misión estaba prevista hasta el año 2016, pero se dio por concluída en mayo de 2013 tras el fallo de dos giróscopos, lo que impedía mantener el instrumento apuntando de manera correcta el campo de observación inicial. Como solución a este problema se propuso observar campos próximos al plano de la eclíptica (ver Figura 1.13). Así, la presión ejercida por el viento solar, los dos giróscopos restantes y los propulsores permitirían el control del apuntado y que y el satélite pudiera seguir observando.

Gracias al apuntado ultra estable de la misión original, que contaba con cuatro giróscopos, la precisión fotométrica era de 20 partes por millón. En la misión extendida, la pérdida de dos giróscopos redujo la precisión de apuntado, induciendo una deriva de los campos observados que periódicamente debía ser corregida. La fotometría proporcionada por la misión extendida necesita ser corregida para mitigar el efecto de dicha deriva y obtener así una fotometría más precisa, que en todo caso se ha visto reducida a 300 partes por millón.

El telescopio comenzó su segunda misión en marzo de 2014, prologándose hasta el 30 de octubre de 2018, fecha en la que la NASA anunció la retirada del instrumento, tras 19 campañas de observación y con el combustible agotado.

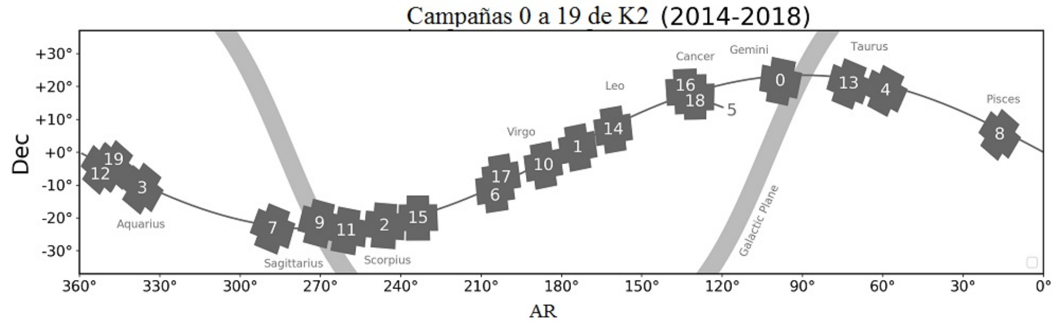

FIGURA 1.13: Campos de las diferentes campañas de observación del Telescopio Espacial Képler en su misión extendida (K2). Tomado de https://keplerscience.arc.nasa.gov/.

A fecha 26/12/18, el número de exoplanetas confirmados por Képler es de 2704 (2328 en el campo original y 359 en las diferentes campañas de K2), mientras que el número de candidatos aun por confirmar es de 2898 (2425 en el campo original y 473 en las campañas de K2)[12]. Estos números aumentarán, con multitud de objetos aun por descubrir entre todas las curvas de luz generadas por el satélite.

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[12] Datos obtenidos de https://exoplanetarchive.ipac.caltech.edu/

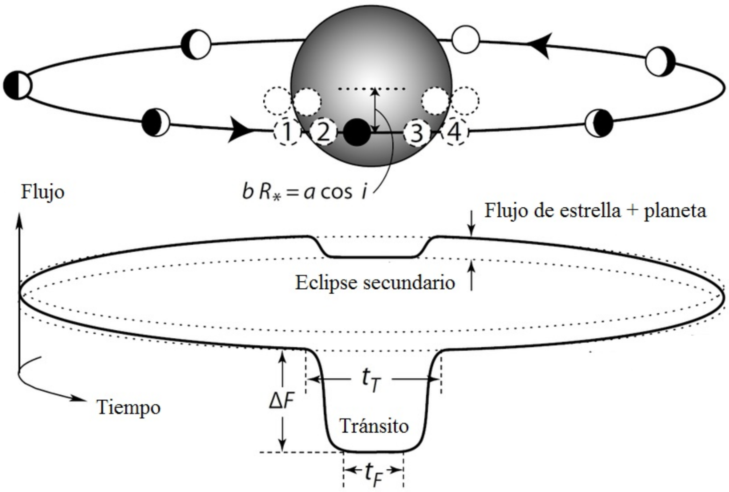

FIGURA 1.14: Esquema de un tránsito. Durante el tránsito, el planeta bloquea parte de la luz de la estrella. Tras el tránsito, la fase del planeta crece y el flujo total aumenta, para disminuir de nuevo cuando el planeta pasa por detrás de la estrella. Los círculos indican las distintas etapas del tránsito para diferentes parámetros de impacto. t_τ es la duración total del tránsito, mientras que t_F es el tiempo entre el segundo y el tercer contacto. Tomado de *The exoplanet handbook* (Perryman, 2011).

1.7.3. Método de tránsito

El Telescopio Espacial Képler usa el método de *tránsitos* para detectar candidatos a exoplanetas. Esta técnica, válida para sistemas con inclinación $i \sim 90^{\circ}$ (plano orbital coincidente con la visual desde la Tierra), consiste en detectar las disminuciones periódicas en el brillo de la estrella que tienen lugar cada vez que un planeta *transita* por delante del disco de esta. El método da información del tamaño del planeta así como de su órbita (ver Figura 1.14).

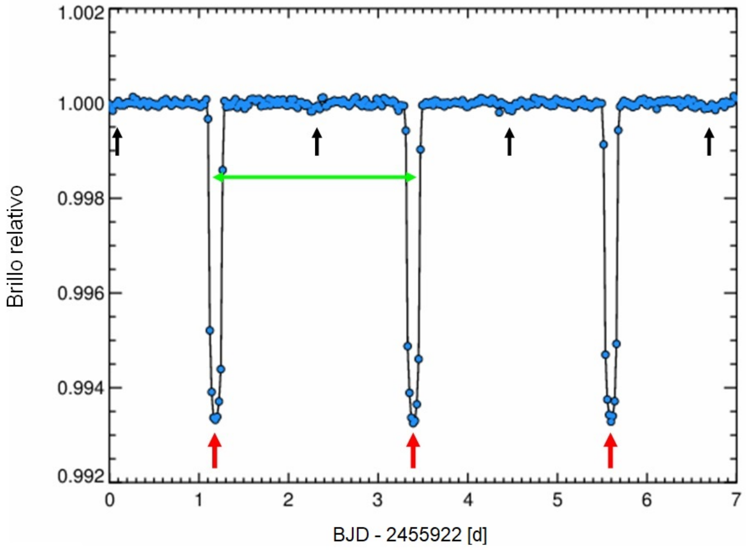

FIGURA 1.15: Curva de luz del telescopio espacial Képler de la estrella HAT-P-7, con tres tránsitos del *Júpiter caliente* HAT-P-7 b. Tomado de https://www.cfa.harvard.edu/ avanderb/tutorial/tutorial2.html.

La Figura 1.15, presenta siete días de la curva de luz (con datos de Képler) de la estrella KIC 10666592, situada en el campo original del telescopio espacial Képler. La estrella es orbitada por el *Júpiter caliente* HAT-P-7 b (Pál y col., 2008).

Se necesitan al menos tres tránsitos con una relación señal/ruido $> 7.1\sigma$ (Jenkins, 2002) para considerar un posible candidato (las flechas rojas en la Figura 1.15 señalan la posición de los tres tránsitos presentes en la curva de luz). Notemos que, a pesar de que el planeta es un gigante gaseoso muy próximo a su estrella, la disminución del brillo que tiene lugar cuando el planeta transita es tan solo de ~ 1 %. Cuanto mayor sea el planeta, más luz bloqueará y más profundo será el tránsito. El radio del planeta se puede obtener modelando la curva de luz, incluyendo el oscurecimiento del limbo de la estrella. Ahora bien, en primera aproximación se puede estimar el radio del planeta (R_p) midiendo la profundidad del tránsito (ΔF) y sabiendo el radio de la estrella (R_*) a partir de la siguiente expresión (solo válida si el flujo del planeta es despreciable respecto al de la estrella, y la superficie de esta presenta un brillo homogéneo):

$$\Delta F = \left(\frac{R_p}{R_*} \right)^2 \tag{1.2}$$

El período orbital del planeta es el tiempo transcurrido entre tránsitos consecutivos (flecha verde en la figura 1.15), mientras que cuando el planeta pasa por detrás de la estrella se produce una levísima disminución de brillo: el eclipse secundario (flechas negras en la figura 1.15).

La Figura 1.16 presenta en detalle el tránsito de HAT-P-7b, tras promediar en intervalos de 20 segundos el $\sim$6 % de toda la fotometría obtenida por Képler para HAT-P-7. t_τ es la duración total del tránsito (tiempo entre las fases 1 y 2 en la Figura 1.14), mientras que t_f es el tiempo transcurrido con el planeta completamente inmerso en el disco estelar (fases 2 y 3 en la Figura 1.14). Entre las fases 2 y 3, el perfil del tránsito no es plano debido al *oscurecimiento del limbo* de la estrella.

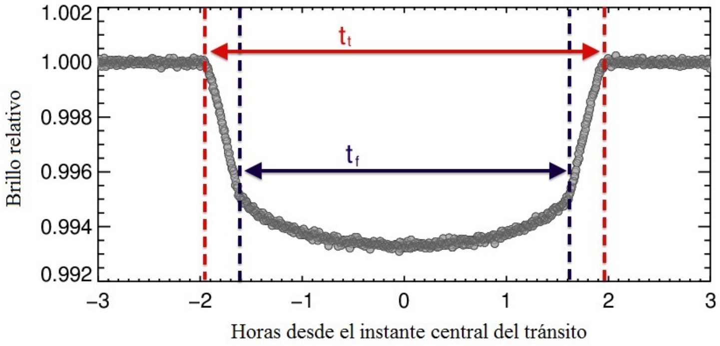

FIGURA 1.16: Tránsito de HATP-7-b, resultado de promediar el $\sim$6 % de la fotometría de HAT-P-7 obtenida por Képler y agrupar los datos en intervalos de 20 segundos. Tomado de https://www.cfa.harvard.edu/~avanderb/k2.html.

La duración del tránsito y su profundidad codifican la información de lo más o menos cerca que el planeta transita del centro del disco estelar (parámetro de impacto, $b = a \cdot \cos i / R_*$, con a la distancia estrella - planeta). Cuanto más lejos del centro (mayor *b*), menor será la duración del tránsito y menos abruptas serán la entrada y la salida del tránsito (ver Figura 1.17).

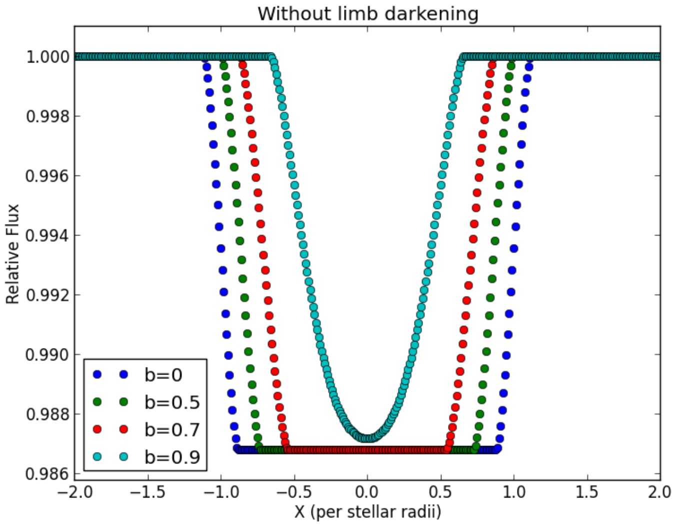

FIGURA 1.17: Simulación de tránsitos de un planeta con R_p = 10 $R_\oplus$ sobre una estrella con R_* = 0.8 $R_\odot$, variando el parámetro de impacto y sin tener en cuenta el oscurecimiento del limbo. Tomado de https://blog.planethunters.org/

1.7.4. Metodología

Todas las curvas de luz de estrellas GTO de CARMENES obtenidas de surveys diseñados para la detección de exoplanetas (SuperWASP, MEarth, HATNet y K2), fueron investigadas para detectar la presencia de tránsitos. Para ello se empleó el método Box Least Squares (BLS) de Kovács, S. y T. (2002), implementado en el paquete LCTools[13].

Se eligieron las campañas 13, 14 y 15 de K2 para analizar las curvas de luz de las estrellas enanas rojas presentes en ellas, buscando candidatos a exoplanetas mediante el método de tránsitos. Se seleccionaron dichas campañas por ser las más recientes en ese momento, y por lo tanto las más susceptibles de albergar nuevos candidatos. De entre los múltiples candidatos detectados, los esfuerzos de confirmación y caracterización se centraron en aquellos de mayor interés (sistemas con dos o más planetas, planetas tipo Tierra o super-Tierra en zona de habitabilidad, planetas en estrellas pertenecientes a cúmulos o grupos de movimiento de edad conocida).

Búsqueda de candidatos

Para identificar candidatos a exoplanetas en las campañas de K2 investigadas se utilizaron las curvas de luz de Andrew Vanderburg, disponibles en el Mikulski Archive for Space Telescopes (MAST)[14]. En dichas curvas la fotometría ha sido extraída teniendo en cuenta la no uniformidad en la respuesta de los pixeles del detector, correlacionando las medidas de flujo con el apuntado del telescopio y eliminando la

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[13] https://sites.google.com/a/lctools.net/lctools/home

[14] https://archive.stsci.edu/

dependendia, tal y como se detalla en Vanderburg y J. A. (2014).

De entre las ∼30.000 curvas de luz que integran cada campaña, se seleccionaron las correspondientes a enanas M filtrando por temperatura ($T < 4000$ K) y gravedad superficial ($logg > 4.5$). Aunque la práctica totalidad de las enanas M de las campañas 13, 14 y 15 fueron investigadas, se dio preferencia a las más brillantes (m$_V$ $\leq$13), de más fácil caracterización espectroscópica, con un posible seguimiento posterior en velocidad radial más sencillo para establecer la masa de los planetas, así como para su caracterización atmosférica.

Para buscar los tránsitos en cada curva de luz, en primer lugar se procedió a quitar tendencias aplicando un filtro de mediana, con el que se sustituye el valor de cada punto por la mediana de un cierto número de puntos contiguos. Por defecto se adoptó el número razonable de 16 puntos contiguos, inspeccionando visualmente que el ajuste era adecuado en las curvas con candidatos de interés. A continuación se buscaban señales de posibles tránsitos mediante el método BLS (Box Least Squares, Kovács, S. y T., 2002). Cuando una señal es detectada, esta se sustrae de la curva y el método vuelve a aplicarse en búsqueda de más señales (ver Figura 1.18).

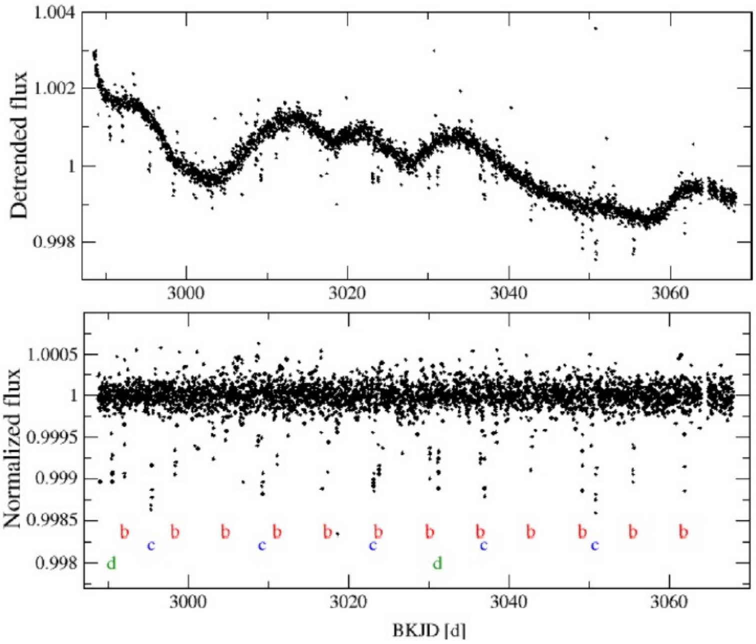

FIGURA 1.18: El panel superior presenta la curva de luz corregida (datos de K2) de la estrella K2-155. El panel inferior presenta la misma curva sustraídas las tendencias, e indicando los tránsitos de los planetas K2-155 b, c y d. Tomado de Díez Alonso y col. (2018a).

Caracterización estelar

Detectadas señales de interés en una estrella, el primer paso era caracterizar correctamente sus parámetros (tipo espectral, temperatura efectiva, radio...) ya que de ellos dependen los de sus planetas. Para todas las estrellas con planetas presentadas en este trabajo, el tipo espectral fue estimado comparando modelos teóricos (Kesseli y col., 2017) con espectros adquiridos mediante el espectrógrafo HARPS-N (Cosentino y col., 2012), instalado en el Telescopio Nazionale Galileo, o mediate la cámara - espectrógrafo OSIRIS (Cepa y col., 2000), instalada en el Gran Telescopio Canarias (ambos telescopios situados en el Roque de los Muchachos, la Palma, Islas Canarias) (ver Figura 1.19). También se analizaron espectros públicos, como los disponibles en la base de datos EXOFOP-K2[15] o los adquiridos por el Radial Velocity Experiment (RAVE DR5, Kunder y col., 2017).

Deducir las propiedades físicas de las estrellas poco masivas por comparación de sus espectros con modelos teóricos presenta dificultades notables; el modelado de la convección en el interior estelar (Browning, 2008), la variedad de moléculas presentes en sus atmósferas (Allard, P. H. y D., 2000) o las altas presiones que obligan a tener en cuenta transiciones colisionales (Chabrier e I., 1997), dificultan este trabajo. Por lo tanto, los parámetros estelares fueron estimados por dos o más métodos independientes para finalmente obtener valores promedio (ver los capítulos 3, 4 y 6 para más detalle).

Por un lado, los parámetros estelares (temperatura efectiva, radio, masa), fueron estimados siguiendo los procedimientos presentados en (e.g. Casagrande, C. y M., 2008; Mann y col., 2013; Mann y col., 2015; Newton y col., 2014; Newton y col., 2015). Estos, a partir de los cocientes de los flujos correspondientes a diferentes regiones del espectro, así como de la anchura equivalente de ciertos rasgos espectrales, establecen relaciones empíricas que conectan flujos en diferentes colores (óptico e infrarrojo) con propiedades físicas estelares.

Los parámetros estelares también se estimaron a partir de modelos para estrellas de secuencia principal (e.g. Pecaut y E. E., 2013; Baraffe y col., 2015).

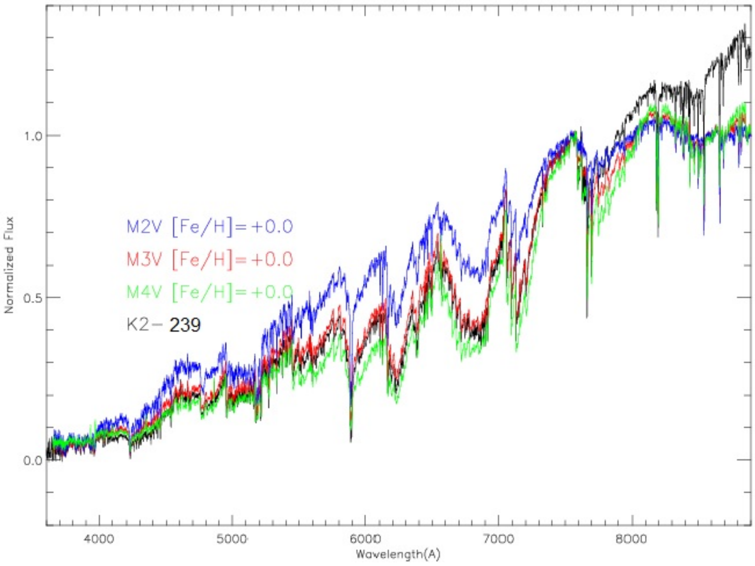

FIGURA 1.19: Espectro de la estrellas K2-239 (M3.0 V) obtenido con la cámara - espectrógrafo OSIRIS, comparado con espectros de referencia de estrellas de tipos M2.0 V a M4.0 V y [Fe/H]∼0. Tomado de Díez Alonso y col. (2018b)

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[15] https://exofop.ipac.caltech.edu/k2/

Caracterización de los planetas

Los parámetros de los planetas fueron obtenidos a partir de sus tránsitos puestos en fase (ver Figura 1.20) y teniendo en cuenta el oscurecimiento al borde de la estrella. Se ajustaron modelos de Mandel y E. (2002), mediante métodos de Monte Carlo y Cadenas de Markov (MCMC). Para ello se usaron los códigos EXOFAST (Eastman, B. S. y E., 2013) y PYANETTI (Barragán, D. y G., 2019).

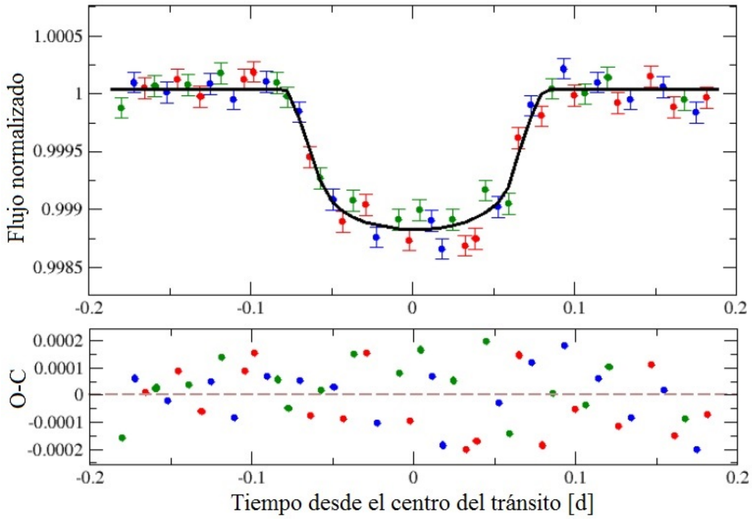

FIGURA 1.20: En el panel superior se presentan en fase los tres tránsitos del exoplaneta K2-286 b presentes en la curva de luz de K2. El código de colores indica el primer tránsito (rojo), segundo (azul) y tercero (verde). La curva negra indica el mejor ajuste obtenido con MCMC. En el panel inferior se presentan los residuales del ajuste. Tomado de Díez Alonso y col. (2018b).

Análisis de falsos positivos

Es fundamental descartar escenarios que puedan resultar en falsos positivos. Por ejemplo que las señales sean debidas a que la propia estrella candidata sea una binaria eclipsante, o que procedan de estrellas cuya posición relativa en el plano del cielo sea próxima, que puedan pasar inadvertidas y que a su vez sean binarias eclipsantes o que presenten tránsitos planetarios. Para ello se analizaron imágenes de archivo de los surveys POSS-I (Minkowski y G. O., 1963), 2MASS (Cutri y col., 2003) y Pan-STARRS 1 (Chambers y Pan-STARRS Team, 2018), así como imágenes de alta resolución, adquiridas expresamente o disponibles en la base de datos EXOFOP-K2[16] (ver Figura 1.21). Además se realizaron validaciones estadísticas con el paquete VESPA (Morton, 2012) que evalúa las probabilidades de diferentes escenarios (en particular binarias eclipsantes, binarias eclipsantes de campo y sistemas triples jerárquicos).

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[16] https://exofop.ipac.caltech.edu/k2/

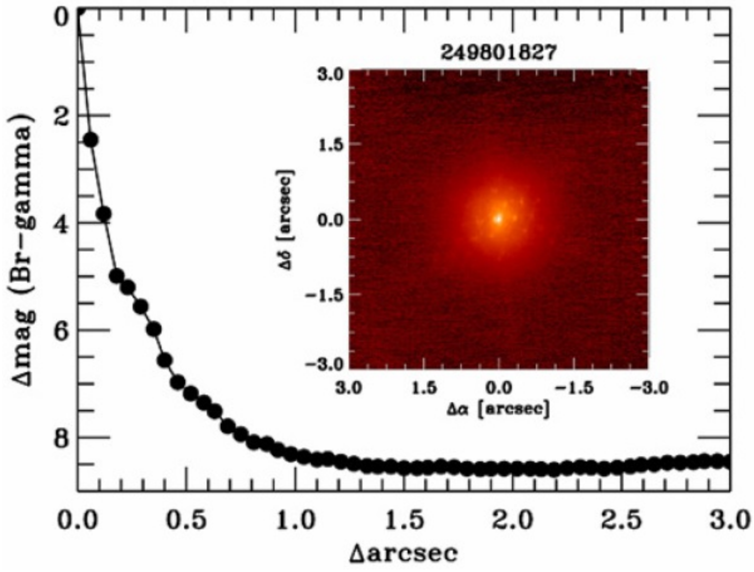

FIGURA 1.21: Imagen de alta resolución de la estrella K2-240 y curva de contraste correspondiente, obtenida con el instrumento NIRC2 instalado en el telescopio Keck-2. Tomado de Díez Alonso y col. (2018b) (disponible en la base de datos EXOFOP-K2).

Estimación de masa, V_r inducida y amplitud de señal en espectroscopía de transmisión

El método de tránsitos informa sobre el radio de los planetas, pero no sobre su masa. Aun así, esta fue estimada mediante relaciones masa - radio empíricas (Weiss y G. W., 2014), y probabilísticas (Wolfgang, L. A. y E. B., 2016; Chen y D., 2017).

Con las masas y asumiendo órbitas circulares, estimamos un límite inferior para la semiamplitud en velocidad radial que cada planeta inducirá en su estrella, obteniendo valores que oscilan entre 0.5 $m{\cdot}s^{-1}$ (K2-239 c) y 2.5 $m{\cdot}s^{-1}$ (K2-240 b). Concluimos por lo tanto, que las masas de estos planetas podrán ser determinadas con precisión a partir de un seguimiento en velocidad radial mediante espectrógrafos de alta resolución como CARMENES o ESPRESSO (Pepe y col., 2014).

Para todos los planetas también se estimó la amplitud de la señal en espectroscopía de transmisión, obteniendo valores que oscilan entre 5 ppm (K2-286 b) y 35 ppm (K2-155 b), dentro de las capacidades del futuro Telescopio Espacial James Webb.

1.7.5. Resultados

En las curvas de luz con datos de estrellas GTO de CARMENES procedentes de los surveys MEarth, SuperWASP y HATNet no se detectó ninguna señal candidata a tránsito planetario, mientras que sí se detectaron los tránsitos presentes en las curvas de luz de K2 de las estrellas K2-18 (J11302+076, Sarkis y col., 2018) y K2-33 (J16102-193, Mann y col., 2016; David y col., 2016).

La investigación exhaustiva de las curvas de luz de estrellas enanas M de las campañas 13 (un total de 1748 estrellas analizadas), 14 (6095 estrellas analizadas) y 15 (5341 estrellas analizadas) de K2 resultó en los siguientes sistemas:

TABLA 1.3: Parámetros de los planetas del sistema K2-155.

Parámetro	K2-155 b	K2-155 c	K2-155 d
Período orbital (P) [d]	6.342±0.002	13.850±0.006	40.718±0.005
Semieje mayor (a) [UA]	$0.0562^{+0.0013}_{-0.0014}$	$0.0946^{+0.0031}_{-0.0030}$	$0.1937^{+0.0064}_{-0.0059}$
Radio (R_p) [$R_\oplus$]	$1.8^{+0.2}_{-0.1}$	$2.6^{+0.7}_{-0.2}$	$1.9^{+0.7}_{-0.2}$
Masa (M_p) [$M_\oplus$] (1)	$4.7^{+0.5}_{-0.3}$	$6.5^{+1.5}_{-0.5}$	$4.9^{+1.7}_{-0.6}$
Temperatura de equilibrio (T_{eq}) [K]	708^{+38}_{-31}	583^{+52}_{-35}	381^{+47}_{-25}

TABLA 1.4: Parámetros de los planetas del sistema K2-239.

Parámetro	K2-239 b	K2-239 c	K2-239 d
Período orbital (P) [d]	5.240 ± 0.001	7.775 ± 0.001	10.115 ± 0.001
Semieje mayor (a) [UA]	0.0441 ± 0.0008	0.0576 ± 0.0009	0.0685 ± 0.0012
Radio (R_p) [$R_\oplus$]	1.1 ± 0.1	1.0 ± 0.1	1.1 ± 0.1
Masa (M_p) [$M_\oplus$] (1)	1.4 ± 0.4	0.9 ± 0.3	1.3 ± 0.4
Temperatura de equilibrio (T_{eq}) [K]	502^{+22}_{-18}	427^{+24}_{-19}	399^{+18}_{-15}

K2-155

K2-155 (m$_V$=12.81) es una estrella caracterizada en nuestro trabajo como K6 V. Ha sido monitorizada en la campaña 13 de K2, y en su curva de luz se aprecian los tránsitos de tres super-Tierras. El planeta más exterior, K2-155 d, se encuentra próximo al límite interior de la zona de habitabilidad de K2-155. Los parámetros de los planetas se presentan en la Tabla 1.3.

K2-239

K2-239 (m$_V$=14.55), monitorizada por K2 en la campaña 14, ha sido caracterizada en este trabajo como M3.0 V. La estrella es transitada por tres planetas de tipo Tierra en una configuración compacta y resonancia 2:3:4. Los parámetros de los planetas se presentan en la Tabla 1.4.

K2-240

K2-240 (m$_V$= 13.39) es una estrella caracterizada en este trabajo como M0.5 V, monitorizada por K2 en la campaña 15. La estrella es transitada por dos super-Tierras cuyos parámetros se resumen en la Tabla 1.5.

TABLA 1.5: Parámetros de los planetas del sistema K2-240.

Parámetro	K2-240 b	K2-240 c
Período orbital (P) [d]	6.034 ± 0.001	20.523 ± 0.001
Semieje mayor (a) [UA]	0.0513 ± 0.0009	0.1159 ± 0.0020
Radio (R_p) [$R_\oplus$]	$2.0^{+0.2}_{-0.1}$	$1.8^{+0.3}_{-0.1}$
Masa (M_p) [$M_\oplus$] (1)	$5.0^{+0.5}_{-0.2}$	$4.6^{+0.7}_{-0.3}$
Temperatura de equilibrio (T_{eq}) [K]	586^{+24}_{-18}	389^{+19}_{-17}

(1): Las masas de los planetas se han estimado usando la relación de Weiss y G. W. (2014).

TABLA 1.6: Parámetros de K2-286 b

Parámetro	Valor
Período orbital (P) [d]	27.359 ± 0.005
Semieje mayor (a) [AU]	$0.1768^{+0.0175}_{-0.0205}$
Radio (R_p) [$R_\oplus$]	2.1 ± 0.2
Masa (M_p) [$M_\oplus$] (2)	6.8 ± 4.3
Temperatura de equilibrio (T_{eq}) [K]	347^{+21}_{-11}

(2): De las relaciones masa-radio de Wolfgang, L. A. y E. B. (2016) y Chen y D. (2017).

K2-286

K2-286 (m_V=12.76) es una estrella monitorizada en la campaña 15 de K2 y caracterizada en este trabajo como M0 V. Es transitada por una super-Tierra con un período orbital de 27.36 días y con una T_{eq} estimada de 347^{+21}_{-11} K. De acuerdo con modelos optimistas (Zsom y col., 2013), el planeta orbita en la zona de habitabilidad. K2-286 es una estrella menos activa que otras enanas M con exoplanetas, por lo que K2-286 b puede experimentar un ambiente más benigno que otros exoplanetas similares. El radio del planeta (2.1 ± 0.2 $R_\oplus$) lo sitúa en el límite superior del *gap* en la distribución de radios situado entre 1.5 y 2.0 $R_\oplus$ (Fulton y col., 2017). Los parámetros de K2-286 b se presentan en la Tabla 1.6.

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Capítulo 2

New rotation periods from photometric time series

Este capítulo se corresponde con la publicación *CARMENES input catalogue of M dwarfs IV. New rotation periods from photometric time series* (Díez Alonso y col., 2019b).

Este trabajo se enmarca en el primer objetivo de la tesis: la determinación del período de rotación de una muestra de 337 estrellas enanas M pertenecientes al catálogo de *CARMENES (Carmencita)*, con la finalidad de diferenciar las señales en velocidad radial causadas por exoplanetas de las inducidas por la propia actividad estelar, así como estudiar la relación de estos períodos de rotación con propiedades de las estrellas enanas M como su actividad, estructura interna o edad.

Para las 337 estrellas se han buscado series fotométricas en surveys públicos (ASAS, ASAS-SN, MEarth, SuperWASP, Catalina, K2 y HATNet). También se han realizado observaciones para 20 estrellas sin datos en los surveys investigados (o de calidad insuficiente) en colaboración con observatorios astronómicos amateurs y profesionales. Se han obtenido 622 curvas de luz para un total de 334 estrellas.

Para todas las curvas se han obtenido periodogramas *Lomb-Scargle* (también se ha realizado análisis *GLS*, más robusto ante *aliasing*, y *procesos Gaussianos* en casos puntuales) para identificar las señales más significativas, potencialmente relacionadas con la rotación estelar. Como resultado de este análisis se han identificado 142 señales de rotación estelar. 73 se publican por primera vez, mientras que 69 reproducen (o mejoran) períodos de rotación reportados previamente en la literatura.

Otros resultados relevantes de este trabajo son:

- No detección del *gap* en ~ 30 días en la distribución de períodos de rotación.
- Conexión entre P_{rot} y actividad, especialmente a través de $vsini$ y $pEW(H_\alpha)$.
- Identificación de tres estrellas activas con 0.34 d $< P_{rot} <$ 23.6 d.
- Falta de correlación de la amplitud de la variabilidad fotométrica con P_{rot}, $vsini$ y $pEW(H_\alpha)$.
- Determinación de diez ciclos de larga actividad, seis de los cuales han sido reportados por primera vez.
- Estudio de la relación entre P_{ciclo} y P_{rot}, no encontrando correlación entre ambos.

En el apéndice A se presentan las tablas con los datos de las 622 curvas de luz recopiladas, y de los 142 períodos de rotación obtenidos. Al final del mismo se presenta un ejemplo de curva de luz, periodograma Lomb-Scargle y curva de rotación para cada survey u observatorio. En el apéndice B se recopila, para las 142 estrellas con P_{rot} determinado, la curva de luz del survey utilizado para obtener el P_{rot} (panel superior), su periodograma Lomb-Scargle (panel central) y la curva de rotación correspondiente (panel inferior).

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CARMENES input catalogue of M dwarfs

IV. New rotation periods from photometric time series★

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ABSTRACT

Aims. The main goal of this work is to measure rotation periods of the M-type dwarf stars being observed by the CARMENES exoplanet survey to help distinguish radial-velocity signals produced by magnetic activity from those produced by exoplanets. Rotation periods are also fundamental for a detailed study of the relation between activity and rotation in late-type stars.

Methods. We look for significant periodic signals in 622 photometric time series of 337 bright, nearby M dwarfs obtained by long-time baseline, automated surveys (MEarth, ASAS, SuperWASP, NSVS, Catalina, ASAS-SN, K2, and HATNet) and for 20 stars which we obtained with four 0.2–0.8 m telescopes at high geographical latitudes.

Results. We present 142 rotation periods (73 new) from 0.12 d to 133 d and ten long-term activity cycles (six new) from 3.0 a to 11.5 a. We compare our determinations with those in the existing literature; we investigate the distribution of $P_{\rm rot}$ in the CARMENES input catalogue, the amplitude of photometric variability, and their relation to $v \sin i$ and pEW(Hα); and we identify three very active stars with new rotation periods between 0.34 d and 23.6 d.

Key words. stars: activity – stars: late-type – stars: rotation – techniques: photometric

1. Introduction

In current exoplanet search programmes, knowledge of the stellar rotation periods is essential in order to distinguish radial-velocity signals induced by real planets or by the rotation of the star itself (Saar & Donahue 1997; Queloz et al. 2001; Boisse et al. 2011). This is even more important when the goal is to detect weak signals induced by Earth-like exoplanets around low-mass stars (Scalo et al. 2007; Léger et al. 2009; Dumusque et al. 2012; Anglada-Escudé et al. 2016). For this purpose, star spots on the photosphere of stars can help us because they induce a photometric modulation from which we can infer not only the rotation period of the stars (Kron 1947; Bouvier et al. 1993; Messina & Guinan 2002; Strassmeier 2009), but also long-term activity cycles (Baliunas & Vaughan 1985; Berdyugina & Järvinen 2005).

M dwarfs are strongly affected by star spots because of the presence of large active regions on their surfaces, which are

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★ Tables A.1 and A.2, and tables of the photometric measurements are only available at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr` (`130.79.128.5`) or via `http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/621/A126` due to the depth of the convective layers (Delfosse et al. 1998; Mullan & MacDonald 2001; Browning 2008; Reiners & Basri 2008; Barnes et al. 2011) As a result, these late-type stars are the most likely to present this kind of modulation in photometric series (Irwin et al. 2011; Kiraga 2012; West et al. 2015; Suárez Mascareño et al. 2016). The low masses and small radii of M dwarfs also make them ideal targets for surveys aimed at detecting small, low-mass, potentially habitable Earth-like planets (Joshi et al. 1997; Segura et al. 2005; Tarter et al. 2007; Reiners et al. 2010; France et al. 2013). Therefore, the inclusion of M-dwarf targets in exoplanet surveys has increased steadily from the first dedicated radial-velocity searches (Butler et al. 2004; Bonfils et al. 2005; Johnson et al. 2007), through transit searches from the ground and space (Berta et al. 2013; Kopparapu et al. 2013; Crossfield et al. 2015; Dressing & Charbonneau 2015; Gillon et al. 2016, 2017; Dittmann et al. 2017), to up-to-date searches with specially designed instruments and space missions such as CARMENES (Quirrenbach et al. 2014), HPF (Mahadevan et al. 2014), IRD (Tamura et al. 2012), SPIRou (Artigau et al. 2014), TESS (Ricker et al. 2015), or GIARPS (Claudi et al. 2016). As a result, there is a growing number of projects aimed at photometrically following up large samples of M dwarfs in the solar neighbourhood with the goals of determining their rotation periods and discriminating between signals induced by rotation from those induced by the presence of planets (Irwin et al. 2011; Suárez Mascareño et al. 2015; Newton et al. 2016). Some of the targeted M dwarfs have known exoplanets, or are suspected to harbour them, while others are just being monitored by radial-velocity surveys with high-resolution spectrographs. Some exoplanets may transit their stars, although transiting exoplanets around bright M dwarfs are rare (Gillon et al. 2007; Charbonneau et al. 2009).

This work is part of the CARMENES project[1]. It is also the fourth item in the series of papers devoted to the scientific preparation of the target sample being monitored during CARMENES guaranteed time observations (see also Alonso-Floriano et al. 2015a; Cortés-Contreras et al. 2017; Jeffers et al. 2018). Here we present the results of analysing long-term, wide-band photometry of 337 M dwarfs currently being monitored by CARMENES (Reiners et al. 2018b). For many of them we had not been able to find rotation periods in the existing literature (see below).

To determine the rotation periods of our M dwarfs, we make extensive use of public time series of wide-area photometric surveys and databases such as the All-Sky Automated Survey (ASAS; Pojmański 1997), Northern Sky Variability Survey (NSVS; Woźniak et al. 2004), Wide Angle Search for Planets (SuperWASP; Pollacco et al. 2006), Catalina Real-Time Transient Survey (Catalina; Drake et al. 2009), and The MEarth Project (MEarth; Charbonneau et al. 2009; Irwin et al. 2011). Since the amplitude of the modulations induced by star spots, in the range of millimagnitudes, is also within reach of current amateur facilities (Herrero et al. 2011; Baluev et al. 2015), we also collaborate with amateur astronomers to obtain data for stars that have never been studied by systematic surveys or that need a greater number of observations.

After collecting and cleaning the time series, we look for significant peaks in power spectra, determine probable rotation periods and long activity cycles, compare them with previous determinations and activity indicators when available, and make all our results available to the whole community in order to facilitate the disentanglement of planetary and activity signals in current and forthcoming radial-velocity surveys of M dwarfs.

2. Data

2.1. Sample of observed M dwarfs

During guaranteed time observations (GTOs), the double-channel CARMENES spectrograph has so far observed a sample of 336 bright, nearby M dwarfs with the goal of detecting low-mass planets in their habitable zone with the radial-velocity method (Quirrenbach et al. 2015; Reiners et al. 2018b): 324 have been presented by Reiners et al. (2018b), 3 did not have enough CARMENES observations at the time the spectral templates were being prepared for the study, and 9 are new spectroscopic binaries (Baroch et al. 2018). Here we investigate the photometric variability of these 336 M dwarfs and of G 34–23 AB (J01221+221AB), which Cortés-Contreras et al. (2017) found to be a close physical binary just before the GTOs started. This results in a final sample size of 337 stars.

As part of the full characterisation of the GTO sample, for each target we have collected all relevant information: astrometry, photometry, spectroscopy, multiplicity, stellar parameters, and activity, including X-ray count rates, fluxes, and hardness ratios, Hα pseudo-equivalent widths, reported flaring activity, rotational velocities $v \sin i$, and rotational periods $P_{\rm rot}$ (Caballero et al. 2016). In particular, for 69 stars of the CARMENES GTO sample we had already collected rotation periods from the existing literature (e.g. Kiraga & Stepien 2007; Norton et al. 2007; Hartman et al. 2011; Irwin et al. 2011; Kiraga 2012; Suárez Mascareño et al. 2015; West et al. 2015; Newton et al. 2016, see below).

Of the 337 investigated stars, we were unable to collect or measure any photometric data useful for variability studies for only 3. In these three cases, the M dwarfs are physical companions at relatively small angular separations of bright primaries (J09144+526 = HD 79211, J11110+304 = HD 97101 B, and J14251+518 = θ Boo B). For the other 334 M dwarfs, we looked for peaks in the periodograms of two large families of light curves that we obtained (*i*) from wide-area photometric surveys and public databases, and (*ii*) with 20–80 cm telescopes at amateur and semi-professional observatories. A more detailed photometric survey of particular GTO targets is being carried out within the CARMENES consortium with more powerful telescopes, such as the Las Cumbres Observatory Global Telescope Network (Brown et al. 2013) and the Instituto de Astrofísica de Andalucía 1.5 m and 0.9 m telescopes at the Observatorio de Sierra Nevada. Results of this photometric monitoring extension will be published elsewhere.

In the first four columns of Table A.1 we give the Carmencita identifier (Caballero et al. 2016), discovery name, and 2MASS (Skrutskie et al. 2006) equatorial coordinates of the 337 M dwarfs investigated in this work.

2.2. Photometric monitoring surveys

We searched for photometric data of our target stars, available through either VizieR (Ochsenbein et al. 2000) or, more often, the respective public web pages of the four main wide-area surveys listed below and summarised in the top part of Table 1.

- MEarth: The MEarth Project[2] (Nutzman & Charbonneau 2008; Irwin et al. 2011). This consists of two robotically-controlled 0.4 m telescope arrays, MEarth-North at the the

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[1] `http://carmenes.caha.es`

[2] `http://www.cfa.harvard.edu/MEarth`

Table 1. Number of investigated light curves and basic parameters of used public surveys and observatories.

Survey	Location	Instrument configuration	Band	No. of light curves
MEarth	Mount Hopkins, USA	8 × Apogee U42	RG715, I[a]	184
ASAS	Las Cumbres, Chile	Apogee AP10	V	174
SuperWASP	Roque de los Muchachos, Spain Sutherland, South Africa	8 × Andor DW436	Clear, Broad[b] Broad[b]	89
NSVS	Los Álamos, USA	4 × Apogee AP10	Clear[c]	86
Catalina	Mt. Lemmon/Mt. Bigelow, USA	Variable[d]	$V_{\rm CSS}$[d]	37
ASAS-SN	Worldwide[e]	FLI ProLine PL230	V	14
K2	(Earth-trailing heliocentric orbit)	0.95 m *Kepler* + 42 × CCD	Clear	13
AstroLAB IRIS	Zillebeke, Belgium	0.68 m Keller + SBIG STL-6303E	B, V	7
Montcabrer	Cabrils, Spain	0.30 m Meade LX200 + SBIG ST-8XME	R, I	6
HATNet	Mt. Hopkins, USA Mauna Kea, USA	5 + 2 × Apogee AP10[f]	R_C, I_C	5
Montsec	San Esteban de la Sarga, Spain	0.80 m Joan Oró + MEIA2[g]	R_C	4
Carda	Villaviciosa, Spain	0.20 m Celestron SC 8″ + SBIG ST-7E	Clear	3
Total				622

Notes. (a) MEarth: broad 715 nm long-pass filter in first (2008–2010) and third seasons (2011+), custom-made $I_{715-895}$ interference filter in second season (2010–2011). (b) SuperWASP: from 2006 onwards a broad-band filter was installed with a passband from 400 to 700 nm. (c) NSVS: unfiltered optical response 450–1000 nm, effective wavelength of R band. (d) Catalina: see Christensen et al. (2015) for the latest camera configurations. (e) ASAS-SN: the network consists of 20 telescopes, distributed among five units in Hawai'i and Texas in the USA, two sites in Chile, and South Africa. (f) HATNet: see Bakos (2018) for the latest camera configurations. (g) Montsec: the MEIA2 instrument at the Telescopi Joan Oró on the Observatori Astronomic del Montsec consists of a camera iKon-L with an Andor CCD42-40 chip and a Custom Scientific filter wheel.

Fred Lawrence Whipple Observatory on Mount Hopkins, Arizona, and MEarth-South telescope at the Cerro Tololo Inter-American Observatory, Coquimbo. The project monitors the brightness of about 2000 nearby M dwarfs with the goal of finding transiting planets (Berta et al. 2013; Dittmann et al. 2017), but it has also successfully measured rotation periods of M dwarfs (Irwin et al. 2009, 2011; Newton et al. 2016). On every clear night and for about six months, each star is observed with a cadence of 20 min. In general we used data from three observing batches (2008–2010, 2010–2011, and 2011–2015) from the MEarth-North array ($\delta = +20$ to $+60$) provided by the fifth MEarth data release DR5, but we also used a few DR6 light curves (2011–2016).

- ASAS: All-Sky Automated Survey[3] (Pojmański 2002). This is a Polish project devoted to constant photometric monitoring of the whole available sky (approximately 20 million stars brighter than $V \sim 14$ mag). It consists of two observing stations in Las Cumbres Observatory, Chile (ASAS-3 from 1997 to 2010, ASAS-4 since 2010), and Haleakalā Observatory, Hawai'i (ASAS-3N since 2006). Both are equipped with two wide-field instruments observing simultaneously in the V and I bands, and a set of smaller narrow-field telescopes and wide-field cameras. We used only the V-band ASAS-3 data for stars with $\delta < +28$ deg observed between 1997 and 2006, which are available through the ASAS All Star Catalogue. In particular, we retrieved all light curves within a search radius of 15 arcsec, discarded all data points with C or D quality flags, and computed an average magnitude per epoch of the five ASAS-3 apertures weighted by each aperture magnitude error.
- SuperWASP: Super-Wide Angle Search for Planets[4] (Pollacco et al. 2006). The UK-Spanish WASP consortium runs two identical robotic telescopes of eight lenses each, SuperWASP-North at the Observarorio del Roque de los Muchachos, La Palma, and SuperWASP-South at the South African Astronomical Observatory, Sutherland. WASP has discovered over a hundred exoplanets through transit photometry (Collier Cameron et al. 2007; Barros et al. 2011). For our work, we downloaded light curves of the first SuperWASP public data release (DR1 – Butters et al. 2010) from the Czech site[5]. The SuperWASP DR1 contains light curves for about 18 million sources in both hemispheres. Although the two robotic telescopes are still operational, DR1 only provided data collected from 2004 to 2008. The average number of data points per light curve is approximately 6700.
- NSVS: Northern Sky Variability Survey[6] (Woźniak et al. 2004). This was located at Los Álamos National Laboratory, New Mexico. The NSVS catalogue contains data from approximately 14 million objects in the range $V = 8$–15.5 mag with a typical baseline of one year from April 1999 to March 2000, and 100–500 measurements for each source. In a median field, bright unsaturated stars have photometric scatter of about 20 mmag. It covered the entire northern hemisphere, and part of the southern hemisphere down to $\delta = -28$ deg.

In addition to these four main catalogues, which accounted for a total of 533 light curves (86%), we complemented our dataset with light curves compiled from the Catalina Surveys CSDR2[7] (Catalina; Drake et al. 2009, 2014), K2 (Howell et al. 2014),

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[3] `http://www.astrouw.edu.pl/asas`

[4] `https://wasp.cerit-sc.cz/form`

[5] `http://wasp.cerit-sc.cz`

[6] `https://skydot.lanl.gov/nsvs/nsvs.php`

[7] `https://catalina.lpl.arizona.edu`

the All-Sky Automated Survey for Supernovae[8] (ASAS-SN; Kochanek et al. 2017), and the Hungarian-made Automated Telescope Network[9] (HATNet; Bakos et al. 2004; Bakos 2018). None of our targets was in the catalogues of the CoRoT (Auvergne et al. 2009), *Kepler* (Borucki et al. 2010), or the Transatlantic Exoplanet Survey (TrES; Alonso et al. 2007) surveys. Finally, we did not use other wide surveys, such as Lincoln Near-Earth Asteroid Research (LINEAR; Stokes et al. 2000); XO (McCullough et al. 2005); Kilodegree Extremely Little Telescope (KELT; Pepper et al. 2007), which will soon have an extensive data release (Pepper, priv. comm.); HATSouth (Bakos et al. 2013); or the Asteroid Terrestrial-impact Last Alert System (ATLAS; Heinze et al. 2018), with the first data release published after collecting all light curves included in this work. All the public surveys used, amounting 602 light curves, are summarised in Table 1.

2.3. Our observations

For 20 GTO M dwarfs without data in public surveys or published periods, or with unreliable or suspect periods in the existing literature (e.g. short $P_{\rm rot,lit}$ but low $v \sin i$ and faint Hα emission, or vice versa), we made our own observations in collaboration with amateur and semi-professional astronomical observatories in Spain and Belgium: Carda[10] (MPC Z76) in Asturias, Montcabrer[11] (MPC 213) and Montsec[12] in Barcelona (MPC C65), and AstroLAB IRIS[13] near Ypres. Most of our targets had northern declinations, which suitably fit the geographical latitudes of our observatories (between +41.5 deg and +50.8 deg).

The cadence of observations for each target was either continuous every night or just one observation per night during a long run, depending on rule-of-thumb estimations of their rotation periods based on literature values of rotational velocity and Hα emission. Exposure times varied widely, from a few seconds to several minutes. We took special care to select enough reference stars with stable light curves and relatively red $J - K_s$ colours within the respective fields of view (f.o.v.; variable from 12.3×12.3 arcmin^2 to 43×43 arcmin^2).

For the image reduction and light-curve generation, we used standard calibration procedures (bias and flat-field correction) and widely distributed software such as `MaxIm`[14], `AstroImageJ`[15] (Collins et al. 2017), `FotoDif`[16], and `LesvePhotometry`[17] with parameters appropriate for each observatory, atmospheric condition, and star brightness (see again Table 1).

3. Analysis

We searched for significant signals in the periodograms of the 622 light curves compiled or obtained by us as described in Sect. 2. Prior to this, we cleaned our light curves by discarding outlying data points caused by the combination of target faintness and sub-optimal weather. Some of our M dwarfs could also undergo flaring activity (most flares in our light curves are difficult to identify because of the typical low cadence). We used the same cleaning procedure as Suárez Mascareño et al. (2015, 2016), rejecting iteratively all data points that deviated more than 2.5σ from the mean magnitude (which might eventually bias the amplitude of the variations).

The last six columns of Table A.1 show the corresponding survey, number of data points $N_{\rm obs}$ before and after the cleaning, time interval length Δt between first and last visit, mean $\overline{m}$ and standard deviation σ_m of the individual magnitudes, and mean error $\overline{\delta m}$. See Sect. 4.4 for a discussion on the variation of σ_m as a function of $\overline{m}$, and the possibility of finding aperiodic or irregular variable stars in our data.

Next, we used the Lomb–Scargle (LS) periodogram (Scargle 1982) with the `peranso` analysis software (Paunzen & Vanmunster 2016), which implements multiple light-curve and period analysis functions. We evaluated the significance of the signals found in the periodograms with the Cumming (2004) modification of the Horne & Baliunas (1986) formula. In this way, the false alarm probability (FAP) becomes

$$\mathrm{FAP} = 1 - [1 - p(z > z_0)]^M, \quad (1)$$

with $p(z > z_0)$ being the probability that z, the target spectral density, is greater than z_0, the measured spectral density; and M the number of independent frequencies. In our case, $p(z > z_0) = \mathrm{e}^{-z_0}$, where z_0 is the peak of the hypothetical signal; $M = \Delta t\, \Delta f$, where Δt is the time baseline, $\Delta f = f_2 - f_1$; and f_2 and f_1 are the maximum and minimum search frequencies, respectively. The `peranso` software also measures amplitudes of light curves.

We searched for significant frequencies with FAP < 2% and within the standard frequency interval. On the one hand, we set the highest frequency at the Nyquist frequency to about half of the minimum time interval between consecutive visits (from $f \sim 100\,\mathrm{d}^{-1}$ for some of our intensive campaigns to $f \sim 1\,\mathrm{d}^{-1}$ for most of the public-survey light curves). On the other hand, we set the lowest frequency at half the length of the monitoring (typically $f \sim 0.005\,\mathrm{d}^{-1}$). Only in the case of ASAS, the public survey with the longest time baseline (up to ten years), did we search for low frequencies down to $0.0005\,\mathrm{d}^{-1}$. For stars with significant signals shorter than 2 d we used a significant frequency oversampling (~10×). When a periodogram displayed several significant peaks, we paid special attention to identifying aliases and picked up the strongest signal with astrophysical meaning (e.g. with $P_{\rm rot}$ consistent with existing additional information on the star, especially its rotational velocity, $v \sin i$; see Sect. 4.3). Figures B.1–B.9 illustrate our analysis with one representative example of a raw stellar light curve and corresponding LS periodogram and phase-folded light curve for each dataset with identified period.

There is a justified concern in the literature about the use of the LS periodogram for period determination (e.g. McQuillan et al. 2013). As a result, for the light curves of stars classified as new spectroscopic binaries by Baroch et al. (2018), with K2 data, or with periods shorter than 1 d, or different by more than 10% from those in the literature (see Sect. 4.1) we also applied the generalised LS periodogram method (GLS; Zechmeister & Kürster 2009).

For the spectroscopic binaries and K2 stars, we additionally applied the Gaussian process regression (GP; Rasmussen & Williams 2005) with the `celerite` package (Foreman-Mackey et al. 2017). To build a celerity model for our case, we defined a covariance/kernel for the GP model, which

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[8] `http://www.astronomy.ohio-state.edu/asassn/`
[9] `https://hatnet.org/`
[10] `http://www.auladeastronomia.es/`
[11] `http://cometas.sytes.net`
[12] `http://www.oadm.cat`
[13] `http://astrolab.be`
[14] `http://diffractionlimited.com/product/maxim-dl/`
[15] `http://www.astro.louisville.edu/software/astroimagej/`
[16] `http://www.astrosurf.com/orodeno/fotodif/`
[17] `http://www.dppobservatory.net/AstroPrograms/Software4VSObservers.php`

Table 2. Cycle periods obtained for stars in our sample.

Karmn	Name	$P_{\rm cycle}$ (a)	FAP (%)	A_λ (mag)	Survey	$P_{\rm cycle,lit}$ (a)	FAP$_{\rm lit}$ (%)	$A_{\lambda,\rm lit}$ (mag)	Ref.
J06105–218	HD 42581 A	8.3 ± 3.1	$<10^{-4}$	0.026	ASAS	8.4 ± 0.3	<0.1	0.0128	SM16
J07361-031	BD–02 2198	11.5 ± 1.9	$<10^{-4}$	0.035	ASAS	...	...	...	...
J08161+013	GJ 2066	4.1 ± 0.7	$<10^{-4}$	0.012	ASAS	...	...	...	...
J10122–037	AN Sex	3.2 ± 0.4	$<10^{-4}$	0.020	ASAS	...	...	...	...
J11477+008	FI Vir	4.5 ± 2.0	0.15	0.012	ASAS	4.1 ± 0.3	1.7	0.0071	SM16
J15218+209	OT Ser	6.5 ± 0.8	$<10^{-4}$	0.055	ASAS	...	...	...	...
J16303–126	V2306 Oph	3.9 ± 1.0	$<10^{-4}$	0.014	ASAS	4.4 ± 0.2	<0.1	0.0083	SM16
J19169+051N	V1428 Aql	3.3 ± 0.4	$<10^{-4}$	0.013	ASAS	9.3 ± 1.9	<0.1	0.0077	SM16
J19346+045	BD+04 4157	3.0 ± 0.8	$<10^{-4}$	0.013	ASAS	...	...	...	...
J22532–142	IL Aqr	4.5 ± 0.7	$<10^{-4}$	0.013	ASAS	...	...	...	...

Reference. SM16: Suárez Mascareño et al. (2016).

consisted of a stochastically-driven damped oscillator and a jitter term (Angus et al. 2018). We then wrapped the kernel defined in this way in the GP and computed the likelihood. In all investigated cases except two, the GLS and GP periods were identical within their uncertainties to the LS periods computed with `peranso`. The only two significant differences were J18356+329, for which GLS did not recover $P_{\rm rot} = 0.118$ d, the shortest period in our sample and identical to that reported by Hallinan et al. (2008), and J16254+543, for which GLS found $P_{\rm rot} = 76.8$ d, a value similar to that in the literature (Suárez Mascareño et al. 2015), but for which the LS algorithm found 100 ± 5 d.

In Table A.2 we show the periods, amplitudes, FAPs, and corresponding surveys of 142 M dwarfs. When available, we show the GLS periods. We tabulate the uncertainty in $P_{\rm rot}$ from the full width at half maximum of the corresponding peak in the periodogram (Schwarzenberg-Czerny 1991). For GLS periods, we tabulate formal uncertainties, which are significantly smaller than the real ones.

When several datasets are available, and even though the periodogram peaks are detected in both, we list the $P_{\rm rot}$ of the dataset with the lowest FAP. For the sake of completeness, Table A.2 includes five stars with FAP = 2–10% for which we recover periods similar to those previously published (Testa et al. 2004; Suárez Mascareño et al. 2015, 2016), but which did not pass our initial FAP criterion. One such period is for J11477+008 = FI Vir, for which Suárez Mascareño et al. (2016) reported a rotation period of 165 d consistent with ours. Its K2 light curve, which spans only 80 d, shows a clear modulation that matches such a long period, the longest one reported by us. Something similar occurs with J13458–179 = LP 798–034, whose K2 light curve shows a 20 mmag peak-to-peak modulation of about three months. We did not find any periods in the existing literature or our ASAS data for this star, which is not listed in Table A.2.

We also looked for long-period cycles in ASAS light curves of stars with identified $P_{\rm rot}$ and time baseline $\Delta t \approx 9$ a. Ten stars have significant signals at $P_{\rm cycle} \geq 3.0$ a, and are listed in Table 2. Two of these (J06105–218 and J15218+209) have cycle periods longer than half Δt, and one has a cycle period even longer than the full Δt, but its modulation is very clear (see Fig. 1). Curiously, the star with the longest rotation period and highest FAP, J11477+008, also displays a long-term activity cycle. This flaring M4 dwarf is also the star with the smallest ratio $P_{\rm cycle}/P_{\rm rot} \sim 10$.

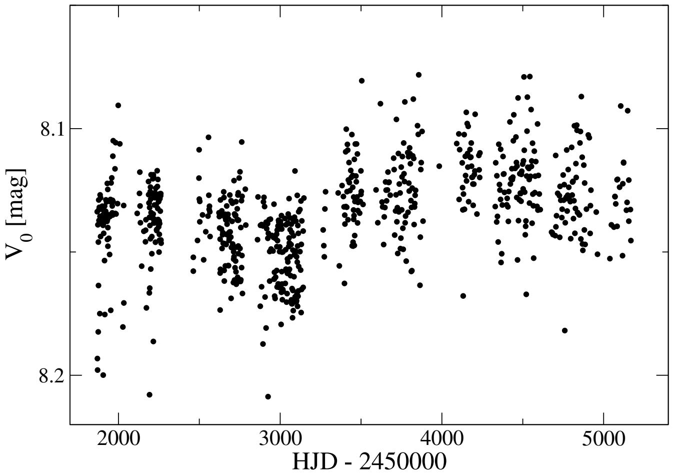

Fig. 1. ASAS V-band photometric data for the M0.5 V star J06105-218 = HD 42581A. It may display an activity cycle modulation with $P_{\rm cycle} \sim 8.3$ a superimposed to a rotation period $P_{\rm rot} = 27.3$ d (the modulation in the light curve of J15218+209 is similar).

Of the ten values of $P_{\rm cycle}$ shown in Table 2, six are new, three are identical within their uncertainties to previous determinations by Suárez Mascareño et al. (2016), and one is revised from 9.3 a to about 3.3 a. There are two additional stars, not listed in Table 2, with significant signals (FAP < 2%) at 2–3 a, but without identified or reported rotation periods (J06371+175 and J22559+178). It may be that they truly display a long-term modulation overlaid on a low-amplitude rotation period not detected yet, as they could be pole-on.

4. Results and discussion

4.1. Rotation periods

Of the 142 stars with periods in Table A.2, 69 (49%) had rotation periods previously reported in the existing literature and tabulated in Carmencita (Caballero et al. 2016); see Table A.2 for full references. Therefore, we present 73 new photometric periods of M dwarfs in this study. This number is comparable to the number of new rotation periods of M dwarfs reported by Norton et al. (2007), Irwin et al. (2011), and Suárez Mascareño et al. (2016), but is far lower than other more comprehensive searches by Hartman et al. (2011), Kiraga (2012), and Newton et al. (2017).

Table 3. Stars with published rotation periods not recovered in this work.

Karmn	Name	$P_{\mathrm{rot,lit}}$ (d)	Ref.
J03133+047	CD Cet	126.2	New16
J05019–069	LP 656–038	88.5	Kir12
J07274+052	Luyten's star	115.6 ± 19.4	SM15
J09003+218	LP 368–128	0.439	New16
J09360–216	GJ 357	74.3 ± 1.7	SM15
J11033+359	Lalande 21185	48.0	KS07
J13299+102	BD+11 2576	28 ± 2.9	SM15
J11421+267	Ross 905	39.9	SM15
J13457+148	HD 119850	52.3 ± 1.7	SM15
J14010–026	HD 122303	43.4	SM16
J15194–077	HO Lib	132 ± 6.3	SM15
J17578+046	Barnard's star	130	KS07
J18051–030	HD 165222	127.8 ± 3.2	SM15
J22096–046	BD–05 5715	39.2 ± 6.3	SM15

References. KS07: Kiraga & Stepien (2007); Har11: Hartman et al. (2011); Kir12: Kiraga (2012); SM15: Suárez Mascareño et al. (2015); New16: Newton et al. (2016); SM16: Suárez Mascareño et al. (2016).

However, there is a fundamental difference in the samples; ours exclusively contains bright, nearby M dwarfs that are targets of dedicated exoplanet surveys. In particular, the mean J-band magnitude and heliocentric distance of our CARMENES GTO sample are only 7.7 mag and 11.6 pc (cf. Caballero et al. 2016), much brighter and closer than any M dwarf sample photometrically investigated previously.

We were not able to recover the rotation periods of 14 stars reported by Kiraga & Stepien (2007), Kiraga (2012), Suárez Mascareño et al. (2015), and Newton et al. (2016), and listed in Table 3. In most of these cases, unrecovered published $P_{\mathrm{rot,lit}}$ values were long, of low significance, and came from low-cadence, relatively noisy, ASAS data.

In Fig. 2 we compare the rotation periods that we found and those reported in the existing literature for the 69 stars in common. Except for four discordant stars, the agreement is excellent, with maximum deviations rarely exceeding 10%, and with virtually all values identical within their uncertainties. There are four outliers with deviations between $P_{\mathrm{rot,lit}}$ and $P_{\mathrm{rot,this\,work}}$ larger than 20%:

- J00051+457 = GJ 2. A rotation period of 21.2 d was previously measured by Suárez Mascareño et al. (2015) from a series of high-resolution spectroscopy of activity indicators, while we measure 15.37 d on an ASAS light curve;
- J16570–043 = LP 686–027. This is an active, "RV-loud star" (pEW(Hα) = –4.2 ± 0.1 Å and $v \sin i \approx 10.1\,\mathrm{km\,s^{-1}}$ (Jeffers et al. 2018; Reiners et al. 2018b; Tal-Or et al. 2018). Our analysis of the ASAS data reproduced the 1.21 d period of Kiraga (2012), but with an FAP $\gg$ 5%. However, our analysis of NSVS data, with ~4 more epochs and a baseline ~9 times longer than ASAS, resulted in a shorter $P_{\mathrm{rot}} \sim 0.55$ d with a lower FAP = 1.4%;
- J18363+136 = Ross 149. We found two significant signals in our ASAS data of roughly the same power at 1.02 d and 50.2 d, which are aliases of one another. The first period is identical to $P_{\mathrm{rot,lit}} = 1.017$ d discovered by Newton et al. (2016) in MEarth data. However, we tabulate the 50.2 d period based on the very slow rotation velocity of the star ($v \sin i < 2\,\mathrm{km\,s^{-1}}$; Reiners et al. 2018b);

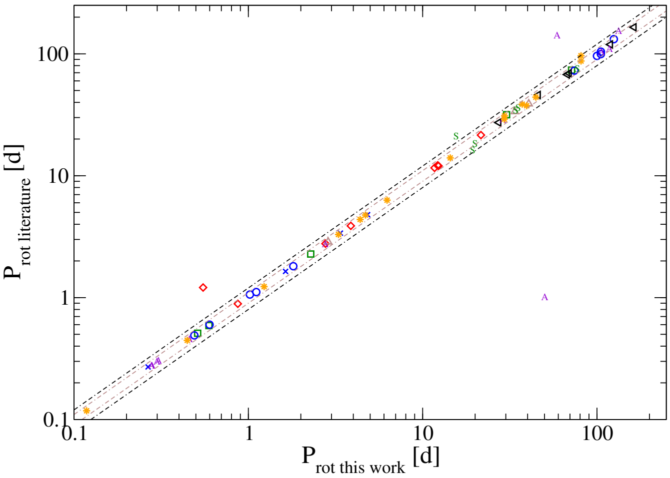

Fig. 2. Periods from the literature $P_{\mathrm{rot,lit}}$ as a function of our period, $P_{\mathrm{rot,this\,work}}$, for stars with previously published rotation periods. Dashed lines show 10% and 20% deviations from the 1:1 relation. Different symbols and colours stand for the literature source: blue crosses: Norton et al. (2007); green squares: Hartman et al. (2011); blue circles: Irwin et al. (2011); red diamonds: Kiraga (2012); brown up-triangles: Kiraga & Stepien (2007); black left-triangles: Suárez Mascareño et al. (2016); violet A's: Newton et al. (2016); green S's: Suárez Mascareño et al. (2018); orange asterisks: Greimel & Robb (1998), Fekel & Henry (2000), Testa et al. (2004), Rivera et al. (2005), Hallinan et al. (2008), Kiraga & Stępień (2013), Suárez Mascareño et al. (2015), West et al. (2015), David et al. (2016), Cloutier et al. (2017), Vida et al. (2017), and Lothringer et al. (2018).

- J20260+585 = Wolf 1069. Newton et al. (2016) reported a possible or uncertain period of 142.09 d. With MEarth data, we found instead a signal at 59.0 d. However, neither of the two signals is visible in the SuperWASP dataset.

4.2. Period distribution

Using MEarth data, Newton et al. (2016) reported that the distribution of M-dwarf rotation periods displays a lack of stars with intermediate rotation periods around 30 d. This lack at intermediate periods could be understood as a bimodal P_{rot} distribution, with peaks at 0.5–2 d and 50–100 d, and a valley in between. While there is a significant overabundance of periods larger than 30 d in our sample, as illustrated in Fig. 3, the distribution of periods shorter than 30 d (and longer than 0.5 d) is flat within Poissonian statistics. Therefore, we see only one wide peak in the period distribution at P_{rot} = 20–120 d or, conversely, a lack of stars with intermediate and short rotation periods P_{rot} = 0.6–20 d. However, rather than contradicting the results presented by Newton et al. (2016), we attribute the lack of short periods to the different temporal sampling of the surveys used (see below). The authors also stated that the rotators with the highest quality grade were biased towards such short periods, while the sparse temporal sampling of most surveys used here (excluding SuperWASP and MEarth) prevented us from detecting periods of a few days. If the available periods for the ~2200 Carmencita stars are taken into account (cf. Fig. 3), the peak at P_{rot} = 20–120 d becomes much less apparent, and the period distribution is rather flat from 0.6 d to 8 d, approximately. There might be a dip at P_{rot} = 8–20 d.

Regarding survey sampling, we analysed the distribution of time elapsed between consecutive exposures of our light curves. The SuperWASP distribution has two peaks, one very narrow at slightly less than one minute (the CCD read-out time) and

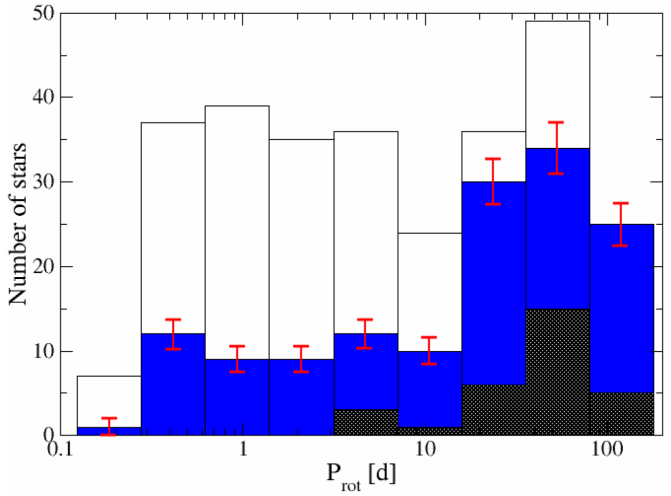

Fig. 3. Distribution of rotation periods in our work (shaded, with Poissonian uncertainties) and in Carmencita (white). Rotation periods found with ASAS are shaded darker. The size of the bins follows the definitions given by Freedman & Diaconis (1981). Compare with Fig. 3 in Newton et al. (2016).

another wider peak, centred at 10–20 min, a bit more optimistic than the 40 min stated by Pollacco et al. (2006). The NSVS distribution also has two peaks, one at around 1 min and the other at 1 d, much wider and sparser than SuperWASP and with a baseline of only one year (Woźniak et al. 2004). Together with SuperWASP, the MEarth dataset is, with a field cadence of between 15 and 40 min (~20 min according to Irwin et al. 2011) and "sequentially for the entire time [that] they are above airmass 2", the most appropriate one for sampling the $P_{\rm rot} = 0.6$–20 d interval. The ASAS sampling is much poorer than the other three main surveys, with a peak of the distribution centred at around one week. The nominal sampling value of 2 d (Pojmański 2002) is attained only for some bright stars and during a fraction of the observing time. However, the sampling strategy and the very long duration of the ASAS survey, of several years, makes it excellent for searching for periods longer than 20 d.

This partly explains the apparent lack of rotation periods in the range between 0.6 and 20 d of GTO stars with respect to Carmencita stars in Fig. 3. Our GTO stars are brighter than the rest of the Carmencita stars (Alonso-Floriano et al. 2015a) so the observed lack of shorter periods in our sample is probably caused by the inclusion of bright ASAS targets, combined with the observational cadence of ASAS, which is optimised towards detecting long periods. We thus have a combination of a Malmquist bias and a sampling effect.

A larger (volume- or magnitude-limited) sample of M dwarfs with a homogeneous, denser, longer monitoring could be needed to settle the question if there is a real lack of rotation periods between 0.6 d or 8 d and 20 d at low stellar masses. We may have to wait for the 8.4 m Large Synoptic Survey Telescope, which will monitor the entire available sky every three nights on average.

4.3. Activity

4.3.1. RV-loud stars

A comprehensive study linking rotational velocity, Hα emission, and rotation periods of M dwarfs was already presented by Jeffers et al. (2018) in a previous publication of this series. Using different tracers of magnetic activity, it can be seen that the rotational velocity increases with M-dwarf activity until saturation in rapid rotators (Stauffer et al. 1984; Hawley et al. 1996; Delfosse et al. 1998; Kiraga & Stepien 2007; Mohanty & Basri 2003; Reiners et al. 2009; Browning et al. 2010; Newton et al. 2017, and references therein).

As a complement to these studies, we present the following brief discussion on the rotation periods of the most active stars in our sample, most of which were tabulated by Tal-Or et al. (2018). They presented a list of 31 RV-loud stars: CARMENES GTO M-dwarf targets that displayed large-amplitude radial-velocity variations due to activity. Most of these stars, close to activity saturation, were also part of the investigation on wing asymmetries of Hα, Na I D, and He I lines in CARMENES spectra by Fuhrmeister et al. (2018). We found rotation periods from photometric time series for all of them except for nine stars[18], J12156+526 = StKM 2–809, J14173+454 = RX J1417.3+4525, J15499+796 = LP 022–420, J16555–083 = vB 8, J18189+661 = LP 071–165, J19255+096 = LSPM J1925+0938, and J20093–012 = 2MASS J20091824–0113377, which are either extremely active (e.g. Barta 161 12, LP 022–420), too faint and late for the surveys used (e.g. vB 8, 2MASS J20091824–0113377), or both (e.g. LSPM J1925+0938). The most active of these nine stars without an identified period could actually be variable, but irregular (see below).

As expected from their typically large $v \sin i$ values, most of the other 22 RV-loud stars have short or very short rotation periods: 20 stars have $P_{\rm rot} < 10$ d, and 11 have $P_{\rm rot} < 1$ d. The list of RV-loud stars with identified periods contains some very well-known variable stars, such as V388 Cas, V2689 Ori, YZ CMi, DX Cnc, GL Vir, OT Ser, V1216 Sgr, V374 Peg, EV Lac, and GT Peg. However, there are three such RV-loud stars for which there was no published value of rotation period. Of these, two have identified periods shorter than one day: J02088+494 = G 173–039 ($P_{\rm rot} = 0.748$ d) and J04472+206 = RX J0447.2+2038 ($P_{\rm rot} = 0.342$ d). They both have high rotational velocities of $v \sin i \approx 24$–48 km s^{-1} (Reiners et al. 2018a; Tal-Or et al. 2018). The third star without a previously reported rotation period is J19169+051S = V1298 Aql (vB 10, $P_{\rm rot} = 23.6$ d), which has a slow rotational velocity of only 2.7 km s^{-1}, but it does have an M8.0 V spectral type (Alonso-Floriano et al. 2015a; Kaminski et al. 2018) and has long been known to display variability of up to 0.2 mag peak-to-peak in V band (Herbig 1956; Liebert et al. 1978).

The 31 RV-loud stars in Tal-Or et al. (2018) are not the only CARMENES GTO M-dwarf targets that display large-amplitude radial-velocity variations due to activity, as all stars with ten or fewer observations during the first 20 months of operation were discarded from the study. In total, 46 stars in our sample have rotation periods shorter than 10 d, and 19 shorter than 1 d. Of the latter, only seven were not tabulated as RV-loud stars by Tal-Or et al. (2018): four M4.0–5.5 dwarfs with previously reported rotation period and $v \sin i > 16$ km s^{-1}, the strong X-ray emitter RBS 365 (J02519+224, M4.0 V, $v \sin i = 27.4 \pm 0.6$ km s^{-1}), the β Pictoris moving group candidate 1RXS J050156.7+010845 (J05019+011, M4.0 V, $v \sin i = 6.1 \pm 0.9$ km s^{-1}; see Alonso-Floriano et al. 2015b, and references therein), and the unconfirmed close astrometric binary G 34–23 AB (J01221+221 AB; not in the GTO sample, see Sect. 2). Because of the magnitude difference between the

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[18] J01352–072 = Barta 161 12, J09449–123 = G 161–071.

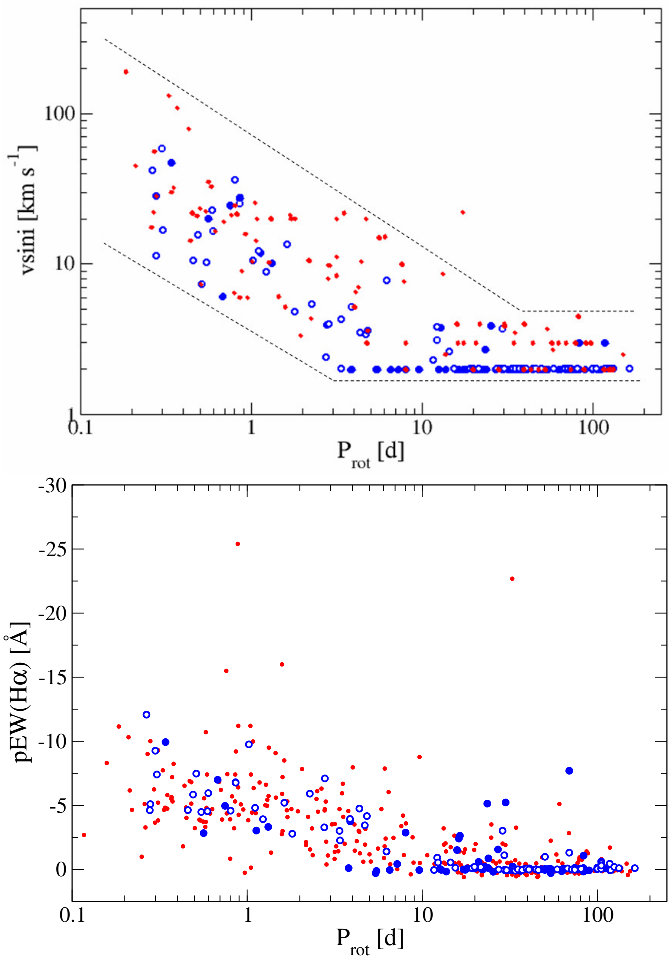

Fig. 4. $v \sin i$ vs. $P_{\rm rot}$ (*top panel*) and pEW(Hα) vs. $P_{\rm rot}$ (*bottom panel*) for stars with new (blue filled circles) and re-computed rotation periods in this study (blue open circles) and stars in Carmencita with previously published rotation periods (red dots). In the top panel, the dotted lines indicate the lower and upper envelopes of the $v \sin i$–$P_{\rm rot}$ relation, and most of the values at $v \sin i = 2$ or $3\,{\rm km\,s^{-1}}$ are upper limits. Compare with Figs. 6 and 8 in Jeffers et al. (2018). Here we present 154 new or improved $v \sin i$–$P_{\rm rot}$ and pEW(Hα)–$P_{\rm rot}$ pairs, with periods from this work and velocities and Hα equivalent widths from Reiners et al. (2018b). Outlier stars in both panels are discussed in the text.

two components in the pair ($\Delta I = 0.86 \pm 0.12$ mag according to Cortés-Contreras et al. 2017) the most likely variable is the primary, G 34–23 A. New analyses of RV scatter and activity of CARMENES GTO stars, including the other six single stars just described and the three RV-loud stars with new periods described above, most of them with $P_{\rm rot} < 1$ d, are ongoing and will be presented elsewhere.

4.3.2. Linking $P_{\rm rot}$, $v \sin i$, Hα, and A

We go deeper into the $P_{\rm rot}$–$v \sin i$ discussion with the top panel in Fig. 4. To build this plot we took 305 rotation periods and rotation velocities from the existing literature and compiled in the Carmencita catalogue (see references in Sect. 2.1). As expected and widely discussed by West et al. (2015) and Jeffers et al. (2018), among others, the shorter the rotation period $P_{\rm rot}$ of an M dwarf, the higher the rotation velocity $v \sin i$. The vertical width is due to the indetermination in inclination angle i and the spread in spectral types, and thus stellar radii R according to the formula

$$v \sin i = \frac{2\pi R \sin i}{P_{\rm rot}}. \tag{2}$$

We can outline conservative lower and upper envelopes of the $P_{\rm rot}$–$v \sin i$ relation. The horizontal regime at long periods and low rotational velocities is due to the instrumental limit in determining $v \sin i$ from high-resolution spectra, not to any real astrophysical effect on the stars[19]. In our plot there is only one outlier, G 131–047 AB (J00169+200 AB), which has $P_{\rm rot} = 17.3$ d from West et al. (2015) and $v \sin i = 22\,{\rm km\,s^{-1}}$ from Mochnacki et al. (2002). The star, a non-GTO star from Carmencita, is another unconfirmed close astrometric binary with components separated by only 1.08 arcsec (Cortés-Contreras et al. 2017), so it might also be a double-line spectroscopic binary. A double narrow cross-correlation function could appear to Mochnacki et al. (2002) as a single wide function, which would explain the high rotational velocity for its rotation period. In any case, our plot will be a reference for future studies of the $P_{\rm rot}$–$v \sin i$ relation, as we used the most precise values of rotational velocities (Reiners et al. 2018b) and of rotation periods (this study), together with an exhaustive compilation of data for nearby bright M dwarfs.

In the bottom panel of Fig. 4 we also link our rotation periods and those compiled in Carmencita with the corresponding pseudo-equivalent widths of the Hα line, pEW(Hα), possibly the most widely used activity indicator in low-mass stars. From the plot, again, the shorter the rotation period, the stronger the Hα emission (cf. Jeffers et al. 2018). And again, there are outliers. The most remarkable ones, with pEW(Hα) < –20 Å, are J07523+162 = LP 423–031 and J08404+184 = AZ Cnc. They just displayed well-documented flaring activity during their spectroscopic observations (Haro & Chavira 1966; Jankovics et al. 1978; Dahn et al. 1985; Shkolnik et al. 2009; Reiners & Basri 2010; Alonso-Floriano et al. 2015a). Other stars at the outer boundary of the general distribution have either moderate flaring activity (slightly larger |pEW(Hα)| for their $P_{\rm rot}$) or early M spectral types (slightly smaller |pEW(Hα)| for their $P_{\rm rot}$).

We searched for correlations between amplitude A and $P_{\rm rot}$, $v \sin i$, and pEW(Hα), as illustrated in Figs. 5 and 6. However, contrary to our expectations, we did not find that the most active stars (fastest rotators, strongest Hα emitters) always have the largest photometric amplitudes. For example, the star with the largest amplitude measured in our sample, $A_{\rm SuperWASP} = 0.091$ mag, is the most strongly active star J22468+443 = EV Lac (Pettersen et al. 1984; Favata et al. 2000; Zhilyaev et al. 2000; Osten et al. 2005, 2010), while the star with the third largest amplitude, $A_{\rm SuperWASP} = 0.059$ mag, is J14257+236W = BD+24 2733A, a relatively inactive M0.0 V star with $P_{\rm rot} \approx 111$ d, $v \sin i < 2\,{\rm km\,s^{-1}}$, and absent H$\alpha$ emission (Maldonado et al. 2017; Reiners et al. 2018b; Jeffers et al. 2018).

Previous works have investigated the relation between A and $P_{\rm rot}$. Hartman et al. (2011) found no correlation for K and early to mid M dwarf stars if $P_{\rm rot} < 30$ d, and an anti-correlation if $P_{\rm rot} > 30$ d. They found no correlation for mid to late M dwarfs. Newton et al. (2016) analysed the MEarth sample in two groups,

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[19] An ultra-high-resolution spectrograph of $\mathcal{R} \gtrsim 200\,000$ at an 8 m-class telescope would be needed to measure rotational velocities of a large sample of M dwarfs with an accuracy of $1\,{\rm km\,s^{-1}}$ (Reiners et al. 2018b).

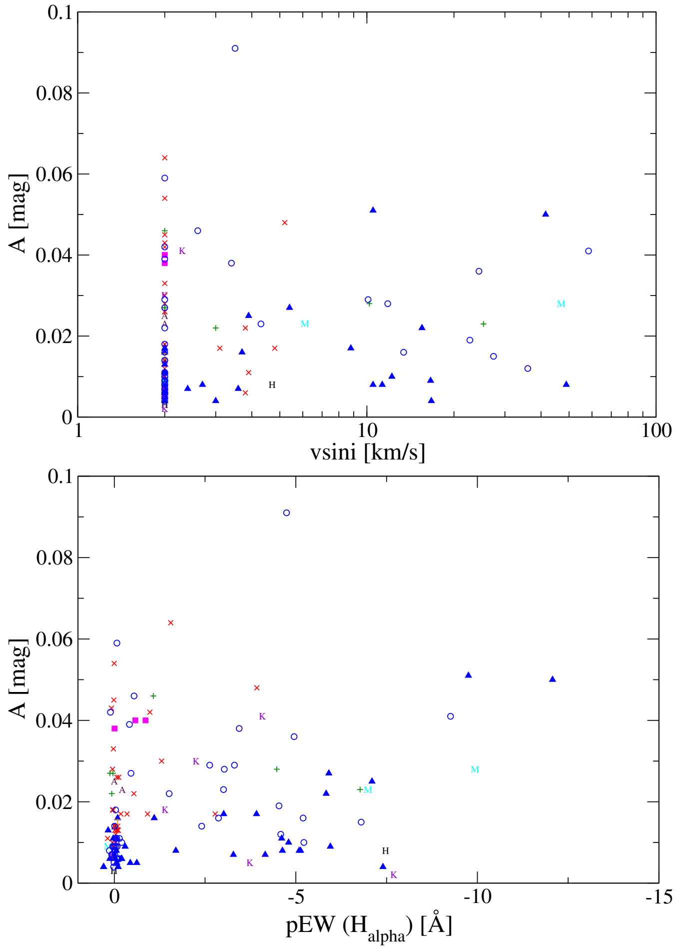

Fig. 5. Our amplitude of photometric variability as a function of $v \sin i$ (*top panel*) and pEW(Hα) (*bottom panel*). Red crosses: ASAS data, blue triangles: MEarth, blue open circles: SuperWASP, green pluses: NSVS, magenta squares: AstroLAB IRIS, maroon C's: ASAS-SN, black H's: HATNet, violet K's: K2, cyan M's: Montcabrer, orange T's: Montsec.

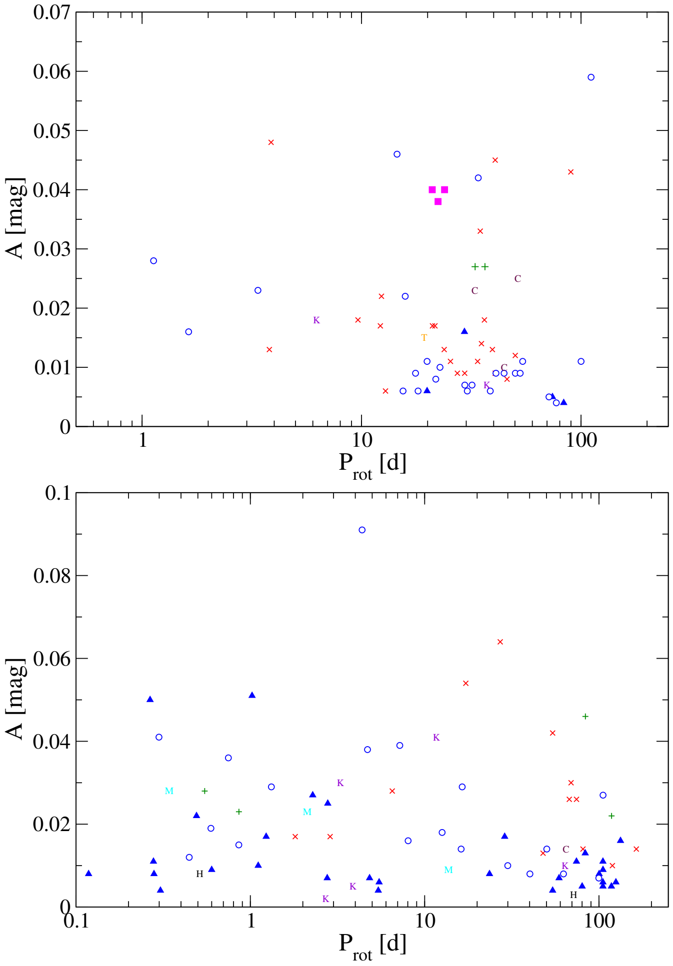

Fig. 6. Our amplitude of photometric variability as a function of rotation period for M0.0–M3.0 V stars (*top panel*) and M3.5–M8.5 V stars (*bottom panel*). Same symbol legend as in Fig. 5.

$0.25\,M_\odot < M < 0.5\,M_\odot$ and $0.08\,M_\odot < M < 0.25\,M_\odot$, and found an anti-correlation A–$P_{\rm rot}$ in the first group and no correlation in the second group. We repeated the same exercise separating our sample in early to mid (M0.0–3.0 V; $N = 63$) and mid to late (M3.5–8.5 V; $N = 78$) stars (Fig. 6). We performed a Spearman rank correlation analysis and obtained a relation coefficient of –0.24 with p-value 0.06 for early to mid stars, and a coefficient of –0.21 with p-value 0.06 for mid to late stars. Therefore, in both cases we found a suggestive (but non-significant) anti-correlation between A and $P_{\rm rot}$. We note the overabundace of M0.0–3.0 V stars with periods $P_{\rm rot}$ = 10–100 d with respect to M3.5–8.5 V stars).

4.4. Aperiodic variables

We also looked for aperiodic or irregular variable stars that display a large scatter in their light curves, but for which we failed to find any significant periodicity. For this reason, we used the common approach of plotting the standard deviation $\sigma(m)$ of each individual light curve as a function of the mean magnitude $\overline{m}$ (see e.g. Caballero et al. 2010, for a practical application). We performed this exercise for only three of the main surveys because average magnitudes of MEarth light curves were set to zero, different pass bands and instrumental set-ups must not be mixed up, and the complementary surveys and our own observations do not have enough data points for a robust analysis.

The $\sigma(m)$ vs. $\overline{m}$ plots for ASAS, SuperWASP, and NSVS are shown in Fig. 7. All NSVS stars follow the expected trend for their mean magnitude (see Irwin et al. 2007 for a detailed description of virtually all parameters affecting $\sigma(m)$ in a photometric survey). Of the SuperWASP stars, only J09003+218 = LP 368–128, a faint M6.5 V (Dupuy & Liu 2012; Alonso-Floriano et al. 2015a), has a much larger scatter than its peers. Newton et al. (2016) found a period of 0.439 d that we did not reproduce in our datasets (Table 3). However, we attribute its large $\sigma(m)$, of about 0.5 mag, to its magnitude, which is over 1 mag fainter than the second-faintest star in the SuperWASP sample. Finally, there are three outliers among the ASAS stars: J12248-182 = Ross 695, J04520+064 = Wolf 1539, J09307+003 = GJ 1125. We ascribe the origin of their large $\sigma(m)$ to their short angular separation to bright background stars that contaminate the ASAS light curves. In the three cases, they are located at variable angular separations $\rho \approx$ 25–50 arcsec to stars 1.2–2.5 mag brighter in the V band than our M dwarfs. As a result, the variability observed is not intrinsic to the stars themselves.

A few aperiodic or irregular variable stars also appeared in our monitoring with amateur and semi-professional telescopes. For example, with Carda we measured intra-night trends of over

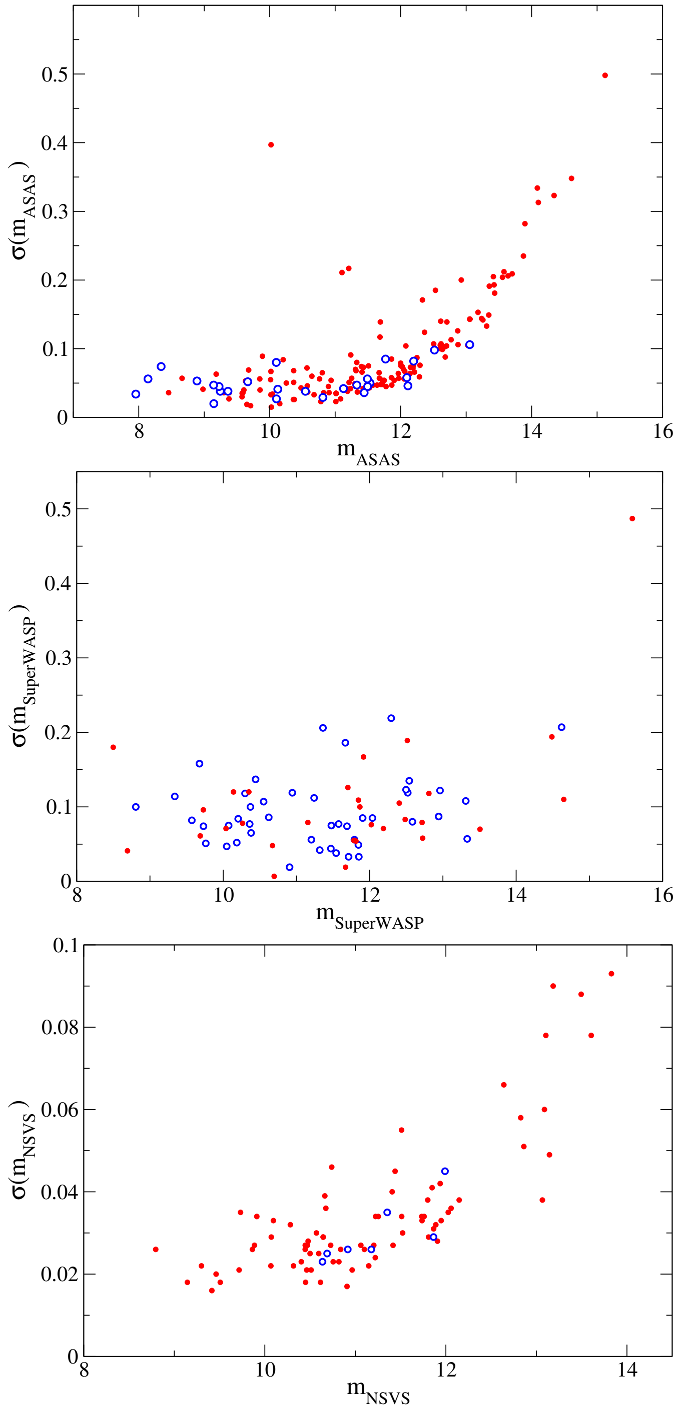

Fig. 7. Standard deviation $\sigma(m)$ vs. mean $\overline{m}$ for ASAS, SuperWASP, and NSVS magnitudes. Blue open circles and red filled circles represent stars with and without $P_{\rm rot}$ computed in this work, respectively. Most of the structure, specifically in the *top* and *bottom panels*, is not of astrophysical origin but related to the different sources of noise.

0.030 mag in the known variable star J05337+019 = V371 Ori, and a 15 min, 0.030 mag-amplitude flare in the poorly investigated, X-ray emitting star J06574+740 = 2MASS J06572616+7405265.

4.5. Long-period cycles

Baliunas et al. (1996) suggested the observable $P_{\rm cycle}/P_{\rm rot}$ to study the relation between cycle and rotation periods. They proposed $P_{\rm cycle}/P_{\rm rot} \sim D^i$, being D the dynamo number and i the slope of the relation. Slopes $i \sim 1$ would imply no correlation, while values different from unity would imply a correlation between the length of the cycle and rotation period. Previous works have explored this relation (Oláh et al. 2009; Gomes da Silva et al. 2012; Suárez Mascareño et al. 2016) and find a weak correlation for F, G, and K stars. Here we repeated the exercise restricting the analysis to M dwarf stars. For this, we carefully selected 47 single, inactive M dwarfs with previous published $P_{\rm cycle}$ and $P_{\rm rot}$ (Savanov 2012; Robertson et al. 2013; Suárez Mascareño et al. 2016, 2018; Wargelin et al. 2017; Küker et al. 2019) and the stars of our sample for which we have found $P_{\rm cycle}$ and $P_{\rm rot}$ (see Table 2). In our sample of field M dwarfs we did not include fast-rotating, probably very young M dwarfs tabulated by Vida et al. (2013, 2014) and Distefano et al. (2016, 2017).

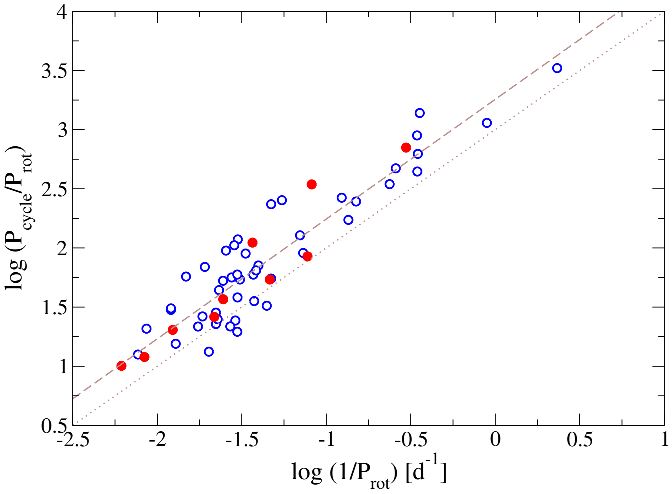

Fig. 8. $P_{\rm cycle}/P_{\rm rot}$ vs. $1/P_{\rm rot}$ in log–log scale for M dwarf stars with previous published $P_{\rm cycle}$ and $P_{\rm rot}$ (blue open circles) and stars with new $P_{\rm cycle}$ from this work (red filled circles). Dashed (i = 1.01) and dotted (i = 1.00, with arbitrary offset) lines mark our sample fit and non-correlation, respectively.

Figure 8 shows the plot $P_{\rm cycle}/P_{\rm rot}$ vs. $1/P_{\rm rot}$ in log–log scale. We found a slope i = 1.01 ± 0.06, in agreement with the results of Savanov (2012) and Suárez Mascareño et al. (2016), who also did not find a correlation between $P_{\rm cycle}$ and $P_{\rm rot}$ in M dwarfs.

5. Conclusions

As a complement to the CARMENES survey for exoplanets, we searched for rotation periods from photometric series of 337 M dwarfs. We collected public data from long-term monitoring surveys (MEarth, ASAS, SuperWASP, NSVS, Catalina, ASAS-SN, K2, and HATNet). For 20 stars without data in these public surveys or for those with poor data, we carried out photometric monitoring in collaboration with amateur observatories. In total, we investigated 622 light curves of 334 M dwarfs. We analysed each light curve by computing LS periodograms and identifying significant signals. In some cases, we also applied GLS and Gaussian processes analyses. We found 142 signals that we interpret as rotation periods. Of these, 73 are new and 69 match or even improve previous determinations found in the existing literature. We also found long activity cycles for ten stars of the sample, six of which we report here for the first time. We explored the relation between $P_{\rm cycle}$ and $P_{\rm rot}$ for a sample of 47 M dwarfs with previous reported cycle and rotation periods, and the ten M dwarfs with cycle and rotation periods presented in this work, and did not find any correlation between $P_{\rm cycle}$ and $P_{\rm rot}$.

Although the main aim of this work was to catalogue rotation periods of M dwarfs being searched for exoplanets with the radial-velocity method, and therefore to be able to discriminate between stellar activity and true exoplanet signals, we also presented results on (*i*) the absence of a lack of stars with intermediate periods at about 30 d with respect to stars with shorter periods in the rotation period distribution; (*ii*) the link between rotation period and activity, especially through rotational velocity and Hα pseudo-equivalent width; (*iii*) the identification of three very active, possibly young stars with new rotation periods between 0.34 d and 23.6 d; and (*iv*) the lack of apparent correlation between amplitude of photometric variability and $P_{\rm rot}$, $v \sin i$, and pEW(Hα).

The CARMENES Consortium will continue to improve or find new rotation periods, using them to discard or confirm radial-velocity exoplanets, and will make them public for use by other groups worldwide.

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Appendix A: Long tables

Tables A.1 and A.2 are available at the CDS.

Appendix B: Example light curves and periodograms

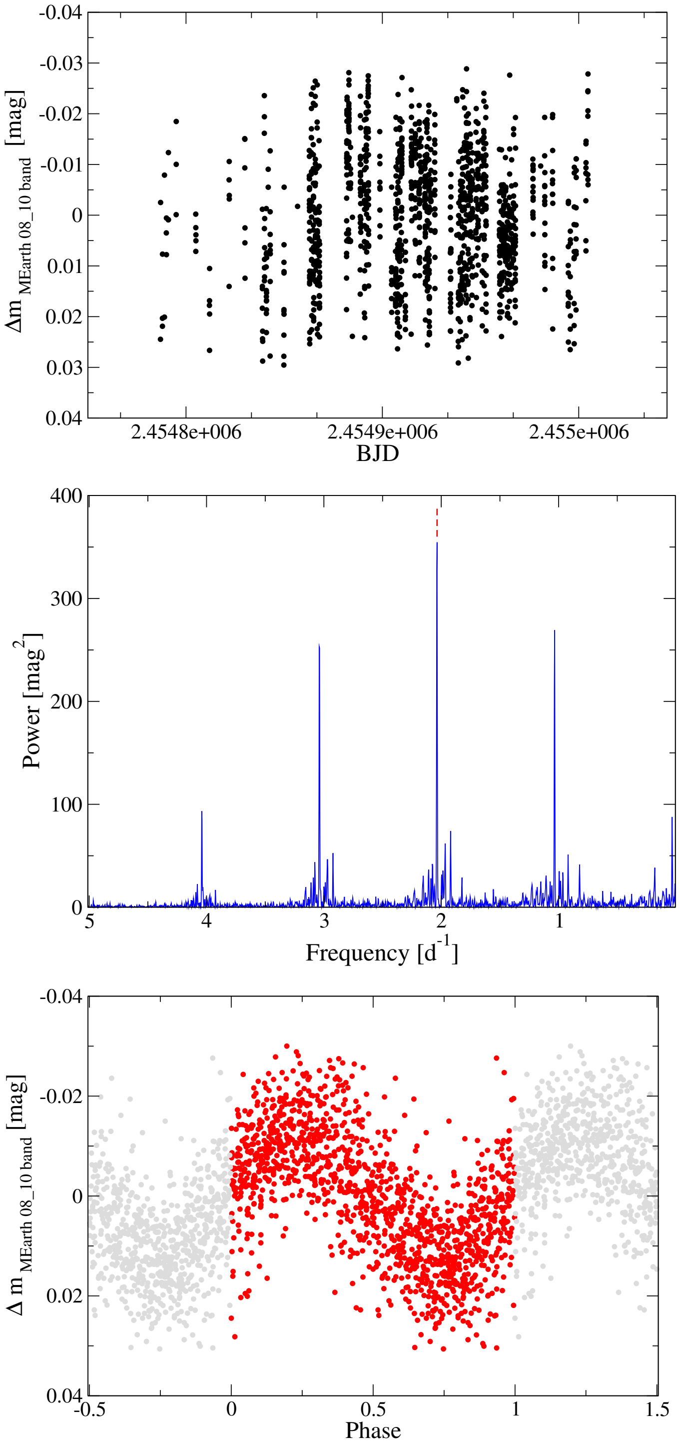

Fig. B.1. MEarth RG715-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.491$ d (*bottom*) for the M5.0 V star J12189+111 = GL Vir.

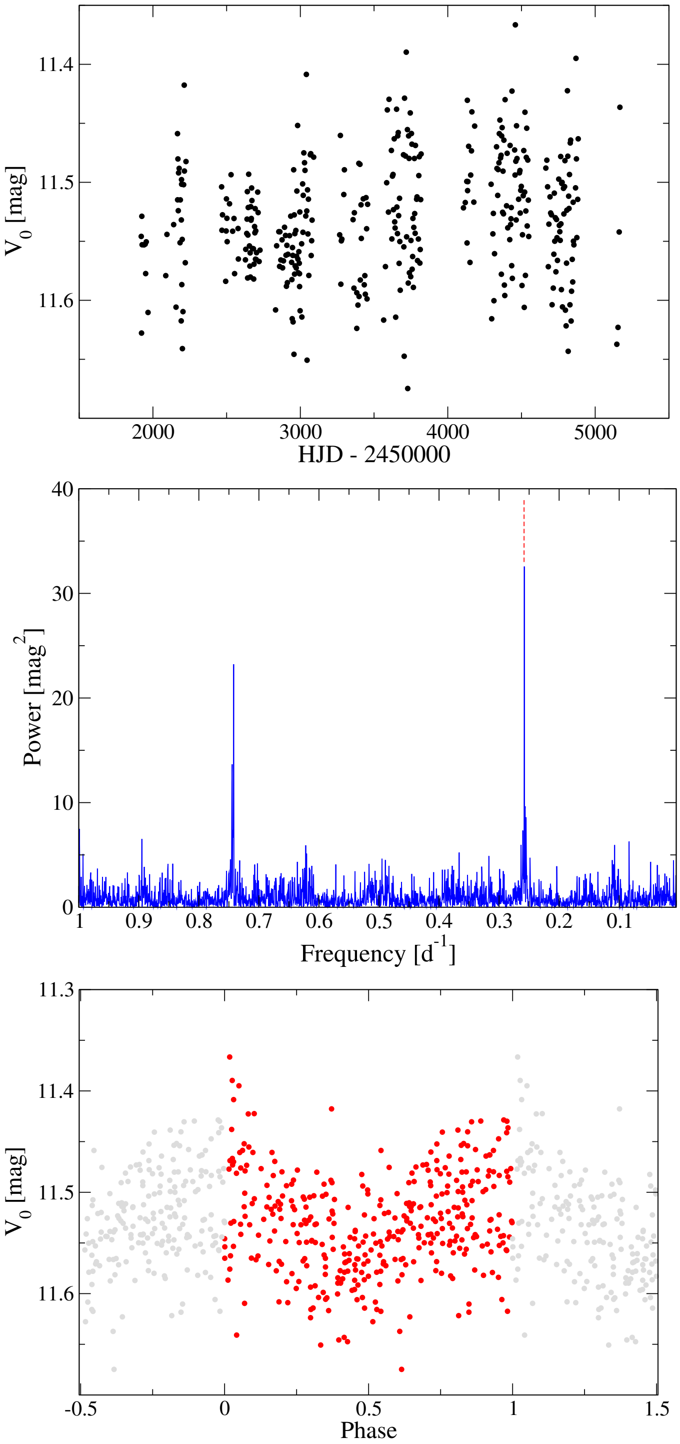

Fig. B.2. ASAS-3 *V*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 3.87$ d (*bottom*) for the M3.0 V star J03473–019 = G 080–021.

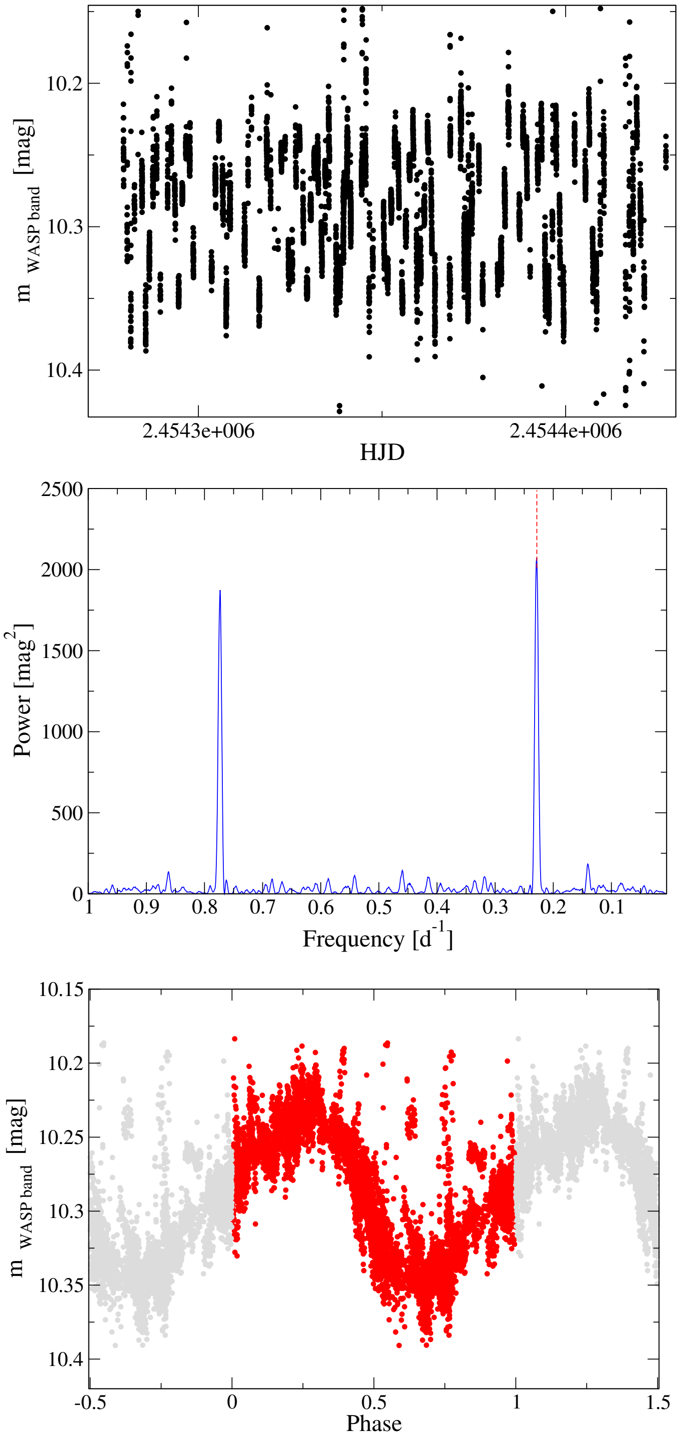

Fig. B.3. SuperWASP broad-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 4.379$ d (*bottom*) for the M3.5 V star J22468+443 = EV Lac.

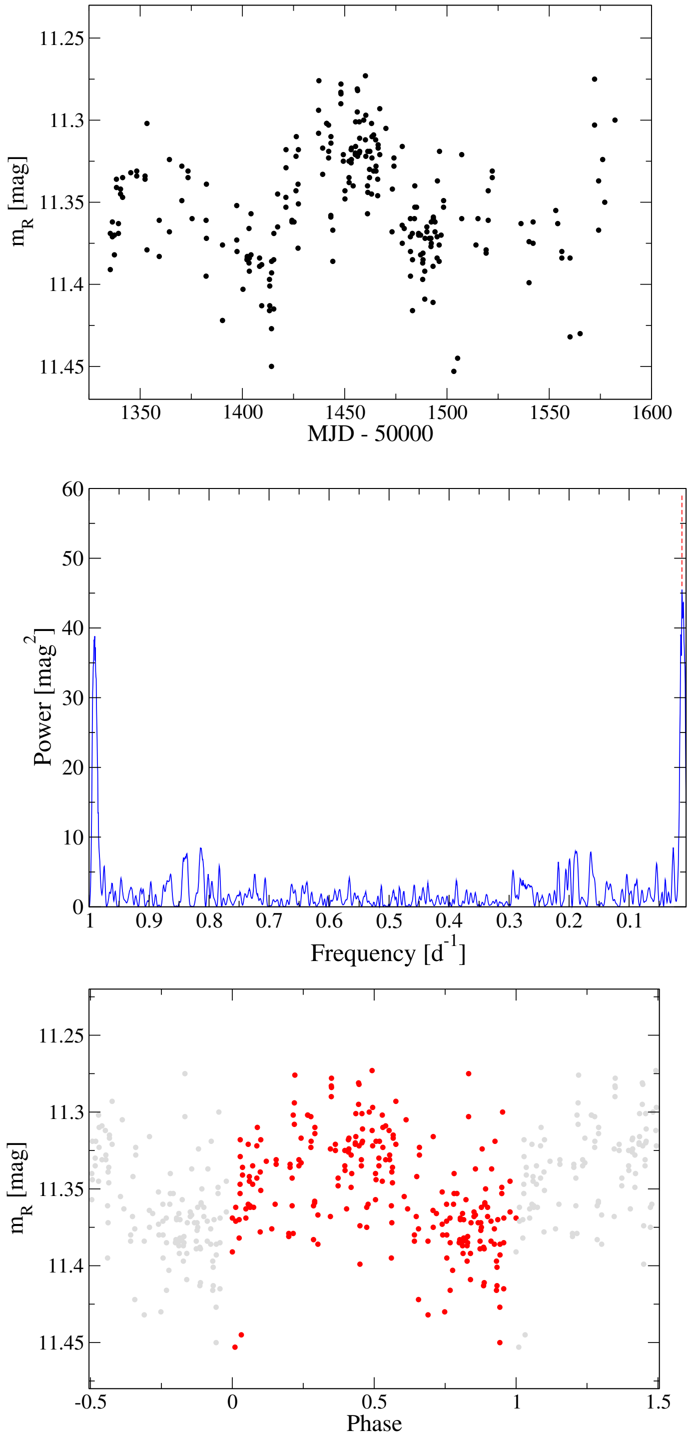

Fig. B.4. NSVS clear-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 87$ d (*bottom*) for the M4.0 V star J23431+365 = GJ 1289.

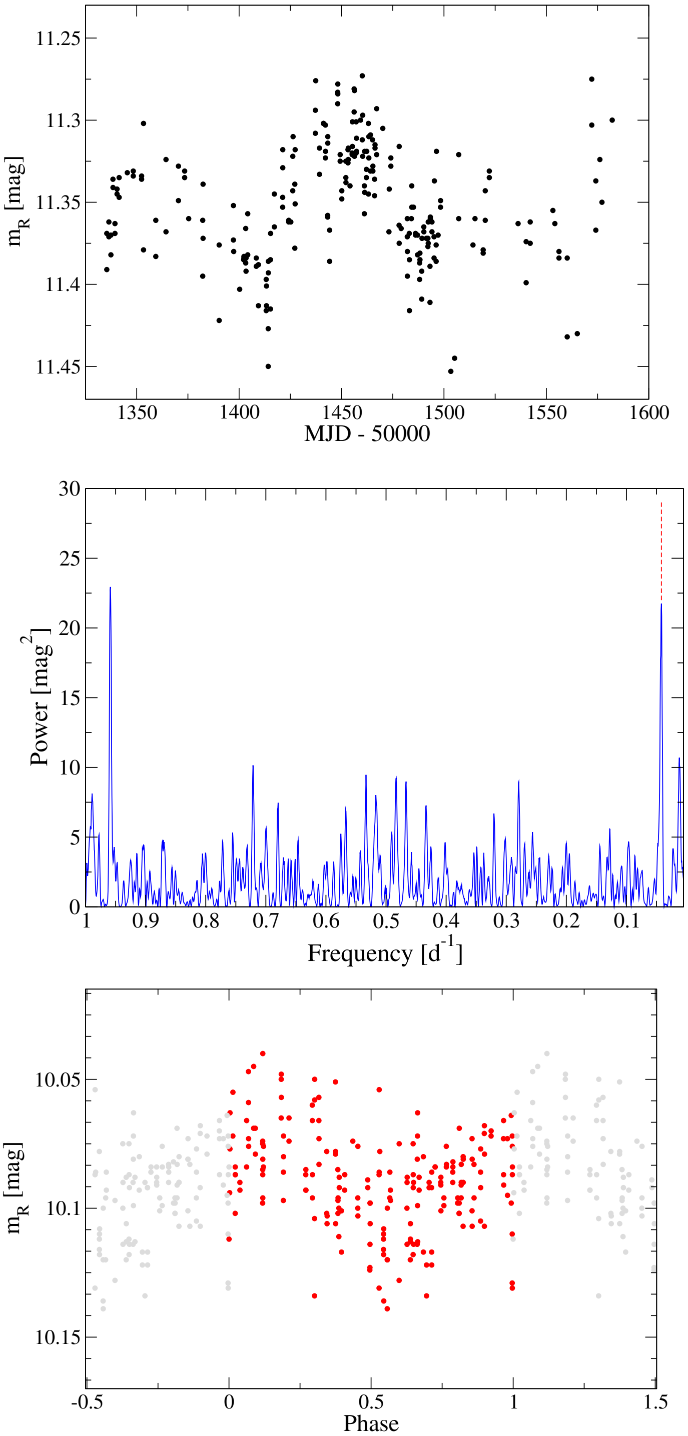

Fig. B.5. AstroLAB IRIS *R*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 23.9$ d (*bottom*) for the M3.0 V star J09428+700 = GJ 362.

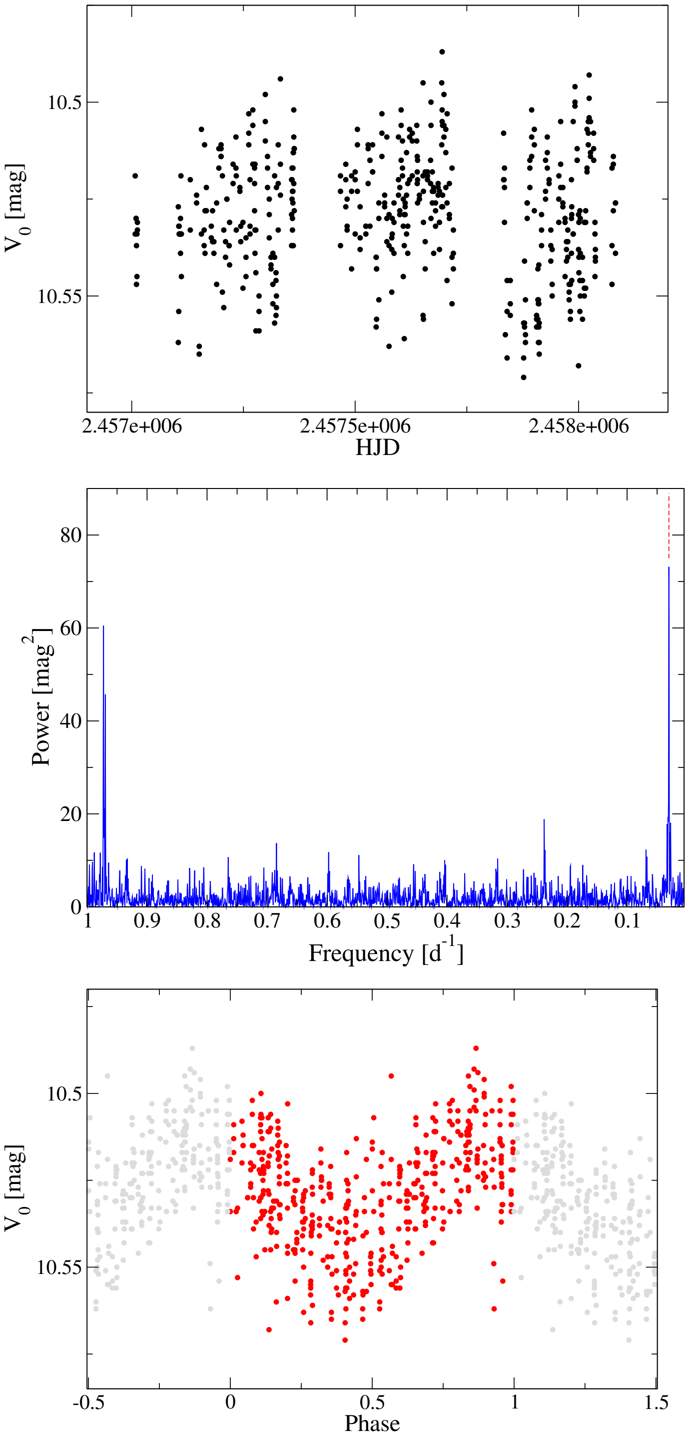

Fig. B.6. ASAS-SN *V*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 32.8$ d (*bottom*) for the M2.5 V star J20305+654 = GJ 793.

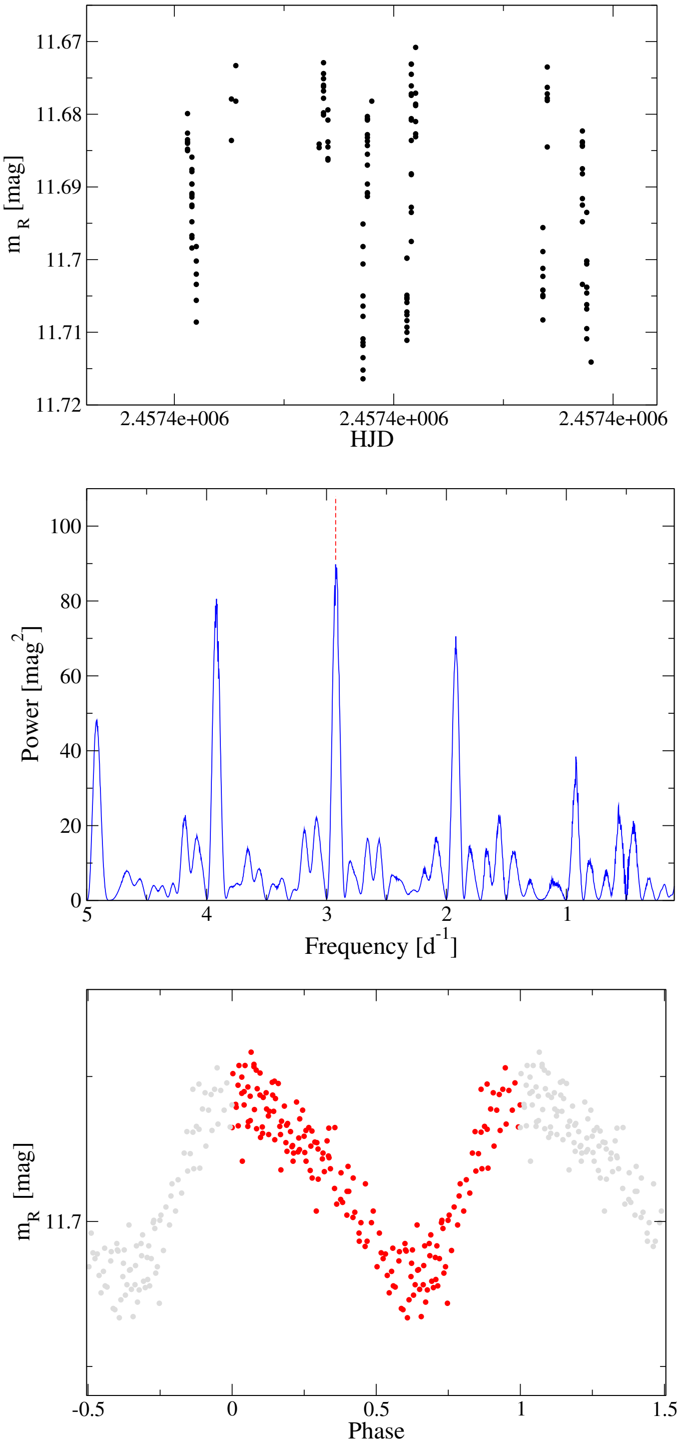

Fig. B.7. Montcabrer *R*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.342$ d (*bottom*) for the M5.0 V star J04772+206 = RX J0447.2+2038 (compare with Fig. B.8).

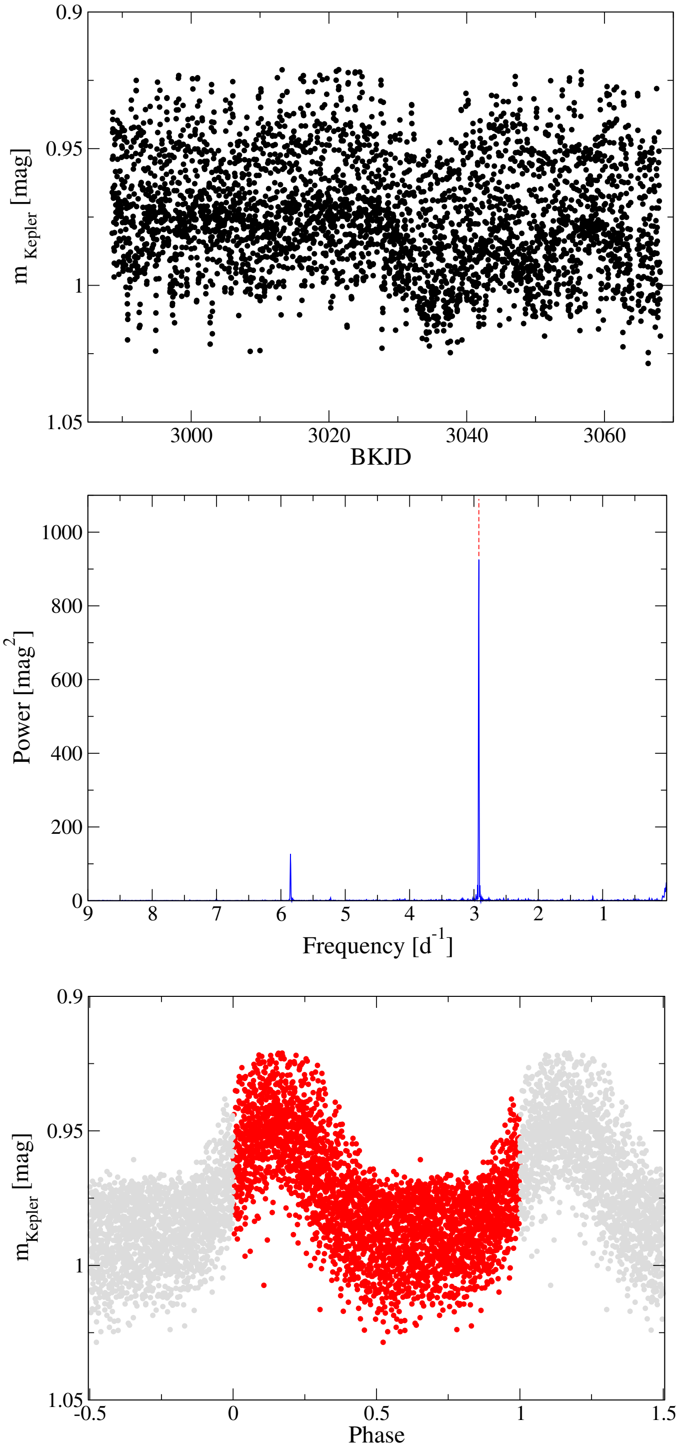

Fig. B.8. K2 photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.342$ d (*bottom*) for the M5.0 V star J04772+206 = RX J0447.2+2038 (compare with Fig. B.7).

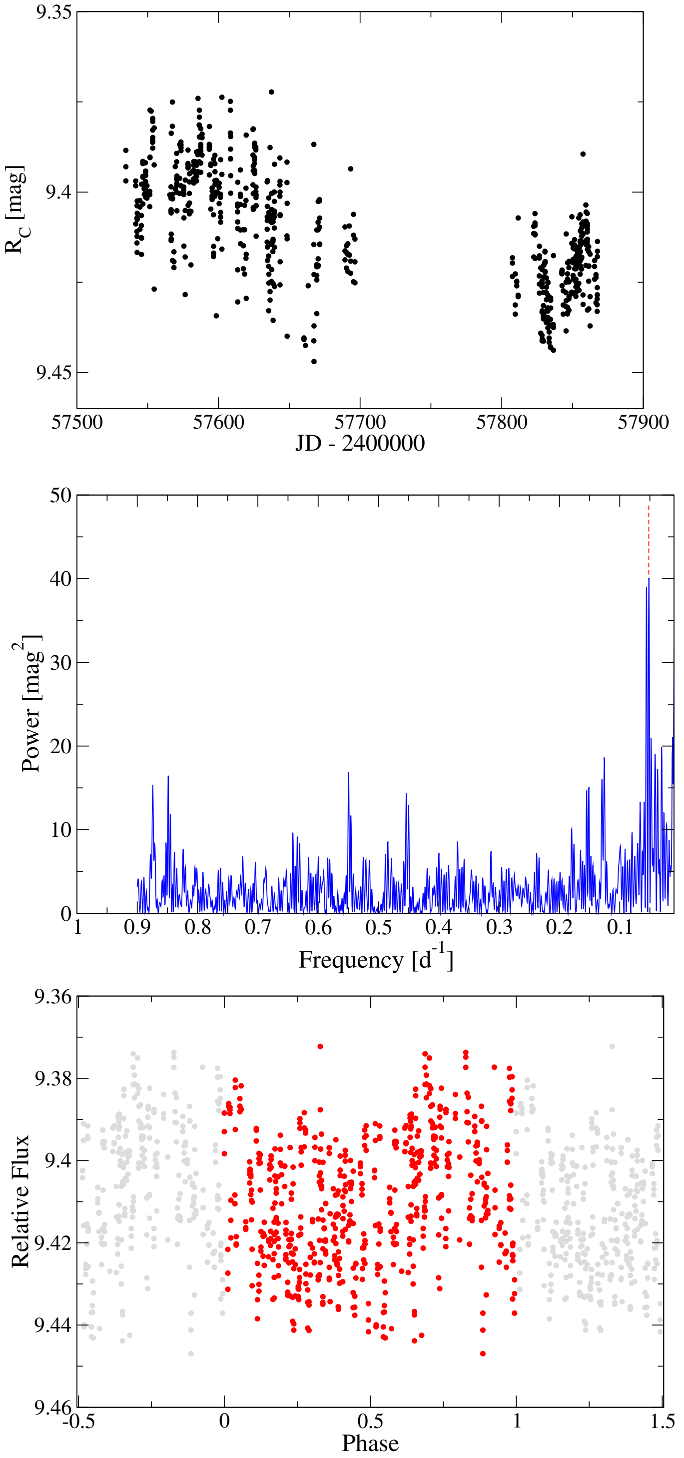

Fig. B.9. Montsec R_C-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 19.3$ d (*bottom*) for the M0.5 V star J17355+616 = BD+61 1678C.

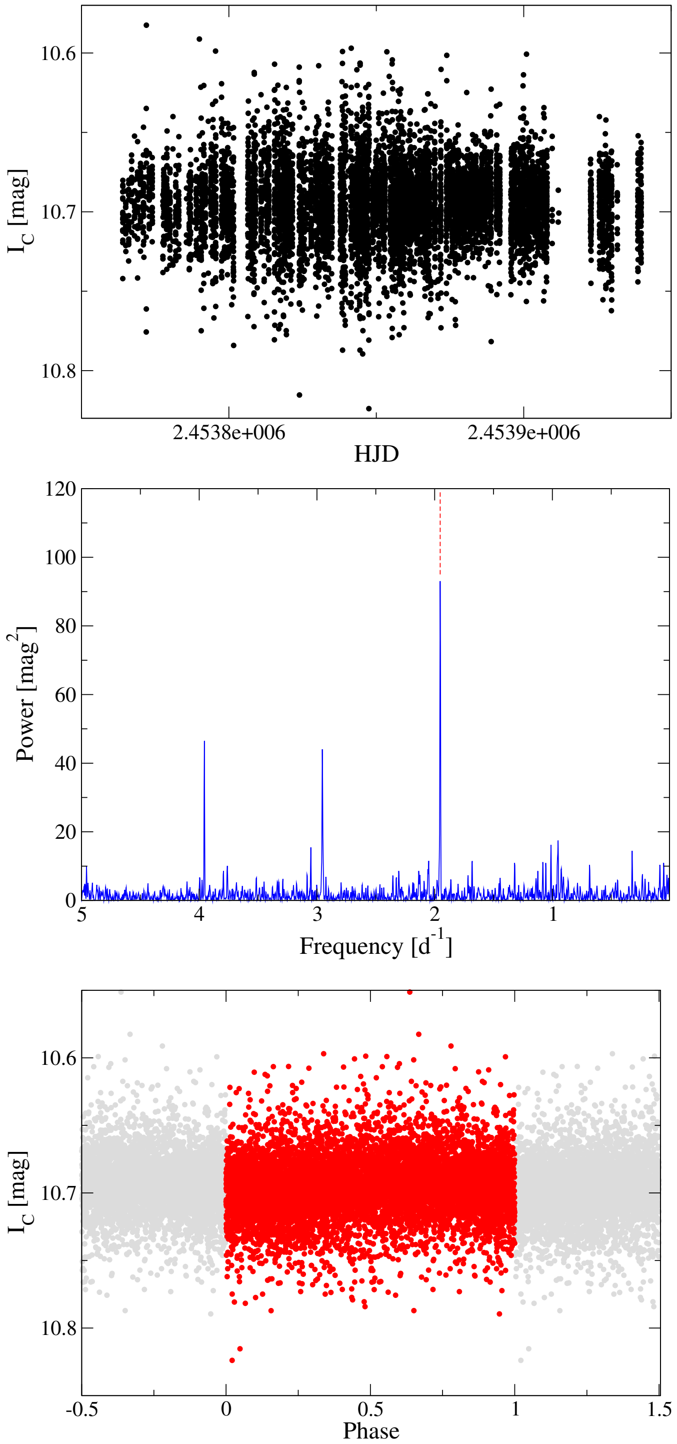

Fig. B.10. HATNet I_C-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.512$ d (*bottom*) for the M5.0 V star J16313+408 = G 180–060.

Capítulo 3

A system of three super-Earths in a cool dwarf star

Este capítulo se corresponde con la publicación *A system of three super-Earths in a cool dwarf star* (Díez Alonso y col., 2018a).

Este trabajo se enmarca en el segundo de los objetivos de la tesis: la detección y caracterización básica de sistemas planetarios que puedan ser caracterizados plenamente con un posterior seguimiento en velocidad radial.

En él se presenta el descubrimiento, la confirmación y la caracterización de un sistema de tres super-Tierras transitando la estrella enana fría *LP-415 17* (*K2-155*) (m_V=12.81), observada en la campaña 13 de la misión extendida del telescopio espacial Képler (K2). Cabe destacar que se trata de los primeros exoplanetas en cuyo descubrimiento participa un equipo de investigación de la Universidad de Oviedo.

En un análisis preliminar realizado a partir de los parámetros estelares publicados en la base de datos de K2 [1] (Huber y col., 2016), la estrella fue clasificada como de tipo espectral M0 V. Ahora bien, en un estudio más profundo llevado a cabo por comparación de modelos sintéticos con espectros de alta resolución adquiridos con el instrumentos HARPS-N, instalado en el Telescopio Nazionale Galileo (Observatorio Roque de los Muchachos), se concluyó que se trata de una enana de tipo espectral K6. La $T_{\rm eff}$ = 4258± 150 K, fue estimada mediante el método del flujo infrarrojo (González Hernández y col., 2018), aplicando calibraciones $T_{IRFM} - (color, [Fe/H])$ para estrellas enanas. Metalicidad y $log\ g$ fueron obtenidos por comparación del espectro con espectros sintéticos, mientras que por comparación con parámetros tabulados (Bertelli y col., 1994) se obtuvo $R = 0.58^{+0.06}_{-0.03}\ R_{\odot}$) y $M = 0.65^{+0.06}_{-0.03}\ M_{\odot}$).

Aunque nuestro estudio tiene por objeto las enanas de tipo espectral M, dado que se trata de una estrella enana fría con un sistema planetario de tres super-Tierras, se presenta aquí el resultado de la investigación. Además, K2-155 es $[Fe/H] = -0.3 \pm 0.2$ una de las estrellas frías más brillantes (m_V=12.81) y de menor metalicidad de las que se tenga constancia de albergar sistemas planetarios.

De forma paralela, el sistema fue detectado, validado y caracterizado por Hirano y col., 2018b. En su trabajo, se caracteriza a la estrella K2-155 como de tipo espectral M0 V, sensiblemente más fría y de menor radio que lo presentado en (Díez Alonso y col., 2018a). En consecuencia, las temperaturas y radios obtenidos por Hirano y col., 2018b para los planetas del sistema son inferiores, aunque dentro del régimen

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[1] https://archive.stsci.edu/k2/

de las super-Tierras. La diferencia más significativa es su estimación de la energía recibida por K2-155 d, para la que se estima $S = 1.7 \pm 0.4 S_{\oplus}$[2], implicando que el planeta se encuentra en (o cercano) a la zona de habitabilidad de K2-155.

En nuestro trabajo, asumiendo m_V=12.81, se estima la distancia a K2-155 en 82^{+29}_{-12} pc. Posteriormente a su aceptación fue publicada una distancia de 72.95 ± 0.28 pc por la misión Gaia en su DR2 (Gaia Collaboration y col., 2018). El hecho de que la estrella se encuentre ligeramente más próxima puede implicar un tipo espectral más cercano al M0 V, y por lo tanto un menor radio y una menor temperatura de equilibrio para sus planetas.

La curva de luz fue analizada mediante el método Box Least Squares (BLS), identificando tres señales de tránsito. Para confirmar la naturaleza planetaria de las señales y descartar posibles falsos positivos, se analizaron imágenes de alta resolución obtenidas con el instrumento NESSI (telescopio WIYN, Kitt peak, Arizona), se inspeccionaron imágenes de archivo y se realizó una validación estadística.

Para obtener los parámetros de los planetas, los tránsitos correspondientes a cada planeta fueron puestos en fase y analizados ajustando modelos mediante MCMC. Su masa fue estimada en base a relaciones empíricas a partir del radio inferido.

Para cada planeta se estimó la amplitud de la señal inducida en velocidad radial (obteniendo ~ 2 m·s^{-1}), así como la amplitud de su señal en espectroscopía de transmisión ($\sim 10^{-5}$), resultando que los tres están dentro de las capacidades de caracterización de instrumentos como ESPRESSO (VLT) o el Telescopio Espacial James Webb, con los que se podrá realizar una caracterización precisa de sus masas y un estudio de sus atmósferas.

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[2] De Díez Alonso y col. (2018a) se deriva $S = 3.4^{+2.9}_{-1.0} S_{\oplus}$

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A system of three transiting super-Earths in a cool dwarf star

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ABSTRACT

We present the detection of three super-Earths transiting the cool star LP415-17, monitored by K2 mission in its 13th campaign. High-resolution spectra obtained with High Accuracy Radial velocity Planet Searcher-North/Telescopio Nazionale Galileo (HARPS-N/TNG) showed that the star is a mid-late K dwarf. Using spectral synthesis models, we infer its effective temperature, surface gravity, and metallicity, and subsequently determined from evolutionary models a stellar radius of 0.58 $R_{\odot}$. The planets have radii of 1.8, 2.6, and 1.9 $R_{\oplus}$ and orbital periods of 6.34, 13.85, and 40.72 d. High-resolution images discard any significant contamination by an intervening star in the line of sight. The orbit of the furthest planet has radius of 0.18 au, close to the inner edge of the habitable zone. The system is suitable to improve our understanding of formation and dynamical evolution of super-Earth systems in the rocky–gaseous threshold, their atmospheres, internal structure, composition, and interactions with host stars.

Key words: techniques: photometric – techniques: spectroscopic – planets and satellites: detection – stars: individual: LP415-17 – stars: low mass

1 INTRODUCTION

Transiting planetary systems are of great value for the characterization of exoplanetary atmospheres (Charbonneau, Brown & Latham 2000; Kreidberg et al. 2014), the understanding of planetary formation and evolution (Owen et al. 1999), and for the study of the interactions with their host stars (Cauley et al. 2017). Cool dwarf stars are well suited to find Earth size and super-Earth size planets by the transit method, since transits produce deeper dimmings than in solar-type stars. The amplitude of signals in transit transmission spectroscopy is also higher for stars with small radius, favouring these type of stars for future atmospheric studies of their planetary systems (Gillon et al. 2016).

The Kepler mission (Borucki et al. 2010) has achieved a large number of detections of transiting planets (Howard et al. 2012). In its second mission (Howell et al. 2014), the satellite performs observations of different ecliptic plane fields for periods of time spanning about 80 d. Multiple signals of exoplanet candidates are present in concluded campaigns (Vanderburg et al. 2015; Crossfield et al. 2016). Campaign 13th has focused in the Hyades and Taurus region, centred in α = 04:51:11, δ = +20:47:11, between 2017 March 08 and 2017 May 27. In this campaign K2 observed 26.242 targets at standard long cadence mode and 118 targets at short cadence mode. LP415-17 (α = 04:21:52.487, δ = +21:21:12.96) has been observed in low cadence mode.

In this letter, we present the detection of three super-Earths transiting the star LP415-17 (EPIC 210897587, 2MASS 04215245 + 2121131). In Section 2 we describe the characterization of the star from spectra acquired with HARPS-N spectrograph and the analysis of the K2 photometric time series. We also discuss possible contaminating sources and the main parameters derived for the planets. In Section 3 we present estimations of the masses, discuss the stability of the system and its suitability for future characterization by transmission spectroscopy. In Section 4 we summarize the main conclusions derived from this work.

2 METHODS

2.1 Stellar characterization

We obtained three spectra, 1800 s of exposure time each, with HARPS-N (Cosentino et al. 2012) a fibrefed high-resolution echelle spectrograph installed at the 3.6 m Telescopio Nazionale Galileo in the Roque de los Muchachos Observatory (Spain) with a resolving

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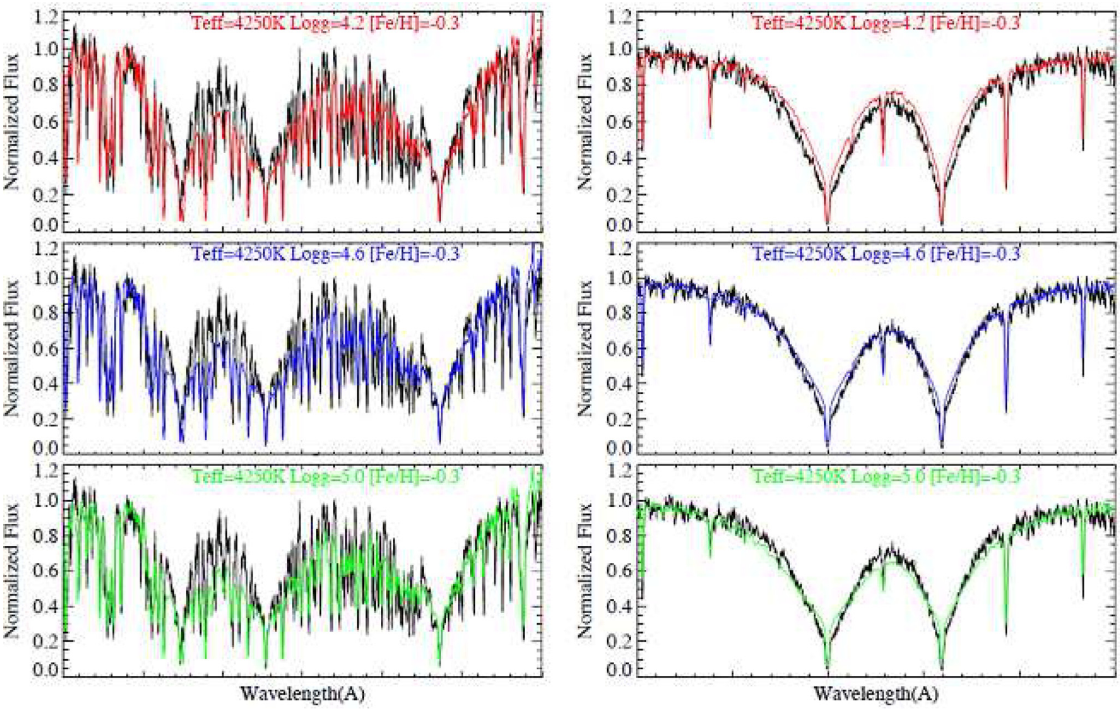

Figure 1. Synthetic spectral models centred in the magnesium triplet (left) and Na D doublet (right), calculated with $T_{\rm eff} = 4250$ K, [Fe/H]$= -0.3$, and $\log g = 3.4$ (top), $\log g = 4.6$ (middle), and $\log g = 4.0$ (bottom), compared with the observed spectrum. The best fit is obtained with $\log g = 4.6$.

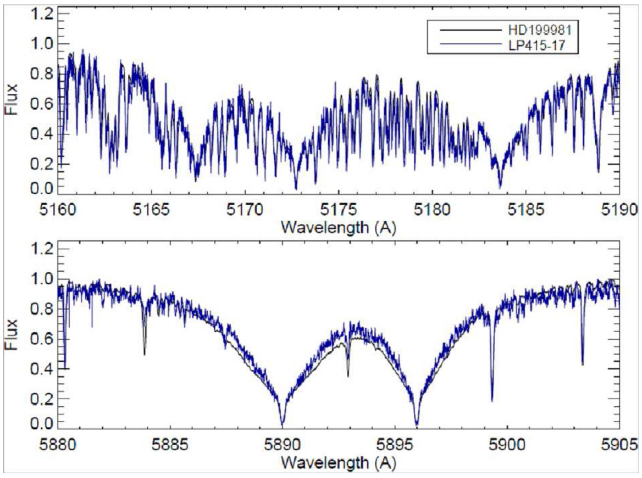

Figure 2. Spectrum of LP415-17 compared with the observed spectrum of HD199981.

power of $R = 115\,000$ over a spectral range from 380 to 690 nm. We have averaged them to obtain a final spectrum smoothed with 10-pixel step to improve the visualization of spectral features. We compared this spectrum with synthetic models (Allende Prieto et al. 2014) generated with ASSET (Koesterke et al. 2008), adopting Kurucz atmospheric models (Castelli & Kurucz 2003; Mészáros et al. 2012). Synthetic spectra have been broadened with a macroturbulence profile of 1.64 km s^{-1} (Fischer & Valenti 2005), with a rotation profile taking $v_{\rm rot} = 1.8$ km s^{-1} (Gray 2005) and with a Gaussian profile for instrumental broadening at resolution of 115 000 (FWHM ∼2.6 km s^{-1}). The effective temperature has been estimated using the infrared flux method (González Hernández & Bonifacio 2009). We apply $T_{\rm IRFM}$ – (colour, [Fe/H]) calibrations for dwarf stars, correcting for extinction the stellar magnitudes according to $A_X = R_X \times E(B - V)$. R_X was obtained from McCall (2004), and the reddening $E(B - V)$ from the dust maps (Schlegel et al. 1998), but corrected using the equations in Bonifacio et al. (2000) for the estimated distance to the star (82 pc) and Galactic latitude. We obtained $E(B - V) = 0.087$ and $T_{\rm IRFM} = 4258 \pm 150$ K.

The metallicity and $\log g$ have been obtained via comparison of the observed spectrum with synthetic spectra, resulting [Fe/H] $= -0.3 \pm 0.2$ and $\log g = 4.6 \pm 0.3$ (Fig. 1). We compare the stellar parameters and metallicity with a grid of tabulated isochrones (Bertelli et al. 1994), and obtain $R_* = 0.58^{+0.06}_{-0.03}$ R$_\odot$, $M_* = 0.65^{+0.06}_{-0.03}$ M$_\odot$, and $M_{\rm V} = 7.95^{+0.34}_{-0.66}$ mag. In Fig. 2 we compare the observed spectrum of LP415-17 with that of the well-characterized star HD199981 (Kordopatis et al. 2013), whose parameters (K6V, $T_{\rm eff} = 4263$ K, $\log g = 4.97$) are very close to our results for LP415-17.

Adopting $m_{\rm V} = 12.54$, we estimate a distance to LP415-17 of $D_* = 82^{+29}_{-12}$ pc. We measured a radial velocity from the HARPS-N spectrum, which combined with the proper motions reported in Table 1 results in velocity components $U = -38.2$ km s^{-1}, $V = -69.4$ km s^{-1}, and $W = 31.8$ km s^{-1}. A comparison with the kinematic and metallicity properties of the Copenhagen Survey of the Solar neighbourhood (Nordström et al. 2004) suggests that LP415-17 could be a member of the Hercules stream, which according to Bensby, Oey & Feltzing (2007) could be a combination of thin and thick disc stars originating in interactions of the inner disc with the bar of our Galaxy.

From the observed spectrum we determine a R'_{HK} index of -4.85 ± 0.13 which according to Suárez Mascareño et al. (2015) indicates a likely rotation period of $34.8 \pm 8.\ 2$ d. Table 1 summarizes stellar parameters for LP415-17.

Table 1. Stellar parameters for LP415-17.

Parameter	Value	Source
V (mag)	12.806 ± 0.005	^{a}
R (mag)	12.286 ± 0.006	^{a}
I (mag)	12.289 ± 0.090	^{a}
J (mag)	10.274 ± 0.021	^{b}
H (mag)	9.686 ± 0.021	^{b}
K (mag)	9.496 ± 0.014	^{b}
T_{eff} (K)	4258 ± 150	^{c}
[Fe/H]	-0.3 ± 0.2	^{c}
Radius, $\mathrm{R}_{\odot}$	$0.58^{+0.06}_{-0.03}$	^{c}
Mass, $\mathrm{M}_{\odot}$	$0.65^{+0.06}_{-0.03}$	^{c}
$\log g$ (cgs)	4.6 ± 0.3	^{c}
M_V (mag)	$7.95^{+0.34}_{-0.66}$	^{c}
$\log_{10}(R'_{HK})$	-4.85 ± 0.13	^{c}
P_{rot} (d)	34.8 ± 8.2	^{c}
Distance (pc)	82^{+29}_{-12}	^{c}
V_{r} (km s^{-1})	19.1 ± 0.5	^{c}
μ_α (mas yr^{-1})	201.9 ± 6.9	^{a}
μ_δ (mas yr^{-1})	-71.3 ± 4.3	^{a}
U, V, W (km s^{-1})	$-38.2, -69.4, 31.8$	^{c}

[a] UCAC4 (Zacharias et al. 2013).
[b] 2MASS (Cutri et al. 2003).
[c] This work.

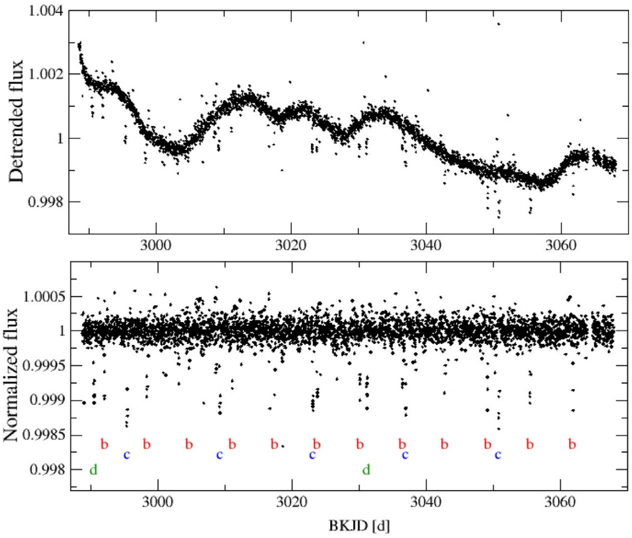

Figure 3. Top: K2 detrended light curve for LP415-17. Bottom: normalized light curve. Characters b, c, and d indicate times of observed transits of planets b, c, and d.

2.2 K2 photometric data

The light curve of LP415-17 exhibits clear signals of at least three transiting objects (Fig. 3). We analysed the K2 corrected photometry from the star following the work of Vanderburg & Johnson (2014), applying a spline fit to detrend stellar variability and search for periodic signals with a box least squares (BLS) method (Kovács et al. 2002) on flattened data. Once BLS finds a transit signal, it is fitted and removed, and another search for transit signals is performed. Following this method, we find three transit signals of planet candidates with orbital periods 6.342 ± 0.002 d (b), 13.850 ± 0.006 d (c), and 40.718±0.005 d (d).

To estimate the main parameters for each planet we analysed each phase-folded transit using MCMC, fitting models from Mandel & Agol (2002) with the EXOFAST package (Eastman et al. 2013), resampling the light curve 10 times uniformly spaced over 29.4 min for each data point and averaging (Kipping 2010) (Fig. 4). We set priors on host star ($T_{\mathrm{eff}} = 4258$ K, $\log g = 4.6$, [Fe/H] $= -0.3$), orbital periods ($P_{\mathrm{orb}} = 6.34$ (b), 13.85 (c), 40.72 (d)) d. Due to tidal circularization, $e = 0$ for planet b. We also assume $e = 0$ for c and d, for being transiting planets in multiplanetary systems (Van Eylen & Albrecht 2015). The parameters obtained for planets b, c, and d are summarized in Table 2.

Planet d only shows two transits in the K2 13th campaign observation window. Separate analysis of these two transits reveals coincident transit parameters, supporting the idea that this signal is created by the same object. The parameters for each observed transit of planet d are summarized in Table 2.

The planets have estimated radii $1.8^{+0.2}_{-0.1}$ $\mathrm{R}_{\oplus}$ (b), $2.6^{+0.7}_{-0.2}$ $\mathrm{R}_{\oplus}$ (c), and $1.9^{+0.7}_{-0.2}$ $\mathrm{R}_{\oplus}$ (d), orbital periods 6.342 ± 0.002 d (b), 13.850 ± 0.006 d (c), and 40.718 ± 0.005 d (d), and semimajor axis $0.0562^{+0.0013}_{-0.0014}$ au (b), $0.0946^{+0.0031}_{-0.0030}$ au (c), and $0.1937^{+0.0064}_{-0.0059}$ au (d).

2.3 False positives analysis

To exclude false positives from possible companions, we analysed speckle images of the star at 562 and 832 nm, obtained with NESSI at the 3.5 m WIYN telescope (Kitt peak, Arizona), available at ExoFOP-K2.[1,2] Images exclude companions at 0.2 arcsec with $\delta_{\mathrm{mag}} < 3.5$ and at 1 arcsec with $\delta_{\mathrm{mag}} < 6$. We searched for possible contaminating background sources in images from POSS-I (Minkowski & Abell 1963) (year 1953) and 2MASS (Cutri et al. 2003) (year 1998). LP415-17 exhibits high proper motion $\mu_\alpha = 201.9$ mas yr^{-1} and $\mu_\delta = -71.3$ mas yr^{-1} so we can inspect for background sources at LP415-17's position during the K2 13th campaign. No background object is found at the current star position (Fig. 5).

Speckle images from WIYN, inspection of POSS-I and 2MASS images, statistical analysis performed with VESPA package (Morton 2012, 2015) (obtaining FPP $< 10^{-5}$ for all the planets), and taking into account FPP overestimation for multiplanet systems (Lissauer et al. 2011; Sinukoff et al. 2016), make us to reject possible contaminating sources, concluding that the transit signals in LP 415-17 are of planetary origin.

3 DISCUSSION

Following the mass–radius relation (Weiss & Marcy 2014)

$$\frac{M_{\mathrm{p}}}{M_{\oplus}} = 2.69 \cdot \left(\frac{R_{\mathrm{p}}}{R_{\oplus}}\right)^{0.93}$$

for planets satisfying $1.5 \le R_{\mathrm{p}}/R_{\oplus} \le 4$, we obtain $M_{\mathrm{b}} = 4.7\ \mathrm{M}_{\oplus}$, $M_{\mathrm{c}} = 6.5\ \mathrm{M}_{\oplus}$, $M_{\mathrm{d}} = 4.9\ \mathrm{M}_{\oplus}$ for planets b, c, and d, respectively. Assuming $M_{\mathrm{p}} \ll M_{*}$, circular orbits, and $\sin i \sim 1$, we compute induced amplitudes in stellar velocity variations of 2.2 m s^{-1} for planet b, 2.3 m s^{-1} for planet c, and 1.2 m s^{-1} for planet d.

Given the visual magnitude of the star ($V = 12.8$) the required radial velocity monitoring at 1 m s^{-1} precision is hard to obtain for HARPS-like spectrographs in medium size telescopes, however is well suited for ESPRESSO (Pepe et al. 2014; González Hernández,

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[1] https://exofop.ipac.caltech.edu/k2/

[2] Images where taken by Hirano et al. (2018). We noticed their work in this system during the revision process.

Table 2. Parameters for planets b, c, and d.

Planet parameters	*b*	*c*	*d*		
Orbital period, P (d)	6.342 ± 0.002	13.850 ± 0.006	40.718 ± 0.005		
Semimajor axis, a (au)	$0.0562^{+0.0013}_{-0.0014}$	$0.0946^{+0.0031}_{-0.0030}$	$0.1937^{+0.0064}_{-0.0059}$		
Radius, $R_{\rm p}$ ($R_\oplus$)	$1.8^{+0.2}_{-0.1}$	$2.6^{+0.7}_{-0.2}$	$1.9^{+0.7}_{-0.2}$		
Mass, $M_{\rm p}$ ($M_\oplus$)^a	$4.7^{+0.5}_{-0.3}$	$6.5^{+1.5}_{-0.5}$	$4.9^{+1.7}_{-0.6}$		
Equilibrium temperature, $T_{\rm eq}$ (K)	708^{+38}_{-31}	583^{+52}_{-35}	381^{+47}_{-25}		
Transit parameters	*b*	*c*	*d*	*d* (2990.500)$^{\rm b}$	*d* (3031.218)$^{\rm b}$
Number of transits	12	5	2	–	–
Epoch, BKJD (d)	2992.068 ± 0.002	2995.426 ± 0.001	2990.500 ± 0.003	2990.500 ± 0.003	3031.218 ± 0.002
Radius of planet in stellar radii ($R_{\rm p}/R_*$)	$0.0261^{+0.0009}_{-0.0008}$	$0.0321^{+0.0016}_{-0.0010}$	$0.0273^{+0.0021}_{-0.0015}$	$0.0280^{+0.0011}_{-0.0009}$	$0.0292^{+0.0027}_{-0.0018}$
Semimajor axis in stellar radii (a/R_*)	$18.5.0^{+1.1}_{-1.6}$	$27.0^{+2.2}_{-4.2}$	$63.3^{+6.4}_{-13}$	$73.2^{+4.2}_{-6.7}$	75.0^{+13}_{-20}
Linear limb-darkening coeff, u_1	$0.644^{+0.063}_{-0.080}$	$0.614^{+0.065}_{-0.084}$	$0.597^{+0.085}_{-0.110}$	$0.551^{+0.083}_{-0.11}$	$0.540^{+0.10}_{-0.12}$
Quadratic limb-darkening coeff, u_2	$0.122^{+0.074}_{-0.061}$	$0.148^{+0.071}_{-0.060}$	$0.142^{+0.091}_{-0.072}$	$0.174^{+0.093}_{-0.077}$	$0.183^{+0.11}_{-0.088}$
Inclination, i (deg)	$88.3^{+1.2}_{-1.9}$	$88.96^{+0.71}_{-0.88}$	$89.61^{+0.27}_{-0.48}$	$89.75^{+0.17}_{-0.20}$	$89.62^{+0.26}_{-0.37}$
Impact parameter, b	$0.34^{+0.24}_{-0.23}$	$0.45^{+0.37}_{-0.31}$	$0.44^{+0.33}_{-0.30}$	$0.33^{+0.20}_{-0.21}$	$0.50^{+0.22}_{-0.31}$
Transit depth, δ	$0.00068^{+0.00005}_{-0.00004}$	$0.00103^{+0.00010}_{-0.00006}$	$0.00074^{+0.00012}_{-0.00008}$	$0.00078^{+0.00006}_{-0.00005}$	$0.00085^{+0.00017}_{-0.00010}$
Total duration, T_{14} (d)	$0.1004^{+0.0050}_{-0.0048}$	$0.1470^{+0.0130}_{-0.0260}$	$0.1860^{+0.0097}_{-0.0018}$	$0.1713^{+0.0056}_{-0.0051}$	$0.156^{+0.018}_{-0.011}$
Ingress/egress duration, τ (d)	$0.0030^{+0.0009}_{-0.0003}$	$0.0056^{+0.0039}_{-0.0008}$	$0.0060^{+0.0050}_{-0.0010}$	$0.0052^{+0.0014}_{-0.0005}$	$0.0058^{+0.0049}_{-0.0016}$

[a] The masses are estimated using mass–radius relation from Weiss & Marcy (2014).

[b] Derived parameters for individual transits of planet d.

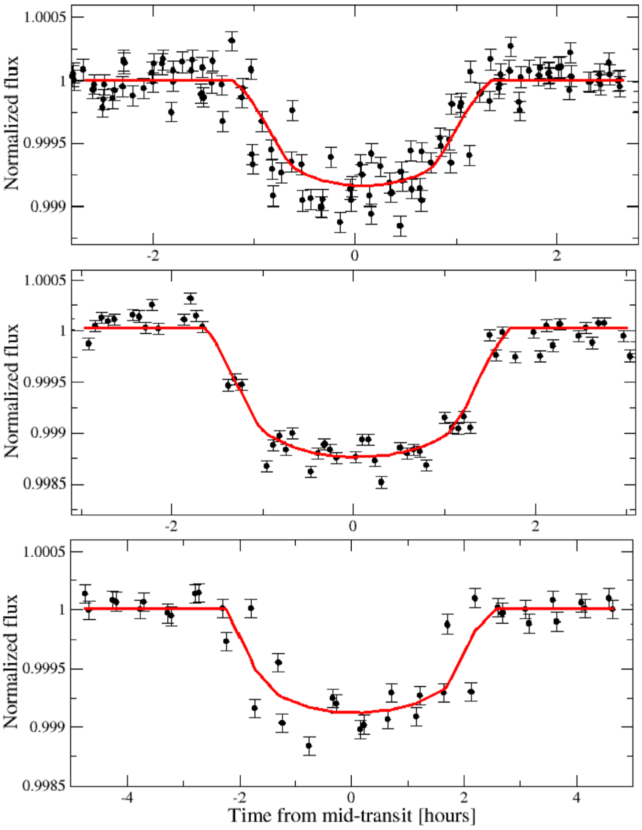

Figure 4. Phase-folded light curves corresponding to planets b (top), c (middle), and d (bottom). Solid curves represent best model fits obtained by MCMC.

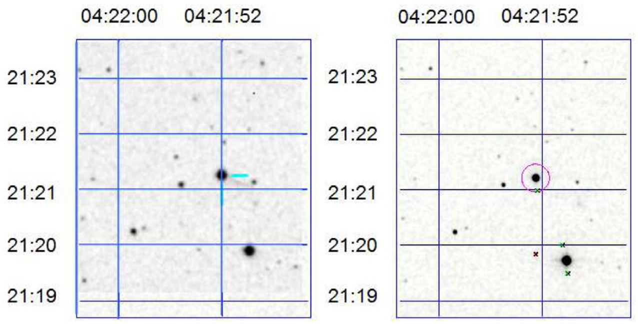

Figure 5. POSS-I image (1953, left) and 2MASS (1998, right). No background source is present at star's position in K2 13th campaign.

Pepe & Molaro 2017) at the Very Large Telescope (VLT). The moderated chromospheric activity of the star is likely to induce RV signals of order less than 3 m s^{-1} (Suárez Mascareño et al. 2017) which should not prevent the detection of the dynamical signals induced by the planets and the determination of their masses and densities. We estimate the incident flux for planet d as $F_{\rm p} = 2.63$ $F_\oplus$. Habitable zone estimations (Kane et al. 2016) place the inner edge of the habitable zone at 1.5 $F_\oplus$, so planets b, c, and d are closer to the star than the inner part of the habitable zone.

The amplitude of the signal in transit transmission spectroscopy can be estimated as $\frac{R_{\rm p}\cdot h_{\rm eff}}{(R_*)^2}$ (Gillon et al. 2016) with $h_{\rm eff}$ the effective atmospheric height, which is related to the atmospheric scale height $H = K\cdot T/\mu\cdot g$ (K Boltzmann's constant, T atmospheric temperature, μ atmospheric mean molecular mass, g surface gravity). We adopt $h_{\rm eff} = 7H$ (Miller-Ricci & Fortney 2010) for a transparent volatile dominated atmosphere ($\mu = 20$) with 0.3 Bond albedo. With these assumptions we estimate the amplitudes of transit transmission spectroscopy signals as 2.2×10^{-5} (b), 3.5×10^{-5} (c), and 1.2×10^{-5} (d).

We tested the stability of the system simulating its evolution for 10^6 yr with the MERCURY package (Chambers 1999), using Bulirsch–Stoer integrator, adopting circular orbits and masses from the mass–radius relation. Our simulations show no significant changes in the eccentricity (always below 0.0005 for all the planets) or in the inclination of the orbits (always below 1.6°, 1.2°, and 1° for planets b, c, and d), pointing towards a dynamically stable system.

4 CONCLUSIONS

We presented a system with three transiting super-Earths orbiting a mid-late type K dwarf star, discovered with photometric data from K2. The star has been studied and characterized in detail, analysing its spectrum and long-time photometric series. The detected planets have radii $1.8^{+0.2}_{-0.1}$ $R_\oplus$ (b), $2.6^{+0.7}_{-0.2}$ $R_\oplus$ (c), and $1.9^{+0.7}_{-0.2}$ $R_\oplus$ (c), and orbital periods 6.342 ± 0.002 d (b), 13.850 ± 0.006 d (c), and 40.718 ± 0.005 d (d). Additional photometric monitoring is required to confirm planet d and radial velocity monitoring with ultrastable spectrographs at 8–10 m telescopes is necessary to determine accurate planetary masses. The amplitudes of atmospheric signals in transmission spectroscopy have been estimated at ~20 ppm, making the system a good target to incoming facilities such as *James Webb Telescope*.

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Capítulo 4

Two planetary systems with transiting Earth-size and super-Earth planets orbiting late-type dwarf stars

Este capítulo se corresponde con la publicación *Two planetary systems with transiting Earth-size and super-Earth planets orbiting late-type dwarf stars* (Díez Alonso y col., 2018b).

Al igual que el trabajo presentado en el capítulo anterior, este nuevo trabajo se enmarca en el segundo de los objetivos de la tesis: la detección y caracterización básica de sistemas planetarios que puedan ser caracterizados plenamente con un posterior seguimiento en velocidad radial.

Se presenta la detección y caracterización de dos nuevos sistemas planetarios compuestos por Tierras y super-Tierras que transitan estrellas frías, observadas por el telescopio espacial Képler en las campañas 14 y 15 de su misión extendida (K2).

El primer sistema se encuentra en la estrella K2-239 ($m_V = 14.55$) y está constituído por tres Tierras en una configuración compacta en resonancia 2:3:4. La estrella ha sido caracterizada en este trabajo como tipo espectral M3.0 V ($T_{\rm eff}$ = 3420± 18 K, R = 0.36 ± 0.01 $R_\odot$) mediante espectros adquiridos con el instrumento OSIRIS, instalado en el Gran Telescopio Canarias (Observatorio Roque de los Muchachos, La Palma) así como a través de relaciones empíricas. Hacemos notar aquí que en la Figura 1 del trabajo, se aprecia cierta discrepancia en el espectro a partir de $\sim$ 800 nm, que puede deberse a la corrección de flujo o a la corrección telúrica del mismo.

Posteriormente a la publicación de este trabajo, la misión Gaia en su DR2 (Gaia Collaboration y col., 2018) publicó un valor para la distancia a K2-239 de 31.1 ± 0.1 pc, inferior a la estimación de 49 ± 3 pc presentada en este trabajo. Esta sobrestimación de la distancia no afecta a los parámetros calculados para la estrella (y por extensión los de sus planetas) ya que estos fueron determinados a partir de relaciones empíricas y parámetros tabulados en los que no inteviene la distancia. Por otra parte, esta distancia inferior tampoco permite asociar a K2-239 a ningún grupo de movimiento conocido.

El segundo sistema, constituído por dos super-Tierras, se encuentra en la estrella K2-240 ($m_V = 13.39$). La estrella ha sido caracterizada en este trabajo como tipo espectral M0.5 V ($T_{\rm eff}$ = 3810± 17 K, $R = 0.54 \pm 0.01~R_{\odot}$) a partir de espectros procedentes del survey RAVE (Radial Velocity Experiment, Kunder y col., 2017) y relaciones empíricas.

Para descartar fuentes próximas y posibles falsos positivos, se analizaron imágenes de alta resolución (obtenidas para K2-239 con la cámara OSIRIS, y disponibles en la base de datos EXOFOP para K2-240). En ambos casos también se analizaron imágenes de archivo (POSS-I y 2MASS).

Los parámetros de cada planeta se derivaron ajustando modelos mediante MCMC a los tránsitos puestos en fase. Las masas fueron estimadas mediante relaciones empíricas. También se estimó la amplitud de la señal en velocidad radial que cada planeta induce en su estrella, resultando semi-amplitudes $\sim 0.5~\rm m{\cdot}s^{-1}$ para los planetas del sistema K2-239, y $\sim 1~\rm m{\cdot}s^{-1}$ para los planetas del sistema K2-240. Estas semiamplitudes se encuentran dentro de las capacidades de caracterización de instrumentos como ESPRESSO (VLT), lo que permitirá una determinación precisa de sus masas.

La amplitud de la señal en espectroscopía de transmisión ha sido estimada para cada uno de los planetas, obteniendo amplitudes $\sim 10^{-5}$. Teniendo en cuenta que orbitan estrellas moderadamente brillantes, los planetas de estos sistemas son candidatos a caracterización atmosférica con instrumentos como el James Webb Telescope.

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Two planetary systems with transiting Earth-sized and super-Earth planets orbiting late-type dwarf stars

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ABSTRACT

We present two new planetary systems found around cool dwarf stars with data from the K2 mission. The first system was found in K2-239 (EPIC 248545986), characterized in this work as M3.0V and observed in the 14th campaign of K2. It consists of three Earth-sized transiting planets with radii of 1.1, 1.0, and 1.1 $R_\oplus$, showing a compact configuration with orbital periods of 5.24, 7.78, and 10.1 d, close to 2:3:4 resonances. The second was found in K2-240 (EPIC 249801827), characterized in this work as M0.5V and observed in the 15th campaign. It consists of two transiting super-Earths with radii 2.0 and 1.8 $R_\oplus$ and orbital periods of 6.03 and 20.5 d. The equilibrium temperatures of the atmospheres of these planets are estimated to be in the range of 380–600 K and the amplitudes of signals in transmission spectroscopy are estimated at ∼10 ppm.

Key words: techniques: photometric – techniques: spectroscopic – planets and satellites: detection – stars: low mass – stars: individual: K2-239, K2-240.

1 INTRODUCTION

Low-mass stars are primary targets in the search for Earth-sized planets and in the study of their properties. Low-mass stars ($0.1\ \mathrm{M}_\odot < M < 0.6\ \mathrm{M}_\odot$) account for 70 per cent of the stellar population in the Milky Way (Henry, Kirkpatrick & Simons 1994), meaning they have a hugely significant impact in the overall statistics of planets in the Galaxy. Exoplanets with close-in orbits tend to be terrestrial when the mass of the star decreases (Howard et al. 2012), with an average of ∼0.5 Earth-sized rocky planet with $P_{\mathrm{orb}} < 50$ d around each low-mass star (Dressing & Charbonneau 2015).

Transiting Earth-sized planets induce deeper dimmings in the light curve of low mass stars and stronger radial velocity signals than in more massive stars. Temperate planets orbit closer and have shorter orbital periods, so it is easier to detect planets in the habitable zone (orbital range in which a planet's atmosphere can warm the surface to allow surface liquid water; Anglada-Escudé et al. 2016; Gillon et al. 2017). Signals in transit transmission spectroscopy (Charbonneau et al. 2002) are also stronger for stars with a small radius, so planets orbiting near bright low-mass stars are also suitable for atmospheric characterization (Kreidberg et al. 2014).

Detecting transiting planetary systems is of great value in terms of estimating the mass and density of their planets measuring transit timing variations (Gillon et al. 2017), which are stronger for compact systems in resonances. These systems are also suitable for testing the formation scenarios from the study of resonances that could be the result of migrations (Papaloizou & Szuszkiewicz 2005).

Until now, the Kepler mission (Borucki et al. 2010) has been the most successful facility detecting exoplanets by the transit method. Since the beginning of 2014, Kepler has been on its second mission (K2) (Howell et al. 2014), monitoring different fields near the ecliptic plane for ∼80 d. K2 has found many exoplanet candidates

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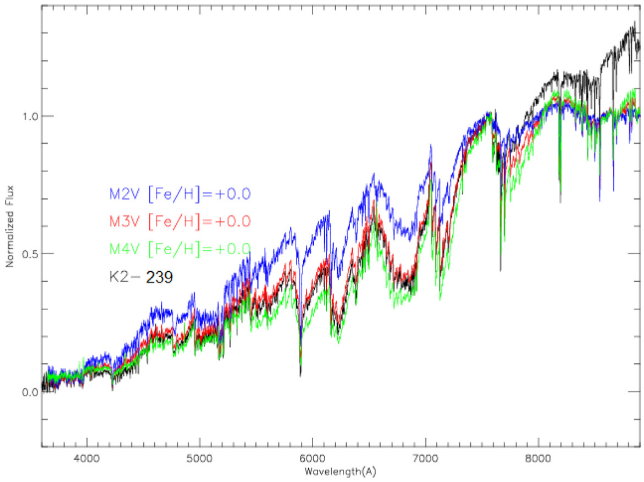

Figure 1. OSIRIS spectrum of K2-239 compared with reference spectra of M2.0V–M4.0V stars. Best fitting is obtained for M3V star with [Fe/H] ~0. All spectra are normalized at λ = 7575 Å.

(Vanderburg et al. 2015; Crossfield et al. 2016; Díez Alonso et al. 2018; Hirano et al. 2018) in each observation campaign.

Campaign 14 was conducted between 2017 May 31 and 2017 August 19, centring on the Leo and Sextant area (central coordinates α = 10:42:44, δ = + 06:51:06). Campaign 15 ran between 2017 August 23 and 2017 November 20, observing the area towards the constellation of Scorpius (central coordinates α = 15:34:28, δ = −20:04:44).

In this study we present the detection of two planetary systems during these campaigns. The first consists of three Earth-sized transiting planets orbiting K2-239 (EPIC 248545986; α = 10:42:22.633, δ = +04:26:28.86), observed in long cadence mode during campaign 14. The second consists of two transiting super-Earths orbiting K2-240 (EPIC 249801827; α = 15:11:23.907, δ = −17:52:30.78), observed in long cadence mode during campaign 15.

2 SPECTROSCOPIC AND PHOTOMETRIC DATA

2.1 Stellar characterization: K2-239

On 2018 March 13 we obtained spectra of K2-239 with the OSIRIS camera spectrograph (Cepa et al. 2000) of the 10.4 m Gran Telescopio Canarias (GTC), located at Observatorio Roque de los Muchachos in La Palma (Canary Islands, Spain). Three medium-resolution spectra ($\lambda/\delta\lambda \sim 2500$) in each of the *U, V, R, and I* bands were reduced in the standard manner, flux calibrated, telluric corrected, and finally combined into a single spectrum (see Fig. 1).

The spectrum was compared with SDSS/BOSS (Baryon Oscillation Spectroscopic Survey) reference spectra of M-type stars from Kesseli et al. (2017). The comparison was made with the HAMMER code (Covey et al. 2007), obtaining the best fit for an M3V star with [Fe/H] ~0. The relative intensity of the NaI lines at 5890 and 8180 Å rule out the possibility of the star being giant, while the relative depth of the strong molecular bands of TiO at 7000–7300 Å points to [Fe/H] ~ 0. Maldonado et al. (2015), working with measurements of spectral index from High Accuracy Radial velocity Planet Searcher spectra, conclude $T_{\mathrm{eff}} \sim 3450 \pm 50$ K for M3V stars, which is in agreement with our estimates of the stellar parameters. Fig. 1 plots our comparison of the OSIRIS spectrum of K2-239 with reference spectra from M2.0V to M4.0V stars.

Table 1. Stellar parameters for K2-239 and K2-240.

Parameter	K2-239	K2-240	Source
V (mag)	14.549 ± 0.040	13.392 ± 0.010	(1)
R (mag)	13.906 ± 0.020	12.804 ± 0.010	(1)
I (mag)	12.718 ± 0.030	11.994 ± 0.050	(1)
J (mag)	10.781 ± 0.026	10.394 ± 0.027	(2)
H (mag)	10.192 ± 0.021	9.745 ± 0.024	(2)
K (mag)	9.971 ± 0.021	9.560 ± 0.023	(2)
T_{eff} (K)	3420 ± 18	3810 ± 17	(3)
[Fe/H]	−0.1 ± 0.1	−0.1 ± 0.1	(3)
Radius ($R_\odot$)	0.36 ± 0.01	0.54 ± 0.01	(3)
Mass ($M_\odot$)	0.40 ± 0.01	0.58 ± 0.01	(3)
Luminosity ($L_\odot$)	0.016 ± 0.001	0.053 ± 0.002	(3)
log g (cgs)	4.9 ± 0.1	4.7 ± 0.1	(3)
P_{rot} (d)	–	10.8 ± 0.1	(3)
Distance (pc)	49 ± 3	70 ± 3	(3)
μ_α (mas yr^{-1})	−41.0 ± 3.9	−53.6 ± 1.5	(1)
μ_δ (mas yr^{-1})	10.5 ± 8.4	−49.8 ± 1.0	(1)
U, V, W (km s^{-1})	−6.8, 4.2, −10.2	−5.4, −23.6, −1.7	(3)

(1) UCAC4 (Zacharias et al. 2013).
(2) 2MASS (Cutri et al. 2003).
(3) This work.

We computed the stellar parameters from J,H,V,K magnitudes listed in Table 1, applying the empirical relationships established by Mann et al. (2013, 2015) and Pecaut & Mamajek (2013), using the tabulated stellar parameters from Pecaut & Mamajek (2013) and the Mass–Luminosity relation for Main-sequence M dwarfs from Benedict et al. (2016). All the parameters are listed in Table 1.

Taking $m_V = 14.549 \pm 0.040$ (Table 1) and $M_V = 11.09 \pm 0.10$ from Pecaut & Mamajek (2013) tabulated parameters, we estimate a distance to K2-239 of 49 ± 3 pc.

We measured a radial velocity from the OSIRIS spectrum $v_{\mathrm{r}} = -8.5 \pm 1.5$ kms^{-1}, which combined with the estimated distance and the proper motions $\mu_\alpha = -41.0 \pm 3.9$ mas yr^{-1} and $\mu_\delta = 10.5 \pm 8.4$ mas yr^{-1}, results in the velocity components listed in Table 1. From the probability distributions of Reddy, Lambert & Allende Prieto (2006), we derive that K2-239 is a member of the Galactic thin disk.

2.2 Stellar characterization: K2-240

K2-240 has been observed by the Radial Velocity Experiment (RAVE; Steinmetz et al. 2006). RAVE's DR5 (Kunder et al. 2017) presents data from medium-resolution spectra ($R \sim 7500$) covering the Ca-triplet region (8410–8795 Å). From RAVE's DR5 we find for K2-240 (RAVE J151123.9-175231) $T_{\mathrm{eff}} = 3800 \pm 87$ K and log $g = 4.50 \pm 0.17$, confirming that K2-240 is a cool dwarf star.

We repeated exactly the same analysis followed for K2-239 to derive the stellar parameters accurately, obtaining the parameters listed in Table1. These parameters are consistent with K2-240 being an M0.5V star.

We also note that a very clear rotation signal is present in the light curve from K2. From a Lomb-Scargle (Scargle 1982) analysis we estimate $P_{\mathrm{rot}} = 10.8 \pm 0.1$ d.

From RAVE's radial velocity $v_{\mathrm{r}} = 0.20 \pm 1.56$ km s^{-1}, our estimated distance of $d = 70 \pm 3$ pc, and proper motions $\mu_\alpha = -53.6 \pm 1.5$ mas yr^{-1} and $\mu_\delta = -49.8 \pm 1.0$ mas yr^{-1}, we com-

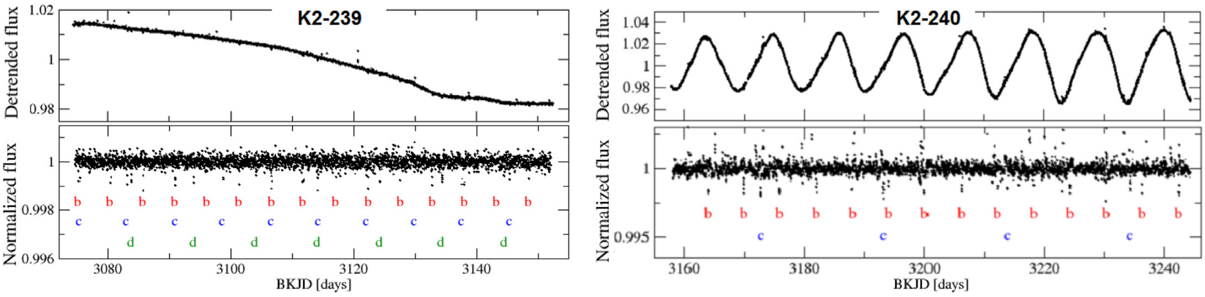

Figure 2. K2 detrended (top) and normalized (bottom) light curves for K2-239 (left) and K2-240 (right). Characters b, c, and d show times of observed transits for planets in each system.

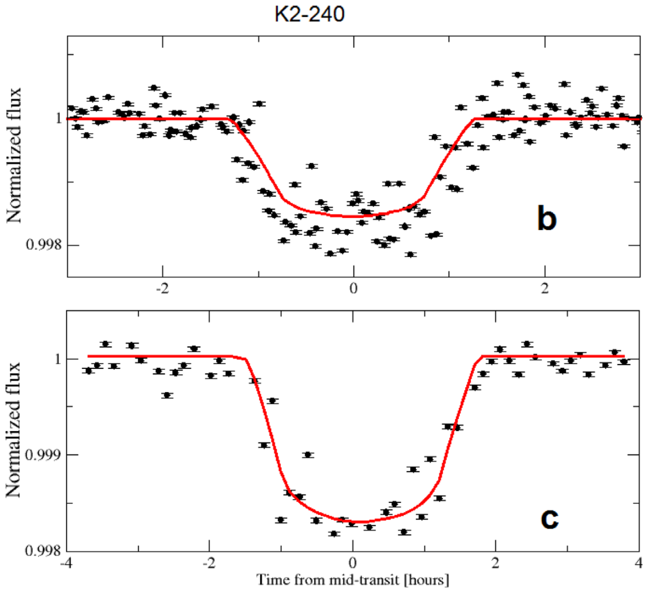

Figure 3. Phase-folded light curves corresponding to planets b (top), c (middle), and d (bottom) in the K2-239 system. Solid curves represent best model fits obtained by MCMC.

pute velocity components listed in Table 1. From the probability distributions of Reddy et al. (2006), we derive that K2-240 is a member of the Galactic thin disk.

2.3 K2 photometric data

We followed the work of Vanderburg & Johnson (2014) to analyse the K2-corrected photometry of our target stars, detrending stellar variability with a spline fit and searching for periodic signals using the Box Least Squares method (Kovács, Zucker & Mazeh 2002) on attained data. This analysis shows three transit signals with periods 5.240 ± 0.001 (b), 7.775 ± 0.001 (c), and 10.115 ± 0.001 d in K2-239 and two transit signals with periods 6.034 ± 0.001 (b) and 20.523 ± 0.001 (c) days in K2-240 (Fig. 2).

We performed Monte Carlo Markov Chain (MCMC) analysis on each phase-folded transit (Figs 3 and 4) to estimate the planetary parameters, fitting models from Mandel & Agol (2002) with the EXOFAST package (Eastman, Gaudi & Agol 2013). For each data point, the light curve was resampled 10 times uniformly spaced over the 29.5-min long cadence of K2 and averaged, following Kipping (2010). For the calculations, we set the values of $T_{\rm eff}$, $\log g$, and [Fe/H] listed in Table 1, and orbital periods listed above.

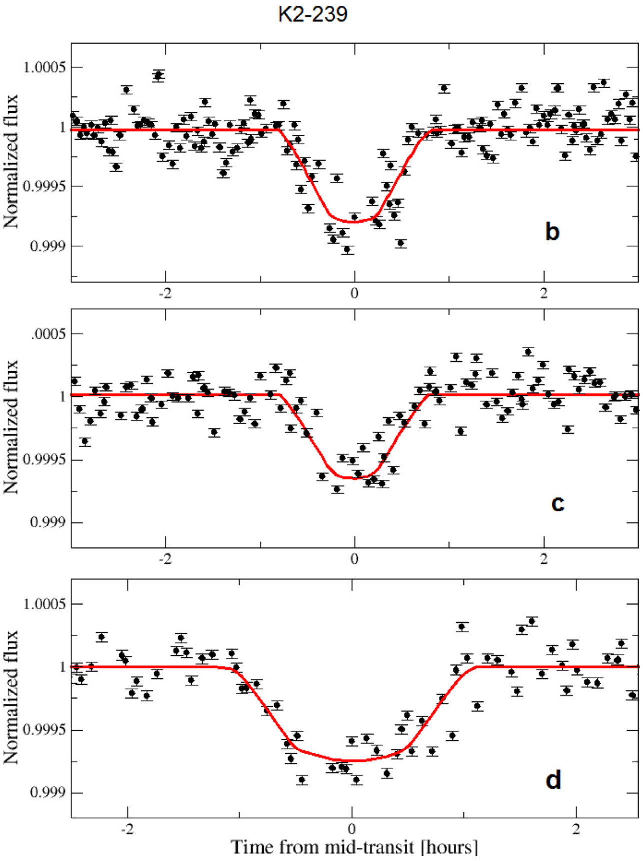

Figure 4. Phase-folded light curves corresponding to planets b (top) and c (bottom) in the K2-240 system. Solid curves represent best model fits obtained by MCMC.

We also worked with the assumption of eccentricity $e = 0$, valid for transiting planets in a multiplanetary system (Van Eylen & Albrecht 2015).

The planets in the K2-239 system have estimated radii of 1.1 ± 0.1 $R_\oplus$ (b), 1.0 ± 0.1 $R_\oplus$ (c), and 1.1 ± 0.1 $R_\oplus$ (d), orbital periods of 5.242 ± 0.001 d (b), 7.775 ± 0.001 d (c), and 10.115 ± 0.001 d (d), and semimajor axis of 0.0441 ± 0.0008 AU (b), 0.0576 ± 0.0009 AU (c), and 0.0685 ± 0.0012 AU (d).

The planets in the K2-240 system have estimated radii of $2.0^{+0.2}_{-0.1}$ $R_\oplus$ (b) and $1.8^{+0.3}_{-0.1}$ $R_\oplus$ (c), orbital periods of 6.034 ± 0.001 d (b) and 20.523 ± 0.001 d (c), and semimajor axis of 0.0513 ± 0.0009 AU (b), 0.1159 ± 0.0020 AU (c). Table 2 summarizes all the parameters obtained for the planets.

Table 2. Parameters for planets in the K2-239 and K2-240 systems.

Planet parameters	K2-239 b	K2-239 c	K2-239 d	K2-240 b	K2-240 c
Orbital period (P) (d)	5.240 ± 0.001	7.775 ± 0.001	10.115 ± 0.001	6.034 ± 0.001	20.523 ± 0.001
Semimajor axis (a) (AU)	0.0441 ± 0.0008	0.0576 ± 0.0009	0.0685 ± 0.0012	0.0513 ± 0.0009	0.1159 ± 0.0020
Radius (R_p) ($R_\oplus$)	1.1 ± 0.1	1.0 ± 0.1	1.1 ± 0.1	$2.0^{+0.2}_{-0.1}$	$1.8^{+0.3}_{-0.1}$
Mass (M_p) ($M_\oplus$)	1.4 ± 0.4	0.9 ± 0.3	1.3 ± 0.4	$5.0^{+0.5}_{-0.2}$	$4.6^{+0.7}_{-0.3}$
Equilibrium temperature (T_{eq}) (K)	502^{+22}_{-18}	427^{+24}_{-19}	399^{+18}_{-15}	586^{+24}_{-18}	389^{+19}_{-17}
Transit parameters	K2-239 b	K2-239 c	K2-239 d	K2-240 b	K2-240 c
Epoch (BKJD) (d)	3075.191	3083.860	3075.381	3163.825	3172.722
Radius of planet in stellar radii (R_p/R_*)	$0.0259^{+0.0013}_{-0.0012}$	$0.0241^{+0.0016}_{-0.0014}$	0.0255 ± 0.0012	0.0362 ± 0.0014	0.0313 ± 0.0024
Semimajor axis in stellar radii (a/R_*)	$24.6^{+1.9}_{-2.0}$	$34.0^{+3.3}_{-3.5}$	$38.8^{+2.9}_{-3.3}$	$21.1^{+1.3}_{-1.6}$	48.0 ± 4.4
Linear limb-darkening coeff (u_1)	$0.344^{+0.058}_{-0.055}$	$0.344^{+0.049}_{-0.050}$	0.345 ± 0.056	$0.402^{+0.068}_{-0.067}$	$0.411^{+0.071}_{-0.067}$
Quadratic limb-darkening coeff (u_2)	0.373 ± 0.053	$0.374^{+0.051}_{-0.050}$	$0.371^{+0.051}_{-0.052}$	$0.308^{+0.062}_{-0.063}$	$0.312^{+0.061}_{-0.064}$
Inclination (i) (deg)	$88.99^{+0.68}_{-0.87}$	$88.77^{+0.70}_{-0.57}$	$89.43^{+0.38}_{-0.45}$	$89.26^{+0.51}_{-0.64}$	$89.66^{+0.22}_{-0.26}$
Impact parameter (b)	$0.44^{+0.33}_{-0.29}$	$0.73^{+0.24}_{-0.39}$	0.39 ± 0.25	$0.28^{+0.20}_{-0.19}$	$0.29^{+0.18}_{-0.19}$
Transit depth (δ)	$0.00067^{+0.00007}_{-0.00006}$	$0.00058^{+0.00008}_{-0.00006}$	0.00065 ± 0.00006	0.00131 ± 0.00010	$0.00098^{+0.00016}_{-0.00015}$
Total duration (T_{14}) (d)	$0.0611^{+0.0067}_{-0.013}$	$0.052^{+0.013}_{-0.027}$	$0.0766^{+0.0058}_{-0.0073}$	$0.0897^{+0.0046}_{-0.0038}$	$0.133^{+0.011}_{-0.010}$

2.4 False positives analysis

We acquired images of K2-239 with the OSIRIS camera spectrograph on 2018 March 13. Night conditions were rather good, and data were collected under photometric conditions, a dark moon, and with an average seeing of 0.7 arcsec. For broad-band imaging, a series of 10 x 1 sec in Sloan *i* filter was obtained. Bias correction, flat fielding, and bad pixel masking were done using standard procedures, and the images were finally aligned (see Fig. 5, top panel). Analyses of final image exclude companions at 0.6 arcsec with $\delta_{mag} < 5.0$ and at 3 arcsec with $\delta_{mag} < 10$.

In the same way, images from POSS-I (Minkowski & Abell 1963) (year 1953) and 2MASS (Cutri et al. 2003) (year 1998, see Fig. 5, top panel) do not show background sources at the current star position.

At ExoFOP–K2[1] an AO image of K2-240 is available, acquired with the NIRC2 instrument at the 10 m Keck 2 telescope (Maunakea, Hawaii). The image excludes companions at 0.2 arcsec with $\delta_{mag} < 5.0$ and at 1 arcsec with $\delta_{mag} < 8.3$ (Fig 5, bottom panel).

Non-detection of blended objects in these images and the extremely low probability of multiple false positives as shown by Lissauer et al. (2011) confirm the planetary origin of transit signals in K2-239 and K2-240.

3 DISCUSSION AND CONCLUSIONS

Assuming the planet radii listed in Table 2, and the mean density for planets satisfying $R_p \leq 1.5 R_\oplus$ from Weiss & Marcy (2014), we obtain $M_b = 1.4 \pm 0.4$ $M_\oplus$, $M_c = 0.9 \pm 0.3$ $M_\oplus$, $M_d = 1.3 \pm 0.4$ $M_\oplus$ for planets b, c, and d, respectively in the K2-239 system. Adopting $M_p \ll M_*$, circular orbits and $\sin i \sim 1$, we computed induced semi-amplitudes in stellar velocity variations of 0.9 ms^{-1} for planet b, 0.5 ms^{-1} for planet c, and 0.7 ms^{-1} for planet d, well-suited for radial velocity monitoring with ultrastable spectrographs such as ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations; Pepe et al. 2014; González Hernández et al. 2017) at the VLT.

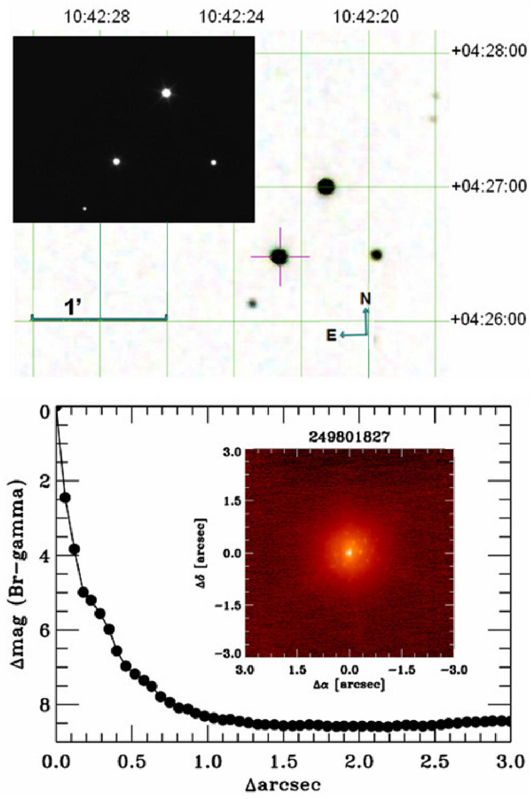

Figure 5. Top panel: OSIRIS/GTC image of K2-239 field taken with seeing 0.6 arcsec in the *i*-band Sloan filter, superimposed on the 2MASS image of the field. Bottom panel: contrast curve and AO image of K2-240 acquired with the NIRC2 instrument at the 10 m Keck-2 telescope.

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[1] https://exofop.ipac.caltech.edu/k2/

The amplitude of the signal in transit transmission spectroscopy can be estimated as $\frac{R_p \cdot h_{\rm eff}}{(R_*)^2}$ (Gillon et al. 2016) with $h_{\rm eff}$ the effective atmospheric height. $h_{\rm eff}$ is related to the atmospheric scale height $H = K \cdot T/\mu \cdot g$ (K Boltzmann's constant, T atmospheric temperature, μ atmospheric mean molecular mass, and g surface gravity). Assuming $h_{\rm eff} = 7 \cdot$H (Miller-Ricci & Fortney 2010) for a transparent volatile dominated atmosphere ($\mu = 20$) with 0.3 Bond albedo, we found amplitudes in transit transmission spectroscopy of 1.2×10^{-5} (b), 1.1×10^{-5} (c), and 10^{-5} (d).

We used the MERCURY package (Chambers 1999) to simulate and test the evolution and stability of the system for 10^6 yr. We simulated using Bulirsch–Stoer integrator, adopting circular orbits and masses from the mass–radius relation. We do not find significant changes in the eccentricity or in the inclination of the orbits, showing a dynamically stable system.

To estimate the masses for the planets of the K2-240 system, we used the mass–radius relation from Weiss & Marcy (2014) for planets satisfying $1.5 \leq R_{\rm p}/R_{\oplus} \leq 4$, obtaining $M_{\rm b} = 5.0^{+0.5}_{-0.2}$ M$_{\oplus}$, $M_{\rm c} = 4.6^{+0.7}_{-0.3}$ M$_{\oplus}$. Under the assumption of $M_{\rm p} \ll M_*$, circular orbits and sin $i \sim 1$, we computed induced semi-amplitudes in stellar velocity variations of 2.5 ms^{-1} for planet b and 1.5 ms^{-1} for planet c. With the same assumptions as in the previous section, we estimate amplitudes in transit transmission spectroscopy of 1.2×10^{-5} (b) and 6.6×10^{-6} (c).

We also tested the stability of K2-240 system with the MERCURY package as described in the previous section. Again our simulations point towards a dynamically stable system.

The planetary systems presented in this work, with equilibrium temperatures estimated in the range of 380–600 K, are suitable targets for incoming facilities; Plato, monitoring in shorter cadence mode, could reveal transit timing variations that allow accurate planetary masses to be estimated. The James Webb Telescope could find signs of planetary atmospheres. Ultrastable spectrographs such as ESPRESSO at VLT, could also carry out radial velocity follow-up, so these are promising targets to improve our understanding of compact Earth-sized planetary systems (K2-239) and super-Earth systems on the rocky–gaseous boundary (EPIC K2-240).

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Based on observations made with the Gran Telescopio Canarias (GTC), installed in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, in the island of La Palma.

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Capítulo 5

A transiting super-Earth close to the inner edge of the HZ of an M0 V star

Este capítulo se corresponde con la publicación *A transiting super-Earth close to the inner edge of the habitable zone of an M0 dwarf star*, aceptada para publicación en *Monthly Notices of the Royal Astronomical Society* el 19 de diciembre de 2018. (Díez Alonso y col., 2019a)

El trabajo es el último de los enmarcados (junto con los presentados en los dos capítulos anteriores) en el segundo objetivo de la tesis. Se expone la detección y caracterización de una super-Tierra orbitando en el límite interior de la zona de habitabilidad de la estrella K2-286. El trabajo ha sido realizado a partir de datos de la campaña 15 del telescopio espacial Képler en su misión extendida (K2).

La estrella ha sido caracterizada como tipo espectral M0 V (T_{eff} = 3926± 100 K, $R = 0.62 \pm 0.02\ R_{\odot}$, $m_V = 12.76$) a partir de espectros adquiridos con el instrumento OSIRIS, instalado en el Gran Telescopio Canarias (Observatorio Roque de los Muchachos, La Palma) y de relaciones empíricas.

Para descartar fuentes próximas y posibles falsos positivos, se analizaron imágenes de alta resolución (obtenidas con la cámara OSIRIS) e imágenes de archivo (POSS-I y PanSTARRS-1). Además se realizó una validación estadística mediante el paquete VESPA.

Los parámetros del planeta se derivaron ajustando modelos mediante MCMC a los tránsitos puestos en fase, obteniendo para K2-286 b un radio R=2.1 $\text{R}_{\oplus}\pm$ 0.2 $R_{\oplus}$, en el límite superior del *gap de Fulton*, lo que lo convierte en un objeto clave para entender la naturaleza del gap. Su masa ha sido estimada mediante relaciones masa - radio probabilísticas, obteniendo M = 6.8±4.3 $M_{\oplus}$. Además, a partir de medidas de velocidad radial y una estimación de la señal inducida por la actividad estelar (Tal-Or y col., 2018), se ha obtenido un límite superior para su masa de 22 $M_{\oplus}$, que excluiría que K2-286 b sea un gigante tipo Júpiter. Este límite superior para la masa podría variar si la contribución estelar fuera significativamente diferente a lo estimado.

Con una temperatura de equilibrio $T_{\text{eq}}=347^{+21}_{-11}$K, el planeta orbita dentro de los límites de la zona de habitabilidad de K2-286 de acuerdo con modelos optimistas, pudiendo mantener agua líquida en su superficie bajo las condiciones adecuadas. Además en el trabajo se expone la baja o moderada actividad de K2-286, por lo que

K2-286 b puede experimentar un ambiente más benigno que otros planetas similares en la zona de habitabilidad de estrellas enanas rojas.

Se ha estimado la amplitud de la señal en velocidad radial inducida, resultando una semi-amplitud de ~ 1.9 m·s^{-1}, dentro de las capacidades de instrumentos como ESPRESSO (VLT), permitiendo una caracterización precisa de su masa mediante seguimiento en velocidad radial.

La amplitud de la señal en espectroscopía de transmisión ha sido estimada en $\sim 5 \cdot 10^{-6}$, dentro de las capacidades de caracterización del James Webb Telescope, de manera que K2-286 b se encuentra entre los planetas *templados* más adecuados para caracterización atmosférica.

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A transiting super-Earth close to the inner edge of the habitable zone of an M0 dwarf star

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ABSTRACT

We present a super-Earth orbiting close to the inner edge of the habitable zone of the cool dwarf star K2-286 (EPIC 249889081), detected with data from the K2 mission in its 15^{th} campaign. The planet has radius of 2.1 ± 0.2 $R_\oplus$, near the 1.5 – 2.0 $R_\oplus$ gap in the radii distribution. The equilibrium temperature is 347^{+21}_{-11} K, cooler than most of the small planets with well measured masses, and the orbital period is 27.359 ± 0.005 days. K2-286, located at a distance of 76.3 ± 0.3 pc, is an M0V star with estimated effective temperature of 3926 ± 100 K, less active than other M dwarf stars hosting exoplanets. The expected radial velocity semi-amplitude induced by the planet on the star is $1.9^{+1.3}_{-1.2}$ $m{\cdot}s^{-1}$, and the amplitude of signals in transit transmission spectroscopy is estimated at 5.0 ± 3.0 ppm. Follow-up observations for mass measurements and transit spectroscopy should be desirable for this relatively bright target ($m_V = 12.76, m_{Ks} = 9.32$) hosting a transiting super-Earth within the inner edge of the habitable zone.

Key words: planets and satellites: detection – techniques: photometric – techniques: spectroscopic – stars: low mass – stars: individual: EPIC 249889081, K2-286

1 INTRODUCTION

In the search and study of super-Earth and Earth-type planets, low mass stars (0.1 $M_\odot$ < M < 0.6 $M_\odot$) are primary targets. These stars account for 70% of the stellar population in the Galaxy (Henry et al. 2006; Bochanski et al. 2010), and planets in such stars tend to be terrestrial as the stellar mass decreases (Howard et al. 2012; Dressing & Charbonneau 2013, 2015; Mulders et al. 2015a,b; Mulders 2018). Since transiting planets induce deeper dimming and also stronger radial velocity (RV) signals, their detection by these methods is easier. The amplitudes of signals in transit transmission spectroscopy (Charbonneau et al. 2002) are higher for stars of smaller radius, and planets transiting bright low-mass stars are therefore suitable for extensive atmospheric characterization (Stevenson et al. 2010; Kreidberg et al. 2014).

With the appropriate physical conditions, planets orbiting within the habitable zone of its host star might be able to support liquid water (Kasting et al. 1993), commonly an assumed condition in the search for extraterrestrial life. Planets orbiting within the habitable zone of M dwarf stars are closer and have shorter orbital periods which favors their detection. These planets are also excellent targets to study potentially habitable atmospheres (Kaltenegger et al. 2011; Rodler & López-Morales 2014).

The rate of discoveries of potentially habitable planets orbiting low mass stars is monotonically increasing (Wright et al. 2016; Anglada-Escudé et al. 2016; Gillon et al. 2017). However, their habitability is subject of debate; these planets orbit very close to their host star, and experience strong gravitational interactions which result in tidal locking (Dole 1964; Kasting et al. 1993). These stars

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are generally very active (Delfosse et al. 1998; Hawley et al. 2014), in particular at early stages in their lifetimes, and the level of activity is usually higher for very late spectral types (West et al. 2004). Planets with close - in orbits around M dwarf stars are exposed to strong flare activity and UV and X-ray irradiation from their host star (Hawley et al. 2014; Howard et al. 2018).

A large number of transiting planets (2372 confirmed and 2426 candidates to date 2018 November 16)[1]) have been detected by NASA's Kepler mission (Borucki et al. 2010). The satellite continued observing different ecliptic plane fields in its second mission [2] (Howell et al. 2014) with temporal windows spanning ~80 days. Many transiting candidates (355 confirmed and 473 candidates to date 2018 November 16) have been found in K2 data (e.g. Vanderburg et al. 2015; Crossfield et al. 2016; Díez Alonso et al. 2018; Alonso et al. 2018).

Campaign 15 focused in the Scorpius region, centered at $\alpha = 15:34:28$, $\delta = -20:04:44$, between 2017 August 23 and 2017 November 30. In this campaign, 23,279 targets have been observed at standard long cadence mode and 119 targets at short cadence mode [3].

In this work, we present the detection of a super-Earth transiting the M0V star K2-286 (EPIC 249889081, α=15:33:28.7, δ=-16:46:23.72). K2-286 has a Kepler magnitude $K_p = 12.2$, so K2-286b is a very favorable target to study its atmospheric properties through transit and secondary eclipse measurement due to the increment in the signal quality that a bright star implies.

In section 2 we describe the characterization of the star K2-286 and the analysis of the K2 photometric time series. We also discuss possible contaminating sources, the main parameters derived for the planet, different models for the habitable zone of K2-286 and also estimate the mass of K2-286b. In section 3 we discuss the fact that K2-286b has estimated radius around the upper edge of the 1.5-2.0 $R_\oplus$ gap in the radii distribution of exoplanets, and describe its suitability for future characterization by radial velocity and transmission spectroscopy follow-up, comparing K2-286b with other small transiting exoplanets with well measured masses. In section 4 we summarize the main conclusions derived from this work.

2 METHODS AND DATA ANALYSIS

2.1 Stellar characterization

Three medium-resolution spectra ($\lambda/\delta\lambda \sim 2500$) covering the *UVRI* bands (spectral ranges 348−461 nm, 444−604 nm, 571−768 nm and 733−980 nm, respectively) were obtained for K2-286 with the OSIRIS camera-spectrograph (Cepa et al. 2000) of the 10.4 m Gran Telescopio Canarias (GTC), located at Observatorio Roque de los Muchachos in La Palma (Canary Islands, Spain).

The data reduction was performed in a standard way (bias substraction, flat-fielding and wavelength calibration, using HgAr+NeXe lamps) with the *onedspec* package in IRAF (Tody 1993). The spectra were flux-calibrated using the flux standard GD−140 ($\alpha = 11:37:22.16$, $\delta = 29:48:24.7$ (J2000), $m_V = 12.45$) provided by GTC team and observed with the same setup and reduced in the same way as our science target. The *standard* IRAF package contains precise spectrophotometric data of GD−140 to derive the sensitivity curve of the instrument in that night in each filter. Finally, we corrected the four spectra with the derived sensitivity curves to achieve a reliable flux calibration. The spectra of each filter were corrected for barycentric velocity and merge to produce the full spectrum shown in Fig. 1.

We compared the resulting spectrum with SDSS/BOSS reference spectra of M-type stars using the HAMMER code (Covey et al. 2007) and using the python version PYHAMMER (Kesseli et al. 2017). The best fit is obtained for an M0V star with [Fe/H] ~ +0.5, although a chi–squared test finds best fit for [Fe/H] ~ 0.0 (see Fig. 1).

To compute the stellar luminosity we used m_k (from 2MASS) and the distance from Gaia ($d = 76.3 \pm 0.3$ pc) to obtain $M_K = 4.90 \pm 0.02$. Following Mann et al. (2015) we estimated $BC_K = 2.48 \pm 0.02$. From M_K and BC_K we compute $L = 0.089 \pm 0.003$ $L_\odot$. We also estimated the luminosity of K2-286 from the tabulated stellar parameters of Pecaut & Mamajek (2013) and M_K, obtaining $L = 0.091 \pm 0.004$ $L_\odot$. We adopt a mean value of $L = 0.090 \pm 0.005$ $L_\odot$ [4].

We estimated the stellar radius applying the empirical relation $R - M_k$ from Mann et al. (2015) with M_k computed from m_k of 2MASS and distance from Gaia. We obtain $R = 0.63 \pm 0.02$ $R_\odot$. We also computed the radius from M_k and the Pecaut & Mamajek (2013) relations, obtaining $R = 0.61 \pm 0.01$ $R_\odot$. We adopt a mean value for the stellar radius of $R = 0.62 \pm 0.02$ $R_\odot$

We obtained $T_{\rm eff}$ for K2-286 from three different approaches. First, we followed the work of Maldonado et al. (2015) who calibrated empirical relationships to determine accurate stellar parameters for early-M dwarfs (spectral types M0 – M4.5) using ratios of pseudo-equivalent widths of spectral features as a temperature diagnostic. With this method we obtain $T_{\rm eff} \sim 3820 \pm 50$ K for K2-286. Second, following Mann et al. (2017) we derived $T_{\rm eff}$ from the Stefan-Boltzmann relation. With the computed L and R, we obtain $T_{\rm eff} \sim 4015 \pm 85$ K. Third, we estimated $T_{\rm eff}$ from optical and infrared photometry following Casagrande et al. (2008), applying the empirical relation between $T_{\rm eff}$ and $(V - J)$, to obtain $T_{\rm eff} \sim 3945 \pm 21$ K. From these three methods, we adopt a mean value for $T_{\rm eff}$ of 3926± 100 K. [5]

We derived the stellar mass applying the $mass - M_k$ relation of Benedict et al. (2016), obtaining $M = 0.64 \pm 0.01$ $M_\odot$. We also estimated the mass of K2-286 with the $mass - M_k$ relation from Mann et al. (2015), obtaining $M = 0.65 \pm 0.01$ $M_\odot$. Finally, from the tabulated stellar parameters of Pecaut & Mamajek (2013) we estimate $M = 0.64 \pm 0.01$ $M_\odot$. We adopt a mean value for the stellar mass of $M = 0.64 \pm 0.02$ $M_\odot$.

The light curve of K2-286 shows modulation associated to rotation with a double dip behavior (Basri & Nguyen 2018). We applied a Generalized Lomb-Scargle (Zechmeister & Kürster 2009) analysis to the light curve of K2-286 to compute the photometric rotation period. We find the strongest signal at 26.6 ± 0.5 d (see Fig. 4).

K2-286 has not been observed with X-ray telescopes as Chandra or XMM-Newton, but the field of K2-286 was observed in

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[1] Number of candidates and confirmed exoplanets found by Kepler in its first and second missions has been obtained from http://exoplanetarchive.ipac.caltech.edu.

[2] The Kepler spacecraft was retired on 2018 October 30.

[3] https://keplerscience.arc.nasa.gov

[4] Mean uncertainties are computed adding in quadrature the individual uncertainties.

[5] Gaia DR2 reports $T_{\rm eff} \sim 4035 \pm 100$ K, while Pecaut & Mamajek (2013) report a temperature of ~ 3870 K for M0V stars, both consistent with our adopted value for $T_{\rm eff}$ of 3926 ± 100 K.

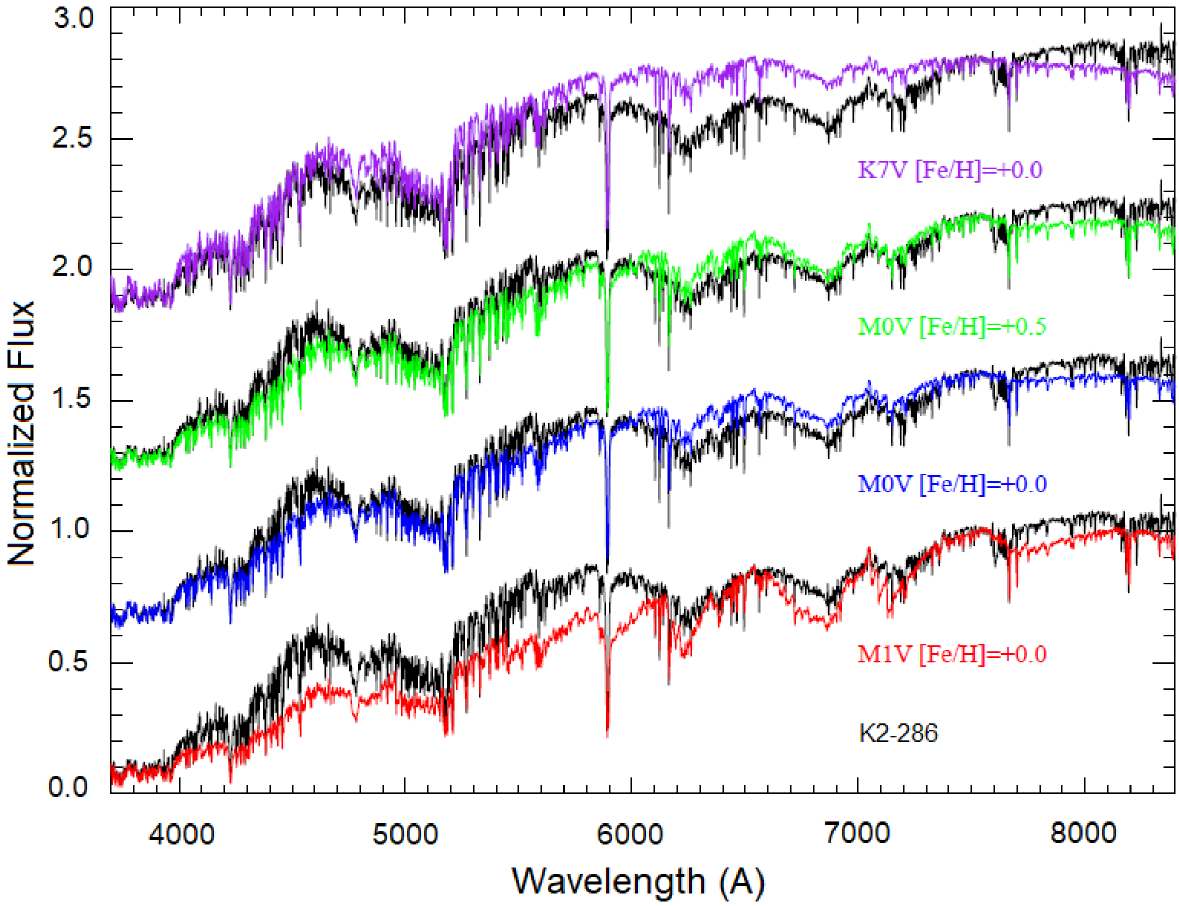

Figure 1. OSIRIS spectrum of K2-286 compared with reference spectra of K7V – M1V stars with [Fe/H] = 0.0 and with an additional reference spectrum of an M0V star with [Fe/H] = +0.5. All spectra are normalized at $\lambda = 7575$ Å.

the ROSAT All sky survey for 350 seconds and the star was not detected. With the X-ray flux upper limit of ROSAT at $F_X < 3.0 \cdot 10^{-13}$ erg·s^{-1}·cm^{-2} we estimate $L_X < 2.1 \cdot 10^{29}$ erg·s^{-1} for K2-286.

Between 2018 July 15 and 2018 August 08 we obtained six spectra, 1800 s of exposure time each, with HARPS-N (Cosentino et al. 2012), a fibrefed high resolution echelle spectrograph installed at the 3.6 m Telescopio Nazionale Galileo in the Roque de los Muchachos Observatory (Spain) with a resolving power of R = 115,000 over a spectral range from 380 to 690 nm. Fig. 2 shows the average spectrum obtained by transforming the reduced bidimensional spectra into one dimension, using a custom criteria for the overlapping between the echelle orders instead of using the one-dimensional spectra provided by the HARPS-N pipeline. This is because the overlapping technique used by the pipeline usually includes some of the noisiest parts of the echelle orders, decreasing the signal to noise ratio, which is crucial in the blue orders (where the noise is higher), especially in faint stars.

Following Noyes et al. (1984), we used the average spectrum to measure the CaII H&K index S as S=(H+K)/(R+V), with H, K, R & V the total flux in each passband, and estimated the mean level of chromospheric activity $\log_{10}(R'_{HK})$ from:

$$R'_{HK} = 1.34 \cdot 10^{-4} \cdot C_{cf} \cdot S - Rphot \qquad (1)$$

where $C_{cf} = 0.11 \pm 0.01$ is a conversion factor and $Rphot = 40 \cdot 10^{-8} \pm 4 \cdot 10^{-8}$ takes into account the photospheric contribution to this index, both of them dependent on the B and V magnitudes. We obtain $\log_{10}(R'_{HK}) = -4.75 \pm 0.06$.

Using the specific relation for M dwarf stars between level of activity and the rotation period found by Suárez Mascareño et al. (2018):

$$log_{10}(P_{rot}) = A + B \cdot \log_{10}(R'_{HK}) \qquad (2)$$

with the fitted parameters $A = -2.15 \pm 0.27$ and $B = -0.731 \pm 0.055$, we estimate a rotation period $P_{rot} = 21.0 \pm 3.7$ days for K2-286.

The photometric (from K2) and spectroscopic observations (from HARPS-N) of K2-286 were made in short campaigns, with one year separation. Differential rotation induces variations in the measured photometric rotation period depending on when the data was taken, and the chromospheric estimation of the rotation period depends on the epoch of the stellar magnetic cycle and also on the superficial inhomogeneities responsible for the emission of CaII H&K and their latitudinal location. A combination of these effects explains the difference between the photometric and chromospheric rotation period, for which we finally adopt $P_{rot} = 23.8 \pm 3.7$ days, the mean value of both measurements.

From Gaia DR2 we adopt a distance $d = 76.3 \pm 0.3$ pc, proper motions $\mu_\alpha = 57.807 \pm 0.084$ mas·yr^{-1} and $\mu_\delta = -105.645 \pm 0.066$

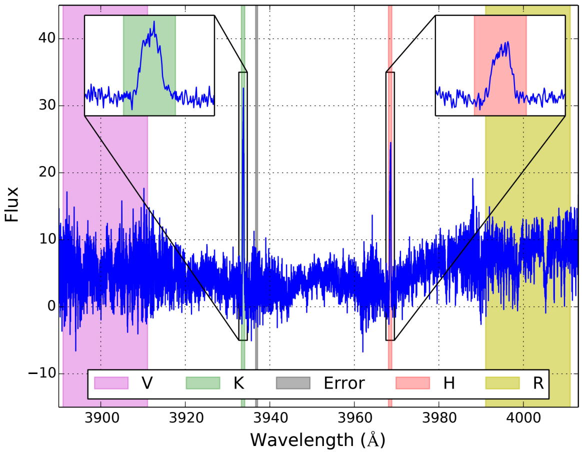

Figure 2. Average one-dimensional spectrum of the six available spectra taken with HARPS-N. The $CaII\,H\&K$ filters are marked in pink and green respectively including a zoom of those lines; the continuum passbands are marked in violet and yellow and the continuum region used for the index error is marked in grey.

mas·yr^{-1}, and $v_r = -17.41 \pm 1.17$ km·s^{-1}. With these parameters we compute velocity components U = 4.9 km·s^{-1}, V = -11.5 km·s^{-1}, W = -45.2 km·s^{-1}.

Reddy et al. (2006), using accurate radial velocities and Hipparcos astrometry, deduced a relation for estimating the probability for a star to belong to the galactic thin disk, thick disk or the halo, by means of the velocity components U,V and W. Following their work we conclude that K2-286 is most likely a member of the thin disk with probability $P = 0.938$ (the probabilities of being a thick disk or halo member are $P = 0.061$ and $P = 0.001$ respectively).

All the parameters for K2-286 are listed in Table 1.

2.2 K2 photometric data

Following the work of Vanderburg & Johnson (2014) we analyzed the K2 corrected photometry of K2-286. The stellar variability was detrended with a moving median filter before searching for periodic signals using the Box Least Squares (BLS) method (Kovács et al. 2002) on attained data. The analysis shows a transit signal with period of 27.359 ± 0.005 days (Fig. 3). Three transit events corresponding to this signal are present in the light curve.

To estimate the parameters for K2-286b we performed MCMC analysis on the phase-folded transit (Fig. 5), using the PYANETI package (Barragán et al. 2017) to fit models from Mandel & Agol (2002) and following Kipping (2010) to treat the 29.5-minute long cadence of K2. For the calculations we set the values of $T_{\rm eff}$, R and M for K2-286 listed in Table 1. We worked with the assumption of eccentricity $e = 0$ as the light curve alone does not constrain properly the eccentricity. We also assumed Gaussian priors for the linear and quadratic limb darkening coefficients $u1 = 0.52$, $u2 = 0.22$ (Sing 2010) with 0.1 standard deviation.

The analysis resulted in an estimated radius of 2.1 ± 0.2 R$_\oplus$, semi-major axis $0.1768^{+0.0175}_{-0.0205}$ AU and orbital period 27.359±0.005 days. Table 2 summarizes all the parameters obtained for K2-286b.

Table 1. Stellar parameters for K2-286

Parameter	Value	Source
V [mag]	12.763 ± 0.010	(1)
R [mag]	12.196 ± 0.020	(1)
I [mag]	11.628 ± 0.020	(1)
J [mag]	10.127 ± 0.024	(2)
H [mag]	9.518 ± 0.022	(2)
K [mag]	9.317 ± 0.020	(2)
$T_{\rm eff}$ [K]	3926 ± 100	(4)
[Fe/H]	0.0 ± 0.5	(4)
Radius [R$_\odot$]	0.62 ± 0.02	(4)
Mass [M$_\odot$]	0.64 ± 0.02	(4)
Luminosity [L$_\odot$]	0.090 ± 0.05	(4)
P_{rot} [d]	23.8 ± 3.7	(4)
log g [cgs]	4.7 ± 0.2	(4)
Distance [pc]	76.3 ± 0.3	(3)
μ_α [mas·yr^{-1}]	57.807 ± 0.084	(3)
μ_δ [mas·yr^{-1}]	−105.645 ± 0.066	(3)
$V_{\rm r}$ [km·s^{-1}]	−17.41 ± 1.17	(3)
U, V, W [km·s^{-1}]	4.9, -11.5, -45.2	(4)

(1) UCAC4 (Zacharias et al. 2013).
(2) 2MASS (Cutri et al. 2003).
(3) Gaia DR2 (Gaia Collaboration et al. 2018).
(4) This work.

2.3 False positives analysis

We acquired images of K2-286 with the OSIRIS camera-spectrograph on June 19 2018. Data were collected under photometric conditions, with an average seeing of 0.7 arc seconds. Two series of 11 x 0.5 and 11 x 0.1 sec in Sloan i filter were obtained for broadband imaging. Bias correction, flat fielding and bad pixel masking were done using standard procedures. The images were finally aligned. Analysis of the final image excludes companions at 1.5 arc seconds with δmag < 5.0 and at 3 arc seconds with δmag < 7 (see Figs. 6 & 7).

Inspection of images of K2-286 from POSS-I (Minkowski & Abell 1963, year 1953) 2MASS (Cutri et al. 2003, year 1998) and PanSTARRS-1 (Chambers et al. 2016, year 2014) do not show background sources at the current star position (see Fig. 8).

We have also used the package VESPA (Morton 2012, 2015) to perform a statistical validation of K2-286b. Using models of stellar populations in the Galaxy, the package computes the probabilities of planetary and non-planetary scenarios, taking into account eclipsing binaries, background eclipsing binaries and hierarchical triple systems scenarios. Running VESPA, we obtain FPP < 10^{-4} for K2-286b.

Non-detection of companions or background sources in OSIRIS/GTC, POSSI, 2MASS and PanSTARRS-1 images, and statistical analysis with VESPA, strongly support the planetary origin of the signals present in the light curve of K2-286.

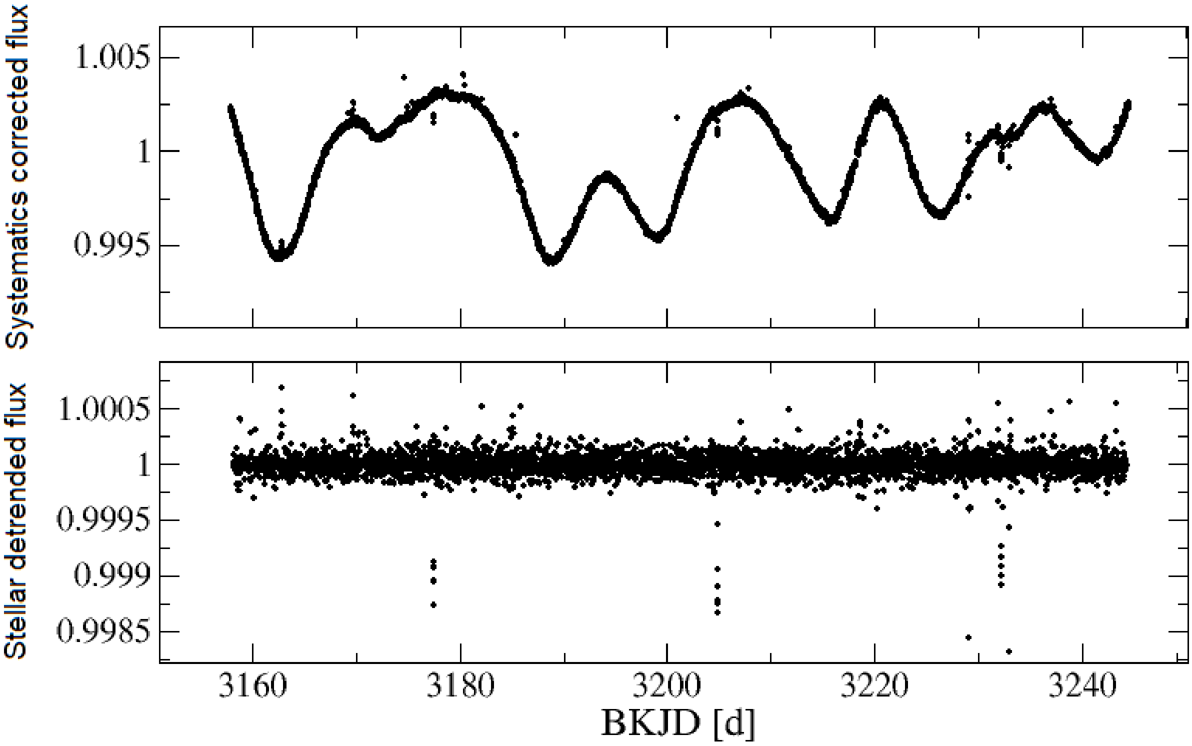

Figure 3. K2 systematics corrected (top) and stellar detrended (bottom) light curves for K2-286.

Table 2. Parameters for planet K2-286b

Planet parameter	Value
Orbital period (P) [d]	27.359 ± 0.005
Semi-major axis (a) [AU]	$0.1768^{+0.0175}_{-0.0205}$
Radius (R_p) [$R_\oplus$]	2.1 ± 0.2
Mass (M_p) [$M_\oplus$] (1)	6.8±4.3
Equilibrium Temperature (T_{eq}) [K]	347^{+21}_{-11}
Transit parameter	**Value**
Epoch (BKJD) [days]	3177.417 ± 0.002
Radius of planet in stellar radii (R_p/R_*)	$0.0315^{+0.0008}_{-0.0005}$
Semi major axis in stellar radii (a/R_*)	63^{+4}_{-7}
Linear limb-darkening coeff (u_1)	0.52 ± 0.01
Quadratic limb-darkening coeff (u_2)	0.22 ± 0.01
Inclination (i) [deg]	$89.67^{+0.21}_{-0.25}$
Impact Parameter (b)	$0.35^{+0.21}_{-0.23}$
Transit depth (δ)	$0.00112^{+0.00026}_{-0.00016}$
Total duration (T_{14}) [d]	$0.125^{+0.031}_{-0.017}$

(1): From Wolfgang et al. (2016) and Chen & Kipping (2017) mass-radius relations.

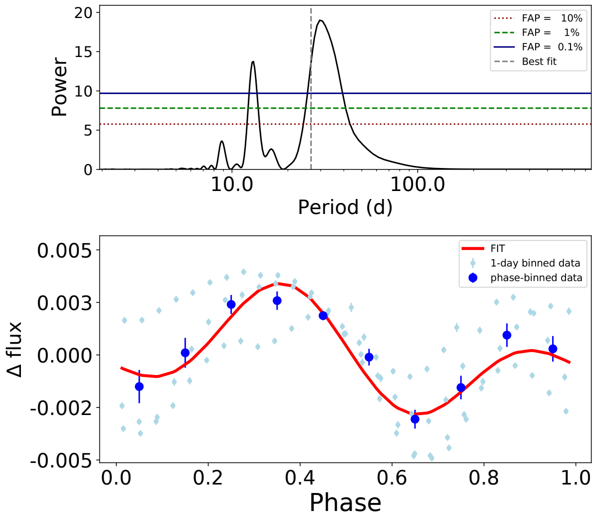

Figure 4. Top panel: GLS periodogram of light curve of K2-286. Strongest signal is present at 26.6 ± 0.5 d. Bottom panel: light curve and fit corresponding to the period of 26.6 ± 0.5 d.

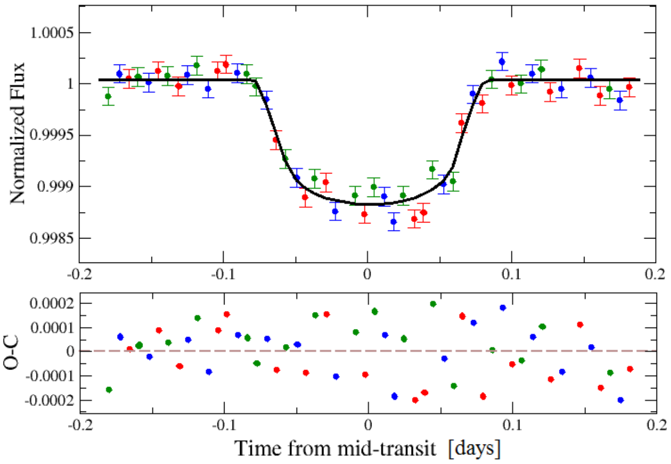

Figure 5. Top: Phase-folded light curve of planet K2-286b (red, blue and green dots correspond to first, second and third transit). Solid curve represents best model fit obtained by MCMC. Bottom: residuals of the fit.

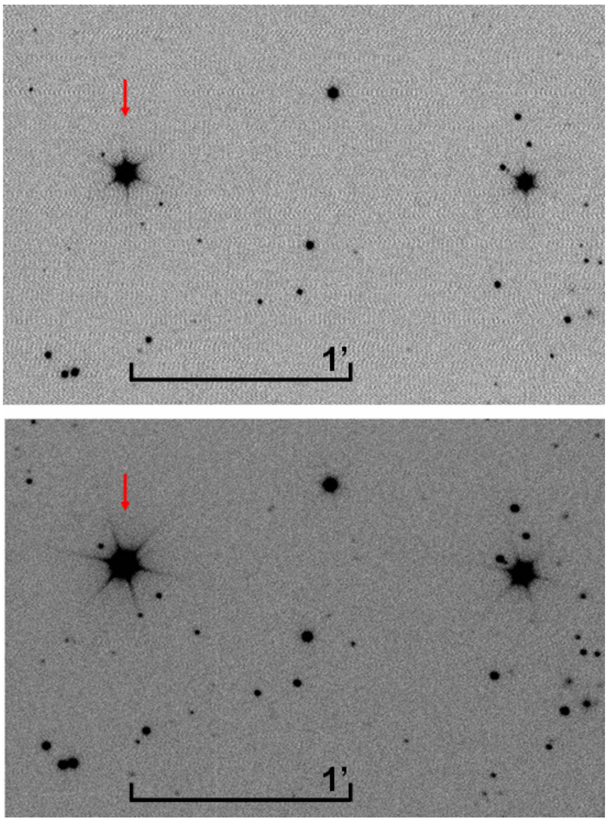

Figure 6. OSIRIS/GTC images of K2-286 field from 11 x 0.1 sec (top) and 11 x 0.5 sec (bottom) series in the i-band Sloan filter. Arrows point K2-286. The closest three stars clearly seen, located at 8.4, 13.4 and 15.2 arc seconds, have magnitude differences with respect to the main target of roughly 7.8, 7.2 and 7.7 mag.

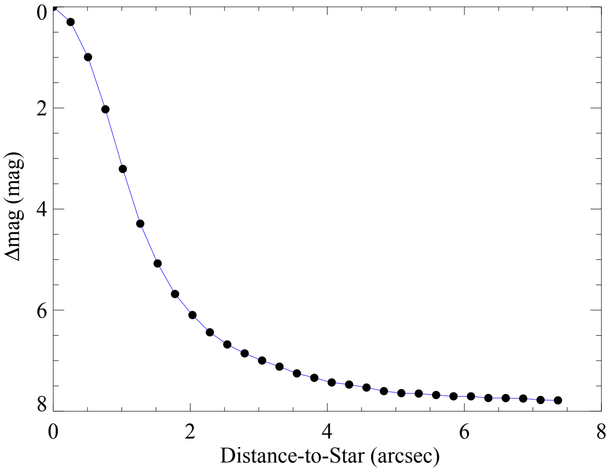

Figure 7. Contrast curve for K2-286 from the OSIRIS/GTC image.

2.4 Habitability

Assuming a Bond albedo $A = 0.3$ and an Earth-like greenhouse effect, we estimate a surface temperature of 376^{+26}_{-19} K for K2-286b. However, different models predict different distances for the inner and outer edges of the habitable zone (HZ) of a star.

In this work we compare the conservative model from Kopparapu et al. (2013), that explores the HZ for planets with atmospheres similar to the Earth's atmosphere, with the optimistic model from Zsom et al. (2013), that studies the HZ for planets with atmospheres not necessarily like the Earth's atmosphere, but any combination able to support liquid water. In the inner edge of this optimistic model, a desert planet with small or moderate reserves of water at the poles could generate high albedo, very little greenhouse effect, and very little loss of water.

For the conservative model of Kopparapu et al. (2013) we find a distance $d = 0.241$ AU for the inner edge of the habitable zone of K2-286. For the optimistic model of Zsom et al. (2013) and assuming albedo $A = 0.2$, we estimate the inner edge of the HZ at a distance $d = 0.179$ AU. If we assume albedo $A = 0.8$ we obtain $d = 0.121$ AU.

With an orbital radius of $0.1768^{+0.0175}_{-0.0205}$ AU, K2-286b would be outside the habitable zone in the conservative model, but within the HZ in the optimistic model (see Fig 9). These estimations show that

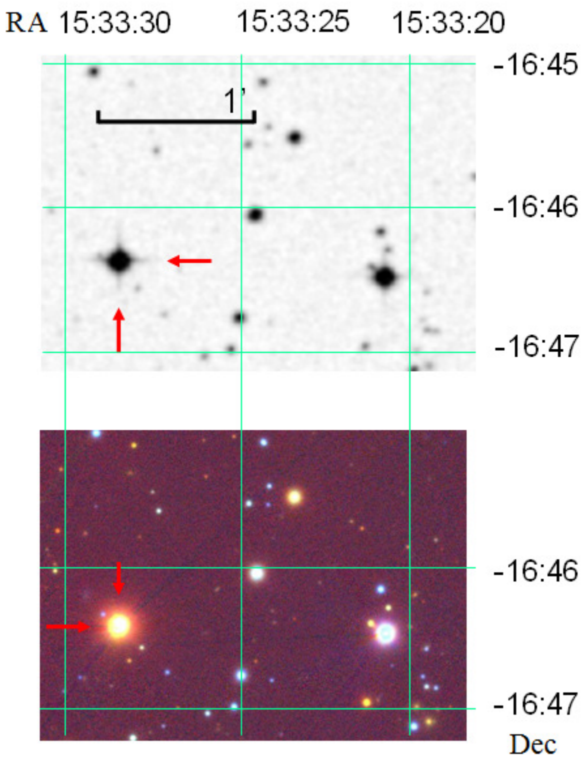

Figure 8. POSS-I image (1953, top) and $y/i/g$ stack from PanSTARRS-1 (2014, bottom). Arrows point K2-286.

K2-286b might be able to support liquid water with the adequate atmospheric conditions.

As stated in section 2.1, K2-286 has not been detected as an X-ray source by ROSAT, setting an upper limit for its X-ray luminosity of $L_X < 2.1 \cdot 10^{29}$ erg·s^{-1}. The estimated $\log_{10}(R'_{HK}) = -4.75 \pm 0.06$ does not indicate strong activity. Also, visual inspection of the light curve of K2-286 during the 15 campaign observing window of K2, doesn't show strong flare activity. With a host star of spectral type M0V, K2-286b may experience a more benign environment than other planets orbiting M dwarf stars of later types, as Proxima Centauri (M5.5V) and TRAPPIST-1 (M8.0V) systems.

2.5 Mass estimation

Fulton et al. (2017) analyzed the size distribution of a sample of 2025 Kepler planets with precise measured radius, and detected a gap in the radius distribution of close-in planets (orbital period < 100 days) at 1.5–2.0 $R_\oplus$. Fulton & Petigura (2018) confirmed this result using a catalog of ~1000 planets with precise properties from Gaia parallaxes. This gap may be related to photoevaporation, gas poor formation or impact erosion (Fulton et al. 2017). Our estimated radius for K2-286b is $R = 2.1 \pm 0.2$ $R_\oplus$, in the upper limit of the gap. A precise measurement for the mass of K2-286b is a key point to understand its composition, internal structure, and to test the planetary formation and evolution models.

In Fig. 10 we plot the RV measurements obtained from the HARPS-N observations against orbital phase with the period of 27.359 days. To obtain the RV values we first fit the cross-correlation function given by the HARPS-N pipeline, applying weights to each echelle order and using a Gaussian model (Baranne et al. 1996). Then we average the values per night and subtract the weighted average RV to obtain the relative values. The relative RV values are fit by a sinusoid with the period and phase as fixed parameters. The only free parameter is the RV semi-amplitude, which is obtained by an MCMC simulation using the python emcee package (Foreman-Mackey et al. 2013). The results of this simulation are shown in Fig. 10. The figure presents various sinusoidal fits with semi-amplitude values that cover the error range given by the MCMC. The best sinusoidal fit is obtained for a semi-amplitude of $4.52^{+3.29}_{-2.94}$ m·s^{-1}.

Following Suárez Mascareño et al. (2018) we estimate that the semi-amplitude of the period signal induced by the rotation/activity of the star is 4.4 m·s^{-1}. In order to impose an upper limit on the planet signal contribution to the measured semi-amplitude, we quadratically subtract the expected magnetic signal (4.4 m·s^{-1}) from the maximum semi-amplitude compatible with the MCMC determination (7.8 m·s^{-1}). In spite of the very similar rotational period of the star and orbital period of the planet, we do not know if the induced signals are in phase, so signals were quadratically subtracted. We obtain that the maximum amplitude of the planet signal is 6.4 m·s^{-1}, which leads to a maximum mass of 22 $M_\oplus$ and excludes that K2-286b is a gas giant. More RV data would certainly be needed to obtain a mass determination.

Since the previous estimation provides only an upper limit, we estimated the mass of K2-286b applying the following alternative methods:

First, using the probabilistic mass-radius relation from Wolfgang et al. (2016), which quantifies the intrinsic dispersion and the uncertainties on the relation parameters. Assuming that the relation can be described as a power law with a dispersion that is constant and normally distributed, they found that:

$$\frac{M_P}{M_\oplus} \sim N\left(\mu = C \cdot \left(\frac{R_P}{R_\oplus}\right)^{\gamma}, \sigma = \sigma_M\right) \qquad (3)$$

Adopting $C = 2.7$, $\gamma = 1.3$ and $\sigma_M = 1.9$ from the Wolfgang et al. (2016) baseline dataset best fit, we find $M = 7.1 \pm 1.9$ $M_\oplus$ for K2-286b.

Second, applying the probabilistic mass – radius relation implemented in the package FORECASTER (Chen & Kipping 2017), we obtained $M = 6.4 \pm 3.9$ $M_\oplus$.

From these two methods we estimate a mean value for the mass of K2-286b of 6.8± 4.3 $M_\oplus$, within the limits established by our measure of the mass discussed previously.

3 DISCUSSION

Planets with $R < 1.6$ $R_\oplus$ have densities consistent with purely rocky composition (Weiss & Marcy 2014; Rogers 2015), while planets with $R > 1.6$ $R_\oplus$ have densities that suggest a rocky core surrounded by a gaseous envelope (Weiss & Marcy 2014; Rogers 2015). Fig. 12 shows the possible location of K2-286b in the planetary mass – radius space (Zeng & Sasselov 2013). A sample of representative transiting exoplanets with well measured radii and masses are also plotted. The uncertainties in mass and radius allow a wide range for the composition of K2-286b, excluding only a 100% Fe planet.

In Fig. 13 we plot T_{eq} against mass for a sample of transiting exoplanets with $R < 3$ $R_\oplus$ and with well measured masses obtained from radial velocity follow–up (the sample was obtained from the

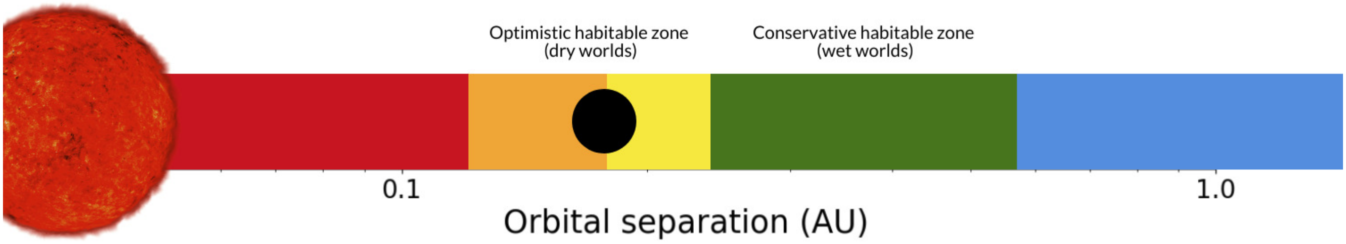

Figure 9. Orange: inner edge of the optimistic habitable zone of K2-286 with albedo A=0.8. Yellow: same with A=0.2. Green: habitable zone limits for the conservative model. Black filled circle represents the location of K2-286b.

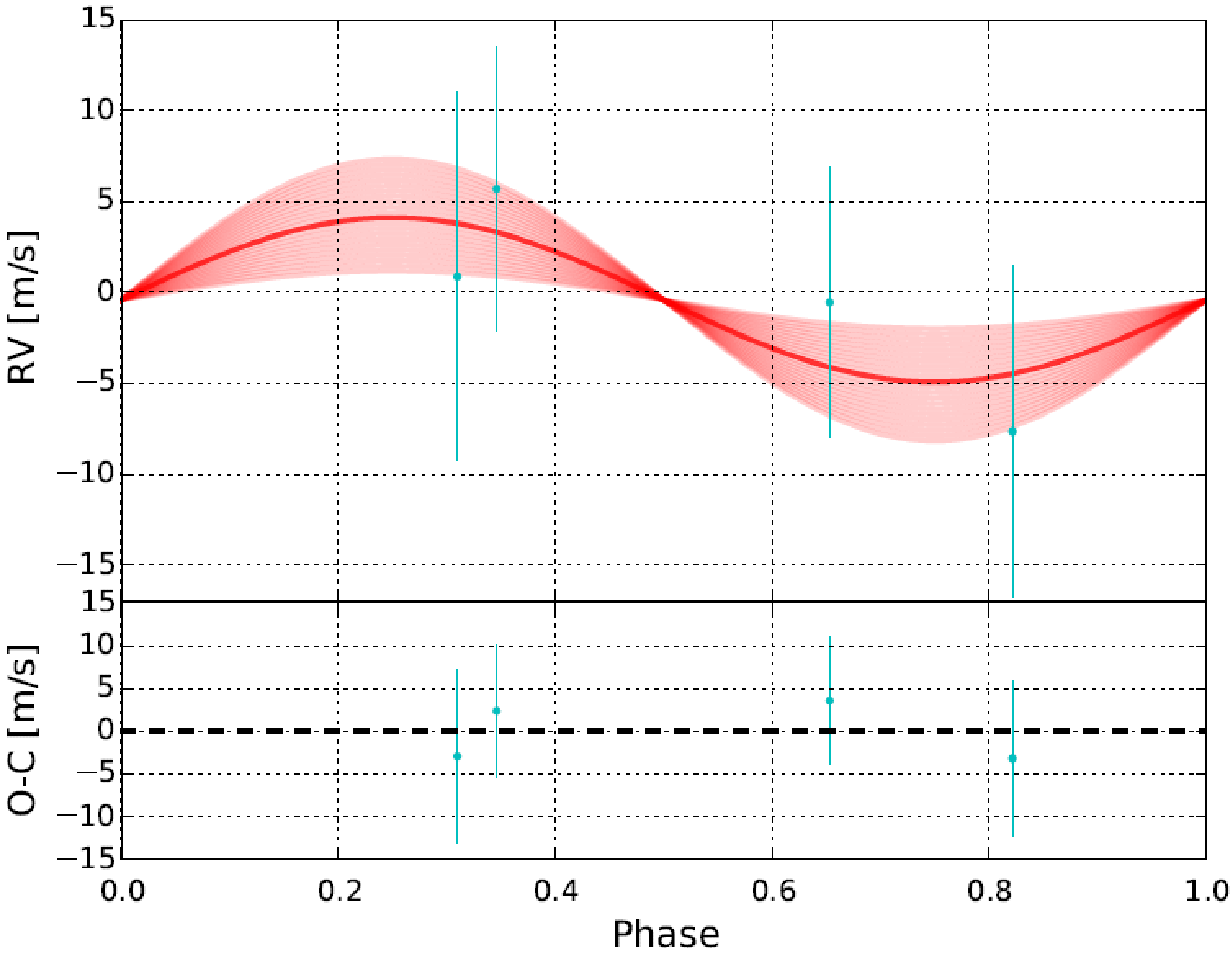

Figure 10. Top panel: HARPS-N *RV* measurements against orbital phase with the period of 27.359 days and mid-transit time of Tc = 3177.417 (BKJD). The 0.5 phase value corresponds to the epoch of mid-transit. The value at ~ 0.65 phase is the weighted mean of three spectra acquired consecutively the same night. Overlaid is the best sinusoidal fit with a *RV* semi-amplitude of $4.52^{+3.29}_{-2.94}$ $\mathrm{m\cdot s^{-1}}$ and a distribution of other fits for various semi-amplitudes according to the MCMC results (see Fig. 11). Bottom panel: residuals from the fit.

Exoplanet Archive [6] to date 2018 September 9). K2-286b is plotted adopting the estimated mass from the mass-radius relations discussed previously. The plot shows that K2-286b is cooler than most of them, so a precise measurement of the mass of K2-286b would be of special interest for a better understanding of the mass - radius relation over a wider range of temperatures.

With the estimated mass for K2-286b of 6.8± 4.3 $M_\oplus$ and the assumption of $M_p \ll M_*$, circular orbit and $\sin i \sim 1$, we estimate

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[6] https://exoplanetarchive.ipac.caltech.edu/

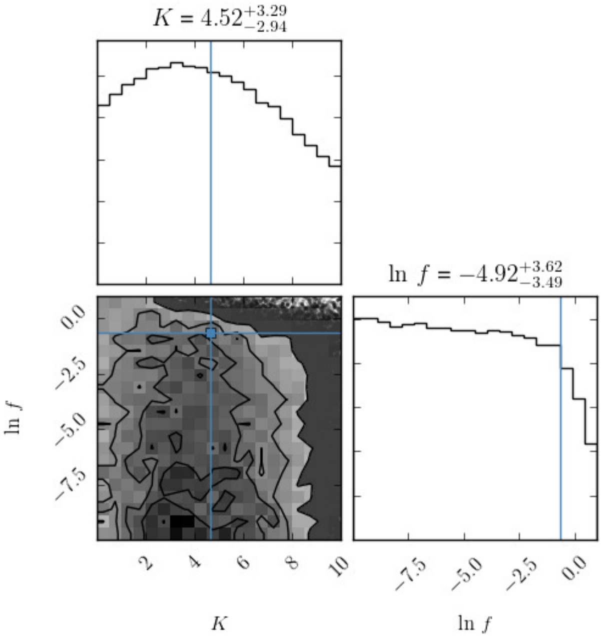

Figure 11. Results of the MCMC fit of the *RV* values, with *K* the radial velocity semi-amplitude, and the likelihood parameter ln *f* (see Fig. 10).

the induced semi-amplitude in stellar velocity variations at $1.9^{+1.3}_{-1.2}$ m·s^{-1}.

The measured *RV* semi-amplitude of $4.52^{+3.29}_{-2.94}$ m·s^{-1} from HARPS-N and the estimated contribution of 4.4 ± 0.5 m·s^{-1} due to the stellar activity are consistent, within the uncertainties, with the estimation of $1.9^{+1.3}_{-1.2}$ m·s^{-1} for K2-286b, and therefore with the estimated mass of 6.8± 4.3 $M_\oplus$.

The estimated induced semi-amplitude in stellar velocity variations for K2-286b is well-suited for radial velocity monitoring with ultra-stable spectrographs such as ESPRESSO at the VLT, which is expected to reach ~ 0.5 m·s^{-1} *RV* precision for a m_V ~ 13.0 star in 60 minutes in the single HR mode (R ~ 134000), or EXPRES for the Discovery Channel Telescope (Jurgenson et al. 2016).

In Figures 14 & 15 we plot T_{eq} against the estimated induced semi amplitudes in stellar velocity variations and the V mag of the host star (respectively) for the same sample of planets as in Fig. 13.

Understanding the structure of K2-286b will also require transmission spectroscopy observations. The amplitude of the signal in transit transmission spectroscopy can be estimated as $\frac{R_p \cdot h_{\rm eff}}{(R_*)^2}$ (Gillon et al. 2016) with $h_{\rm eff}$ the effective atmospheric height. $h_{\rm eff}$ is related to the atmospheric scale height H = K·T/μ ·g (K Boltzmann's constant, T atmospheric temperature, μ atmospheric mean molecular mass, g surface gravity). Assuming $h_{\rm eff}$ = 7·H (Miller-Ricci & Fortney 2010) for a transparent volatile dominated atmosphere (μ = 20) with 0.3 Bond albedo, we estimate the amplitude in transit transmission spectroscopy at 5.0 ± 3.0 ppm. This estimated value is well suited for a future characterization by upcoming facilities such as the James Webb Space Telescope. In Figure 16 we compare the estimated amplitude of the signal in transit transmission spectroscopy of K2-286b with the same sample of transiting small planets with well measured masses. K2-286b has the highest amplitude of signal in the temperate region of the plot, so it is one of the most favourable temperate targets for atmospheric characterization.

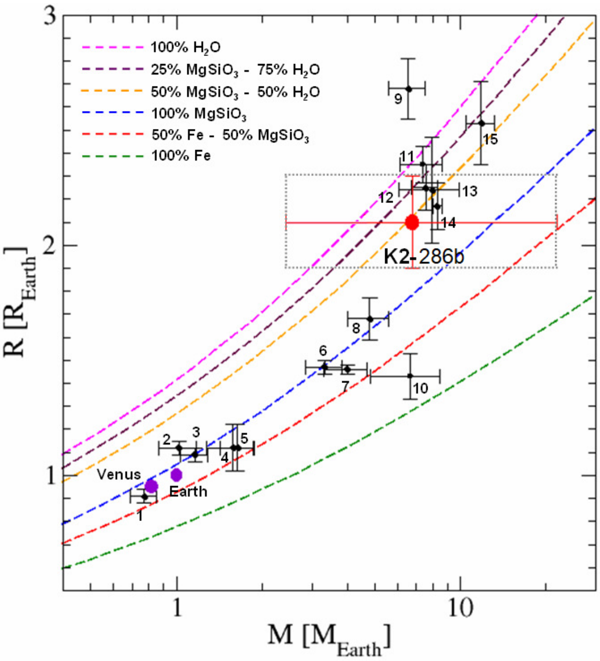

Figure 12. Position of K2-286b (red dot) in the planetary mass - radius space (Zeng & Sasselov 2013), adopting the estimated mass from discussed mass-radius relations. Dotted area shows the conservative upper mass limit from the HARPS-N measurements, lower mass limit from probabilistic empirical relations, and radius limits from MCMC analysis of the phase-folded transit. Representative transiting exoplanets with well measured radius and mass are also plotted. The numbers indicate planets (1,2,3) Trappist-1e,b,c (Grimm et al. 2018), (4) Kepler-78b (Pepe et al. 2013), (5) GJ-1132b (Berta-Thompson et al. 2015), (6) Kepler-10b (Dumusque et al. 2014), (7) Kepler-93b (Dressing et al. 2015), (8) Corot-7b (Barros et al. 2014), (9) GJ-1214b (Charbonneau et al. 2009), (10) LHS 1140b (Dittmann et al. 2017), (11) Kepler-10c (Rajpaul et al. 2017; Berger et al. 2018), (12) HD 97658b (Van Grootel et al. 2014), (13) K2-18b (Cloutier et al. 2017), (14) 55 Cnc e (Endl et al. 2012), (15) HIP 116454b (Vanderburg et al. 2015).

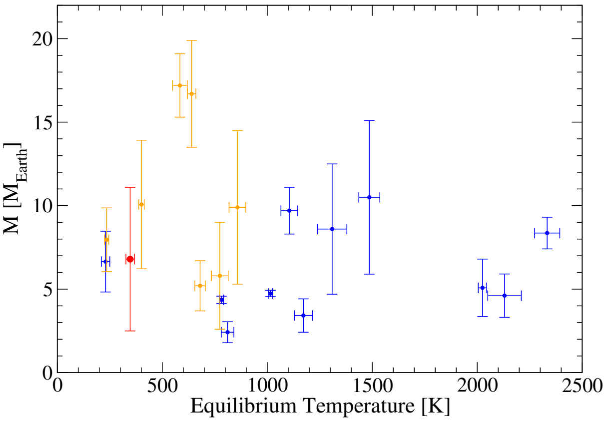

Figure 13. Mass versus T_{eq} for transiting exoplanets with R < 3 $R_\oplus$ and well measured mass. Blue dots: planets with 1 $R_\oplus$ < R < 2 $R_\oplus$, orange dots: 2 $R_\oplus$ < R < 3 $R_\oplus$. Red dot: K2-286b. Estimated mass from discussed mass-radius relations is adopted for K2-286b.

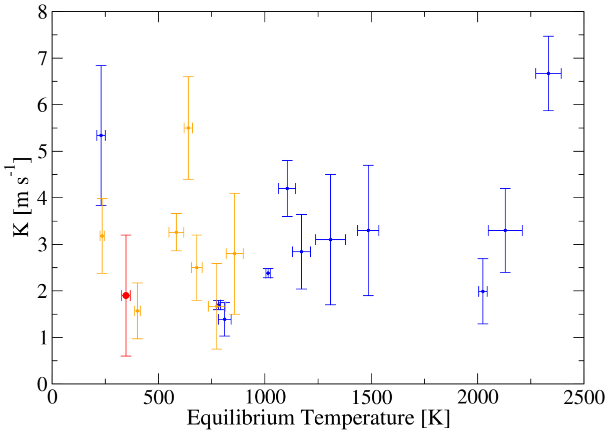

Figure 14. Semi-amplitude of induced radial stellar velocity versus T_{eq} for transiting exoplanets with $R < 3$ $\mathrm{R}_\oplus$ and well measured mass. Blue dots: planets with 1 $\mathrm{R}_\oplus$ $< R <$ 2 $\mathrm{R}_\oplus$, orange dots: 2 $\mathrm{R}_\oplus$ $< R <$ 3 $\mathrm{R}_\oplus$. Red dot: K2-286b. The semi-amplitude of K2-286b is estimated adopting mass from discussed mass-radius relations.

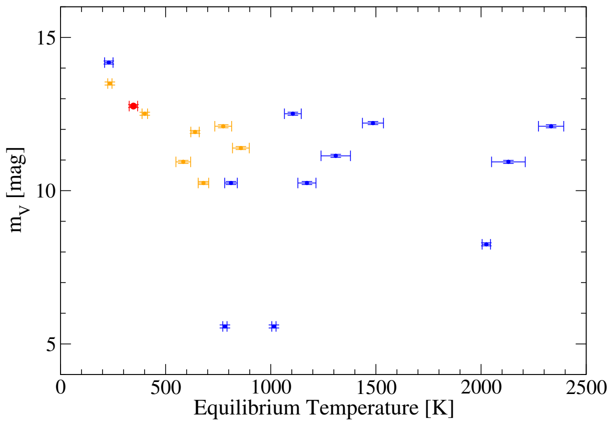

Figure 15. V mag versus T_{eq} for transiting exoplanets with $R < 3$ $\mathrm{R}_\oplus$ and well measured mass. Blue dots: planets with 1 $\mathrm{R}_\oplus$ $< R <$ 2 $\mathrm{R}_\oplus$, orange dots: 2 $\mathrm{R}_\oplus$ $< R <$ 3 $\mathrm{R}_\oplus$. Red dot: K2-286b.

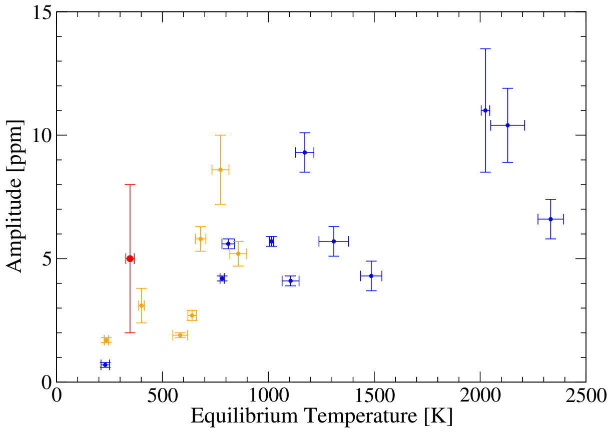

Figure 16. Amplitude of the signal in transit transmission spectroscopy versus T_{eq} for transiting exoplanets with $R < 3$ $\mathrm{R}_\oplus$ and well measured mass. Blue dots: planets with 1 $\mathrm{R}_\oplus$ $< R <$ 2 $\mathrm{R}_\oplus$, orange dots: 2 $\mathrm{R}_\oplus$ $< R <$ 3 $\mathrm{R}_\oplus$. Red dot: K2-286b. Amplitude of signal for K2-286b is estimated adopting mass from discussed mass-radius relations.

4 CONCLUSIONS

In this work we present the discovery of a super-Earth orbiting close to the inner edge of the habitable zone of the cool dwarf star K2-286. From acquired spectra we characterized the star as M0V, with $T_{\rm eff}$ = 3926 ± 100 K. We also derived the rest of stellar parameters from empirical relations.

To confirm the planetary origin of the signals found in the light curve of K2-286, we have discarded possible contaminating sources analyzing acquired and archival images, which show no companions or background stars. We have also statistically validated the planetary origin of the signals.

Analyzing the K2 photometric data we find a planetary radius of 2.1 ± 0.2 $\mathrm{R}_\oplus$, in the upper limit of the 1.5–2.0 $\mathrm{R}_\oplus$ gap in the radii distribution of exoplanets. *RV* measurements impose an upper limit to the mass of 22 $\mathrm{M}_\oplus$, excluding that K2-286b is a gas giant, and from probabilistic mass - radius relations we estimate a planetary mass of 6.8± 4.3 $\mathrm{M}_\oplus$.

K2-286b has an estimated equilibrium temperature of 347^{+21}_{-11} K. With an orbital period of 27.259 ± 0.005 d and orbital radius of $0.1768^{+0.0175}_{-0.0205}$ AU, K2-286b orbits within the HZ limits according to optimistic models discussed in this work. We have also shown that K2-286 does not exhibit strong stellar activity so K2-286b may experience a more benign environment than other planets orbiting M dwarf stars of later types and might host liquid water depending on its atmospheric conditions. We also have shown that K2-286b is cooler than most of the small exoplanets with well measured masses and radii.

The induced semi-amplitude in stellar velocity variations has been estimated at $1.9^{+1.3}_{-1.2}$ m·s^{-1}, within the capabilities of high-resolution spectrographs such as ESPRESSO at VLT or EXPRES for the Discovery Channel Telescope, making possible to completely characterize the properties of K2-286b performing radial velocity follow up.

We have also estimated the amplitude of the signal in transit transmission spectroscopy at 5.0 ± 3.0 ppm, within the capabilities of atmospheric characterization by the James Webb Telescope, and shown that K2-286b is one of the most favorable temperate targets for atmospheric characterization.

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Capítulo 6

Conclusiones y trabajo futuro

6.1. Conclusiones

Esta tesis ha contado con dos líneas principales de investigación:

- Por una parte, se ha estudiado una muestra de estrellas observadas sistemáticamente por el instrumento CARMENES, con el fin de determinar sus períodos de rotación. Gracias a estos P_{rot} seremos capaces de distinguir entre señales en velocidad radial inducidas por actividad magnética estelar y señales inducidas por exoplanetas. Su obtención es también valiosa para estudiar la relación del P_{rot} con las propiedades físicas de las estrellas enanas M como actividad, estructura interna o edad.

- Por otra, y dado que para obtener los P_{rot} de ciertas estrellas trabajamos con curvas de luz del telescopio espacialKépler en su misión extendida (K2), hemos investigado la práctica totalidad de las enanas rojas de las campañas 13, 14 y 15, con el objetivo de detectar, confirmar y caracterizar planetas en estas estrellas. De todos los candidatos encontrados, nos hemos centrado en los de mayor interés y más adecuados para un seguimiento posterior en velocidad radial con espectrógrafos de última generación como CARMENES (para determinar sus masas con precisión) o con instrumentos como el James Webb Telescope (para su caracterización atmosférica).

La investigación ha dado lugar a cuatro publicaciones; una es relativa al primer objetivo de la tesis, el estudio de la rotación de las estrellas observadas por CARMENES, mientras que las otras tres, enmarcadas en el segundo objetivo de la tesis, presentan el descubrimiento, confirmación y caracterización de nueve exoplanetas en cuatro estrellas enanas frías observadas por K2. Los resultados principales de estas publicaciones (y de la tesis) se resumen en los siguientes puntos:

- Se han buscado períodos de rotación fotométricos para 337 estrellas observadas por CARMENES. Para ello se han extraido curvas de luz de los surveys MEarth, ASAS, SuperWASP, NSVS, Catalina, ASAS-SN, K2 y HATNet, aparte de otros surveys también investigados pero en los que no se encontraron datos para las estrellas de la muestra. Para 20 estrellas se han realizado observaciones propias en colaboración con observatorios amateurs y profesionales.
- Se han encontrado un total de 622 curvas de luz para 334 estrellas. Para detectar señales periódicas (y en particular señales originadas por la rotación), se obtuvo el periodograma Lomb-Scargle para todas las curvas. Ciertas estrellas

críticas también se analizaron con periodograma GLS y métodos Gaussianos. Como resultado de este análisis se han obtenido 142 señales que identificamos como rotación. 73 períodos se obtienen por vez primera, mientras que los 69 restantes coinciden con los períodos reportados previamente en la literatura. Además se han detectado 10 señales que interpretamos como ciclos de larga actividad, seis de los cuales se reportan por vez primera en la literatura.

- Con las estrellas de nuestra muestra para las que hemos obtenido P_{rot} y P_{ciclo}, junto con 47 enanas rojas con $P_{\rm rot}$ y P_{ciclo} reportado previamente, se ha explorado la relación entre ambos. Encontramos que no existe correlación para estrellas M, en acuerdo con los estudios realizados previamente.
- En nuestra muestra, no detectamos el *gap* reportado en $\sim$30 d en la distribución de los períodos de rotación.
- Se encuentra una relación clara entre el P_{rot} y actividad ($vsini$, pEW(H$_\alpha$)).
- No encontramos correlación entre la amplitud de la variabilidad fotométrica y P_{rot}, $vsini$ y pEW(H$_\alpha$).
- Identificamos tres estrellas muy activas cuyos períodos (entre 0.34 y 23.6 d) se reportan por vez primera en la literatura.
- Se ha investigado la práctica totalidad de las curvas de luz de las enanas M observadas por el Telescopio Espacial Képler en su misión extendida (K2), en las campañas 13, 14 y 15. El objetivo es detectar (mediante el método de tránsitos), confirmar y caracterizar exoplanetas de interés (en estrellas brillantes, en zona de habitabilidad, sistemas planetarios, pertenecientes a cúmulos o grupos de movimiento) que puedan ser monitorizados por instrumentos como CARMENES para una caracterización precisa de su masa, o por el James Webb Telescope, para su caracterización atmosférica. El resultado ha sido la detección, confirmación y caracterización de 9 exoplanetas en cuatro enanas rojas:

    - K2-155 (K6 V, m$_V$=12.81) cuenta con tres super-Tierras, con radios 1.8 (b), 2.6 (c) y 1.9 (d) $R_\oplus$, que transitan cada 6.34 (b), 13.85 (c) y 40.72 (d) d. El planeta más exterior, K2-155 d, orbita próximo al límite interior de la zona de habitabilidad de K2-155.

    - K2-239 (M3.0 V, m$_V$=14.55) es transitada por tres planetas de tipo Tierra, con radios 1.1 (b), 1.0 (c) y 1.1 (d) $R_\oplus$. Sus períodos orbitales son 5.24 (b), 7.76 (c) y 10.12 (d) d, resultando una configuración compacta en resonancia 2:3:4.

    - K2-240 (M0.5 V, m$_V$=13.39) tiene un sistema de dos super-Tierras con radios 2.0 (b) y 1.8 (c) $R_\oplus$, transitando cada 6.03 (b) y 20.52 (c) d.

    - K2-286 (M0 V, m$_V$=12.76), es transitada cada 27.36 d por una super-Tierra que se encuentra en su zona de habitabilidad. El radio del planeta, 2.1 $R_\oplus$, lo sitúa próximo al límite superior del *gap de Fulton* en la distribución de radios de exoplanetas con radio $< 3\ R_\oplus$.

- Para todos los planetas se han realizado estimaciones de la semiamplitud en la velocidad radial inducida en sus estrellas, orientando futuros seguimientos en velocidad radial que caractericen sus masas. También se han estimado las amplitudes de las señales en espectroscopía de transmisión para valorar las posibilidades de caracterización atmosférica.

La determinación de los períodos de rotación fotométricos de las estrellas enanas M observadas por CARMENES se vio limitada por diferentes factores; por un lado encontramos factores intrínsecos a las propias estrellas, como la aparición y desaparición en diferentes regiones de las estructuras que originan estas modulaciones (como manchas y playas), especialmente en diferentes latitudes, lo que unido a la rotación diferencial provoca que se infieran diferentes períodos de rotación. Otro factor intrínseco es la extensión variable de estas regiones, que implica una mayor o menor amplitud de la modulación fotométrica, en muchas ocasiones indetectable dentro de la precisión fotométrica de los surveys investigados.

Por otra parte encontramos factores limitantes relativos a los surveys investigados. En primer lugar, las modulaciones fotométricas inducidas por la rotación en las estrellas M investigadas son, en muchos casos, de amplitud inferior a la precisión del survey en el que se habían encontrado datos, impidiendo su determinación. En segundo lugar, ciertas estrellas no tenían datos en ninguno de los surveys investigados, o si los tenían, estos no eran válidos por su mala calidad, pocas observaciones o insuficiente extensión temporal de las mismas. En tercer lugar, en ciertos surveys la cadencia de observación es del orden de varios días, lo que impidió determinar de manera fiable períodos de rotación de estrellas rápidas (con $P_{rot} <\sim 1$ d).

Los últimos puntos (cantidad, calidad y cadencia de observaciones) pudieron subsanarse realizando observaciones propias, pero esto *solo* fue posible para 20 estrellas dado el tiempo de observación necesario para obtener un P_{rot}.

En cuanto al segundo objetivo de la tesis, la detección de planetas, la menor precisión fotométrica de K2 (300 ppm) con respecto a la misión principal (20 ppm), y las ventanas de observación de $\sim$ 80 días fueron factores limitantes para nuestro estudio.

La menor precisión fotométrica impide la detección de posibles tránsitos de planetas que estén *escondidos* dentro del ruido de las curvas de luz de K2. Este factor impide una mejor derivación de los parámetros planetarios a partir de los tránsitos observados. Igualmente no permite realizar un análisis adecuado de posibles variaciones de tiempo de tránsitos, de cuya detección se podrían estimar las masas planetarias o la presencia de nuevos planetas. Las ventanas de observación de $\sim$ 80 días suponen también un factor limitante para detectar un número mínimo de tránsitos de los que se pueda inferir la presencia de un candidato.

Por otra parte, el formato *letter* elegido para las publicaciones relativas a los sistemas K2-155, K2-239 y K2-240, con su extensión máxima de 5 páginas, supuso una limitación en la profundidad de los resultados a exponer y discutir.

Todos los períodos de rotación reportados en este trabajo, han sido incluídos en la base de datos de CARMENES y están siendo usados para discriminar las señales en velocidad radial inducidas por actividad magnética (Nagel y col., 2019; Perger y col., 2019). Igualmente la compilación supone una valiosa aportación para el estudio de la relación del período de rotación de las estrellas enanas M con sus parámetros físicos.

Por otra parte, los nueve planetas presentados en este trabajo suponen un incremento sustancial en el número de planetas conocidos orbitando estrellas enanas M, mejorando la estadística sobre las propiedades de los sistemas planetarios en torno a estas estrellas. Esto será de ayuda para una mejor comprensión acerca de la ocurrencia de planetas y sistemas planetarios en estrellas enanas M, así como de sus parámetros físicos. Especialmente los planetas K2-155d y K2-286b son de gran interés por su situación respecto a la zona de habitabilidad de sus estrellas.

6.2. Trabajo futuro

Es necesario continuar investigando las estrellas observadas por CARMENES sin P_{rot} determinado en este trabajo, ya sea analizando datos de nuevos *releases* de los surveys investigados (ASAS-3N, ASAS-4, SuperWASP-South o nuevas campañas de MEarth), o buscando datos en nuevos surveys que aun no eran públicos durante la realización de este trabajo (TESS, ASAS-SN o ATLAS). Será también necesario programar campañas de observación para obtener el P_{rot} de las estrellas para las que no se encuentre fotometría en dichos surveys.

Por otra parte, los sistemas planetarios detectados requieren un seguimiento posterior en velocidad radial con espectrógrafos como CARMENES o ESPRESSO, con el fin de determinar sus masas y caracterizar por completo los planetas. Se deberán analizar las observaciones que el Telescopio Espacial TESS realice de estos sistemas, para detectar posibles tránsitos de planetas adicionales, e investigar posibles variaciones en los tiempos de tránsito (TTVs) que puedan dar información de más planetas y de las masas de todos ellos. También será necesario solicitar tiempo de observación con el Telescopio Espacial James Webb, para caracterizar las atmósferas de los mismos mediante espectroscopía de transmisión, especialmente para K2-286 b, que orbita en la región interior de la zona de habitabilidad de su estrella.

Apéndice A

Tablas y curvas de ejemplo incluídas en la publicación de P_{rot} de CARMENES

Table A.1. M dwarfs searched for photometric periods.

Karmn	Name	α (J2000.0)	δ (J2000.0)	Survey	$N_{\rm obs}/N_{\rm used}$	Δt [a]	$\overline{m}$ [mag]	σ_m [mag]	$\overline{\delta m}$ [mag]
J00051+457	GJ 2	00:05:10.78	+45:47:11.6	SuperWASP	5126/4400	1.645	10.185	0.052	0.027
				NSVS	69/69	0.397	9.300	0.022	0.010
J00067-075	GJ 1002	00:06:43.26	–07:32:14.7	ASAS	181/172	7.863	13.899	0.282	0.122
				Catalina	160/140	4.285	11.897	0.096	0.050
				NSVS	106/105	0.397	11.889	0.032	0.020
J00162+198E	LP 404–062	00:16:16.08	+19:51:51.5	ASAS	317/282	6.855	11.690	0.139	0.114
				MEarth-2010	935/910	2.562	0.000	0.007	0.004
J00162+198W	EZ Psc AB	00:16:14.63	+19:51:37.6	MEarth-2010	935/933	0.720	0.000	0.009	0.003
				MEarth-2014	282/278	2.704	0.000	0.015	0.003
				ASAS	316/305	6.855	11.684	0.117	0.110
				NSVS	202/193	0.585	10.595	0.025	0.011
J00183+440	GX And	00:18:22.57	+44:01:22.2	SuperWASP	1233/1102	1.047	8.498	0.180	0.125
				MEarth-2011	622/585	0.448	0.000	0.015	0.007
				MEarth-2014-tel02	2328/2127	2.710	0.001	0.017	0.006
J00184+440	GQ And	00:18:25.50	+44:01:37.6	MEarth-2011	622/578	0.448	0.000	0.015	0.007
				MEarth-2014-tel02	2326/2161	2.710	0.000	0.011	0.006
J00286-066	GJ 1012	00:28:39.48	–06:39:48.1	ASAS	389/368	9.030	11.861	0.085	0.040
J00389+306	Wolf 1056	00:38:58.79	+30:36:58.4	SuperWASP	12312/12309	4.112	10.944	0.119	0.018
J00570+450	G 172–030	00:57:02.61	+45:05:09.9	SuperWASP	3576/3334	1.645	9.729	0.096	0.016
				NSVS	52/52	0.331	9.415	0.016	0.010
J01013+613	GJ 47	01:01:20.06	+61:21:56.0	NSVS	105/103	0.706	10.095	0.033	0.011
J01019+541	G 218–020	01:01:59.53	+54:10:57.8	MEarth-2016-tel01	2549/2531	4.068	0.001	0.010	0.003
				MEarth-2014-tel06	1678/1621	0.776	0.000	0.010	0.003
				SuperWASP	4983/4724	3.962	12.521	0.218	0.016
				ASAS-SN	372/361	2.729	15.274	0.079	0.074
J01025+716	BD+70 68	01:02:32.13	+71:40:47.6	ASAS-SN	474/468	0.585	10.066	0.026	0.006
				NSVS	228/215	0.706	13.494	0.088	0.087
J01026+623	BD+61 195	01:02:38.96	+62:20:42.2	MEarth-2010	207/190	1.386	0.005	0.027	0.002
				MEarth-2011	1268/1227	0.593	0.000	0.014	0.003
				MEarth-2014	175/158	2.677	0.000	0.022	0.003
J01033+623	V388 Cas	01:03:19.72	+62:21:55.7	MEarth-2011	1268/1254	0.593	0.000	0.021	0.003
J01048-181	GJ 1028	01:04:53.69	–18:07:29.3	ASAS	136/128	9.005	14.610	0.348	0.181
				NSVS	101/89	0.276	12.827	0.058	0.042
J01056+284	GJ 1029 AB	01:05:37.32	+28:29:34.0	MEarth-2010	760/738	1.361	0.000	0.007	0.003
				SuperWASP	4695/3975	4.112	14.383	0.171	0.092
J01125-169	YZ Cet	01:12:30.53	–16:59:57.0	ASAS	461/439	9.006	12.095	0.058	0.028
J01221+221	G 034–023	01:22:10.28	+22:09:03.2	SuperWASP	4643/4199	4.115	12.520	0.119	0.031
J01339-176	LP 768–113	01:33:58.00	–17:38:23.5	ASAS	462/444	9.027	13.055	0.106	0.052
J01352-072	Barta 161 12	01:35:13.93	–07:12:51.8	ASAS	397/380	8.981	13.436	0.181	0.076
J01433+043	GJ 70	01:43:20.15	+04:19:17.2	ASAS	322/301	8.899	10.937	0.054	0.020
				NSVS	121/119	0.460	10.072	0.029	0.010
J01518+644	G 244–037	01:51:51.08	+64:26:06.1	NSVS	122/115	0.706	10.570	0.030	0.015
J02002+130	TZ Ari	02:00:12.79	+13:03:11.2	ASAS	141/131	6.05820	12.365	0.124	0.040
				MEarth-2010	1298/1247	0.362	0.001	0.047	0.006
				MEarth-2011	1009/957	0.258	0.010	0.161	0.005
J02015+637	G 244–047	02:01:35.33	+63:46:11.9	Carda	1147/1111	0.041	10.41	0.012	0.004
J02070+496	G 173–037	02:07:03.83	+49:38:44.1	SuperWASP	4440/4175	4.038	11.668	0.186	0.021
J02088+494	G 173–039	02:08:53.60	+49:26:56.6	SuperWASP	6662/6099	4.041	12.497	0.123	0.029
				NSVS	221/220	0.712	11.407	0.040	0.015
J02123+035	BD+02 348	02:12:20.91	+03:34:31.1	ASAS	330/311	8.921	10.042	0.034	0.019
J02222+478	BD+47 612	02:22:14.63	+47:52:48.1	SuperWASP	3414/3004	3.443	9.572	0.082	0.028
				NSVS	53/52	0.572	8.795	0.026	0.010
J02336+249	GJ 102	02:33:37.17	+24:55:39.2	SuperWASP	5884/5176	4.077	12.404	0.105	0.033
				ASAS	215/196	6.976	13.057	0.143	0.066
				MEarth-2010	111/106	1.282	–0.001	0.007	0.003
				MEarth-2014	166/160	2.369	0.001	0.008	0.004
				NSVS	129/121	0.698	11.733	0.034	0.016
				Catalina	377/349	8.098	11.343	0.112	0.005
J02358+202	BD+19 381	02:35:53.28	+20:13:11.9	SuperWASP	3092/2712	3.904	10.552	0.107	0.025
				ASAS	215/196	6.976	13.057	0.143	0.066
				NSVS	59/58	0.616	9.886	0.027	0.010
J02362+068	BX Cet	02:36:15.36	+06:52:19.1	ASAS	215/196	6.976	13.057	0.143	0.066
J02442+255	VX Ari	02:44:15.38	+25:31:25.0	SuperWASP	2808/2592	4.025	10.443	0.137	0.025
				ASAS	183/174	6.912	10.581	0.037	0.015
J02519+224	RBS 365	02:51:54.09	+22:27:30.0	SuperWASP	3359/3047	4.044	12.541	0.135	0.043
				ASAS	340/322	6.976	13.181	0.153	0.130
J02530+168	Teegarden's Star	02:53:00.85	+16:52:53.3	MEarth-2010	514/506	1.392	0.000	0.010	0.006
				MEarth-2011	528/475	0.713	0.032	0.275	0.005
				MEarth-2010-tel01	2228/2130	2.388	0.000	0.012	0.004
				MEarth-2014-tel08	1719/1688	0.381	0.000	0.011	0.004
J02565+554W	Ross 364	02:56:34.35	+55:26:14.5	SuperWASP	4135/3998	4.041	10.264	0.078	0.023
				NSVS	104/103	0.616	9.508	0.018	0.010
J03133+047	CD Cet	03:13:22.99	+04:46:29.4	ASAS	200/182	8.792	14.103	0.313	0.182
				MEarth-2010	1068/1011	1.170	0.001	0.021	0.003
J03181+382	HD 275122	03:18:07.42	+38:15:08.2	SuperWASP	6609/5222	1.449	10.361	0.077	0.023
J03213+799	GJ 133	03:21:21.76	+79:58:02.2	AstroLAB IRIS	199/195	1.041	11.089	0.022	0.006
				NSVS	195/182	0.679	10.645	0.029	0.011
J03217-066	G 077–046	03:21:46.89	–06:40:24.2	ASAS	488/457	9.030	11.331	0.047	0.021
J03463+262	HD 23453	03:46:20.12	+26:12:56.0	SuperWASP	2315/2097	3.635	9.686	0.061	0.025
				ASAS	226/212	6.978	9.580	0.035	0.015
J03473-019	G 080–021	03:47:23.33	–01:58:19.5	ASAS	376/370	8.896	11.531	0.050	0.021
J03531+625	Ross 567	03:53:10.42	+62:34:08.2	NSVS	195/182	0.679	10.645	0.029	0.011
				AstroLAB IRIS	152/148	1.041	11.494	0.029	0.015
J04153-076	o^{02} Eri C	04:15:21.73	–07:39:17.4	ASAS	190/159	4.370	9.182	0.063	0.040
J04198+425	LSR J0419+4233	04:19:52.13	+42:33:30.5	MEarth-2014-tel05	574/551	4.370	0.000	–0.015	0.008
				MEarth-2014-tel06	1807/1736	2.479	0.000	0.058	0.009
J04225+105	LSPM J0422+1031	04:22:31.99	+10:31:18.8	MEarth-2014	515/491	2.435	0.000	0.009	0.004
				ASAS	355/332	8.817	12.505	0.107	0.048
J04290+219	BD+21 652	04:29:00.14	+21:55:21.5	ASAS	435/396	6.970	8.342	0.074	0.019
				SuperWASP	2151/1707	2.553	8.596	0.118	0.041
J04376+528	BD+52 857	04:37:40.92	+52:53:37.2	SuperWASP	1958/1674	1.443	8.693	0.041	0.047

Table A.1. M dwarfs searched for photometric periods (cont.).

Karmn	Name	α (J2000.0)	δ (J2000.0)	Survey	$N_{\rm obs}/N_{\rm used}$	Δt [a]	$\overline{m}$ [mag]	σ_m [mag]	$\overline{\delta m}$ [mag]
J04376-110	BD–11 916	04:37:41.88	–11:02:19.8	ASAS	545/509	9.035	10.366	0.051	0.020
J04429+189	HD 285968	04:42:55.81	+18:57:28.5	ASAS	459/429	6.970	10.018	0.067	0.018
				K2	3605/3485	0.218	0.879	0.158	...
J04429+214	2M J04425586+2128230	04:42:55.86	+21:28:23.0	ASAS	327/311	6.970	11.965	0.064	0.029
				SuperWASP	2151/1705	2.553	8.496	0.118	0.028
J04472+206	RX J0447.2+2038	04:47:12.25	+20:38:10.9	Montcabrer	192/192	0.033	11.692	0.012	0.005
				K2	3605/3572	0.218	0.975	0.022	...
J04520+064	Wolf 1539	04:52:05.73	+06:28:35.6	ASAS	301/294	8.827	11.208	0.217	0.040
J04538-177	GJ 180	04:53:49.95	–17:46:23.5	ASAS	563/530	9.038	10.897	0.045	0.019
J04588+498	BD+49 1280	04:58:50.58	+49:50:57.3	SuperWASP	3535/2696	3.536	10.039	0.071	0.015
J05019+011	1RXS J050156.7+010845	05:01:56.66	+01:08:42.9	Montcabrer	485/483	0.074	10.467	0.011	0.004
J05019-069	LP 656–038	05:01:57.47	–06:56:45.9	ASAS	619/583	9.027	12.194	0.076	0.038
J05033-173	LP 776–049	05:03:20.10	–17:22:24.5	ASAS	848/809	9.038	11.724	0.051	0.033
J05062+046	RX J0506.2+0439	05:06:12.93	+04:39:27.2	NSVS	182/172	0.556	11.864	0.029	0.018
				ASAS	478/464	8.781	12.706	0.139	0.040
J05084-210	2M J05082729-2101444	05:08:27.30	-21:01:44.4	Catalina	154/139	7.588	13.027	0.079	0.058
J05127+196	GJ 192	05:12:42.23	+19:39:56.6	ASAS	353/340	6.970	10.804	0.065	0.019
J05280+096	Ross 41	05:28:00.15	+09:38:38.3	ASAS	382/368	8.726	12.516	0.098	0.048
				MEarth-2010	842/813	0.512	0.000	0.007	0.003
				MEarth-2011	2311/2221	0.441	0.006	0.131	0.004
				MEarth-2014-tel01	1053/981	2.468	0.000	0.008	0.004
				MEarth-2014-tel05	1107/1014	1.520	0.000	0.009	0.004
J05314-036	HD 36395	05:31:27.35	–03:40:35.7	ASAS	439/412	7.435	7.955	0.034	0.015
J05337+019	V371 Ori	05:33:44.81	+01:56:43.4	ASAS	463/444	8.805	11.318	0.068	0.040
				NSVS	168/158	0.484	10.471	0.027	0.011
				Carda	171/169	0.033	10.88	0.012	0.004
J05348+138	Ross 46	05:34:52.12	+13:52:47.2	ASAS	490/471	6.970	11.859	0.058	0.028
J05360-076	Wolf 1457	05:36:00.08	–07:38:58.1	ASAS	756/711	9.036	12.871	0.126	0.061
				NSVS	162/153	0.468	11.737	0.033	0.020
J05365+113	V2689 Ori	05:36:30.99	+11:19:40.2	ASAS	692/657	8.729	8.889	0.053	0.020
J05366+112	2M J05363846+1117487	05:36:38.47	+11:17:48.8	ASAS	684/646	8.729	12.613	0.140	0.067
				NSVS	207/206	0.972	11.416	0.027	0.016
J05394+406	LSR J0539+4038	05:39:24.74	+40:38:43.8	MEarth-2014-tel04	965/928	1.485	–0.005	0.128	0.007
				MEarth-2014-tel08	1267/1198	2.517	0.000	0.015	0.006
J05415+534	HD 233153	05:41:30.73	+53:29:23.9	NSVS	66/66	0.345	9.145	0.018	0.010
J05421+124	V1352 Ori	05:42:08.98	+12:29:25.3	ASAS	519/499	6.970	11.510	0.050	0.026
				MEarth-2014-tel02	1248/1138	2.506	0.000	0.016	0.005
				NSVS	188/187	0.605	10.317	0.022	0.011
J05532+242	Ross 59 AB	05:53:14.04	+24:15:32.9	SuperWASP	2116/1889	3.591	10.397	0.083	0.033
				ASAS	318/302	6.970	10.824	0.036	0.043
J06000+027	G 099–049	06:00:03.51	+02:42:23.6	MEarth-2010	991/975	0.260	0.000	0.010	0.004
				ASAS	452/418	8.773	11.303	0.048	0.021
J06011+595	G 192–013	06:01:11.07	+59:35:50.8	SuperWASP	580/503	1.517	11.156	0.079	0.026
				MEarth-2010	908/865	0.537	0.000	0.007	0.003
				MEarth-2014	906/852	2.544	0.001	0.013	0.005
				NSVS	217/217	0.989	10.447	0.027	0.011
J06024+498	G 192–015	06:02:29.18	+49:51:56.2	MEarth-2010	1614/1550	1.539	0.000	0.010	0.005
				MEarth-2014	350/329	2.528	0.000	0.008	0.003
				SuperWASP	2913/2577	1.946	12.280	0.127	0.026
J06103+821	GJ 226	06:10:19.78	+82:06:25.7	ASAS-SN	718/698	4.323	10.474	0.023	0.006
J06105-218	HD 42581 A	06:10:34.62	–21:51:52.2	ASAS	750/708	9.041	8.141	0.056	0.019
J06246+234	Ross 64	06:24:41.32	+23:25:58.6	SuperWASP	2766/2393	3.668	12.809	0.118	0.039
				ASAS	315/300	6.967	13.416	0.205	0.045
				MEarth-2010	675/639	0.583	0.000	0.008	0.004
				MEarth-2011	211/205	0.411	0.001	0.010	0.003
				NSVS	201/198	0.536	11.937	0.042	0.024
J06318+414	LP 205–044	06:31:50.74	+41:29:45.9	SuperWASP	6338/5690	3.555	14.621	0.207	0.143
				MEarth-2010	142/136	1.478	0.000	0.010	0.004
				MEarth-2011	519/475	0.364	0.001	0.010	0.003
J06371+175	HD 260655	06:37:10.92	+17:33:52.7	ASAS	565/532	6.970	9.606	0.040	0.019
J06396-210	LP 780–032	06:39:37.42	–21:01:33.3	ASAS	1046/981	9.041	12.617	0.107	0.096
				NSVS	126/121	0.410	11.522	0.030	0.019
J06421+035	G 108–021	06:42:11.18	+03:34:52.7	MEarth-2011	3763/3663	0.462	0.000	0.010	0.004
				MEarth-2014	500/465	2.481	0.001	0.015	0.004
				ASAS	486/475	8.581	11.999	0.079	0.043
J06548+332	Wolf 294	06:54:49.03	+33:16:05.9	SuperWASP	4132/3409	3.618	10.075	0.075	0.019
J06574+740	2M J06572616+7405265	06:57:26.16	+74:05:26.5	NSVS	307/285	0.983	11.948	0.033	0.023
				Carda	567/567	0.020	12.41	0.017	0.007
J06594+193	GJ 1093	06:59:28.69	+19:20:57.7	ASAS	447/423	6.970	11.432	0.073	0.023
				NSVS	130/127	4.474	11.148	0.022	0.015
J07001-190	2M J07000682-1901235	07:00:06.83	–19:01:23.6	ASAS	572/549	9.041	13.236	0.144	0.044
J07033+346	LP 255–011	07:03:23.17	+34:41:51.0	SuperWASP	4273/3855	1.422	13.312	0.108	0.025
				MEarth-2014	437/426	2.550	0.000	0.008	0.003
				NSVS	186/186	0.490	11.872	0.029	0.017
				Catalina	271/245	8.442	11.822	0.098	0.050
J07044+682	GJ 258	07:04:25.94	+68:17:19.6	NSVS	169/169	0.391	11.061	0.027	0.013
J07274+052	Luyten's Star	07:27:24.50	+05:13:32.9	ASAS	394/365	8.036	9.889	0.089	0.023
J07287-032	GJ 1097	07:28:45.41	–03:17:52.4	ASAS	519/497	8.956	11.497	0.045	0.030
J07319+362N	BL Lyn	07:31:57.35	+36:13:47.8	SuperWASP	8710/8313	3.643	10.381	0.065	0.022
J07353+548	GJ 3452	07:35:21.88	+54:50:59.0	SuperWASP	3527/2868	2.033	11.363	0.206	0.025
				NSVS	303/299	0.989	10.512	0.021	0.011
J07361-031	BD–02 2198	07:36:07.08	–03:06:38.5	ASAS	471/448	8.956	9.848	0.056	0.026
J07386-212	LP 763–001	07:38:40.89	–21:13:27.6	ASAS	765/709	9.038	11.675	0.057	0.037
J07393+021	BD+02 1729	07:39:23.04	+02:11:01.2	ASAS	487/469	8.956	9.591	0.036	0.017
J07403-174	LP 783–002	07:40:19.22	-17:24:44.9	ASAS	553/539	9.033	12.333	0.171	0.040
J07446+035	YZ CMi	07:44:40.18	+03:33:09.0	MEarth-2010	986/941	1.416	0.001	0.032	0.004
				ASAS	551/529	8.732	11.238	0.091	0.025
J07472+503	2M J07471385+5020386	07:47:13.85	+50:20:38.5	SuperWASP	3072/2714	2.033	12.961	0.122	0.098
				NSVS	282/266	0.973	11.865	0.031	0.017
J07558+833	GJ 1101	07:55:53.97	+83:23:05.0	MEarth-2014	775/728	2.660	0.001	0.011	0.005
				MEarth-2010	315/300	0.665	0.000	0.009	0.003
				NSVS	168/162	0.334	11.800	0.038	0.018

Table A.1. M dwarfs searched for photometric periods (cont.).

Karmn	Name	α (J2000.0)	δ (J2000.0)	Survey	$N_{\rm obs}/N_{\rm used}$	Δt [a]	$\overline{m}$ [mag]	σ_m [mag]	$\overline{\delta m}$ [mag]
J07582+413	GJ 1105	07:58:12.70	+41:18:13.5	SuperWASP	7377/6608	3.599	11.866	0.100	0.032
				MEarth-2010	1193/1152	0.501	0.000	0.010	0.003
				MEarth-2014	810/748	2.602	0.001	0.012	0.005
J08119+087	Ross 619	08:11:57.58	+08:46:22.1	MEarth-2010	889/848	1.288	0.000	0.021	0.004
				MEarth-2011	923/877	0.528	0.001	0.013	0.003
				MEarth-2014	114/110	2.563	0.000	0.008	0.003
				ASAS	119/107	3.929	12.876	0.106	0.060
J08126-215	GJ 300 AB	08:12:40.88	–21:33:05.7	ASAS	779/729	9.016	12.079	0.104	0.043
J08161+013	GJ 2066	08:16:07.98	+01:18:09.2	ASAS	575/540	8.978	10.101	0.080	0.017
J08293+039	2M J08292191+0355092	08:29:21.92	+03:55:09.3	ASAS	392/372	8.580	11.400	0.074	0.023
				NSVS	165/163	0.973	10.615	0.018	0.011
J08298+267	DX Cnc	08:29:49.50	+26:46:34.8	MEarth-2014-tel01	4225/4102	2.574	0.001	0.012	0.004
				MEarth-2014-tel03	3929/3792	1.602	0.000	0.013	0.004
				MEarth-2010	1253/1227	1.608	0.000	0.014	0.005
				SuperWASP	10302/9327	3.599	12.739	0.058	0.035
J08315+730	LP 035–219	08:31:30.11	+73:03:45.9	MEarth-2014-tel04	15475/14901	2.660	0.000	0.009	0.004
				MEarth-2014-tel06	121/120	0.959	0.002	0.009	0.004
				NSVS	297/279	0.990	11.809	0.029	0.018
J08358+680	G 234–037	08:35:49.16	+68:04:09.7	NSVS	293/277	0.990	10.755	0.023	0.012
J08402+314	LSPM J0840+3127	08:40:15.97	+31:27:06.8	SuperWASP	6126/5316	3.569	12.022	0.076	0.024
				MEarth-2014	9913/9392	2.618	0.000	0.009	0.005
				NSVS	105/105	0.457	11.204	0.027	0.012
				Catalina	430/383	8.471	11.006	0.125	0.050
J08413+594	LP 090–018	08:41:20.13	+59:29:50.6	SuperWASP	527/486	1.055	14.488	0.194	0.147
				MEarth-2014	2019/1958	2.649	0.000	0.012	0.003
				MEarth-2011	153/148	0.304	0.000	0.011	0.003
				MEarth-2010	1310/1295	1.684	0.000	0.010	0.004
J08526+283	ρ^{01} Cnc B	08:52:40.85	+28:18:58.9	MEarth-2014-tel02	864/826	2.621	0.000	0.012	0.004
				MEarth-2014-tel04	404/390	0.126	0.001	0.015	0.004
				MEarth-2010	1053/1001	0.643	0.000	0.008	0.002
				ASAS	84/84	1.394	12.532	0.185	0.042
J08536-034	LP 666–009	08:53:36.20	–03:29:32.1	Montcabrer	43/41	0.195	14.496	0.022	0.017
J09003+218	LP 368-128	09:00:23.59	+21:50:05.4	SuperWASP	12255/11262	3.643	15.586	0.487	0.467
				MEarth-2010	1201/1154	0.356	0.000	0.011	0.004
				NSVS	155/152	0.984	13.606	0.078	0.071
				Catalina	522/471	8.551	13.427	0.058	0.050
J09005+465	GJ 1119	09:00:32.54	+46:35:11.8	MEarth-2014	1213/1136	1.600	0.003	0.025	0.005
				MEarth-2010	142/137	0.630	0.001	0.008	0.004
				NSVS	222/213	0.983	11.907	0.028	0.016
				Catalina	210/190	7.888	11.911	0.090	0.050
J09028+680	LP 060–179	09:02:52.85	+68:03:46.4	MEarth-2014	329/317	2.660	0.000	0.009	0.004
				NSVS	204/203	0.392	10.908	0.017	0.012
J09033+056	NLTT 20861	09:03:20.96	+05:40:14.5	MEarth-2010	565/533	2.060	0.003	0.051	0.007
				Catalina	318/299	7.937	14.449	0.024	0.059
J09133+688	G 234–057	09:13:23.83	+68:52:30.5	NSVS	267/245	0.984	10.450	0.018	0.011
J09140+196	LP 427–016	09:14:03.21	+19:40:06.0	ASAS	335/310	6.410	12.199	0.082	0.037
				NSVS	199/194	0.984	11.220	0.024	0.012
J09144+526	HD 79211	09:14:24.86	+52:41:11.8	...	...	...	...	...	...
J09161+018	RX J0916.1+0153	09:16:10.19	+01:53:08.8	Catalina	303/288	7.951	11.774	0.110	0.050
				ASAS	448/423	8.953	12.925	0.200	0.097
				NSVS	156/151	0.973	11.760	0.034	0.014
J09163-186	LP 787–052	09:16:20.66	–18:37:32.9	ASAS	824/735	9.038	10.570	0.072	0.043
J09307+003	GJ 1125	09:30:44.58	+00:19:21.4	ASAS	371/346	8.534	11.104	0.211	0.040
				MEarth-2010	728/701	0.602	0.000	0.010	0.003
				MEarth-2014	1096/1032	2.574	0.000	0.011	0.006
J09360-216	GJ 357	09:36:01.61	–21:39:37.1	ASAS	591/555	9.027	10.907	0.036	0.017
				NSVS	79/79	0.380	10.067	0.022	0.011
J09411+132	Ross 85	09:41:10.33	+13:12:34.4	ASAS	311/293	6.967	10.361	0.026	0.017
J09423+559	GJ 363	09:42:23.28	+55:59:01.6	MEarth-2010	1777/1742	2.071	0.001	0.009	0.003
				MEarth-2014	516/495	2.673	0.001	0.010	0.005
				SuperWASP	2563/2099	0.553	12.396	0.222	0.048
				NSVS	143/142	0.989	11.439	0.045	0.014
J09425+700	GJ 360	09:42:34.94	+70:02:02.4	AstroLAB IRIS	164/161	0.827	9.530	0.025	0.012
J09428+700	GJ 362	09:42:51.82	+70:02:22.2	AstroLAB IRIS	210/204	0.827	10.089	0.023	0.011
J09439+269	Ross 93	09:43:55.63	+26:58:08.6	Montcabrer	1042/975	0.214	9.814	0.008	0.004
J09447-182	GJ 1129	09:44:47.31	–18:12:48.9	ASAS	593/557	9.038	12.249	0.087	0.040
				NSVS	137/133	0.984	11.100	0.026	0.013
J09449-123	G 161–071	09:44:54.22	–12:20:54.4	ASAS	369/356	8.430	13.427	0.193	0.173
				NSVS	142/120	0.984	11.990	0.045	0.020
				Catalina	174/165	7.192	11.906	0.090	0.050
J09468+760	BD+76 3952	09:46:48.45	+76:02:38.8	Montsec	525/508	0.910	10.06	0.006	0.001
J09511-123	BD-11 2741	09:51:09.64	–12:19:47.8	ASAS	801/764	9.041	10.018	0.033	0.016
J09561+627	BD+63 869	09:56:08.69	+62:47:18.6	ASAS-SN	694/684	5.288	9.422	0.132	0.004
J10023+480	BD+48 1829	10:02:21.84	+48:05:20.9	SuperWASP	446/446	2.101	10.141	0.120	0.005
				NSVS	39/37	0.855	9.462	0.020	0.010
J10122-037	AN Sex	10:12:17.69	–03:44:44.1	ASAS	511/493	9.025	9.244	0.038	0.016
J10125+570	LP 092–048	10:12:34.81	+57:03:49.6	SuperWASP	169/163	0.011	11.670	0.019	0.017
				NSVS	162/156	0.989	10.663	0.039	0.011
J10167-119	GJ 386	10:16:46.00	–11:57:41.3	ASAS	568/537	9.038	11.014	0.035	0.018
J10182-204	NLTT 23956 AB	10:18:13.88	–20:28:41.4	ASAS	291/270	8.484	14.087	0.334	0.195
J10251-102	BD–09 3070	10:25:10.88	–10:13:43.4	ASAS	664/602	9.033	10.153	0.020	0.021
J10289+008	BD+01 2447	10:28:55.55	+00:50:27.5	ASAS	413/382	8.636	9.630	0.053	0.016
J10350-094	LP 670–017	10:35:01.11	–09:24:38.5	ASAS	499/475	9.008	12.064	0.067	0.048
				Catalina	185/175	7.318	10.934	0.163	0.050
J10354+694	LP 037–179 AB	10:35:27.26	+69:26:59.5	NSVS	163/151	0.984	10.917	0.026	0.012
J10360+051	RY Sex	10:36:01.21	+05:07:12.8	ASAS	328/311	7.751	12.677	0.103	0.045
				Catalina	405/366	8.570	11.322	0.156	0.050
J10396-069	GJ 399	10:39:40.61	–06:55:25.6	ASAS	666/628	9.008	11.300	0.049	0.022
				NSVS	125/122	0.378	10.463	0.021	0.011
J10416+376	GJ 1134	10:41:38.10	+37:36:39.8	SuperWASP	4712/4062	4.044	12.514	0.189	0.029
				MEarth-2010	1382/1347	0.684	0.002	0.083	0.004
				MEarth-2014	224/211	2.701	0.000	0.009	0.004

Table A.1. M dwarfs searched for photometric periods (cont.).

Karmn	Name	α (J2000.0)	δ (J2000.0)	Survey	$N_{\rm obs}/N_{\rm used}$	Δt [a]	$\overline{m}$ [mag]	σ_m [mag]	$\overline{\delta m}$ [mag]
J10482-113	LP 731–058	10:48:12.58	–11:20:08.2	NSVS	110/109	0.984	13.066	0.038	0.034
				Catalina	127/116	5.169	12.731	0.092	0.050
J10504+331	G 119–037	10:50:26.00	+33:06:05.2	SuperWASP	5090/4563	4.044	12.723	0.058	0.028
J10508+068	EE Leo	10:50:52.01	+06:48:29.3	K2	3538/3538	0.214	1.001	0.004	...
				ASAS	357/344	7.926	11.719	0.048	0.026
				NSVS	145/144	0.976	10.446	0.026	0.011
J10564+070	CN Leo	10:56:28.86	+07:00:52.8	K2	3408/3362	0.212	1.000	0.006	...
				MEarth-2010	773/692	0.610	0.004	0.019	0.005
				MEarth-2014-tel01	2470/2318	2.618	0.001	0.019	0.006
				MEarth-2014-tel04	2431/2281	0.640	0.000	0.016	0.006
J10584-107	LP 731–076	10:58:28.00	-10:46:30.5	Catalina	324/310	7.597	12.505	0.398	0.051
J11000+228	Ross 104	11:00:04.32	+22:49:59.3	ASAS	292/273	6.523	10.025	0.015	0.019
				SuperWASP	8397/7293	4.044	9.983	0.056	0.013
J11026+219	DS Leo	11:02:38.33	+21:58:01.7	SuperWASP	12026/11565	4.044	9.731	0.074	0.011
J11033+359	Lalande 21185	11:03:20.24	+35:58:11.8	ASAS-SN	768/688	4.786	8.080	0.246	0.003
J11054+435	BD+44 2051A	11:05:29.03	+43:31:35.7	MEarth-2010	2726/2683	1.714	0.001	0.059	0.003
				MEarth-2014-tel04	542/491	2.690	–0.030	0.025	0.002
				MEarth-2014-tel07	387/367	0.468	-0.036	0.168	0.002
J11055+435	WX UMa	11:05:31.33	+43:31:17.1	MEarth-2010	2726/2559	1.714	0.001	0.058	0.005
				MEarth-2014	542/505	2.692	–0.001	0.010	0.003
J11110+304	HD 97101 B	11:11:02.46	+30:26:41.6	...	...	...	...	...	...
J11126+189	StKM 1–928	11:12:38.99	+18:56:05.4	ASAS	568/530	6.532	10.761	0.056	0.021
				Catalina	253/235	7.677	11.823	0.738	0.050
J11201-104	LP 733-099	11:20:06.10	–10:29:46.8	ASAS	380/363	8.674	11.212	0.051	0.043
				Catalina	56/55	6.997	10.269	0.069	0.050
J11289+101	Wolf 398	11:28:56.24	+10:10:39.5	MEarth-2010	3179/3017	1.613	0.000	0.007	0.004
				MEarth-2014	945/896	2.635	–0.001	0.010	0.005
J11302+076	K2–18	11:30:14.44	+07:35:16.3	K2	3313/3313	0.219	1.000	0.005	...
				ASAS	338/331	8.038	13.555	0.204	0.100
				Catalina	362/283	8.104	12.394	0.142	0.050
J11306-080	LP 672–042	11:30:41.80	–08:05:42.6	ASAS	489/458	8.704	12.043	0.070	0.031
J11417+427	Ross 1003	11:41:44.72	+42:45:07.3	HATNet	9096/8944	0.446	9.312	0.008	0.008
				SuperWASP	5780/4903	4.044	11.438	0.154	0.022
				NSVS	156/152	0.983	10.739	0.046	0.011
J11421+267	Ross 905	11:42:10.96	+26:42:25.1	SuperWASP	5425/5392	4.036	10.372	0.100	0.019
				ASAS	213/204	6.529	10.644	0.060	0.016
				NSVS	80/77	0.959	9.732	0.035	0.010
J11467-140	GJ 443	11:46:42.82	–14:00:50.5	ASAS	519/484	8.693	11.696	0.048	0.024
				NSVS	82/76	0.923	10.818	0.023	0.011
J11474+667	1RXS J114728.8+664405	11:47:28.57	+66:44:02.6	NSVS	196/185	0.975	13.089	0.060	0.043
				Catalina	67/67	7.211	13.000	0.084	0.050
J11476+002	LP 613–049 A	11:47:40.74	+00:15:20.2	K2	3344/3323	0.219	1.005	0.018	...
				MEarth-2010	675/667	0.599	–0.001	0.019	0.002
				MEarth-2014	848/791	2.602	–0.002	0.023	0.004
				ASAS	348/337	8.679	13.346	0.149	0.068
J11476+786	GJ 445	11:47:41.44	+78:41:28.3	Montsec	627/567	0.912	10.22	0.001	0.003
J11477+008	FI Vir	11:47:44.40	+00:48:16.4	ASAS	386/369	8.681	11.127	0.042	0.018
				MEarth-2014-tel07	786/718	1.118	–0.001	0.020	0.008
				MEarth-2014-tel08	824/776	0.618	–0.001	0.036	0.008
				K2	3203/3203	0.219	1.001	0.004	...
J11509+483	GJ 1151	11:50:57.88	+48:22:39.6	MEarth-2010	1760/1694	0.624	0.000	0.007	0.003
J11511+352	BD+36 2219	11:51:07.37	+35:16:18.9	SuperWASP	4937/4083	4.044	9.676	0.158	0.019
J12054+695	Ross 689	12:05:29.75	+69:32:22.7	MEarth-2010	1726/1685	0.668	0.003	0.105	0.003
J12100-150	LP 734–032	12:10:05.60	–15:04:15.7	ASAS	498/473	9.022	12.100	0.058	0.028
J12111-199	LTT 4562	12:11:11.80	–19:57:37.7	ASAS	529/502	9.025	11.719	0.054	0.026
J12123+544S	HD 238090	12:12:20.85	+54:29:08.7	MEarth-2010	1508/1499	0.649	–0.005	0.032	0.002
				MEarth-2014-tel05	232/194	2.665	0.000	0.014	0.003
J12156+526	StKM 2–809	12:15:39.37	+52:39:08.9	SuperWASP	214/207	2.101	12.485	0.083	0.040
				NSVS	160/148	0.975	11.512	0.034	0.015
				Catalina	165/153	7.522	11.424	0.165	0.050
J12189+111	GL Vir	12:18:59.40	+11:07:33.9	MEarth-2010	1374/1355	1.594	0.001	0.014	0.004
J12230+640	Ross 690	12:23:00.25	+64:01:50.6	NSVS	251/245	0.983	10.688	0.025	0.011
J12248-182	Ross 695	12:24:52.43	–18:14:30.3	ASAS	117/117	5.433	10.022	0.397	0.036
J12312+086	BD+09 2636	12:31:15.79	+08:48:38.1	ASAS	463/428	8.096	9.679	0.069	0.016
J12350+098	GJ 476	12:35:00.70	+09:49:42.5	ASAS	379/366	8.033	11.427	0.042	0.021
				NSVS	177/176	0.984	10.637	0.023	0.011
J12373-208	LP 795–038	12:37:21.57	–20:52:34.9	ASAS	579/557	8.690	13.354	0.191	0.095
				NSVS	96/91	0.984	12.147	0.038	0.021
				Catalina	238/230	7.976	11.906	0.031	0.050
J12388+116	Wolf 433	12:38:52.42	+11:41:46.2	ASAS	339/320	8.005	11.521	0.043	0.023
				NSVS	187/182	0.984	10.500	0.025	0.011
J12428+418	G 123–055	12:42:49.96	+41:53:46.9	SuperWASP	7095/6444	4.044	11.904	0.085	0.027
J12479+097	Wolf 437	12:47:56.64	+09:45:05.0	ASAS	352/336	8.033	11.410	0.066	0.022
				NSVS	177/165	0.984	10.282	0.032	0.010
J13005+056	FN Vir	13:00:33.51	+05:41:08.1	MEarth-2010	1318/1269	1.591	0.000	0.007	0.003
				MEarth-2014-tel02	1010/968	2.594	0.002	0.009	0.004
				MEarth-2014-tel08	1142/1099	1.203	–0.001	0.009	0.004
J13102+477	G 177–025	13:10:12.69	+47:45:19.0	MEarth-2011	878/788	0.670	0.001	0.042	0.004
				MEarth-2014-tel04	2183/2125	2.624	0.000	0.012	0.003
				MEarth-2014-tel05	1956/1898	0.621	0.000	0.011	0.004
				Catalina	151/147	7.625	12.899	0.093	0.050
J13196+333	Ross 1007	13:19:40.15	+33:20:47.8	SuperWASP	14259/12982	3.077	10.673	0.048	0.016
				NSVS	46/45	0.855	9.863	0.026	0.011
				Catalina	212/187	7.123	11.612	0.764	0.050
J13209+342	BD+35 2439	13:20:57.97	+34:16:44.7	SuperWASP	11384/9494	3.118	10.696	0.0067	0.018
				NSVS	54/54	0.855	9.912	0.034	0.011
J13229+244	Ross 1020	13:22:56.74	+24:28:03.4	SuperWASP	7738/7005	3.077	12.716	0.079	0.033
				MEarth-2010	757/733	1.479	0.000	0.009	0.004
				MEarth-2014	309/303	2.591	0.000	0.009	0.004
J13283-023W	Ross 486A	13:28:21.06	–02:21:36.5	ASAS	351/333	8.667	11.236	0.042	0.018
J13293+114	GJ 513	13:29:21.31	+11:26:26.5	ASAS	338/318	7.970	12.150	0.073	0.033
				MEarth-2014	248/214	2.506	0.004	0.016	0.002

Table A.1. M dwarfs searched for photometric periods (cont.).

Karmn	Name	α (J2000.0)	δ (J2000.0)	Survey	$N_{\rm obs}/N_{\rm used}$	Δt [a]	$\overline{m}$ [mag]	σ_m [mag]	$\overline{\delta m}$ [mag]
				NSVS	133/127	0.983	11.180	0.026	0.013
				Catalina	301/283	7.189	11.055	0.109	0.050
J13299+102	BD+11 2576	13:29:59.79	+10:22:37.6	ASAS	568/537	9.038	11.014	0.035	0.018
J13427+332	Ross1015	13:42:43.29	+33:17:25.5	SuperWASP	7630/7592	3.118	11.846	0.109	0.021
J13450+176	BD+18 2776	13:45:05.03	+17:47:10.5	ASAS-SN	795/771	5.093	14.076	0.686	0.033
J13457+148	HD 119850	13:45:43.54	+14:53:31.8	ASAS	314/281	6.547	8.456	0.036	0.015
J13458-179	LP 798–034	13:45:50.75	–17:58:04.8	ASAS	479/467	8.720	11.865	0.047	0.024
				K2	3530/3530	0.215	0.997	0.005	...
J13536+776	RX J1353.6+7737	13:53:38.77	+77:37:08.3	MEarth-2010	4253/4159	1.501	0.001	0.013	0.004
J13582+125	Ross 837	13:58:13.93	+12:34:43.8	ASAS	400/381	7.978	11.011	0.023	0.037
				Catalina	335/314	8.186	11.047	0.216	0.050
J13591-198	LP 799–007	13:59:10.46	–19:50:03.5	ASAS	522/512	8.719	12.701	0.104	0.040
				Catalina	125/120	4.789	11.291	0.131	0.050
				Montcabrer	197/190	0.134	10.674	0.023	0.003
J14010-026	HD 122303	14:01:03.25	–02:39:18.1	ASAS	367/354	8.640	9.708	0.017	0.013
J14082+805	BD+81 465	14:08:12.98	+80:35:50.0	NSVS	60/58	0.973	9.716	0.021	0.010
				Montsec	625/595	0.912	9.77	0.390	0.008
J14152+450	Ross 992	14:15:17.07	+45:00:53.6	SuperWASP	6217/5775	2.129	11.847	0.049	0.019
J14155+046	GJ 1182 AB	14:15:32.54	+04:39:31.2	MEarth-2014	1203/1146	2.468	0.001	0.040	0.003
J14173+454	RX J1417.3+4525	14:17:22.10	+45:25:46.1	SuperWASP	5939/5899	2.128	11.916	0.167	0.021
				Catalina	176/170	8.090	12.705	0.117	0.050
J14251+518	θ Boo B	14:25:11.61	+51:49:53.5	...	...	...	...	...	...
J14257+236W	BD+24 2733A	14:25:43.49	+23:37:01.1	SuperWASP	6583/6408	3.918	9.339	0.114	0.016
J14257+236E	BD+24 2733B	14:25:46.67	+23:37:13.3	SuperWASP	5013/4609	3.918	8.806	0.100	0.018
J14294+155	Ross 130	14:29:29.72	+15:31:57.9	ASAS	333/317	6.547	10.678	0.033	0.016
J14307-086	BD–07 3856	14:30:47.79	–08:38:46.6	ASAS	420/390	8.695	9.378	0.027	0.015
J14310-122	Wolf 1478	14:31:01.20	–12:17:45.2	ASAS	461/440	8.706	11.900	0.054	0.037
				NSVS	108/106	0.984	10.838	0.026	0.012
J14321+081	LP 560–035	14:32:08.50	+08:11:31.3	MEarth-2010	1394/1334	1.539	0.000	0.014	0.006
				MEarth-2014	557/529	0.482	0.001	0.017	0.006
				Catalina	377/363	8.194	13.622	0.027	0.050
J14342-125	HN Lib	14:34:16.83	–12:31:10.7	ASAS	513/477	8.728	11.339	0.037	0.019
J14524+123	G 066–037	14:52:28.54	+12:23:33.0	ASAS	406/396	7.978	11.578	0.047	0.022
				NSVS	188/179	0.984	10.727	0.027	0.011
J14544+355	Ross 1041	14:54:27.91	+35:32:57.0	SuperWASP	13711/12351	3.962	12.188	0.071	0.028
				MEarth-2010	187/178	0.528	0.000	0.006	0.003
				MEarth-2014	334/318	2.556	0.000	0.008	0.004
				NSVS	224/217	0.984	11.254	0.034	0.012
				Catalina	277/261	8.167	11.113	0.129	0.050
J15013+055	G 015–002	15:01:20.11	+05:32:55.4	ASAS	362/342	8.022	12.144	0.064	0.029
J15095+031	Ross 1047	15:09:35.59	+03:10:00.8	ASAS	550/505	8.682	11.509	0.075	0.028
J15194-077	HO Lib	15:19:26.89	–07:43:20.1	ASAS	742/685	8.711	10.574	0.046	0.014
J15218+209	OT Ser	15:21:52.92	+20:58:39.5	SuperWASP	15065/13716	3.153	10.048	0.047	0.013
				ASAS	300/288	6.447	10.013	0.055	0.015
J15305+094	NLTT 40406	15:30:30.33	+09:26:01.4	MEarth-2010	762/703	4.060	0.000	0.011	0.006
				Catalina	370/349	8.197	13.096	0.051	0.050
J15369-141	Ross 802	15:36:58.68	–14:08:00.6	ASAS	476/456	8.176	12.771	0.113	0.055
J15412+759	UU UMi AB	15:41:16.43	+75:59:34.8	MEarth-2010	1432/1405	2.047	0.000	0.011	0.003
				MEarth-2014	1047/975	2.696	0.000	0.029	0.006
J15474-108	LP 743–031 AB	15:47:24.64	–10:53:47.1	ASAS	472/444	8.717	11.310	0.070	0.021
J15499+796	LP 022–420	15:49:55.18	+79:39:51.7	MEarth-2010	229/215	1.992	0.000	0.014	0.004
				MEarth-2014	156/143	2.690	–0.001	0.009	0.003
				NSVS	239/226	0.984	13.144	0.049	0.038
J15598-082	BD–07 4156	15:59:53.37	–08:15:11.4	ASAS	465/425	8.716	10.478	0.043	0.022
J16028+205	GJ 609	16:02:50.98	+20:35:21.8	ASAS	299/285	6.465	12.639	0.099	0.047
				MEarth-2010	209/209	1.995	0.000	0.007	0.003
				MEarth-2014	376/356	2.495	0.000	0.009	0.004
J16092+093	G 137–084	16:09:16.25	+09:21:07.7	ASAS	348/340	8.074	11.083	0.027	0.021
J16102-193	K2–33	16:10:14.74	-19:19:09.5	K2	3341/3341	0.212	0.000	0.0087	...
				NSVS	175/166	0.984	10.478	0.028	0.011
J16167+672S	HD 147379	16:16:42.80	+67:14:19.7	ASAS-SN	759/722	5.836	8.874	0.084	0.005
				AstroLAB IRIS	37/36	0.3046	8.436	0.013	0.012
J16167+672N	EW Dra	16:16:45.37	+67:15:22.4	AstroLAB IRIS	71/68	0.556	10.615	0.013	0.006
J16254+543	GJ 625	16:25:24.59	+54:18:14.9	SuperWASP	19221/16794	2.312	10.205	0.084	0.049
J16303-126	V2306 Oph	16:30:18.09	–12:39:43.4	ASAS	538/497	8.659	10.124	0.041	0.017
J16313+408	G 180–060	16:31:18.79	+40:51:51.6	HATNet	8406/8202	0.482	10.695	0.023	0.022
				SuperWASP	25811/23475	4.255	14.458	0.129	0.104
				MEarth-2010	1249/1231	1.036	0.000	0.012	0.004
				NSVS	256/237	0.983	13.104	0.078	0.049
				Catalina	337/292	8.386	13.008	0.092	0.050
J16327+126	GJ 1203	16:32:45.25	+12:36:46.0	ASAS	385/372	6.592	12.187	0.072	0.034
J16462+164	LP 446–006	16:46:13.72	+16:28:40.7	ASAS	442/418	6.589	11.671	0.065	0.027
J16554-083N	GJ 643	16:55:25.27	–08:19:20.8	ASAS	426/391	8.665	11.769	0.085	0.059
J16555-083	vB 8	16:55:35.29	–08:23:40.1	Catalina	189/171	7.178	13.440	0.067	0.050
				NSVS	73/68	0.929	13.829	0.093	0.110
J16570-043	LP 686–027	16:57:05.71	–04:20:56.0	NSVS	120/120	0.973	11.177	0.026	0.015
				ASAS	443/410	8.626	12.286	0.059	0.034
J16581+257	BD+25 3173	16:58:08.85	+25:44:39.2	ASAS	233/219	6.566	9.665	0.052	0.012
J17033+514	G 203–042	17:03:23.85	+51:24:21.9	SuperWASP	27968/26084	2.339	13.507	0.070	0.051
				ASAS-SN	535/524	2.670	13.943	0.062	0.028
J17052-050	Wolf 636	17:05:13.84	–05:05:38.6	ASAS	542/519	8.665	10.103	0.027	0.015
J17071+215	Ross 863	17:07:07.52	+21:33:14.4	SuperWASP	13190/10764	2.942	11.702	0.126	0.024
				ASAS	235/221	6.564	11.641	0.047	0.020
				NSVS	142/134	4.466	10.674	0.036	0.012
J17115+384	Wolf 654	17:11:34.72	+38:26:34.1	SuperWASP	23748/22484	2.339	11.712	0.033	0.022
J17166+080	GJ 2128	17:16:40.97	+08:03:30.2	ASAS	482/460	8.110	11.477	0.047	0.022
J17198+417	GJ 671	17:19:52.67	+41:42:51.1	SuperWASP	37833/33620	4.244	11.471	0.044	0.017
J17303+055	BD+05 3409	17:30:22.73	+05:32:54.7	ASAS	358/336	7.901	9.300	0.036	0.014
J17338+169	1RXS J173353.5+165515	17:33:53.15	+16:55:12.9	MEarth-2010	685/685	2.027	0.000	0.024	0.003
				NSVS	215/205	0.964	12.640	0.066	0.043
J17355+616	BD+61 1678C	17:35:34.46	+61:40:54.0	Montsec	642/613	0.912	9.410	0.016	0.002
J17378+185	BD+18 3421	17:37:53.30	+18:35:29.5	ASAS	592/559	6.566	9.577	0.030	0.013

Table A.1. M dwarfs searched for photometric periods (cont.).

Karmn	Name	α (J2000.0)	δ (J2000.0)	Survey	$N_{\rm obs}/N_{\rm used}$	Δt [a]	$\overline{m}$ [mag]	σ_m [mag]	$\overline{\delta m}$ [mag]
J17542+073	GJ 1222	17:54:17.10	+07:22:44.7	ASAS	414/387	8.000	13.256	0.142	0.085
				MEarth-2010	638/613	2.047	0.000	0.007	0.002
				MEarth-2014	689/668	2.701	0.000	0.008	0.004
J17578+046	Barnard's Star	17:57:48.49	+04:41:40.5	MEarth-2010	900/852	0.621	0.001	0.021	0.010
				MEarth-2014	1045/992	2.705	–0.002	0.040	0.014
				ASAS-SN	535/528	2.715	9.560	0.032	0.005
J17578+465	G 204–039	17:57:50.96	+46:35:18.2	SuperWASP	14884/13911	4.244	11.576	0.077	0.017
				HATNet	8832/8639	0.758	8.920	0.005	0.003
J18022+642	LP 071–082	18:02:16.60	+64:15:44.6	MEarth-2010	286/274	1.981	0.000	0.011	0.005
				MEarth-2011	1813/1763	0.638	0.000	0.014	0.004
				MEarth-2014-tel01	416/396	2.688	0.000	0.010	0.004
				MEarth-2014-tel05	253/236	1.432	0.000	0.011	0.004
				NSVS	268/258	0.975	11.848	0.041	0.017
J18027+375	GJ 1223	18:02:46.25	+37:31:04.9	SuperWASP	20385/17417	4.274	14.651	0.110	0.163
				MEarth-2010	694/681	1.926	0.000	0.009	0.004
				MEarth-2014-tel03	1051/1027	2.693	–0.001	0.008	0.003
				MEarth-2014-tel08	792/772	1.301	0.000	0.008	0.003
J18051-030	HD 165222	18:05:07.56	–03:01:52.4	ASAS	427/384	8.622	9.383	0.036	0.016
J18075-159	GJ 1224	18:07:32.93	–15:57:46.5	K2	2783/2758	0.187	1.000	0.004	...
				ASAS	510/491	8.693	13.875	0.235	0.175
J18131+260	LP 390–016	18:13:06.57	+26:01:51.9	MEarth	1021/998	2.682	–0.006	0.017	0.004
				SuperWASP	5476/5040	3.279	12.981	0.066	0.041
				HATNet	8881/8764	0.315	9.954	0.042	0.006
J18165+048	G 140–051	18:16:31.54	+04:52:45.6	MEarth-2010	302/300	1.640	0.000	0.009	0.003
				MEarth-2014	385/363	2.694	0.000	0.012	0.004
J18174+483	TYC 3529–1437–1	18:17:25.14	+48:22:02.4	SuperWASP	18943/18229	4.274	11.204	0.056	0.026
J18180+387E	G 204–058	18:18:04.28	+38:46:34.2	SuperWASP	15282/14479	4.244	11.813	0.054	0.028
J18189+661	LP 071–165	18:18:57.26	+66:11:33.2	MEarth-2010	863/832	1.663	0.000	0.009	0.005
				MEarth-2014-tel03	1873/1769	2.690	0.000	0.010	0.004
				MEarth-2014-tel05	1694/1620	0.776	0.000	0.015	0.004
				NSVS	229/210	0.976	12.026	0.035	0.020
J18198-019	HD 168442	18:19:50.85	-01:56:19.1	ASAS	510/504	8.674	9.652	0.019	0.016
J18221+063	Ross 136	18:22:06.71	+06:20:37.7	MEarth-2010	600/578	0.723	0.000	0.006	0.002
				MEarth-2014	464/445	2.701	0.000	0.010	0.004
				ASAS	419/394	8.003	12.611	0.100	0.055
J18224+620	GJ 1227	18:22:27.19	+62:03:02.5	MEarth-2010	1205/1181	0.688	0.001	0.009	0.003
				MEarth-2014-tel03	385/373	2.682	0.000	0.023	0.005
				MEarth-2014-tel08	169/160	0.288	–0.002	0.014	0.004
J18319+406	G 205–028	18:31:58.40	+40:41:10.4	SuperWASP	18751/18037	4.274	11.542	0.038	0.017
J18346+401	LP 229–017	18:34:36.64	+40:07:26.7	SuperWASP	18671/17831	4.274	11.318	0.042	0.017
J18353+457	BD+45 2743	18:35:18.33	+45:44:37.9	SuperWASP	13084/7411	4.274	9.763	0.051	0.326
				MEarth-2010	3598/3415	1.733	0.000	0.012	0.002
				MEarth-2014	405/384	2.696	0.001	0.009	0.002
J18356+329	LSR J1835+3259	18:35:37.90	+32:59:54.6	MEarth-2010	1554/1498	1.615	0.001	0.019	0.009
				NSVS	145/138	0.967	13.185	0.090	0.081
J18363+136	Ross 149	18:36:19.23	+13:36:26.2	ASAS	284/273	6.619	12.295	0.076	0.045
				MEarth-2010	620/594	1.964	0.000	0.006	0.002
				MEarth-2011	1688/1610	0.712	0.000	0.009	0.004
				MEarth-2014	512/499	2.685	0.000	0.011	0.004
				NSVS	154/153	0.940	11.223	0.034	0.018
J18409-133	BD–13 5069	18:40:57.33	–13:22:45.6	ASAS-SN	548/539	3.027	10.643	0.042	0.008
J18419+318	Ross 145	18:41:59.09	+31:49:49.8	NSVS	111/110	0.885	10.403	0.023	0.012
J18480-145	G 155–042	18:48:01.29	-14:34:50.8	ASAS	484/460	8.625	12.211	0.066	0.038
J18482+076	G 141–036	18:48:17.52	+07:41:21.0	MEarth-2010	616/600	2.025	0.000	0.008	0.005
				MEarth-2011	1040/1002	0.672	0.000	0.018	0.003
J18498-238	GJ 729	18:49:49.36	-23:50:10.4	ASAS	640/633	8.646	10.545	0.038	0.018
J18580+059	BD+05 3993	18:58:00.14	+05:54:29.7	ASAS	474/451	8.085	9.226	0.045	0.019
J19070+208A	Ross 730	19:07:05.56	+20:53:16.8	MEarth-2010	639/614	0.692	0.000	0.007	0.003
				ASAS	220/209	6.534	10.781	0.023	0.015
J19072+208	HD 349726	19:07:13.20	+20:52:37.3	ASAS	220/209	6.534	10.813	0.029	0.021
				MEarth-2010	639/620	0.692	0.000	0.007	0.003
J19084+322	G 207–019	19:08:29.96	+32:16:52.0	MEarth-2010	917/884	0.692	0.000	0.010	0.004
J19098+176	GJ 1232	19:09:50.98	+17:40:07.4	MEarth-2010	654/618	0.721	0.000	0.007	0.003
				MEarth-2011	1293/1210	0.513	–0.002	0.014	0.003
J19169+051N	V1428 Aql	19:16:55.26	+05:10:08.6	ASAS	404/389	8.068	9.144	0.047	0.014
				MEarth-2010	1446/1320	1.099	0.021	0.064	0.002
J19169+051S	V1298 Aql (vB 10)	19:16:57.62	+05:09:02.2	MEarth-2010	1446/1389	1.099	0.001	0.022	0.007
				MEarth-2014	773/707	2.697	0.001	0.015	0.004
				Montcabrer	102/93	0.055	16.121	0.092	0.019
J19216+208	GJ 1235	19:21:38.68	+20:52:02.8	ASAS	198/191	6.504	13.578	0.212	0.148
				MEarth-2010	1754/1672	1.661	0.000	0.012	0.005
				MEarth-2011	2139/2097	0.675	0.000	0.010	0.003
J19251+283	Ross 164	19:25:08.46	+28:21:13.2	NSVS	133/131	0.901	11.511	0.055	0.029
J19255+096	LSPM J1925+0938	19:25:30.89	+09:38:23.5	MEarth-2010	1101/1070	0.781	0.002	0.027	0.009
				MEarth-2014-tel06	955/920	2.682	0.000	0.028	0.013
				MEarth-2014-tel08	931/892	0.776	0.000	0.019	0.010
J19346+045	BD+04 4157	19:34:39.82	+04:34:57.2	ASAS	749/696	8.211	9.362	0.038	0.017
J19422-207	2M J19421282-2045477	19:42:12.82	-20:45:47.8	ASAS	169/159	8.542	14.343	0.323	0.178
				Catalina	225/218	7.901	12.370	0.247	0.056
J19511+464	G 208–042	19:51:09.31	+46:28:59.9	SuperWASP	6164/5861	2.156	11.242	0.112	0.004
				HATNet	11559/11470	1.151	9.629	0.010	0.005
				MEarth-2010	477/468	0.612	0.001	0.009	0.002
				MEarth-2014	298/290	2.693	0.001	0.009	0.004
J20093-012	2M J20091824–0113377	20:09:18.24	–01:13:37.7	ASAS	70/67	7.981	15.123	0.498	0.040
				NSVS	126/126	0.923	12.861	0.051	0.057
J20198+229	LP 395–008 AB	20:19:49.25	+22:56:36.7	SuperWASP	986/887	1.281	11.852	0.033	0.028
				ASAS	225/221	6.504	12.005	0.075	0.025
J20260+585	Wolf 1069	20:26:05.29	+58:34:22.5	MEarth-2016-tel01	2635/2579	2.772	0.000	0.008	0.003
				MEarth-2016-tel05	2730/2692	4.060	0.000	0.010	0.003
				SuperWASP	10529/10133	2.156	12.288	0.163	0.034
J20305+654	GJ 793	20:30:32.08	+65:26:58.6	ASAS-SN	476/473	2.945	10.529	0.017	0.005
J20336+617	GJ 1254	20:33:40.31	+61:45:13.6	SuperWASP	5908/5247	2.145	12.295	0.219	0.030

Table A.1. M dwarfs searched for photometric periods (cont.).

Karmn	Name	α (J2000.0)	δ (J2000.0)	Survey	$N_{\rm obs}/N_{\rm used}$	Δt [a]	$\overline{m}$ [mag]	σ_m [mag]	$\overline{\delta m}$ [mag]
J20405+154	GJ 1256	20:40:33.64	+15:29:57.2	ASAS	263/245	6.512	13.640	0.206	0.154
				MEarth-2010	377/366	1.719	0.000	0.015	0.004
				MEarth-2011	1119/1104	0.650	0.001	0.014	0.003
				MEarth-2014-tel03	1541/1458	1.686	0.000	0.011	0.003
				MEarth-2014-tel07	2773/2637	2.716	0.000	0.010	0.003
J20450+444	BD+44 3567	20:45:04.03	+44:29:56.2	SuperWASP	3168/2920	0.410	10.907	0.019	0.014
J20525-169	LP 816–060	20:52:33.04	–16:58:29.0	ASAS	519/504	8.540	11.443	0.036	0.019
J20533+621	BD+61 2068	20:53:19.78	+62:09:15.8	AstroLAB IRIS	101/99	0.630	8.567	0.031	0.007
				ASAS-SN	801/765	3.684	8.801	0.050	0.004
J20556-140N	GJ 810 AB	20:55:37.72	-14:02:07.8	ASAS	409/388	8.476	12.529	0.096	0.046
J20556-140S	GJ 810 B	20:55:37.07	-14:03:54.6	Catalina	215/206	5.454	12.929	0.078	0.050
J20567-104	Wolf 896	20:56:46.59	–10:26:53.4	ASAS	395/370	8.627	11.492	0.056	0.023
J21019-063	Wolf 906	21:01:58.66	–06:19:07.1	ASAS	397/370	8.532	11.251	0.057	0.020
J21152+257	LP 397–041	21:15:12.59	+25:47:45.4	ASAS	217/205	6.438	12.111	0.046	0.034
				SuperWASP	2324/2140	4.225	11.820	0.056	0.040
J21164+025	LSPM J2116+0234	21:16:27.29	+02:34:51.5	ASAS	388/374	8.956	11.971	0.057	0.027
J21221+229	GSC 02187–00512	21:22:06.27	+22:55:53.1	SuperWASP	4464/4221	4.225	10.622	0.086	0.031
J21348+515	Wolf 926	21:34:50.36	+51:32:13.8	SuperWASP	6022/5565	1.645	11.792	0.056	0.026
J21463+382	LSPM J2146+3813	21:46:22.06	+38:13:04.8	SuperWASP	6641/5791	4.211	11.785	0.055	0.023
				MEarth-2010	727/681	2.046	0.000	0.008	0.002
				MEarth-2014	466/442	2.683	0.000	0.015	0.005
				ASAS-SN	452/435	2.852	12.198	0.012	0.011
J21466+668	G 264–012	21:46:40.22	+66:48:10.6	MEarth-2010	230/226	0.579	0.000	0.006	0.002
				MEarth-2011	255/250	0.246	0.000	0.011	0.003
				MEarth-2014	305/288	2.685	0.000	0.007	0.004
J21466-001	Wolf 940	21:46:40.40	–00:10:23.4	ASAS	338/321	9.011	12.681	0.088	0.038
J22012+283	V374 Peg	22:01:13.11	+28:18:24.9	SuperWASP	18405/16388	4.222	11.690	0.074	0.039
				MEarth-2014	1004/938	2.701	0.000	0.036	0.006
J22020-194	LP 819–017	22:02:00.70	–19:28:59.3	ASAS	538/523	8.866	12.052	0.056	0.032
J22021+014	BD+00 4810	22:02:10.26	+01:24:00.6	ASAS	323/313	9.011	9.147	0.020	0.015
J22057+656	G 264–018 A	22:05:45.36	+65:38:55.5	NSVS	149/133	3.590	10.965	0.021	0.015
J22096-046	BD–05 5715	22:09:40.30	–04:38:26.8	ASAS	440/424	8.866	10.366	0.068	0.022
J22114+409	1RXS J221124.3+410000	22:11:24.17	+40:59:58.7	SuperWASP	6216/5736	2.107	13.332	0.057	0.038
J22115+184	Ross 271	22:11:30.08	+18:25:34.1	ASAS	382/361	6.544	10.253	0.050	0.016
J22125+085	Wolf 1014	22:12:35.96	+08:33:11.1	ASAS	252/239	8.874	12.024	0.074	0.033
J22137-176	LP 819–052	22:13:42.78	–17:41:08.2	ASAS	323/302	8.967	13.703	0.209	0.104
				K2	2986/2986	0.183	1.006	0.008	...
J22231-176	LP 820–012	22:23:06.97	–17:36:25.0	ASAS	386/363	8.967	13.313	0.133	0.063
J22252+594	G 232–070	22:25:17.06	+59:24:49.6	ASAS-SN	521/512	3.022	12.965	0.027	0.017
				MEarth-2016	671/656	4.063	0.000	0.008	0.004
				MEarth-2010	246/242	0.611	0.001	0.008	0.002
J22298+414	G 215–050	22:29:48.86	+41:28:48.0	SuperWASP	20894/18133	4.153	12.584	0.080	0.057
				MEarth-2011	426/415	0.169	0.000	0.008	0.004
				MEarth-2014	281/265	2.685	0.000	0.008	0.003
J22330+093	BD+08 4887	22:33:02.25	+09:22:41.1	ASAS	254/243	8.874	10.377	0.026	0.016
J22468+443	EV Lac	22:46:49.81	+44:20:03.1	SuperWASP	5963/5728	2.107	10.298	0.118	0.023
J22503-070	BD–07 5871	22:50:19.43	–07:05:24.5	ASAS	373/355	8.970	9.852	0.040	0.017
J22518+317	GT Peg	22:51:53.49	+31:45:15.3	SuperWASP	13465/12160	4.153	11.477	0.075	0.022
J22532-142	IL Aqr	22:53:16.72	–14:15:48.9	ASAS	400/379	9.003	10.206	0.084	0.017
J22559+178	StKM 1–2065	22:55:59.85	+17:48:39.9	ASAS	568/537	9.038	11.014	0.035	0.018
J22565+165	HD 216899	22:56:34.97	+16:33:13.0	ASAS	238/229	6.425	8.662	0.057	0.016
J23064-050	2MUCD 12171 (Trappist-1)	23:06:29.28	-05:02:28.6	K2	3558/3512	0.216	1.000	0.004	...
				Catalina	314/304	0.766	15.565	0.042	0.062
J23113+085	NLTT 56083	23:11:23.78	+08:31:01.4	ASAS	339/319	8.915	12.605	0.105	0.052
				MEarth-2010	370/358	0.686	0.000	0.007	0.003
				MEarth-2014	468/444	2.701	0.000	0.012	0.004
J23216+172	LP 462–027	23:21:37.52	+17:17:28.5	ASAS	270/250	6.948	11.749	0.054	0.025
J23245+578	BD+57 2735	23:24:30.49	+57:51:15.3	SuperWASP	2350/1898	2.099	10.350	0.120	0.028
J23340+001	GJ 899	23:34:03.28	+00:10:45.2	ASAS	305/287	8.967	11.190	0.038	0.019
				K2	287/284	0.018	1.000	0.001	...
J23351-023	GJ 1286	23:35:10.50	–02:23:21.4	NSVS	157/148	0.503	12.058	0.036	0.021
				Catalina	276/275	7.203	12.690	0.100	0.050
J23381-162	G 273–093	23:38:08.19	–16:14:10.0	ASAS	432/409	8.915	11.330	0.080	0.021
J23419+441	HH And	23:41:54.99	+44:10:40.8	SuperWASP	14988/13827	2.096	12.039	0.085	0.028
J23431+365	GJ 1289	23:43:06.29	+36:32:13.2	NSVS	235/232	0.676	11.352	0.035	0.014
				MEarth-2010	520/509	0.722	0.001	0.008	0.004
				MEarth-2014-tel01	325/332	2.704	0.001	0.012	0.005
J23492+024	BR Psc	23:49:12.56	+02:24:03.8	ASAS	325/307	8.983	8.981	0.041	0.017
				Catalina	87/87	6.071	11.313	0.319	0.05
J23505-095	LP 763–012	23:50:31.59	–09:33:32.1	ASAS	307/297	0.901	13.025	0.105	0.070
				Catalina	190/190	8.092	12.095	0.084	0.050
J23548+385	RX J2354.8+3831	23:54:51.47	+38:31:36.3	SuperWASP	13628/12893	4.153	12.942	0.087	0.067
J23556-061	GJ 912	23:55:39.81	–06:08:32.8	ASAS	311/296	9.033	11.176	0.042	0.017
J23585+076	Wolf 1051	23:58:32.64	+07:39:30.4	ASAS	241/229	8.937	11.777	0.045	0.022

Table A.2. Rotation periods obtained for stars in our sample.

Karmn	$P_{\rm rot}$ [d]	A [mag]	FAP (%)	Survey	$P_{\rm rot,lit}$ [d]	$A_{\rm lit}$ [mag]	FAP$_{\rm lit}$ (%)	Ref.[a]
J00051+457[b]	15.37±0.09	0.003	$< 10^{-4}$	SuperWASP	21.2±0.5	...	<0.1	SM17
J00162+198E	105±44	0.006	$< 10^{-4}$	MEarth	104	0.0049	...	Irw11
J00162+198W	4.83±0.06	0.007	$< 10^{-4}$	MEarth	4.79	...	...	Nor07
J00389+306	50.2±1.3	0.009	$< 10^{-4}$	SuperWASP	...	...	...	...
J01019+541	0.2779±0.0006	0.007	$< 10^{-4}$	MEarth	0.278	...	...	New16
J01025+716	51.5±2.6	0.025	$< 10^{-4}$	ASAS-SN	...	...	...	...
J01026+623	19.9±0.4	0.006	$< 10^{-4}$	MEarth	18.4±0.7	...	<1	SM17
J01033+623	1.02±0.01	0.051	$< 10^{-4}$	MEarth	1.06	0.046	...	Irw11
J01125-169	69.2±2.4	0.030	0.3	ASAS	69.2	0.015	<0.1	SM16
J01339-176	27.1±0.4	0.064	0.05	ASAS	...	...	...	...
J01221+221	0.564±0.001	0.012	$< 10^{-4}$	SuperWASP	...	...	...	...
J02070+496	7.20±0.13	0.039	$< 10^{-4}$	SuperWASP	...	...	...	...
J02088+494	0.74759±0.00019	0.021	$< 10^{-4}$	SuperWASP	...	...	...	...
J02222+478	29.5±0.4	0.007	$< 10^{-4}$	SuperWASP	...	...	...	...
J02358+202	31.9±0.6	0.007	$< 10^{-4}$	SuperWASP	...	...	...	...
J02442+255	38.7±3.7	0.006	$< 10^{-4}$	SuperWASP	...	...	...	...
J02519+224	0.85757±0.00003	0.010	$< 10^{-4}$	SuperWASP	...	...	...	...
J03181+382	77.2±3.0	0.004	$< 10^{-4}$	SuperWASP	...	...	...	...
J03213+799	32.4±1.0	0.030	$< 10^{-4}$	AstroLAB IRIS	...	...	...	...
J03217-066	21.1±0.1	0.017	1.20	ASAS	...	...	...	...
J03473-019	3.87±0.01	0.048	$< 10^{-4}$	ASAS	3.88	...	...	Kir12
J04225+105	5.48±0.01	0.006	$< 10^{-4}$	MEarth	...	...	...	...
J04290+219	25.4±0.3	0.011	1.9	ASAS	...	...	...	...
J04429+189	40.7±0.4	0.013	0.5	ASAS	38.92	...	...	KS07
J04429+214	47.8±1.1	0.045	0.049	ASAS	...	...	...	...
J04472+206[c]	0.3426±0.0003	0.015	$< 10^{-4}$	K2	...	...	...	...
J05019+011	2.12±0.02	0.023	$< 10^{-4}$	Montcabrer	...	...	...	...
J05062+046	0.8650±0.0006	0.012	0.38	NSVS	0.89	...	...	Kir12
J05280+096	17.2±0.1	0.054	0.92	ASAS	...	...	...	...
J05314-036	33.8±0.6	0.011	0.0025	ASAS	33.61	...	...	KS07
J05365+113	12.3±0.1	0.022	$< 10^{-4}$	ASAS	12.04	...	...	Kir12
J06000+027	1.81±0.01	0.014	$< 10^{-4}$	MEarth	1.81	...	...	Irw11
J06024+498	105±6	0.011	$< 10^{-4}$	MEarth	99.6	0.0176	...	Irw11
J06103+821	44.6±1.0	0.010	$< 10^{-4}$	ASAS-SN	...	...	...	...
J06105-218	27.3±0.2	0.009	9.6	ASAS	27.3	0.029	11.4	SM16
J06318+414[d]	0.29952±0.00007	0.024	$< 10^{-4}$	SuperWASP	0.300	...	...	New16
J06421+035	83.4±7.0	0.013	$< 10^{-4}$	MEarth	...	...	...	...
J06548+332	18.1±0.3	0.006	$< 10^{-4}$	SuperWASP	...	...	...	...
J07033+346	8.04±0.03	0.016	$< 10^{-4}$	SuperWASP	...	...	...	...
J07319+362N	16.4±0.3	0.029	$< 10^{-4}$	SuperWASP	...	...	...	...
J07353+548	21.8±1.0	0.008	$< 10^{-4}$	SuperWASP	...	...	...	...
J07361-031	12.2±0.1	0.017	0.038	ASAS	12.16	...	...	Kir12
J07446+035	2.78±0.01	0.025	$< 10^{-4}$	MEarth	2.77	...	...	Kir12
J07472+503	1.32±0.01	0.029	$< 10^{-4}$	SuperWASP	...	...	...	...
J07558+833	1.11±0.01	0.010	$< 10^{-4}$	MEarth	1.11	...	...	Irw11
J08119+087	5.42±0.15	0.004	$< 10^{-4}$	MEarth	...	...	...	...
J08161+013	40.7±0.4	0.009	1.0	ASAS	...	...	...	...
J08298+267	0.45900±0.00001	0.005	$< 10^{-4}$	MEarth	0.459	...	...	New16
J08315+730	105±11	0.005	$< 10^{-4}$	MEarth	...	...	...	...
J08402+314	118±14	0.005	$< 10^{-4}$	MEarth	110.7	...	...	New16
J09140+196	89.9±2.0	0.043	1.8	ASAS	...	...	...	...

Table A.2. Rotation periods obtained for stars in our sample (cont.).

Karmn	$P_{\rm rot}$ [d]	A [mag]	FAP [%]	Survey	$P_{\rm rot,lit}$ [d]	$A_{\rm lit}$ [mag]	FAP$_{\rm lit}$ [%]	Ref.[a]
J09423+559	74.3±2.8	0.011	$< 10^{-4}$	MEarth	72.8	...	...	Irw11
J09425+700	21.0±0.4	0.040	$< 10^{-4}$	AstroLAB IRIS	...	...	...	...
J09428+700	23.9±0.6	0.023	$< 10^{-4}$	AstroLAB IRIS	...	...	...	...
J09439+269	13.7±0.9	0.009	$< 10^{-4}$	Montcabrer	...	...	...	...
J10122-037	21.6±0.2	0.017	$< 10^{-4}$	ASAS	21.56	...	...	Kir12
J10354+694	118±10	0.022	$< 10^{-4}$	NSVS	...	...	...	...
J10416+376	54.3±4.4	0.004	$< 10^{-4}$	MEarth	...	...	...	...
J10508+068[e]	64±19	0.010	$< 10^{-4}$	K2	...	...	...	...
J10564+070	2.704±0.003	0.003	$< 10^{-4}$	K2	...	...	...	...
J11026+219	14.6±0.2	0.046	$< 10^{-4}$	SuperWASP	14	...	...	Fek00
J11302+076	36.4±0.3	0.007	$< 10^{-4}$	K2	38.6	...	0.1	Clo17
J11417+427	71.5±5.1	0.003	$< 10^{-4}$	HATNet	73.5	...	...	Har11
J11421+267	44.6±2.0	0.009	$< 10^{-4}$	SuperWASP	44.1±0.2	...	...	Lot18
J11476+002	11.60±0.04	0.041	$< 10^{-4}$	K2	11.6	...	...	Kir12
J11477+008	163±3	0.014	10.0	ASAS	165.1	0.0078	0.2	SM16
J11509+483	125±23	0.006	$< 10^{-4}$	MEarth	132	...	...	Irw11
J11511+352	22.8±1.0	0.010	$< 10^{-4}$	SuperWASP	...	...	...	...
J12054+695	100±10	0.008	$< 10^{-4}$	MEarth	96.2	...	...	Irw11
J12189+111	0.49102±0.00003	0.013	$< 10^{-4}$	MEarth	0.49	...	...	Irw11
J12230+640	32.9±1.1	0.027	$< 10^{-4}$	NSVS	...	...	...	...
J12350+098	36.6±1.3	0.027	0.00039	NSVS	...	...	...	...
J12428+418	16.2±0.1	0.014	$< 10^{-4}$	SuperWASP	...	...	...	...
J13005+056	0.60022±0.00004	0.005	$< 10^{-4}$	MEarth	0.6	...	...	Irw11
J13102+477	28.8±0.8	0.017	$< 10^{-4}$	MEarth	28.8	0.0091	...	New16
J13536+776	1.23±0.01	0.017	$< 10^{-4}$	MEarth	1.2313	...	...	Wes15
J14152+450	52.8±1.4	0.009	$< 10^{-4}$	SuperWASP	...	...	...	...
J14257+236W	111±12	0.059	$< 10^{-4}$	SuperWASP	...	...	...	...
J14257+236E	17.6±0.5	0.009	$< 10^{-4}$	SuperWASP	...	...	...	...
J15218+209	3.37±0.01	0.023	$< 10^{-4}$	SuperWASP	3.3829	...	...	Nor07
J15305+094	0.3048±0.0006	0.002	0.0003	MEarth	0.305	0.0031	...	New16
J15412+759	83.4±10.4	0.004	$< 10^{-4}$	MEarth	...	...	...	...
J16102-193	6.263±0.015	0.018	$< 10^{-4}$	K2	6.3±0.2	...	...	Dav16
J16254+543	76.79±0.13	0.006	$< 10^{-4}$	SuperWASP	77.8±5.5	...	<1.2	SM17
J16303-126	119±1	0.010	0.7	ASAS	119.3	0.0059	<0.1	SM16
J16313+408	0.512±0.001...	0.008	$< 10^{-4}$	HATNet	0.51	...	...	Har11
J16554-083N	6.52±0.01	0.028	0.006	ASAS	...	...	...	...
J16570-043	0.547±0.001	0.028	1.4	NSVS	1.21	...	...	Kir12
J16581+257	23.8±0.1	0.012	0.0019	ASAS	...	...	...	...
J17052-050	50.2±1.3	0.012	0.00033	ASAS	...	...	...	...
J17115+384	62.6±2.0	0.008	$< 10^{-4}$	SuperWASP	...	...	...	...
J17198+417	71.5±2.6	0.005	$< 10^{-4}$	SuperWASP	...	...	...	...
J17338+169	0.26593±0.0003	0.031	$< 10^{-4}$	MEarth	0.27	...	...	Nor07
J17355+616	19.3±0.3	0.015	$< 10^{-4}$	Montsec	16.3±4.2	...	<0.1	SM17
J17578+465	30.3±0.9	0.006	$< 10^{-4}$	SuperWASP	31.64	...	...	Har11
J18022+642	0.28027±0.00002	0.005	$< 10^{-4}$	MEarth	0.28	...	...	New16
J18075-159	3.866±0.008	0.005	$< 10^{-4}$	K2	...	...	...	...
J18131+260	2.28±0.01	0.027	$< 10^{-4}$	MEarth	2.28	...	...	Har11
J18174+483	15.8±0.1	0.022	$< 10^{-4}$	SuperWASP	...	...	...	...
J18319+406	50.2±1.3	0.014	$< 10^{-4}$	SuperWASP	...	...	...	...
J18346+401	40.2±0.8	0.008	$< 10^{-4}$	SuperWASP	...	...	...	...
J18353+457	34.0±2.9	0.042	$< 10^{-4}$	SuperWASP	34.5±4.7	...	<0.1	SM17
J18356+329	0.118±0.001	0.008	$< 10^{-4}$	MEarth	0.118±0.01	...	...	Hal08

Table A.2. Rotation periods obtained for stars in our sample (cont.).

Karmn	$P_{\rm rot}$ [d]	A [mag]	FAP [%]	Survey	$P_{\rm rot,lit}$ [d]	$A_{\rm lit}$ [mag]	FAP$_{\rm lit}$ [%]	Ref.[a]
J18363+136	50.2±1.6	0.010	$< 10^{-4}$	MEarth	1.017	...	...	New16
J18482+076	2.76±0.01	0.007	$< 10^{-4}$	MEarth	2.756	...	...	New16
J18498-238	2.87±0.01	0.017	$< 10^{-4}$	ASAS	2.869	0.005	...	KS07
J18580+059	35.2±0.3	0.014	$< 10^{-4}$	ASAS	36.3±0.1	...	<0.1	SM17
J19072+208	3.80±0.01	0.013	0.91	ASAS	...	...	...	...
J19084+322	74.1±2.8	0.005	$< 10^{-4}$	MEarth	...	...	...	...
J19098+176	80.1±3.2	0.005	$< 10^{-4}$	MEarth	...	...	...	...
J19169+051N	46.0±0.2	0.008	2.0	ASAS	46	0.0045	<0.1	SM16
J19169+051S	23.6±0.3	0.008	$< 10^{-4}$	MEarth	...	...	...	...
J19216+208	133±9	0.016	$< 10^{-4}$	MEarth	154.7	...	...	New16
J19346+045	12.9±0.8	0.006	0.33	ASAS	...	...	...	...
J19511+464	0.59278±0.00012	0.007	$< 10^{-4}$	SuperWASP	0.59	...	...	Har11
J20198+229	1.13±0.01	0.028	$< 10^{-4}$	SuperWASP	...	...	...	...
J20260+585	57.7±0.4	0.004	$< 10^{-4}$	MEarth	142.09	...	...	New16
J20305+654	32.8±0.5	0.023	$< 10^{-4}$	ASAS-SN	...	...	...	...
J20336+617	12.6±0.7	0.018	$< 10^{-4}$	SuperWASP	...	...	...	...
J20405+154	106±6	0.009	$< 10^{-4}$	MEarth	104.6	...	...	New16
J20450+444	19.9±0.6	0.011	$< 10^{-4}$	SuperWASP	...	...	...	...
J20525-169	67.6±0.6	0.026	0.00085	ASAS	67.6	0.01	<0.1	SM16
J20567-104	9.63±0.01	0.018	0.28	ASAS	...	...	...	...
J21012+332	29.4±0.9	0.016	$< 10^{-4}$	MEarth	29.12	...	...	Wes15
J21152+257	34.8±0.2	0.033	1.2	ASAS	...	...	...	...
J21221+229	41.0±1.7	0.009	$< 10^{-4}$	SuperWASP	...	...	...	...
J21348+515	54.3±1.5	0.011	$< 10^{-4}$	SuperWASP	...	...	...	...
J22012+283	0.44571±0.00002	0.007	$< 10^{-4}$	SuperWASP	0.45	...	...	GR98
J22021+014	29.5±0.1	0.009	4.5	ASAS	31	...	...	Tes04
J22114+409	30.0±1.3	0.010	$< 10^{-4}$	SuperWASP	...	...	...	...
J22115+184	36.3±0.2	0.018	$< 10^{-4}$	ASAS	...	...	...	...
J22252+594	64.6±2.1	0.014	$< 10^{-4}$	ASAS-SN	...	...	...	...
J22298+414	99.8±1.2	0.007	$< 10^{-4}$	SuperWASP	...	...	...	...
J22468+443	4.38±0.03	0.091	$< 10^{-4}$	SuperWASP	4.376	...	...	Tes04
J22518+317	1.63±0.01	0.016	$< 10^{-4}$	SuperWASP	1.64	...	...	Nor07
J22532-142	81.0±0.8	0.014	0.00018	ASAS	96.7	...	...	Riv05
J22565+165	39.5±0.2	0.013	2.5	ASAS	37.5±0.1	...	...	SM15
J23064-050	3.304±0.011	0.004	$< 10^{-4}$	K2	3.295±0.003	...	...	Vid17
J23216+172	74.7±0.7	0.026	0.55	ASAS	...	...	...	...
J23419+441	106±6	0.027	$< 10^{-4}$	SuperWASP	99.58	...	...	New16
J23431+365	83.6±7.0	0.046	$< 10^{-4}$	NSVS	...	...	...	...
J23548+385	4.70±0.04	0.038	$< 10^{-4}$	SuperWASP	4.76	...	...	KS13

[a] *References*. GR98: Greimel & Robb (1998); Fek00: Fekel & Henry (2000); Tes04: Testa et al. (2004); Riv05: Rivera et al. (2005); KS07: Kiraga & Stepien (2007); Nor07: Norton et al. (2007); Hal08: Hallinan et al. (2008); Har11: Hartman et al. (2011); Irw11: Irwin et al. (2011); Kir12: Kiraga (2012); KS13: Kiraga & Stępień (2013); SM15: Suárez Mascareño et al. (2015); Wes15: West et al. (2015); Dav16: David et al. (2016); New16: Newton et al. (2016); SM16: Suárez Mascareño et al. (2016); SM17:Mascareño et al. (2018); Clo17: Cloutier et al. (2017); Vid17: Vida et al. (2017); Lot18:**?**.

[b] J00051+457 = GJ 2: the periodogram of the ASAS light curve displays several secondary peaks around 15.37 d, including at 21.2 d as found by Suárez Mascareño et al. (2015).

[c] J04472+206 = RX J0447.2+2038: we also measured $P_{\rm rot}$ = 0.342±0.002 d in the Montcabrer dataset (see Fig B.7).

[d] J06318+414 = LP 205–044: the periodogram of the SuperWASP light curve displays a second peak at 0.482 d of approximately the same power as at 0.299 d.

[e] J10508+068 = EE Leo: we increased the frequency search to less than half of the inverse of the time baseline of about 80 d, so the tabulated period is uncertain.

Appendix A: Example light curves and periodograms

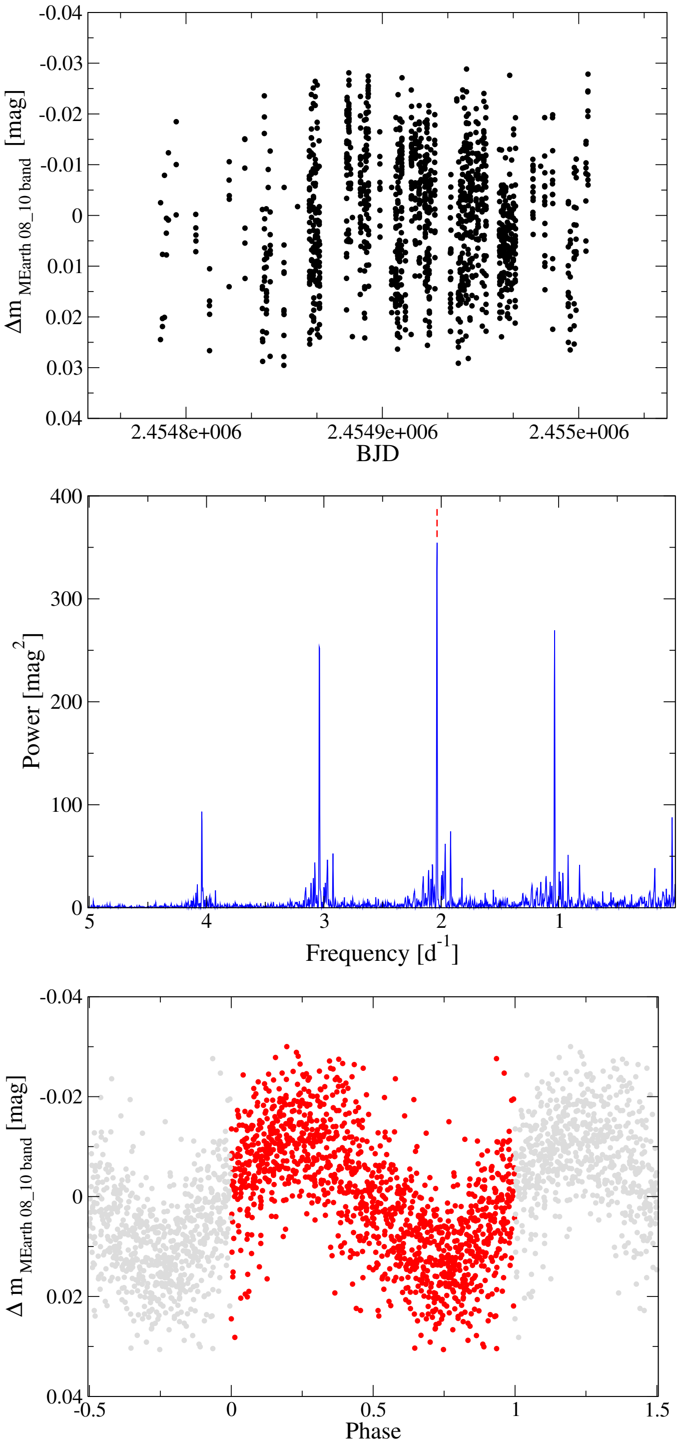


Fig. A.1. MEarth RG715-band photometric data (*top left*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.491$ d (*bottom*) for the M5.0 V star J12189+111 = GL Vir.

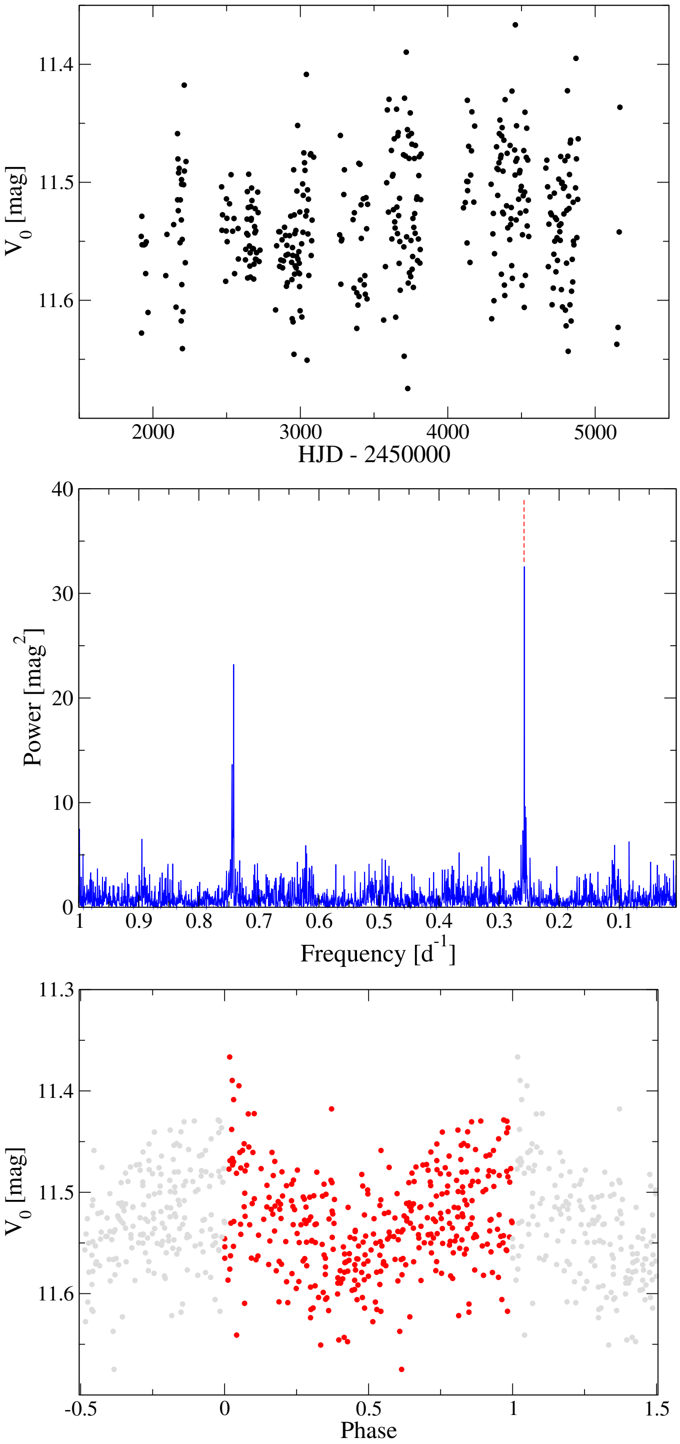


Fig. A.2. ASAS-3 *V*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 3.87$ d (*bottom*) for the M3.0 V star J03473–019 = G 080–021.

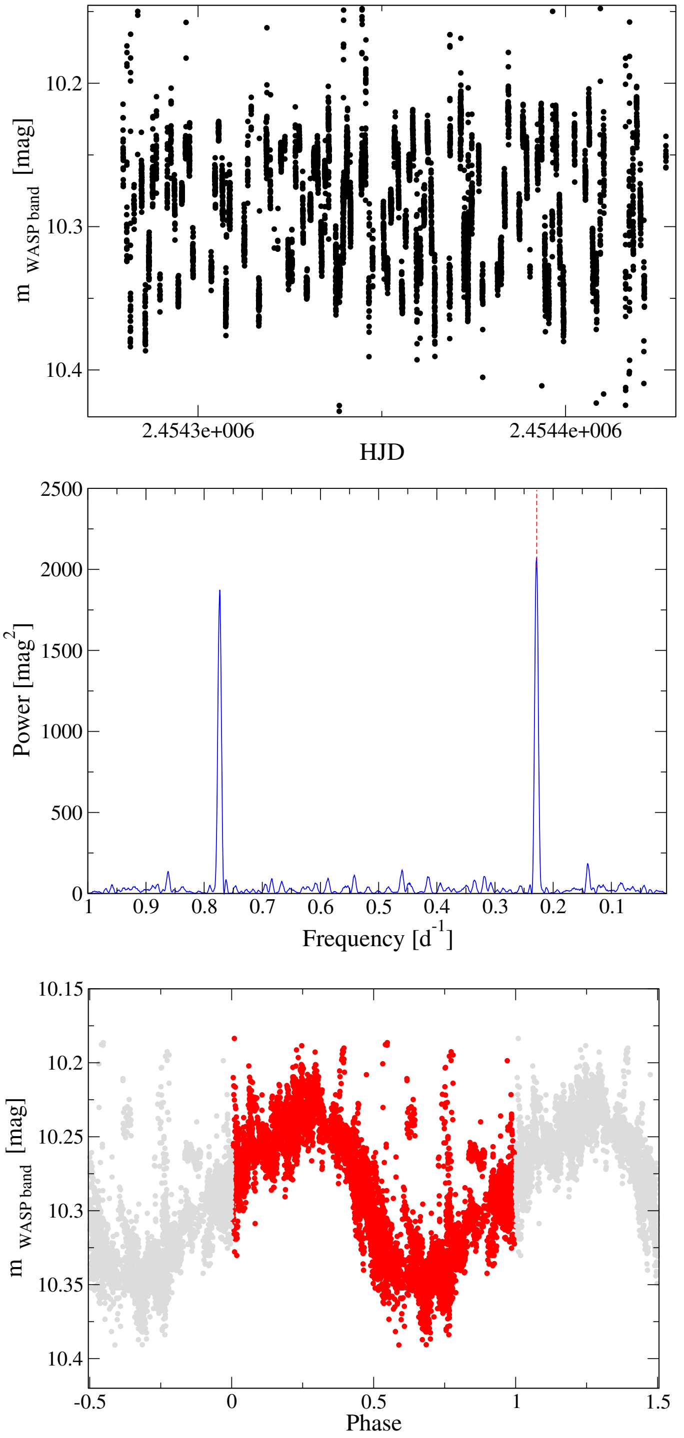


Fig. A.3. SuperWASP broad-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 4.379$ d (*bottom*) for the M3.5 V star J22468+443 = EV Lac.

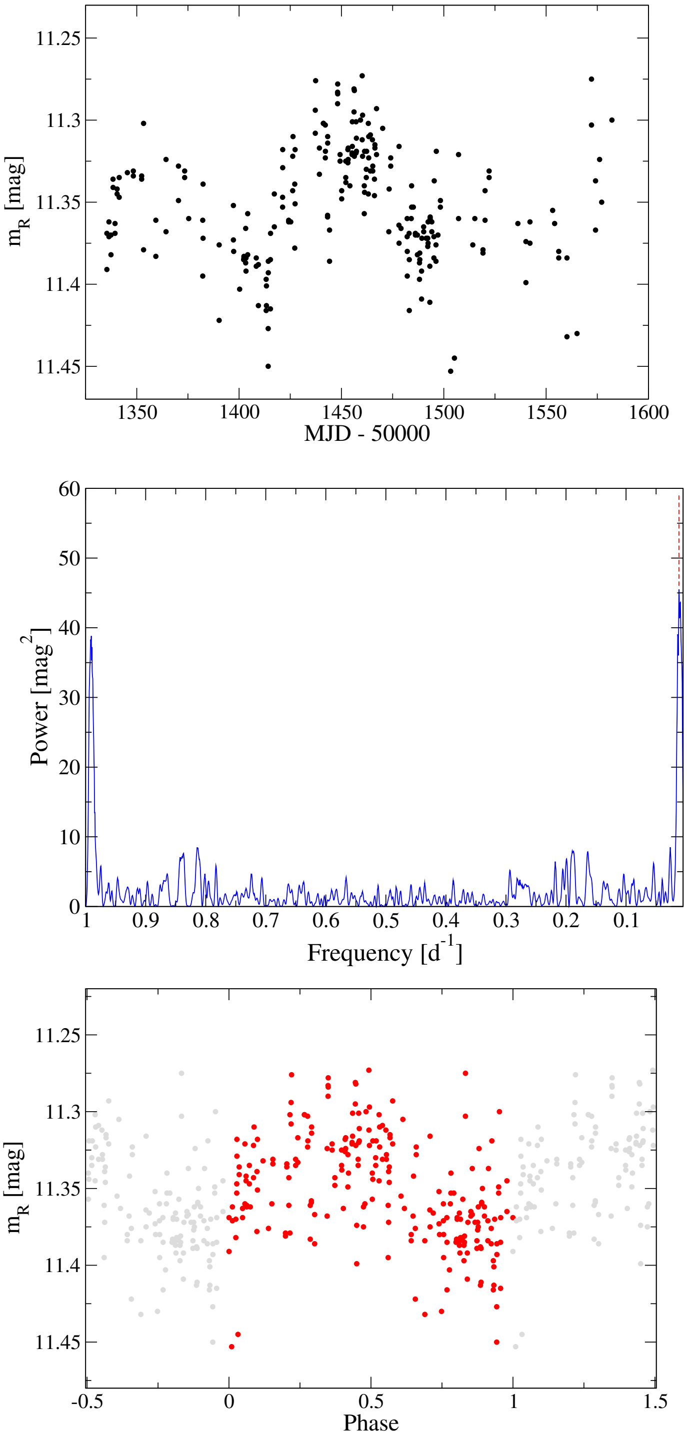


Fig. A.4. NSVS clear-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 87$ d (*bottom*) for the M4.0 V star J23431+365 = GJ 1289.

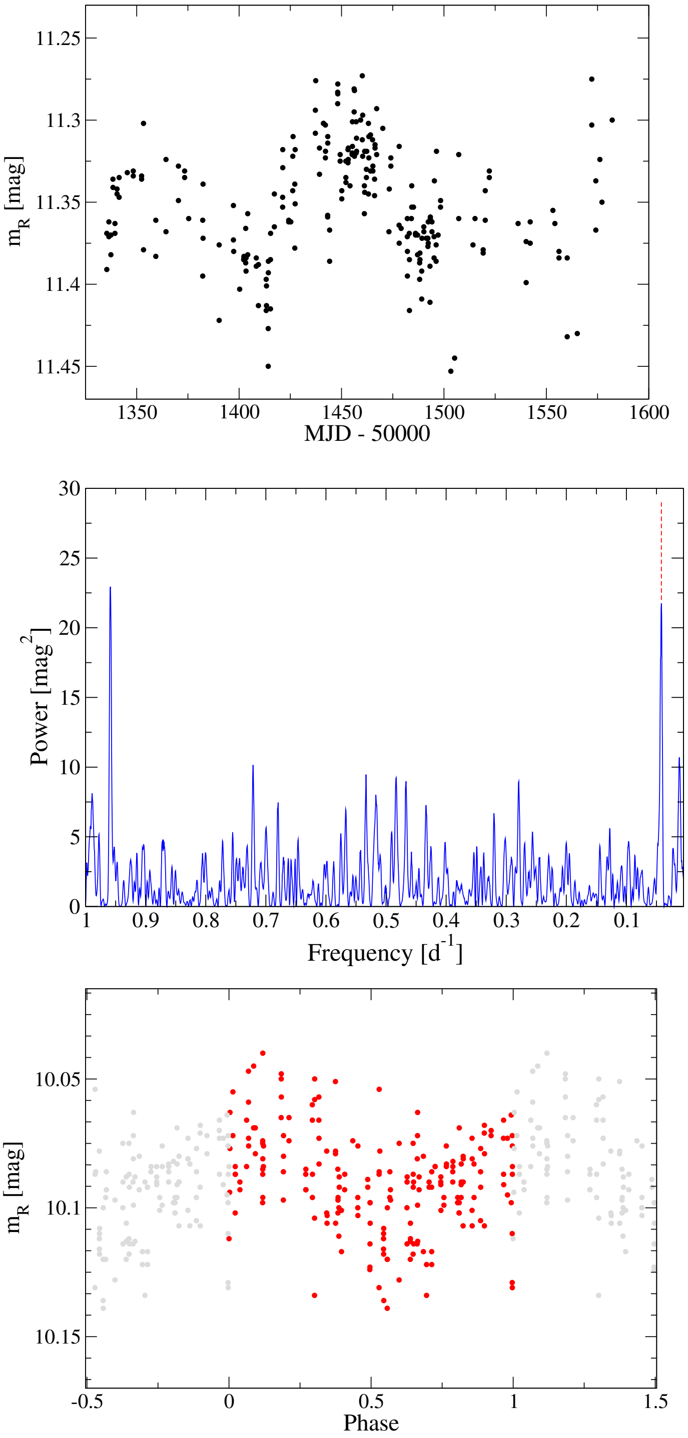


Fig. A.5. AstroLAB IRIS *R*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 23.9$ d (*bottom*) for the M3.0 V star J09428+700 = GJ 362.

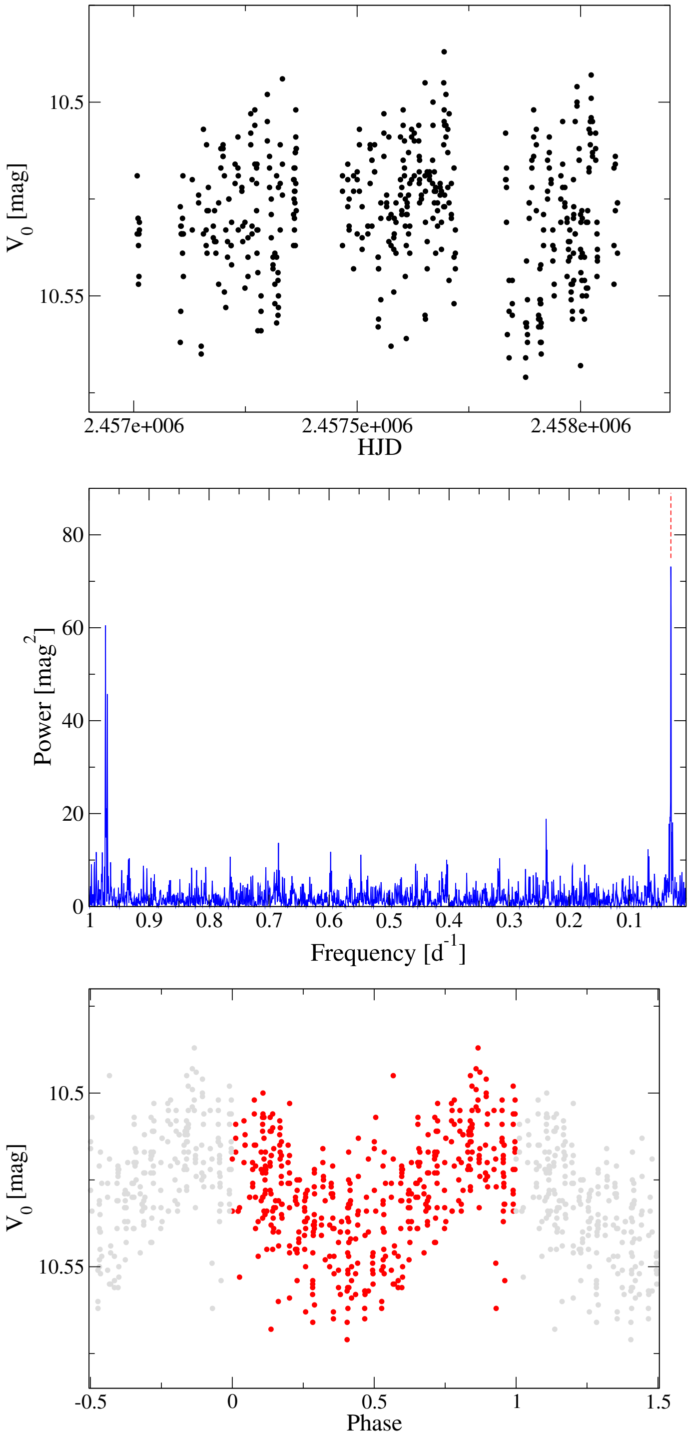


Fig. A.6. ASAS-SN *V*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 32.8$ d (*bottom*) for the M2.5 V star J20305+654 = GJ 793.

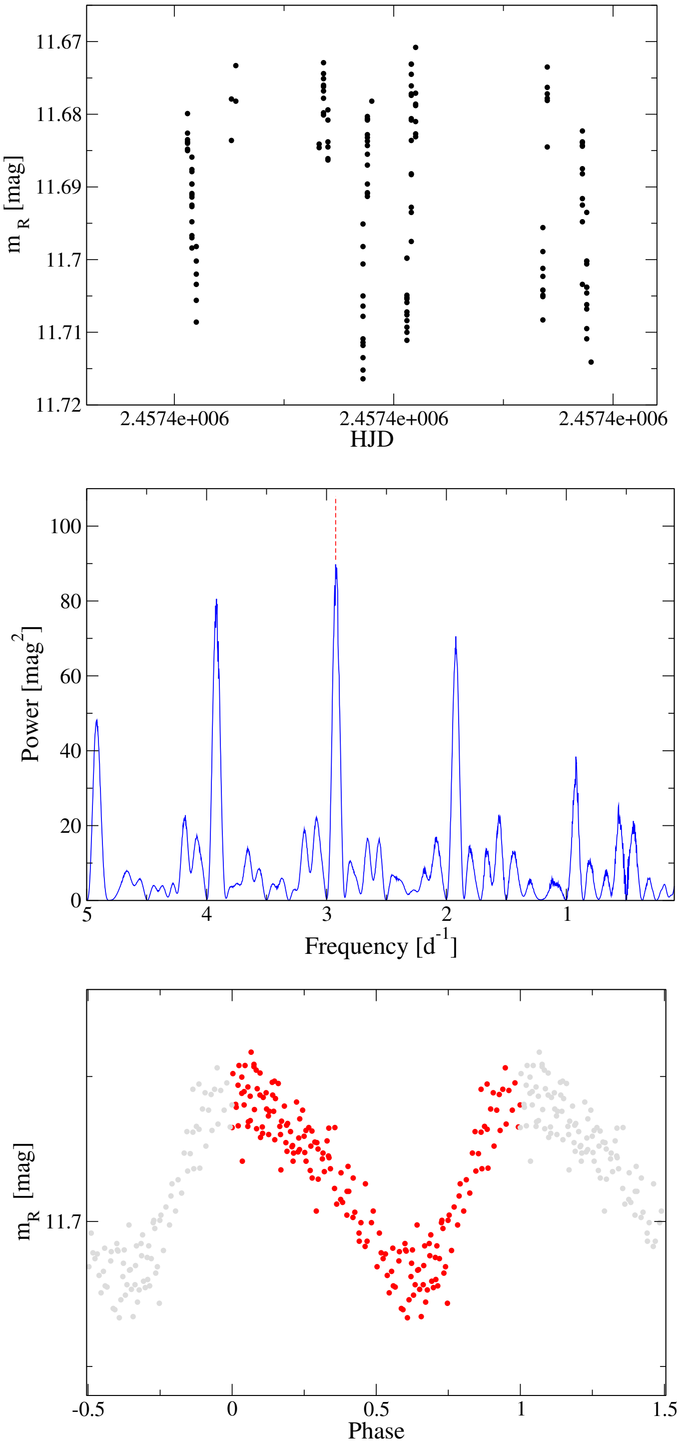


Fig. A.7. Montcabrer *R*-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.342$ d (*bottom*) for the M5.0 V star J04772+206 = RX J0447.2+2038 (compare with Fig. A.8).

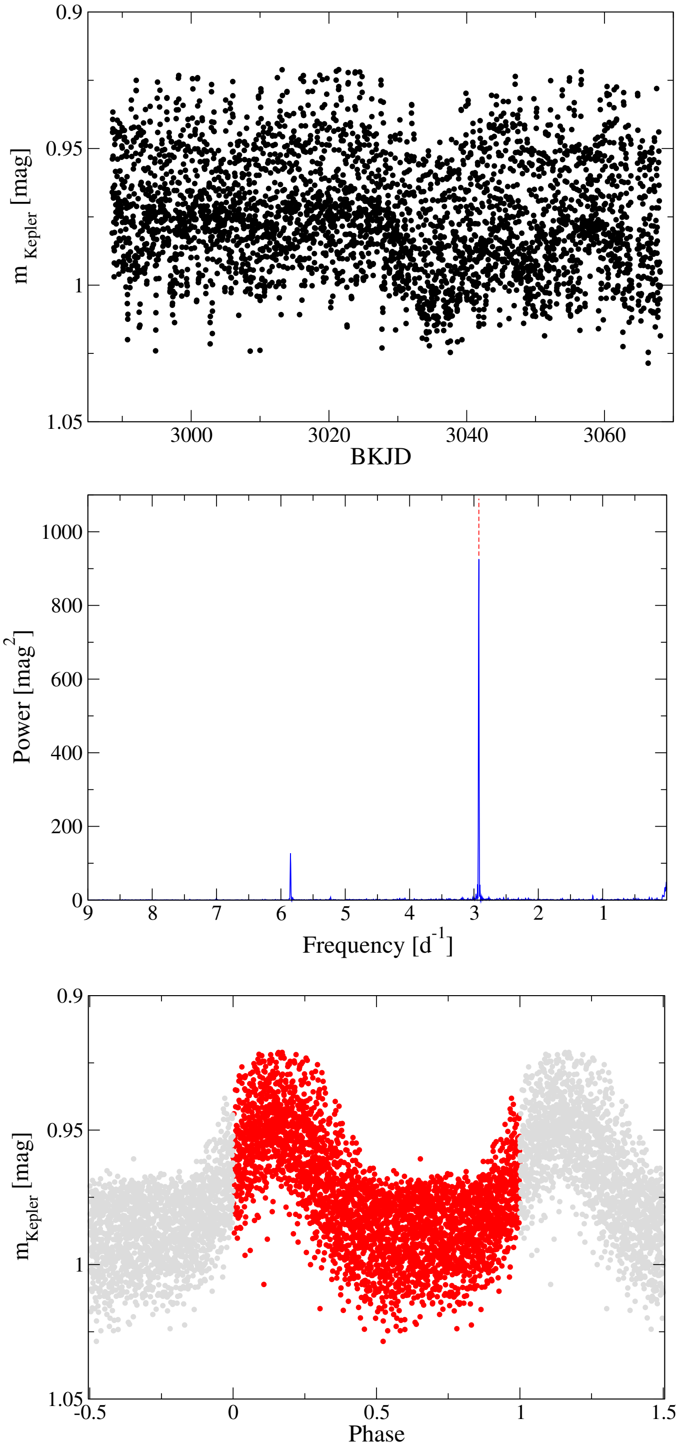


Fig. A.8. K2 photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.342$ d (*bottom*) for the M5.0 V star J04772+206 = RX J0447.2+2038 (compare with Fig. A.7).

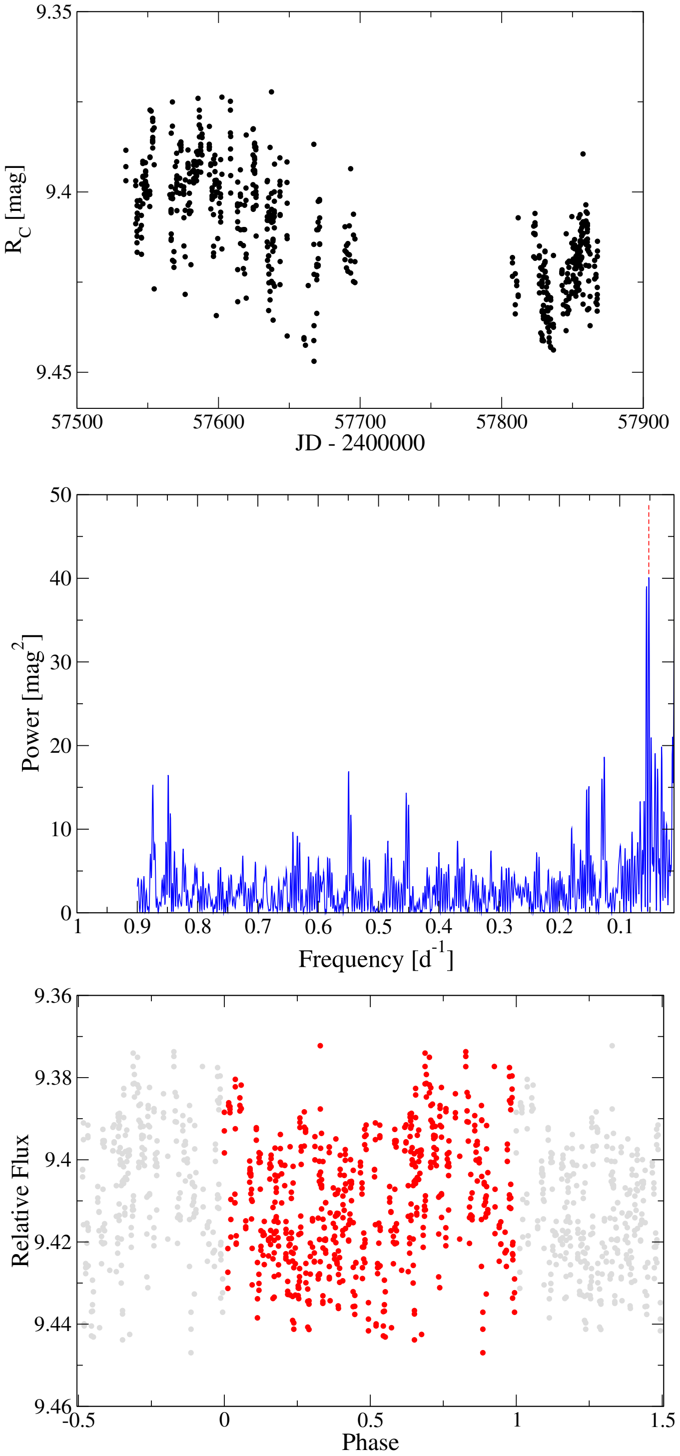


Fig. A.9. Montsec R_C-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 19.3$ d (*bottom*) for the M0.5 V star J17355+616 = BD+61 1678C.

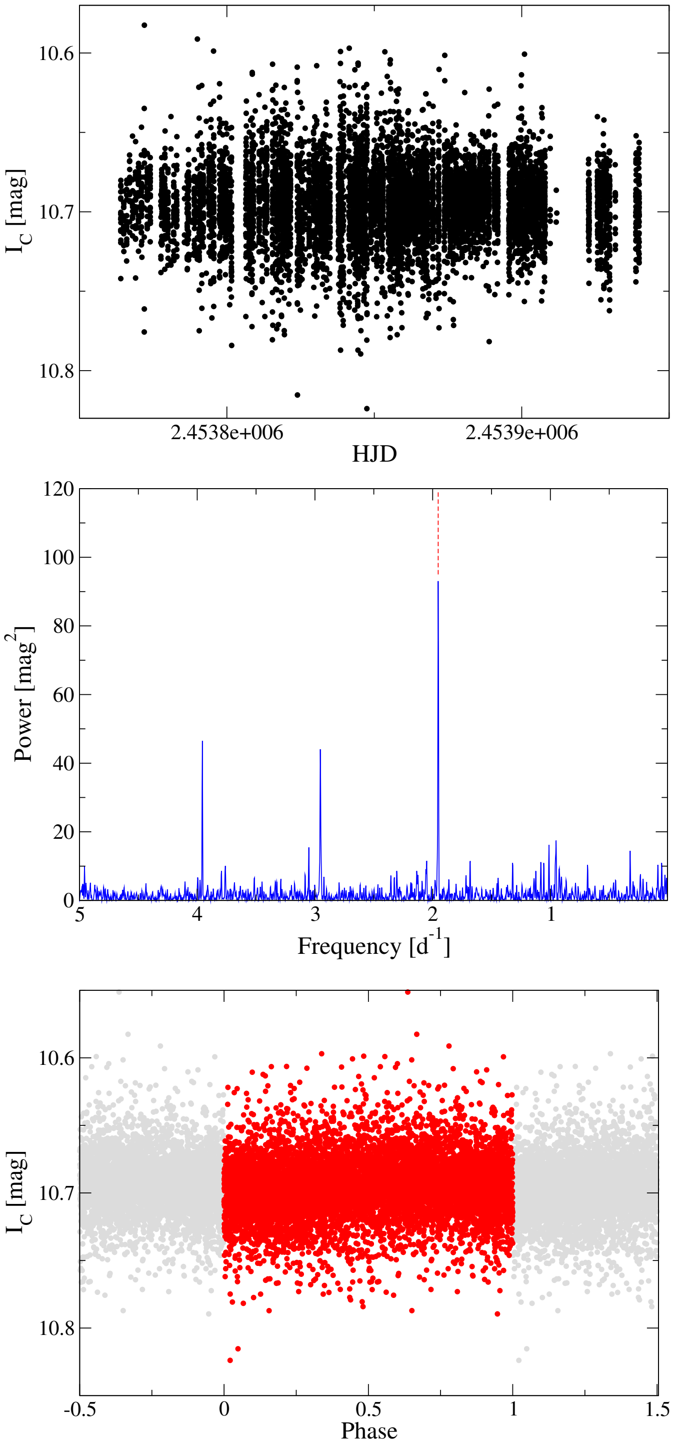
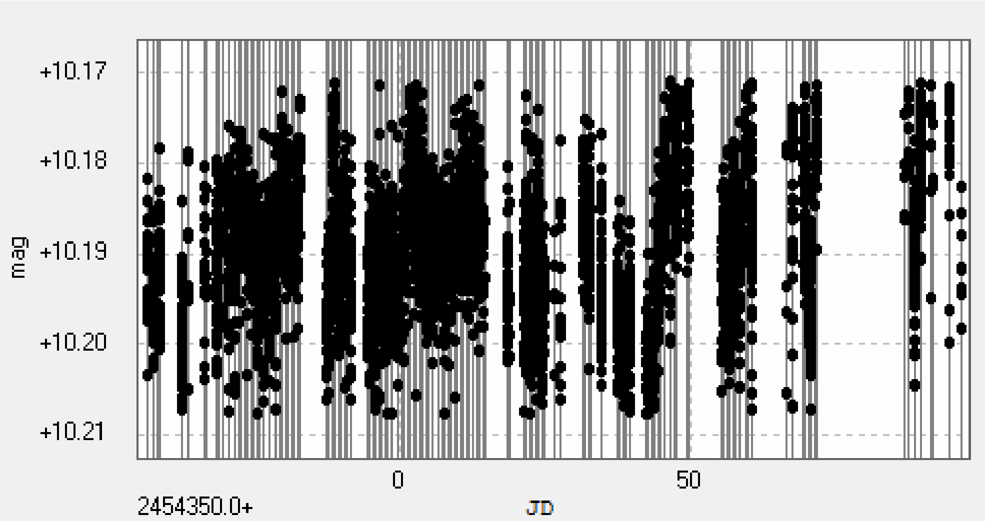


Fig. A.10. HATNet I_C-band photometric data (*top*), Lomb–Scargle periodogram (*middle*), and phase-folded rotation curve for $P = 0.512$ d (*bottom*) for the M5.0 V star J16313+408 = G 180–060.

Apéndice B

Curvas de luz, periodogramas y curvas de rotación de las 142 estrellas con P_{rot} determinado

J00051+457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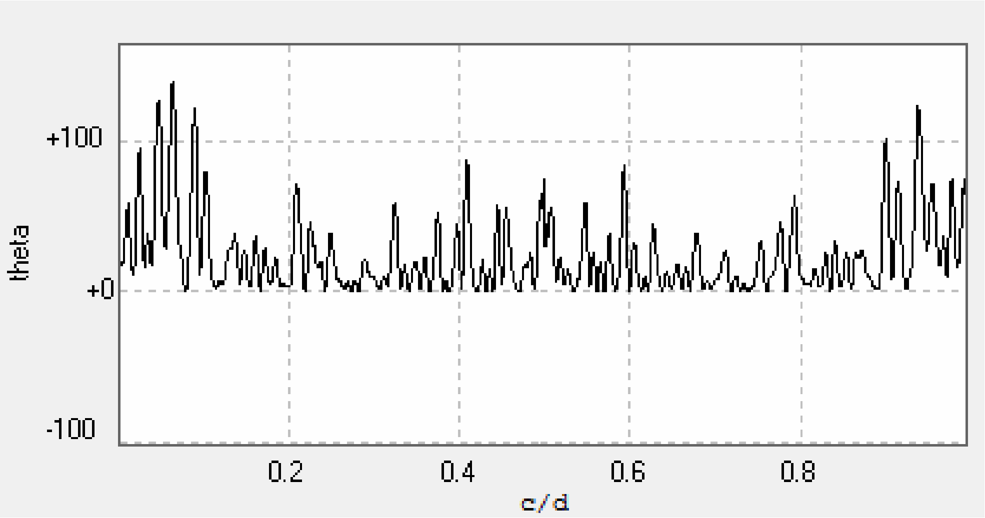
+10.18
+10.19
+10.20
+10.21
mag
0
50
2454350.0+
JD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+0
-100
theta
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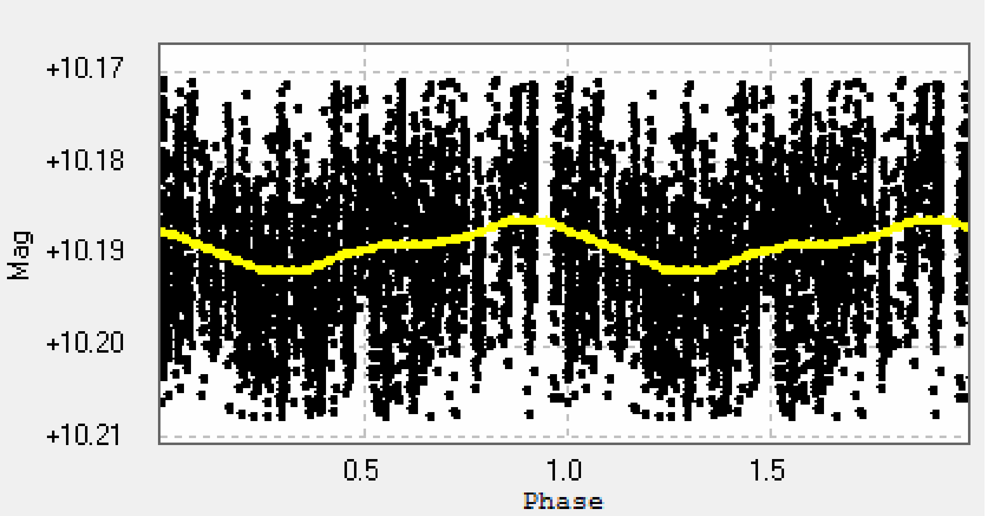
0.4
0.6
0.8
c/d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Mag
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1.5
Phase

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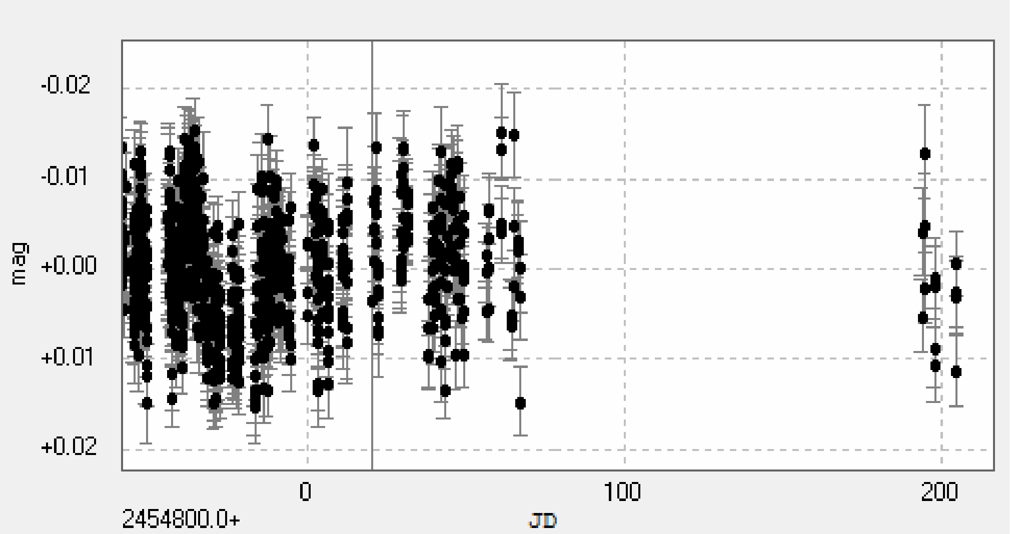
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mag
0
100
200
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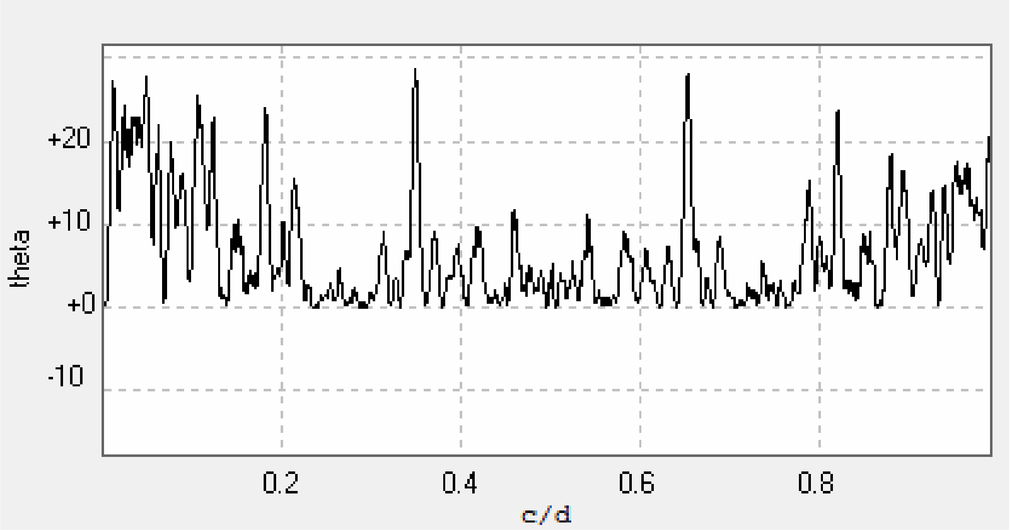
JD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-10
theta
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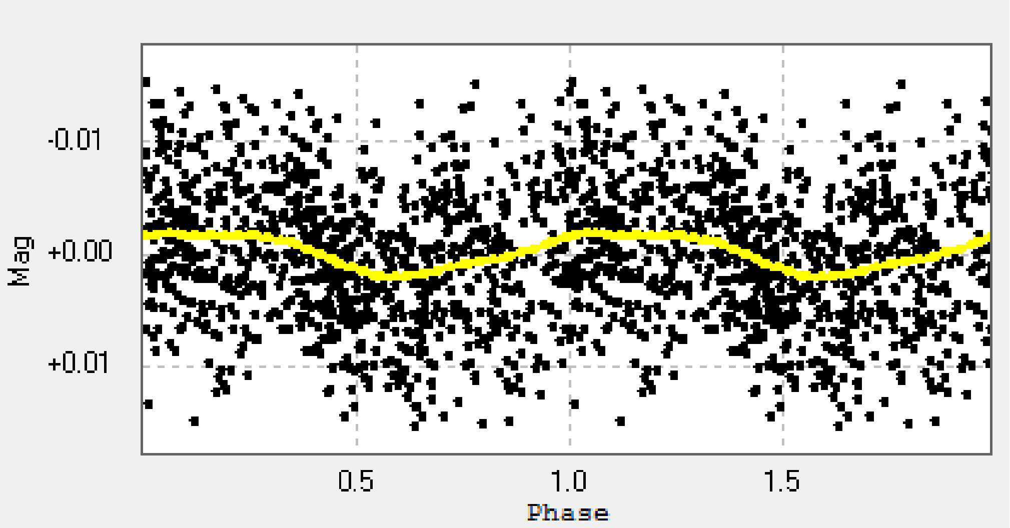
0.4
0.6
0.8
c/d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Phase

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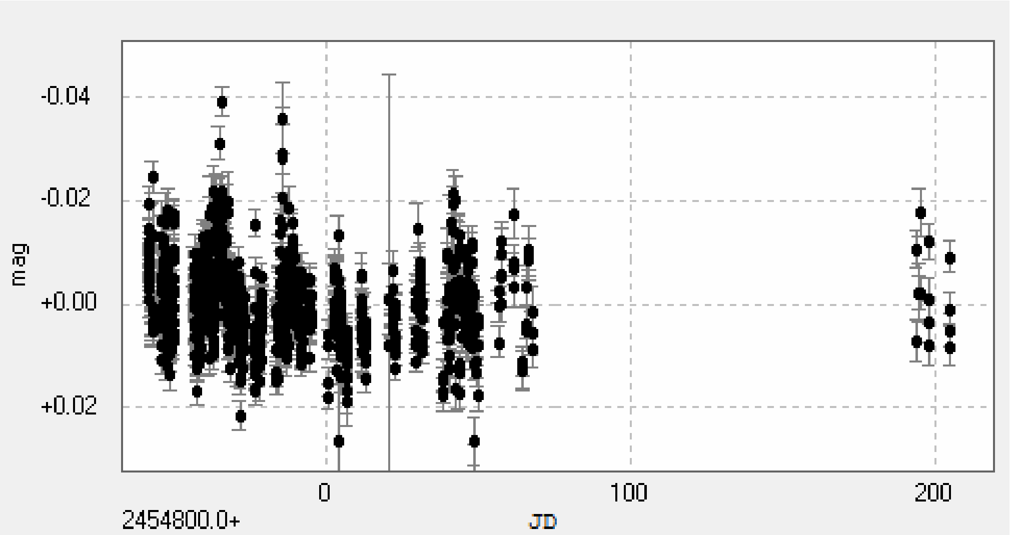
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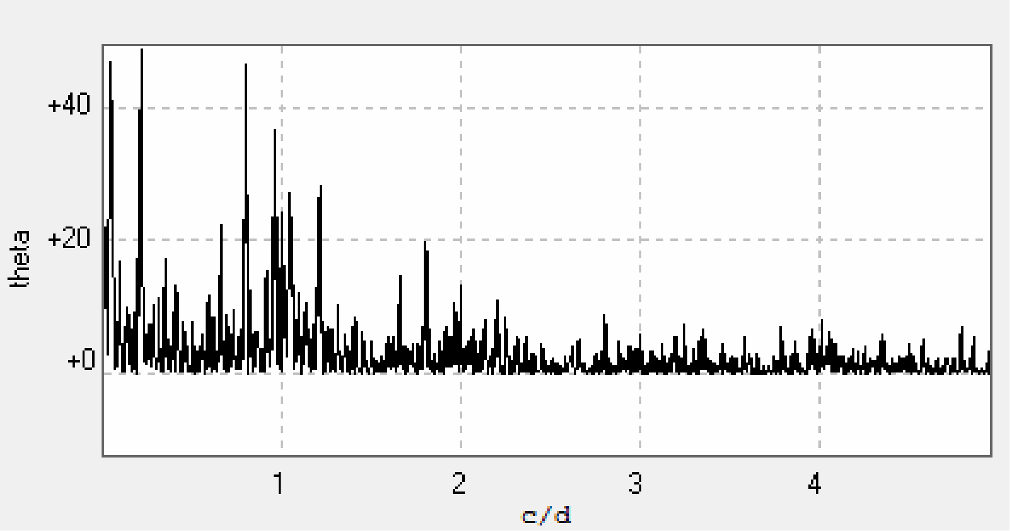
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theta
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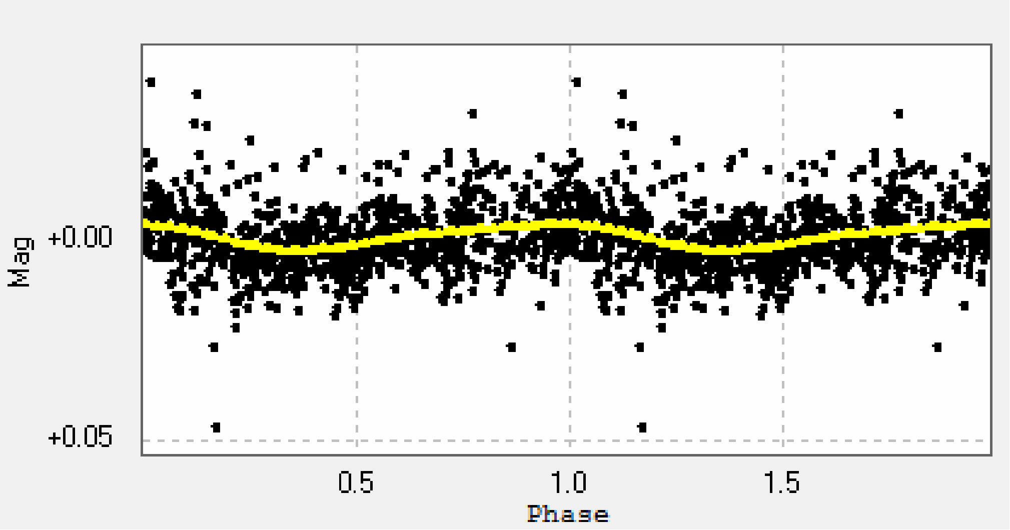
2
3
4
c/d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Phase

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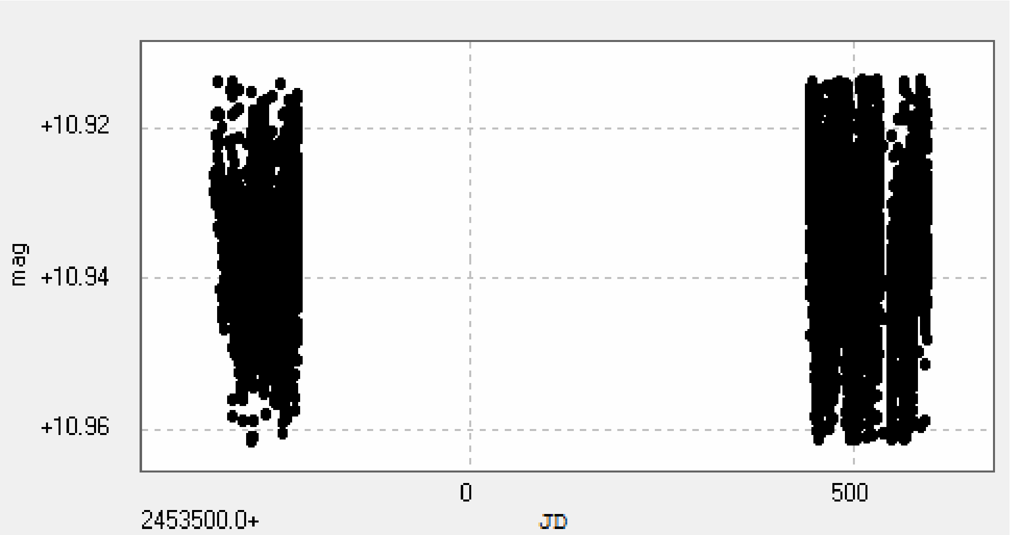
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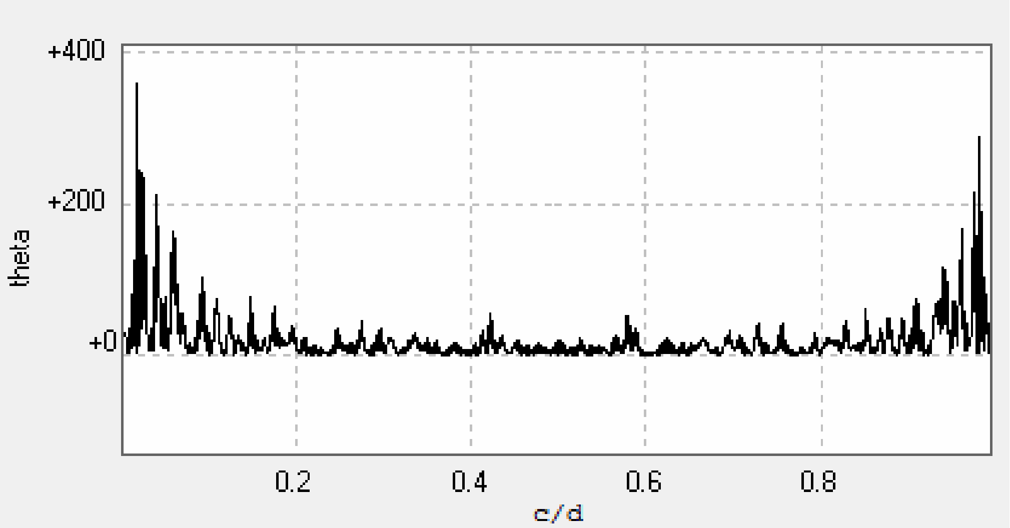
2453500.0+
JD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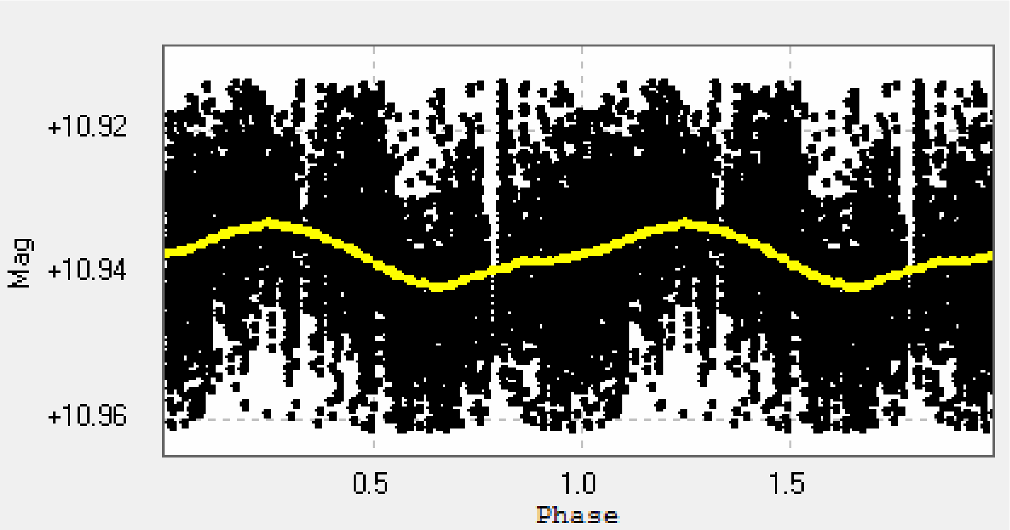
0.8
c/d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Phase

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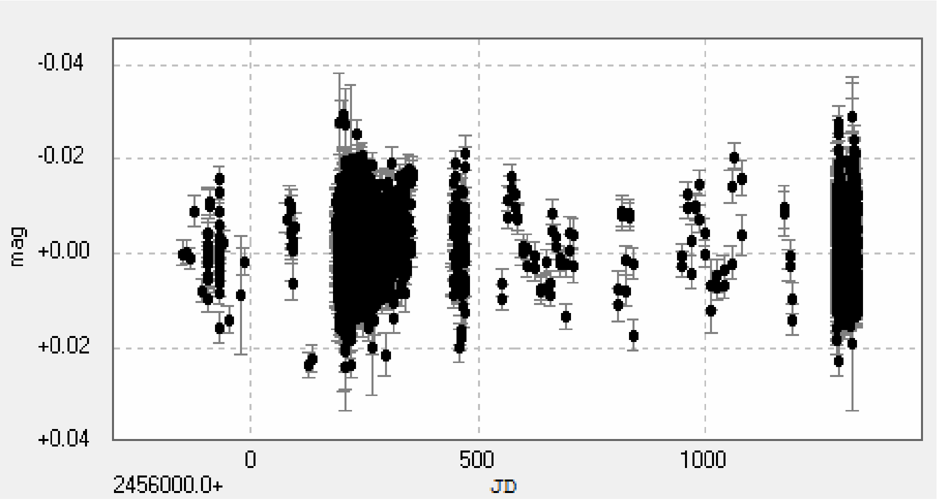

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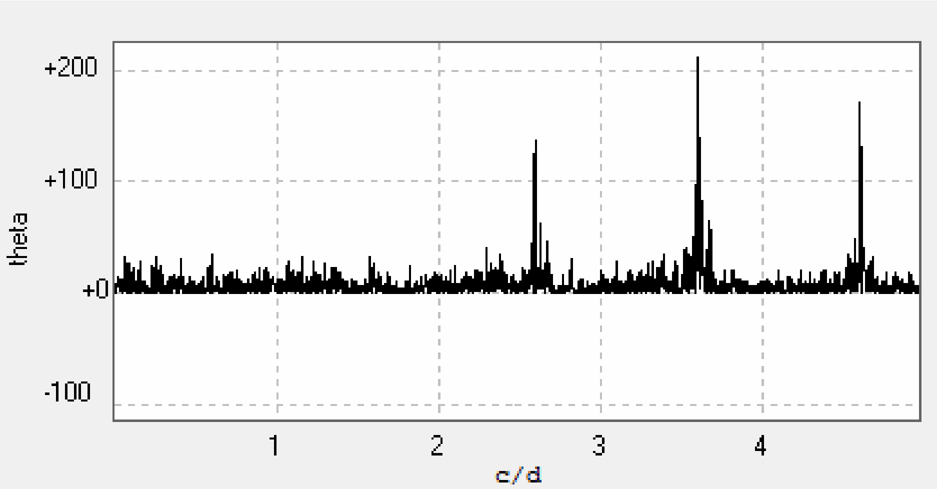

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-100
theta
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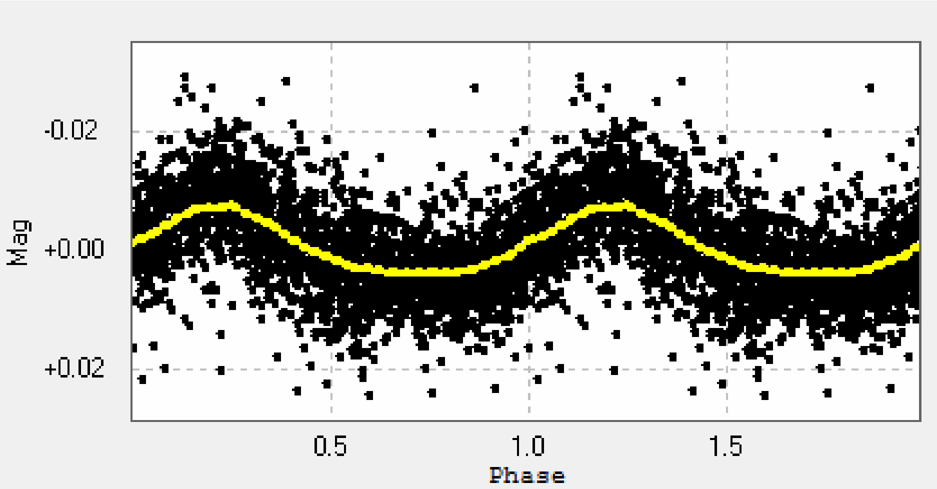
2
3
4
c/d



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Phase

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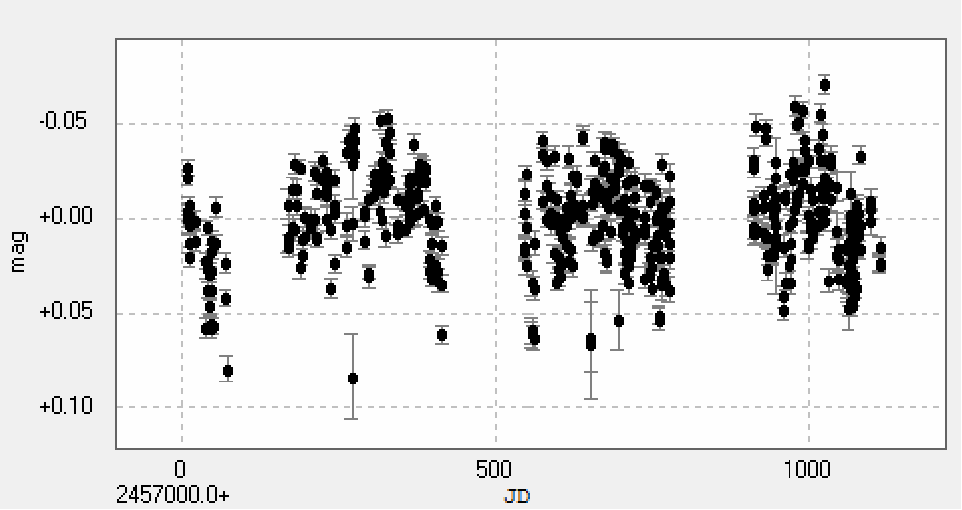
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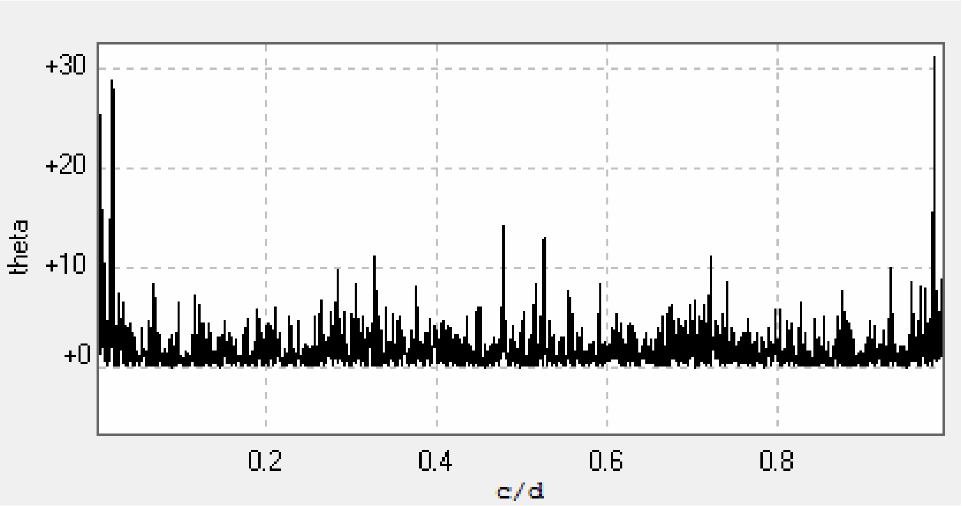
JD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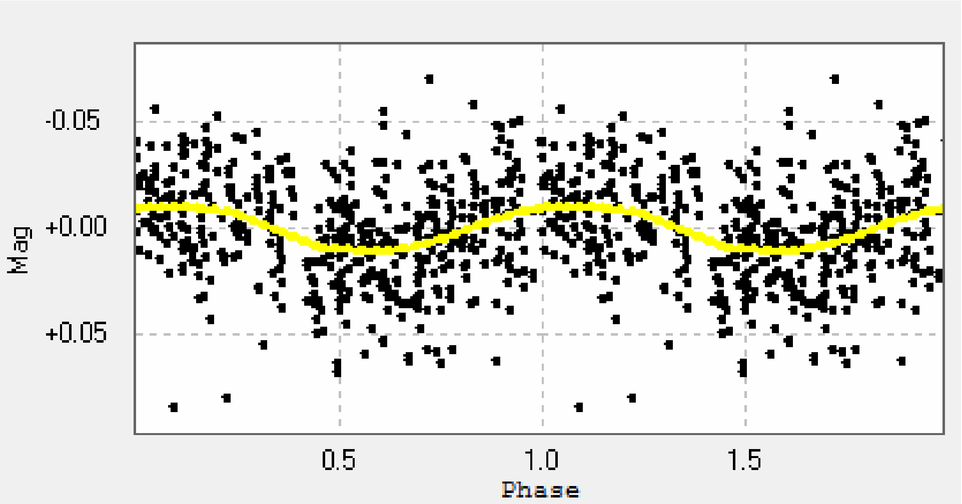
0.8
c/d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Phase

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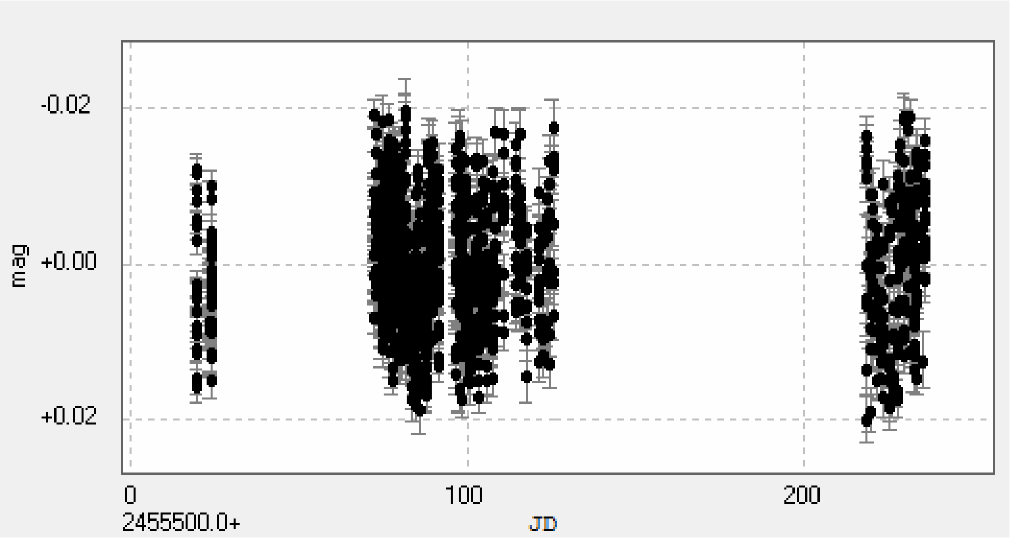
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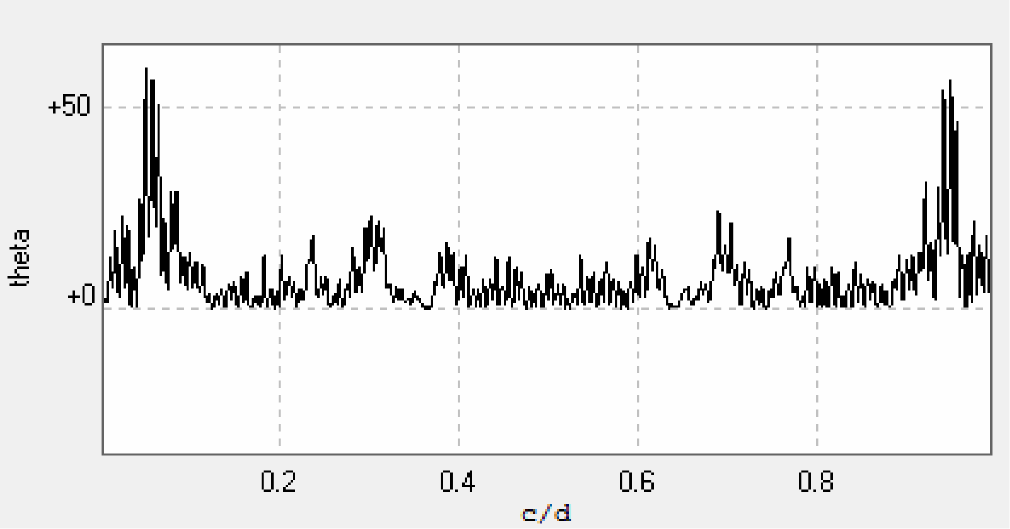
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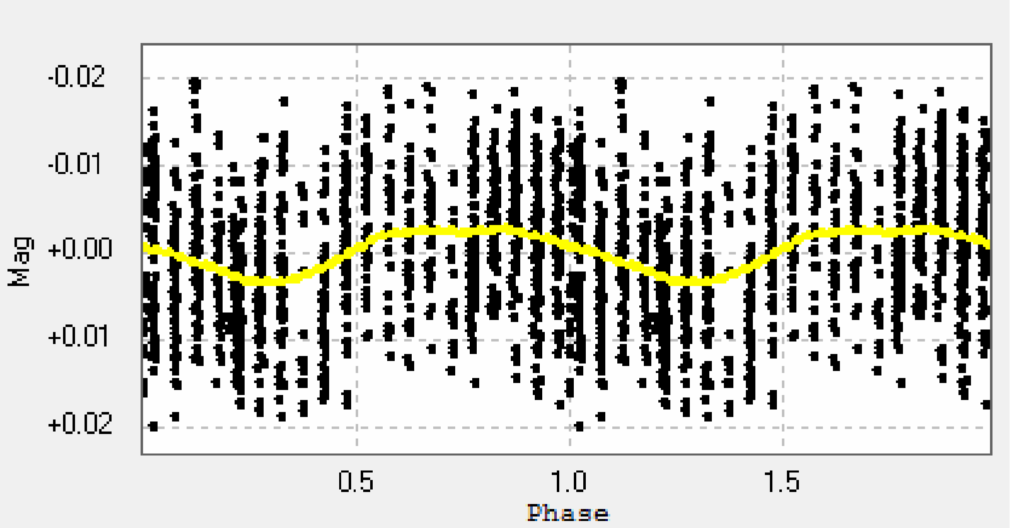
c/d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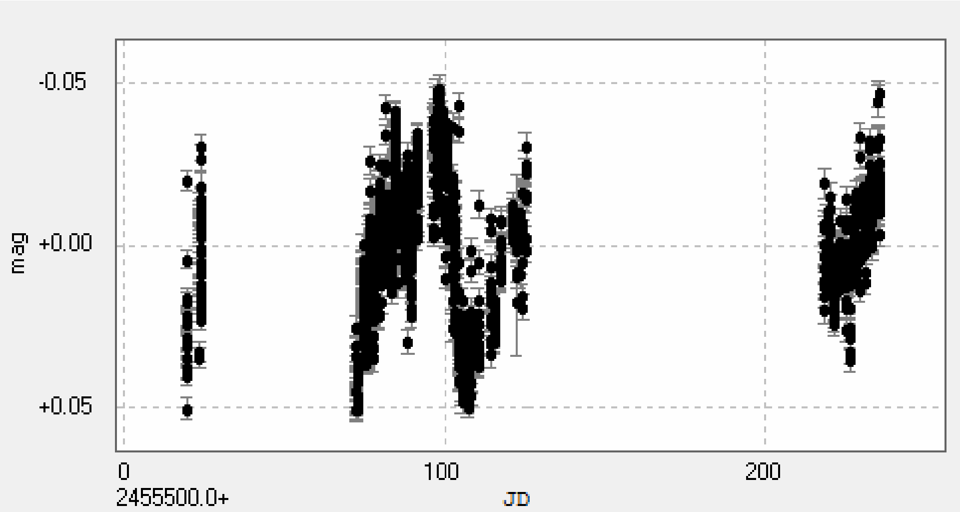
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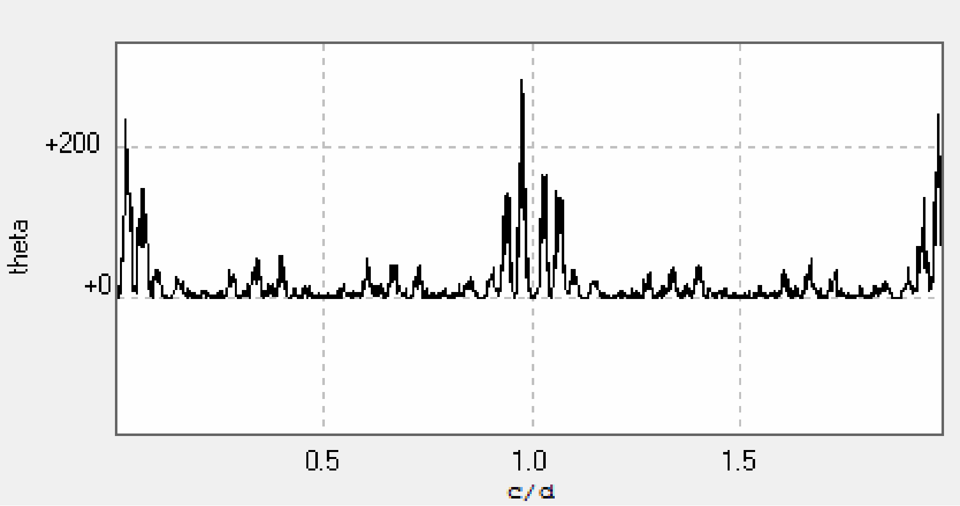
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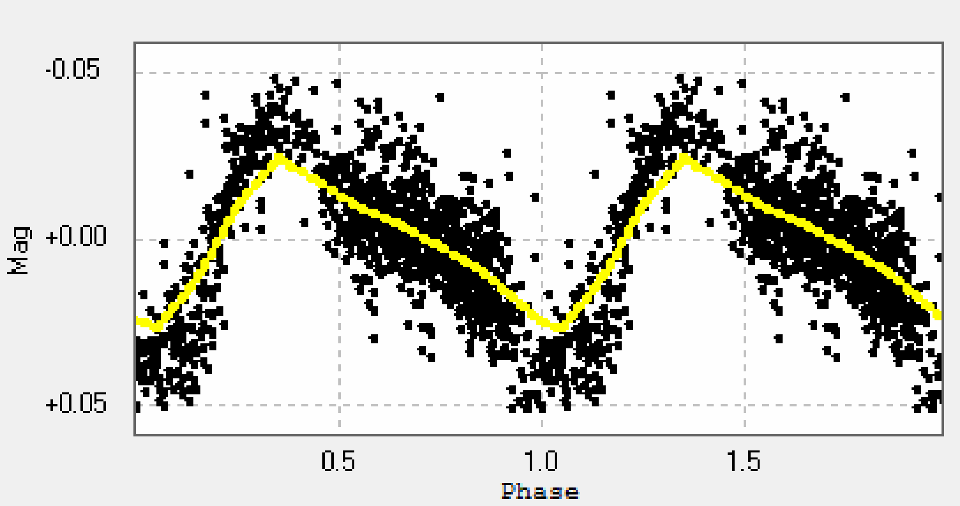
c/d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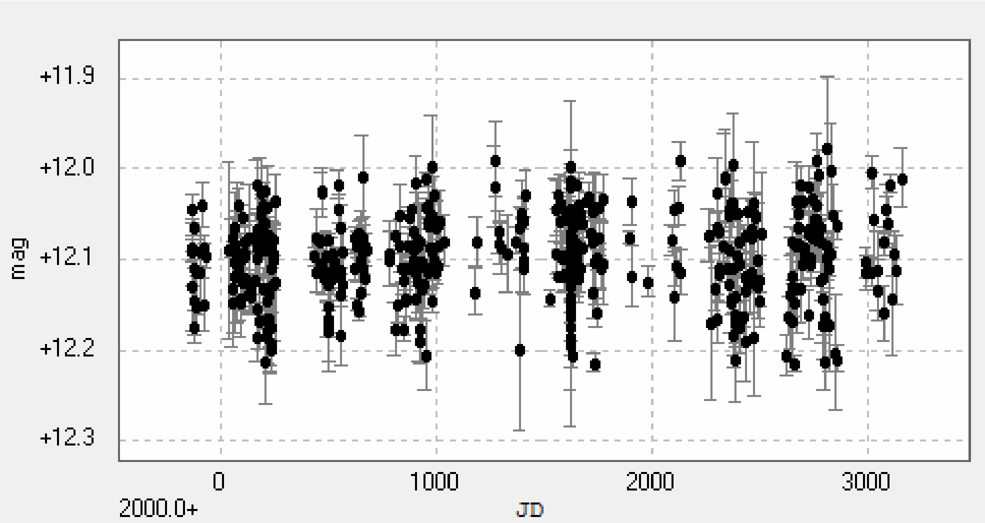
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+12.3
mag
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1000
2000
3000
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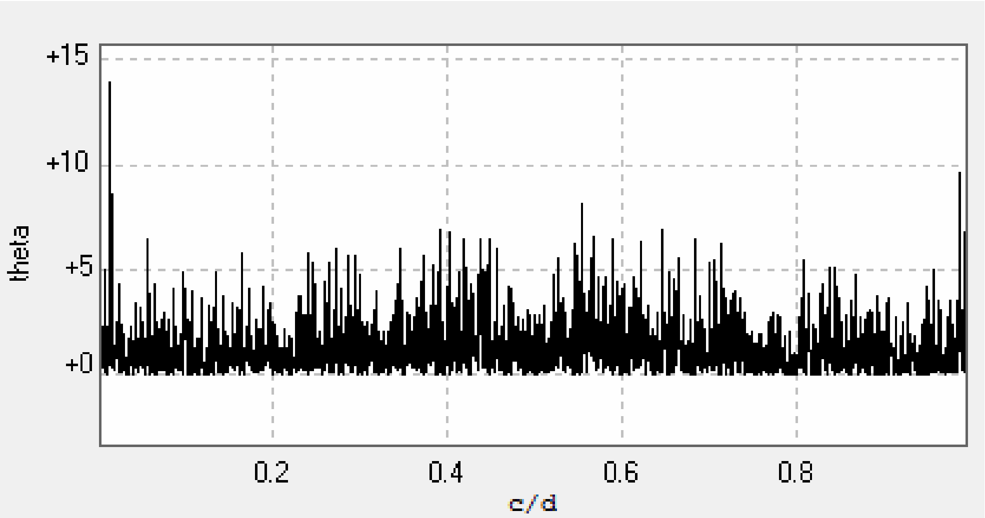
JD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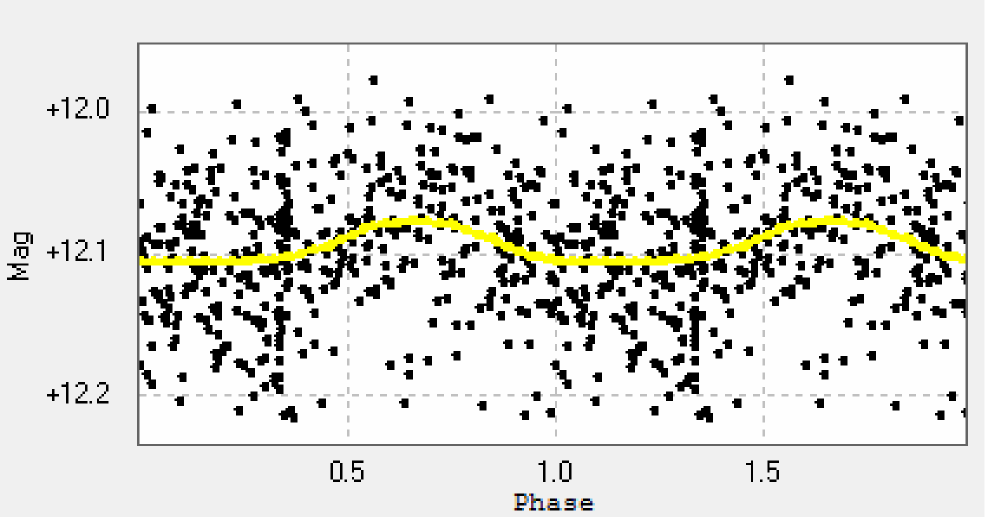
0.8
c/d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+12.2
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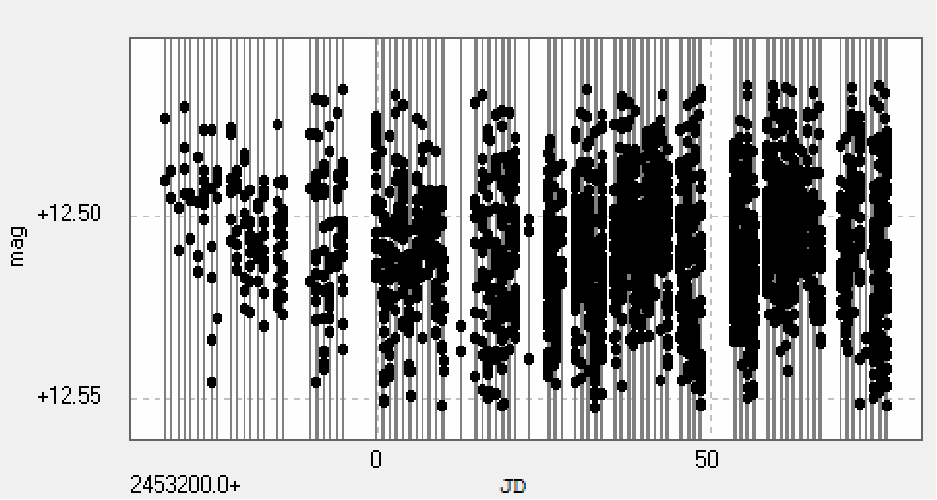
Phase

J01221+221



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0
50
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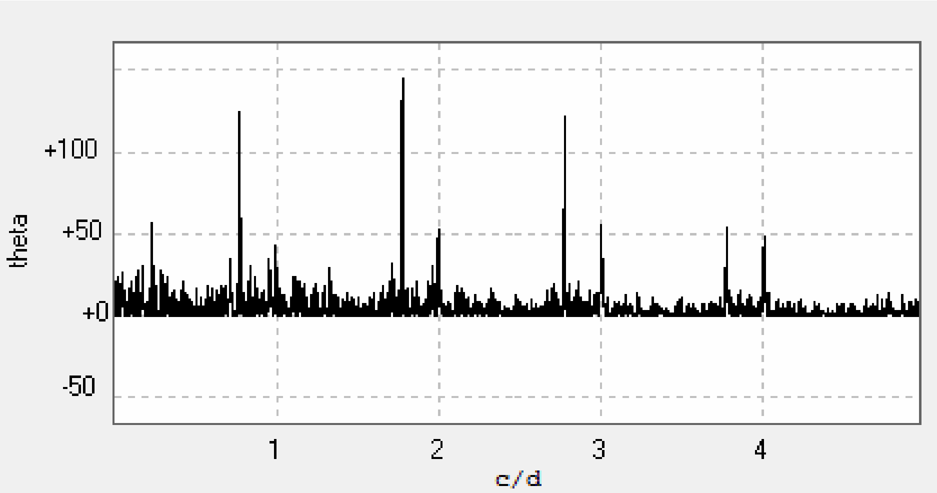
JD



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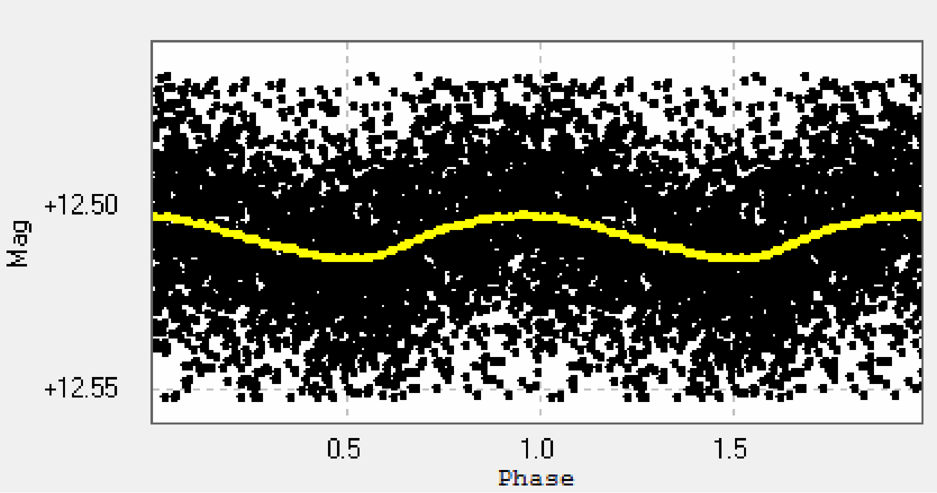
1
2
3
4
c/d



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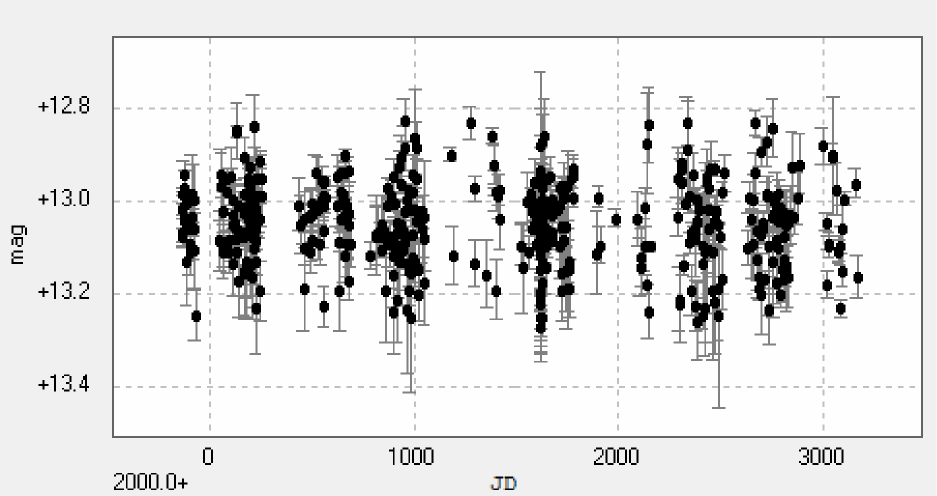
1.5
Phase

J01339-176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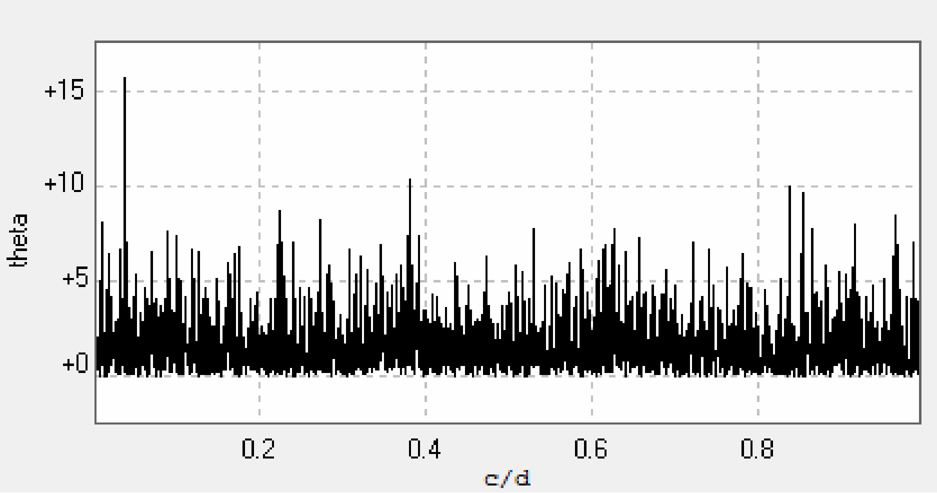
1000
2000
3000
2000.0+
JD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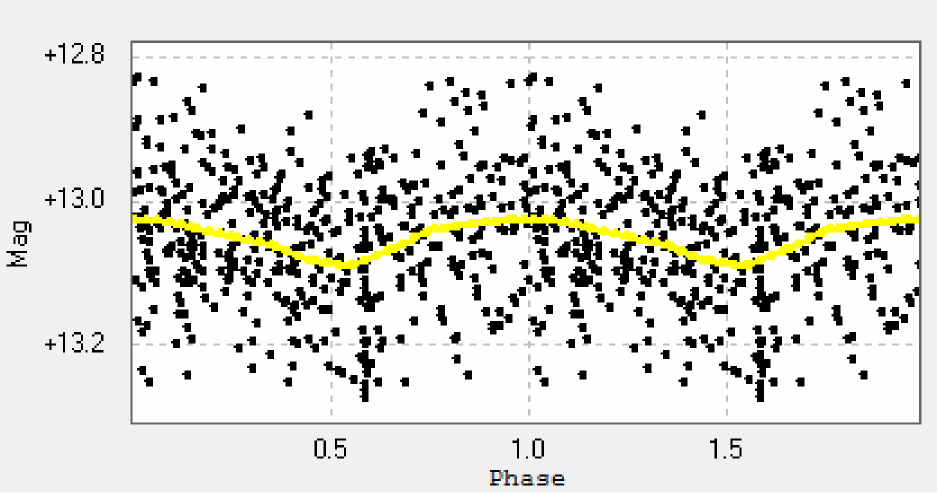
0.8
c/d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Mag
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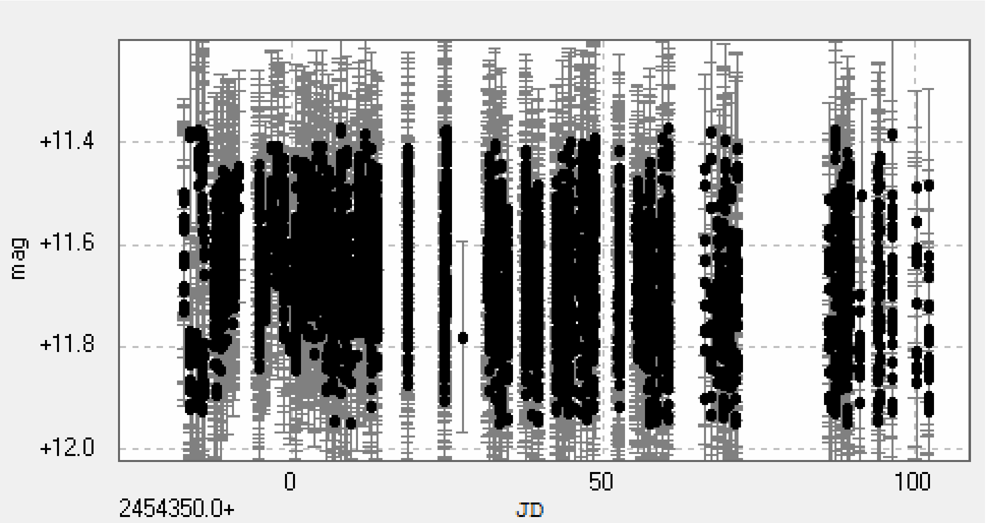
1.5
Phase

J02070+496



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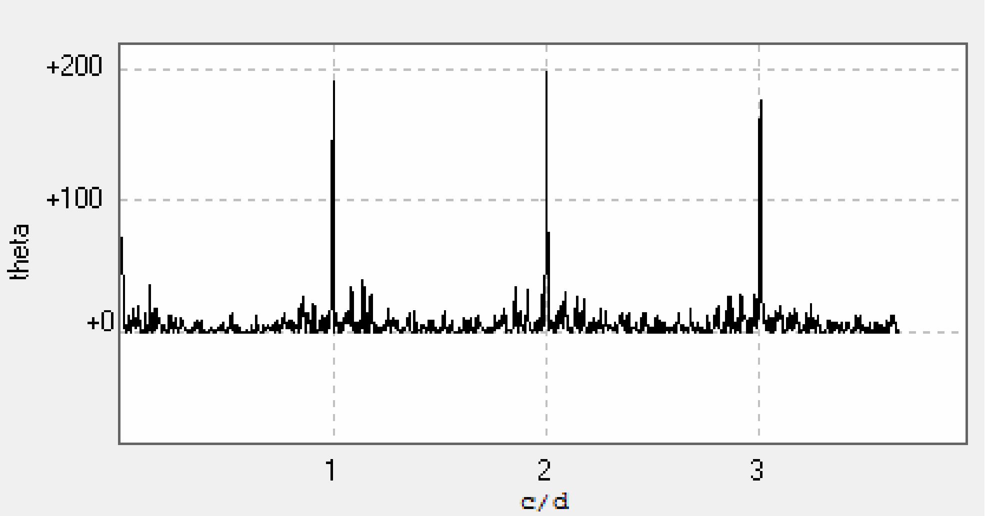
+11.8
+12.0
0
50
100
2454350.0+
JD



theta
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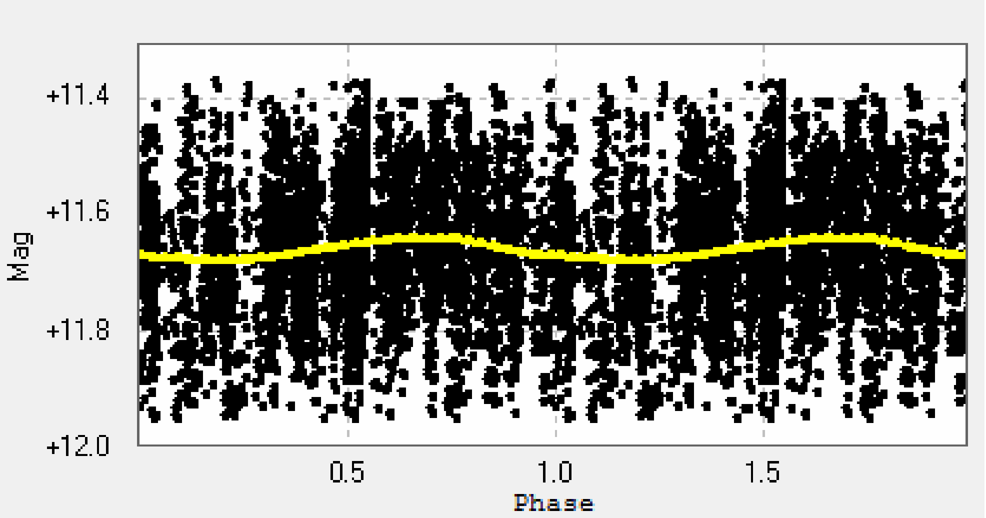
1
2
3
c/d



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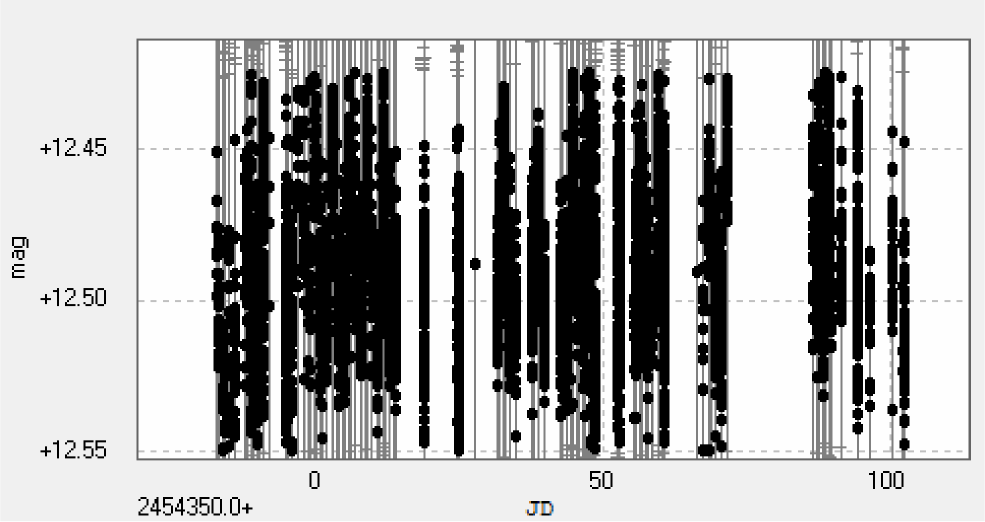
1.5
Phase

J02088+494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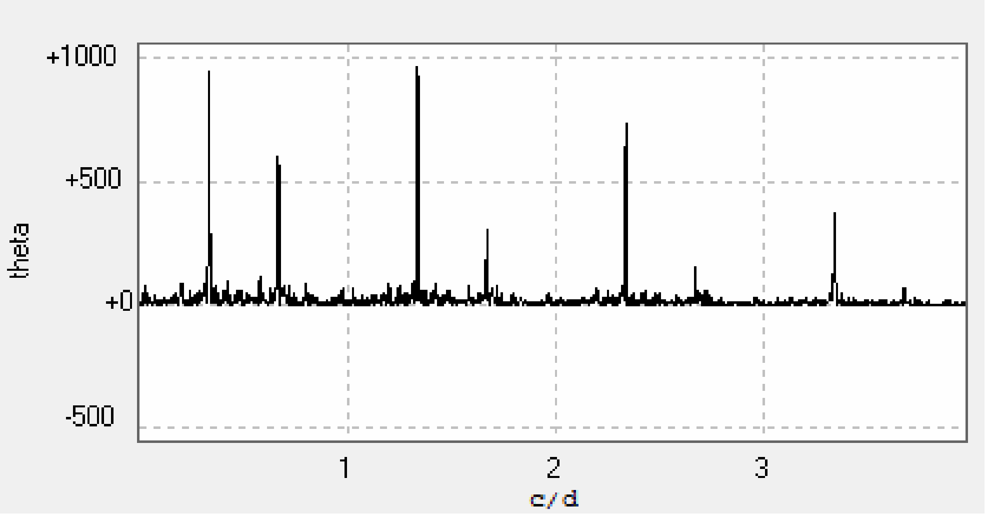
50
100
2454350.0+
JD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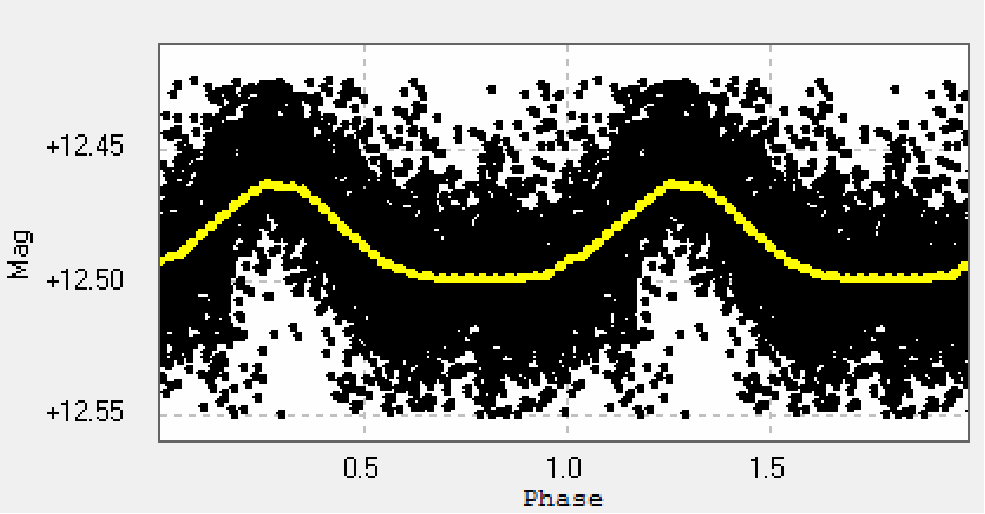
1
2
3
c/d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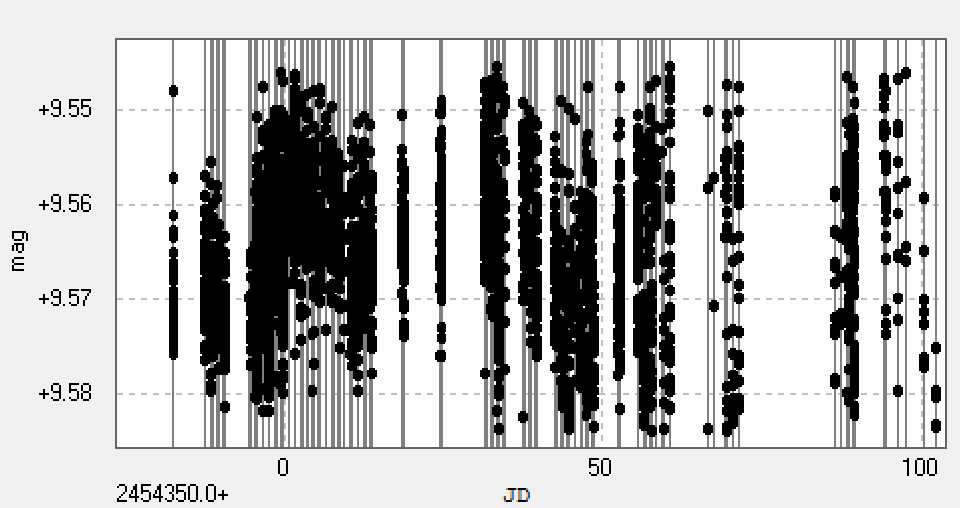
Phase

J02222+478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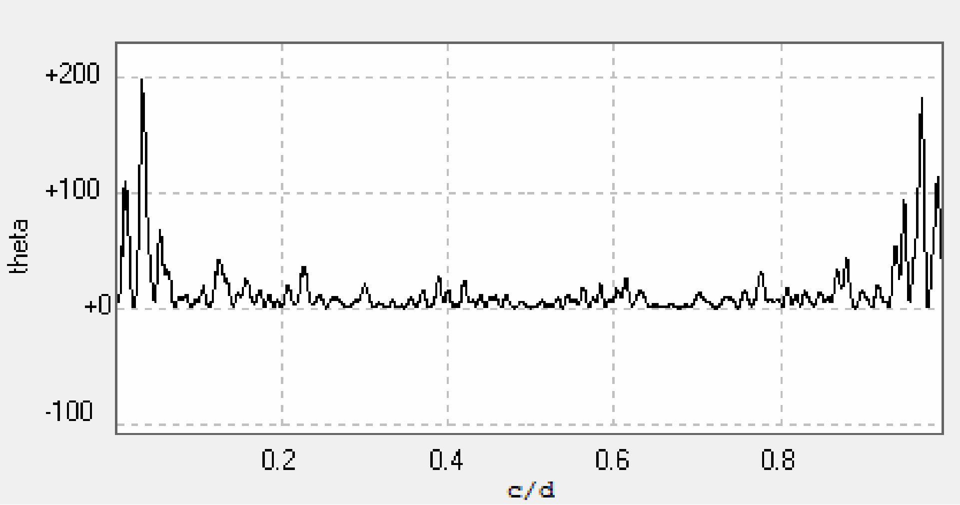
JD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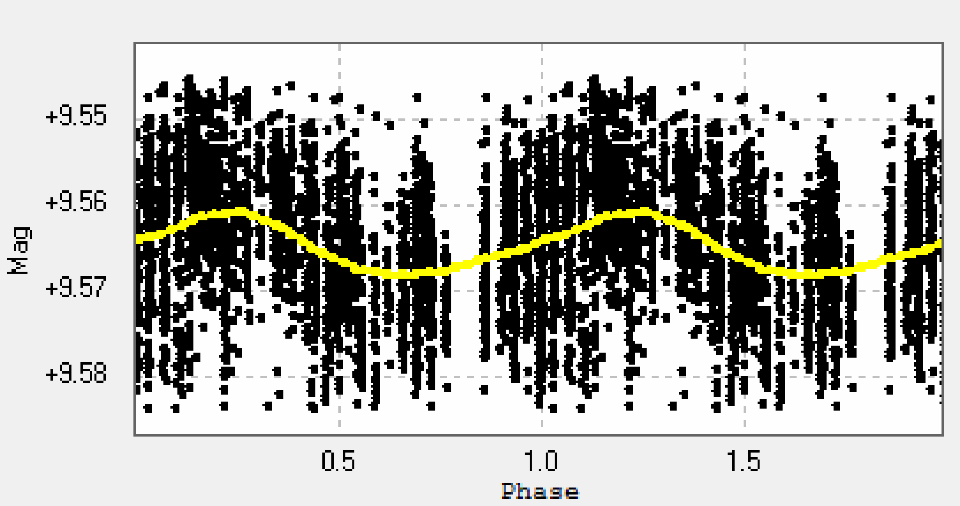
0.6
0.8
c/d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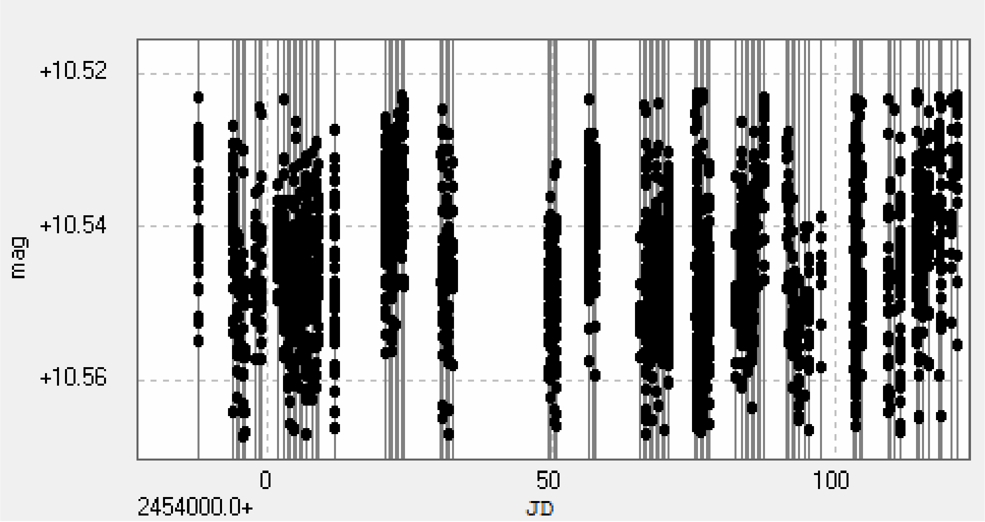
Phase

J02358+202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100
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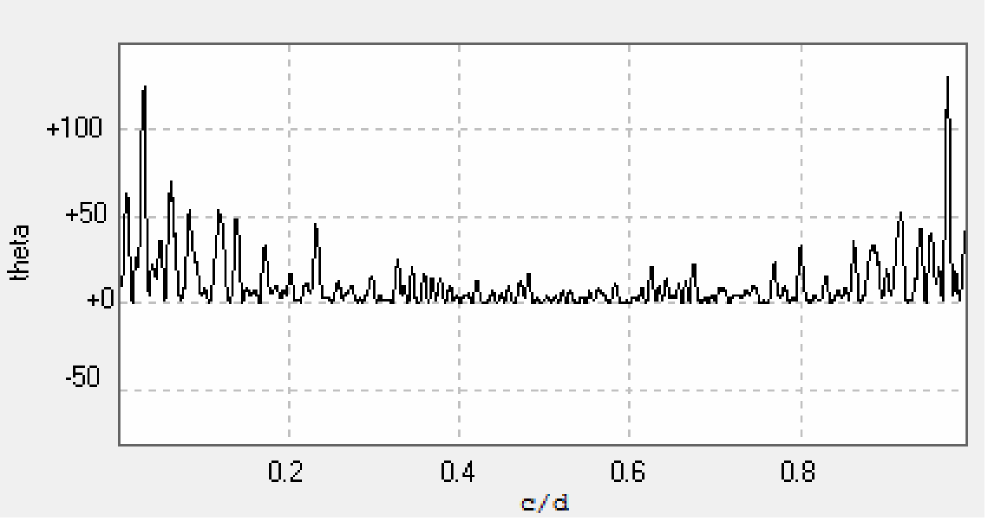
JD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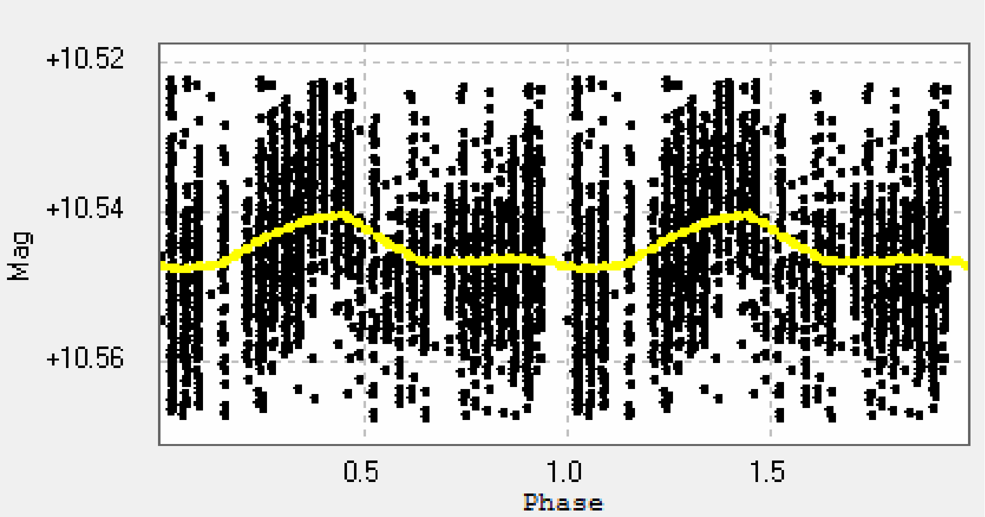
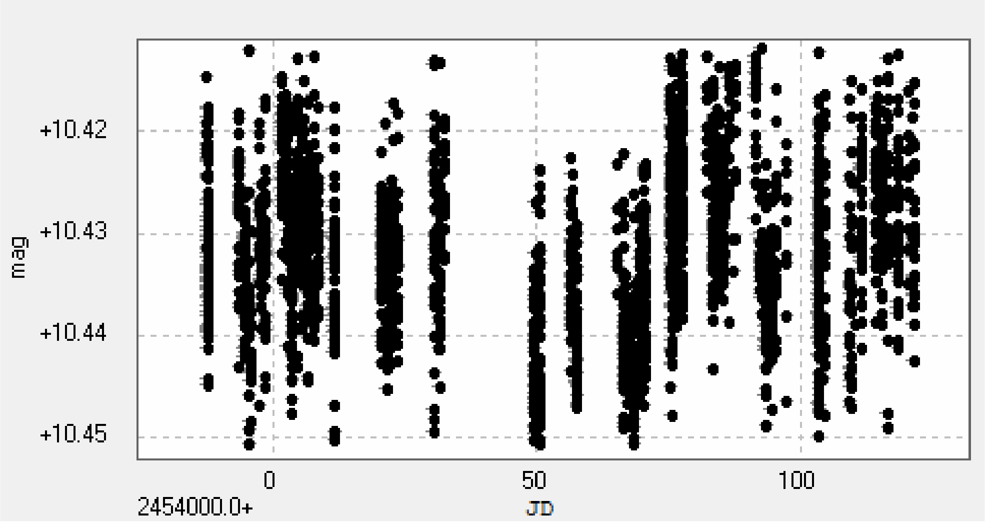
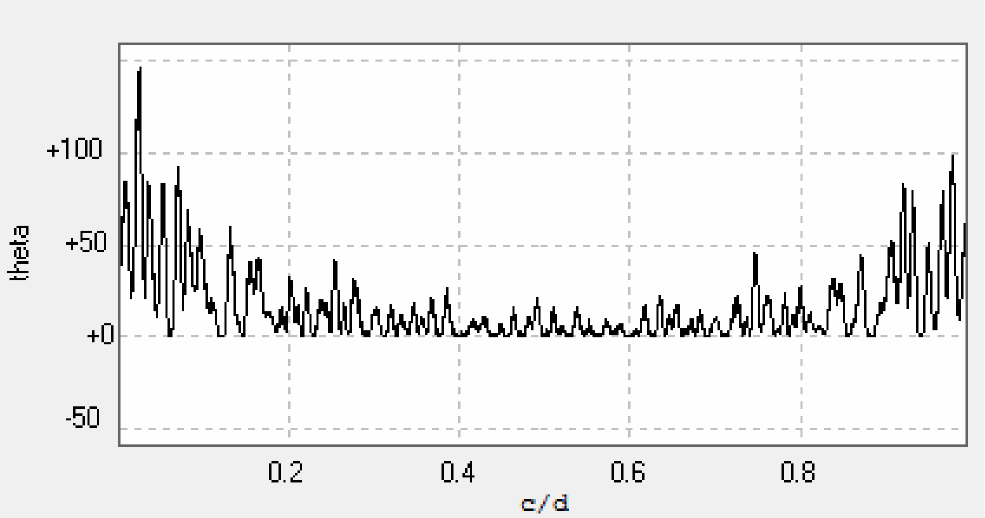
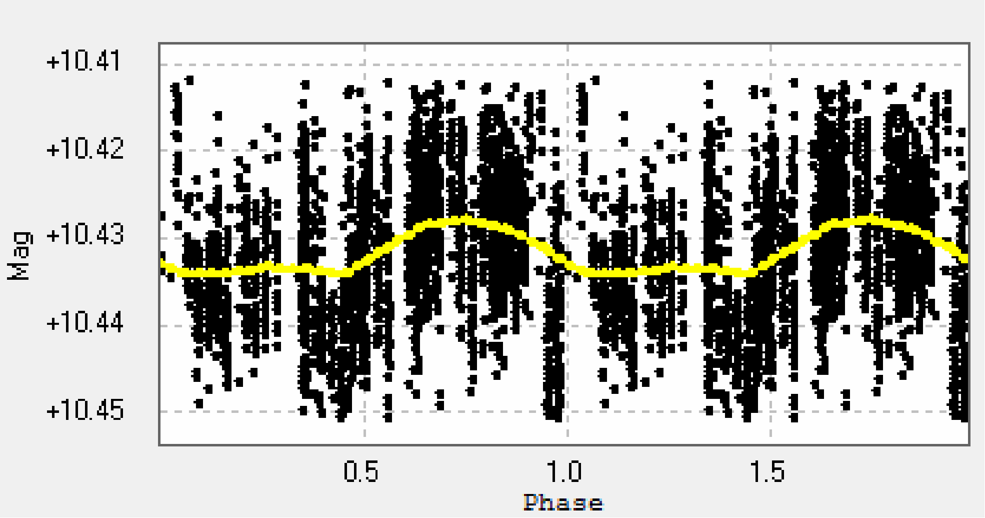
theta
0.2
0.4
0.6
0.8
c/d


+10.52
+10.54
+10.56
Mag
0.5
1.0
1.5
Phase

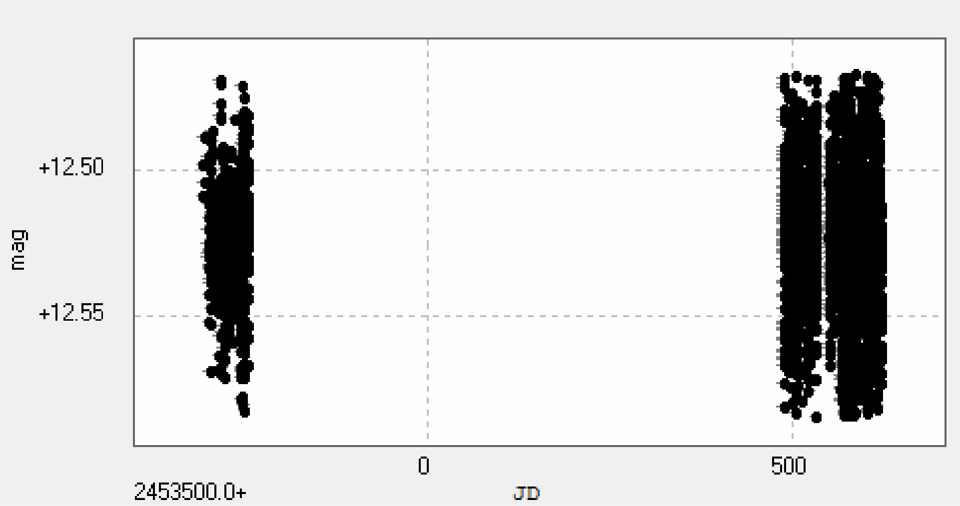
J02442+255

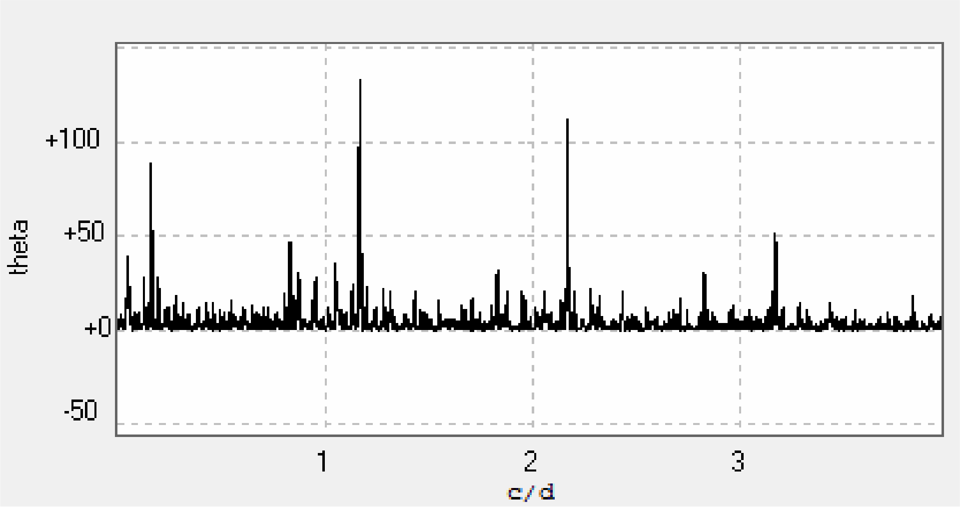

mag
+10.42
+10.43
+10.44
+10.45
0
50
100
2454000.0+
JD

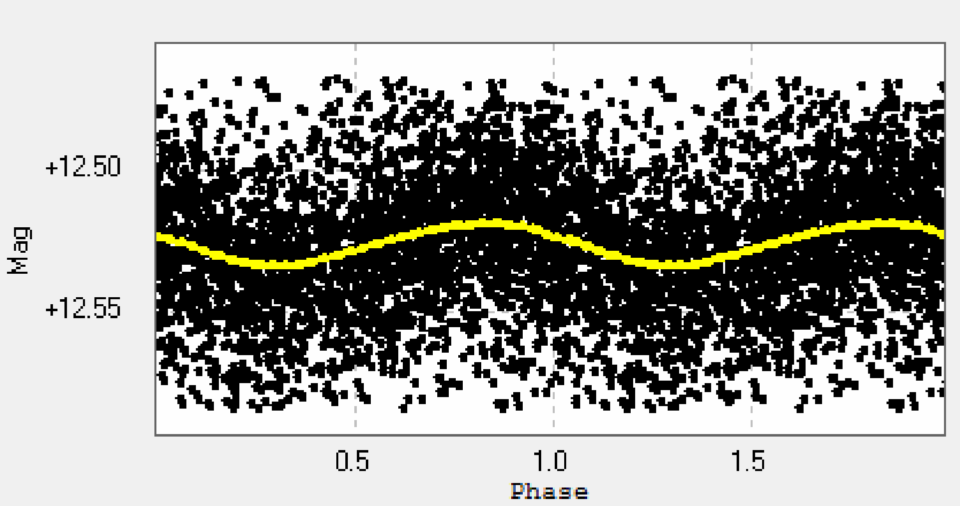

theta
+100
+50
+0
-50
0.2
0.4
0.6
0.8
c/d


Mag
+10.41
+10.42
+10.43
+10.44
+10.45
0.5
1.0
1.5
Phase

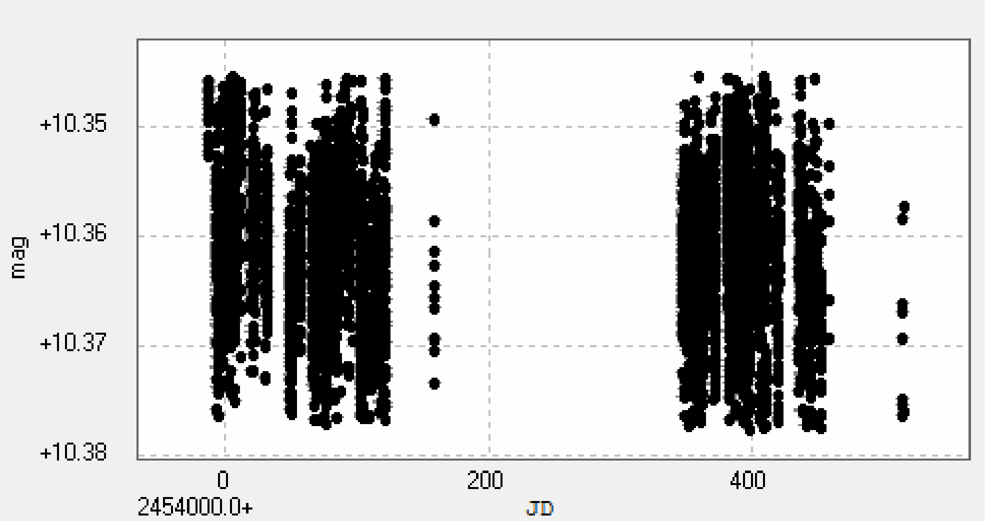
J02519+224


+12.50
+12.55
mag
0
500
2453500.0+
JD

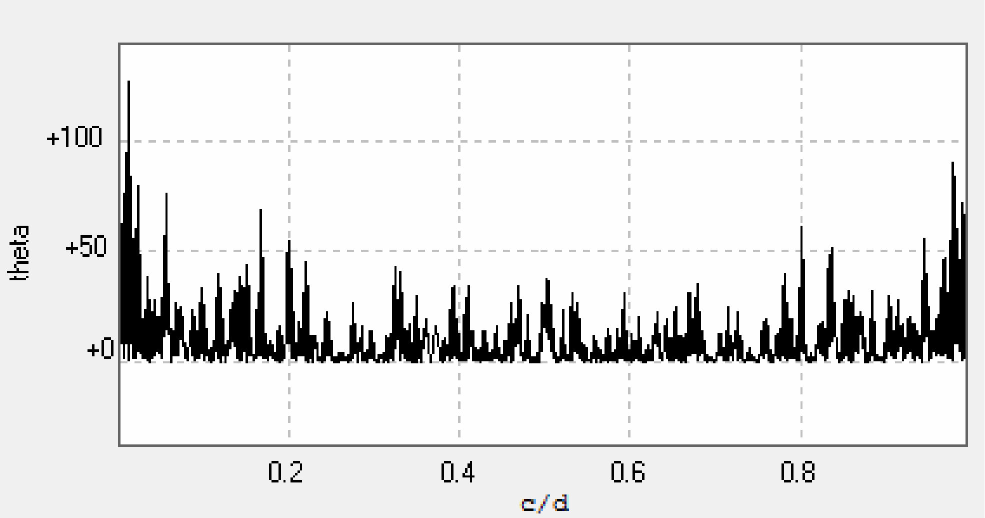

+100
+50
+0
-50
theta
1
2
3
c/d


+12.50
+12.55
Mag
0.5
1.0
1.5
Phase

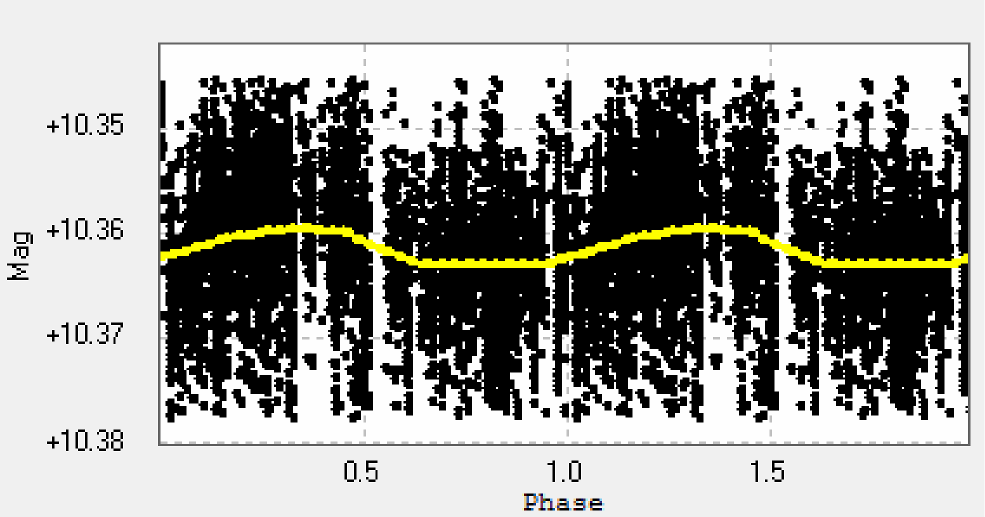
J03181+382



mag
+10.35
+10.36
+10.37
+10.38
0
200
400
2454000.0+
JD

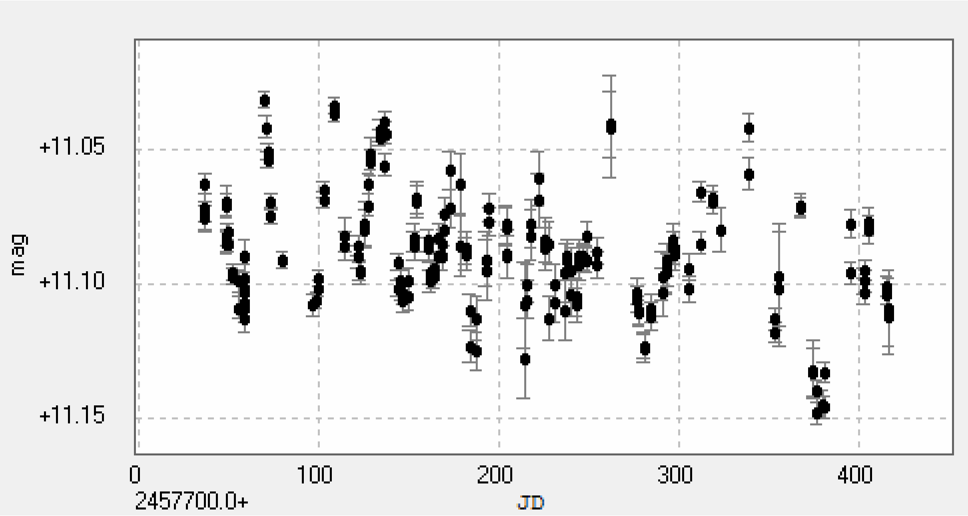


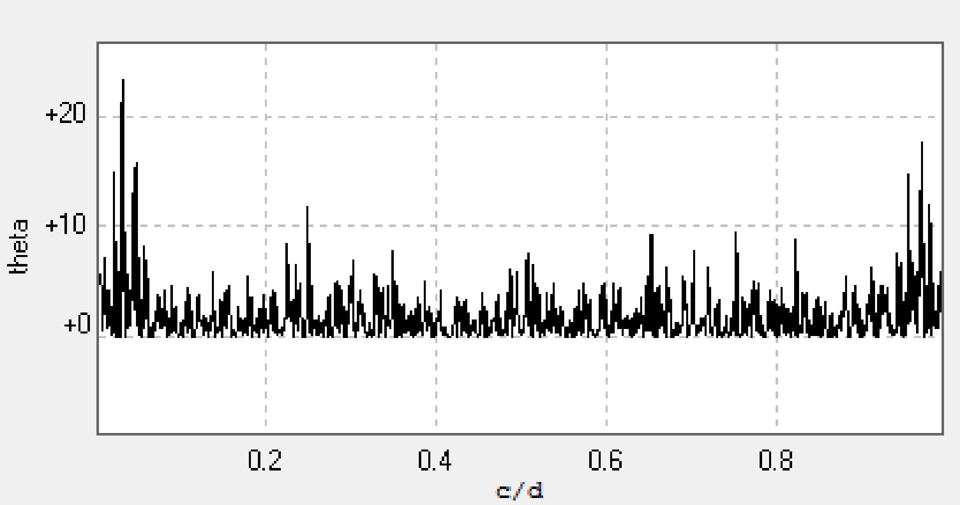
theta
+100
+50
+0
0.2
0.4
0.6
0.8
c/d

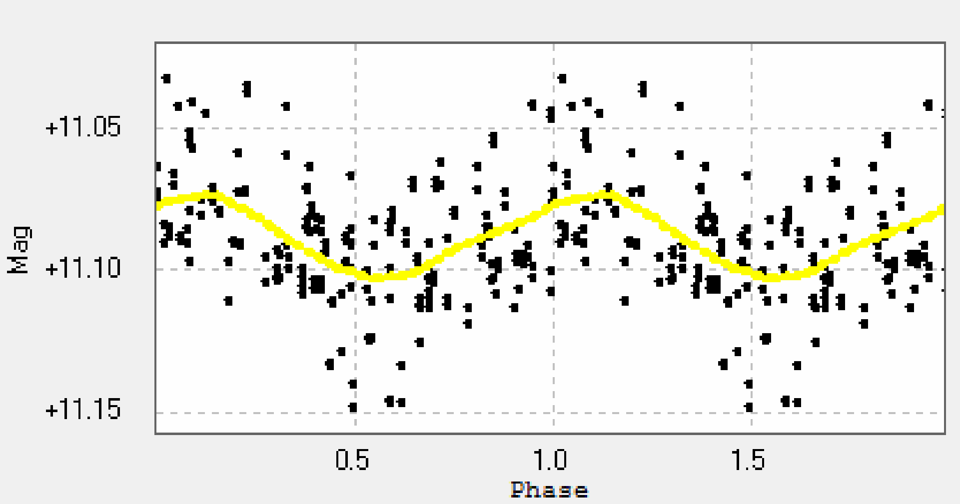


Mag
+10.35
+10.36
+10.37
+10.38
0.5
1.0
1.5
Phase

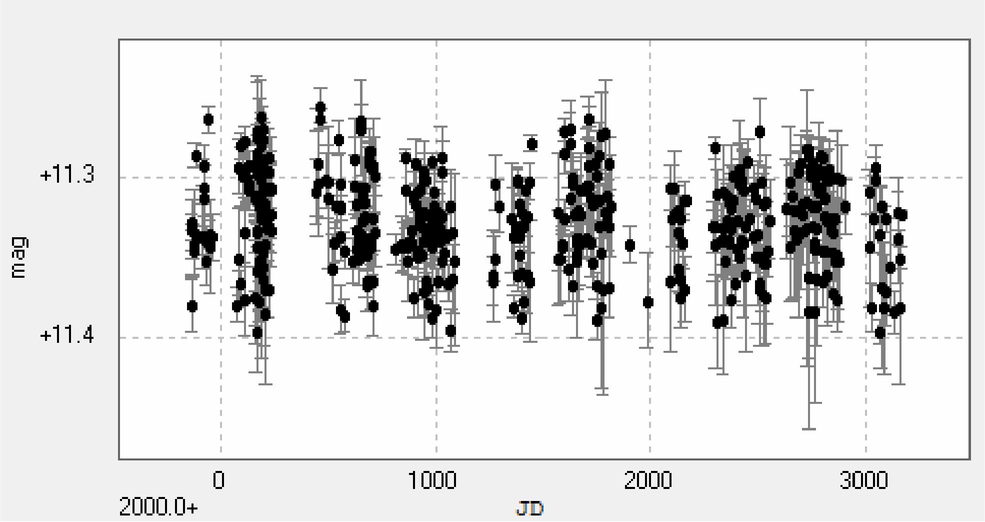
J03213+799

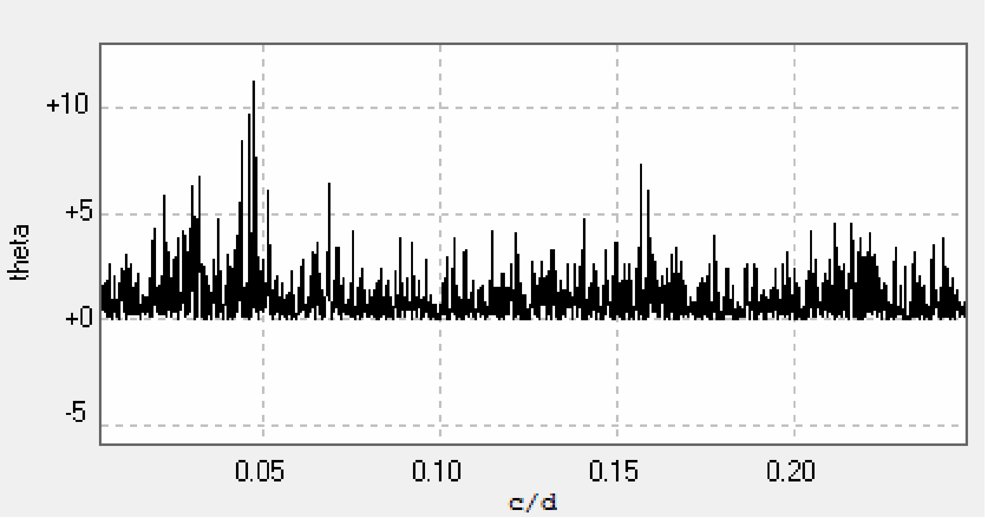

mag
+11.05
+11.10
+11.15
0
100
200
300
400
2457700.0+
JD

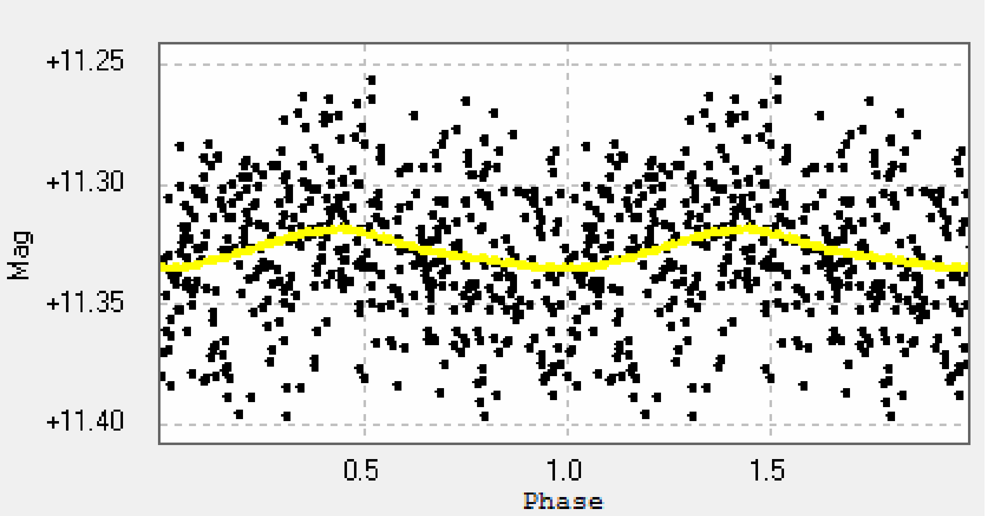

theta
+20
+10
+0
0.2
0.4
0.6
0.8
c/d


Mag
+11.05
+11.10
+11.15
0.5
1.0
1.5
Phase

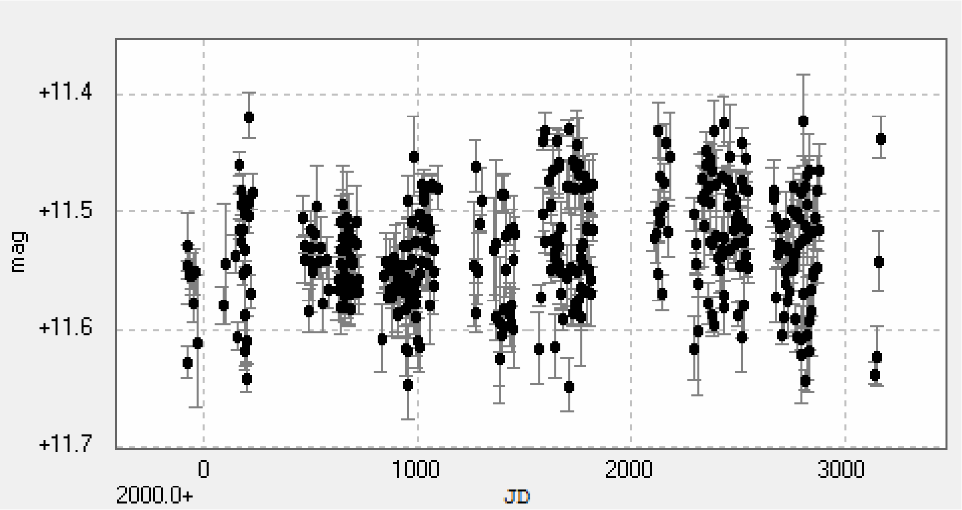
J03217-066

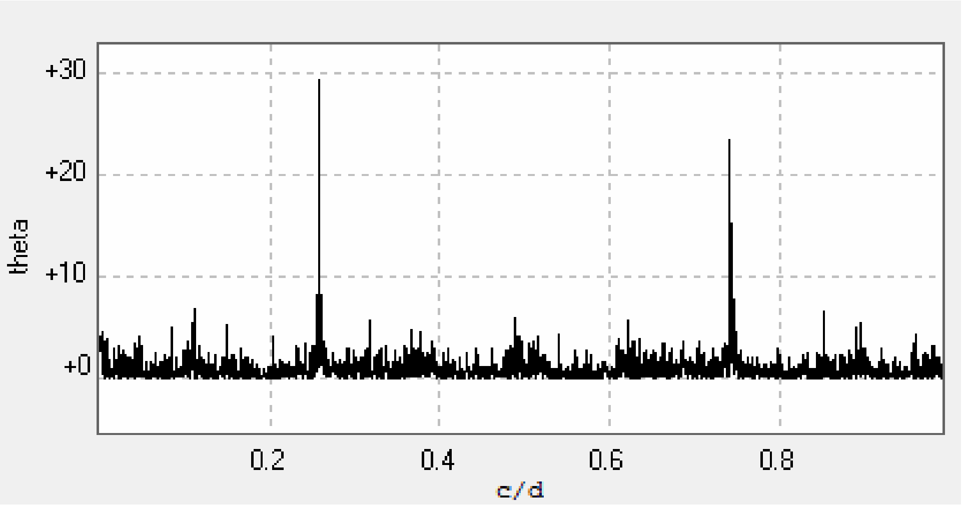

+11.3
+11.4
mag
0
1000
2000
3000
2000.0+
JD

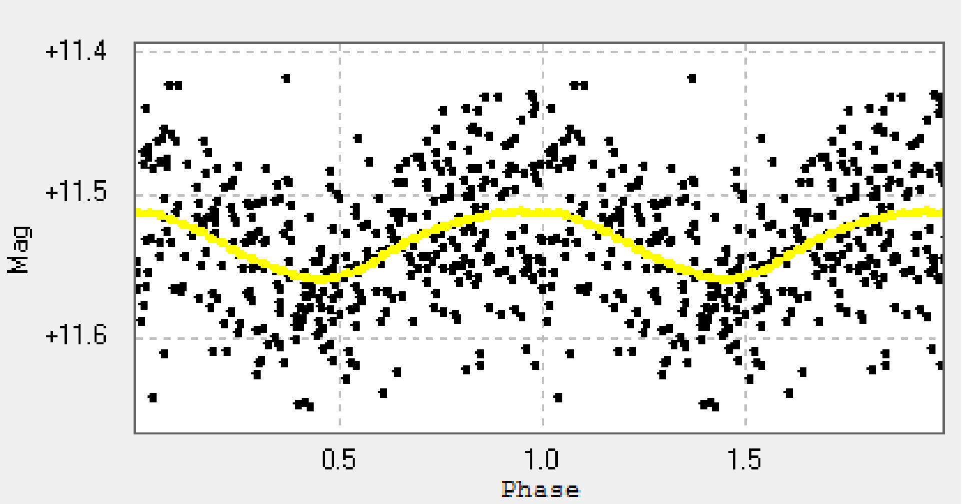

+10
+5
+0
-5
theta
0.05
0.10
0.15
0.20
c/d


+11.25
+11.30
+11.35
+11.40
Mag
0.5
1.0
1.5
Phase

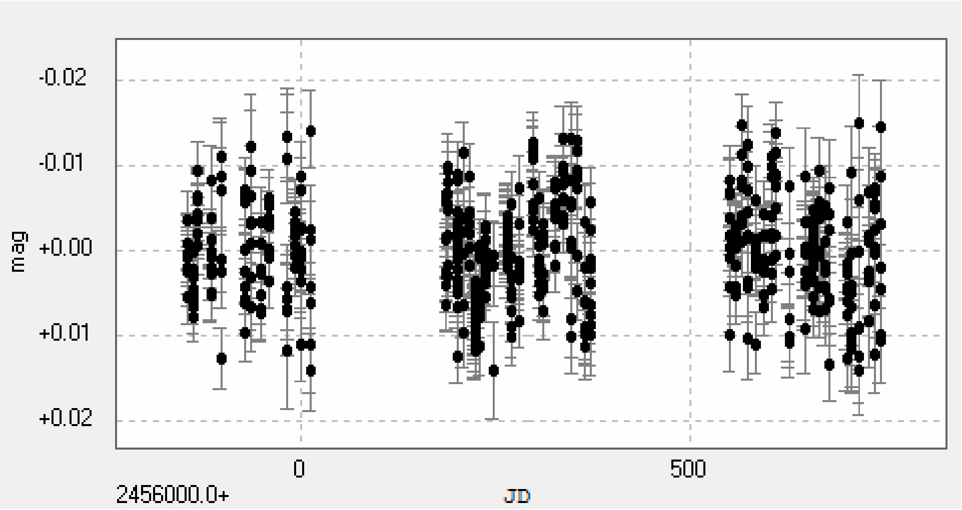
J03473-019


+11.4
+11.5
+11.6
+11.7
mag
0
1000
2000
3000
2000.0+
JD

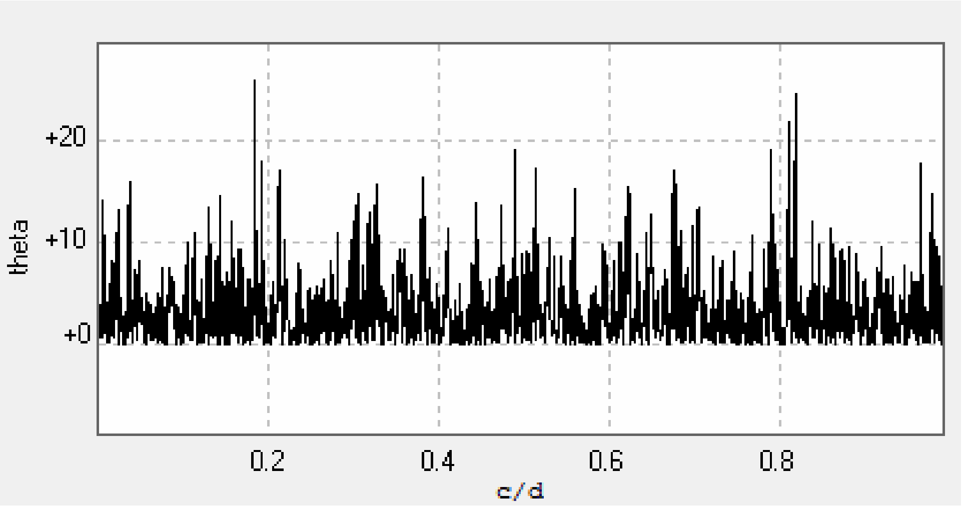

+30
+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d


+11.4
+11.5
+11.6
Mag
0.5
1.0
1.5
Phase

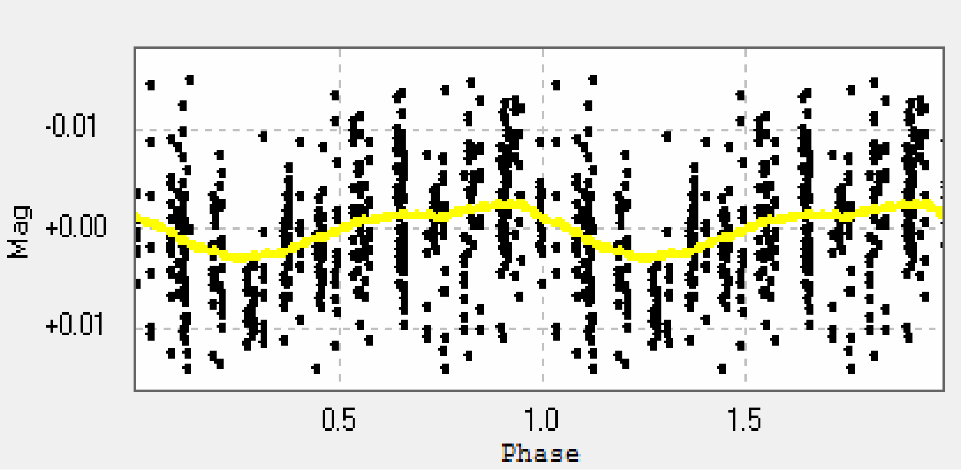
J04225+105



-0.02
-0.01
+0.00
+0.01
+0.02
mag
0
500
2456000.0+
JD

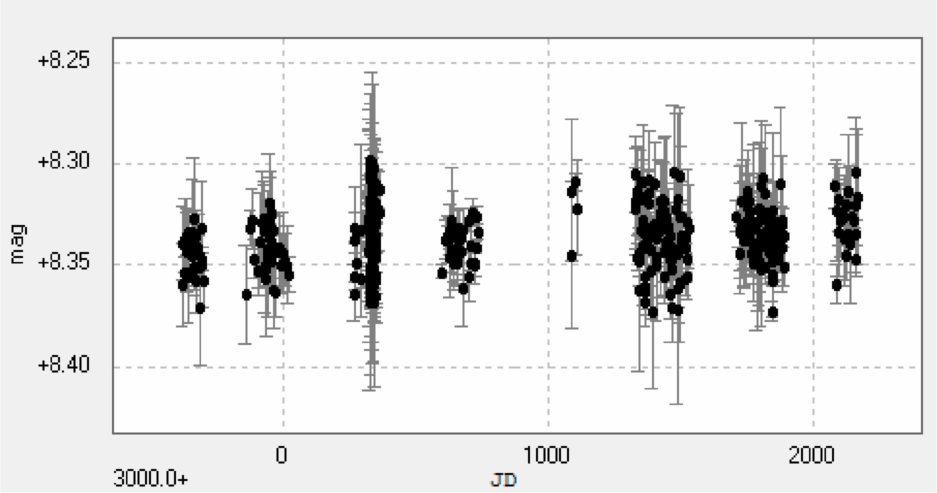


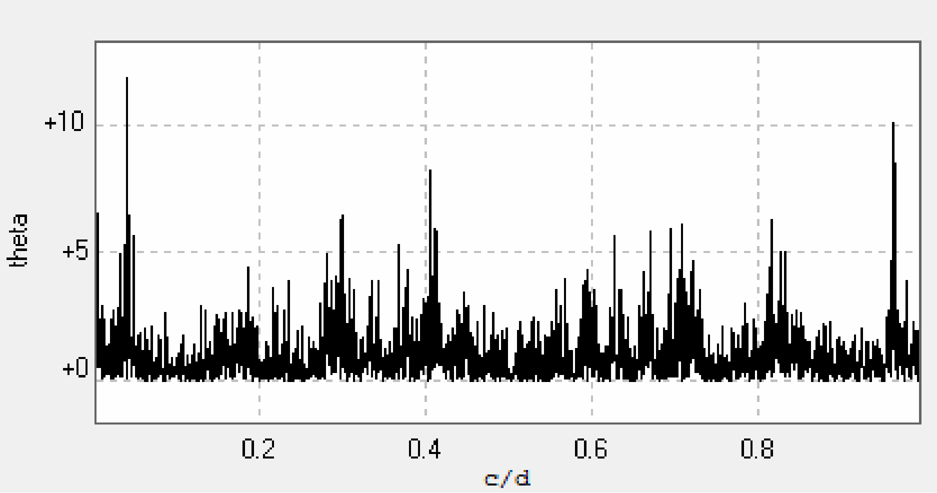
+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d

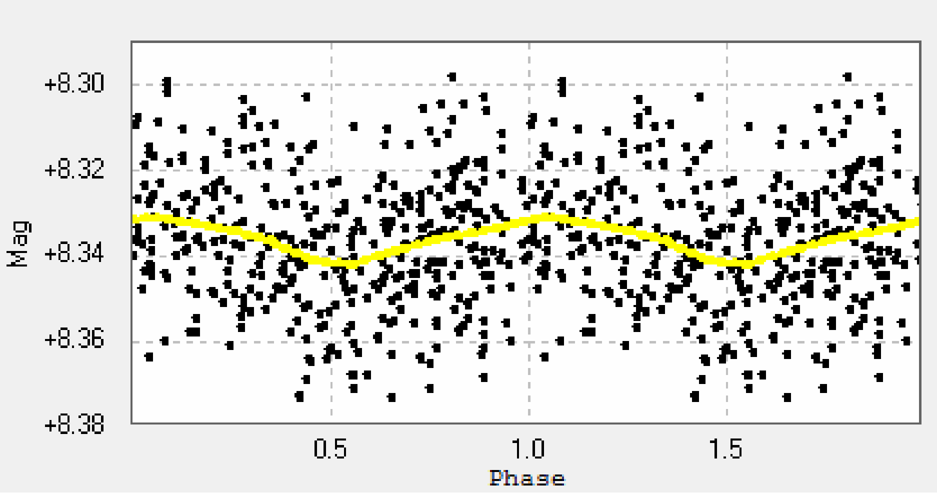


-0.01
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

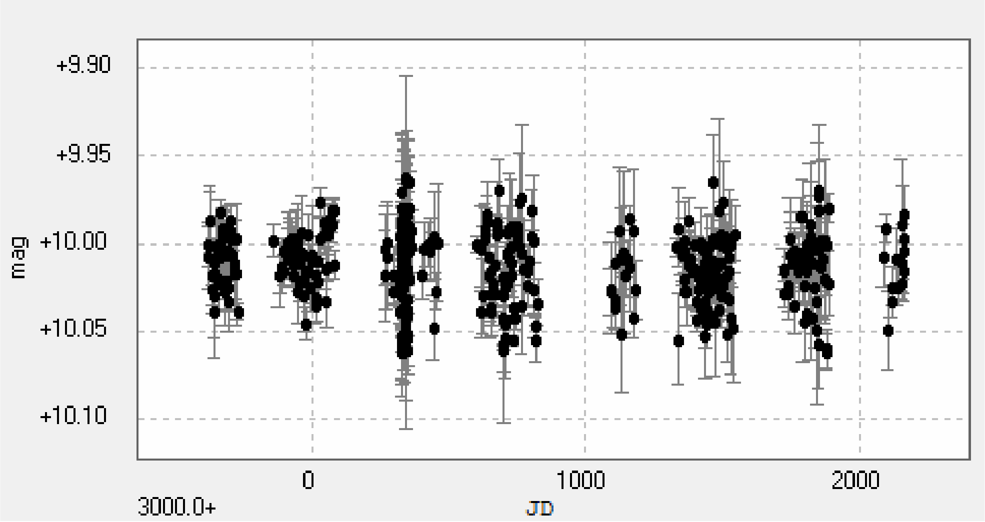
J04290+219


+8.25
+8.30
+8.35
+8.40
mag
0
1000
2000
3000.0+
JD

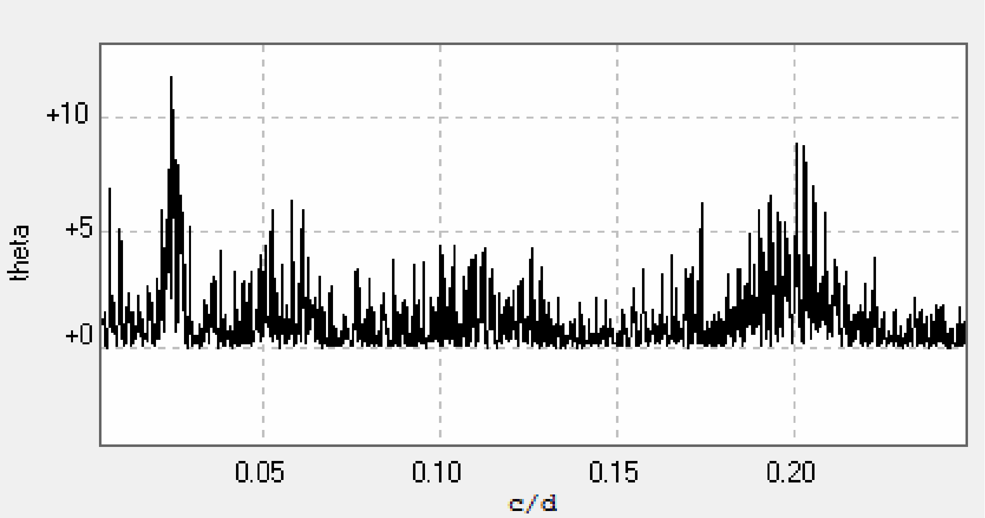

+10
+5
+0
theta
0.2
0.4
0.6
0.8
c/d


+8.30
+8.32
+8.34
+8.36
+8.38
Mag
0.5
1.0
1.5
Phase

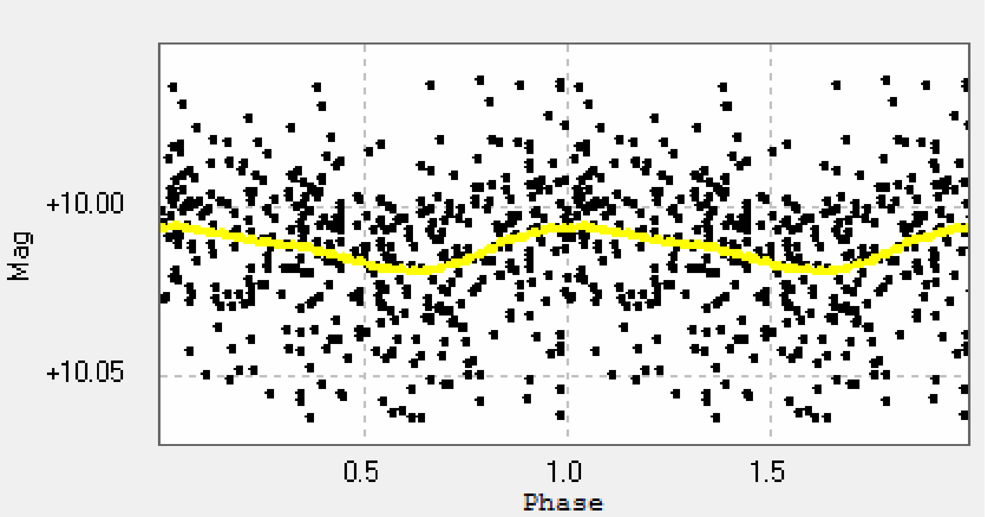
J04429+189



+9.90
+9.95
+10.00
+10.05
+10.10
mag
0
1000
2000
3000.0+
JD

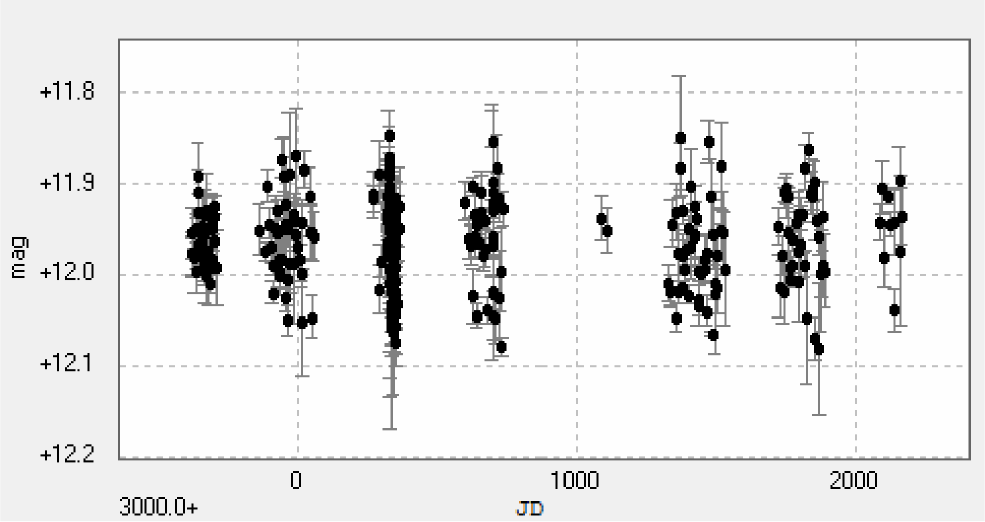


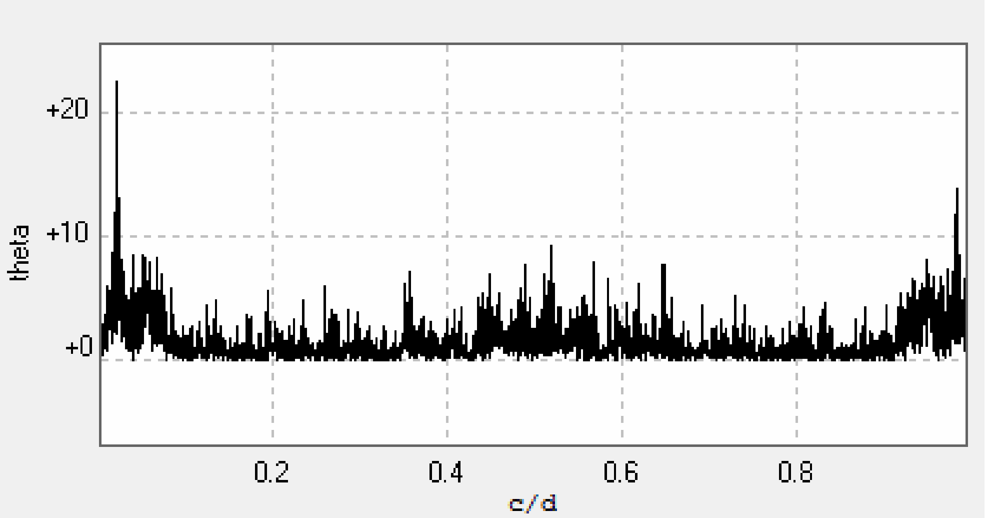
+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d

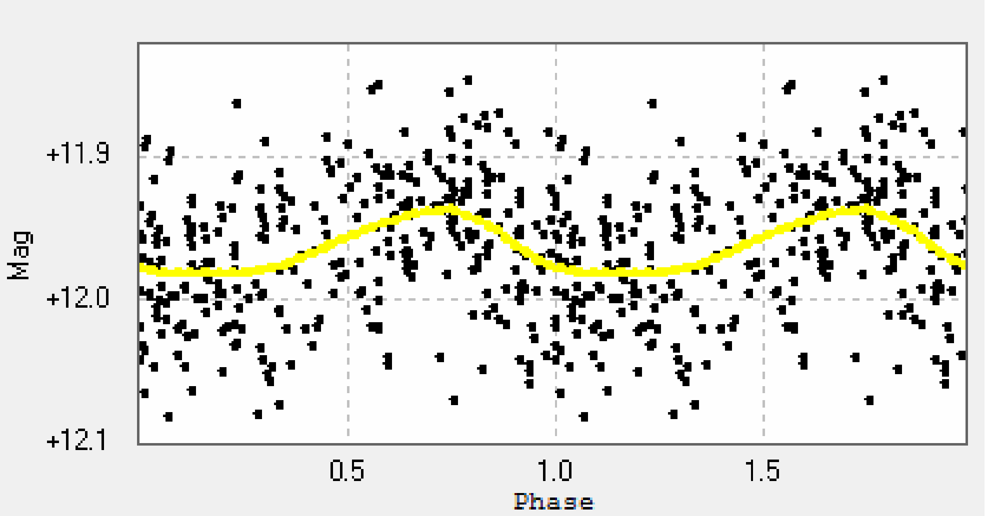


+10.00
+10.05
Mag
0.5
1.0
1.5
Phase

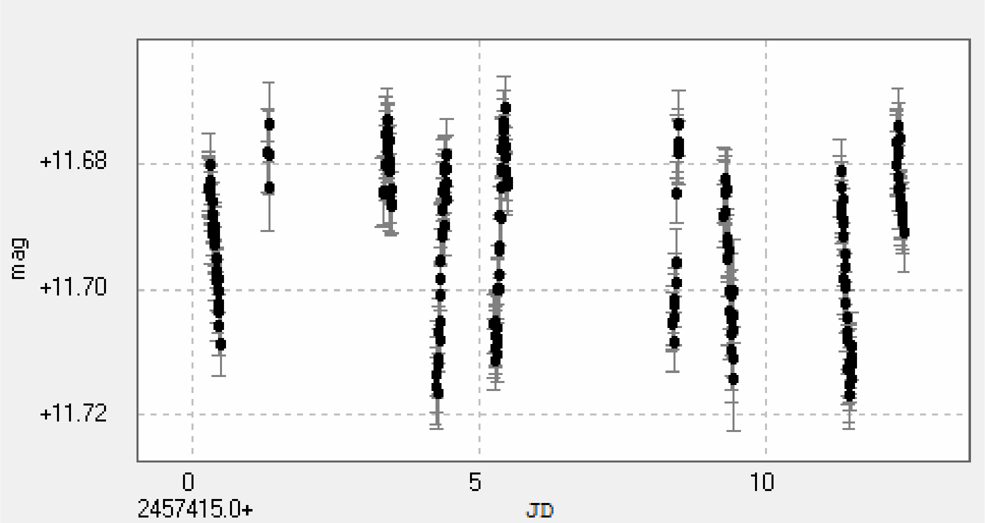
J04429+214

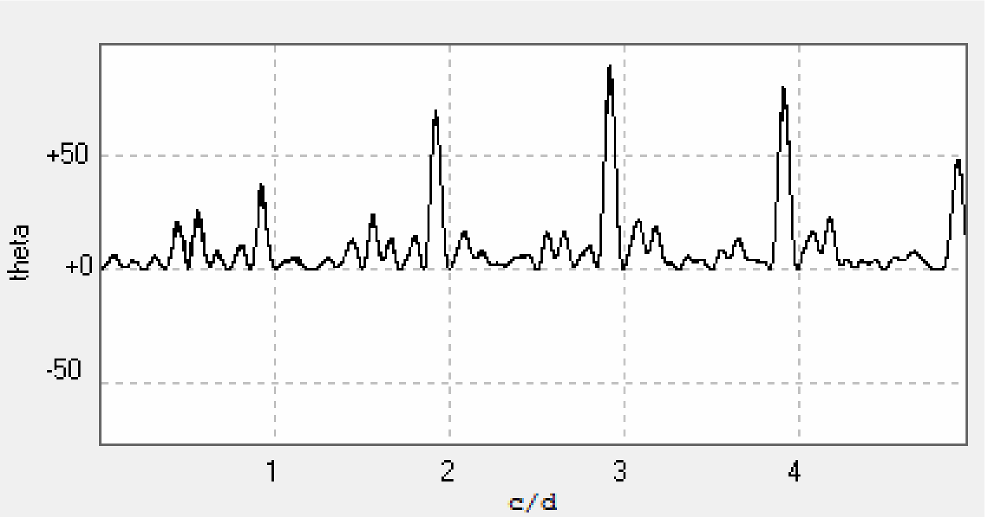

+11.8
+11.9
+12.0
+12.1
+12.2
mag
0
1000
2000
3000.0+
JD

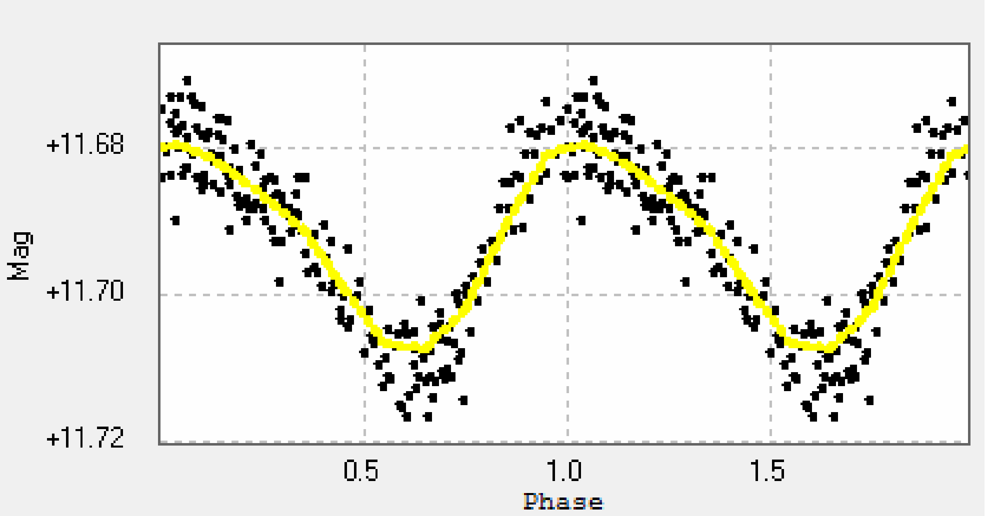

+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d


+11.9
+12.0
+12.1
Mag
0.5
1.0
1.5
Phase

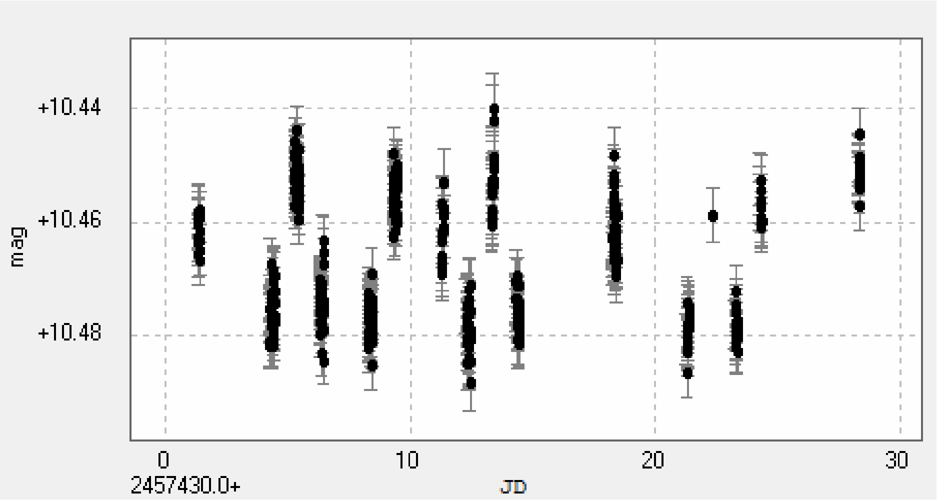
J04472+206

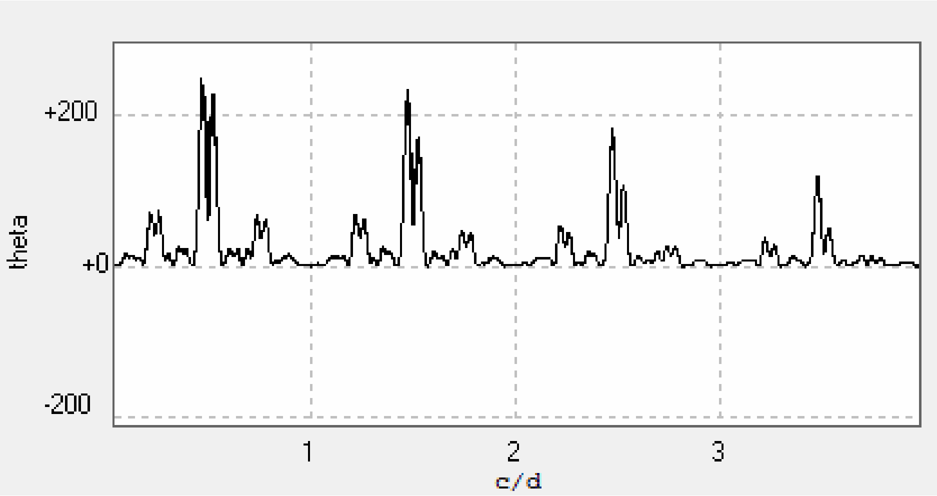

mag
+11.68
+11.70
+11.72
0
5
10
2457415.0+
JD

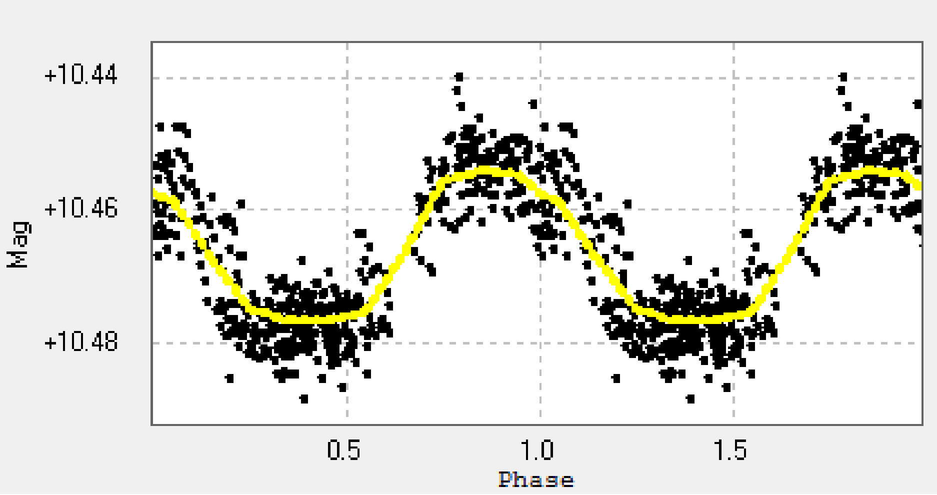

theta
+50
+0
-50
1
2
3
4
c/d


Mag
+11.68
+11.70
+11.72
0.5
1.0
1.5
Phase

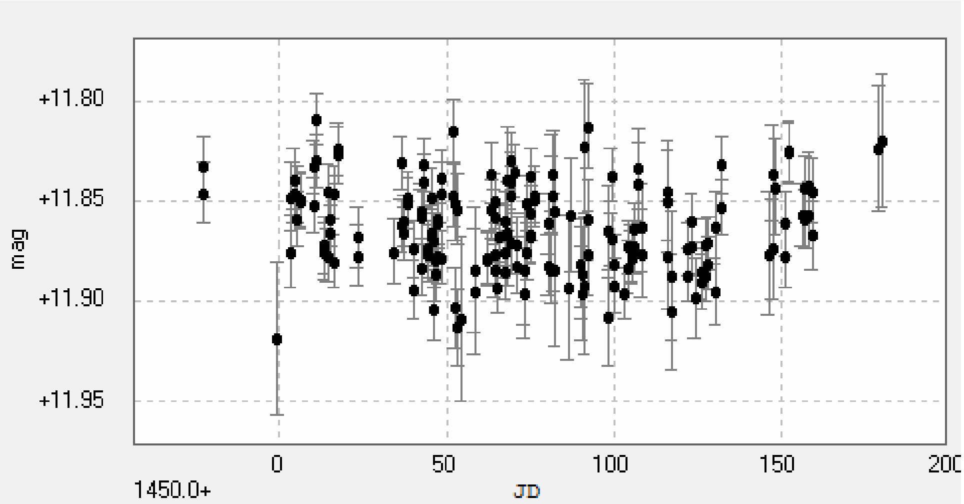
J05019+011

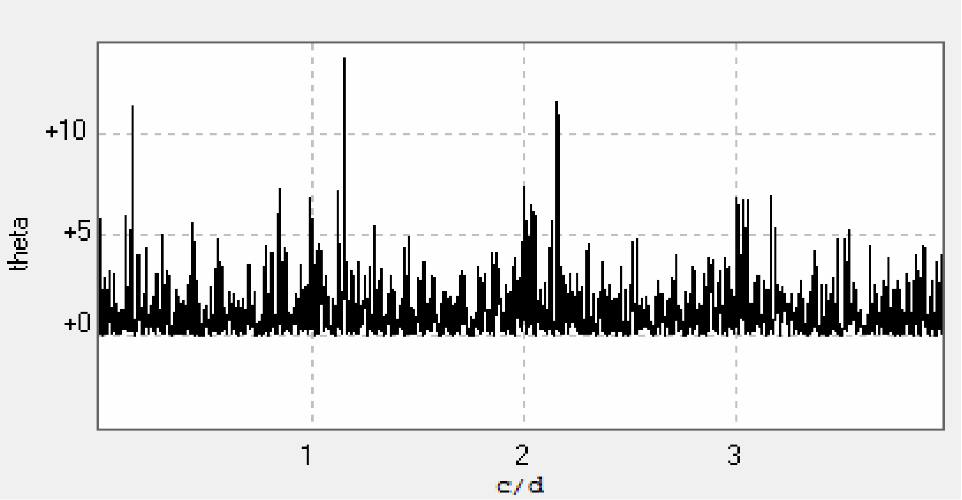

+10.44
+10.46
+10.48
mag
0
10
20
30
2457430.0+
JD

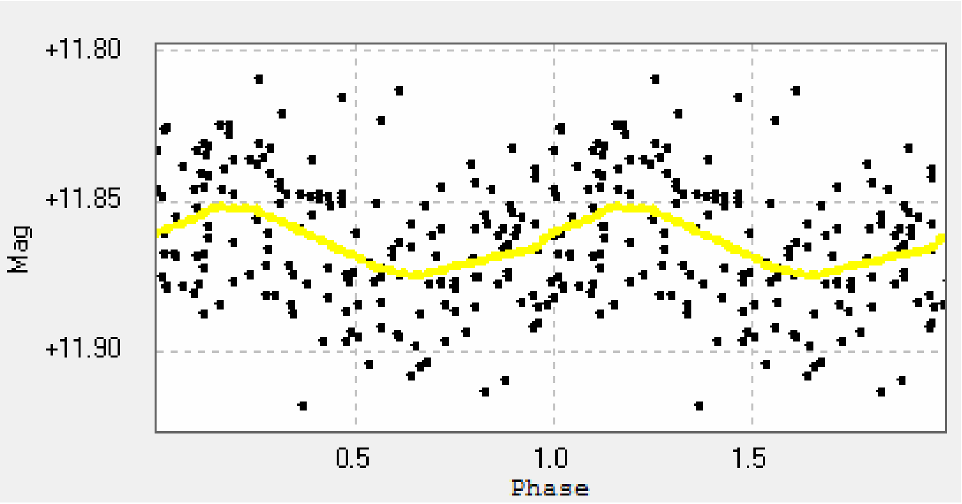

+200
+0
-200
theta
1
2
3
c/d


+10.44
+10.46
+10.48
Mag
0.5
1.0
1.5
Phase

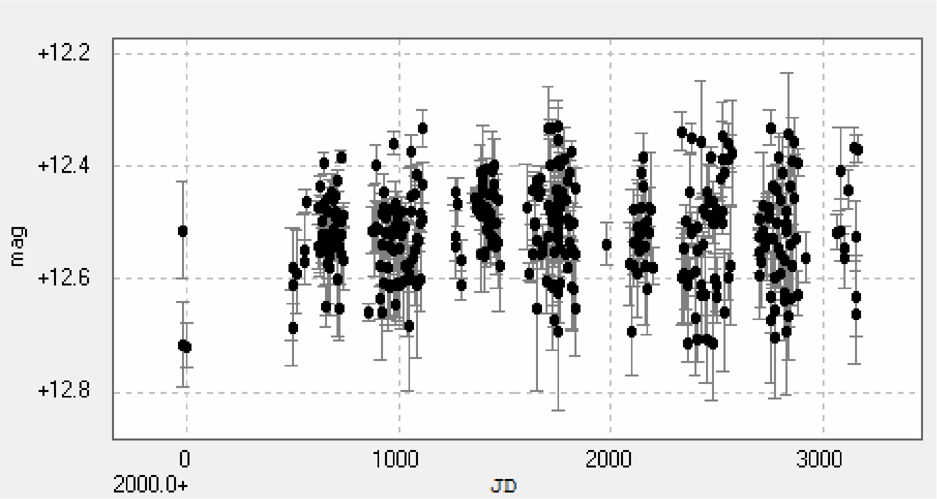
J05062+046

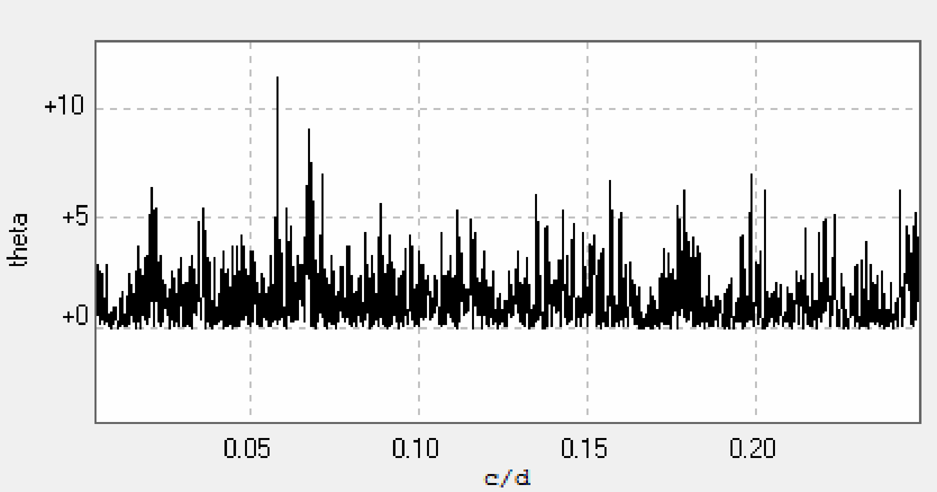

+11.80
+11.85
+11.90
+11.95
mag
0
50
100
150
200
1450.0+
JD

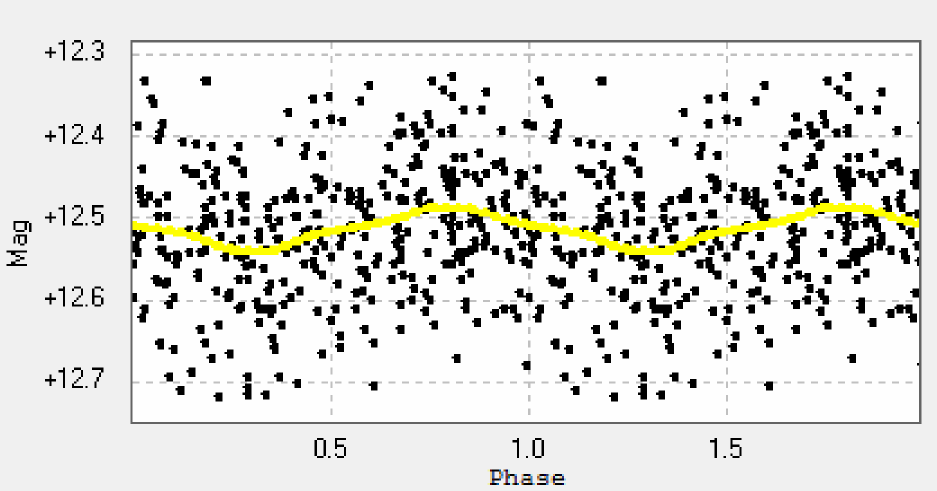

+10
+5
+0
theta
1
2
3
c/d


+11.80
+11.85
+11.90
Mag
0.5
1.0
1.5
Phase

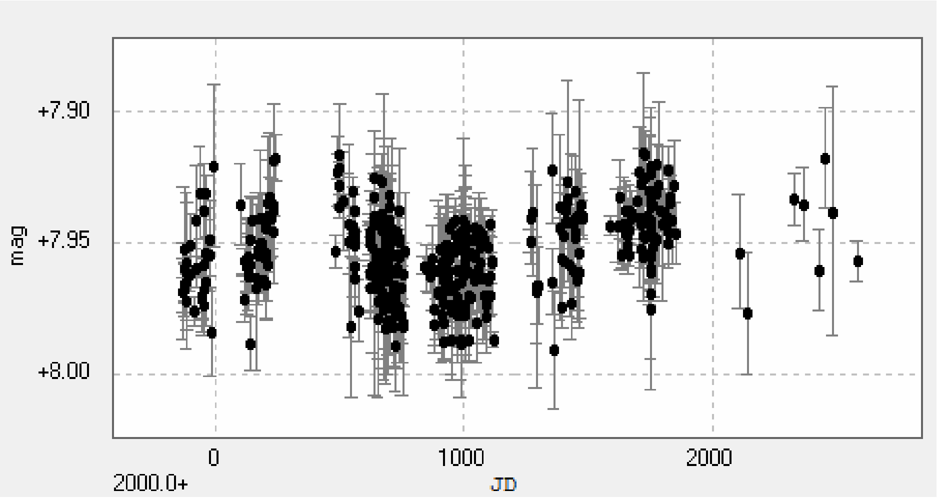
J05280+096


+12.2
+12.4
+12.6
+12.8
mag
0
1000
2000
3000
2000.0+
JD

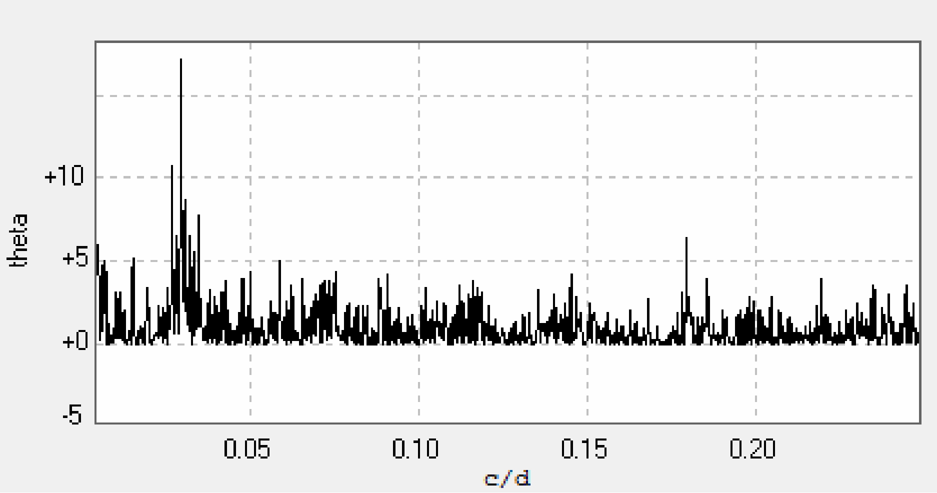

+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d


+12.3
+12.4
+12.5
+12.6
+12.7
Mag
0.5
1.0
1.5
Phase

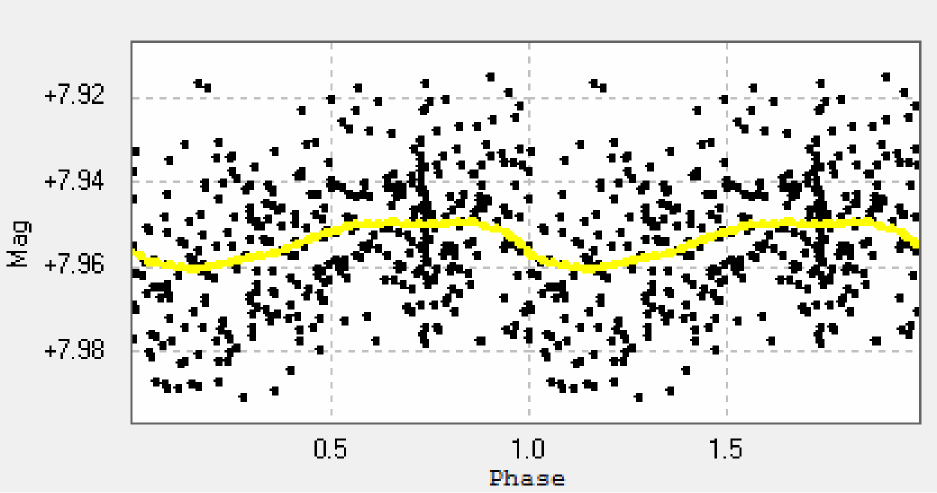
J05314-036



+7.90
+7.95
+8.00
mag
0
1000
2000
2000.0+
JD

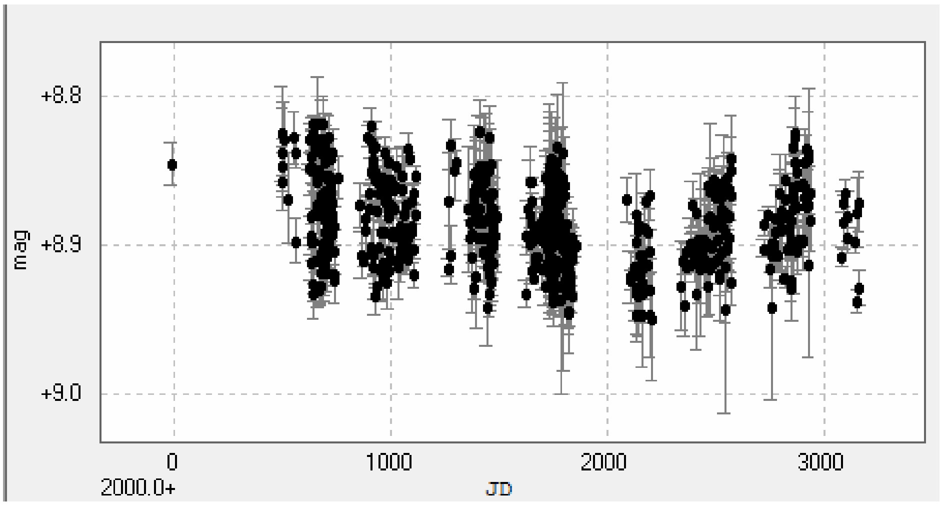


+10
+5
+0
-5
theta
0.05
0.10
0.15
0.20
c/d

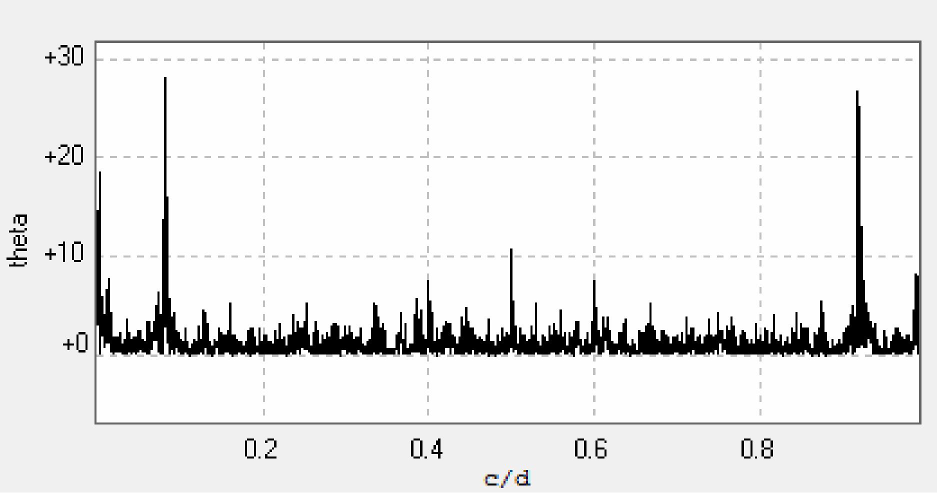


+7.92
+7.94
+7.96
+7.98
Mag
0.5
1.0
1.5
Phase

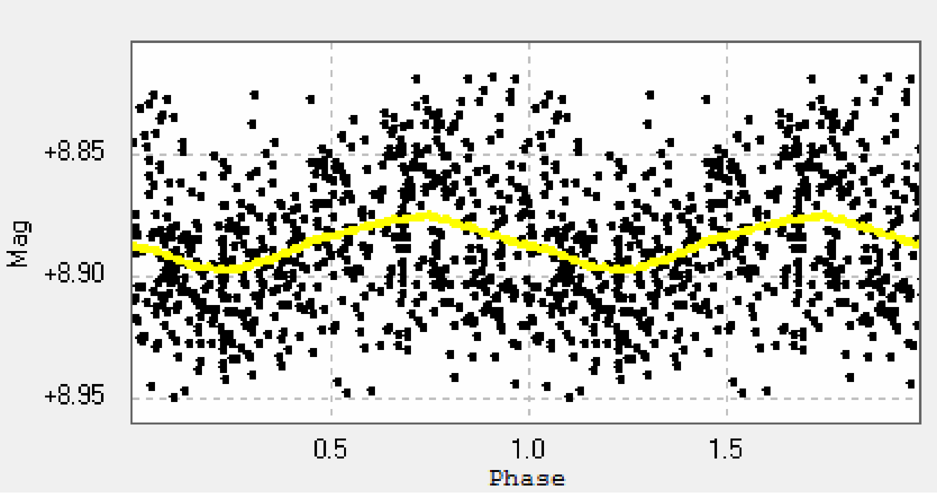
J05365+113



+8.8
+8.9
+9.0
mag
0
1000
2000
3000
2000.0+
JD

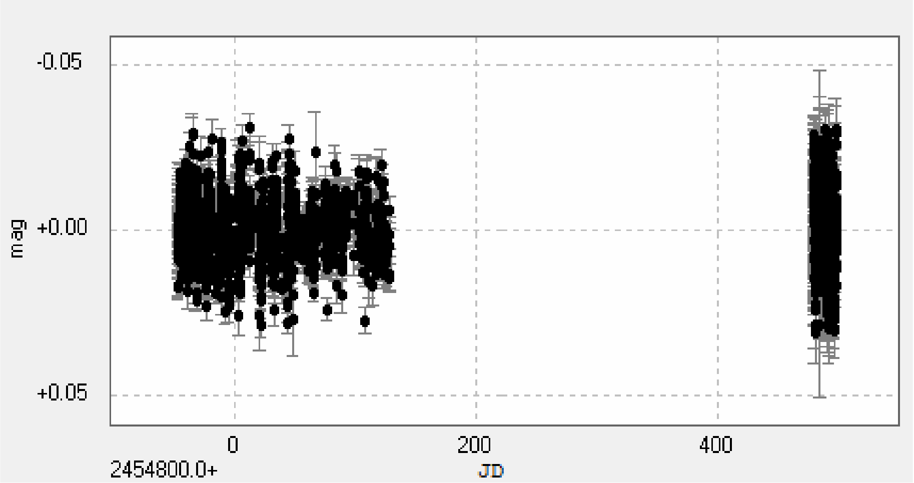


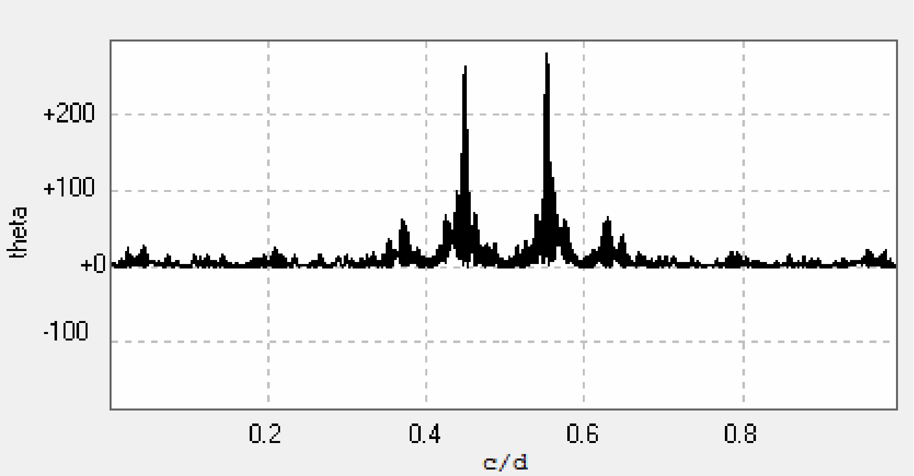
+30
+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d

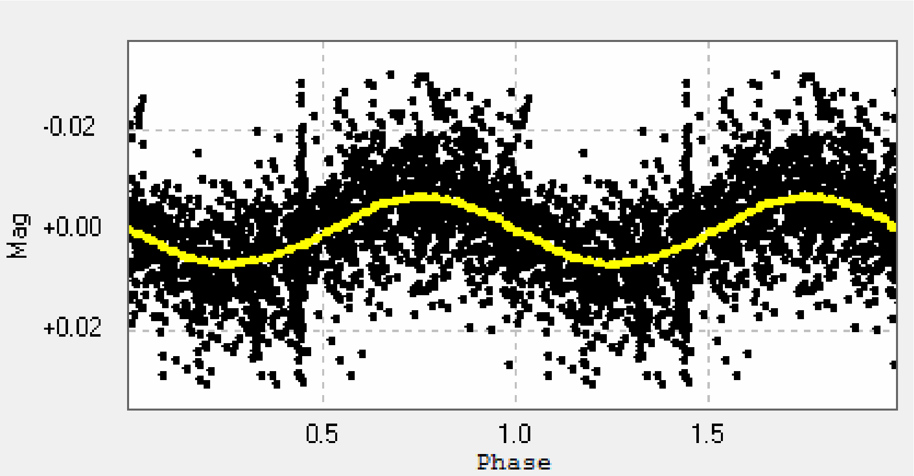


+8.85
+8.90
+8.95
Mag
0.5
1.0
1.5
Phase

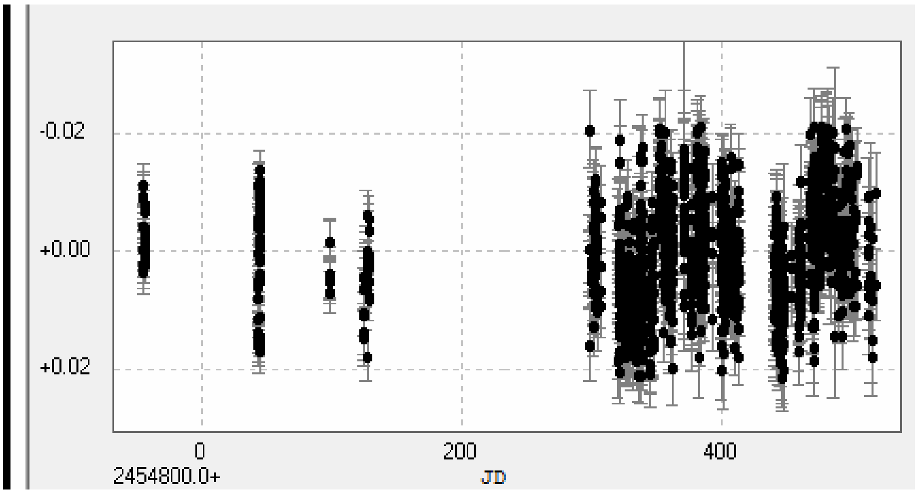
J06000+027


-0.05
+0.00
+0.05
mag
0
200
400
2454800.0+
JD

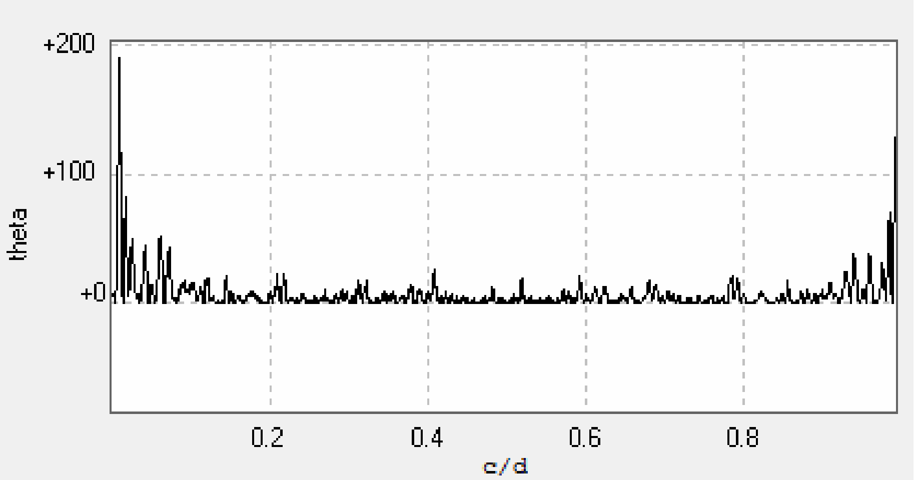

+200
+100
+0
-100
theta
0.2
0.4
0.6
0.8
c/d


-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

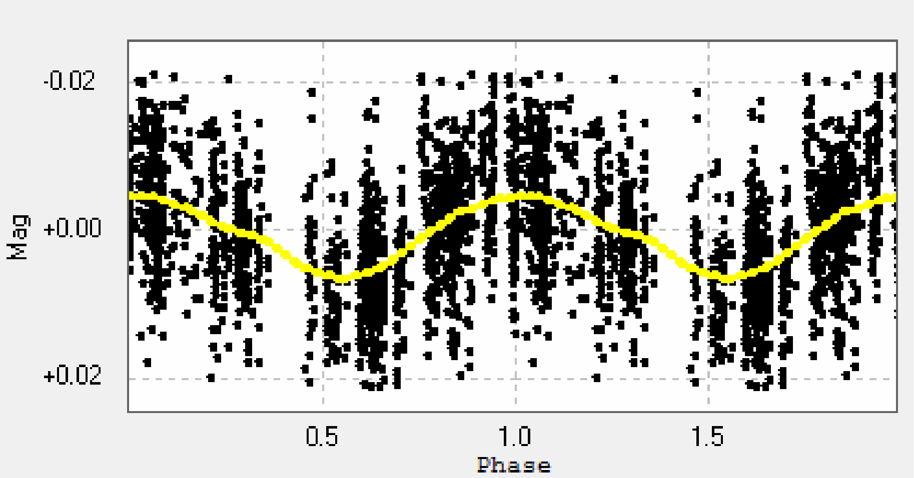
J06024+498



-0.02
+0.00
+0.02
0
200
400
2454800.0+
JD

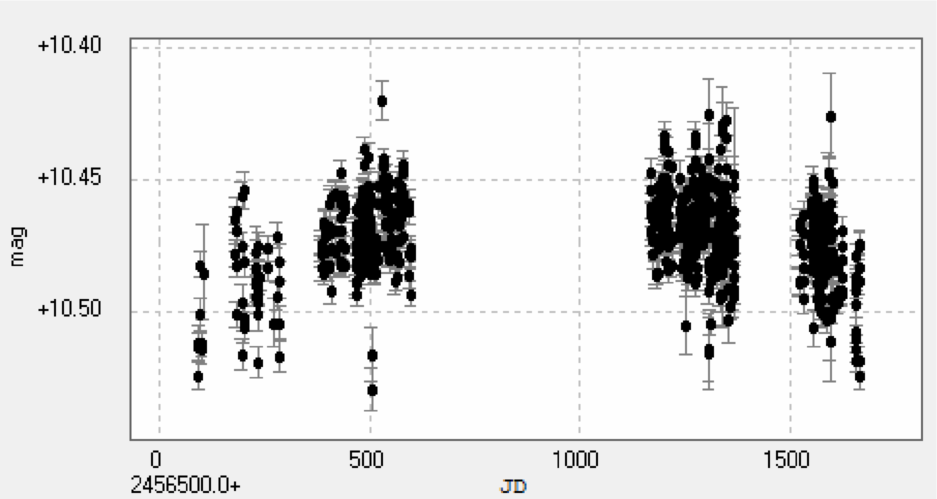


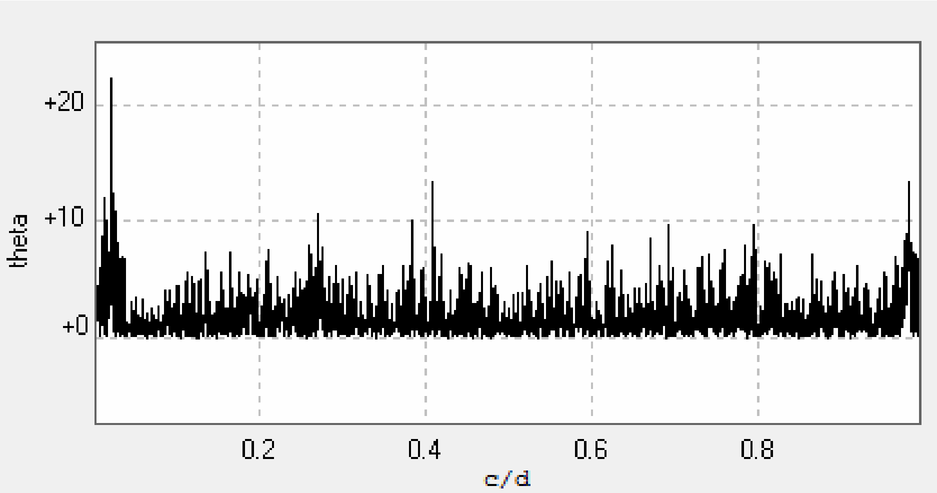
+200
+100
+0
theta
0.2
0.4
0.6
0.8
c/d

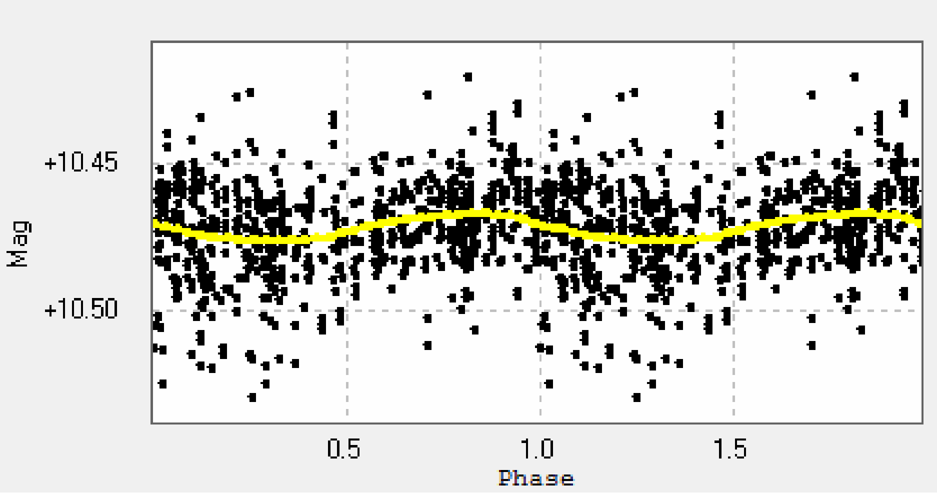


-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

J06103+821


+10.40
+10.45
+10.50
mag
0
500
1000
1500
2456500.0+
JD


+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d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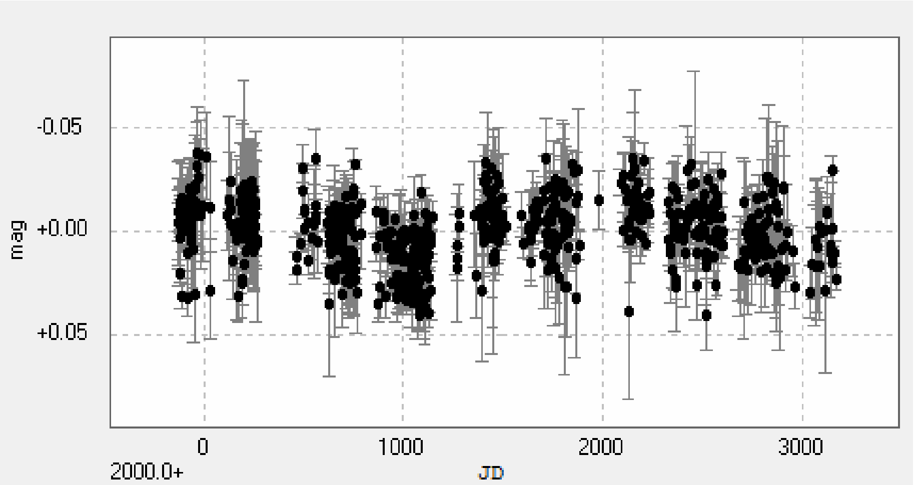
+10.50
Mag
0.5
1.0
1.5
Phase

J06105-218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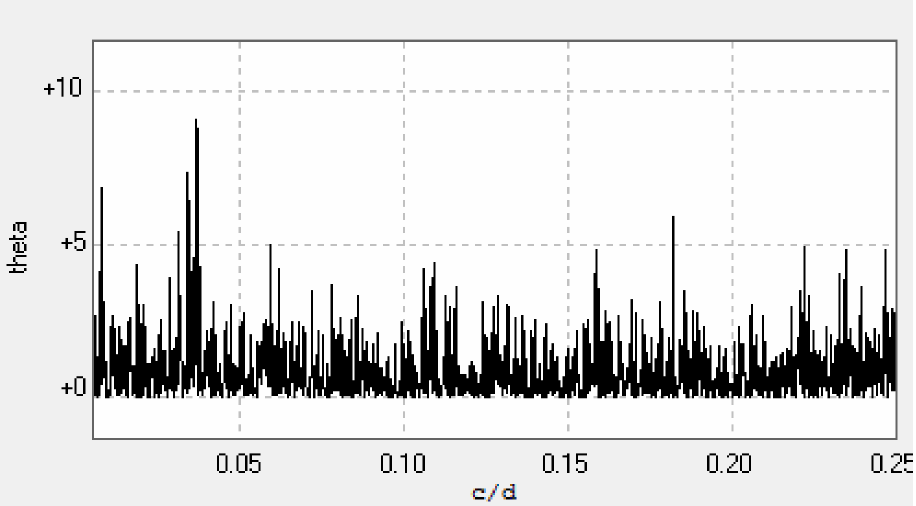
+0.05
mag
0
1000
2000
3000
2000.0+
JD


+10
+5
+0
theta
0.05
0.10
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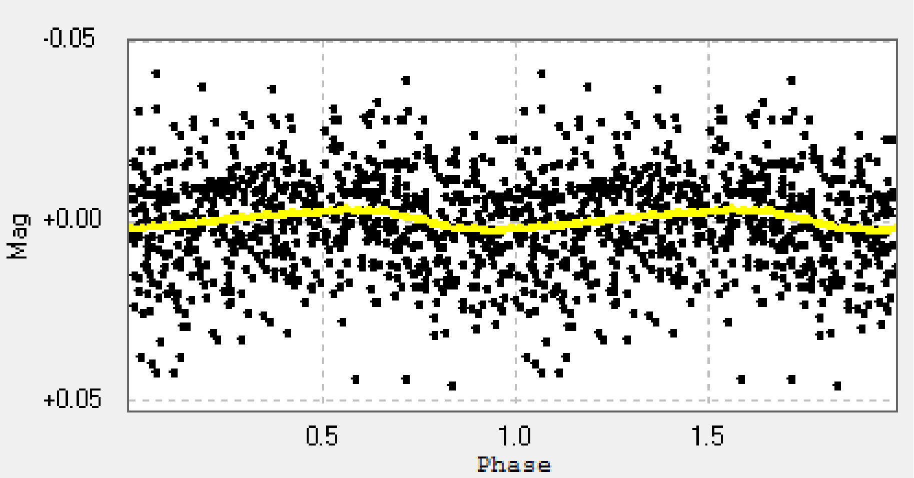
0.20
0.25
c/d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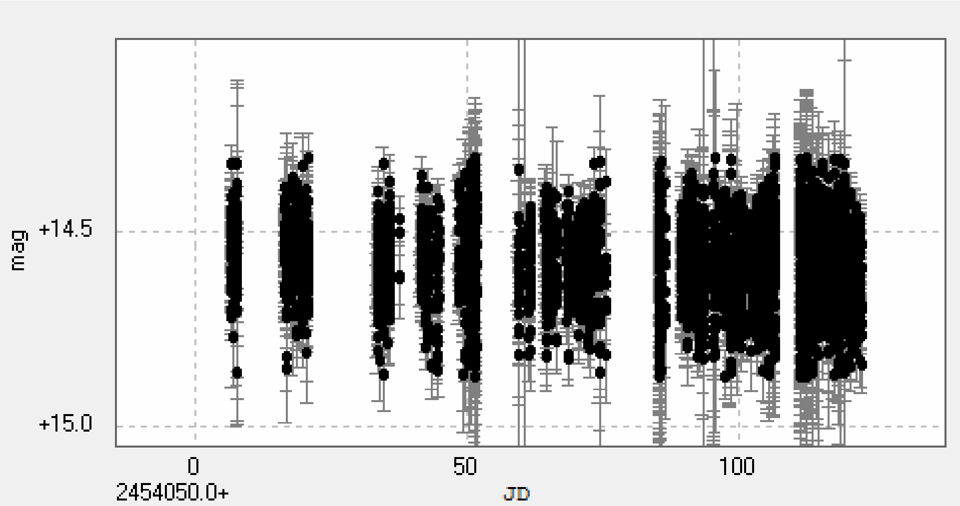
+0.05
Mag
0.5
1.0
1.5
Phase

J06318+414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0
50
100
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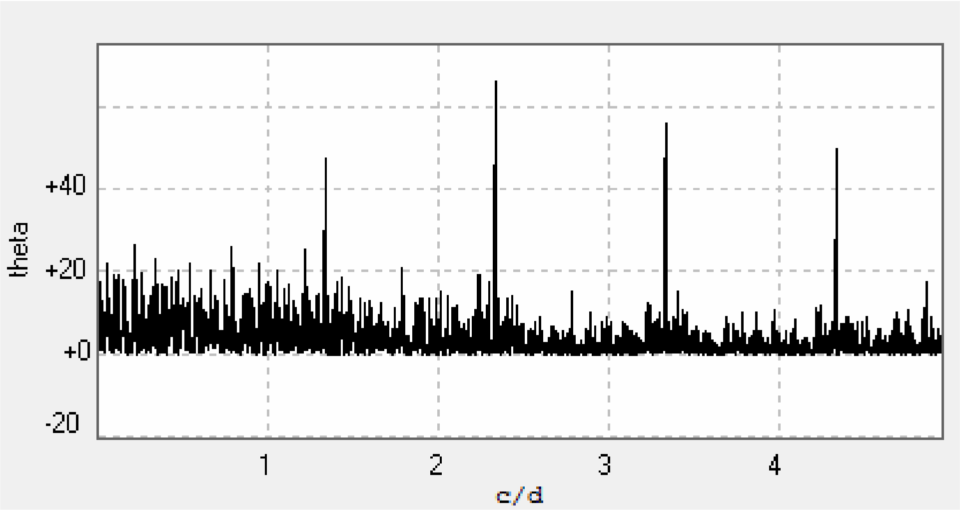
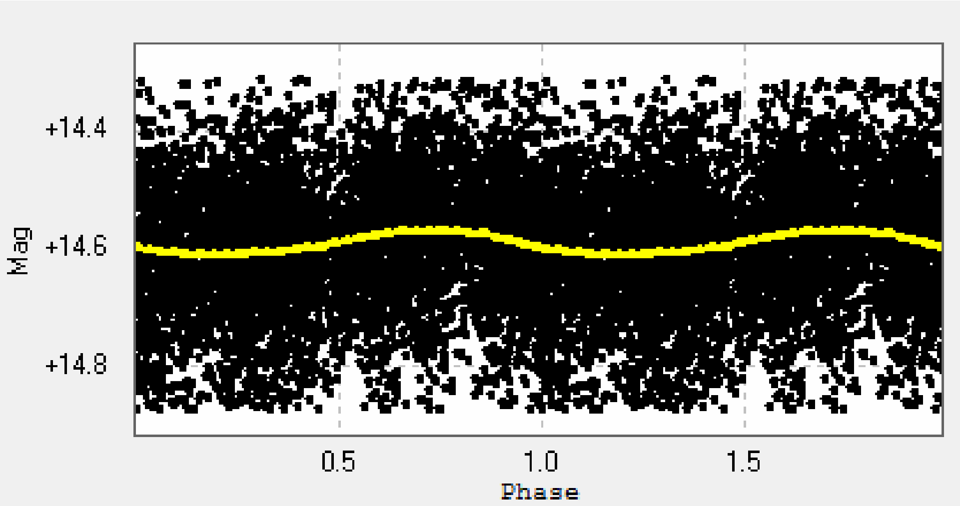
JD


theta
+40
+20
+0
-20
1
2
3
4
c/d


Mag
+14.4
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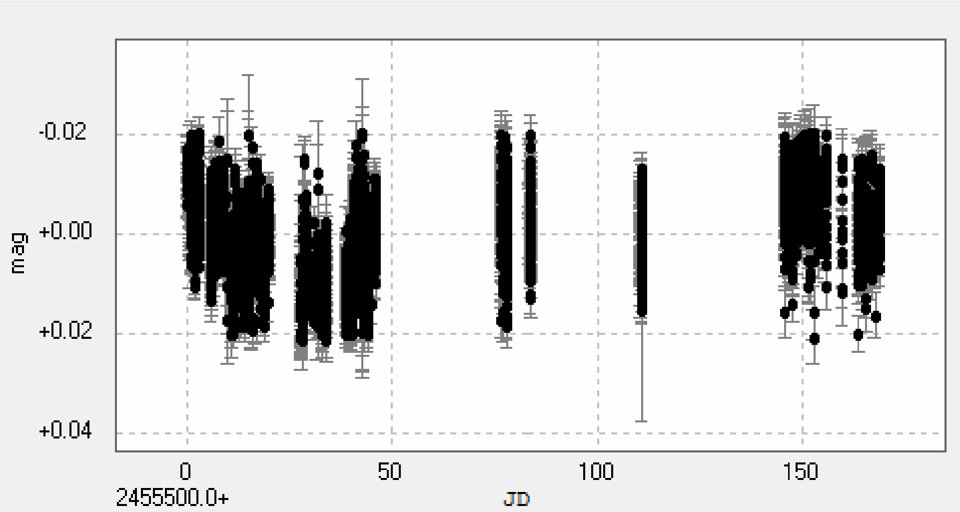
+14.8
0.5
1.0
1.5
Phase

J06421+035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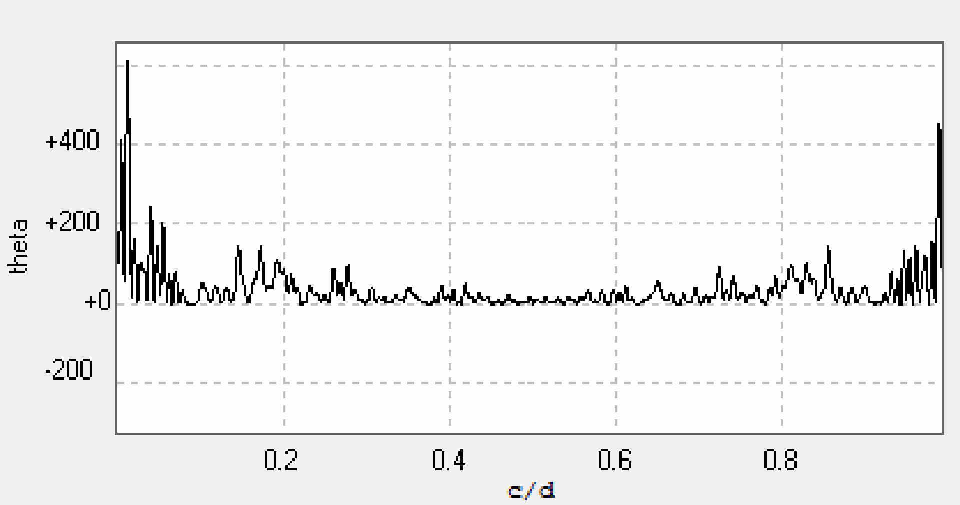
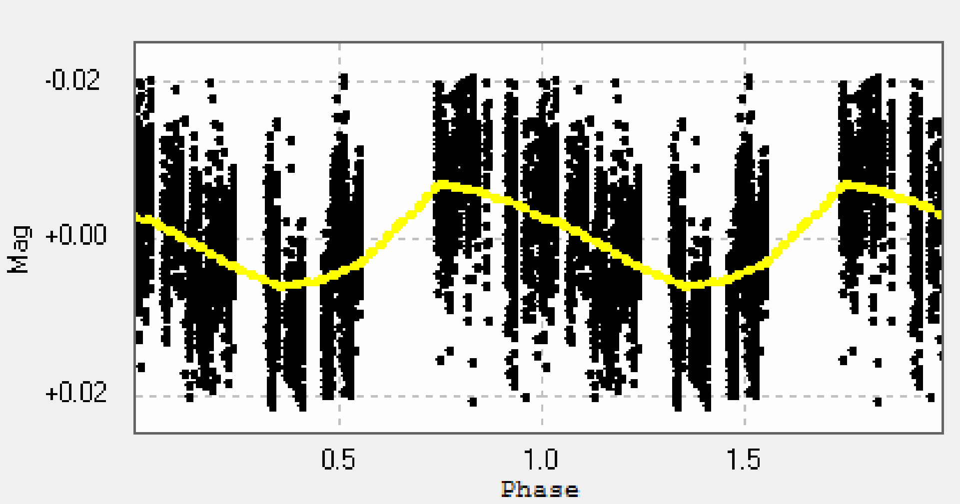
mag
0
50
100
150
2455500.0+
JD


+400
+200
+0
-200
theta
0.2
0.4
0.6
0.8
c/d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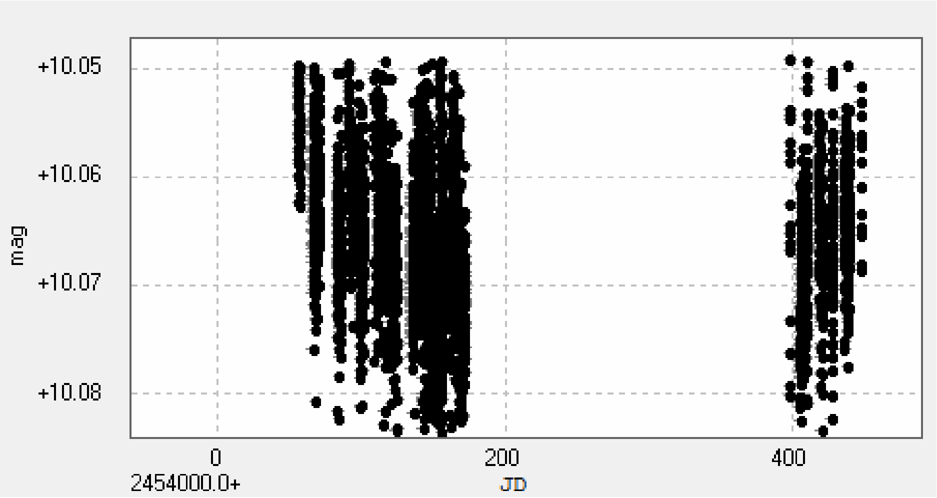
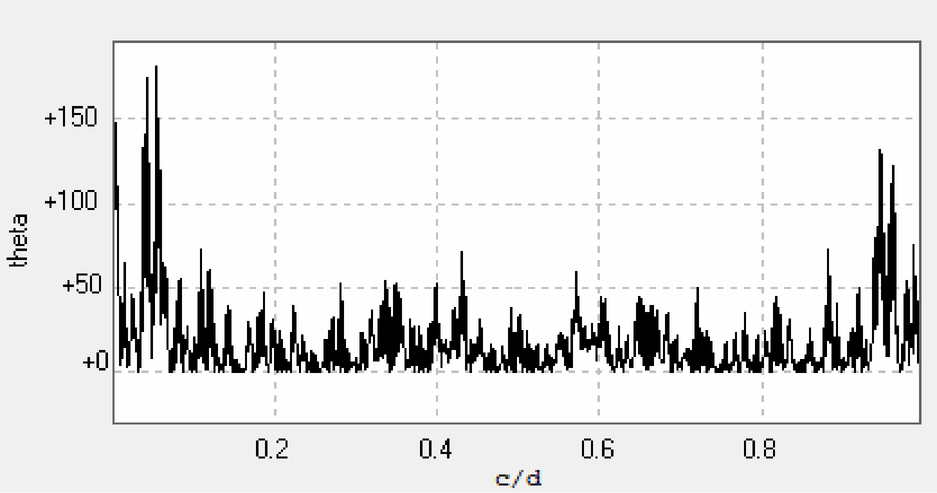
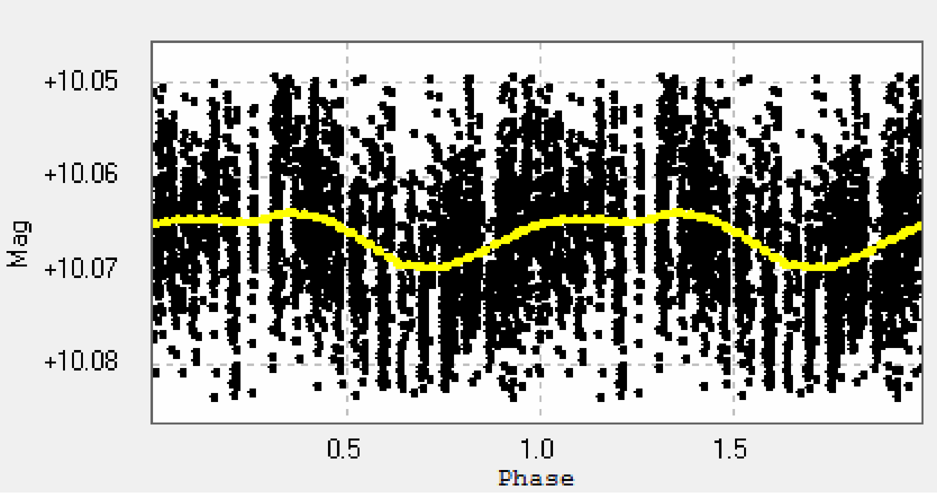
+0.02
Mag
0.5
1.0
1.5
Phase

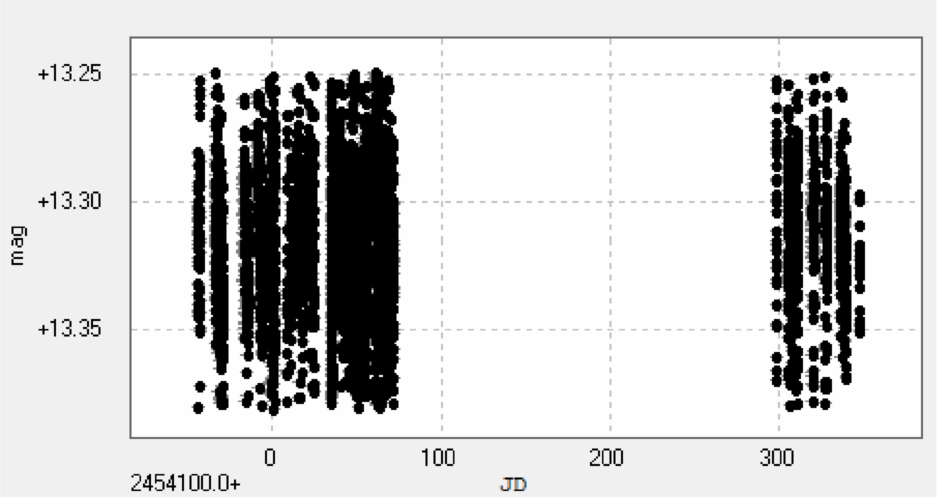
J06548+332


+10.05
+10.06
+10.07
+10.08
mag
0
200
400
2454000.0+
JD

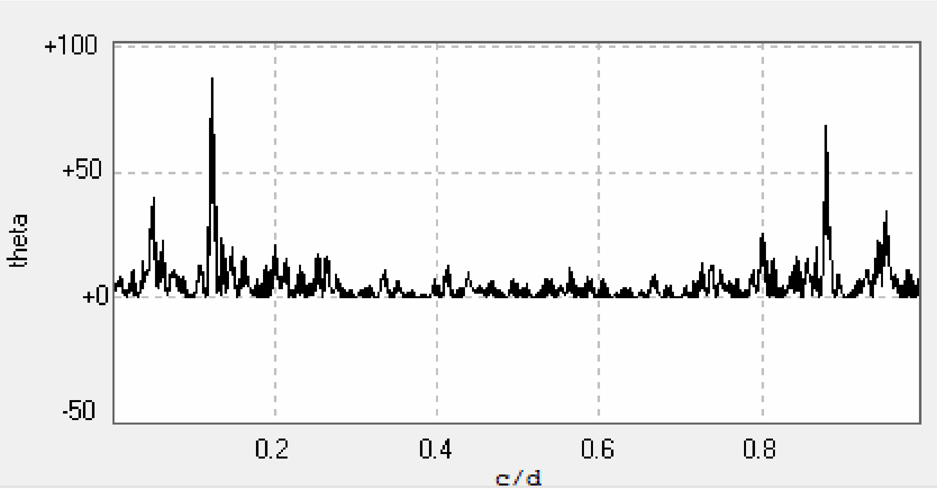

+150
+100
+50
+0
theta
0.2
0.4
0.6
0.8
c/d


+10.05
+10.06
+10.07
+10.08
Mag
0.5
1.0
1.5
Phase

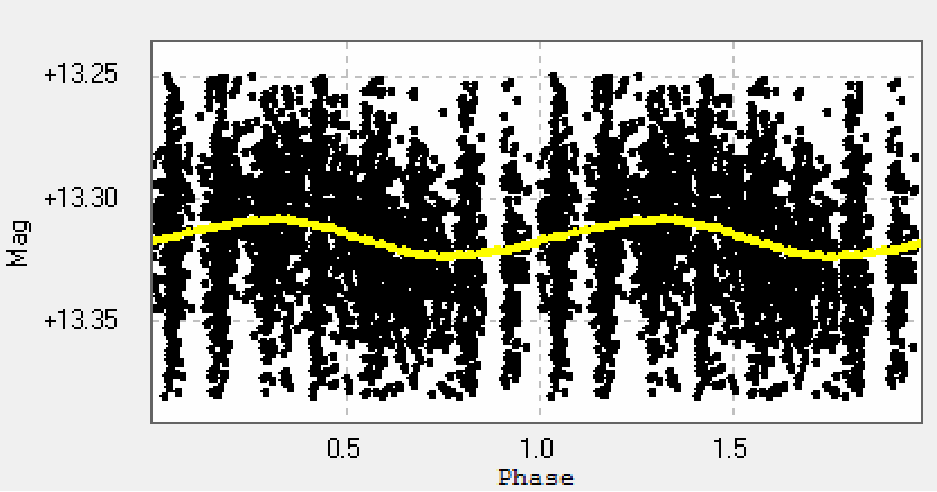
J07033+346



+13.25
+13.30
+13.35
mag
0
100
200
300
2454100.0+
JD

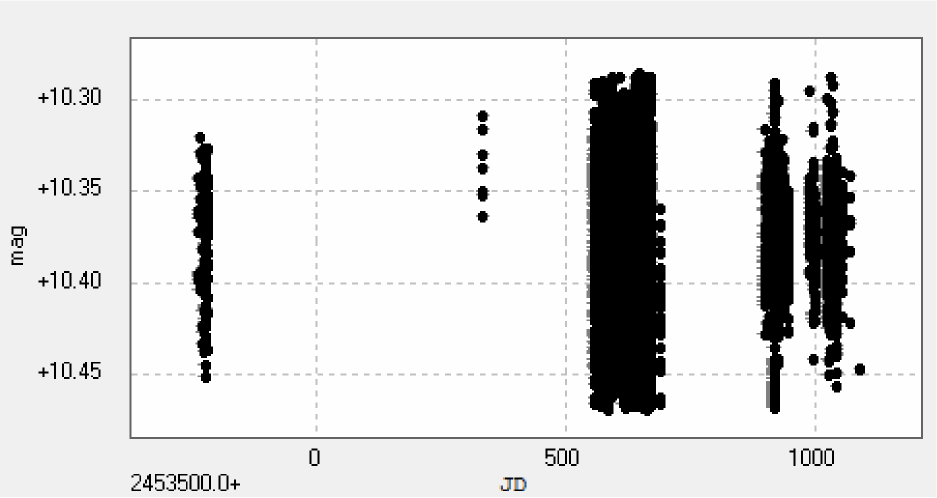


+100
+50
+0
-50
theta
0.2
0.4
0.6
0.8
c/d



+13.25
+13.30
+13.35
Mag
0.5
1.0
1.5
Phase

J07319+362N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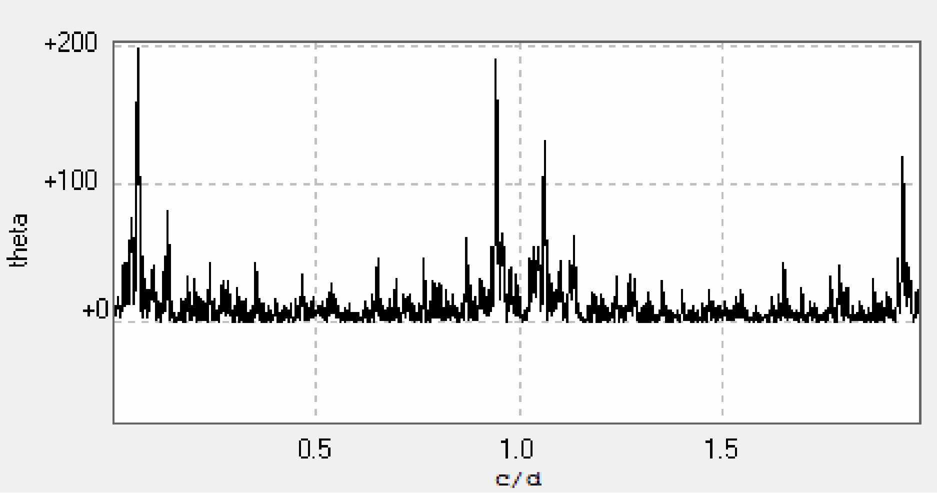
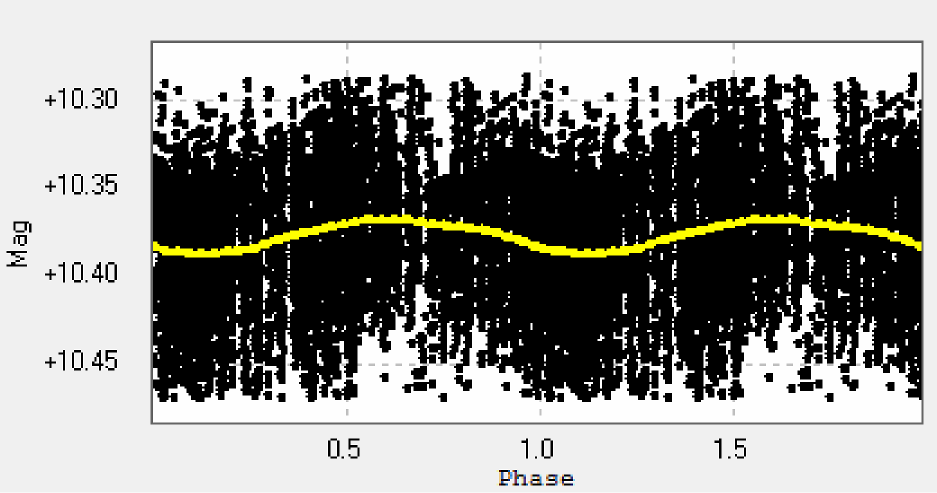
+10.35
+10.40
+10.45
mag
0
500
1000
2453500.0+
JD


+200
+100
+0
theta
0.5
1.0
1.5
c/d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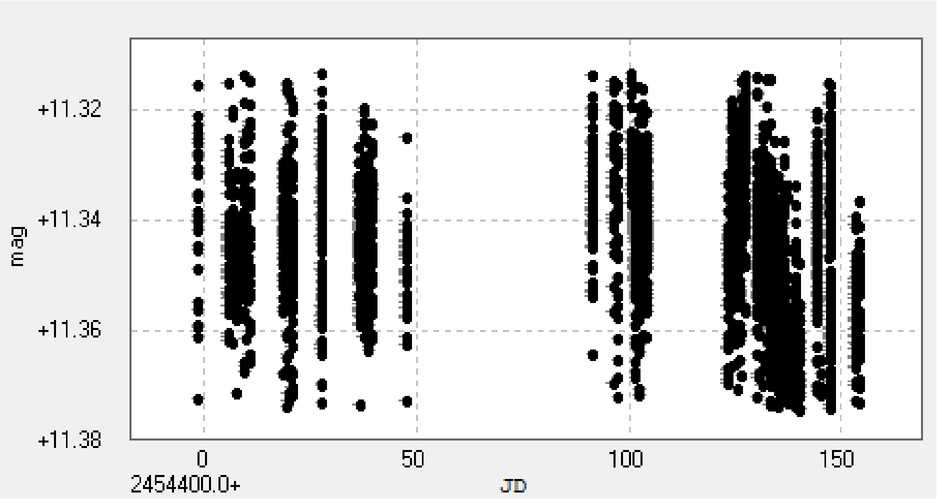
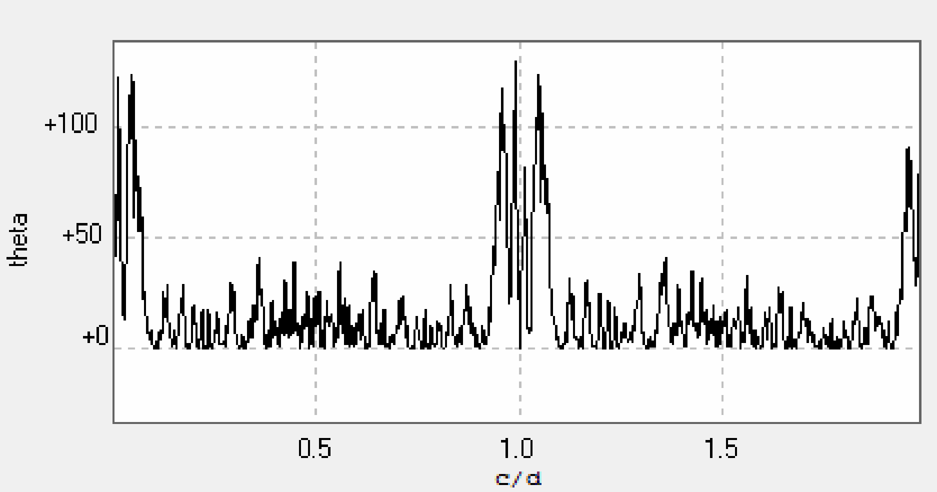
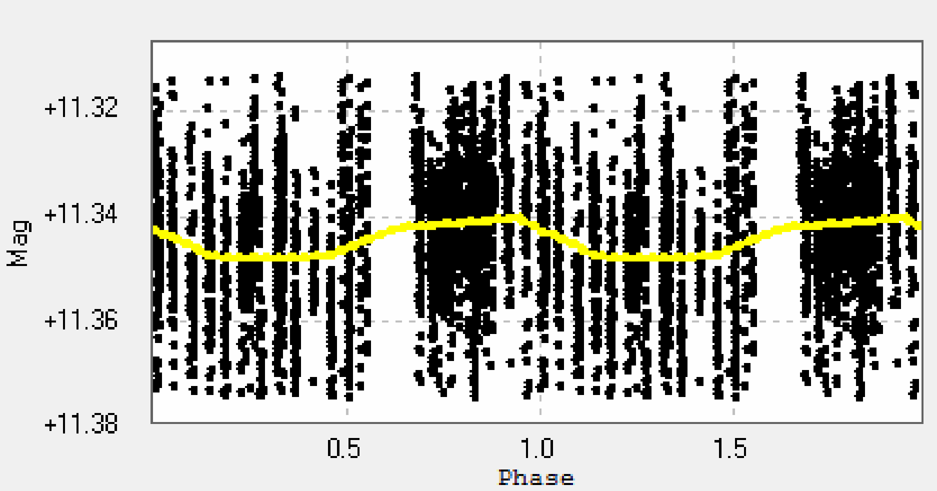
+10.35
+10.40
+10.45
Mag
0.5
1.0
1.5
Phase

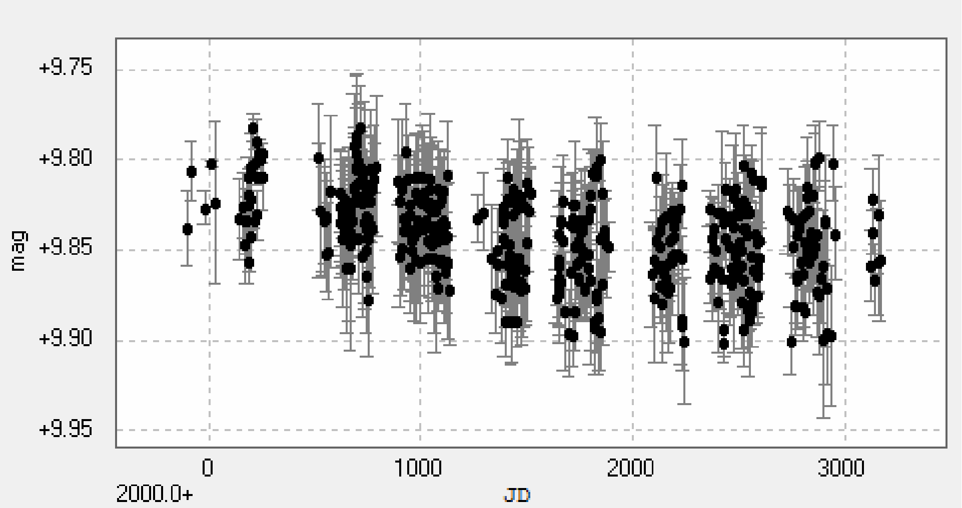
J07353+548

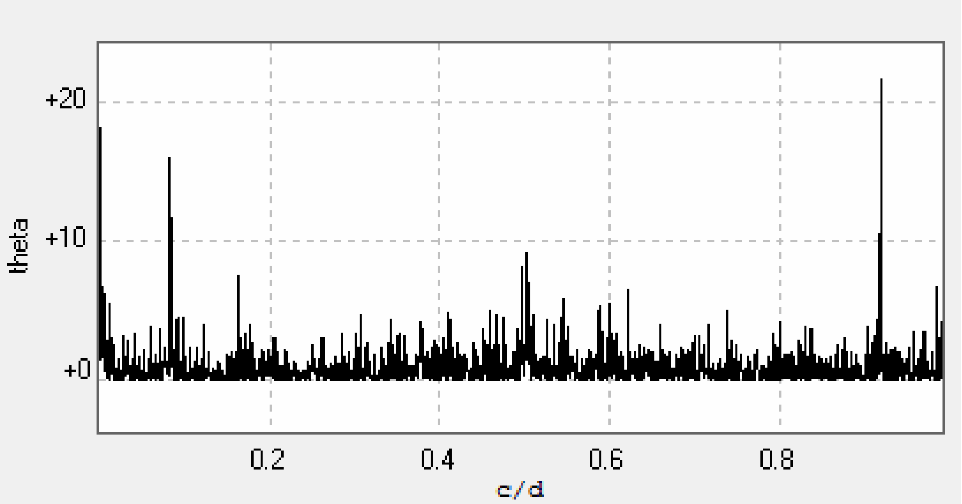

+11.32
+11.34
+11.36
+11.38
mag
0
50
100
150
2454400.0+
JD

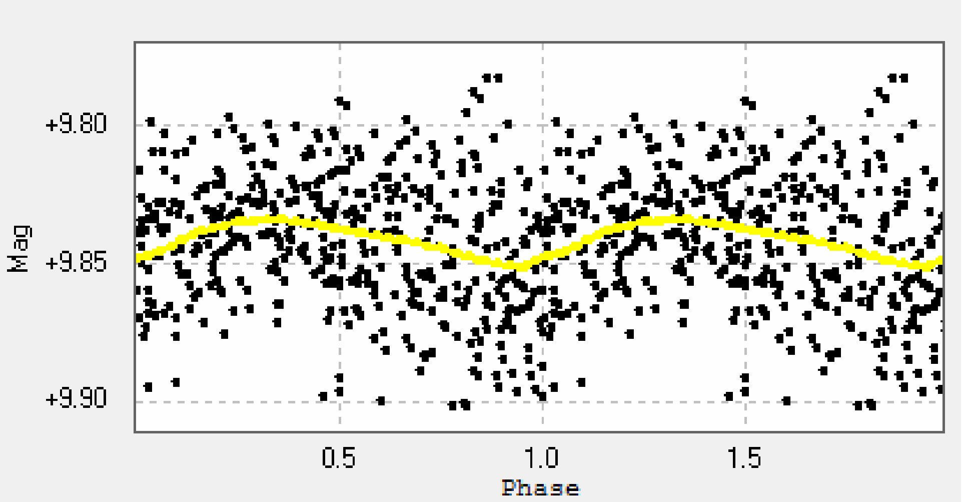

+100
+50
+0
theta
0.5
1.0
1.5
c/d


+11.32
+11.34
+11.36
+11.38
Mag
0.5
1.0
1.5
Phase

J07361-031


+9.75
+9.80
+9.85
+9.90
+9.95
mag
0
1000
2000
3000
2000.0+
JD


+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d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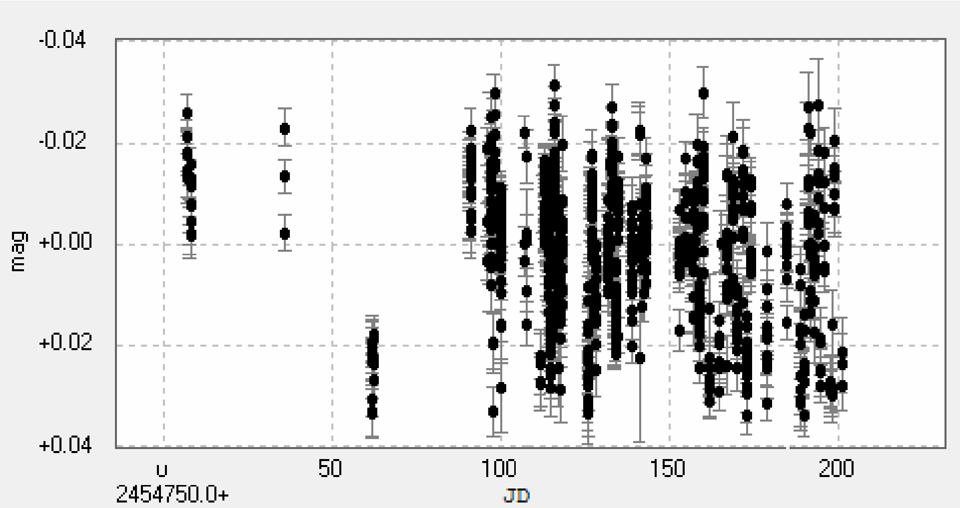
+9.90
Mag
0.5
1.0
1.5
Phase

J07446+035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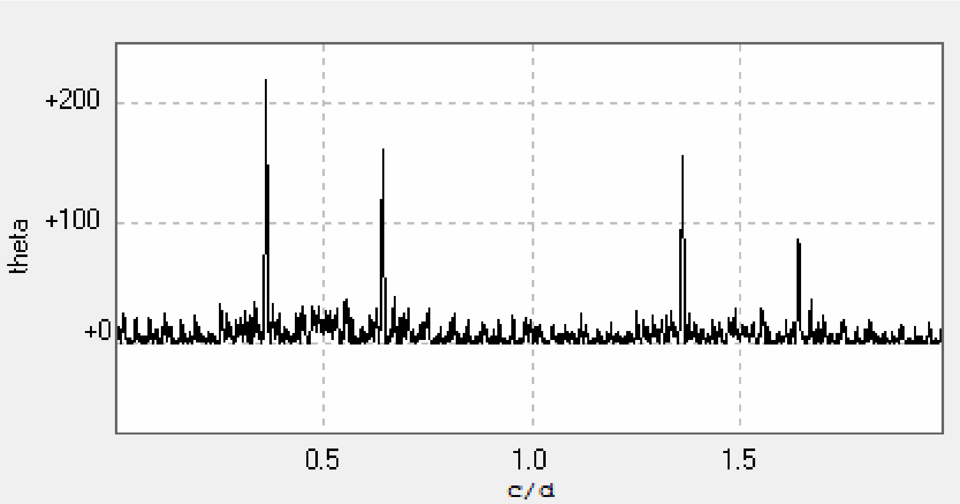
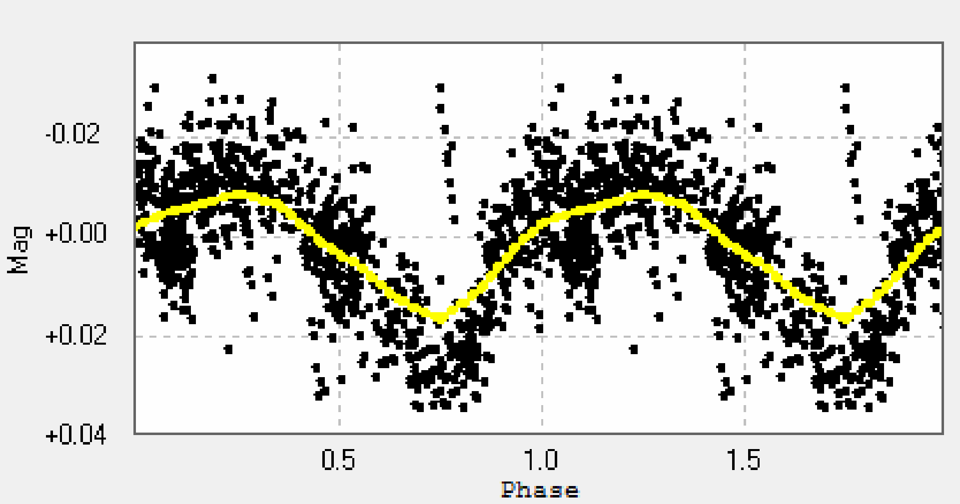
+0.00
+0.02
+0.04
mag
0
50
100
150
200
2454750.0+
JD


+200
+100
+0
theta
0.5
1.0
1.5
c/d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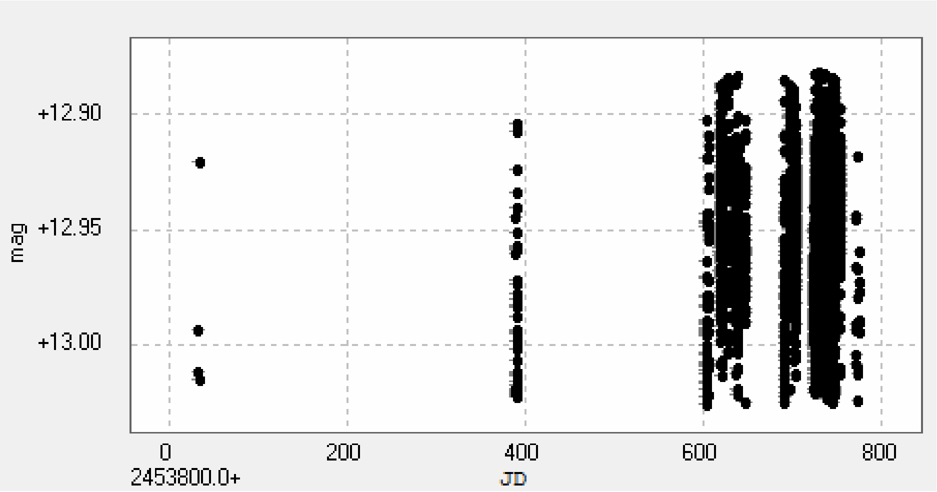
+0.02
+0.04
Mag
0.5
1.0
1.5
Phase

J07472+503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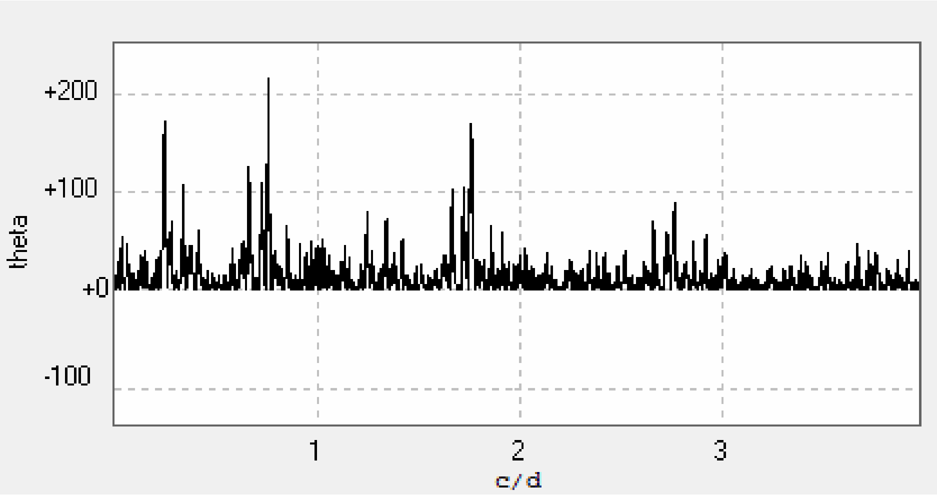
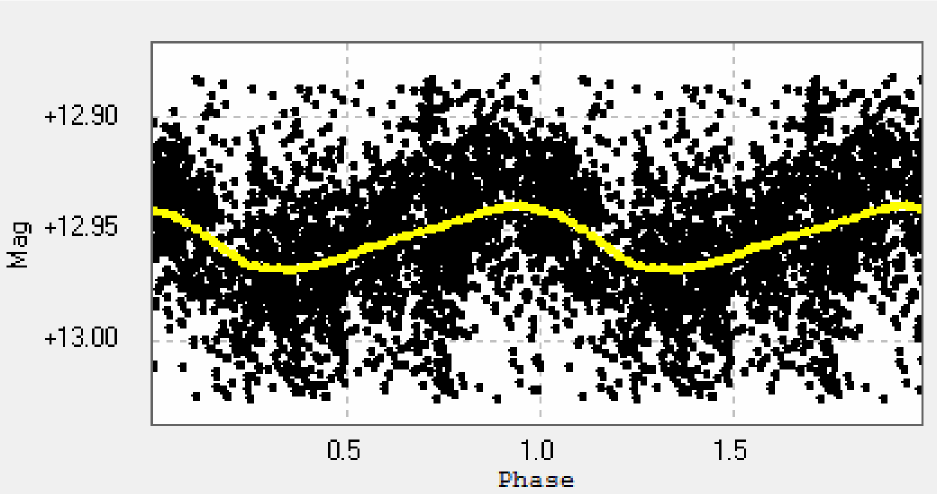
+12.95
+13.00
mag
0
200
400
600
800
2453800.0+
JD


+200
+100
+0
-100
theta
1
2
3
c/d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+13.00
Mag
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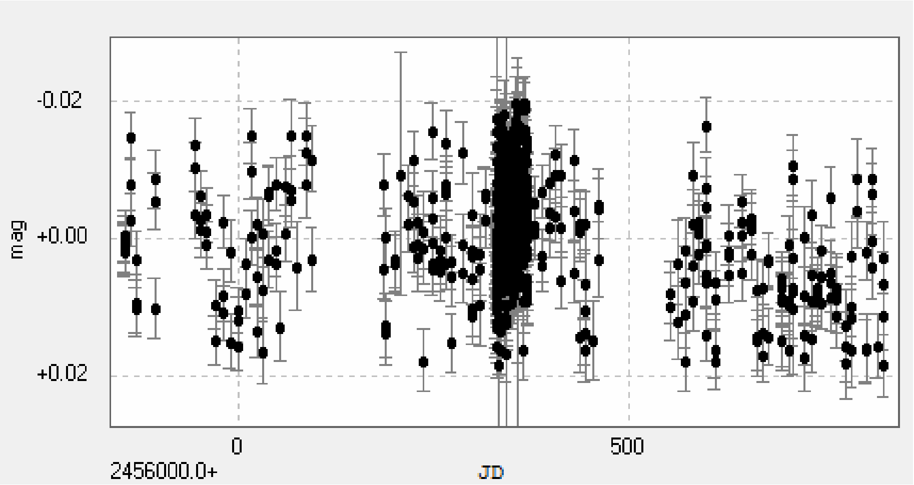
1.0
1.5
Phase

J07558+833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+0.02
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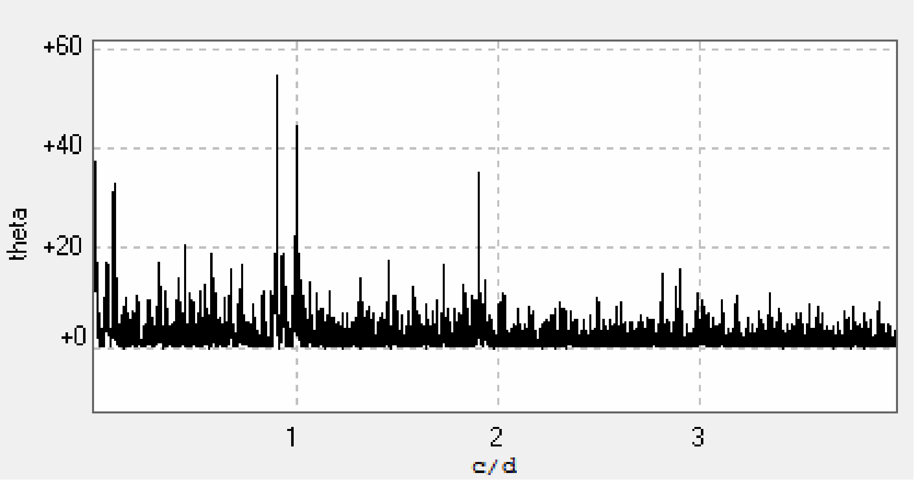
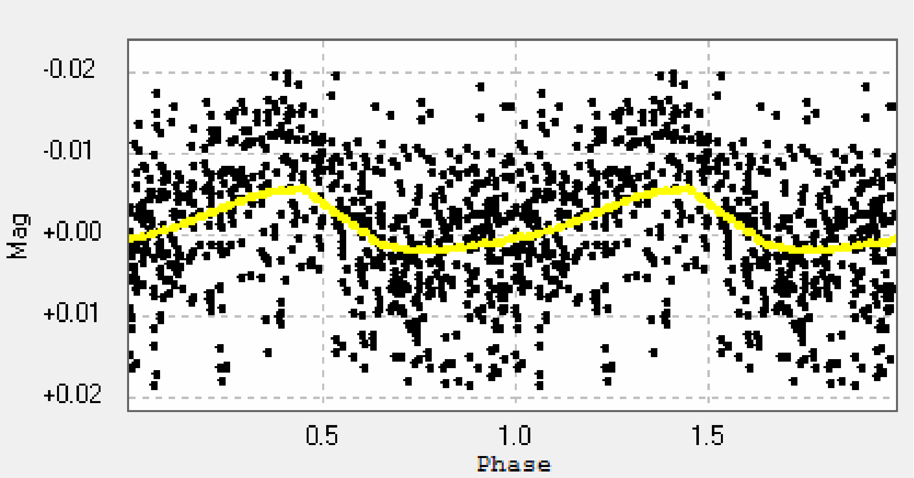
500
2456000.0+
JD


+60
+40
+20
+0
theta
1
2
3
c/d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+0.02
Mag
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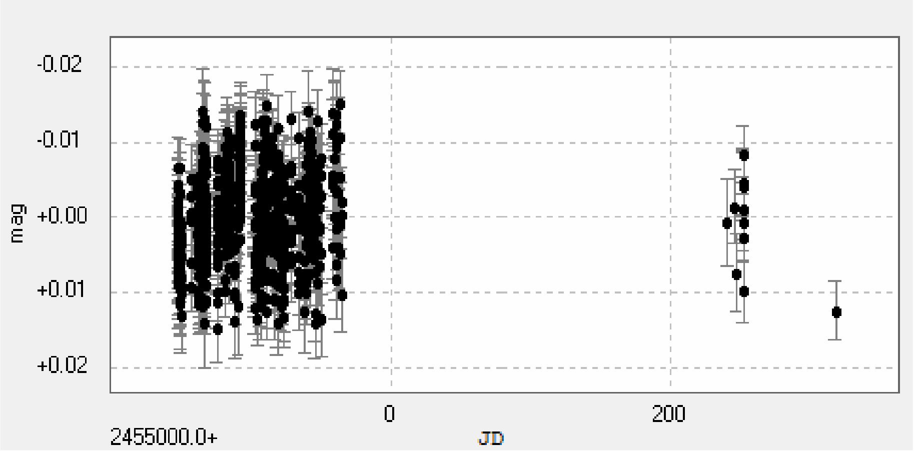
1.0
1.5
Phase

J08119+087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-0.01
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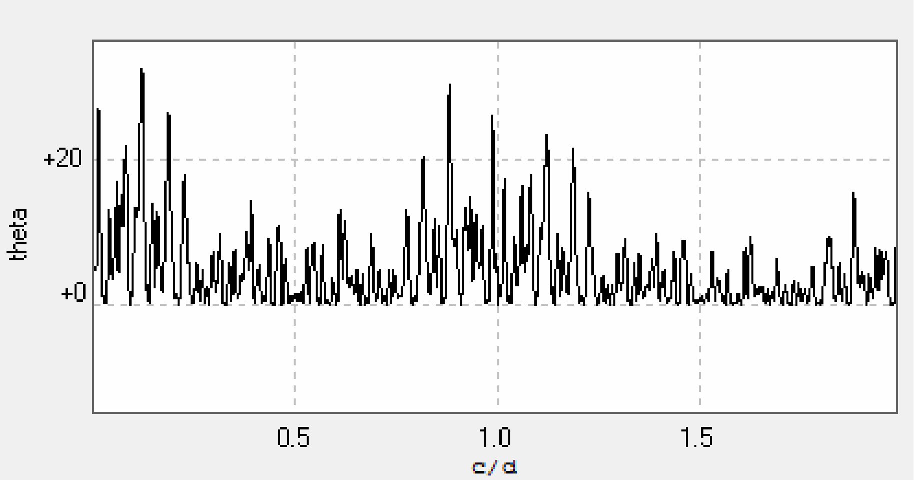
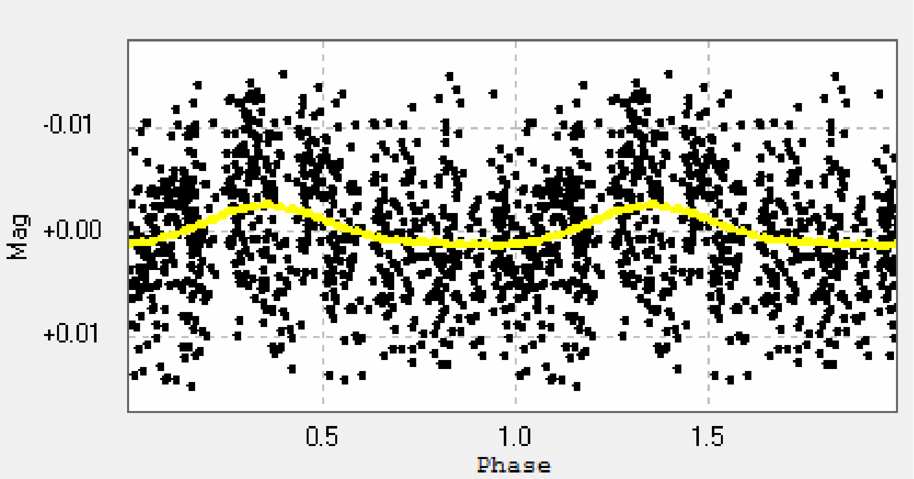
+0.01
+0.02
mag
0
200
2455000.0+
JD


+20
+0
theta
0.5
1.0
1.5
c/d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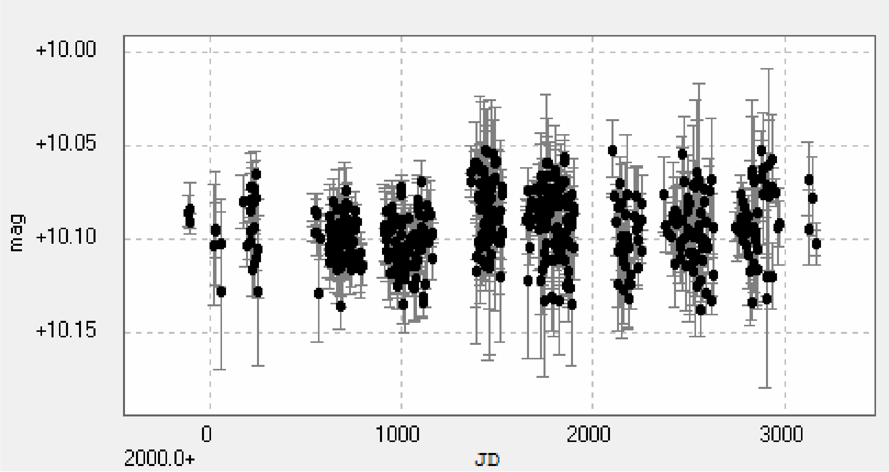
+0.01
Mag
0.5
1.0
1.5
Phase

J08161+013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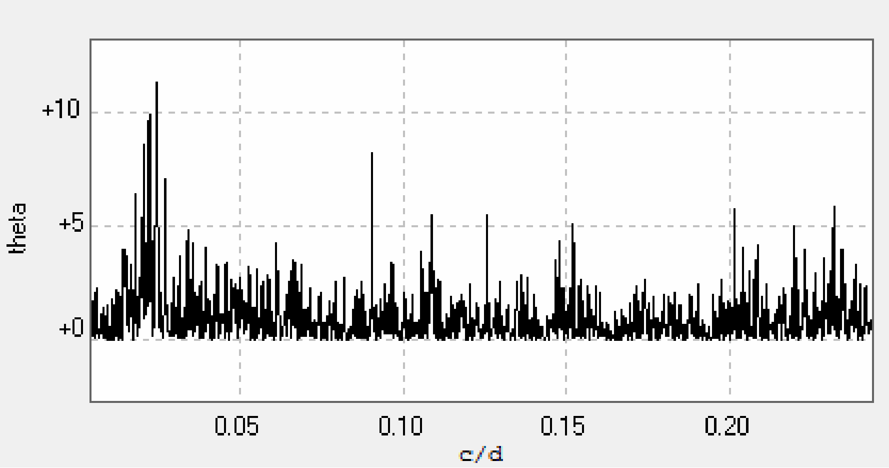
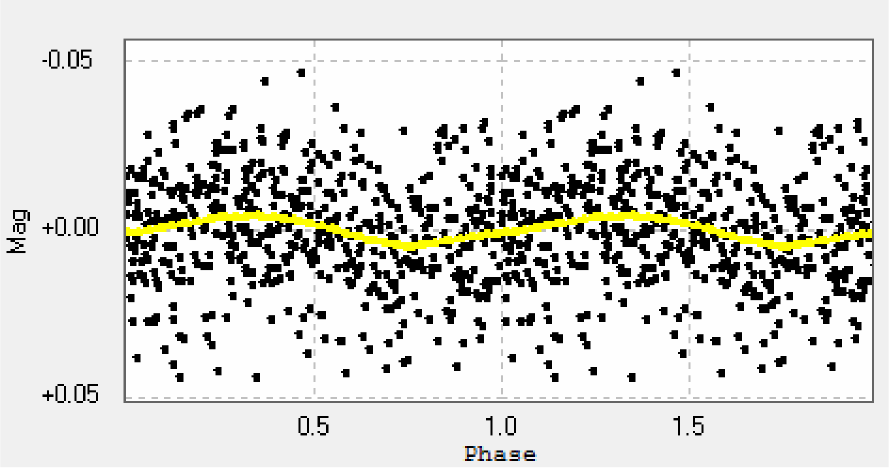
+10.10
+10.15
mag
0
1000
2000
3000
2000.0+
JD


+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d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+0.05
Mag
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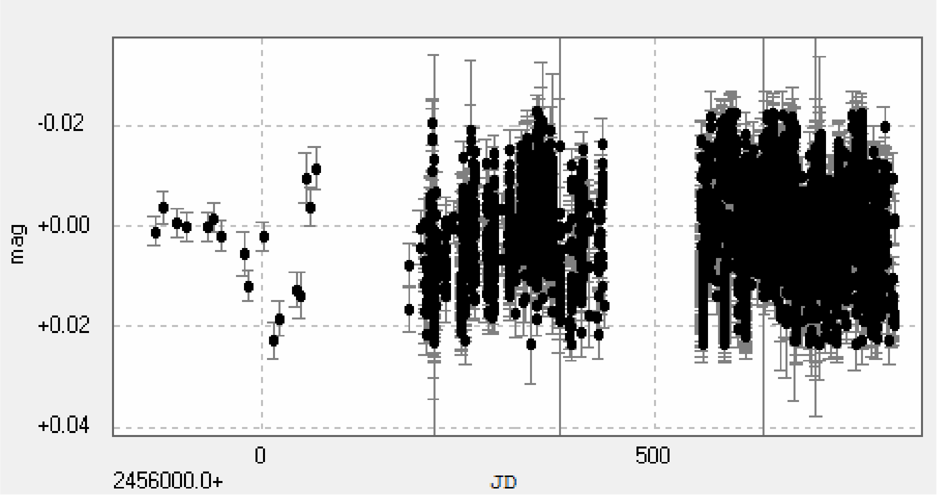
1.0
1.5
Phase

J08298+267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+0.02
+0.04
mag
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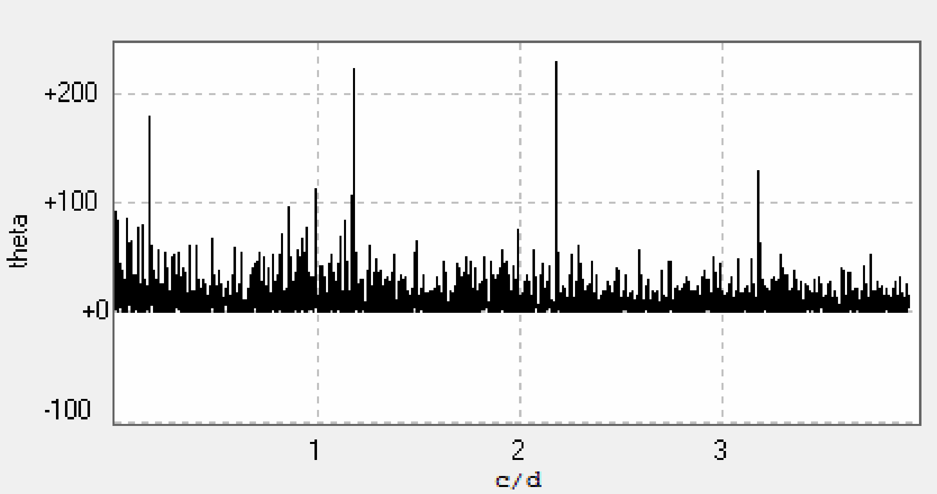
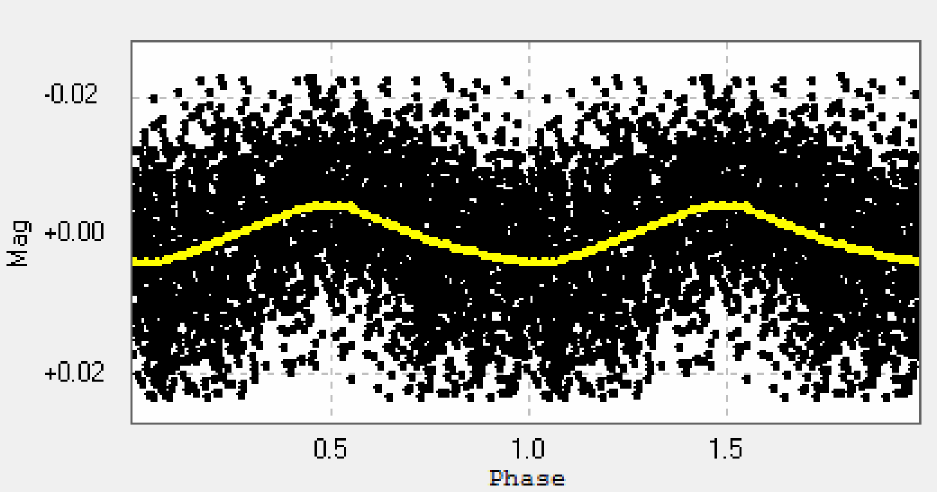
500
2456000.0+
JD


+200
+100
+0
-100
theta
1
2
3
c/d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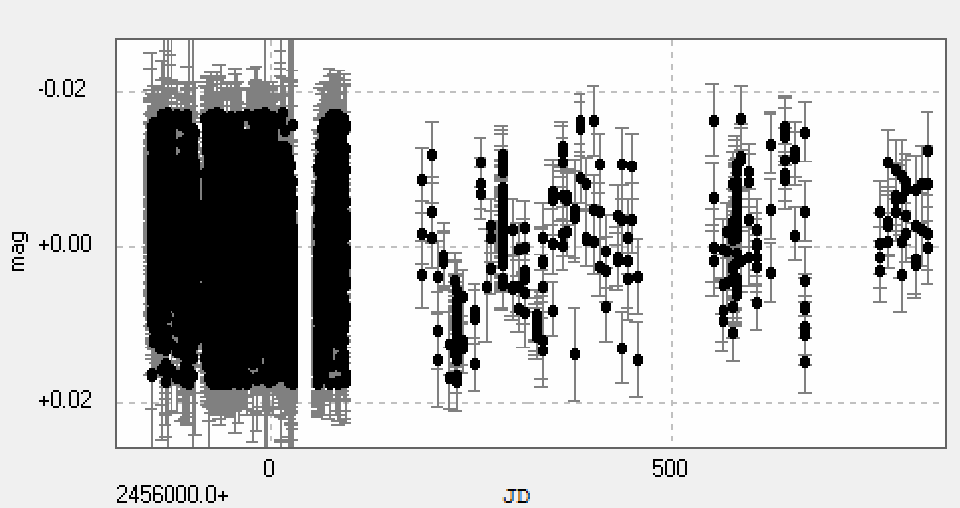
+0.02
Mag
0.5
1.0
1.5
Phase

J08315+730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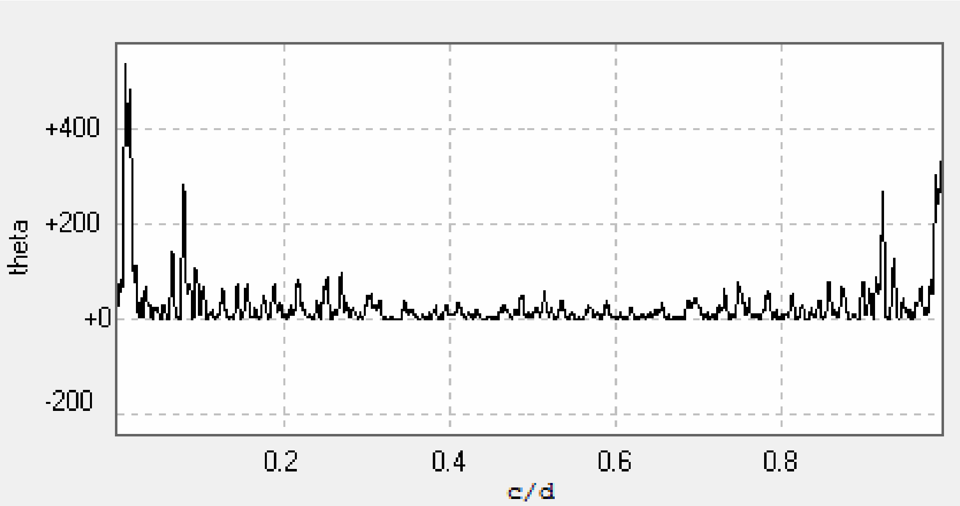
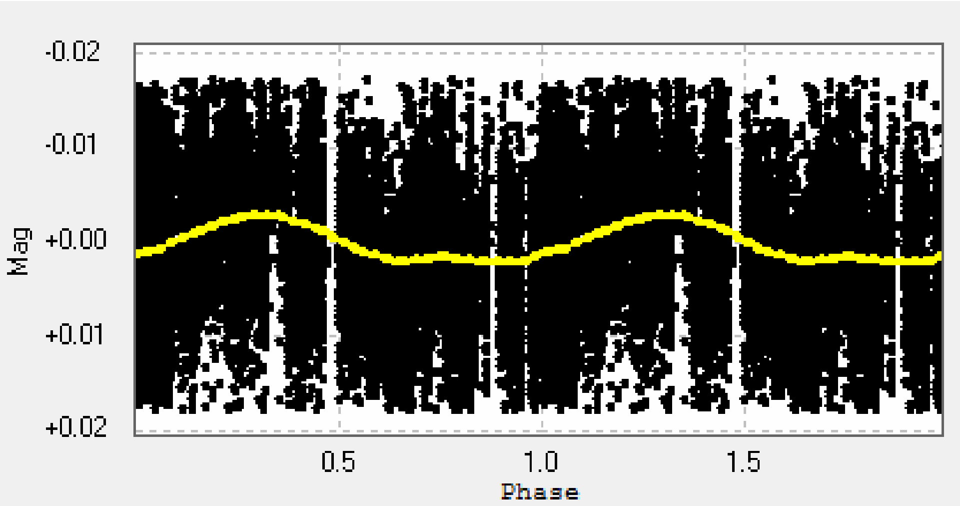
+0.00
+0.02
mag
0
500
2456000.0+
JD


+400
+200
+0
-200
theta
0.2
0.4
0.6
0.8
c/d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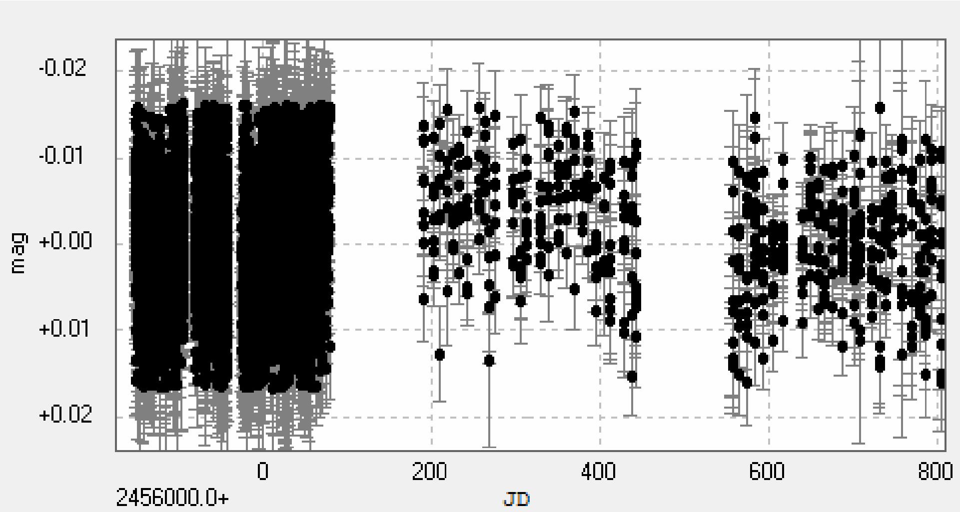
+0.00
+0.01
+0.02
Mag
0.5
1.0
1.5
Phase

J08402+314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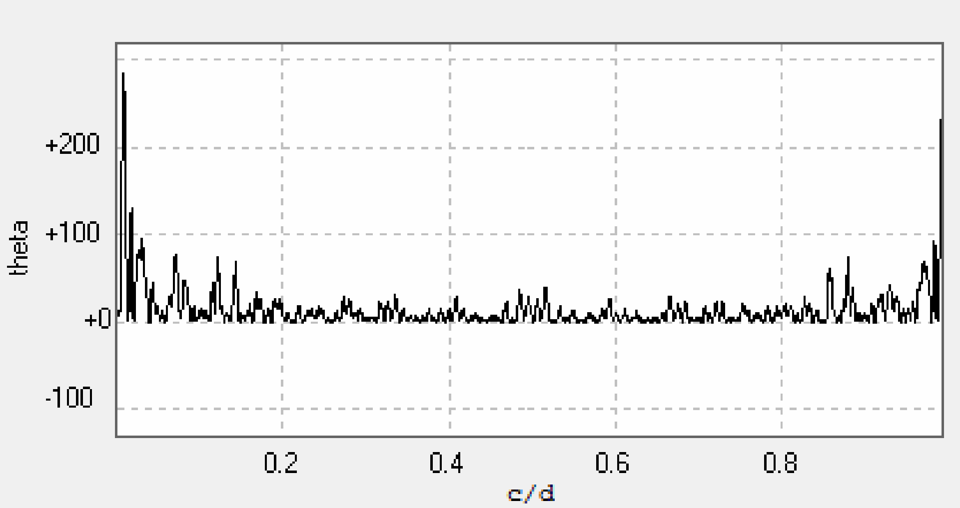
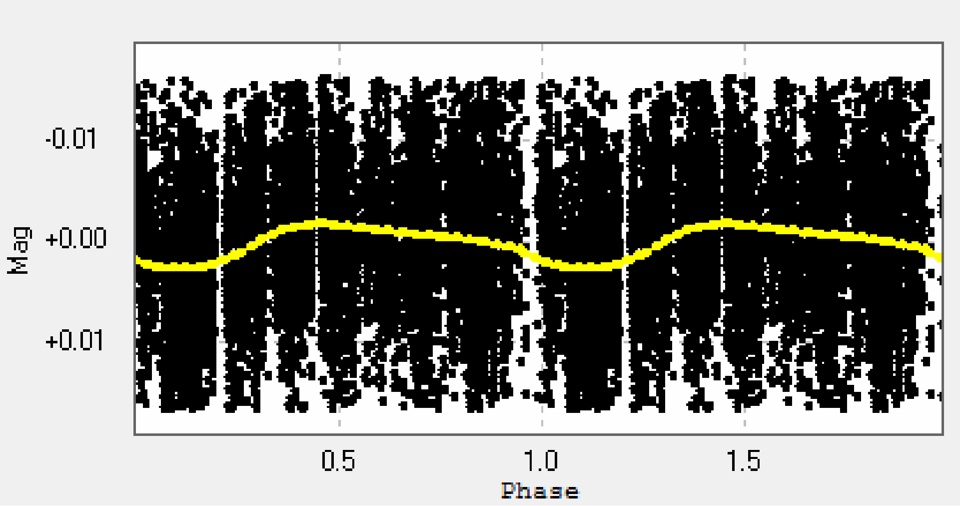
-0.01
+0.00
+0.01
+0.02
mag
0
200
400
600
800
2456000.0+
JD


+200
+100
+0
-100
theta
0.2
0.4
0.6
0.8
c/d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+0.01
Mag
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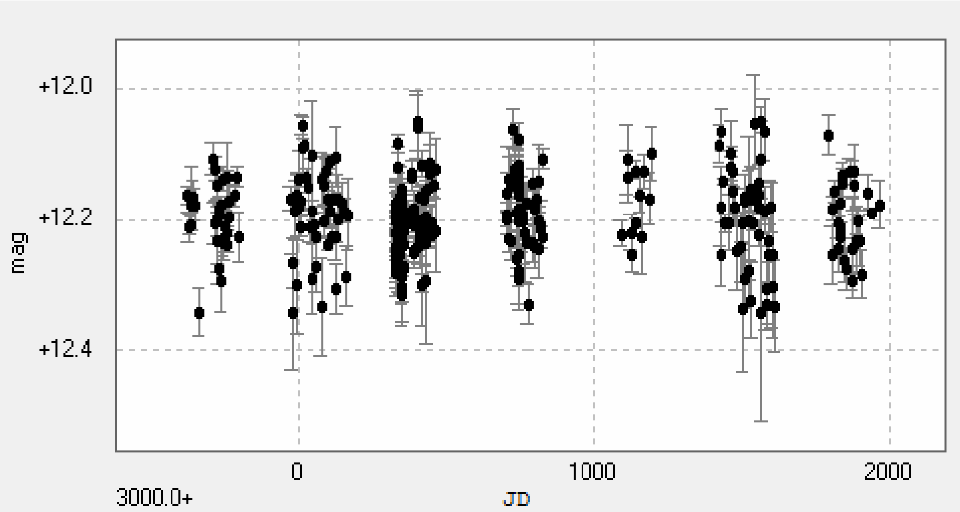
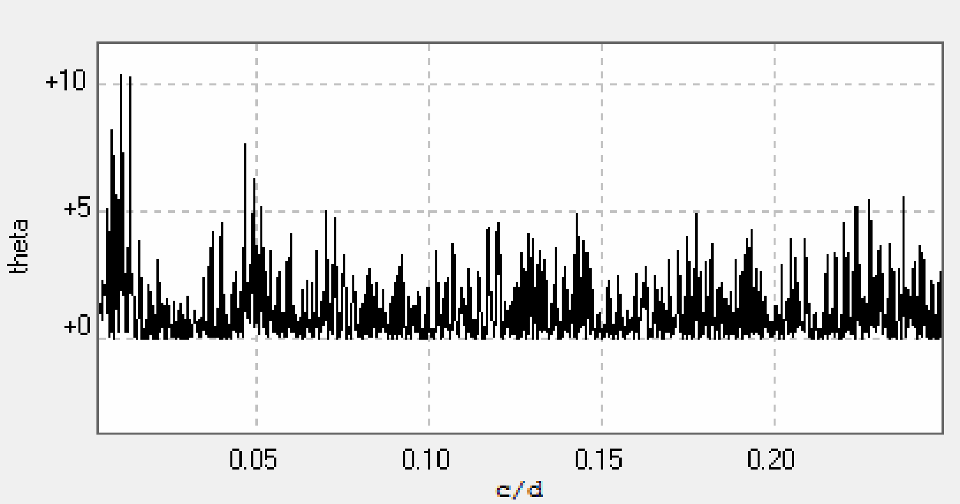
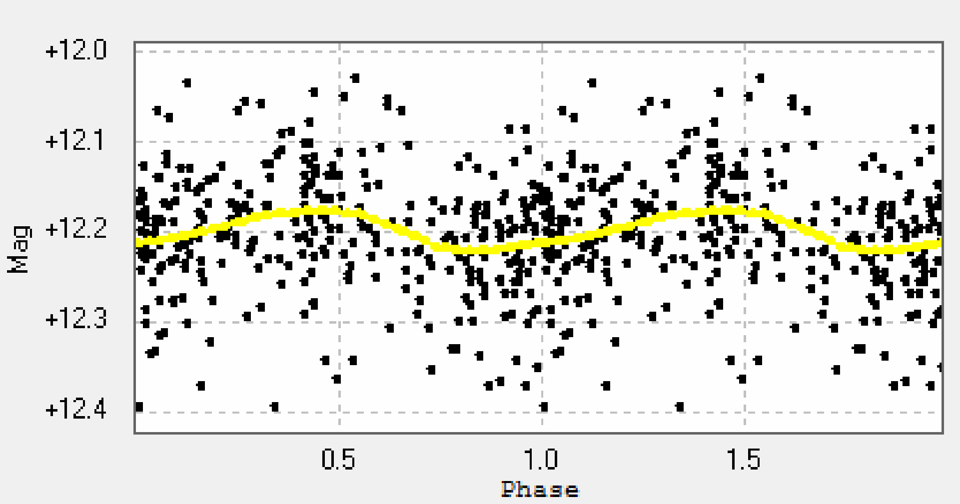
1.0
1.5
Phase

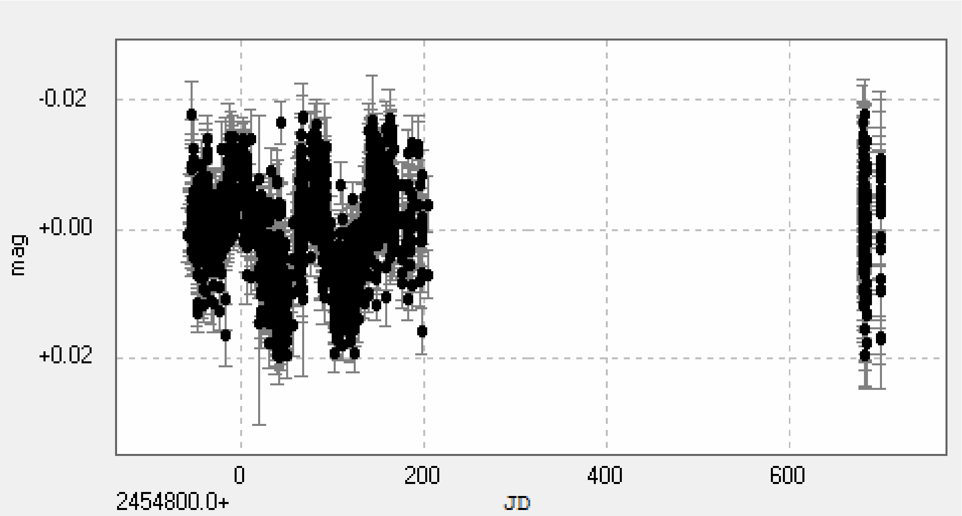
J09140+196

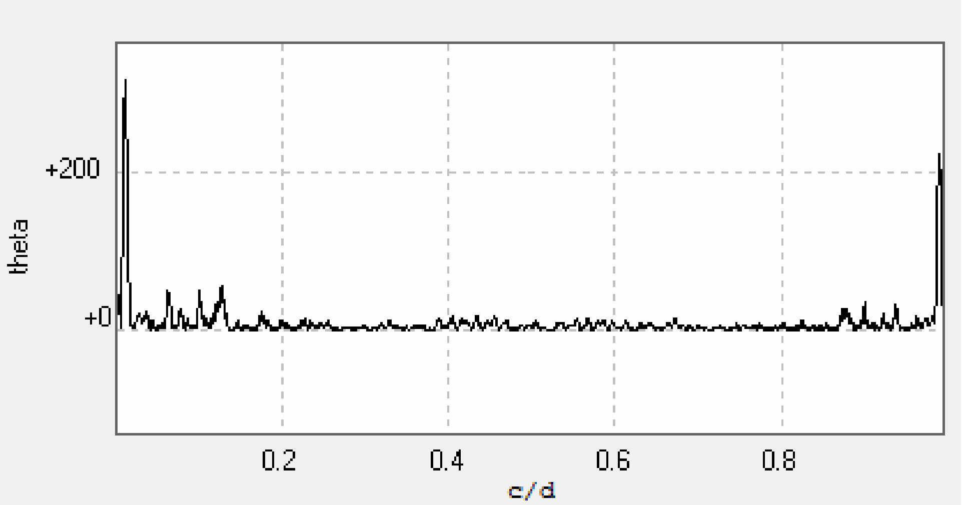

+12.0
+12.2
+12.4
mag
0
1000
2000
3000.0+
JD

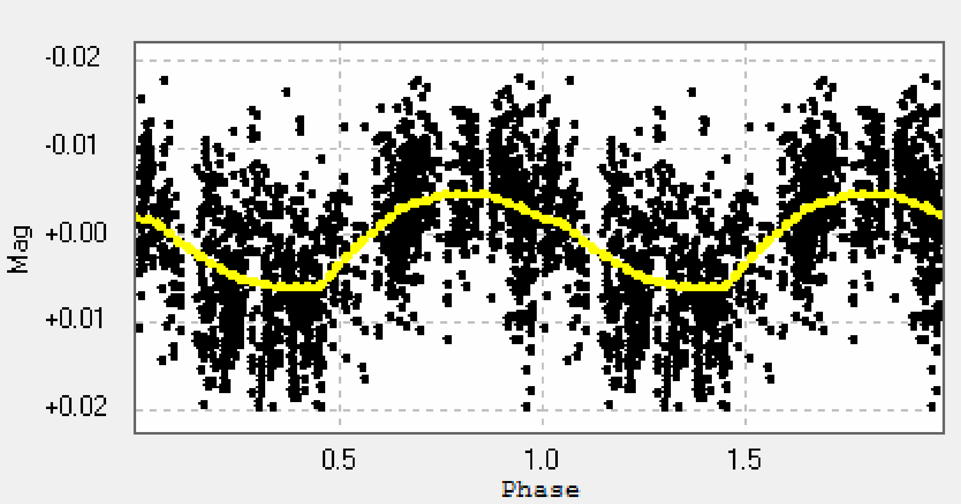

+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d


+12.0
+12.1
+12.2
+12.3
+12.4
Mag
0.5
1.0
1.5
Phase

J09423+559


-0.02
+0.00
+0.02
mag
0
200
400
600
2454800.0+
JD


+200
+0
theta
0.2
0.4
0.6
0.8
c/d


-0.02
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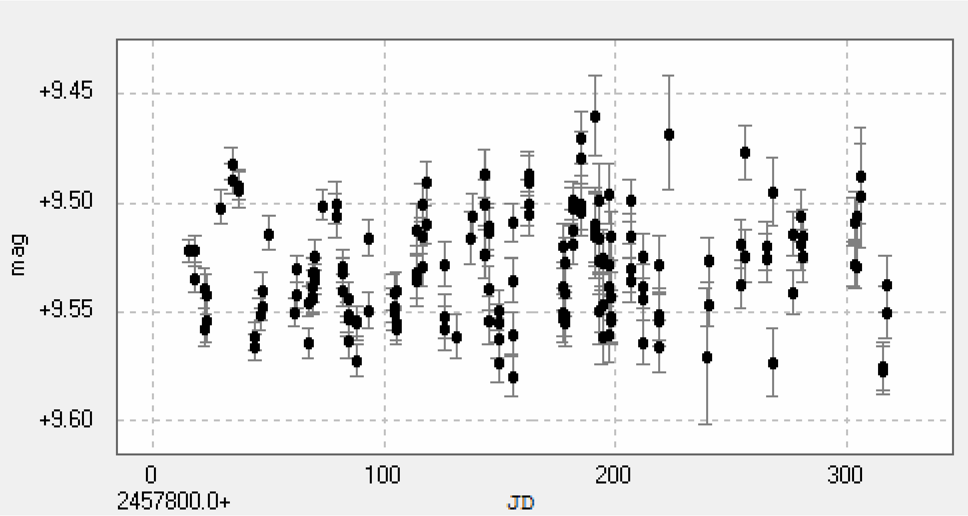
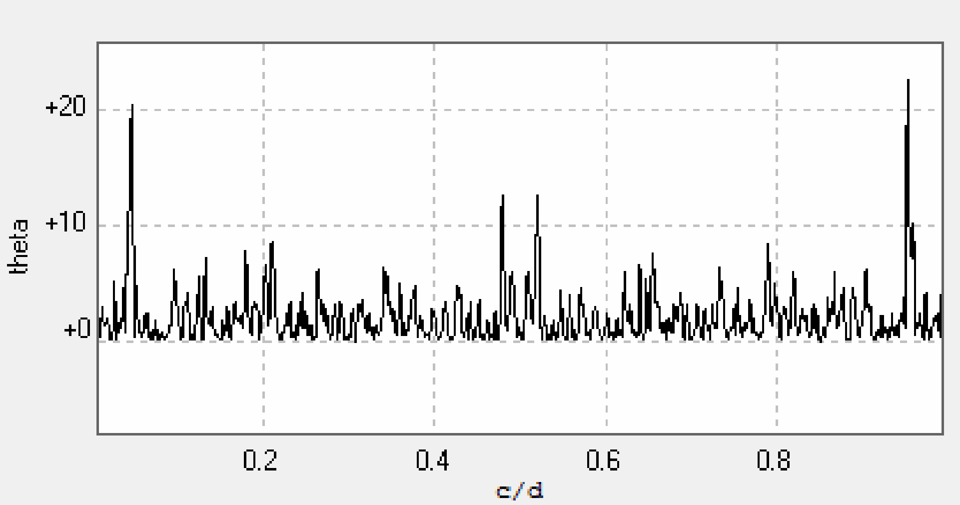
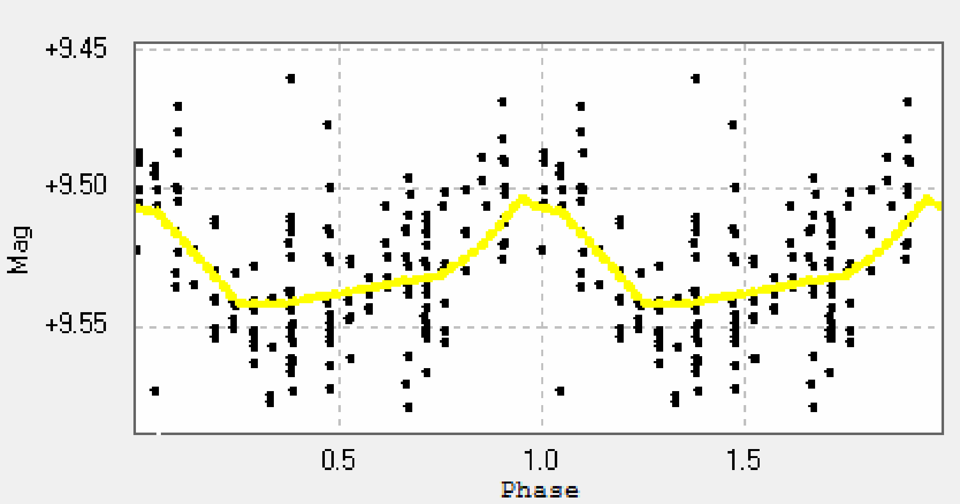
+0.00
+0.01
+0.02
Mag
0.5
1.0
1.5
Phase

J09425+700


+9.45
+9.50
+9.55
+9.60
mag
0
100
200
300
2457800.0+
JD


+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d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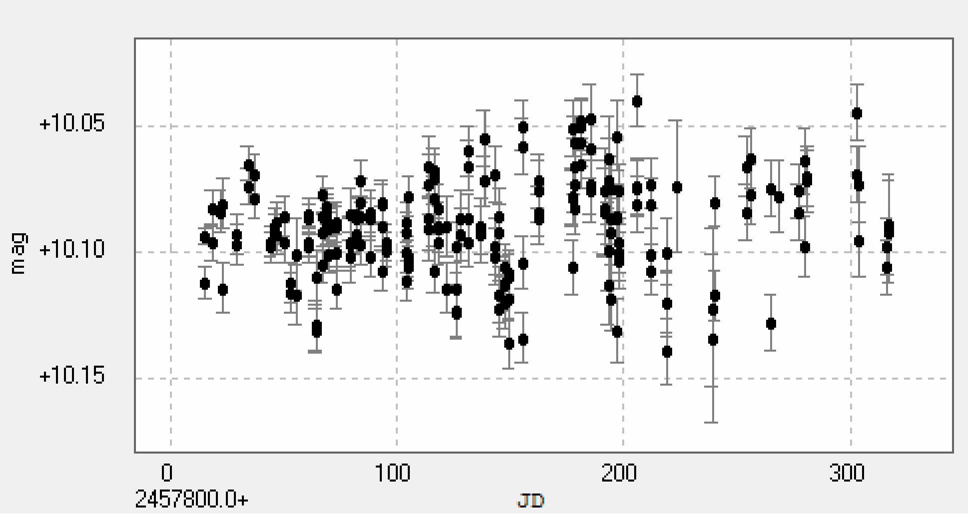
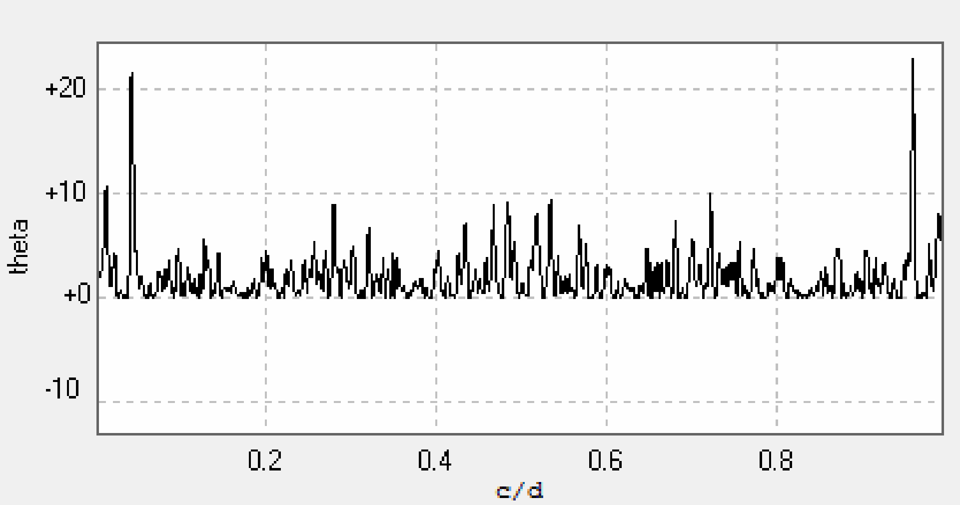
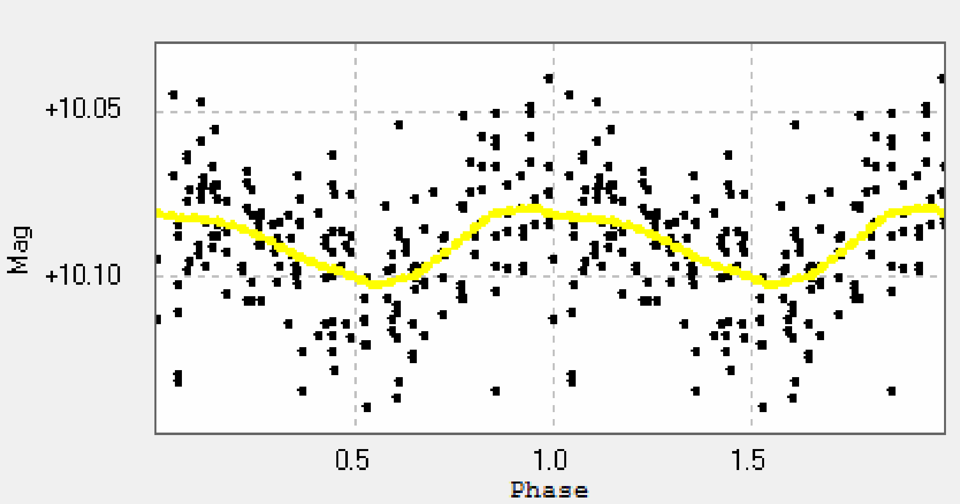
+9.50
+9.55
Mag
0.5
1.0
1.5
Phase

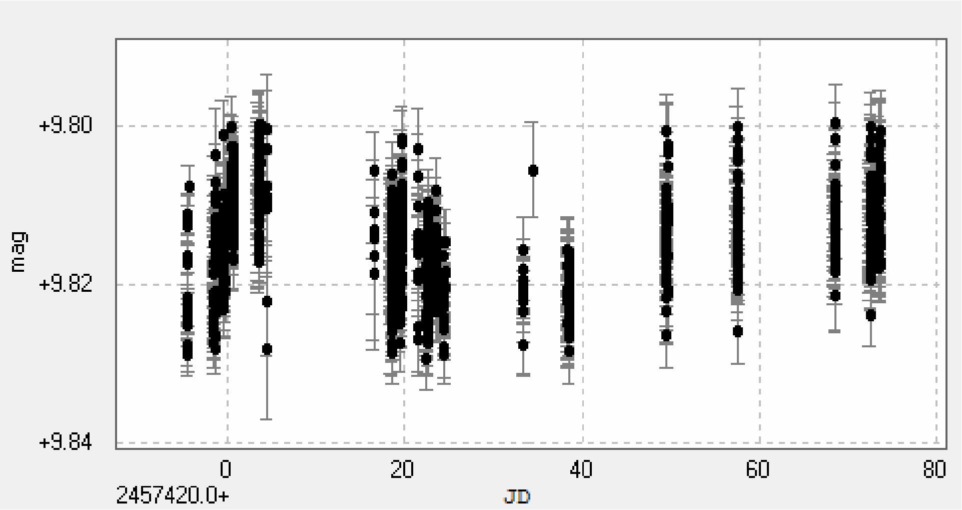
J09428+700


+10.05
+10.10
+10.15
mag
0
100
200
300
2457800.0+
JD

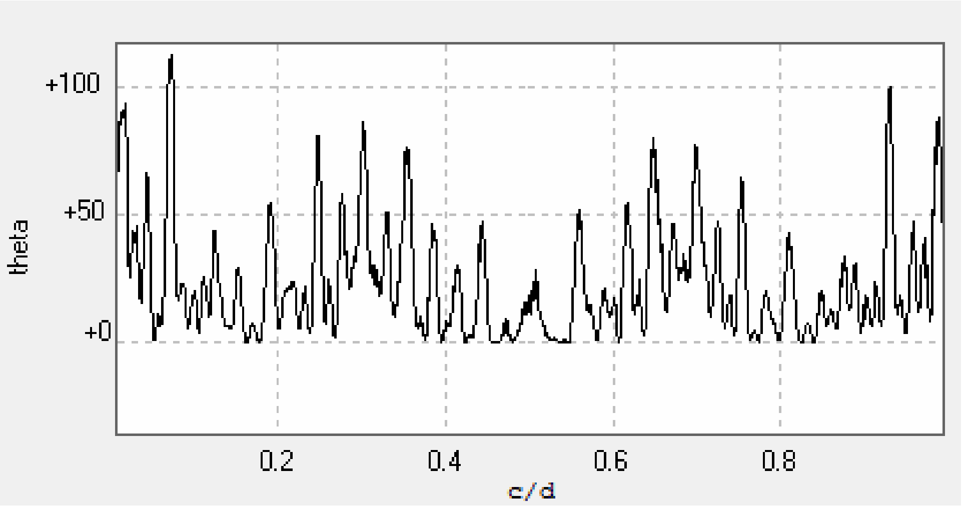

+20
+10
+0
-10
theta
0.2
0.4
0.6
0.8
c/d


+10.05
+10.10
Mag
0.5
1.0
1.5
Phase

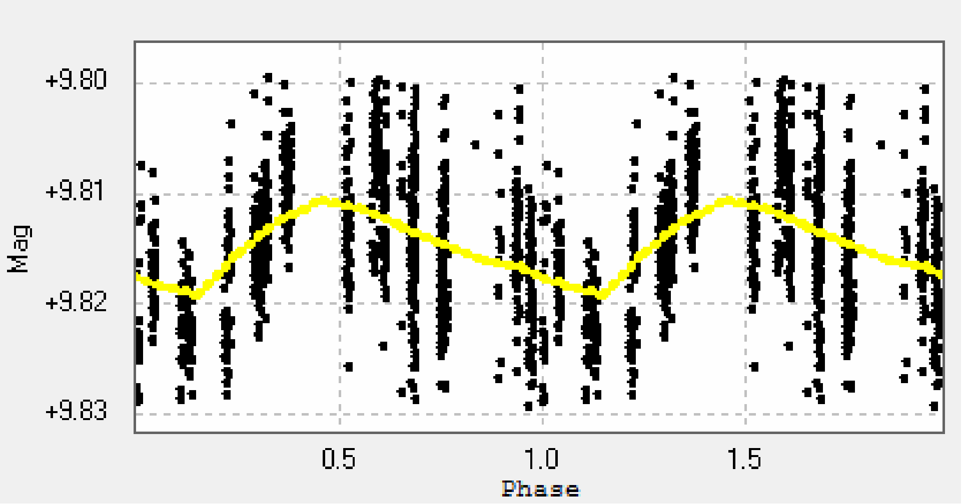
J09439+269



+9.80
+9.82
+9.84
mag
0
20
40
60
80
2457420.0+
JD

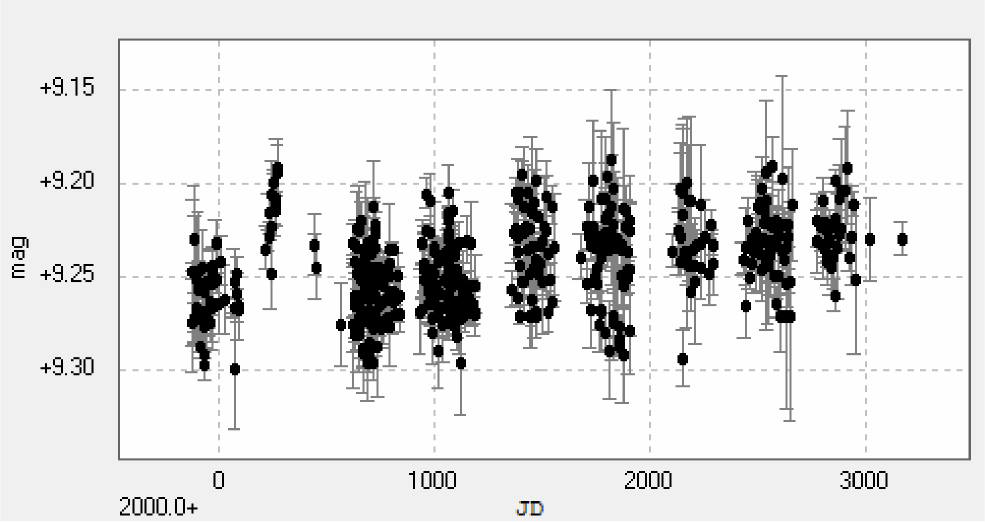


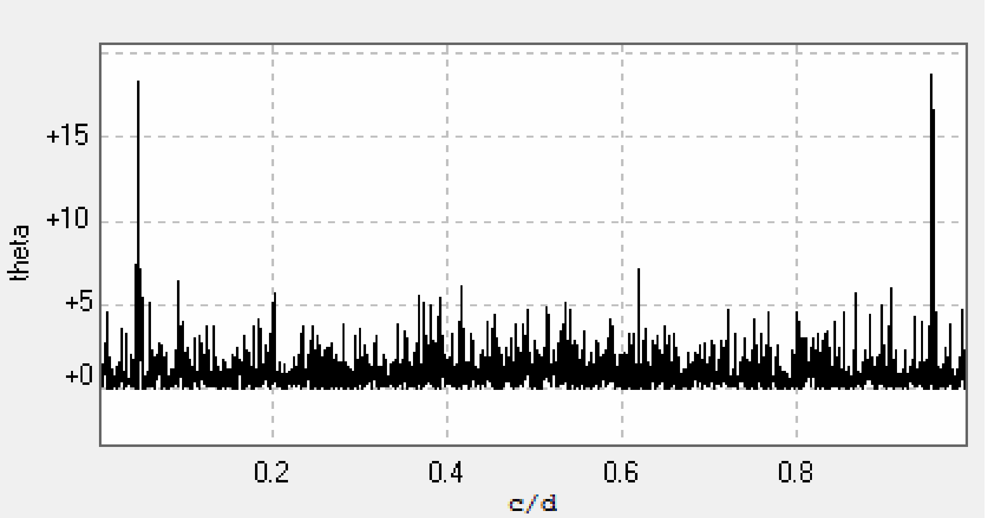
+100
+50
+0
theta
0.2
0.4
0.6
0.8
c/d

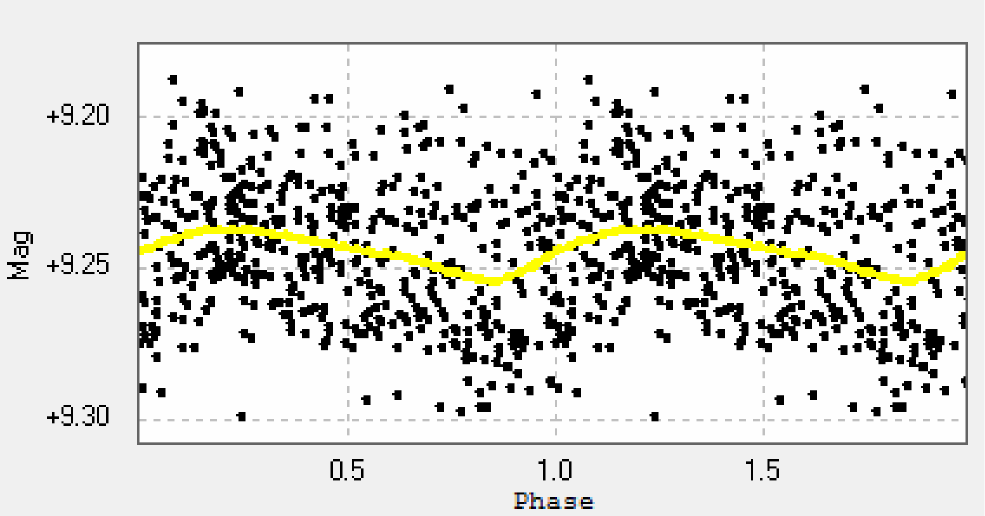


+9.80
+9.81
+9.82
+9.83
Mag
0.5
1.0
1.5
Phase

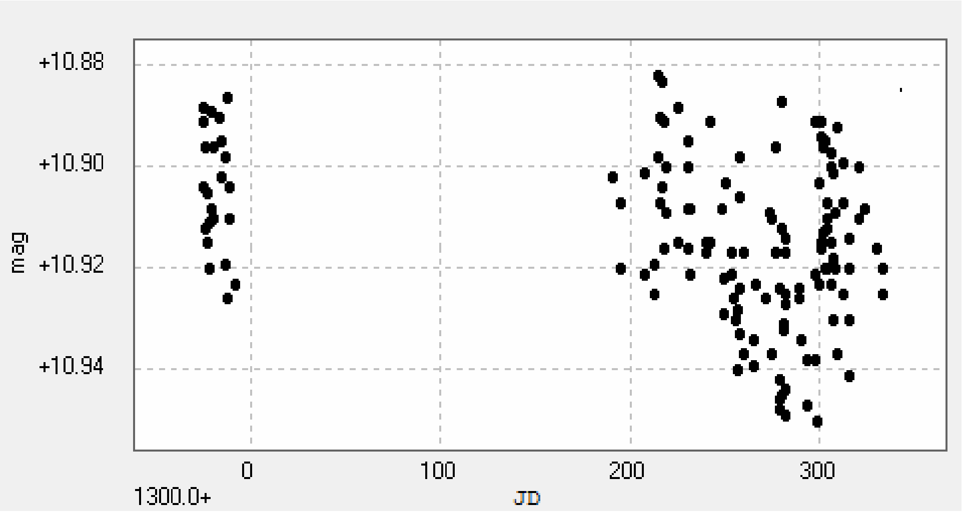
J10122-037

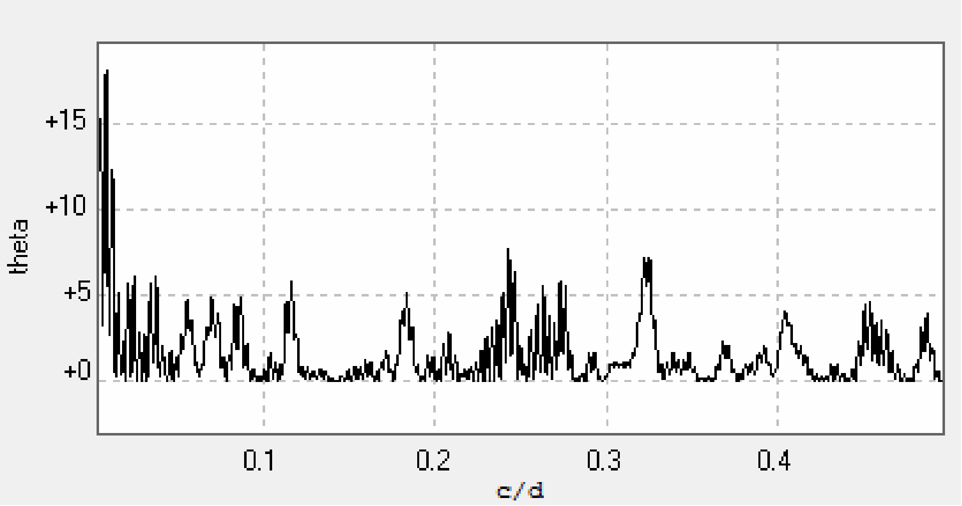

+9.15
+9.20
+9.25
+9.30
mag
0
1000
2000
3000
2000.0+
JD

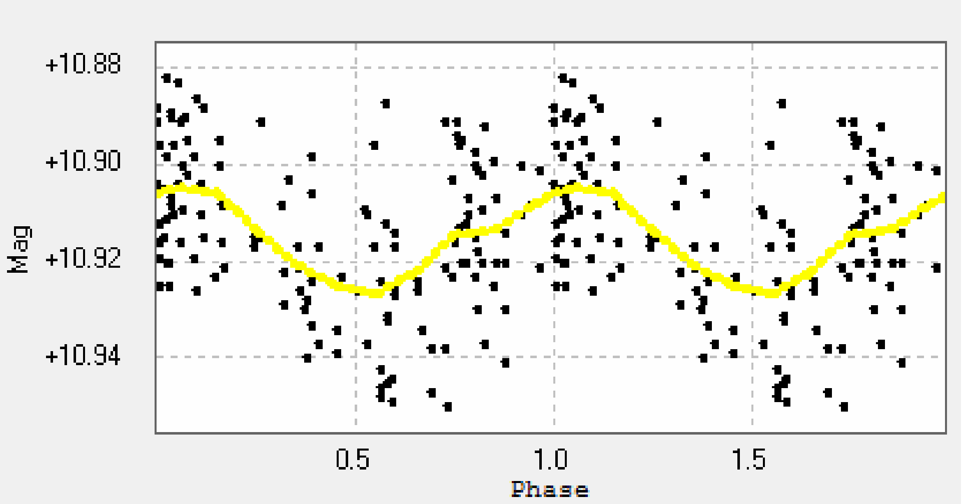

+15
+10
+5
+0
theta
0.2
0.4
0.6
0.8
c/d


+9.20
+9.25
+9.30
Mag
0.5
1.0
1.5
Phase

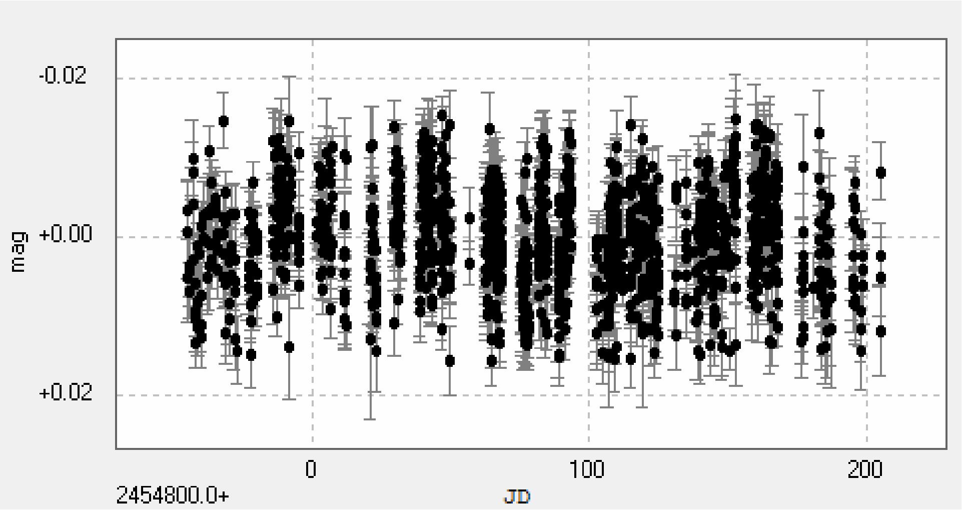
J10354+694

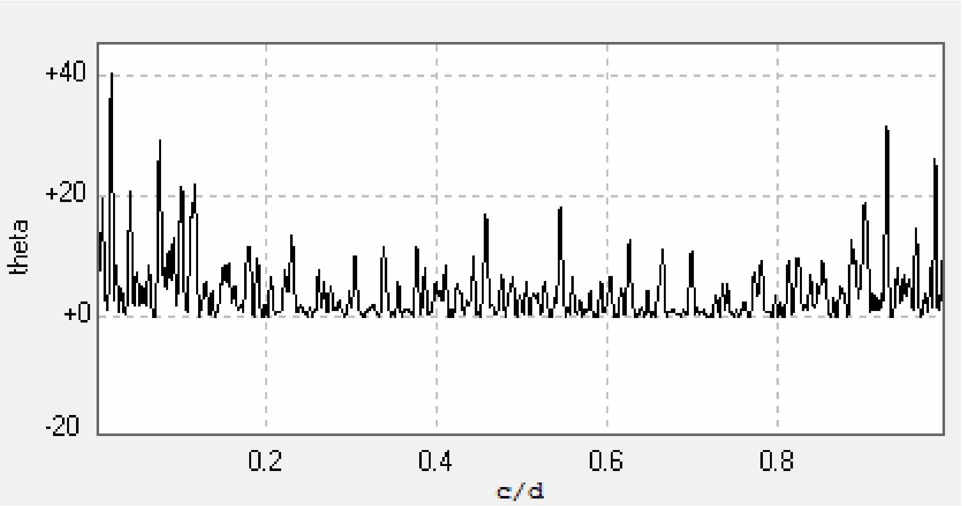

+10.88
+10.90
+10.92
+10.94
mag
0
100
200
300
1300.0+
JD

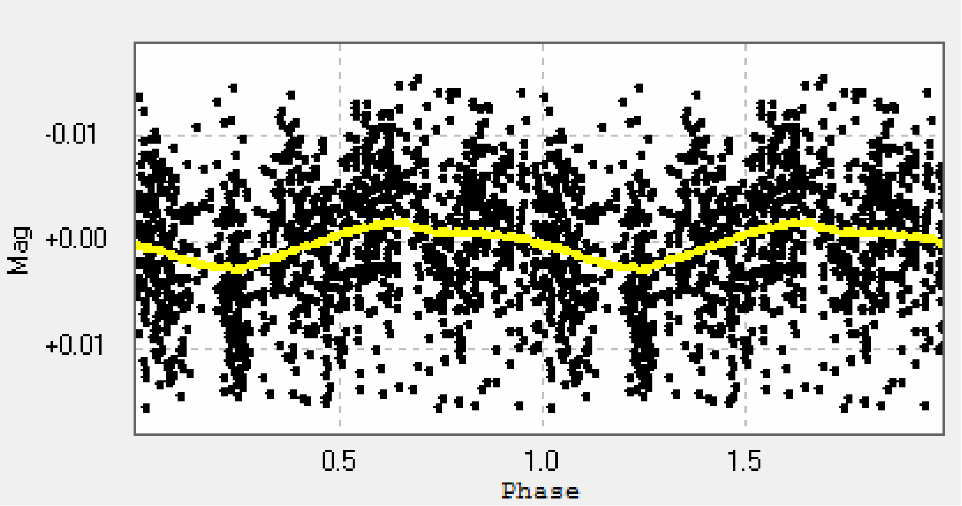

+15
+10
+5
+0
theta
0.1
0.2
0.3
0.4
c/d


+10.88
+10.90
+10.92
+10.94
Mag
0.5
1.0
1.5
Phase

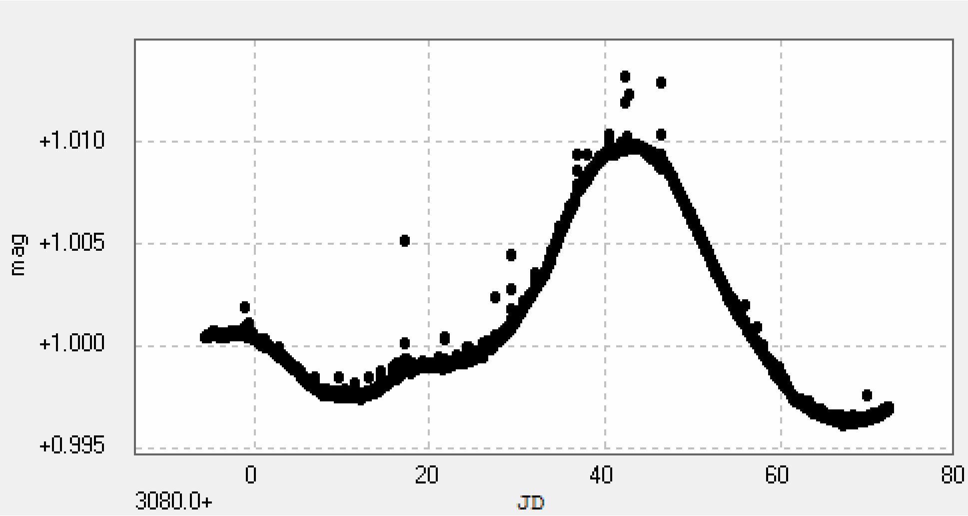
J10416+376

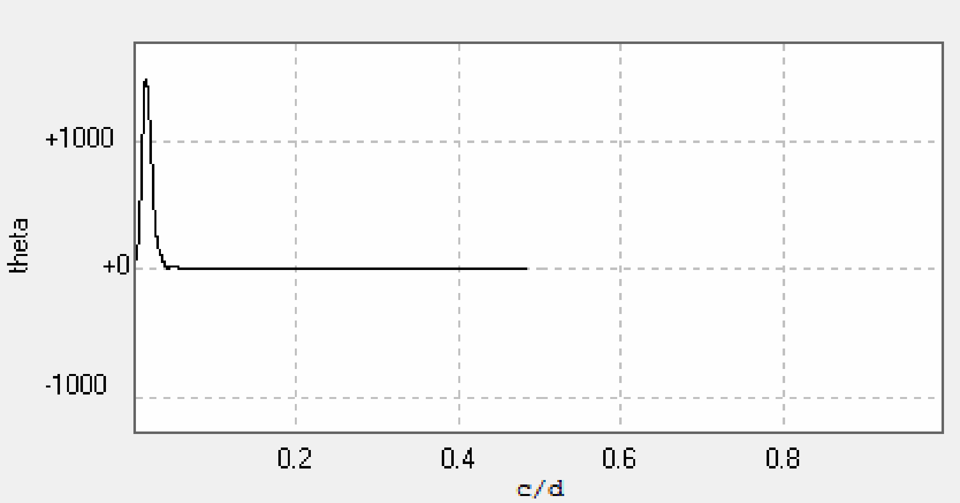

-0.02
+0.00
+0.02
mag
0
100
200
2454800.0+
JD

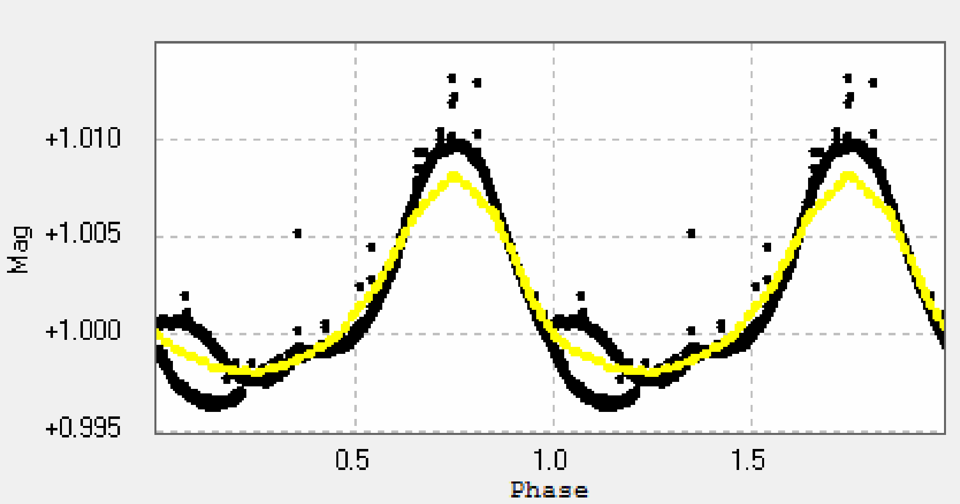

+40
+20
+0
-20
theta
0.2
0.4
0.6
0.8
c/d


-0.01
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

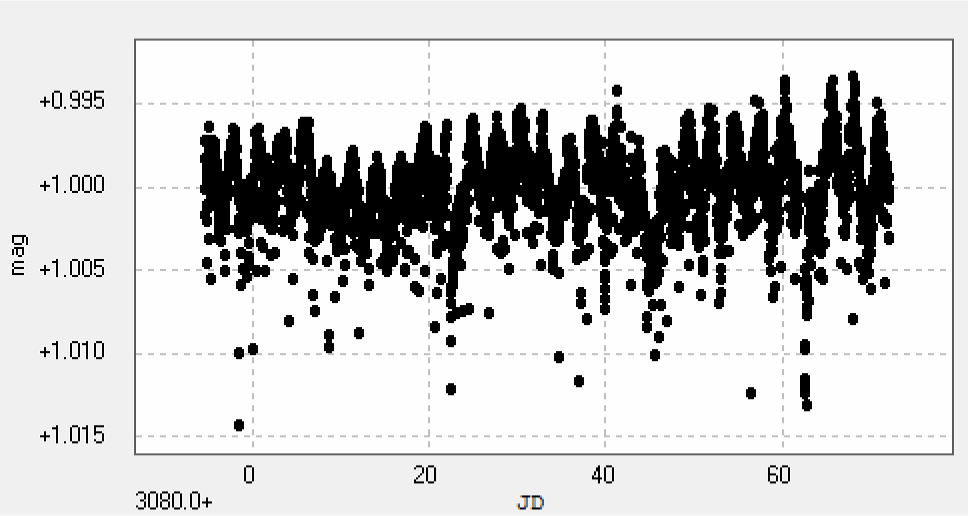
J10508+068

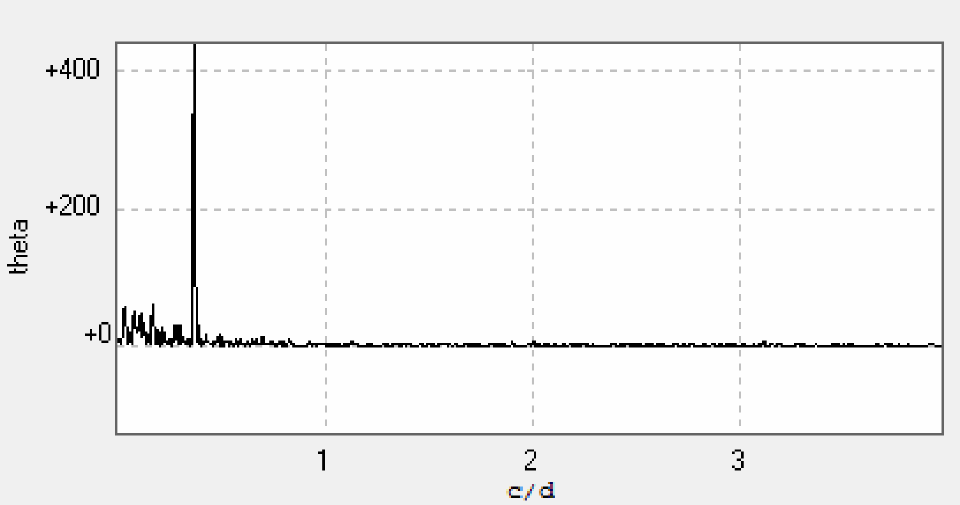

mag
+1.010
+1.005
+1.000
+0.995
0
20
40
60
80
3080.0+
JD

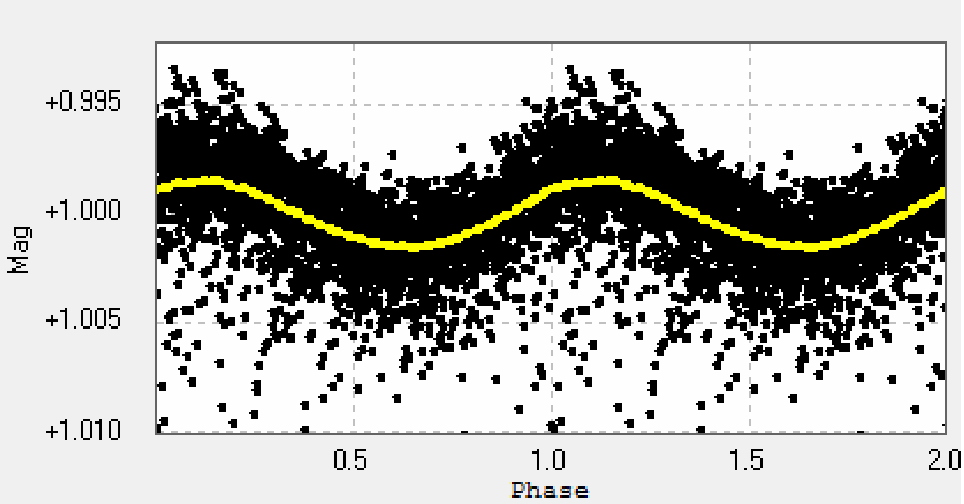

theta
+1000
+0
-1000
0.2
0.4
0.6
0.8
c/d


Mag
+1.010
+1.005
+1.000
+0.995
0.5
1.0
1.5
Phase

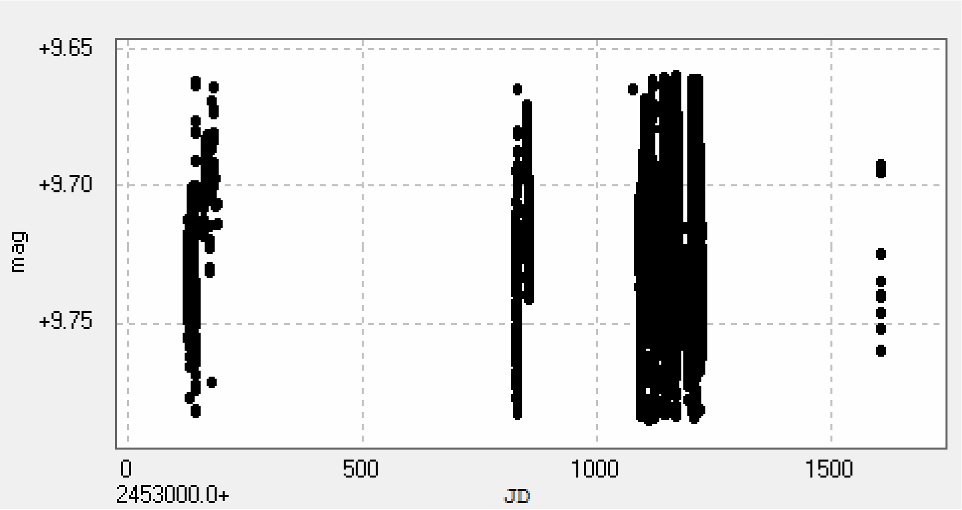
J10564+070

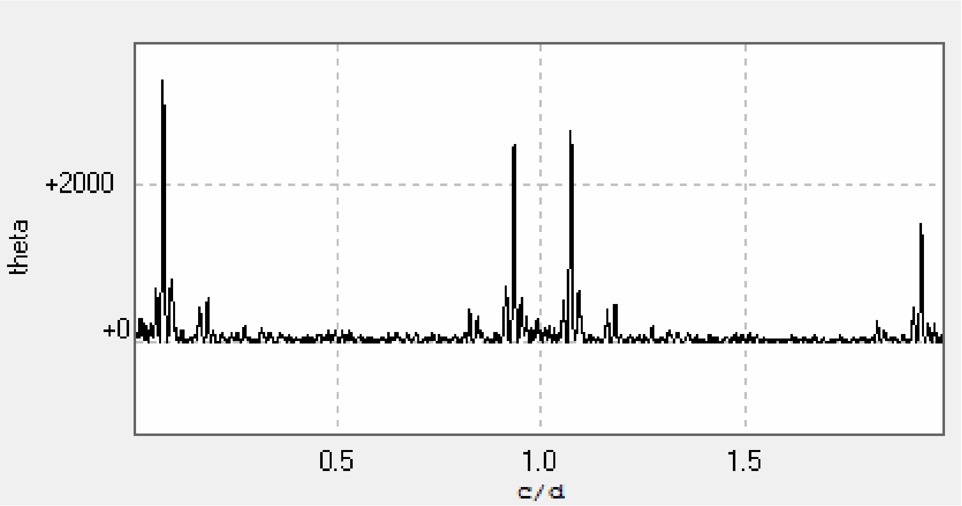

+0.995
+1.000
+1.005
+1.010
+1.015
mag
0
20
40
60
3080.0+
JD

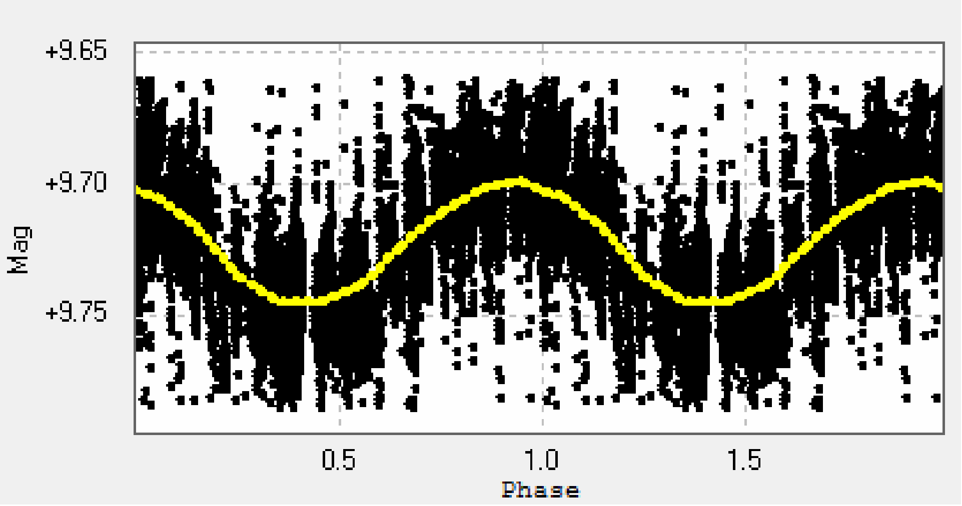

+400
+200
+0
theta
1
2
3
c/d


+0.995
+1.000
+1.005
+1.010
Mag
0.5
1.0
1.5
2.0
Phase

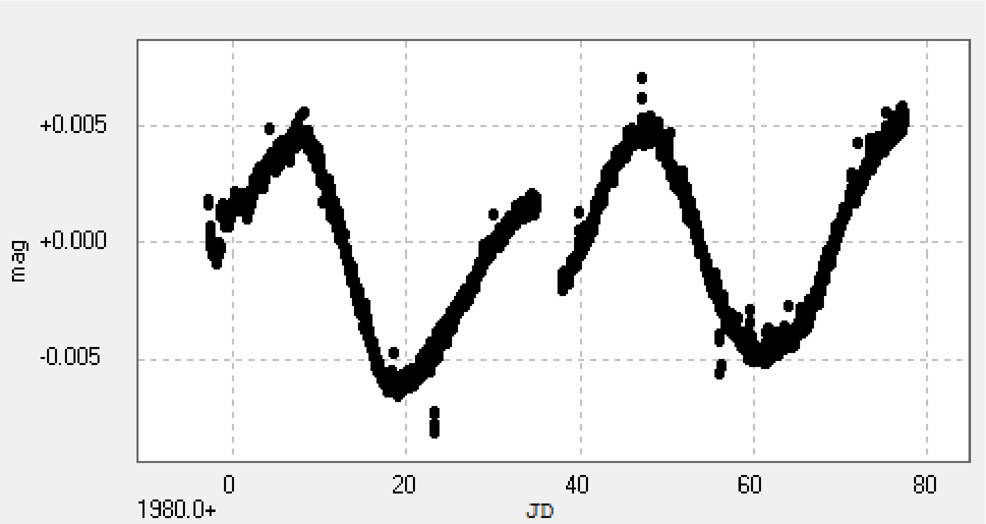
J11026+219

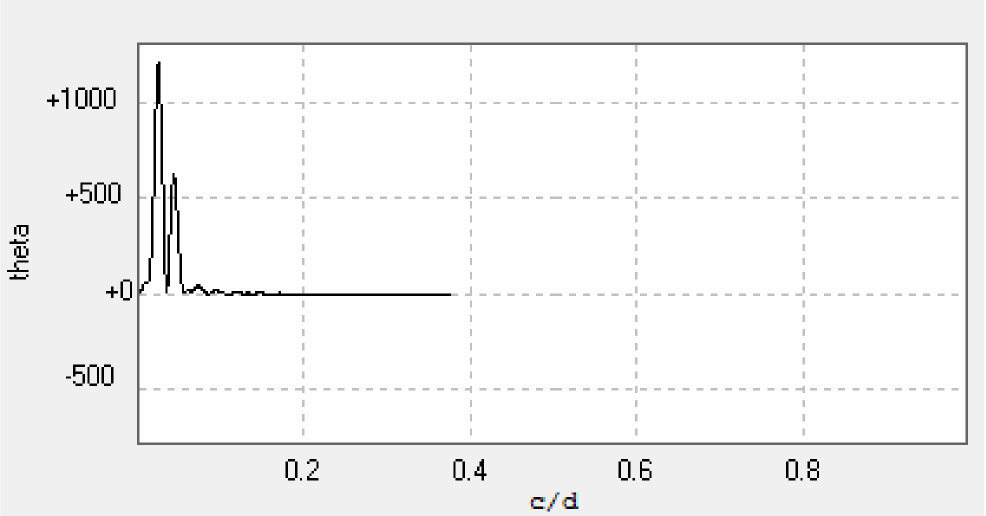

+9.65
+9.70
+9.75
mag
0
500
1000
1500
2453000.0+
JD

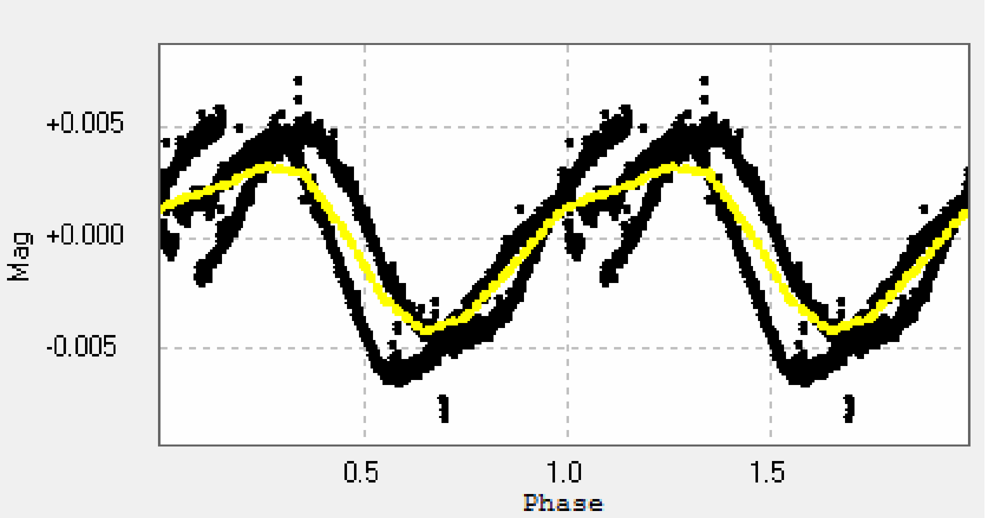

+2000
+0
theta
0.5
1.0
1.5
c/d


+9.65
+9.70
+9.75
Mag
0.5
1.0
1.5
Phase

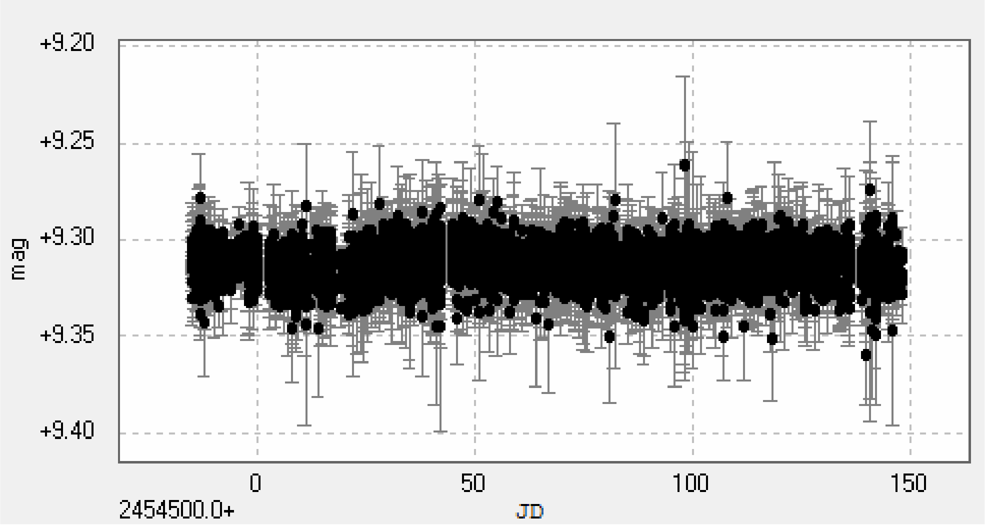
J11302+076


mag
+0.005
+0.000
-0.005
0
20
40
60
80
1980.0+
JD

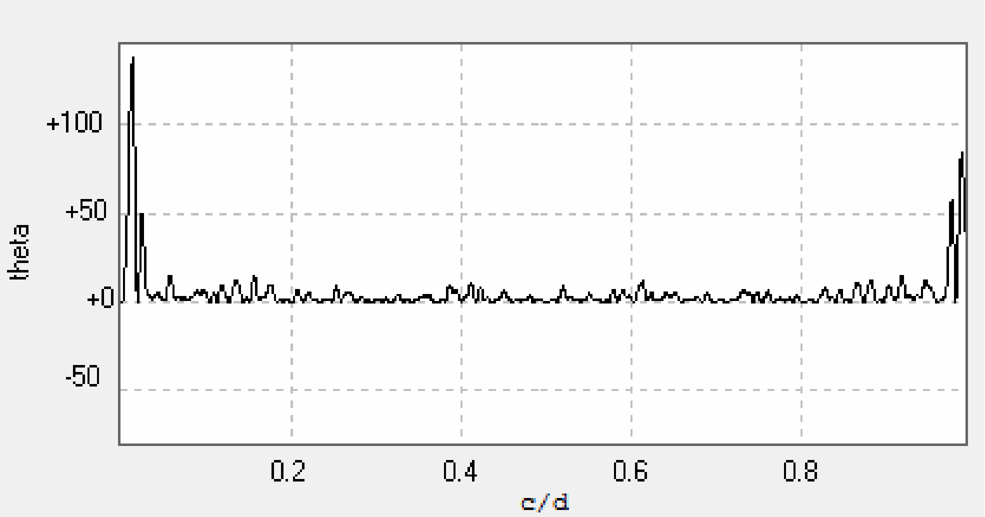

theta
+1000
+500
+0
-500
0.2
0.4
0.6
0.8
c/d


Mag
+0.005
+0.000
-0.005
0.5
1.0
1.5
Phase

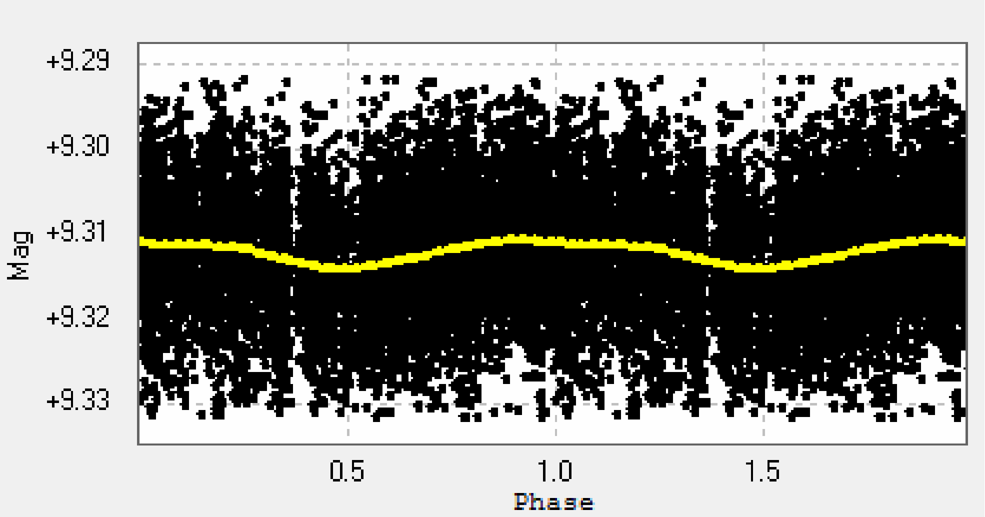
J11417+427



+9.20
+9.25
+9.30
+9.35
+9.40
mag
0
50
100
150
2454500.0+
JD

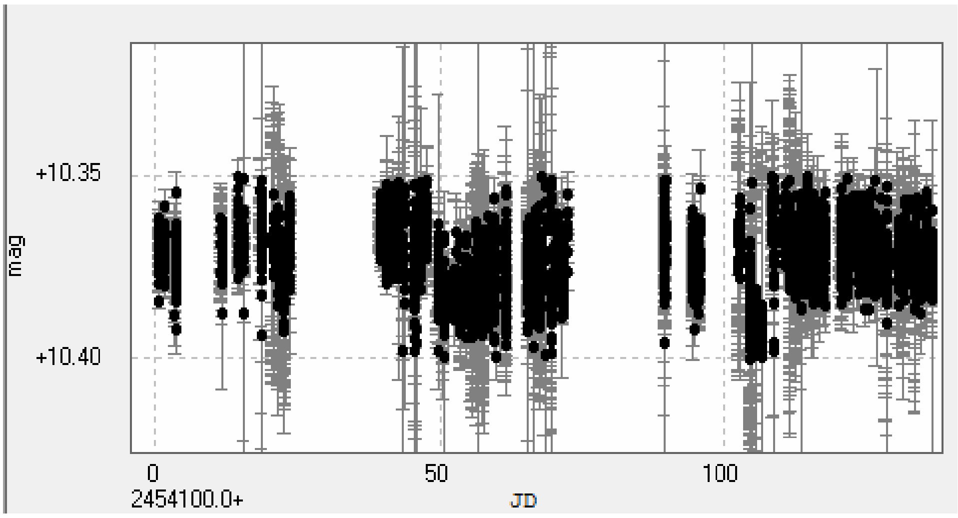


+100
+50
+0
-50
theta
0.2
0.4
0.6
0.8
c/d

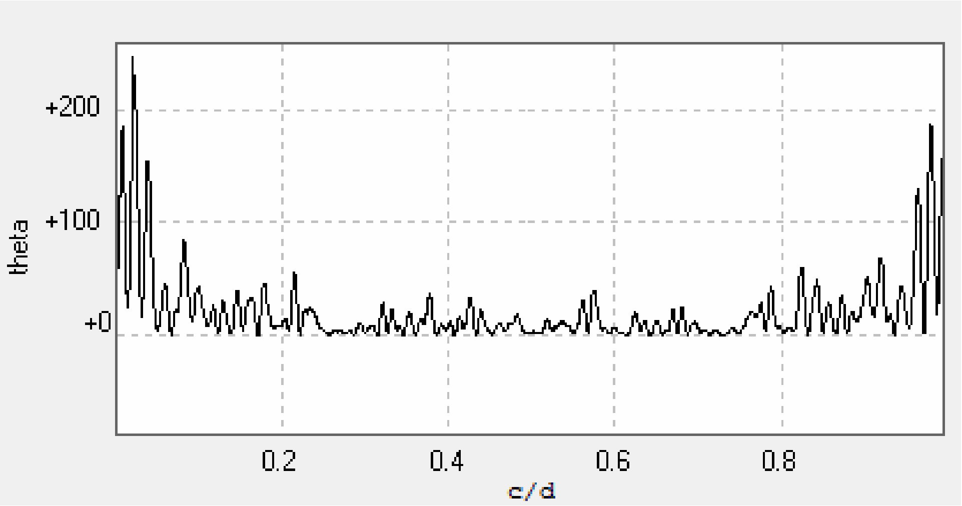


+9.29
+9.30
+9.31
+9.32
+9.33
Mag
0.5
1.0
1.5
Phase

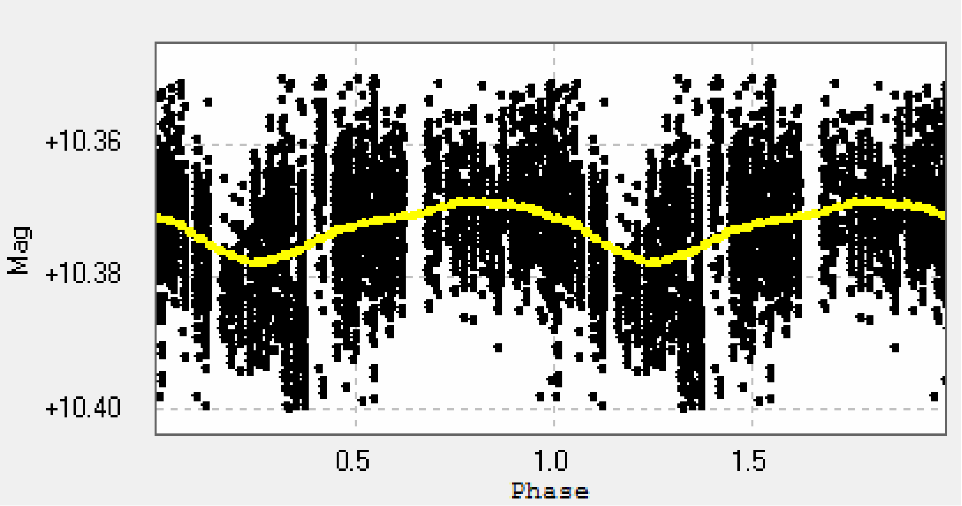
J11421+267



+10.35
+10.40
mag
0
50
100
2454100.0+
JD

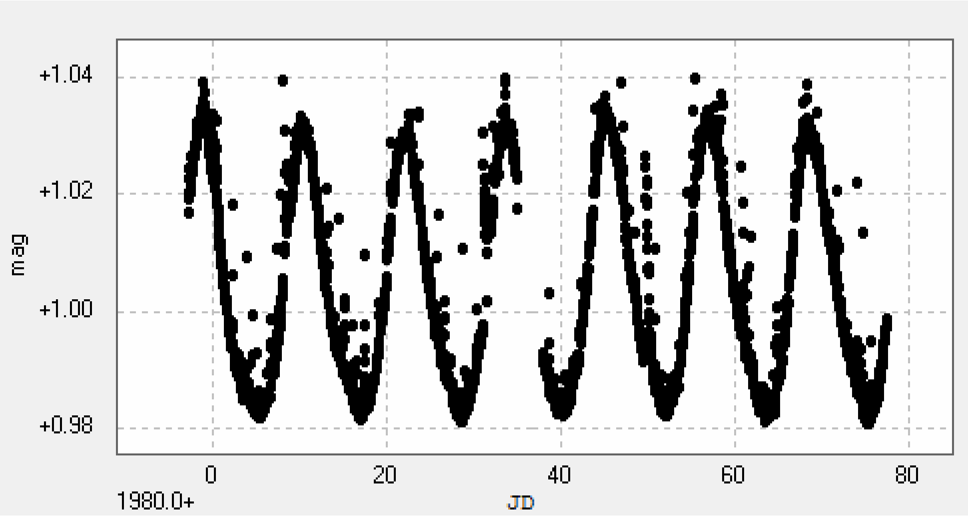


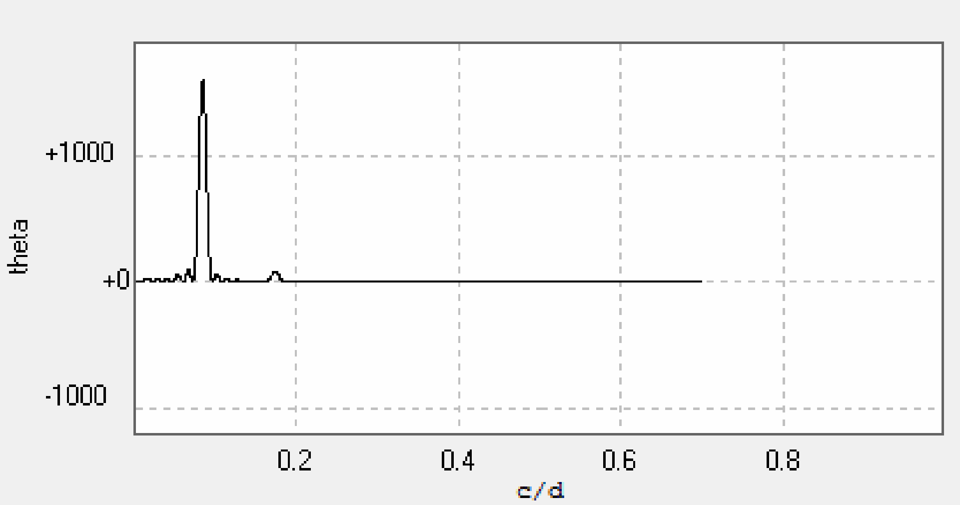
+200
+100
+0
theta
0.2
0.4
0.6
0.8
c/d

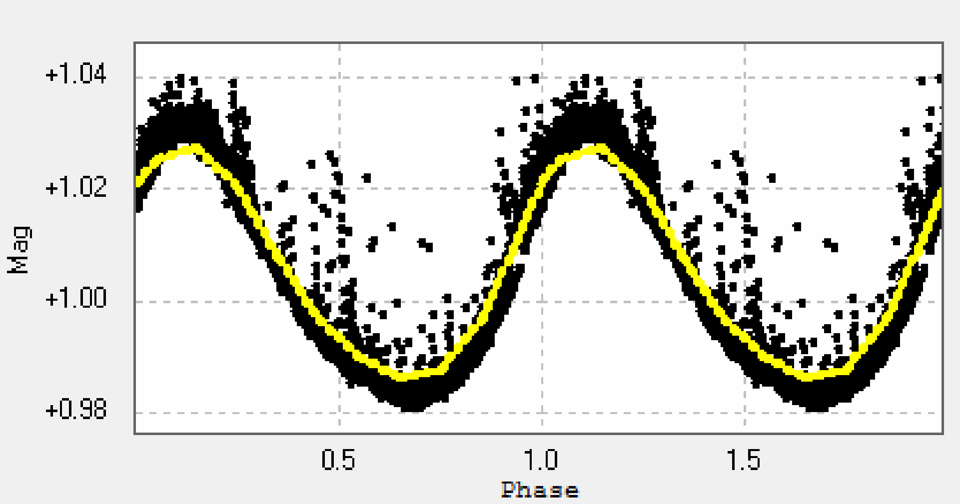


+10.36
+10.38
+10.40
Mag
0.5
1.0
1.5
Phase

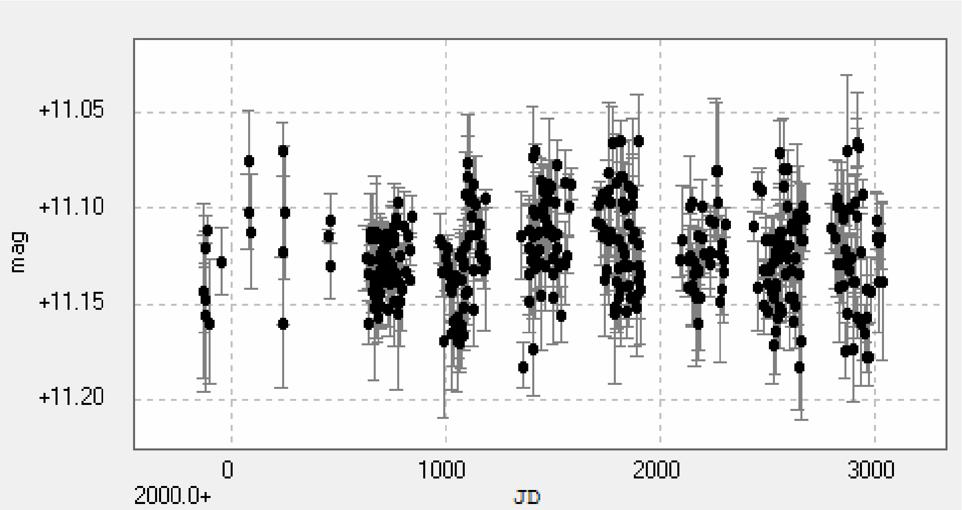
J11476+002

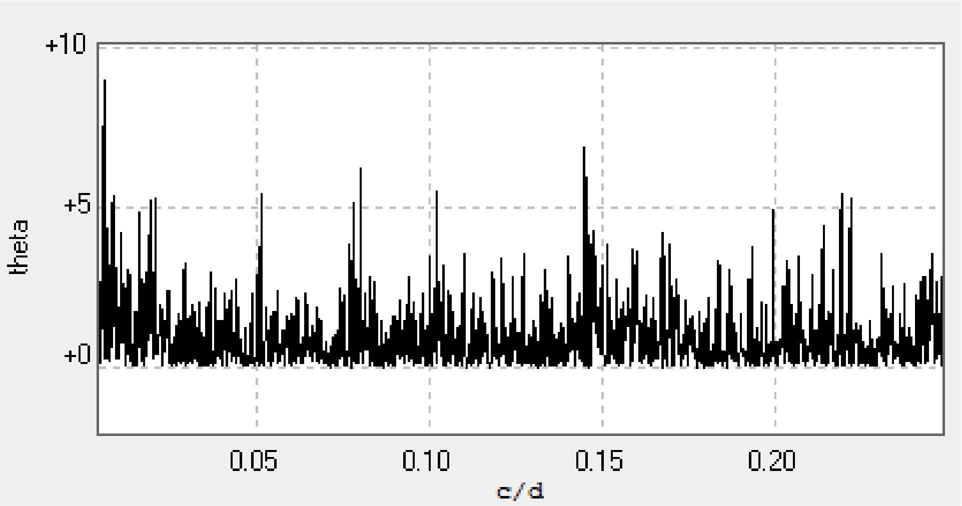

+1.04
+1.02
+1.00
+0.98
mag
0
20
40
60
80
1980.0+
JD

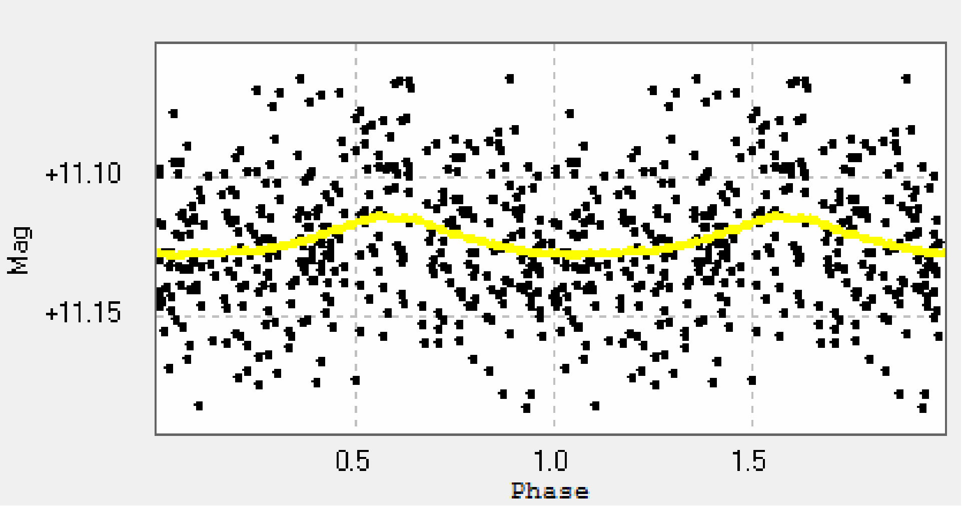

+1000
+0
-1000
theta
0.2
0.4
0.6
0.8
c/d


+1.04
+1.02
+1.00
+0.98
Mag
0.5
1.0
1.5
Phase

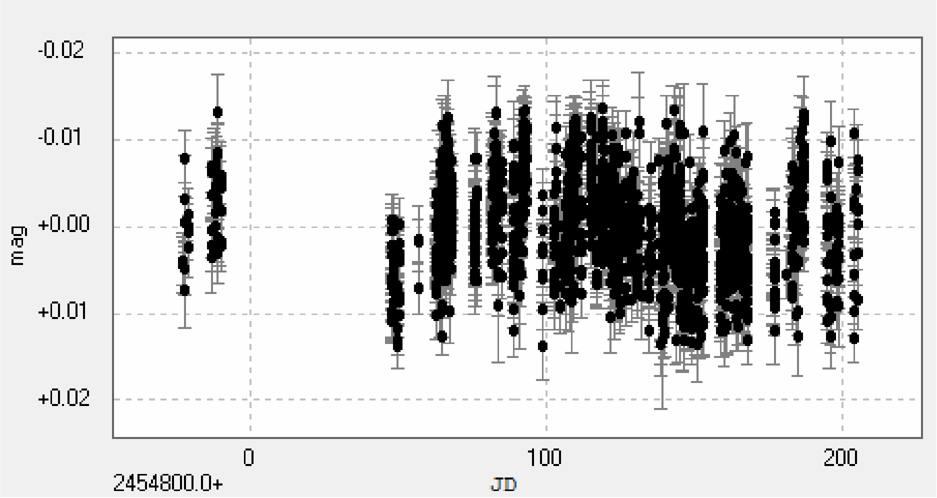
J11477+008

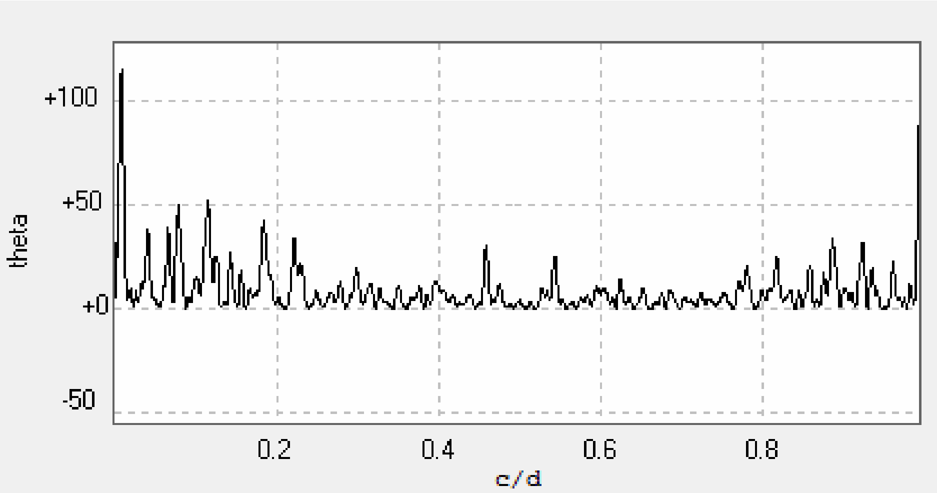

+11.05
+11.10
+11.15
+11.20
mag
0
1000
2000
3000
2000.0+
JD

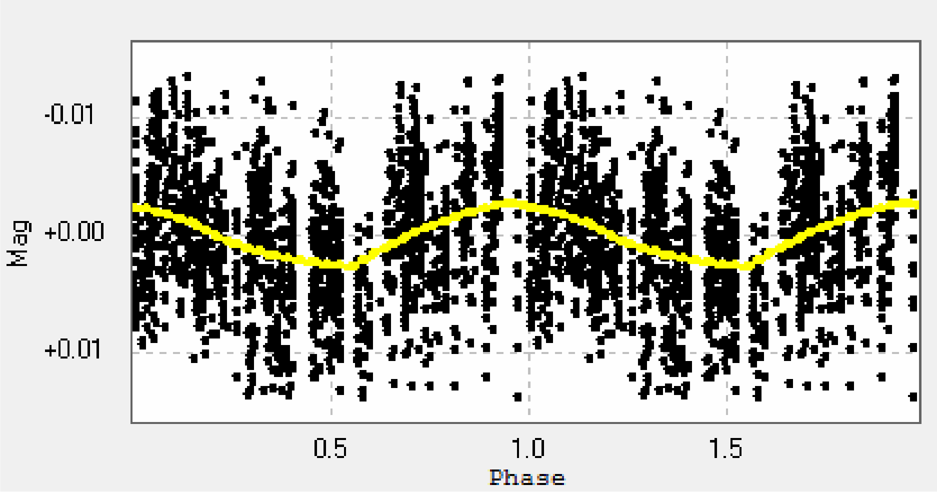

+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d


+11.10
+11.15
Mag
0.5
1.0
1.5
Phase

J11509+483


-0.02
-0.01
+0.00
+0.01
+0.02
mag
0
100
200
2454800.0+
JD


+100
+50
+0
-50
theta
0.2
0.4
0.6
0.8
c/d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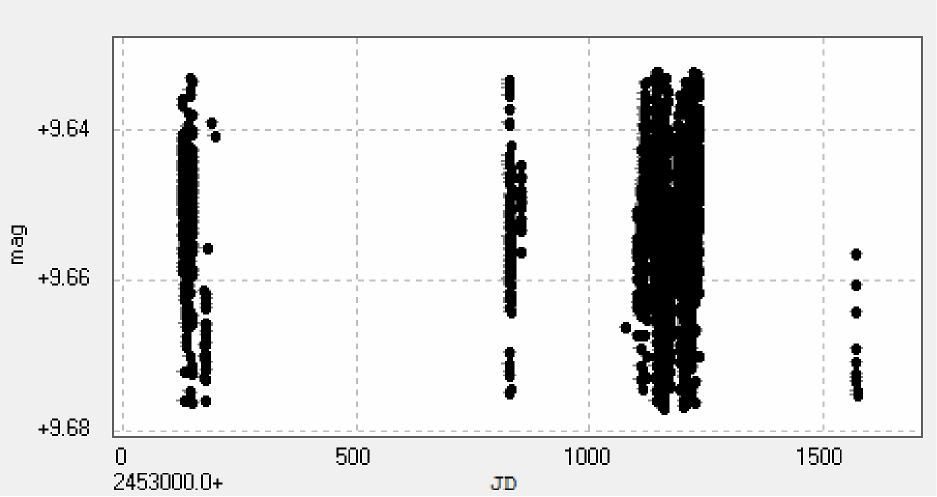
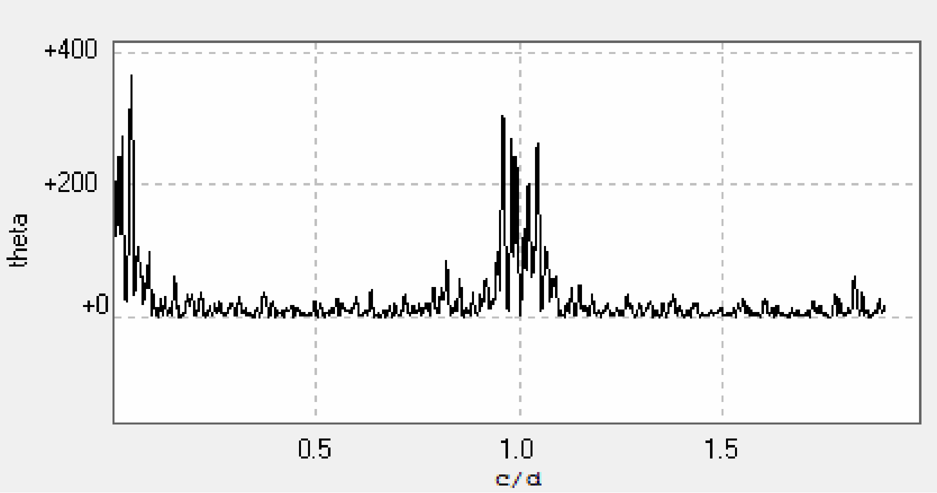
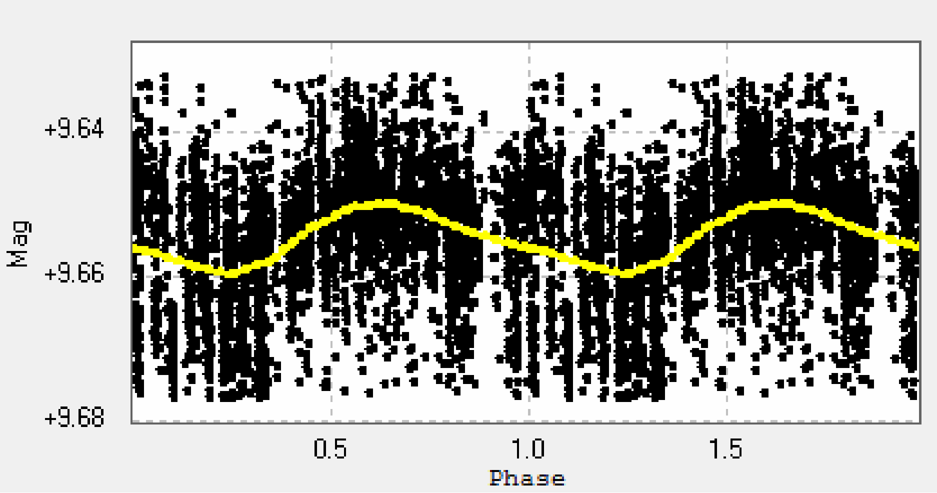
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

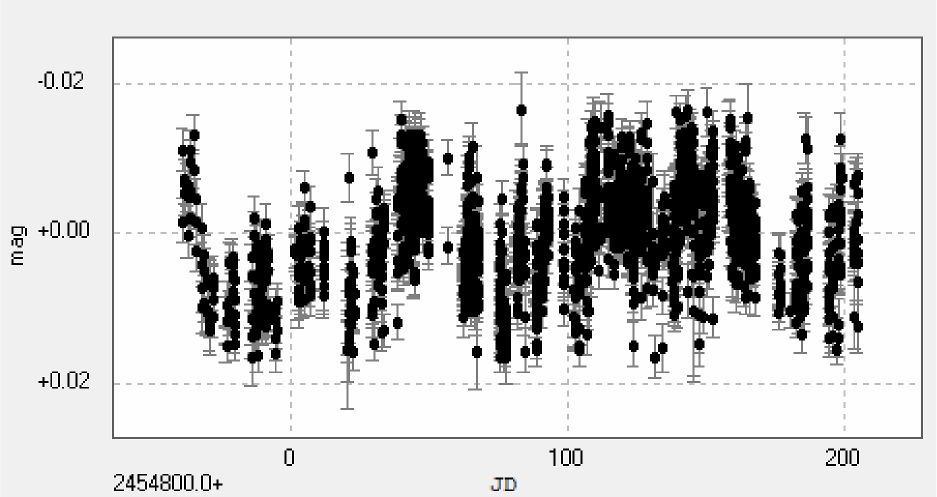
J11511+352

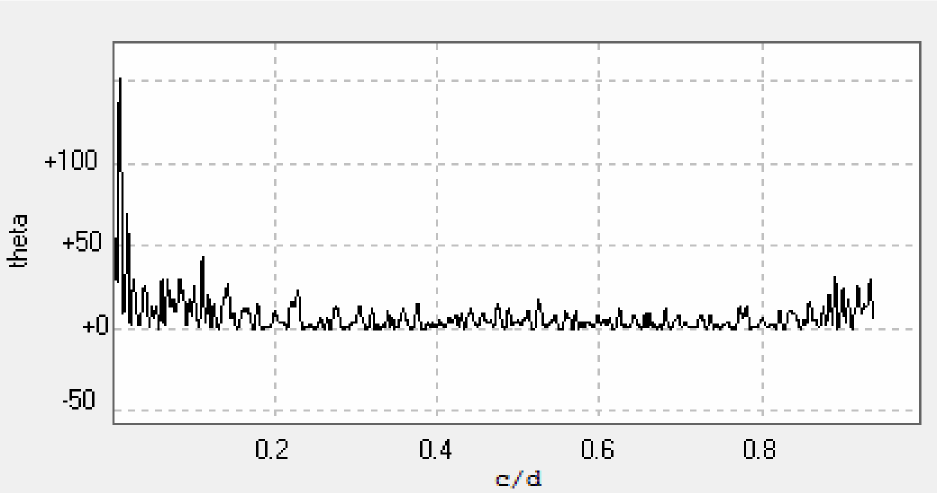

+9.64
+9.66
+9.68
mag
0
500
1000
1500
2453000.0+
JD

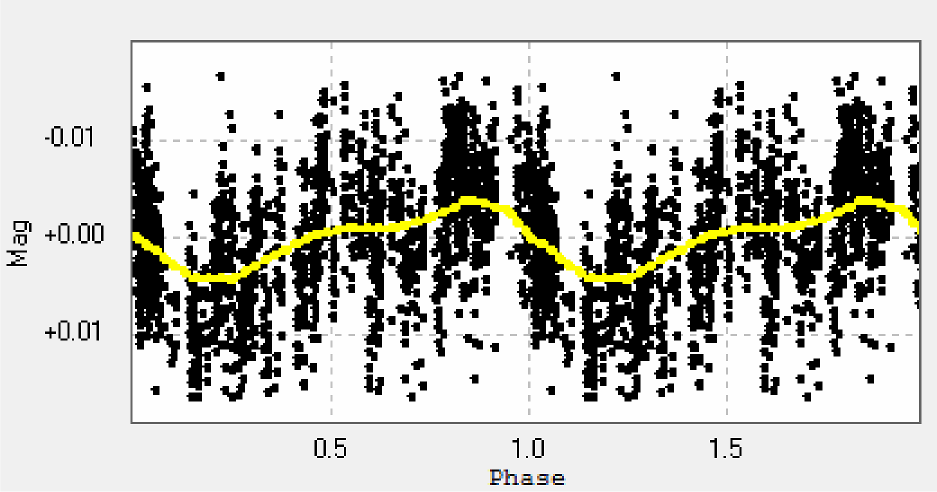

+400
+200
+0
theta
0.5
1.0
1.5
c/d


+9.64
+9.66
+9.68
Mag
0.5
1.0
1.5
Phase

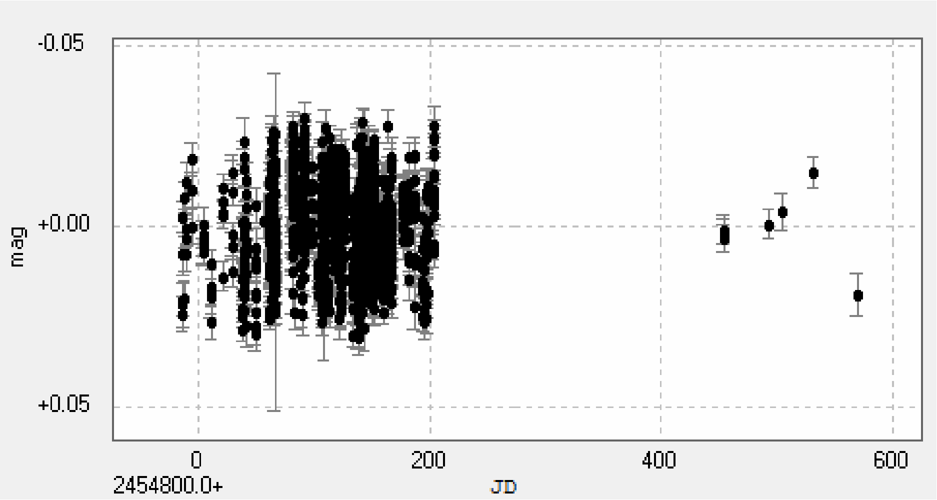
J12054+695

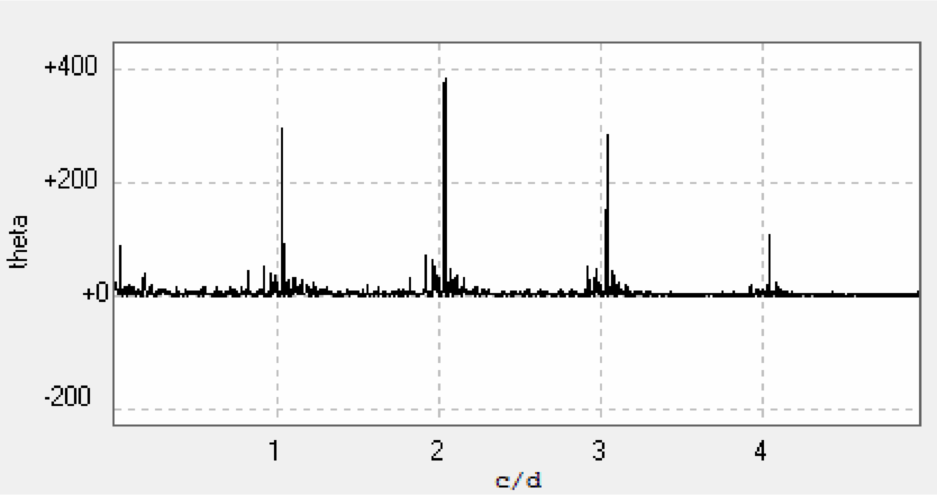

-0.02
+0.00
+0.02
mag
0
100
200
2454800.0+
JD

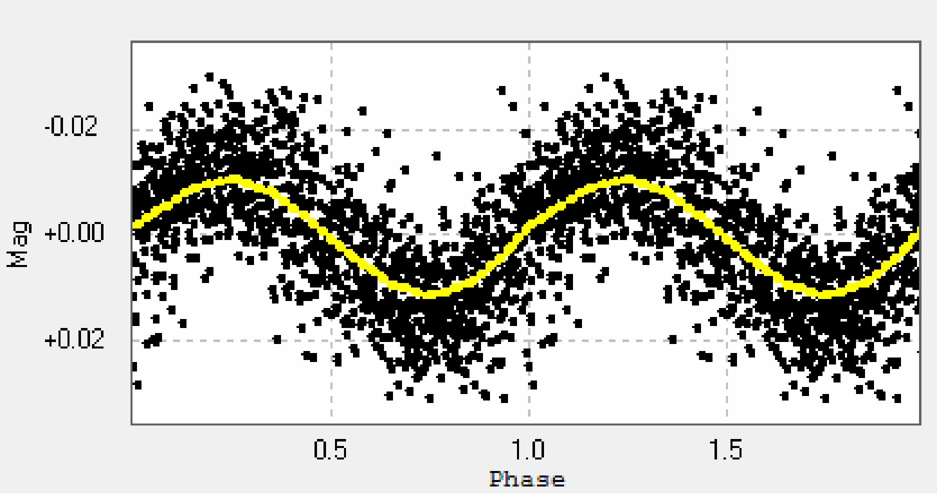

+100
+50
+0
-50
theta
0.2
0.4
0.6
0.8
c/d


-0.01
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

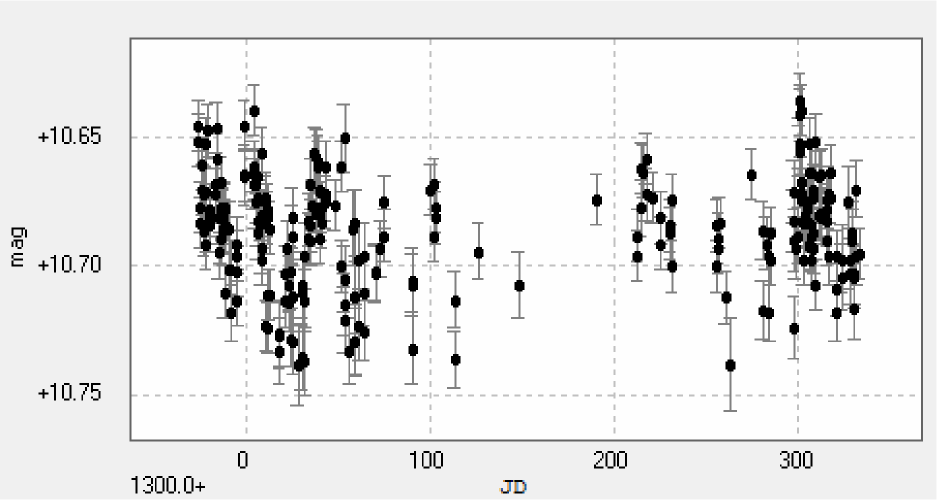
J12189+111


-0.05
+0.00
+0.05
mag
0
200
400
600
2454800.0+
JD

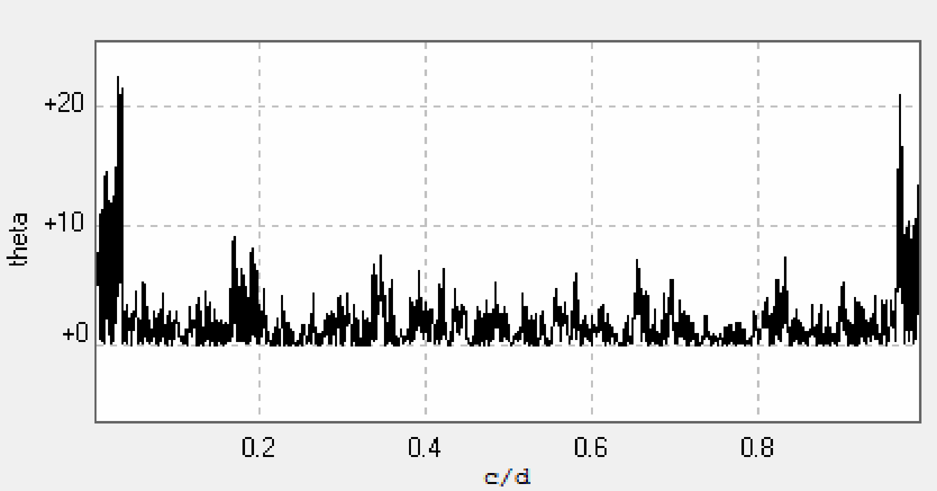

+400
+200
+0
-200
theta
1
2
3
4
c/d


-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

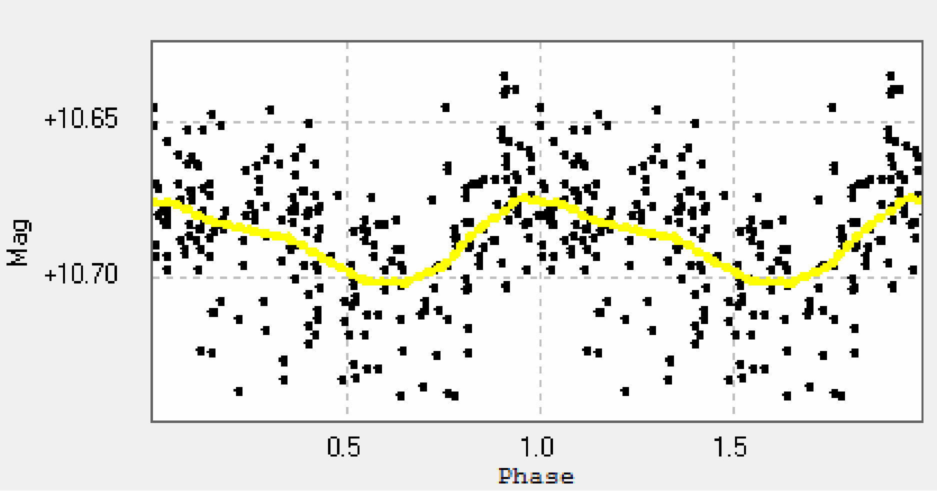
J12230+640



+10.65
+10.70
+10.75
mag
0
100
200
300
1300.0+
JD

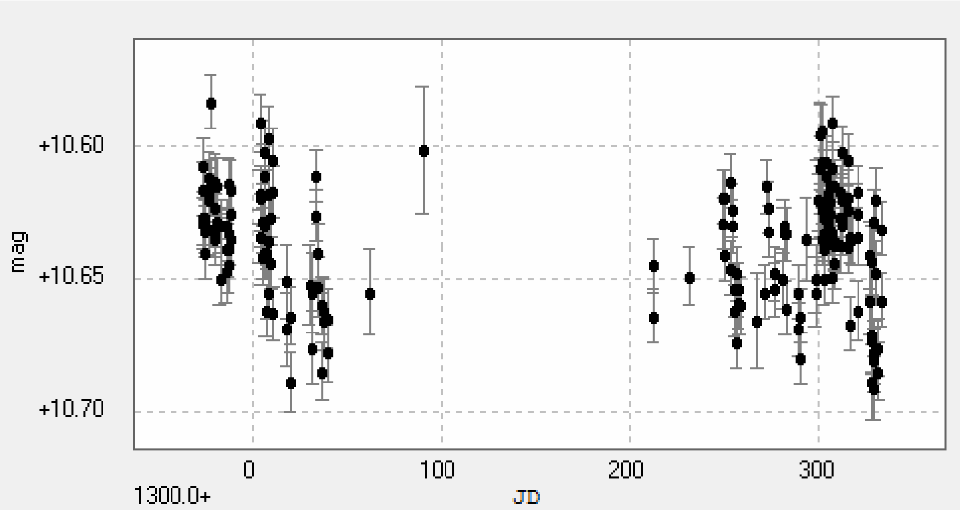


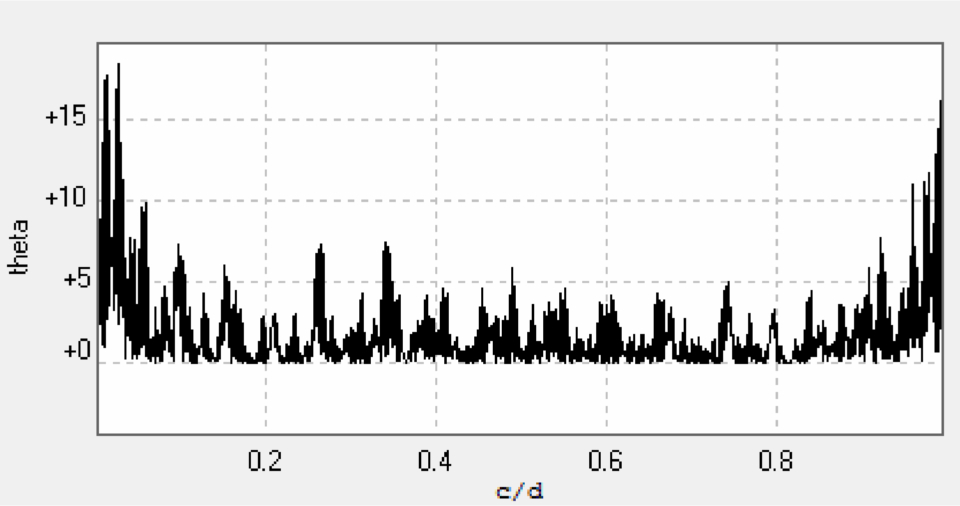
+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d

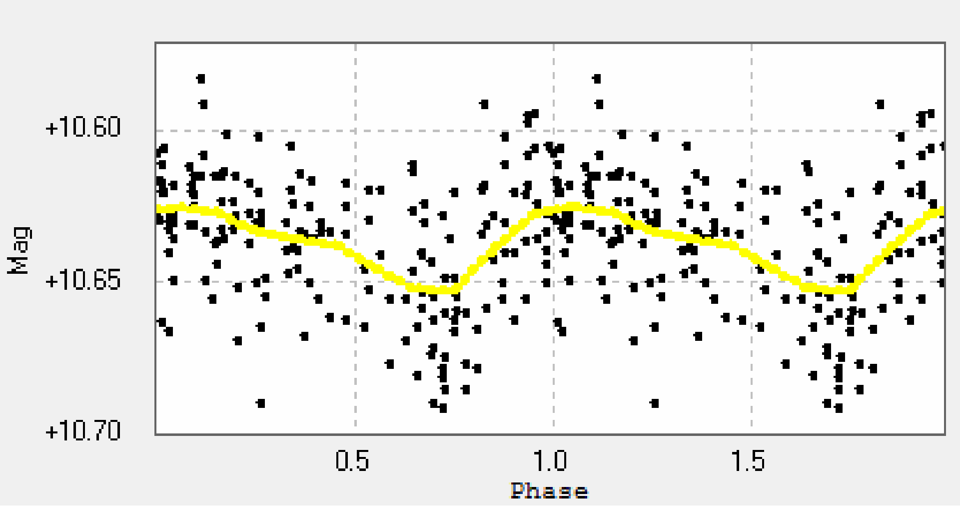


+10.65
+10.70
Mag
0.5
1.0
1.5
Phase

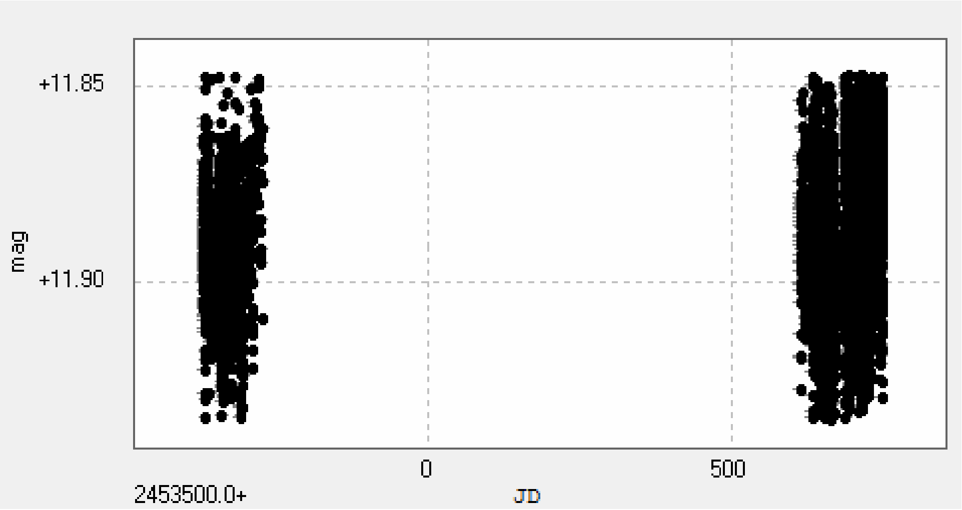
J12350+098

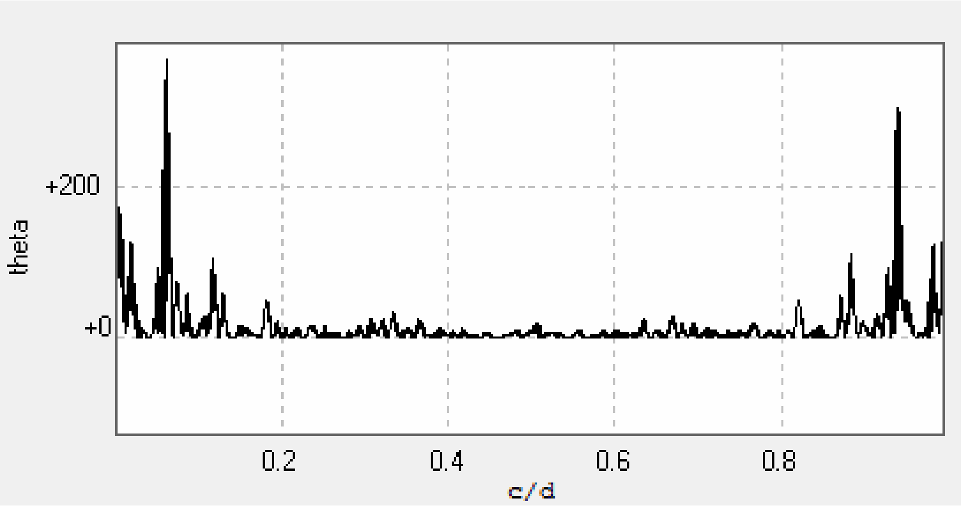

mag
+10.60
+10.65
+10.70
0
100
200
300
1300.0+
JD

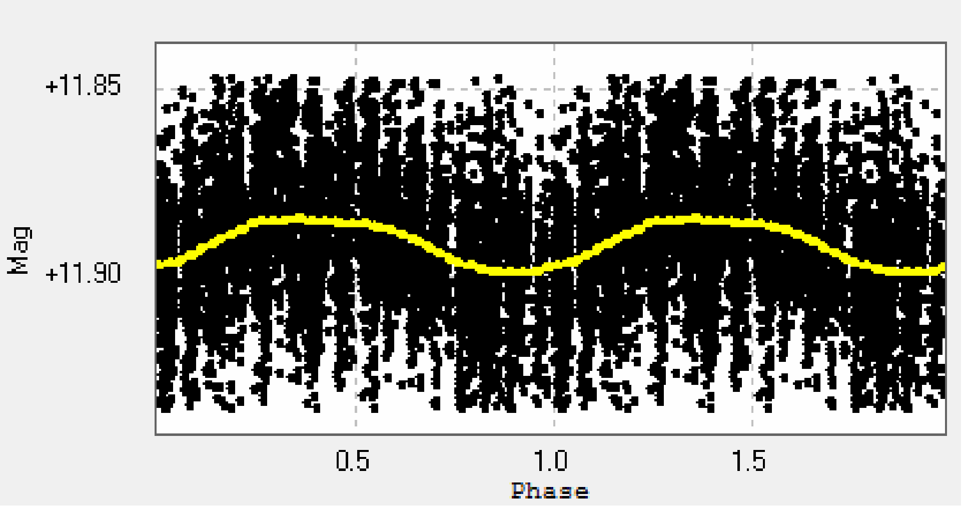

theta
+15
+10
+5
+0
0.2
0.4
0.6
0.8
c/d


Mag
+10.60
+10.65
+10.70
0.5
1.0
1.5
Phase

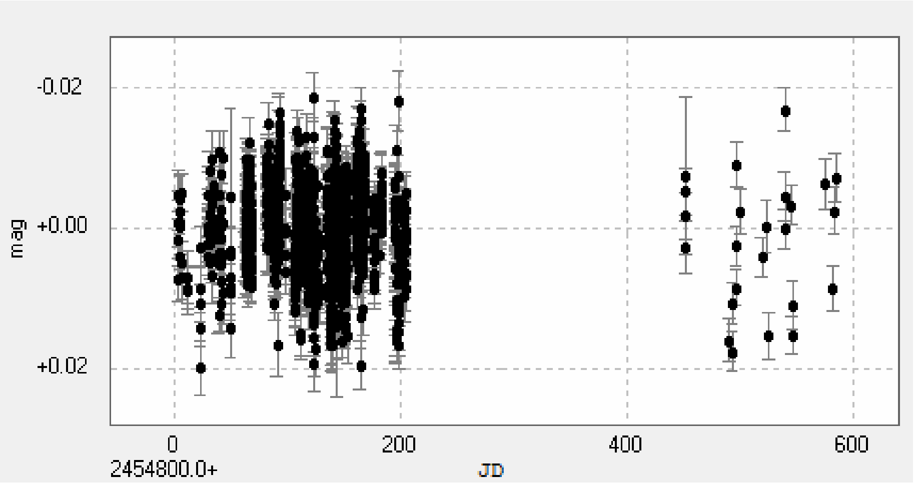
J12428+418


+11.85
+11.90
mag
0
500
2453500.0+
JD

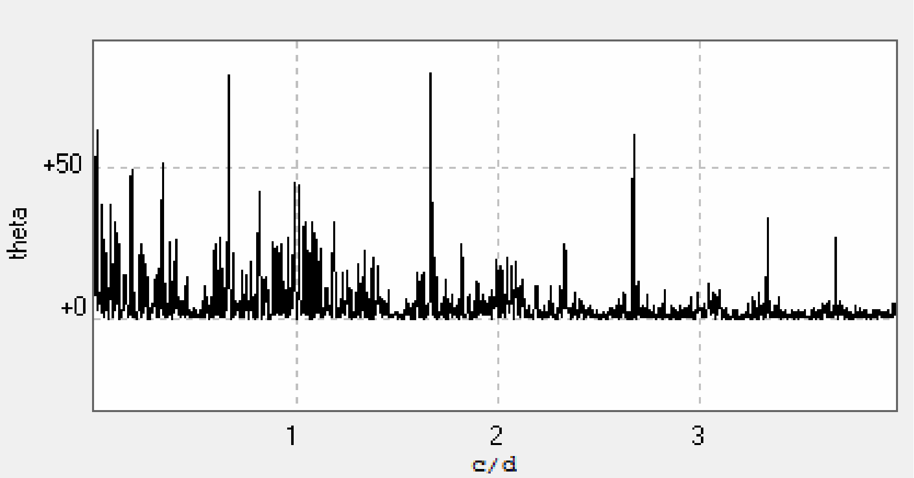

+200
+0
theta
0.2
0.4
0.6
0.8
c/d


+11.85
+11.90
Mag
0.5
1.0
1.5
Phase

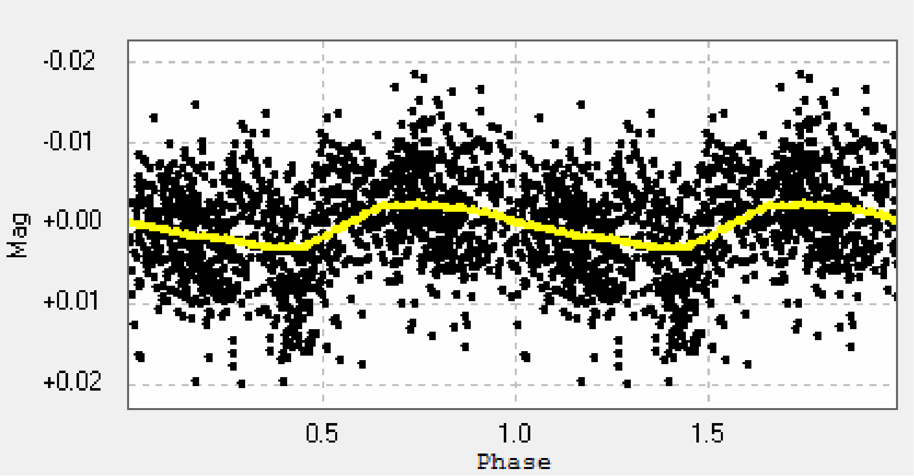
J13005+056



-0.02
+0.00
+0.02
mag
0
200
400
600
2454800.0+
JD

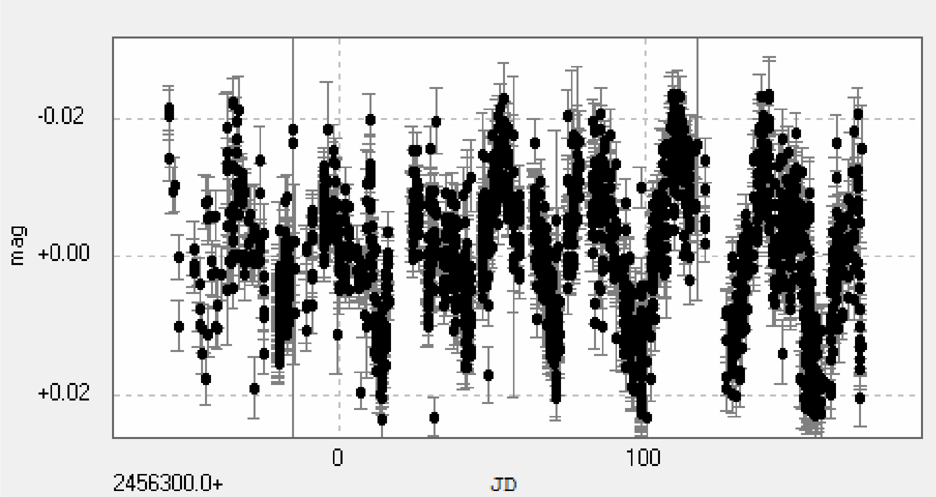


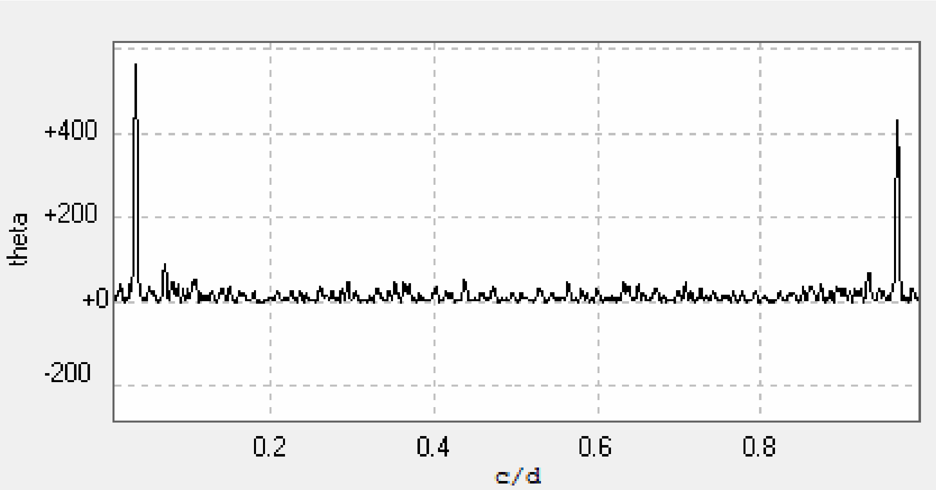
+50
+0
theta
1
2
3
c/d

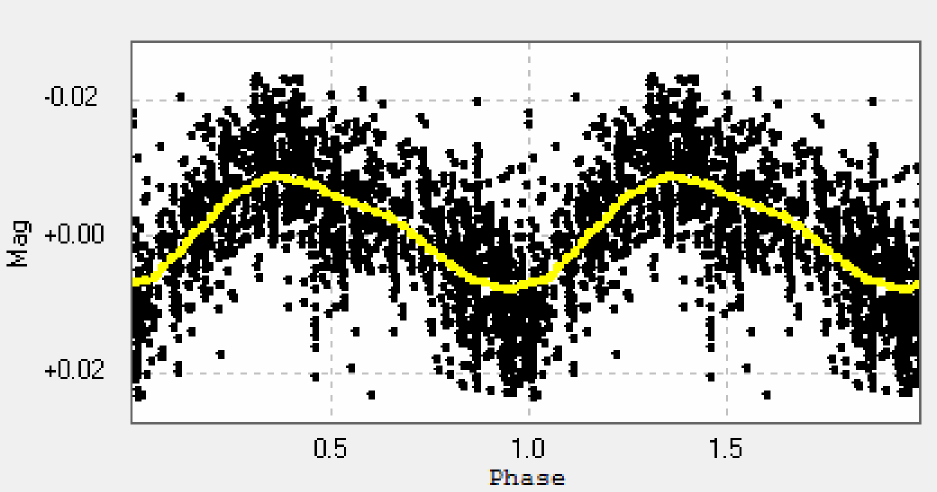


-0.02
-0.01
+0.00
+0.01
+0.02
Mag
0.5
1.0
1.5
Phase

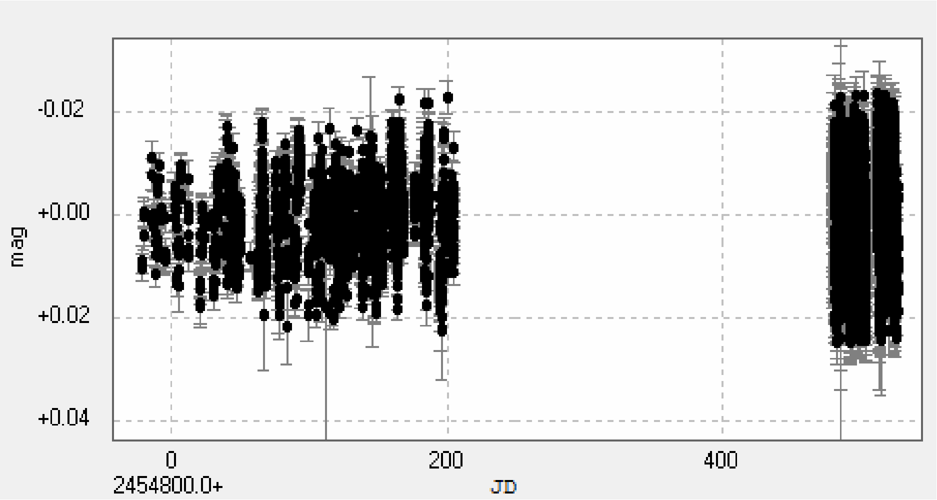
J13102+477


-0.02
+0.00
+0.02
mag
0
100
2456300.0+
JD

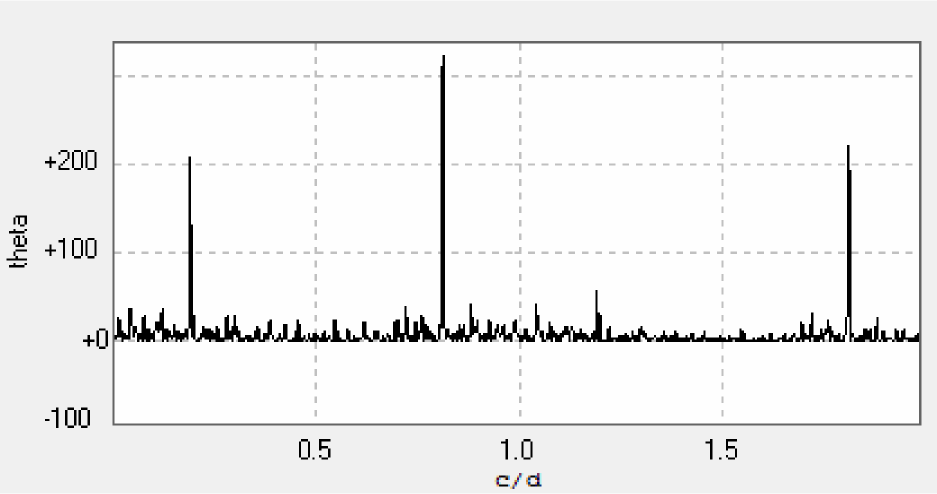

+400
+200
+0
-200
theta
0.2
0.4
0.6
0.8
c/d


-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

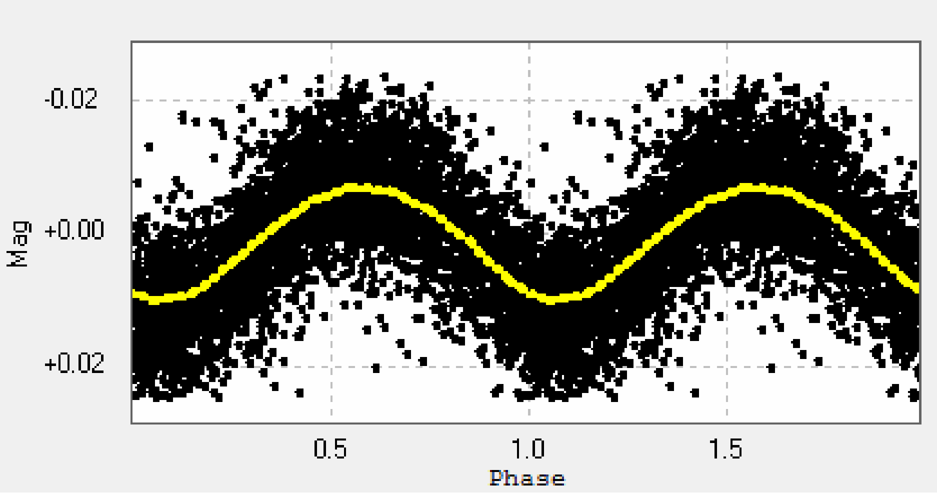
J13536+776



-0.02
+0.00
+0.02
+0.04
mag
0
200
400
2454800.0+
JD

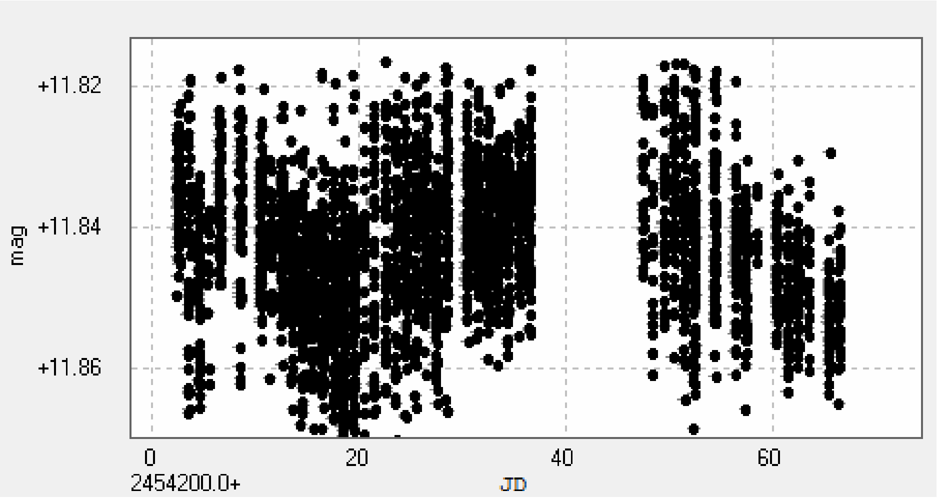


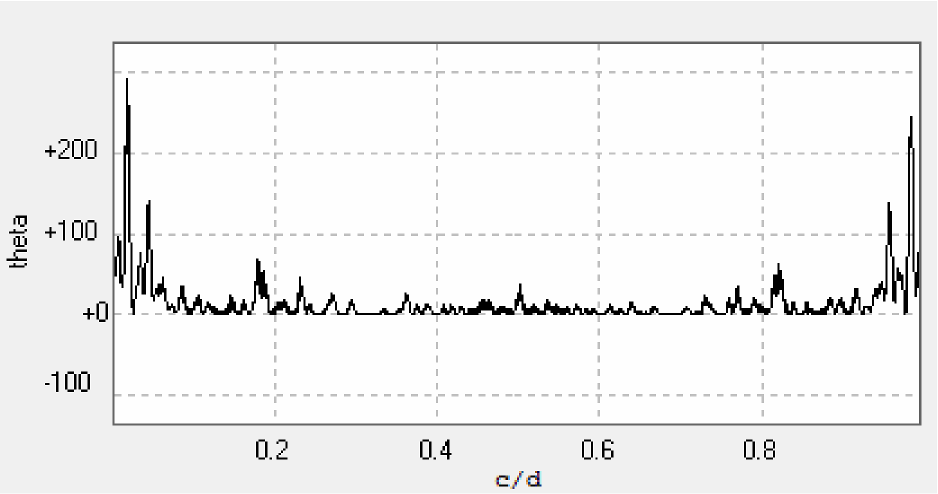
+200
+100
+0
-100
theta
0.5
1.0
1.5
c/d

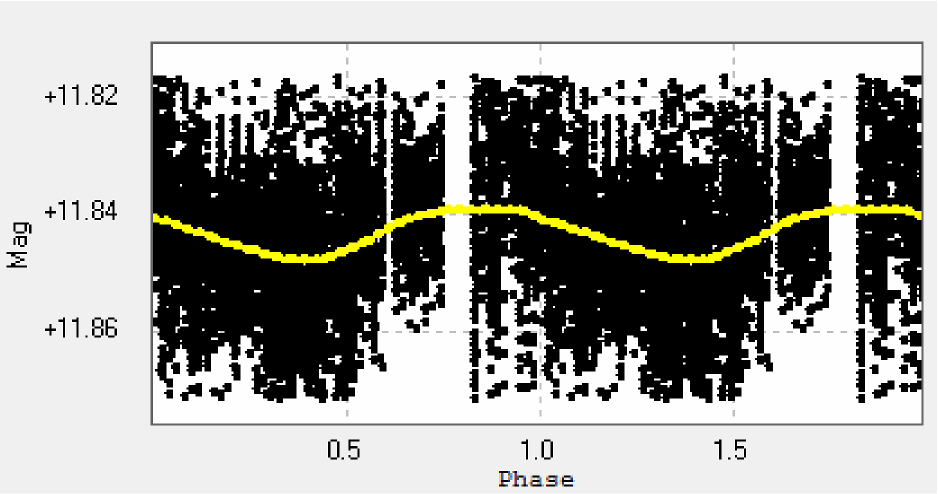


-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

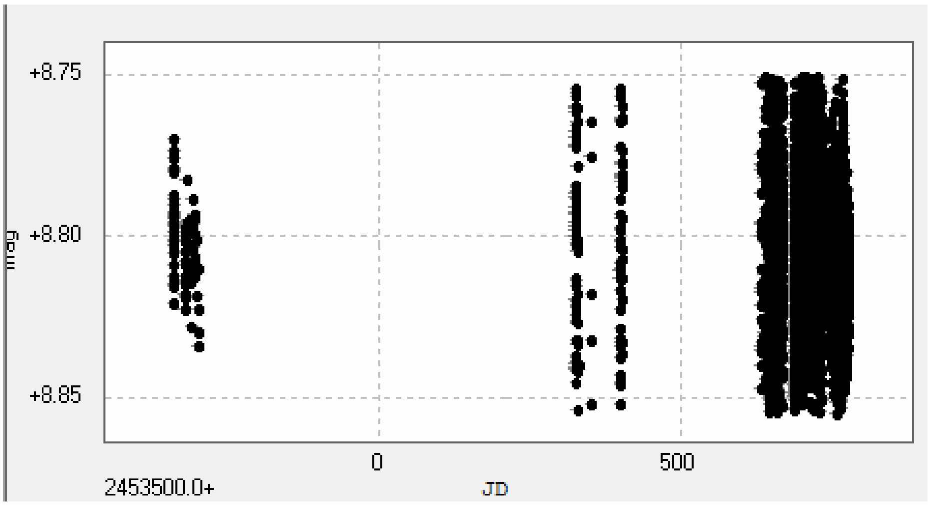
J14152+450


mag
+11.82
+11.84
+11.86
0
20
40
60
2454200.0+
JD

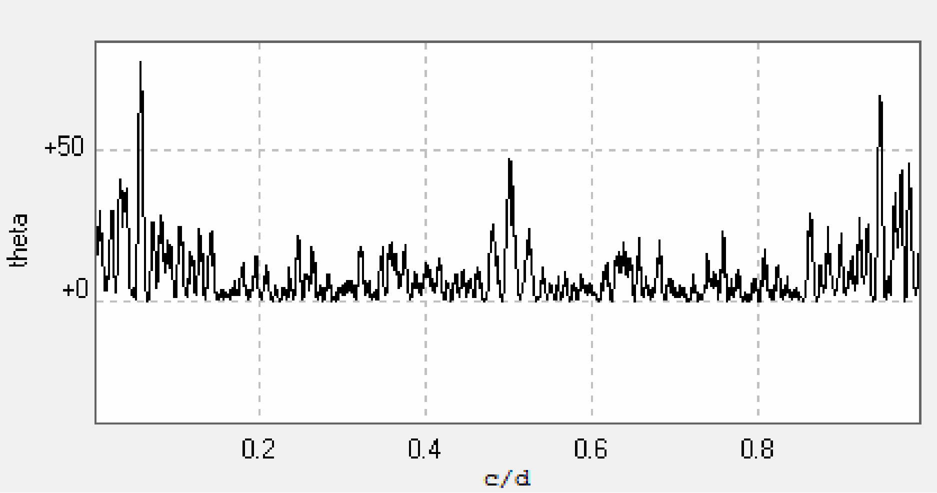

theta
+200
+100
+0
-100
0.2
0.4
0.6
0.8
c/d


Mag
+11.82
+11.84
+11.86
0.5
1.0
1.5
Phase

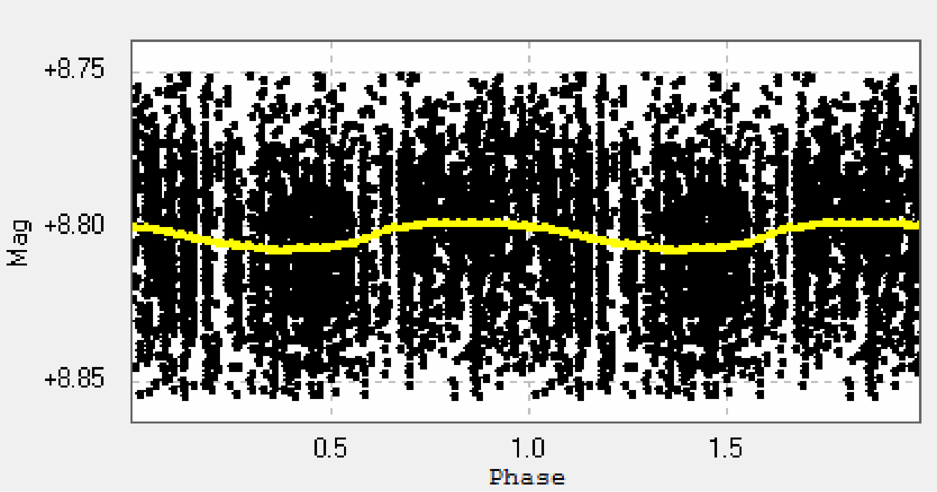
J14257+236E



+8.75
+8.80
+8.85
mag
0
500
2453500.0+
JD

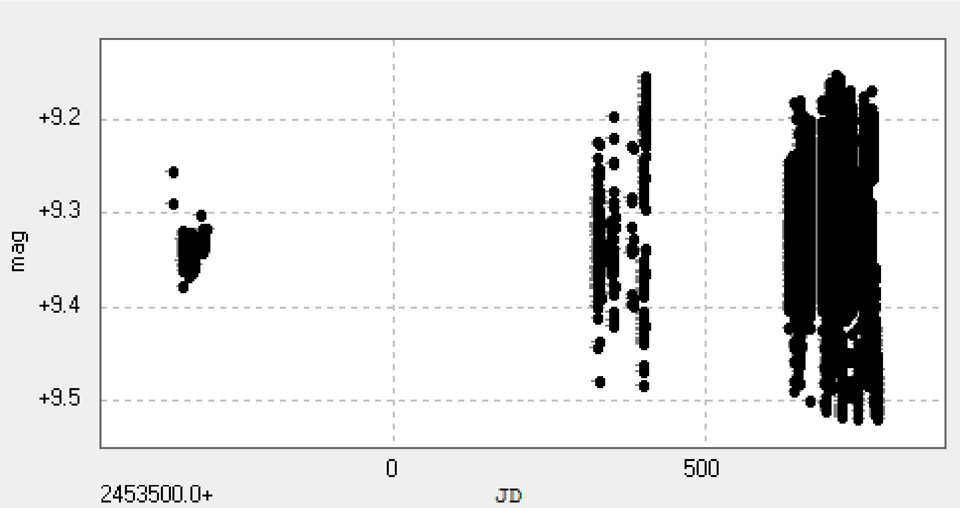


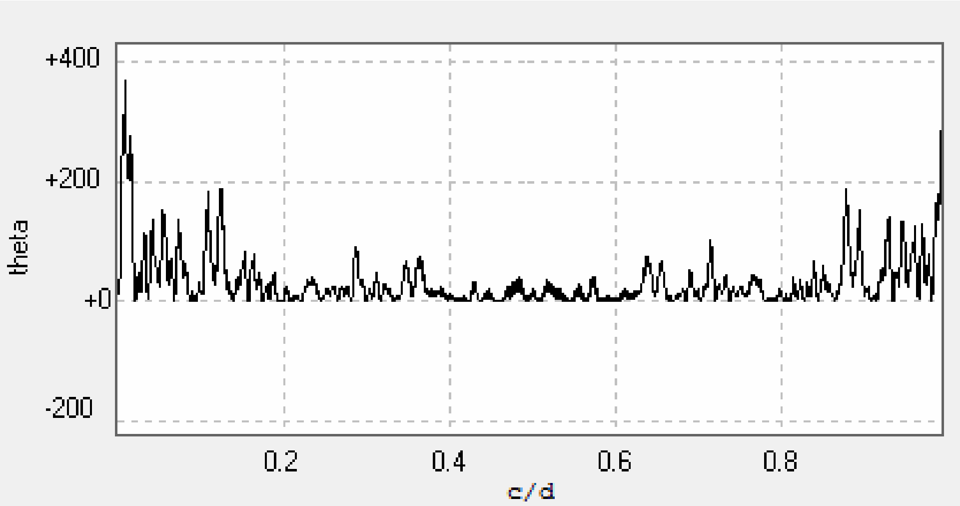
+50
+0
theta
0.2
0.4
0.6
0.8
c/d

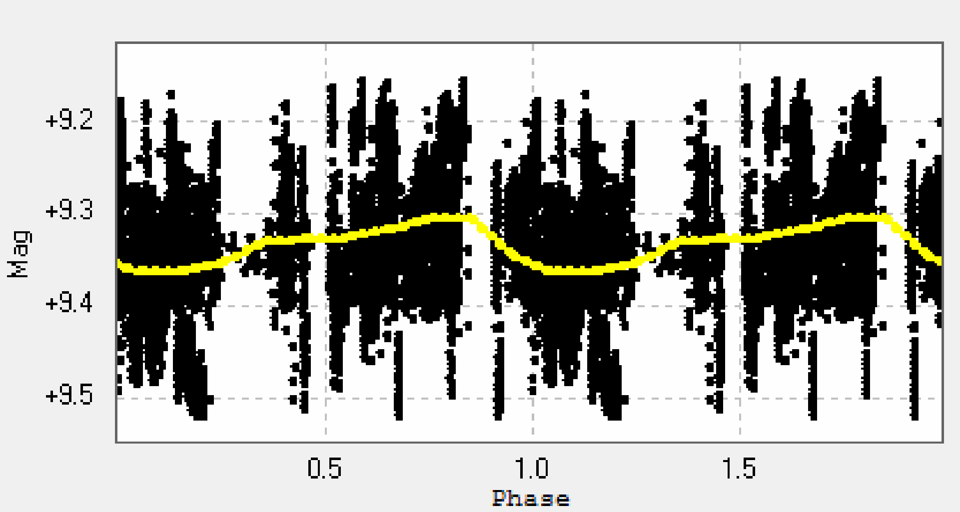


+8.75
+8.80
+8.85
Mag
0.5
1.0
1.5
Phase

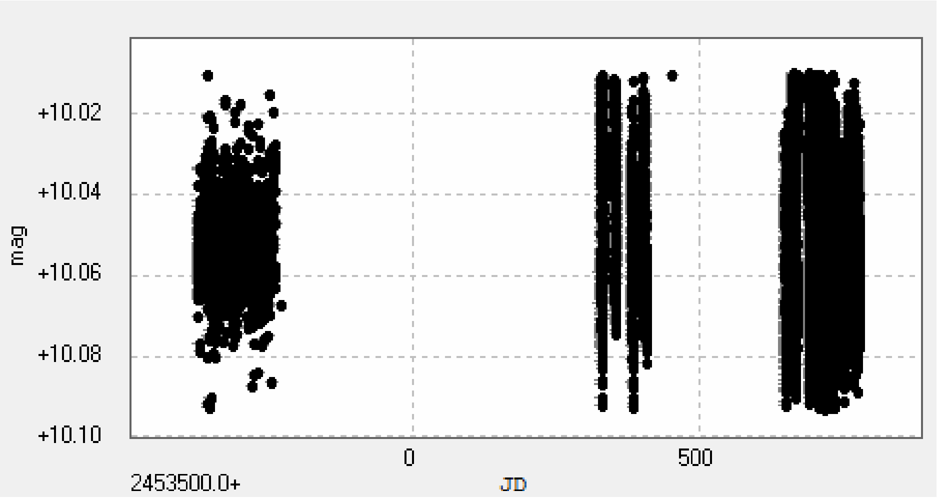
J14257+236W

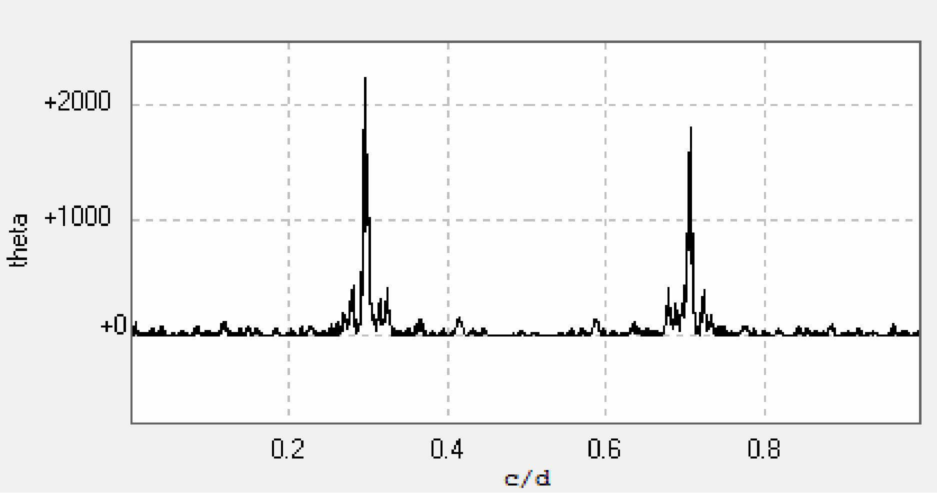

+9.2
+9.3
+9.4
+9.5
mag
0
500
2453500.0+
JD

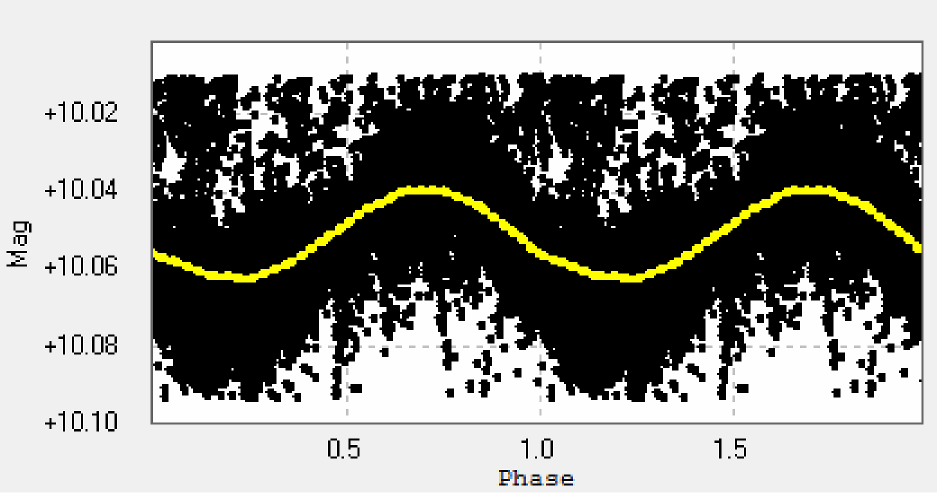

+400
+200
+0
-200
theta
0.2
0.4
0.6
0.8
c/d


+9.2
+9.3
+9.4
+9.5
Mag
0.5
1.0
1.5
Phase

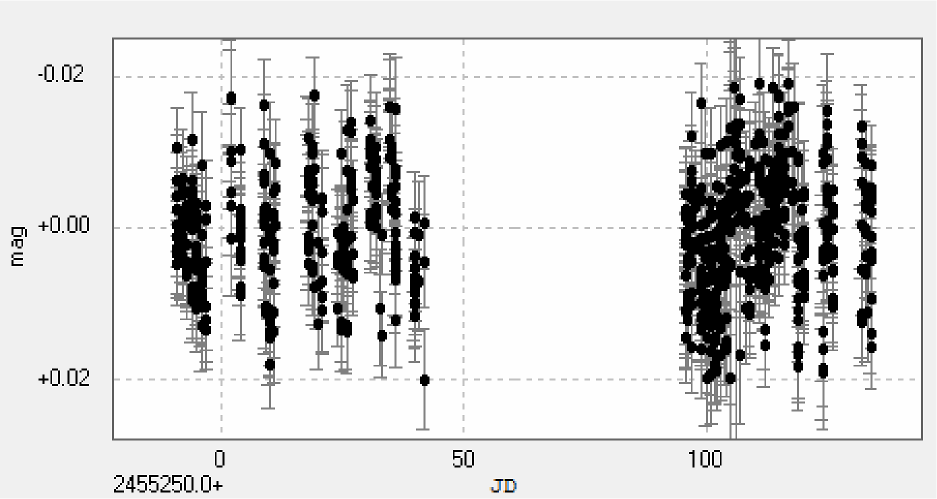
J15218+209

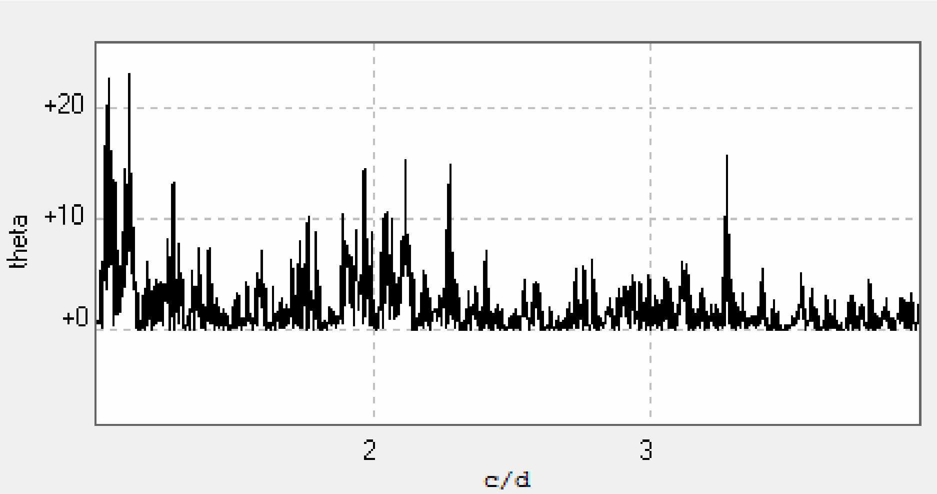

+10.02
+10.04
+10.06
+10.08
+10.10
mag
0
500
2453500.0+
JD

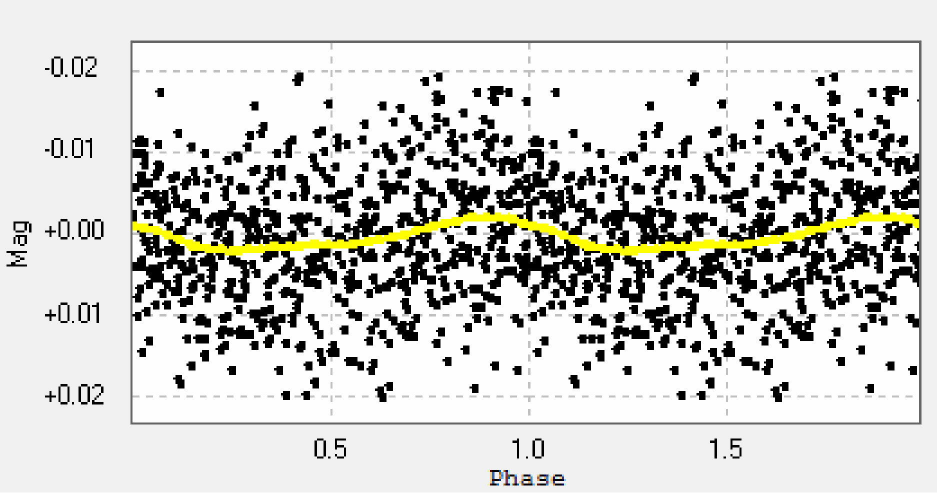

+2000
+1000
+0
theta
0.2
0.4
0.6
0.8
c/d


+10.02
+10.04
+10.06
+10.08
+10.10
Mag
0.5
1.0
1.5
Phase

J15305+094


-0.02
+0.00
+0.02
mag
0
50
100
2455250.0+
JD


+20
+10
+0
theta
2
3
c/d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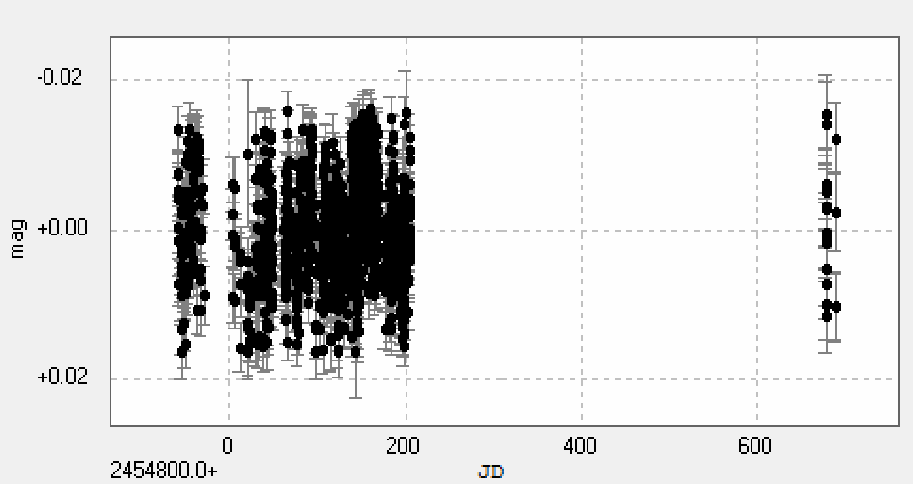
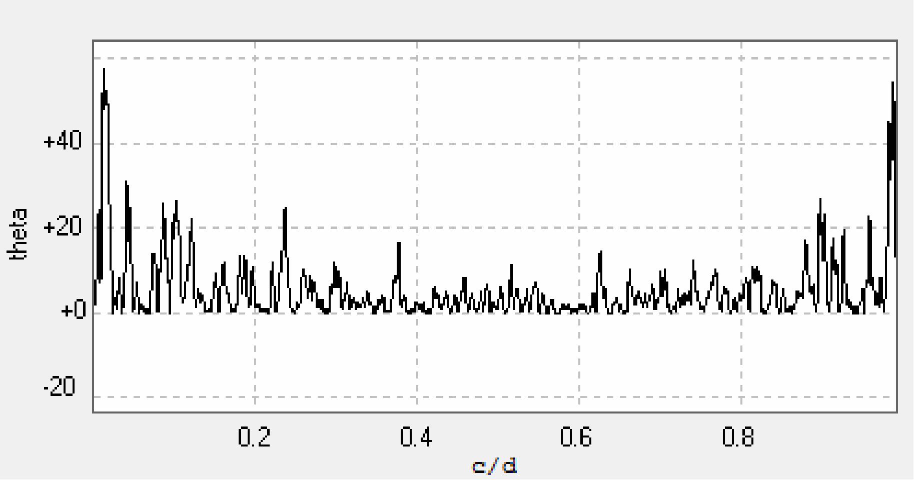
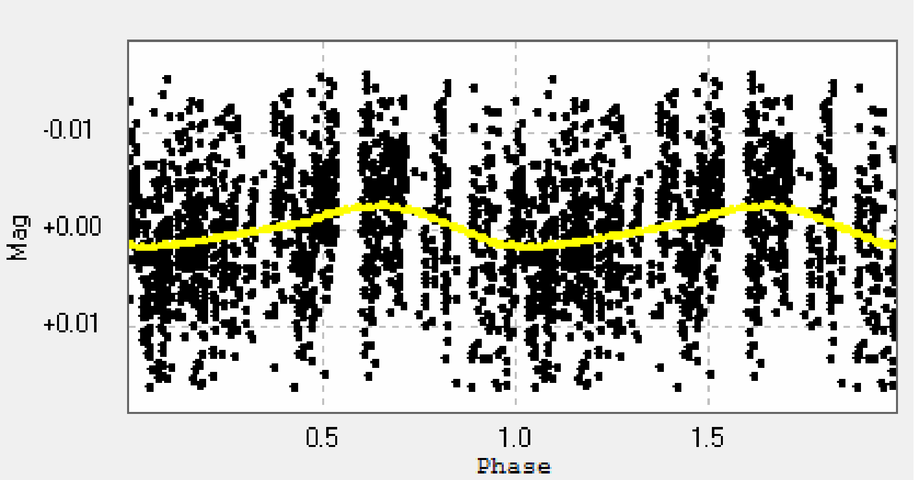
-0.01
+0.00
+0.01
+0.02
Mag
0.5
1.0
1.5
Phase

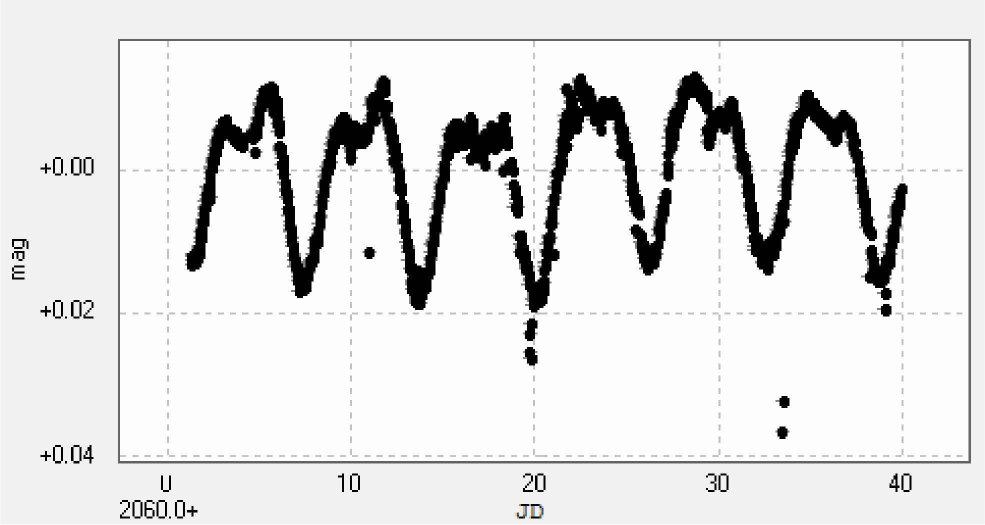
J15412+759


-0.02
+0.00
+0.02
mag
0
200
400
600
2454800.0+
JD

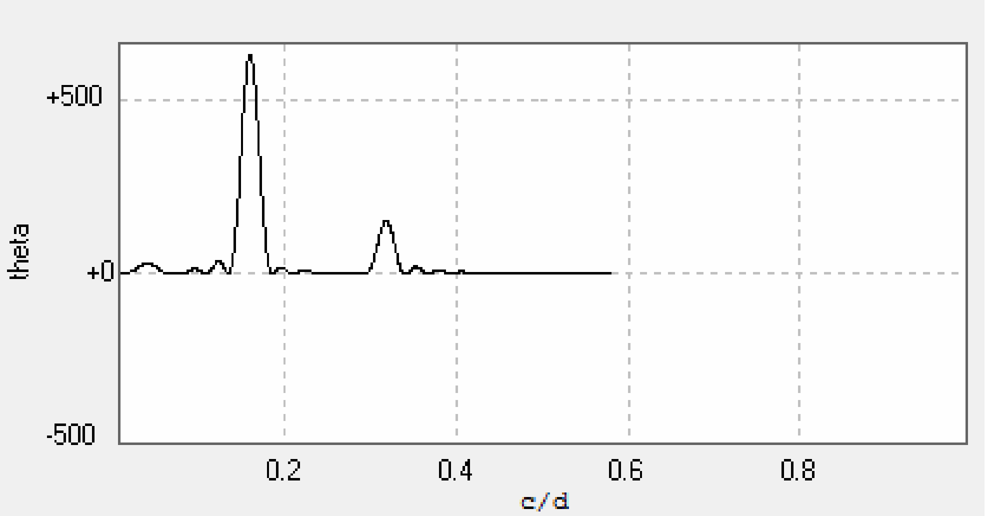

+40
+20
+0
-20
theta
0.2
0.4
0.6
0.8
c/d


-0.01
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

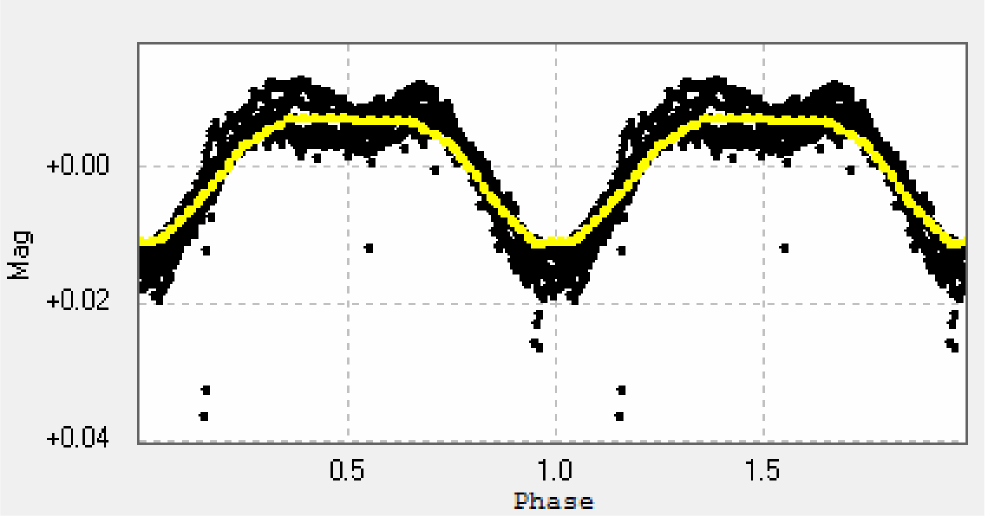
J16102-193



+0.00
+0.02
+0.04
mag
0
10
20
30
40
2060.0+
JD

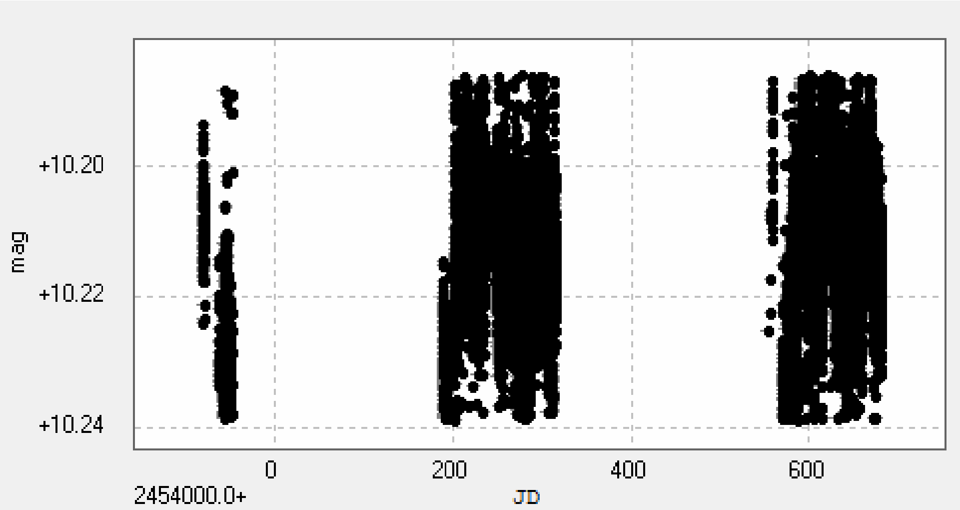


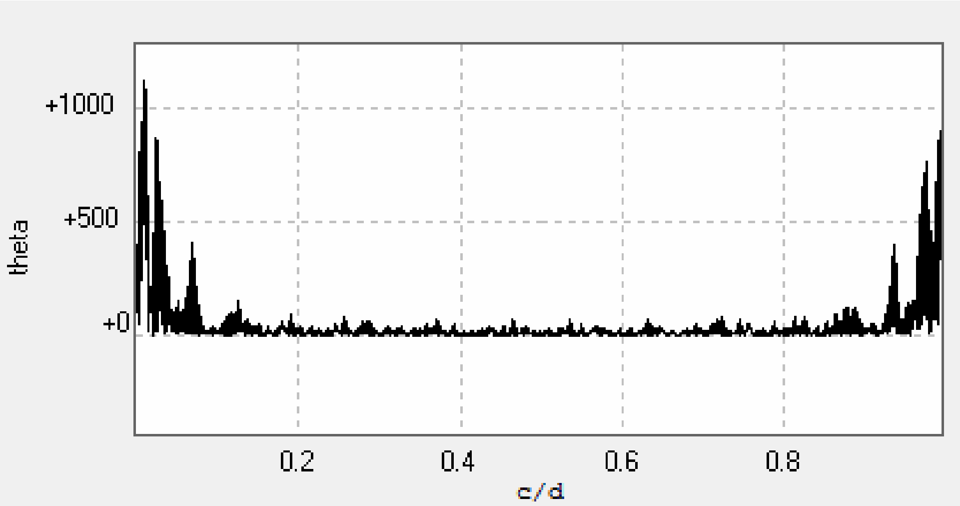
+500
+0
-500
theta
0.2
0.4
0.6
0.8
c/d

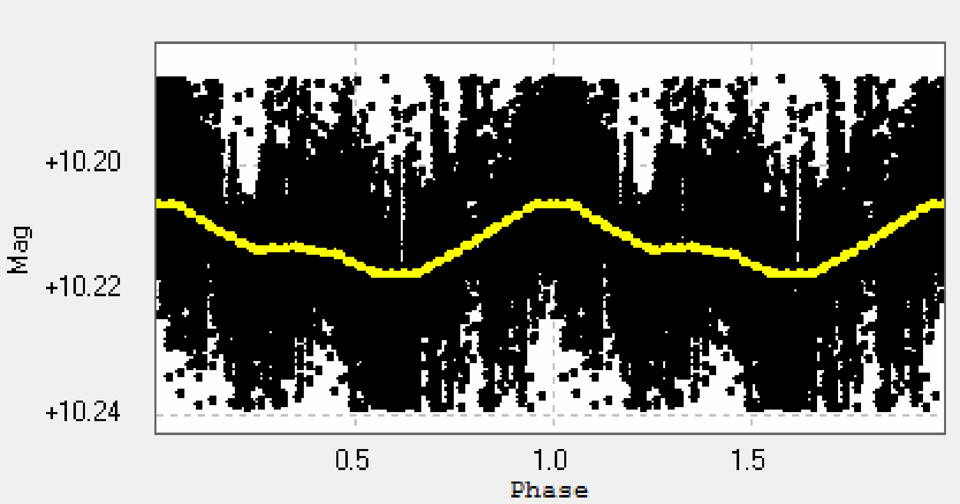


+0.00
+0.02
+0.04
Mag
0.5
1.0
1.5
Phase

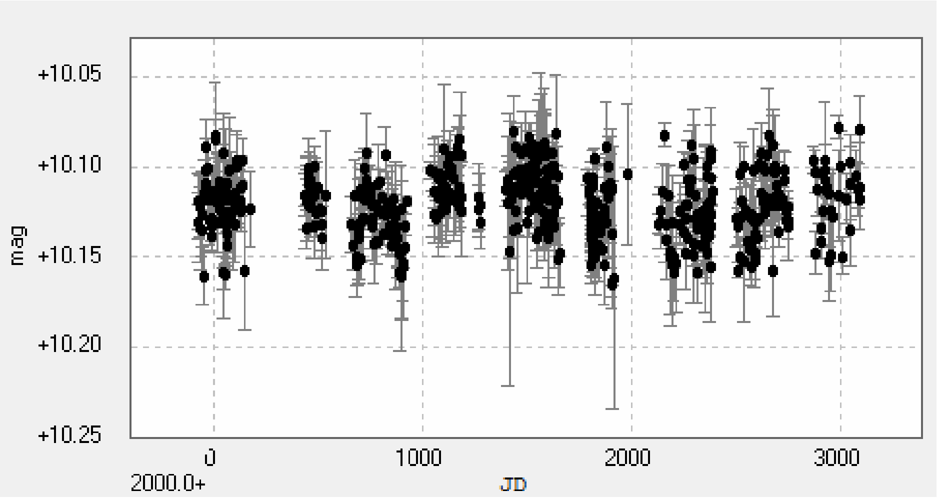
J16254+543

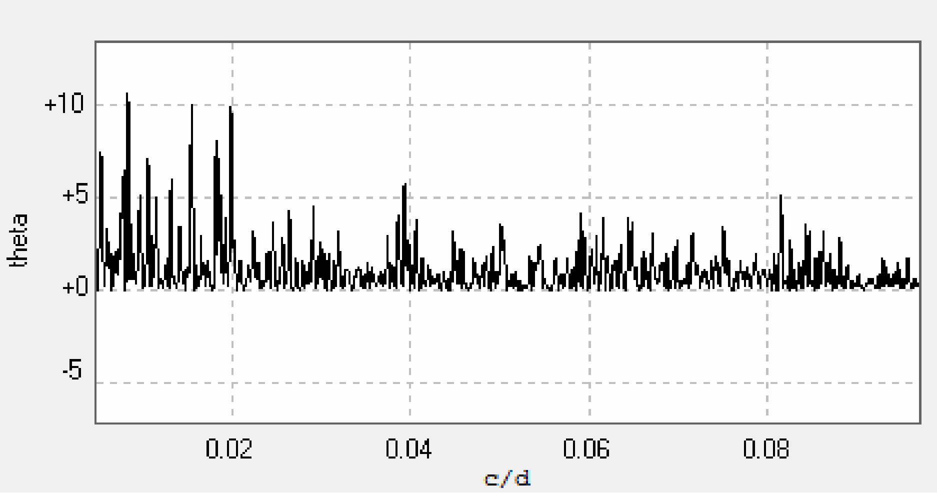

+10.20
+10.22
+10.24
mag
0
200
400
600
2454000.0+
JD

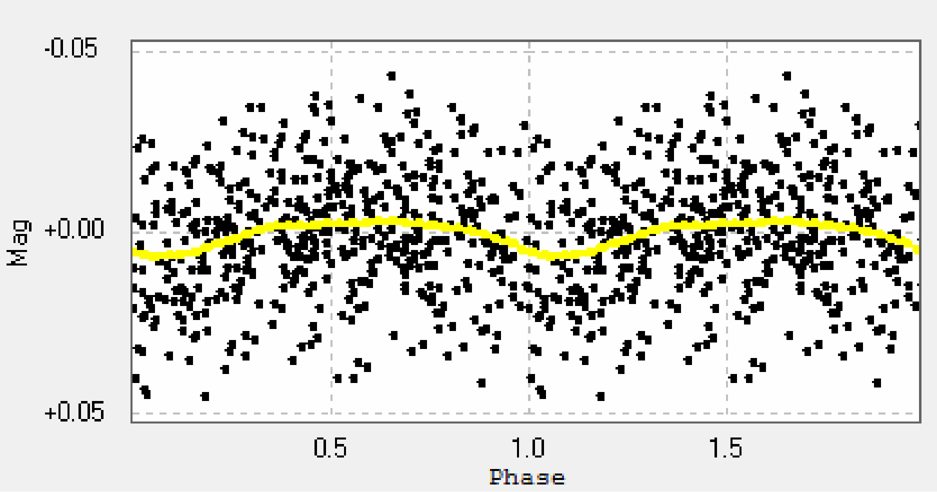

+1000
+500
+0
theta
0.2
0.4
0.6
0.8
c/d


+10.20
+10.22
+10.24
Mag
0.5
1.0
1.5
Phase

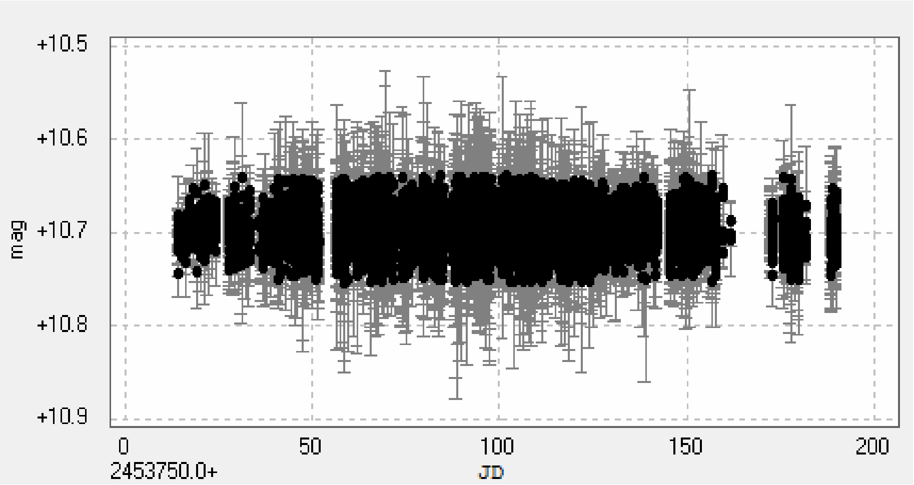
J16303-126

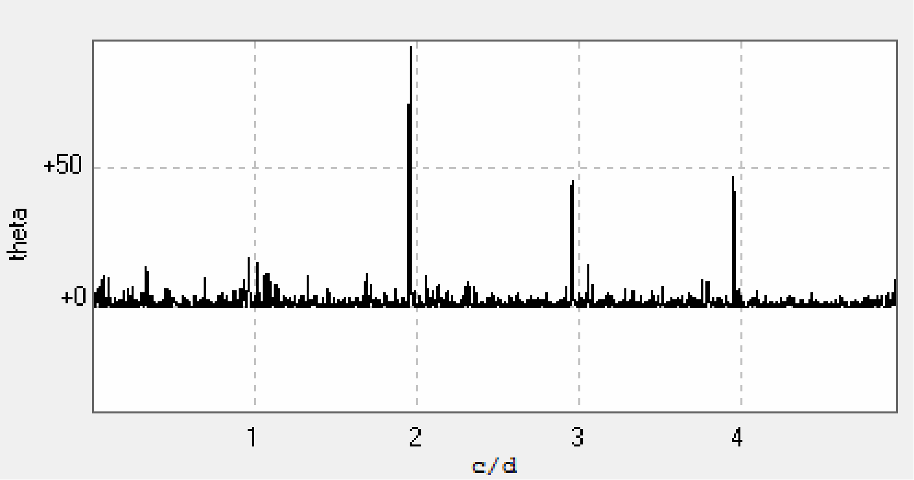

+10.05
+10.10
+10.15
+10.20
+10.25
mag
0
1000
2000
3000
2000.0+
JD

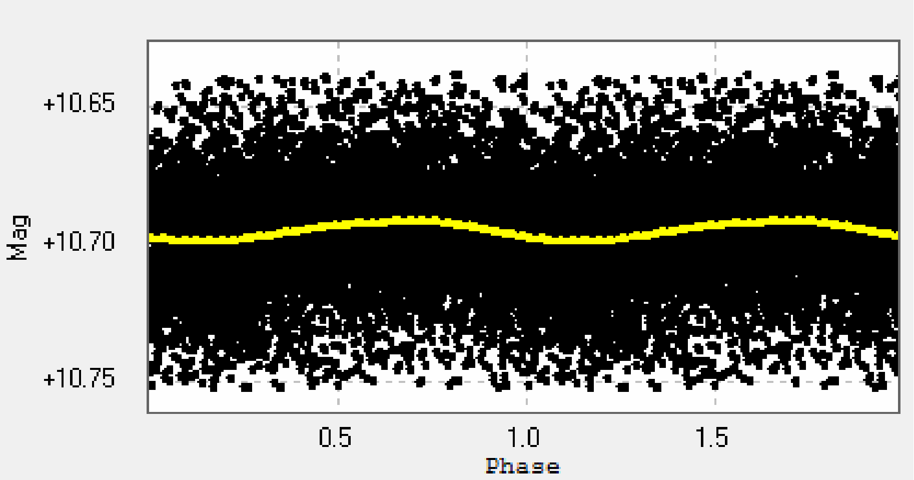

+10
+5
+0
-5
theta
0.02
0.04
0.06
0.08
c/d


-0.05
+0.00
+0.05
Mag
0.5
1.0
1.5
Phase

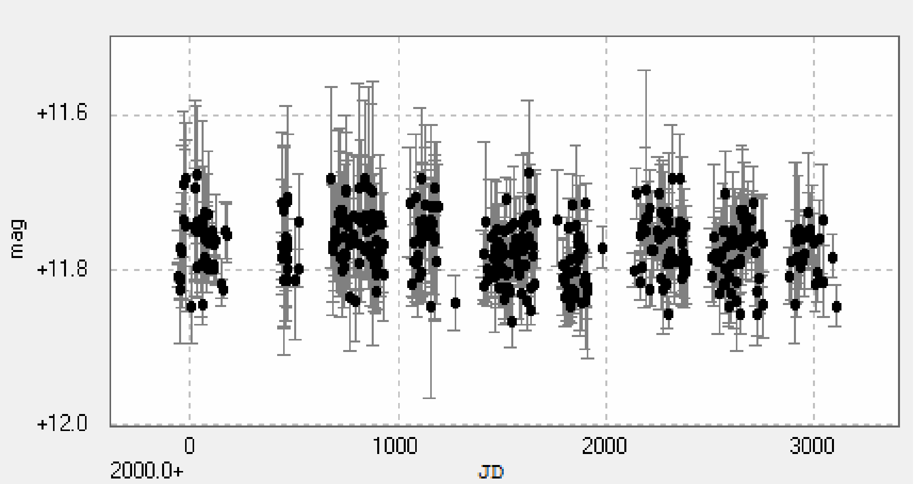
J16313+408


+10.5
+10.6
+10.7
+10.8
+10.9
mag
0
50
100
150
200
2453750.0+
JD

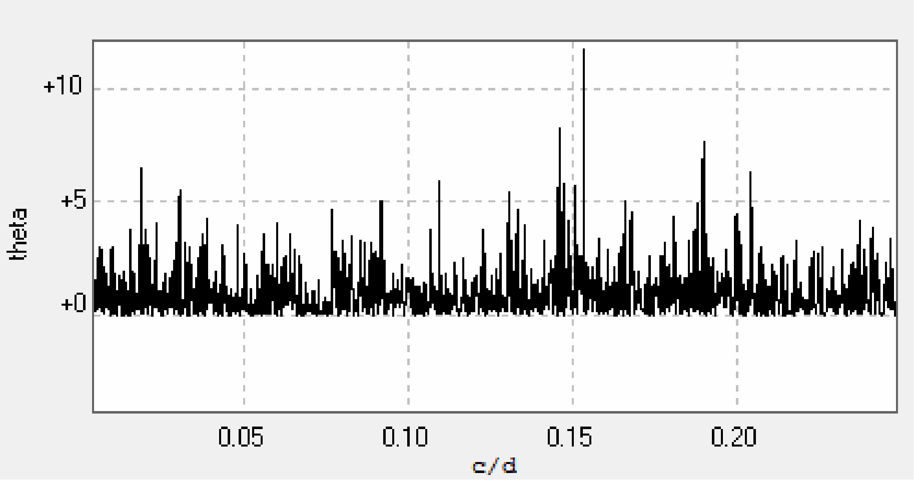

+50
+0
theta
1
2
3
4
c/d


+10.65
+10.70
+10.75
Mag
0.5
1.0
1.5
Phase

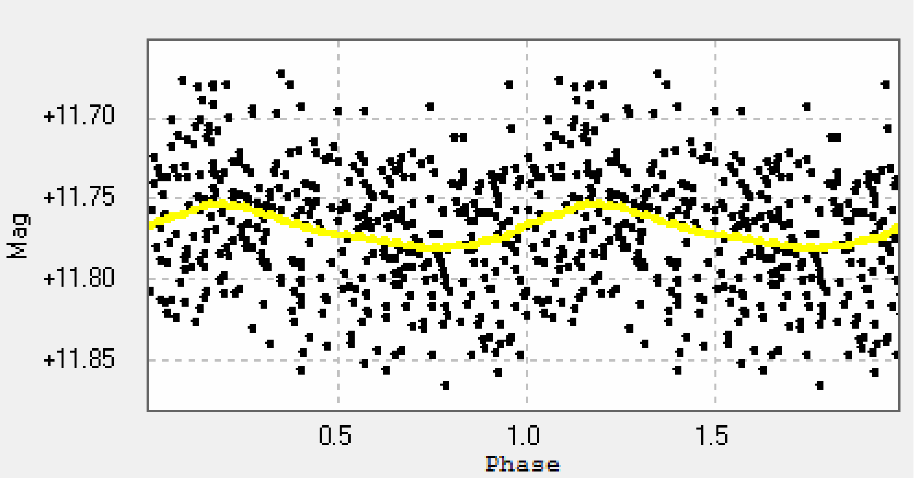
J16554-083N



+11.6
+11.8
+12.0
mag
0
1000
2000
3000
2000.0+
JD

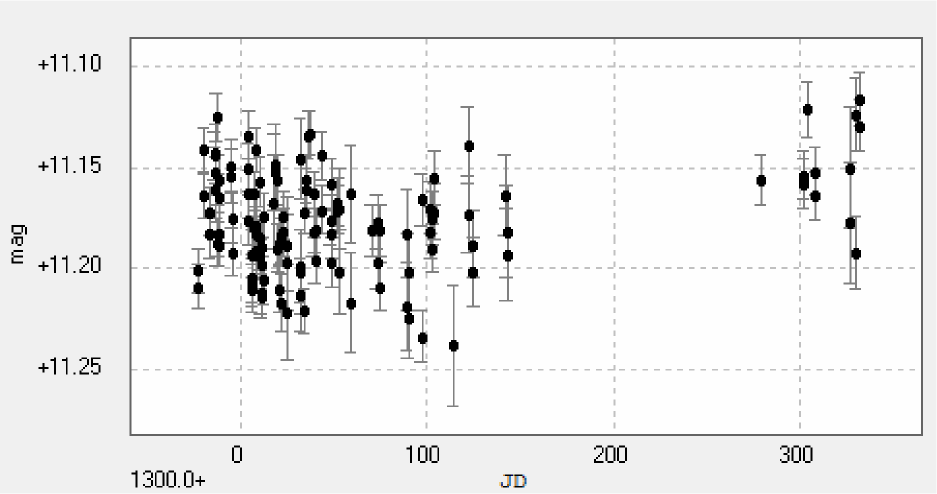


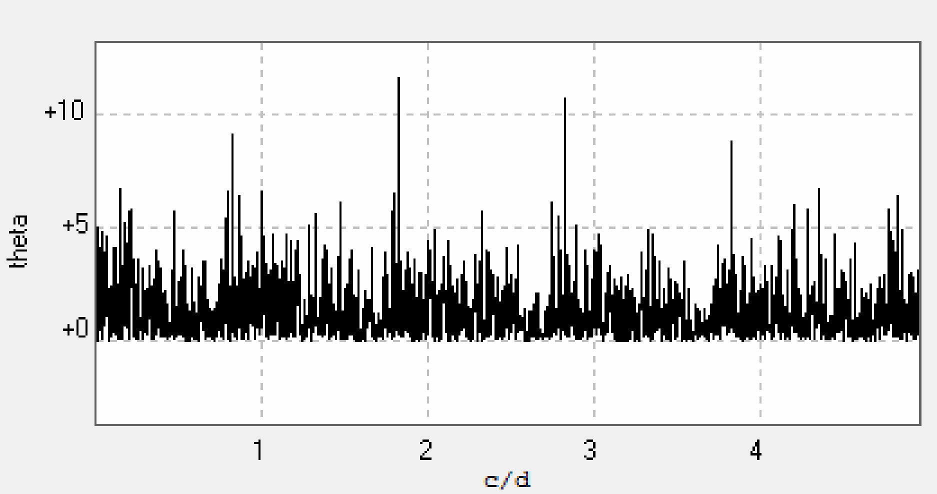
+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d

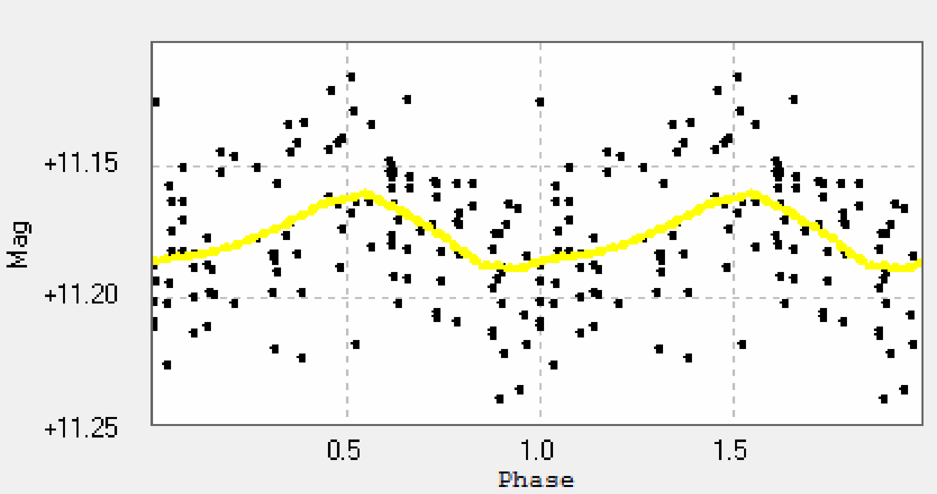


+11.70
+11.75
+11.80
+11.85
Mag
0.5
1.0
1.5
Phase

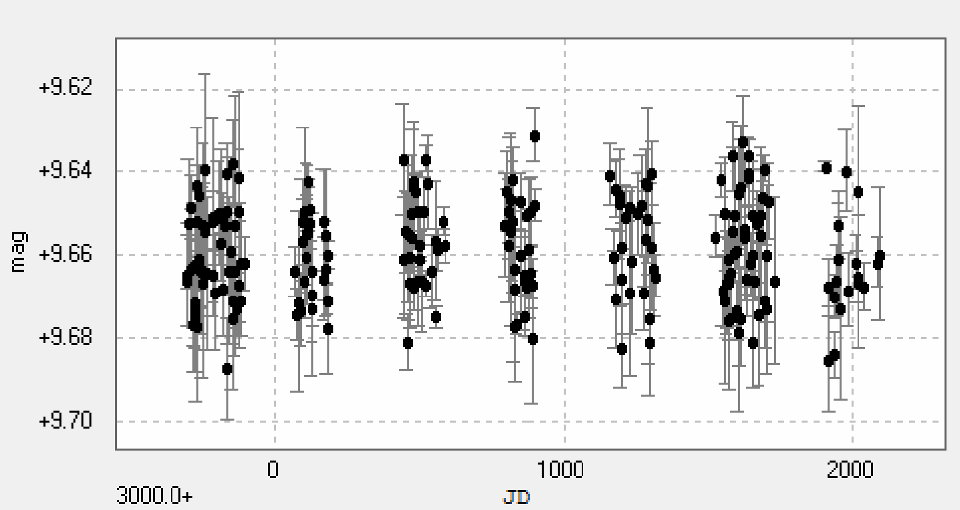
J16570-043

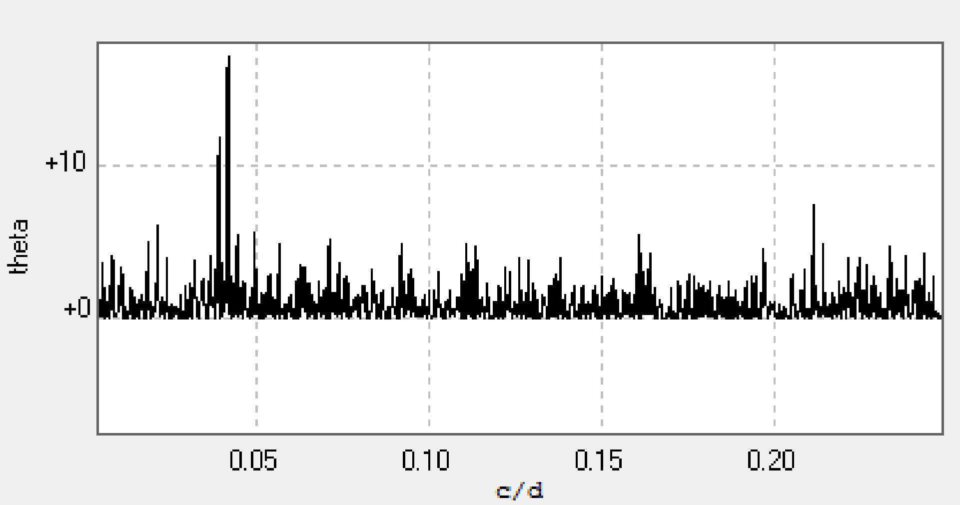

+11.10
+11.15
+11.20
+11.25
mag
0
100
200
300
1300.0+
JD

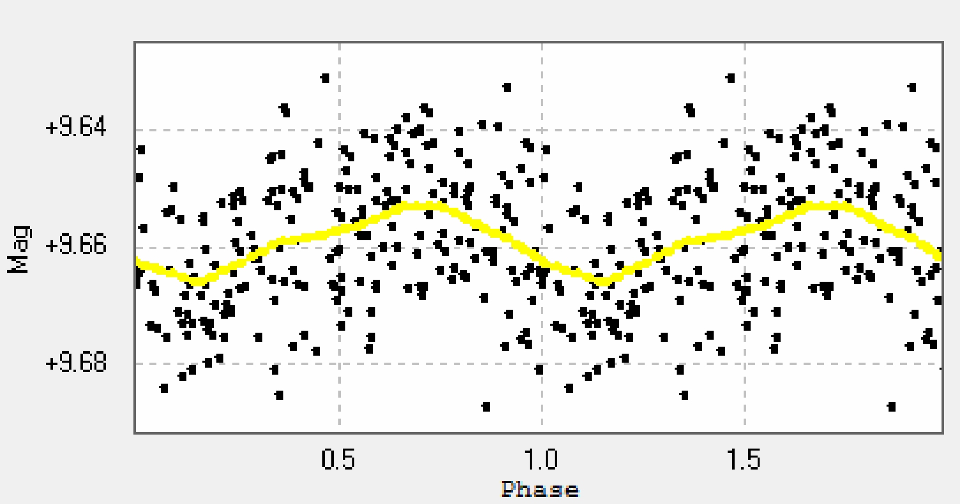

+10
+5
+0
theta
1
2
3
4
c/d


+11.15
+11.20
+11.25
Mag
0.5
1.0
1.5
Phase

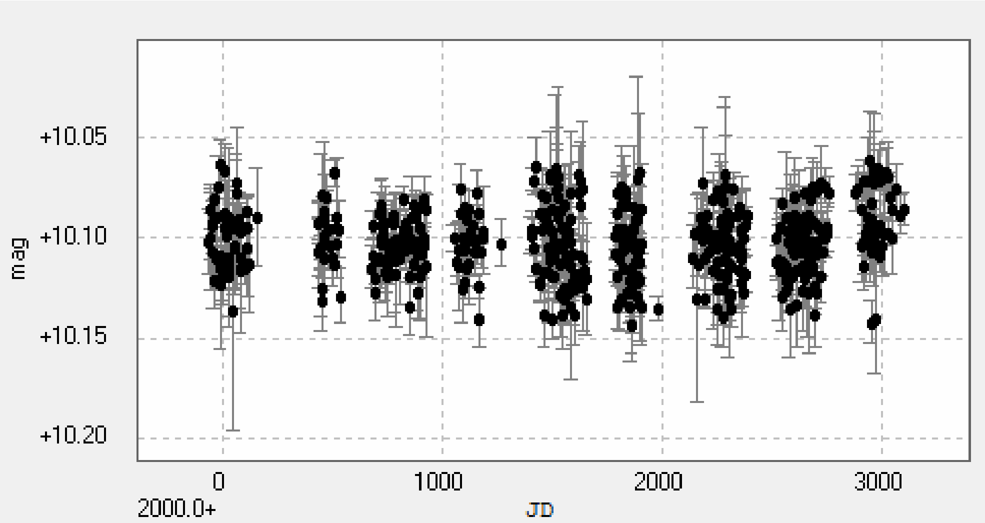
J16581+257

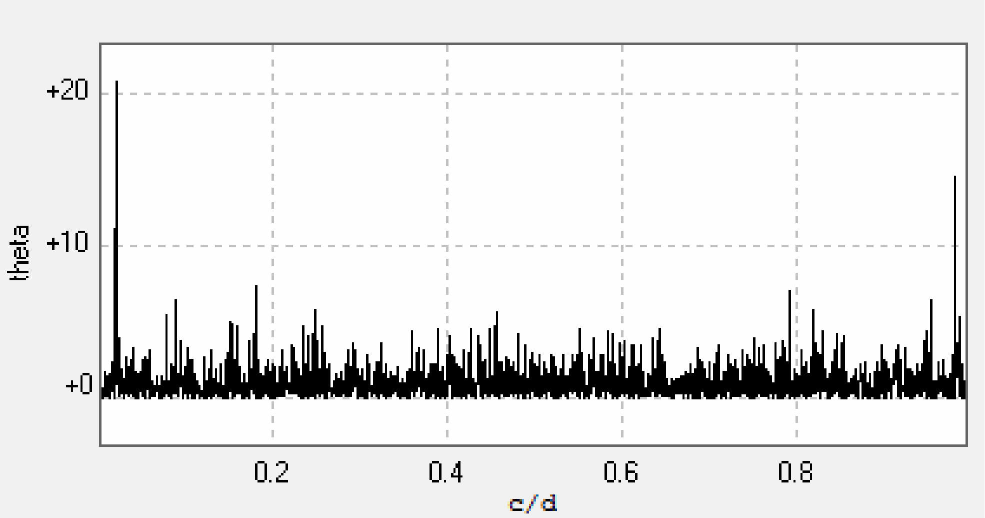

+9.62
+9.64
+9.66
+9.68
+9.70
mag
0
1000
2000
3000.0+
JD

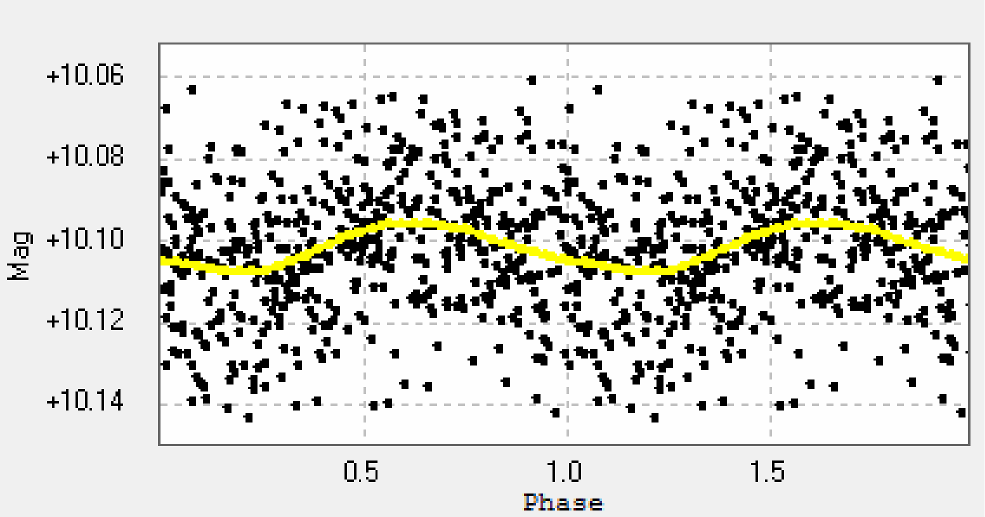

+10
+0
theta
0.05
0.10
0.15
0.20
c/d


+9.64
+9.66
+9.68
Mag
0.5
1.0
1.5
Phase

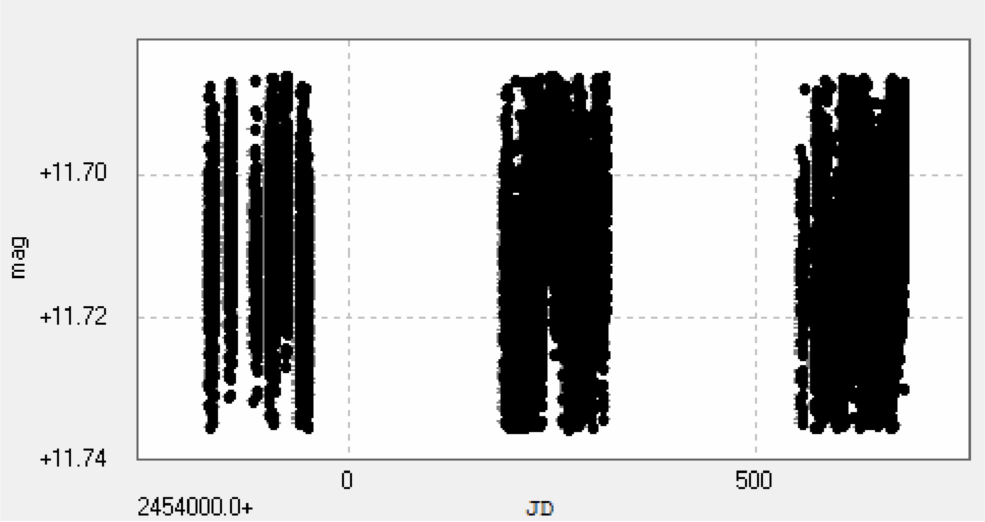
J17052-050


+10.05
+10.10
+10.15
+10.20
mag
0
1000
2000
3000
2000.0+
JD

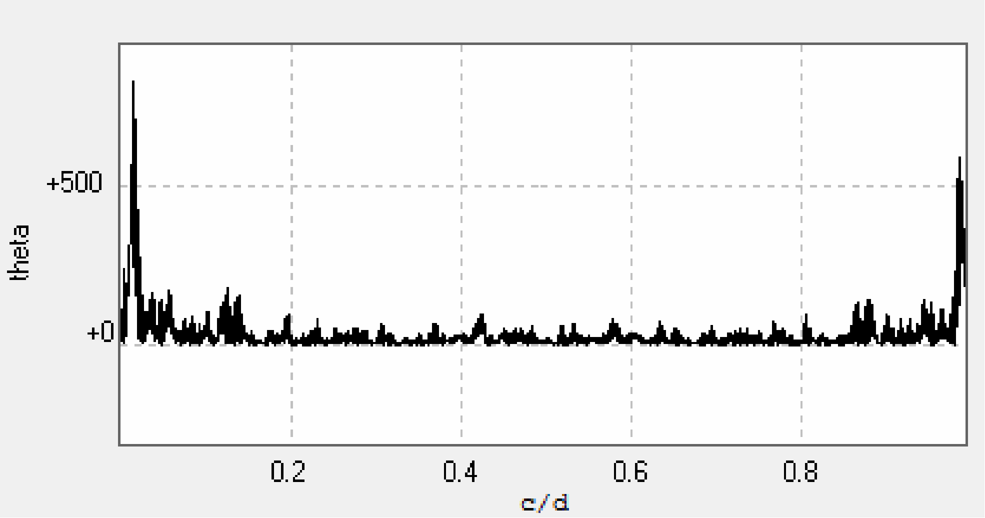

+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d


+10.06
+10.08
+10.10
+10.12
+10.14
Mag
0.5
1.0
1.5
Phase

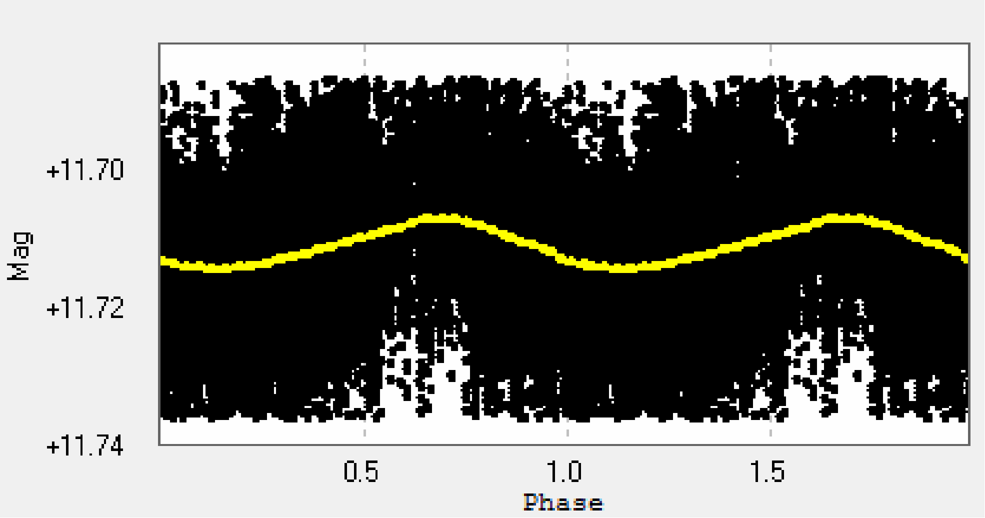
J17115+384



mag
+11.70
+11.72
+11.74
0
500
2454000.0+
JD

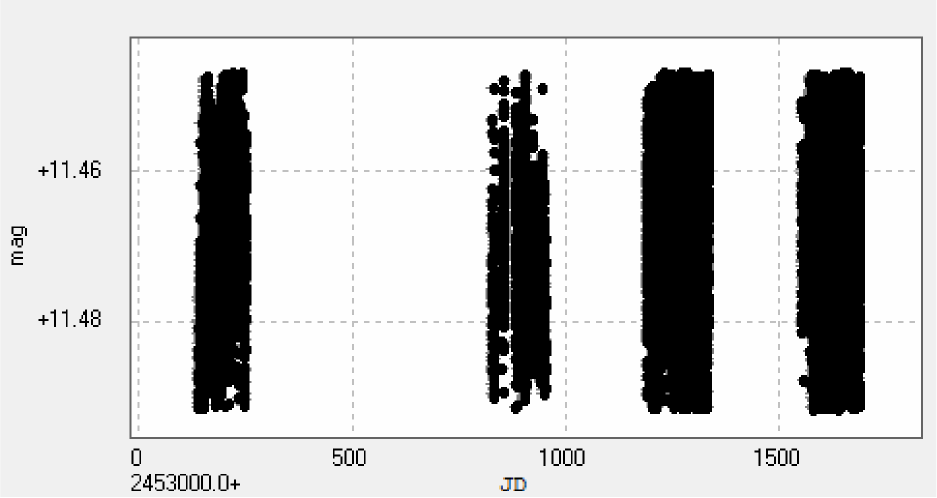


theta
+500
+0
0.2
0.4
0.6
0.8
c/d

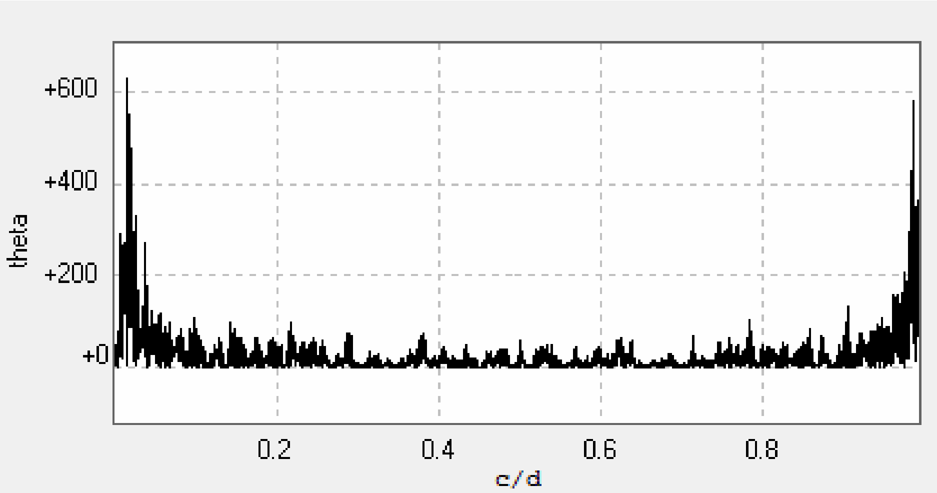


Mag
+11.70
+11.72
+11.74
0.5
1.0
1.5
Phase

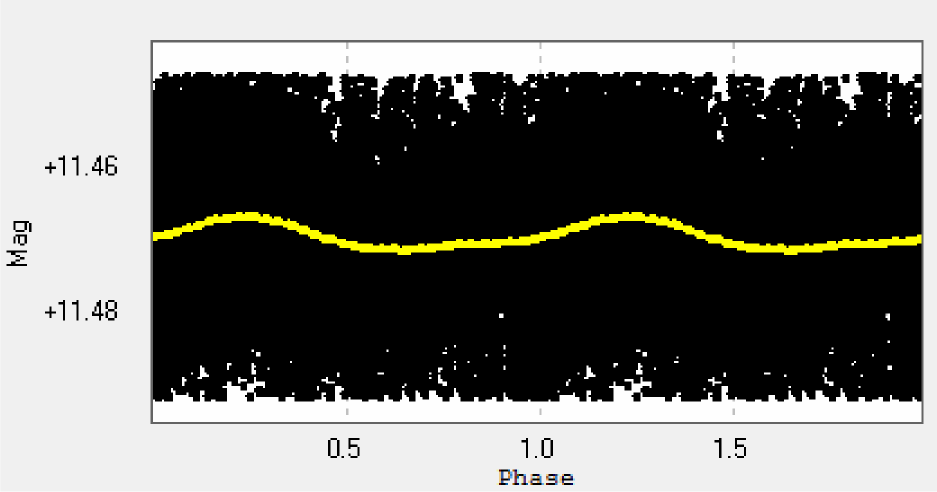
J17198+417



+11.46
+11.48
mag
0
500
1000
1500
2453000.0+
JD

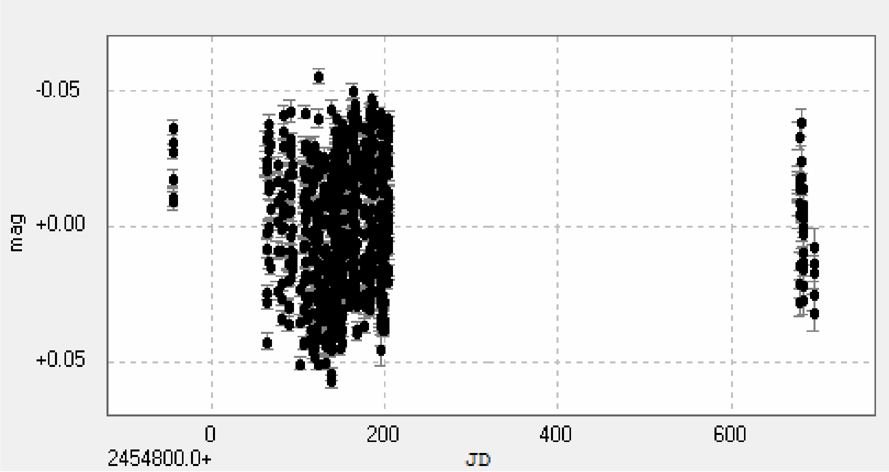


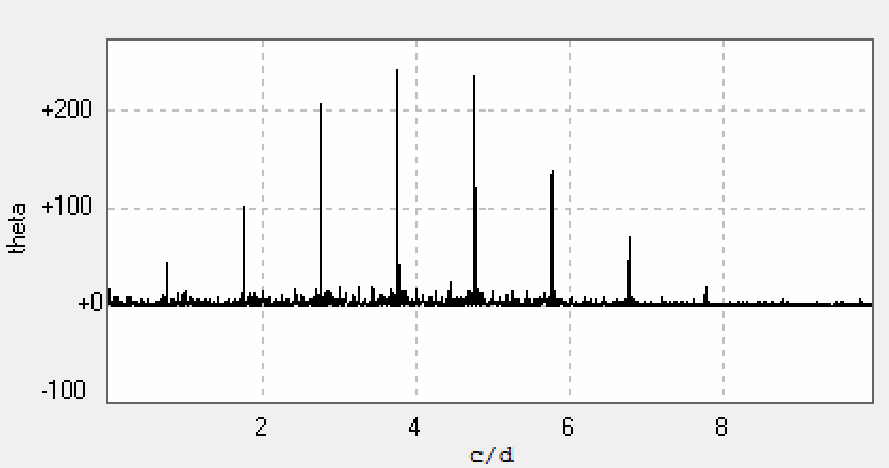
+600
+400
+200
+0
theta
0.2
0.4
0.6
0.8
c/d

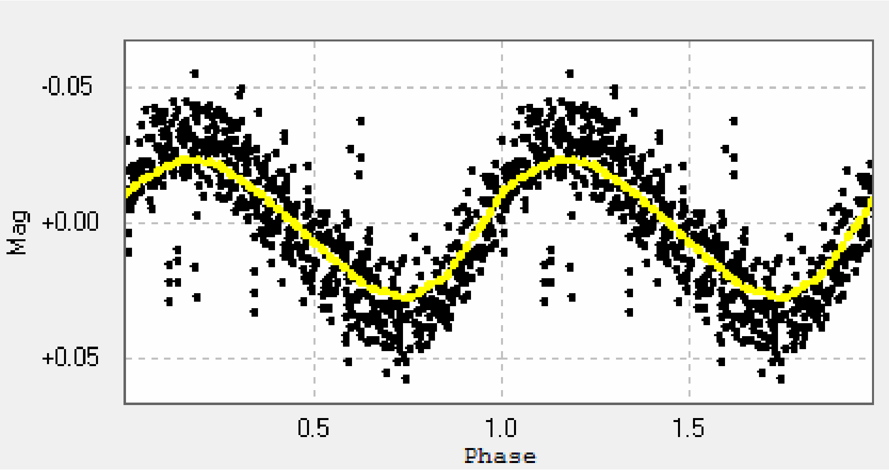


+11.46
+11.48
Mag
0.5
1.0
1.5
Phase

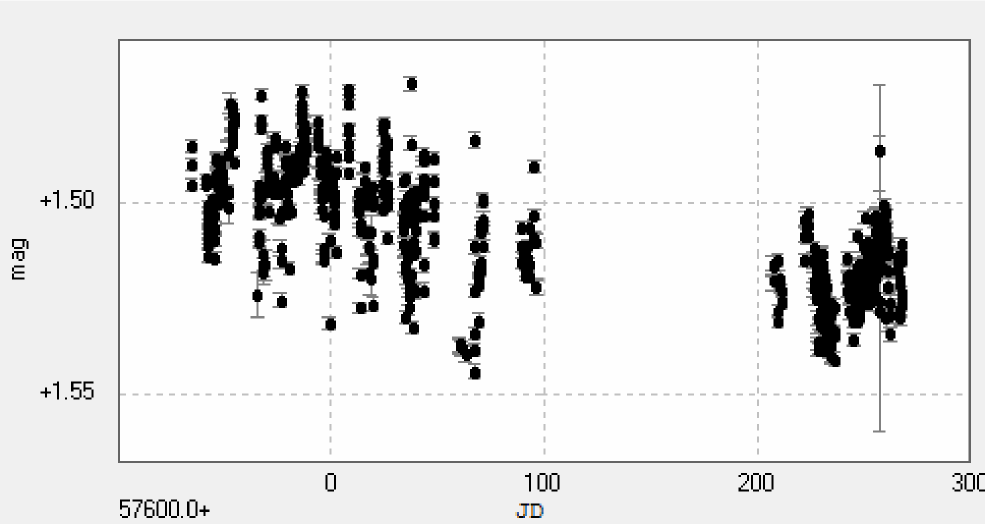
J17338+169


-0.05
+0.00
+0.05
mag
0
200
400
600
2454800.0+
JD

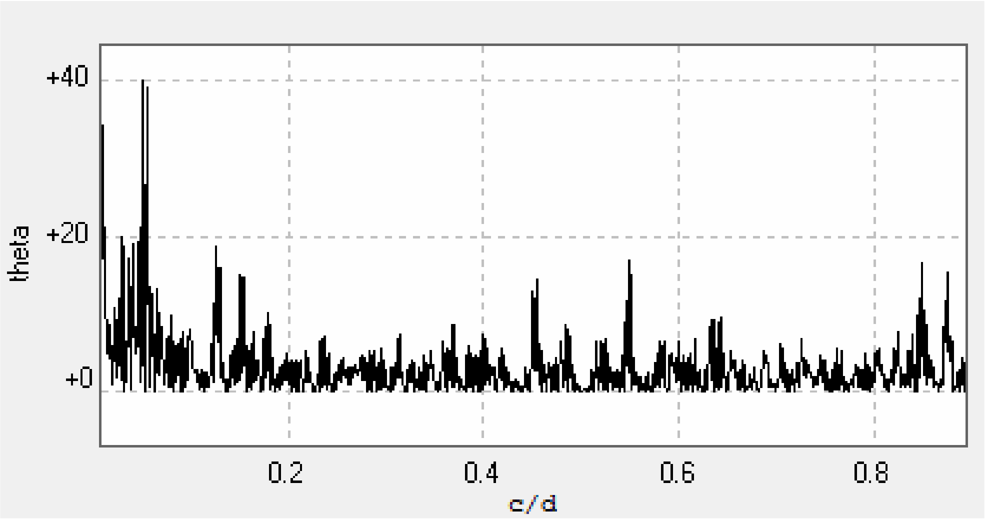

+200
+100
+0
-100
theta
2
4
6
8
c/d


-0.05
+0.00
+0.05
Mag
0.5
1.0
1.5
Phase

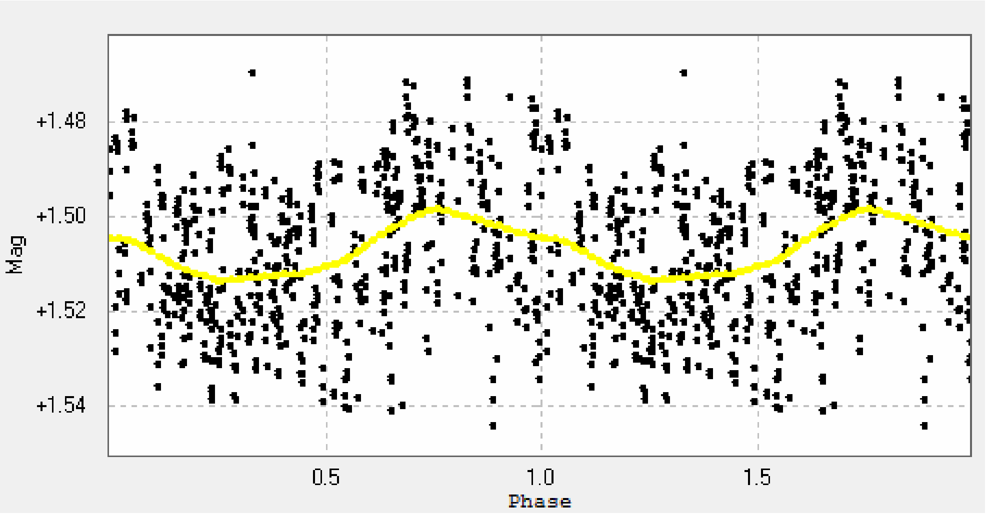
J17355+616



mag
+1.50
+1.55
0
100
200
300
57600.0+
JD

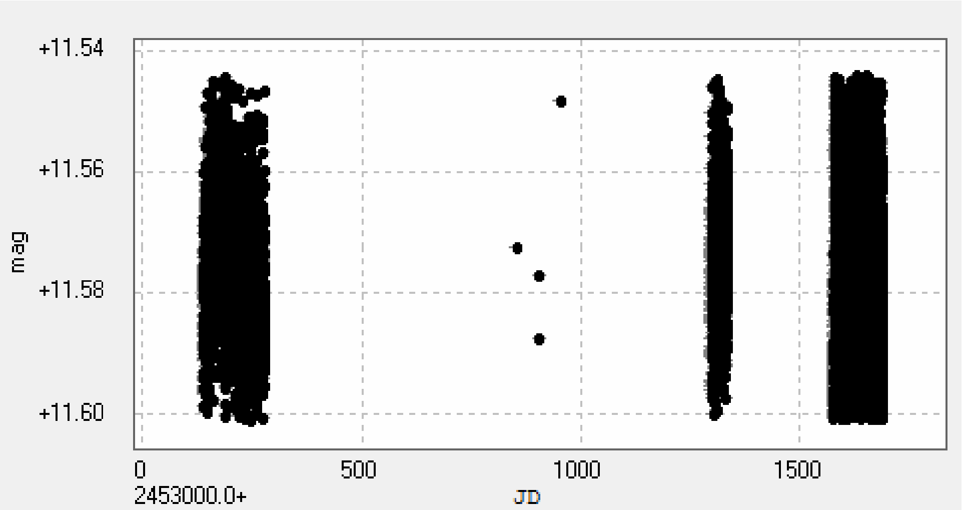


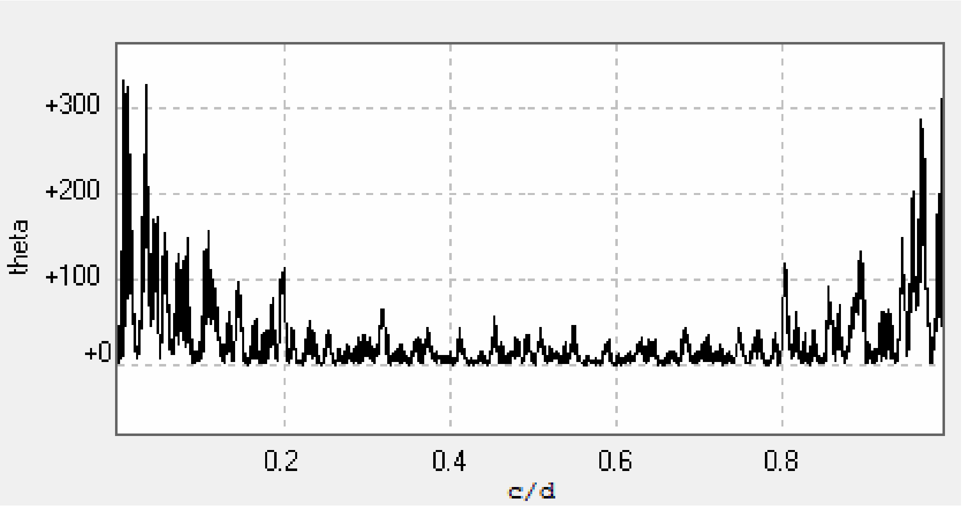
theta
+40
+20
+0
0.2
0.4
0.6
0.8
c/d

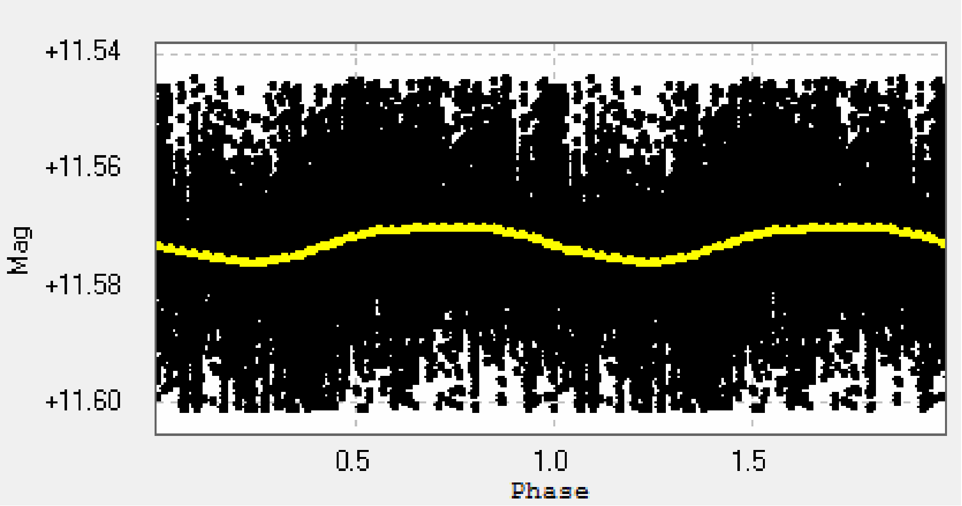


Mag
+1.48
+1.50
+1.52
+1.54
0.5
1.0
1.5
Phase

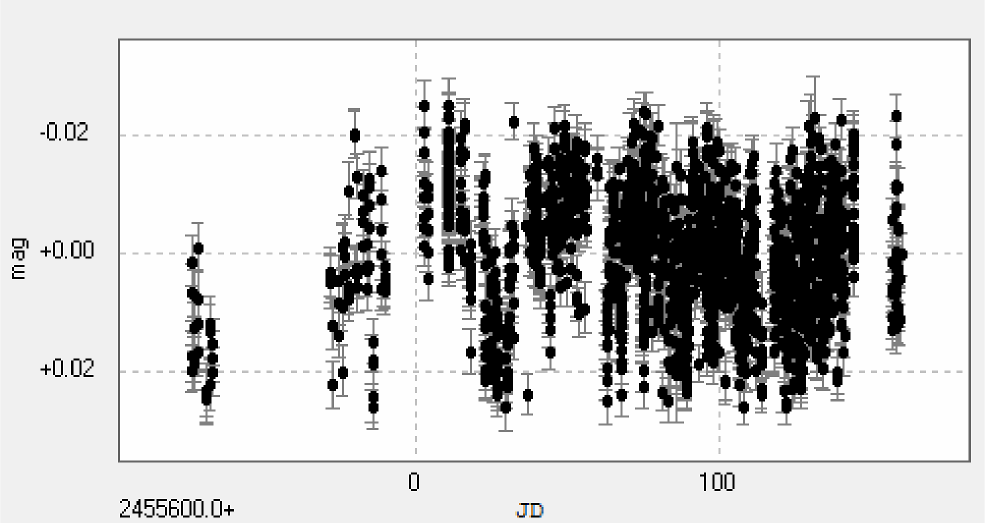
J17578+465


+11.54
+11.56
mag
+11.58
+11.60
0
500
1000
1500
2453000.0+
JD

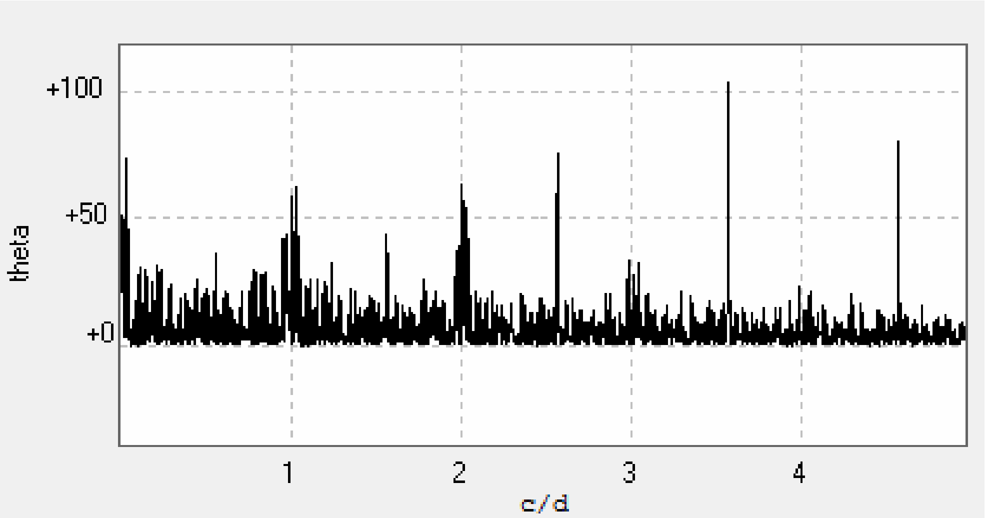

+300
+200
theta
+100
+0
0.2
0.4
0.6
0.8
c/d


+11.54
+11.56
Mag
+11.58
+11.60
0.5
1.0
1.5
Phase

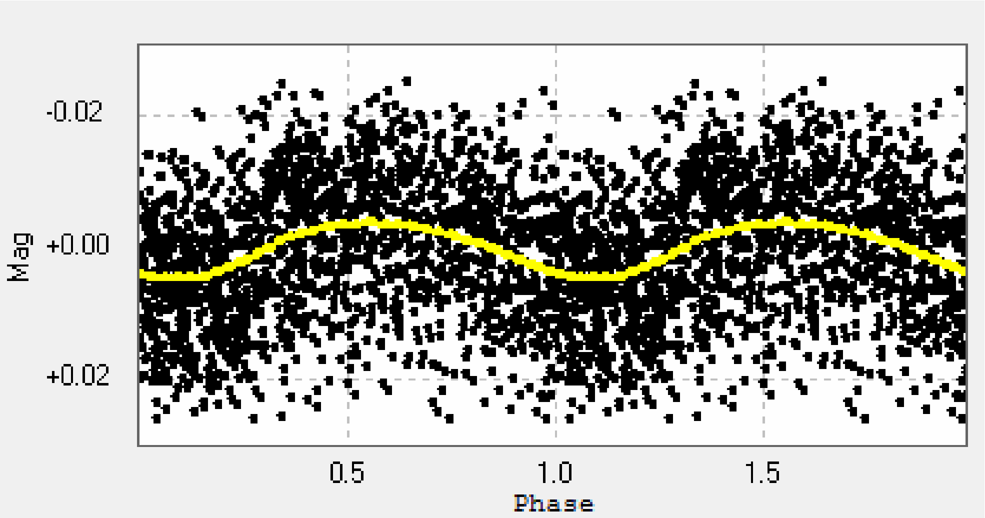
J18022+642



-0.02
+0.00
+0.02
mag
0
100
2455600.0+
JD

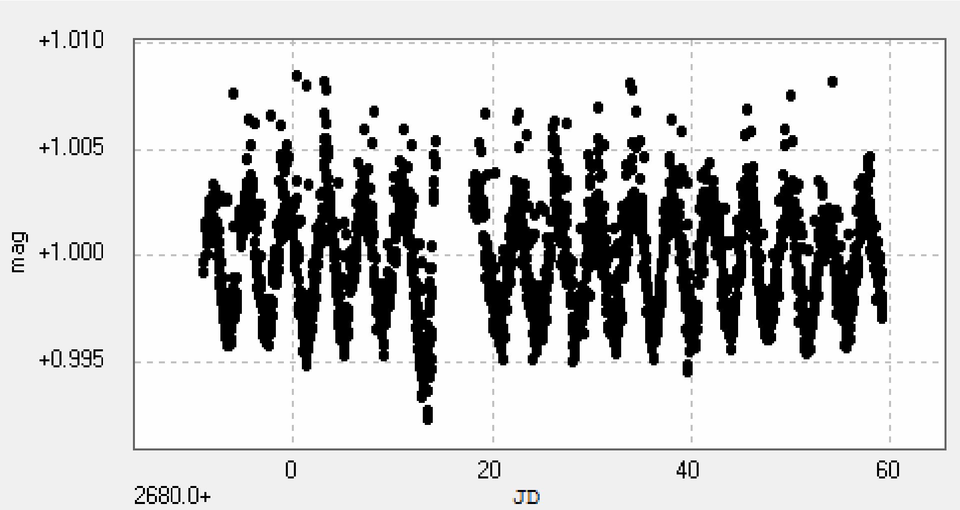


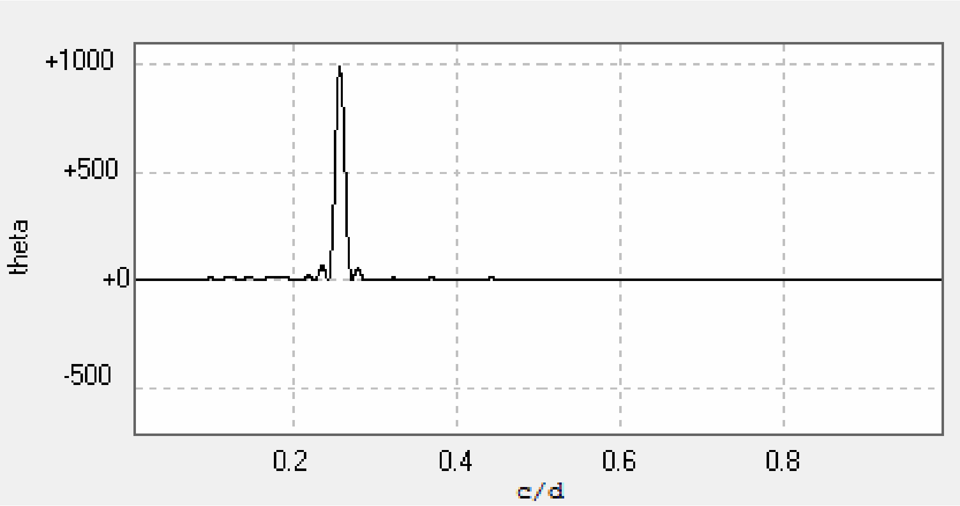
+100
+50
+0
theta
1
2
3
4
c/d

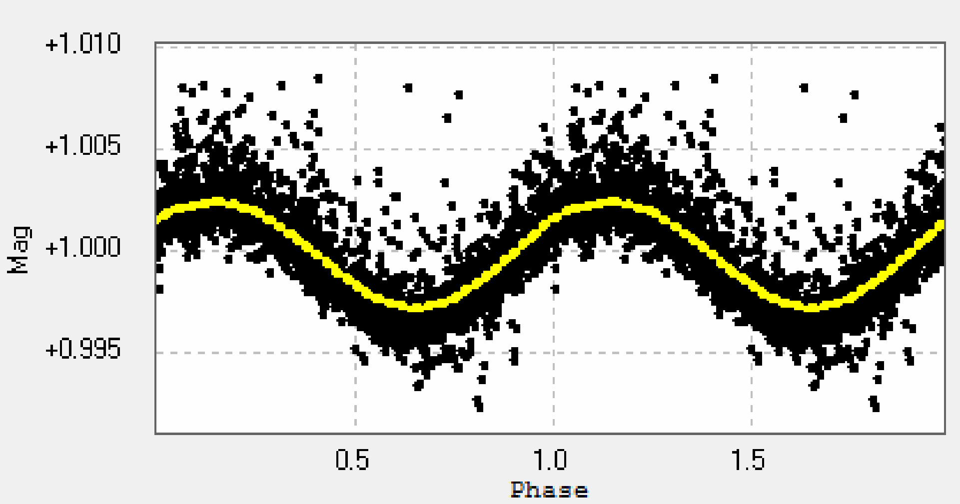


-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

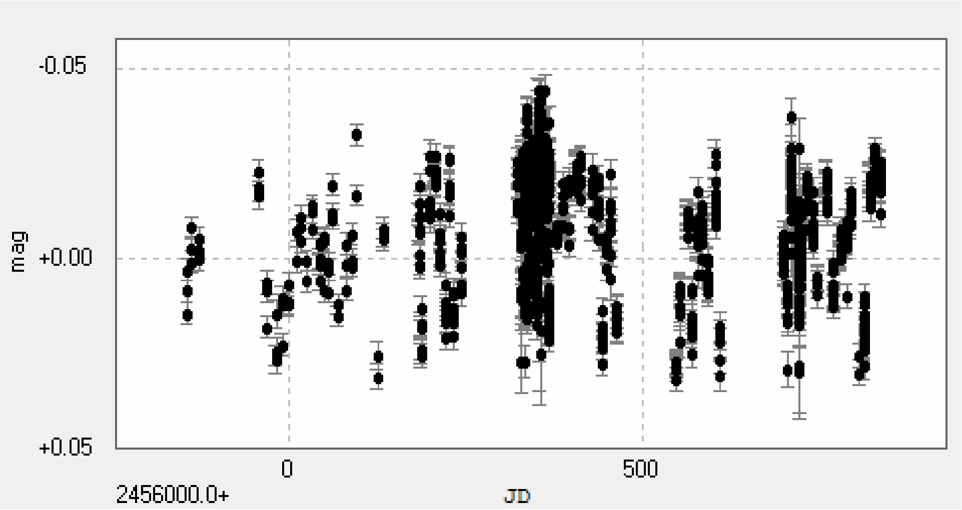
J18075-159

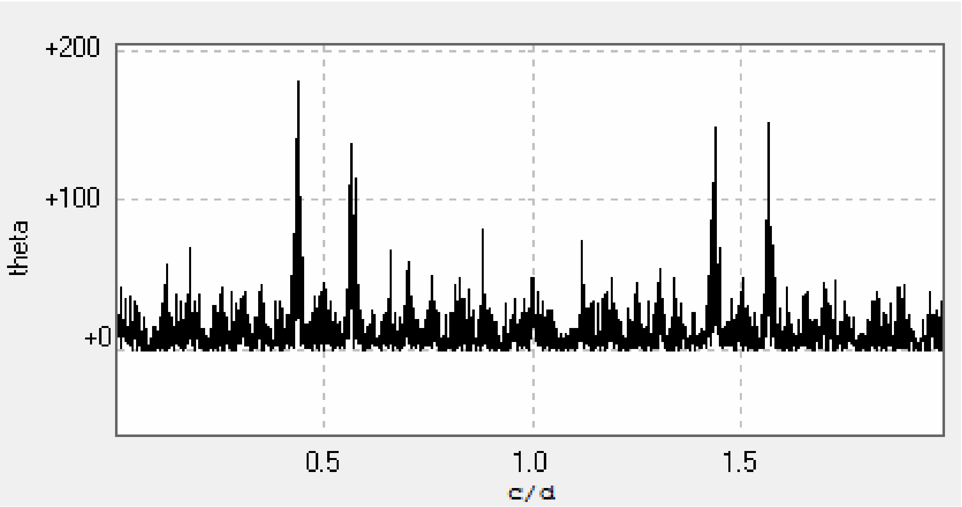

mag
+1.010
+1.005
+1.000
+0.995
0
20
40
60
2680.0+
JD

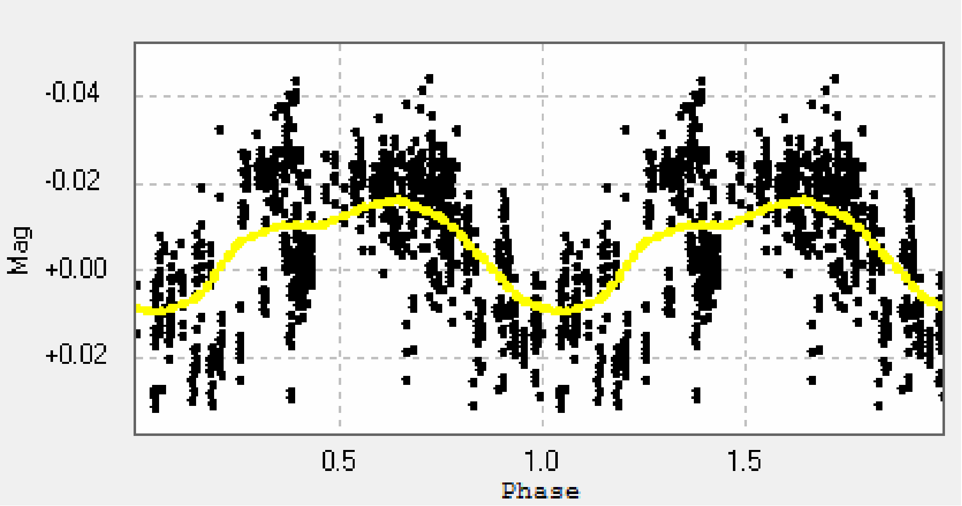

theta
+1000
+500
+0
-500
0.2
0.4
0.6
0.8
c/d


Mag
+1.010
+1.005
+1.000
+0.995
0.5
1.0
1.5
Phase

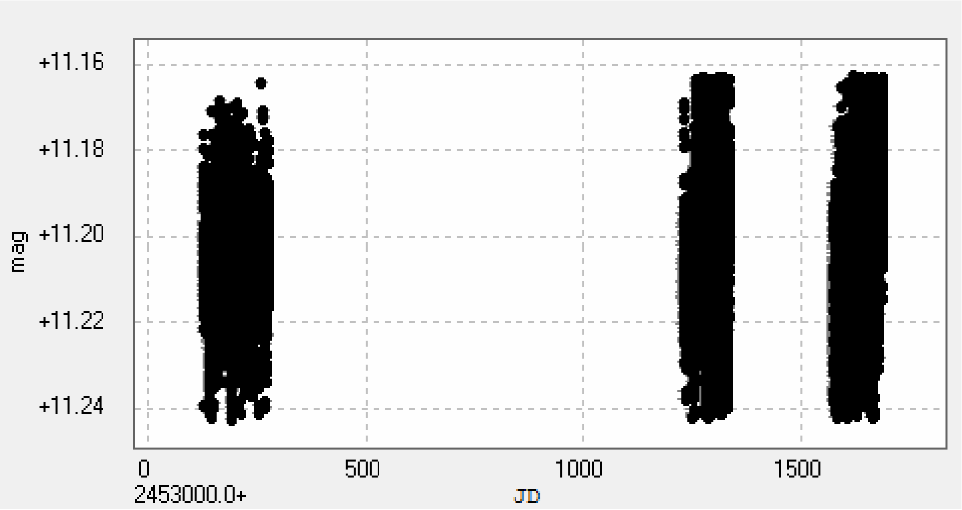
J18131+260


-0.05
+0.00
+0.05
mag
0
500
2456000.0+
JD

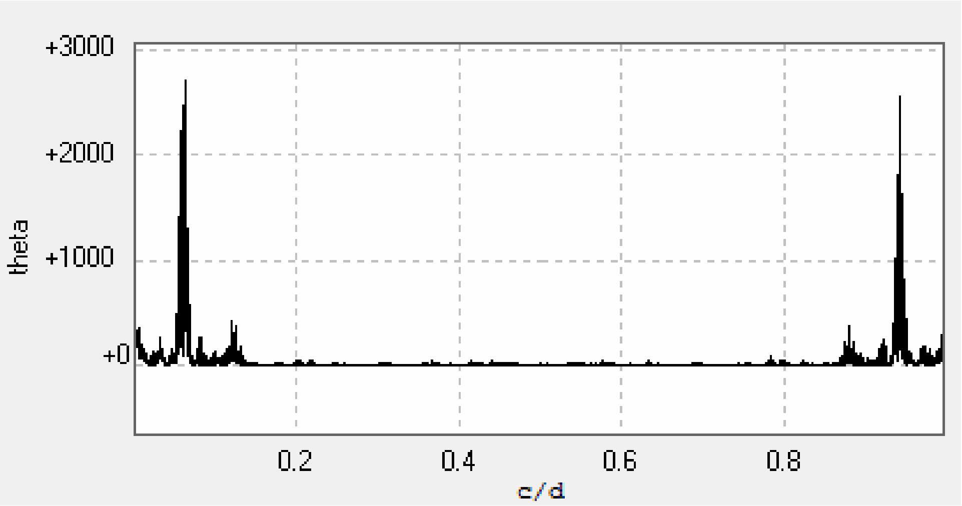

+200
+100
+0
theta
0.5
1.0
1.5
c/d


-0.04
-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

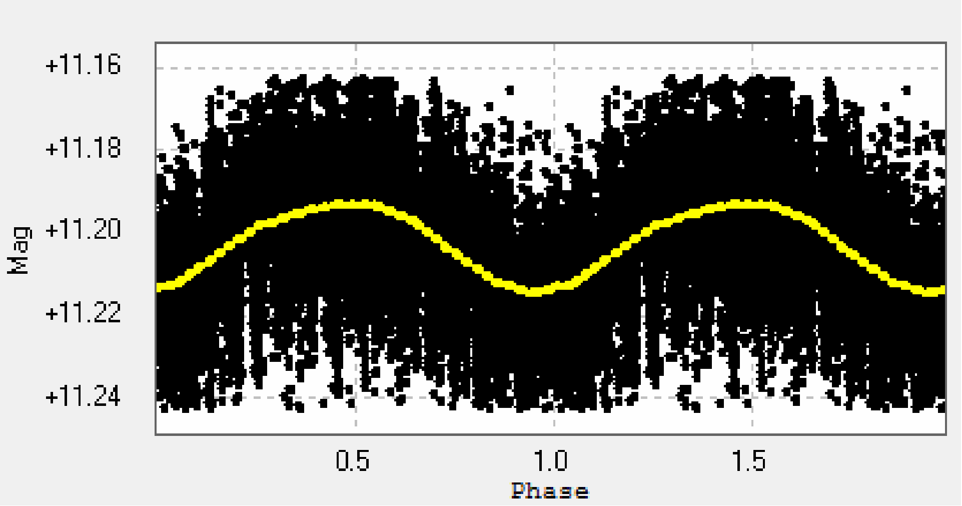
J18174+483



+11.16
+11.18
+11.20
+11.22
+11.24
mag
0
500
1000
1500
2453000.0+
JD

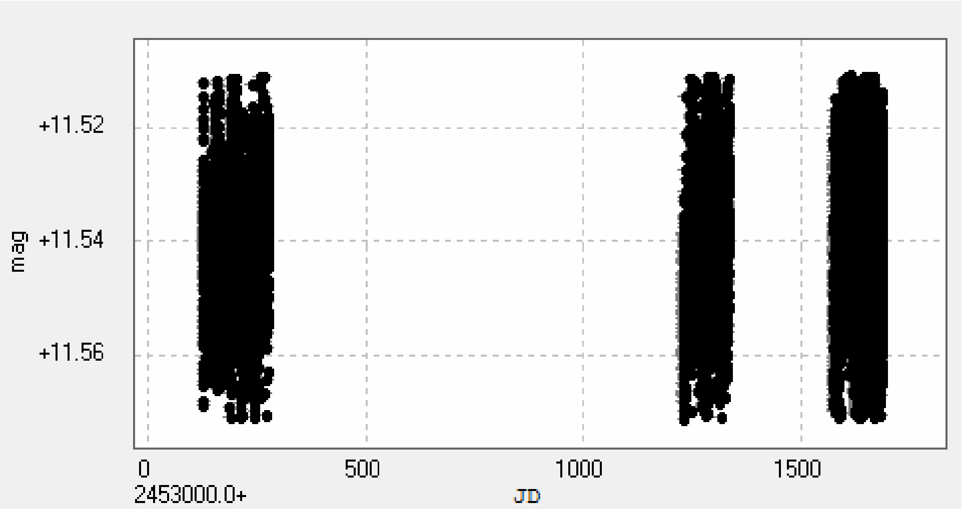


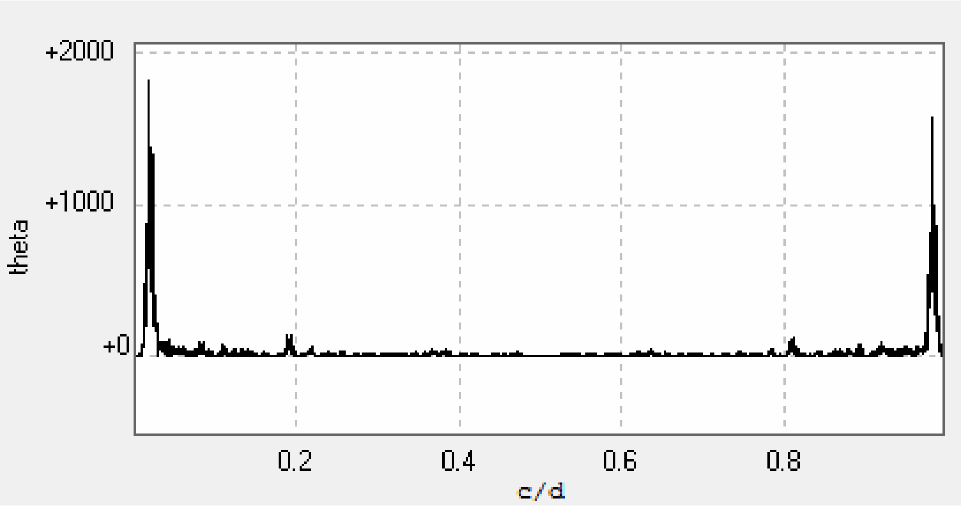
+3000
+2000
+1000
+0
theta
0.2
0.4
0.6
0.8
c/d

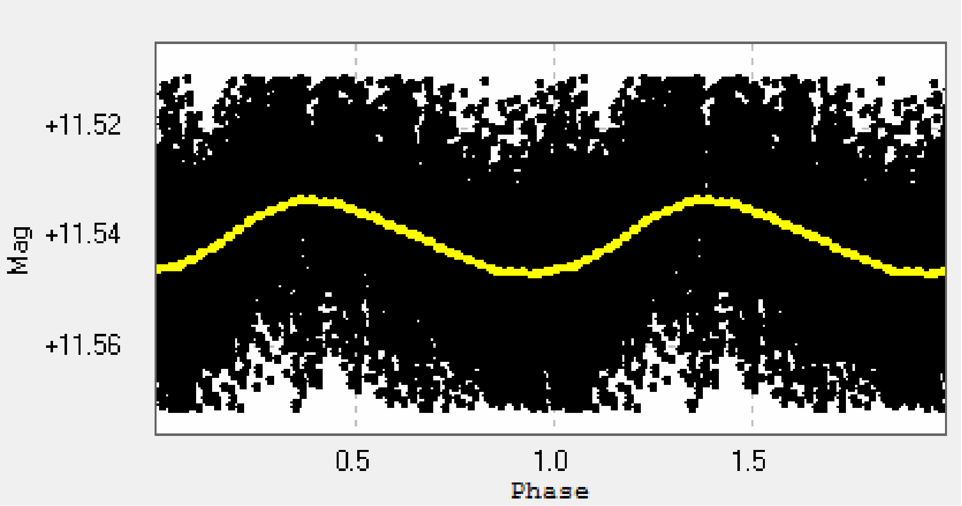


+11.16
+11.18
+11.20
+11.22
+11.24
Mag
0.5
1.0
1.5
Phase

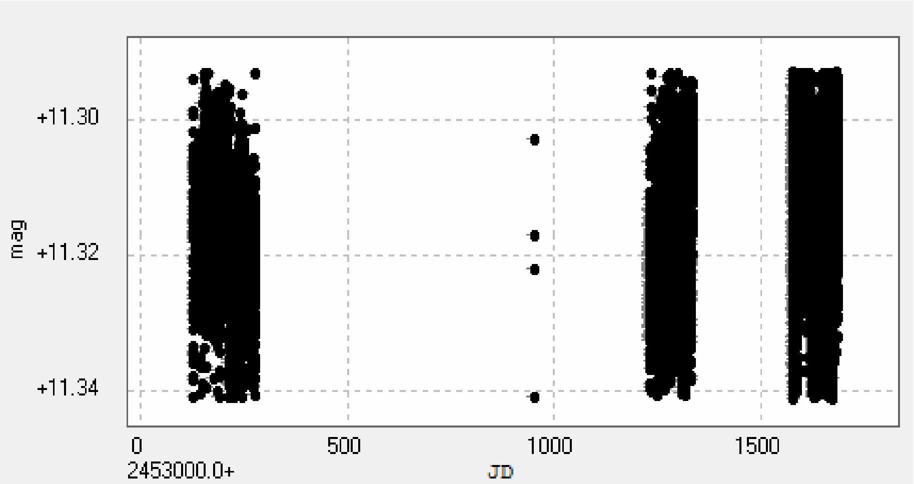
J18319+406

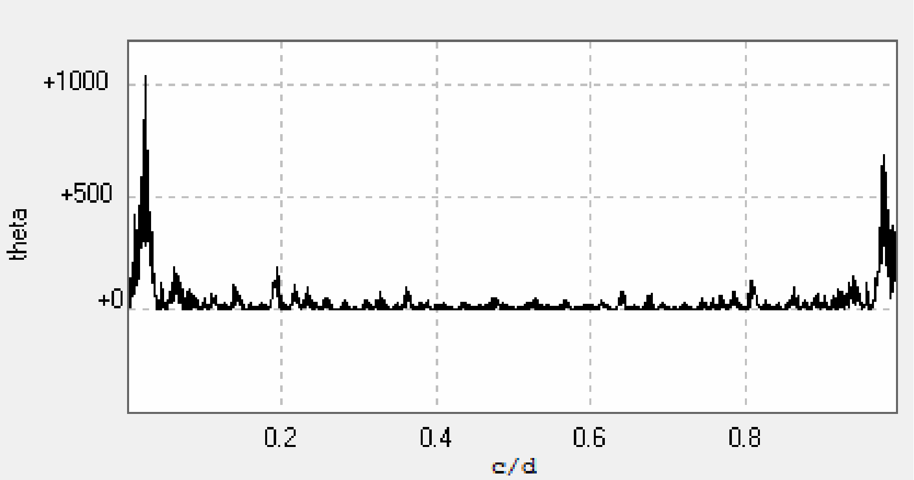

mag
+11.52
+11.54
+11.56
0
500
1000
1500
2453000.0+
JD

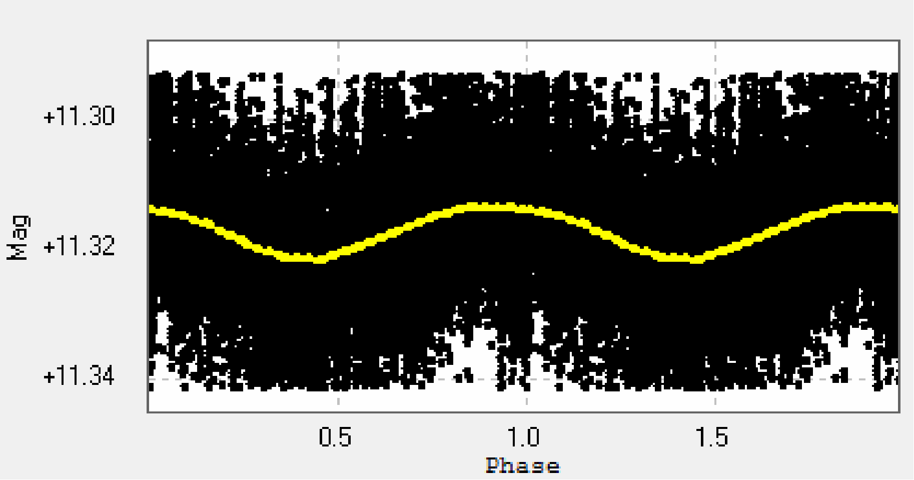

theta
+2000
+1000
+0
0.2
0.4
0.6
0.8
c/d


Mag
+11.52
+11.54
+11.56
0.5
1.0
1.5
Phase

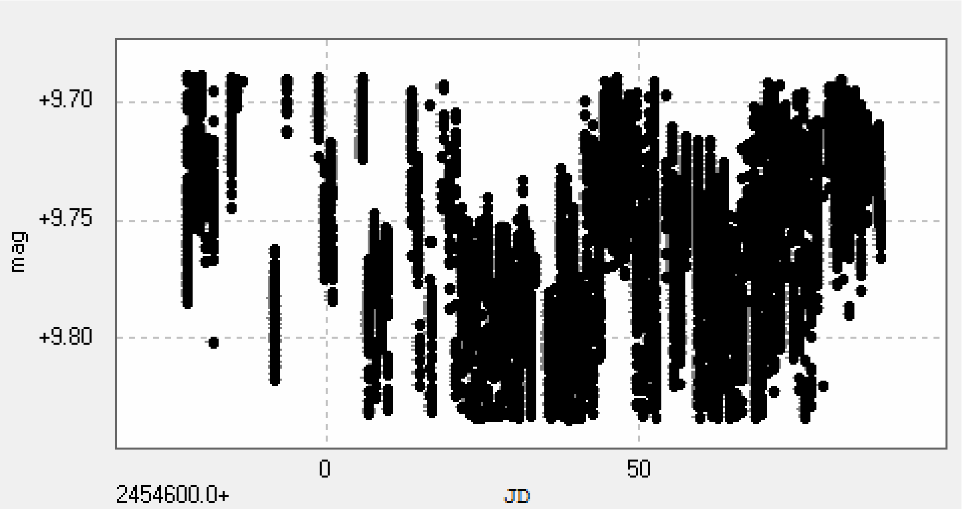
J18346+401

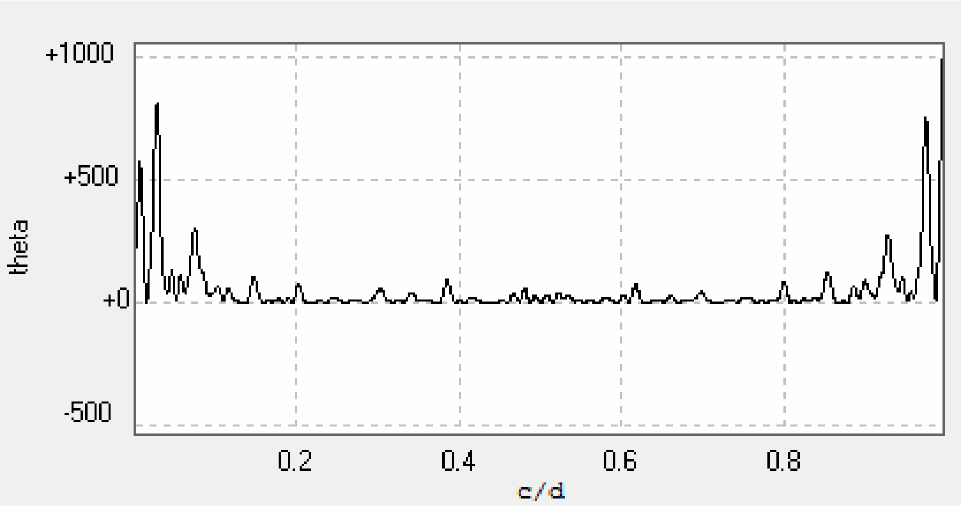

+11.30
+11.32
+11.34
mag
0
500
1000
1500
2453000.0+
JD

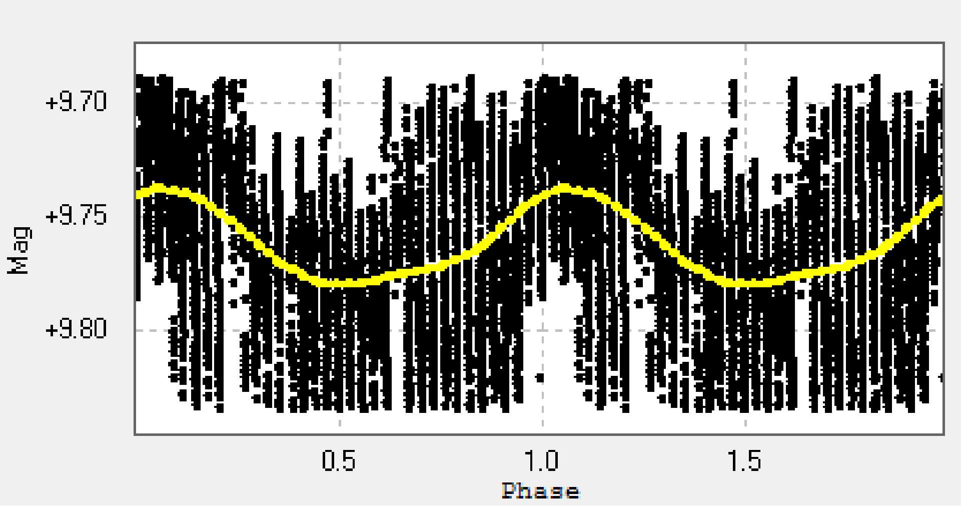

+1000
+500
+0
theta
0.2
0.4
0.6
0.8
c/d


+11.30
+11.32
+11.34
Mag
0.5
1.0
1.5
Phase

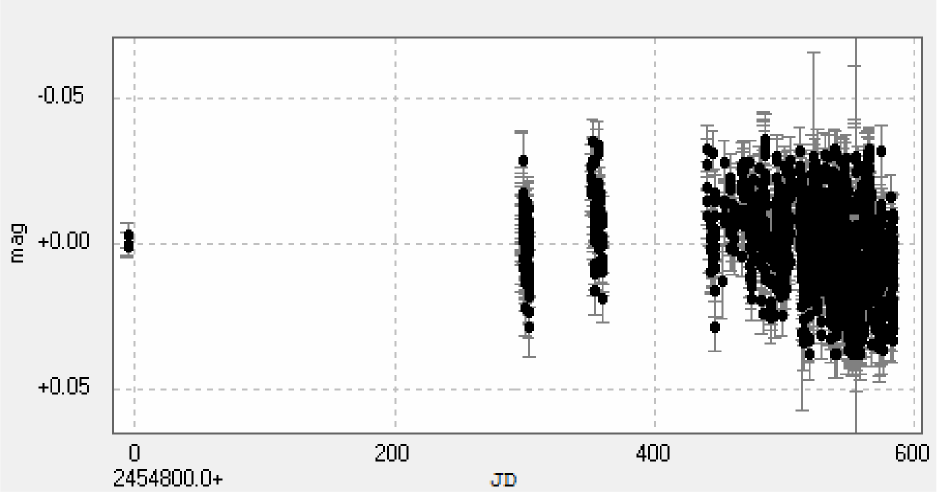
J18353+457

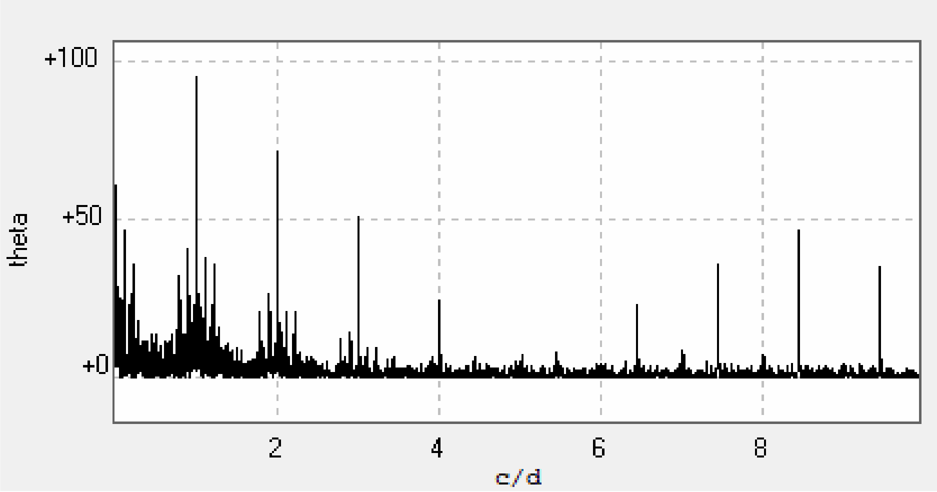

+9.70
+9.75
+9.80
mag
0
50
2454600.0+
JD

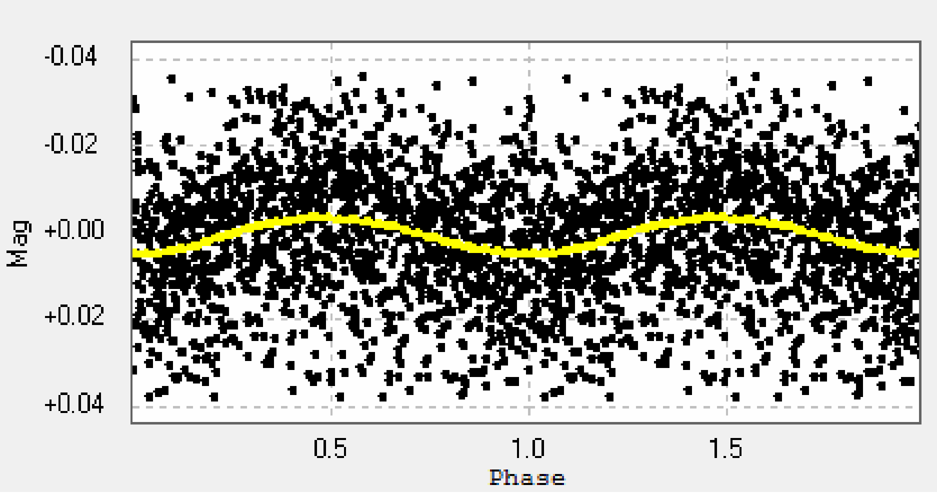

+1000
+500
+0
-500
theta
0.2
0.4
0.6
0.8
c/d


+9.70
+9.75
+9.80
Mag
0.5
1.0
1.5
Phase

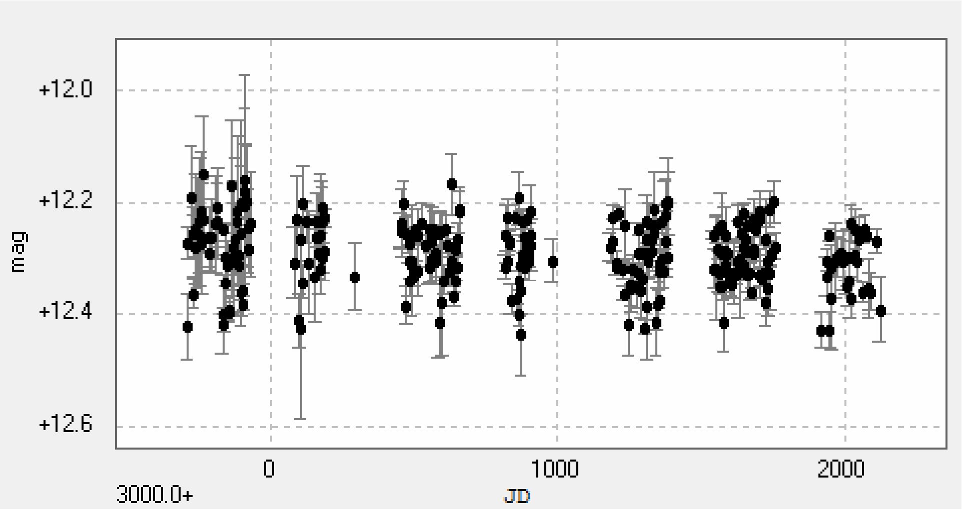
J18356+329


-0.05
+0.00
+0.05
mag
0
200
400
600
2454800.0+
JD

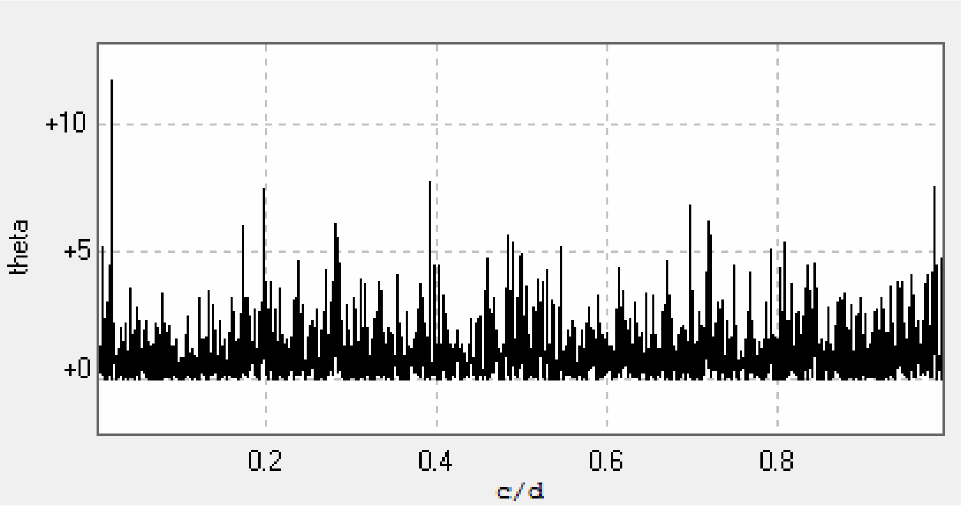

+100
+50
+0
theta
2
4
6
8
c/d


-0.04
-0.02
+0.00
+0.02
+0.04
Mag
0.5
1.0
1.5
Phase

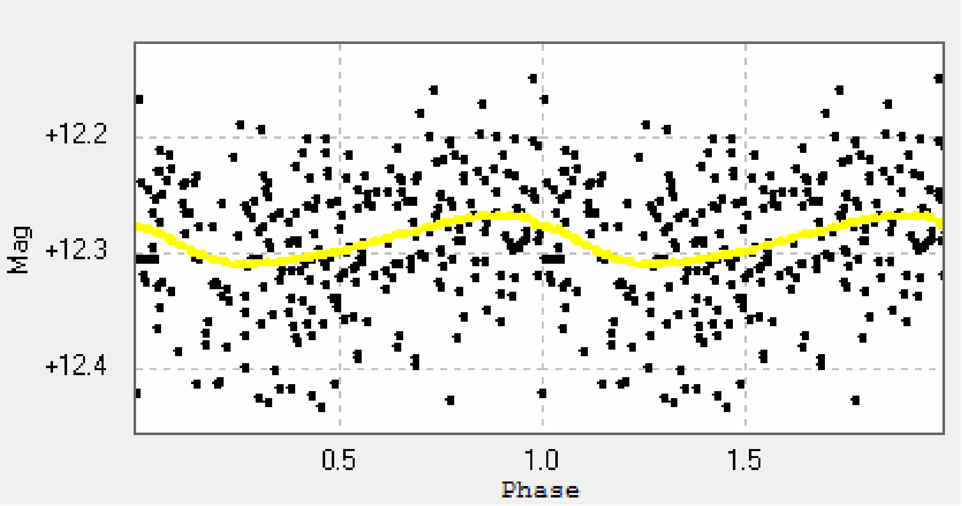
J18363+136



+12.0
+12.2
+12.4
+12.6
mag
0
1000
2000
3000.0+
JD

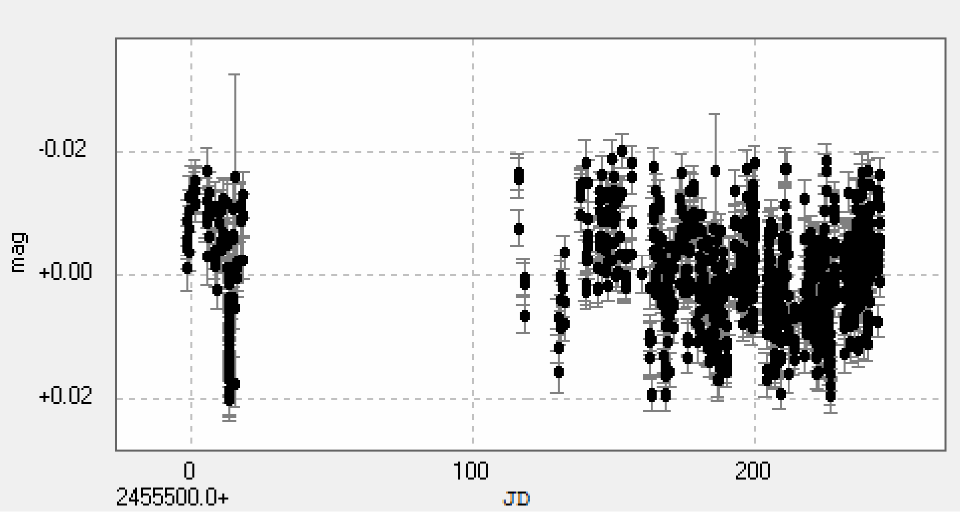


+10
+5
+0
theta
0.2
0.4
0.6
0.8
c/d

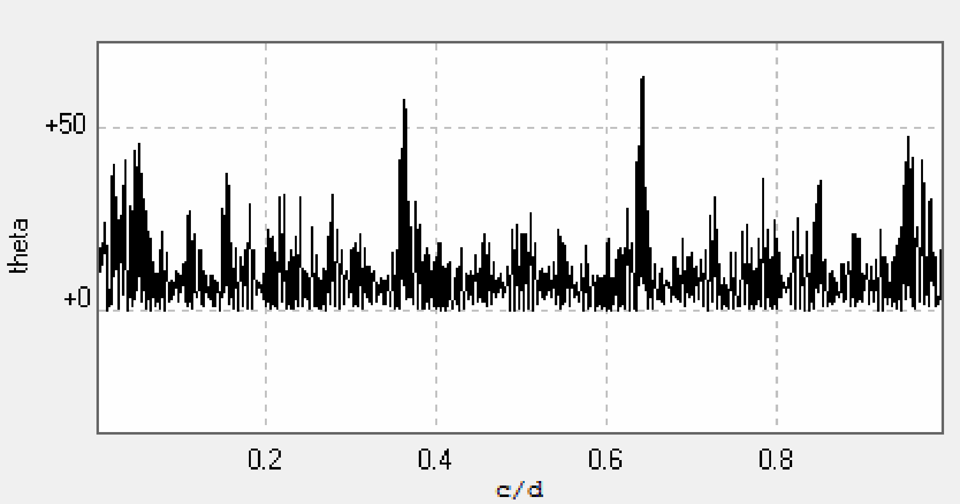


+12.2
+12.3
+12.4
Mag
0.5
1.0
1.5
Phase

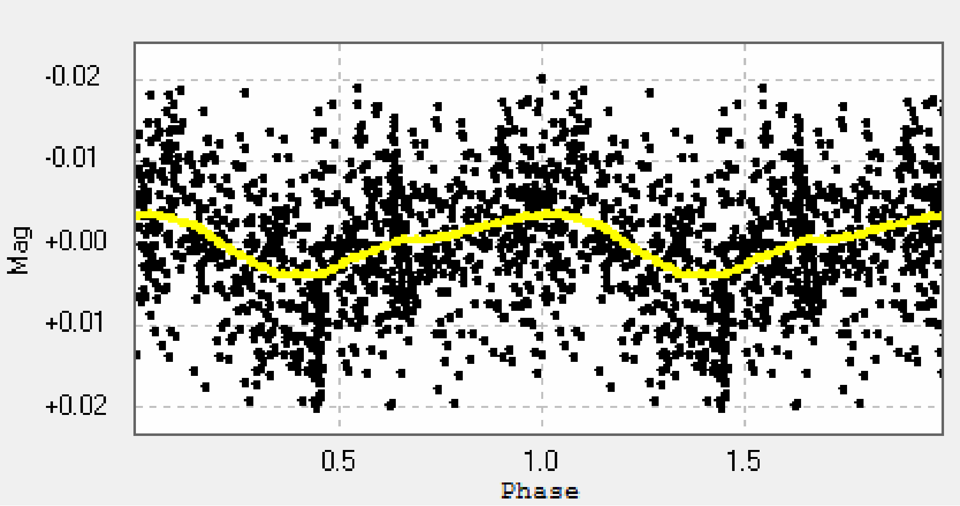
J18482+076



-0.02
+0.00
+0.02
mag
0
100
200
2455500.0+
JD

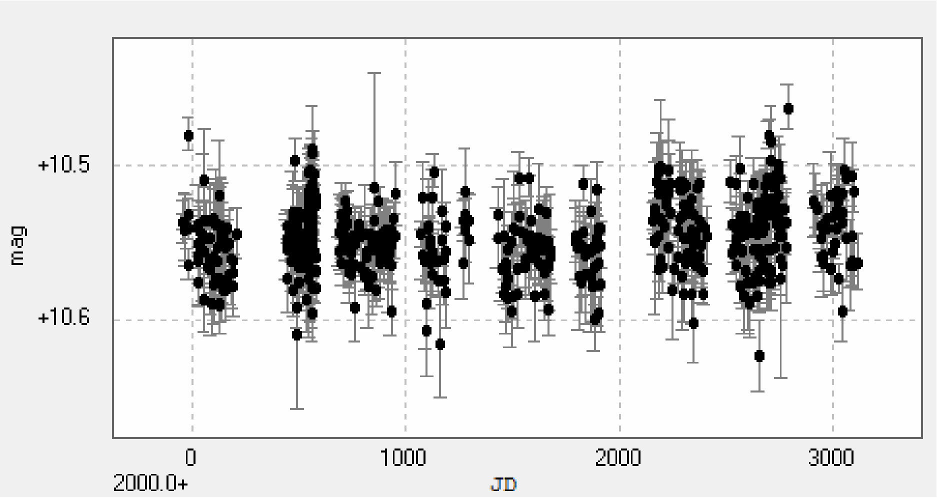


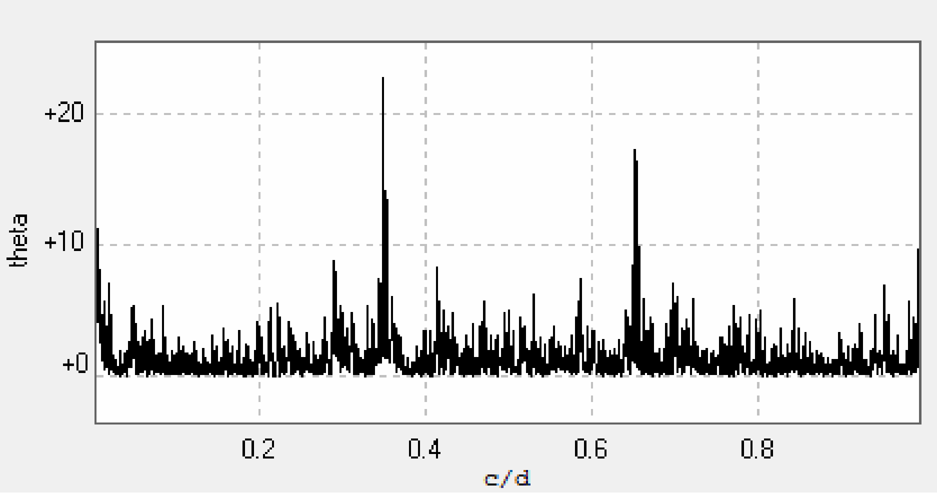
+50
+0
theta
0.2
0.4
0.6
0.8
c/d

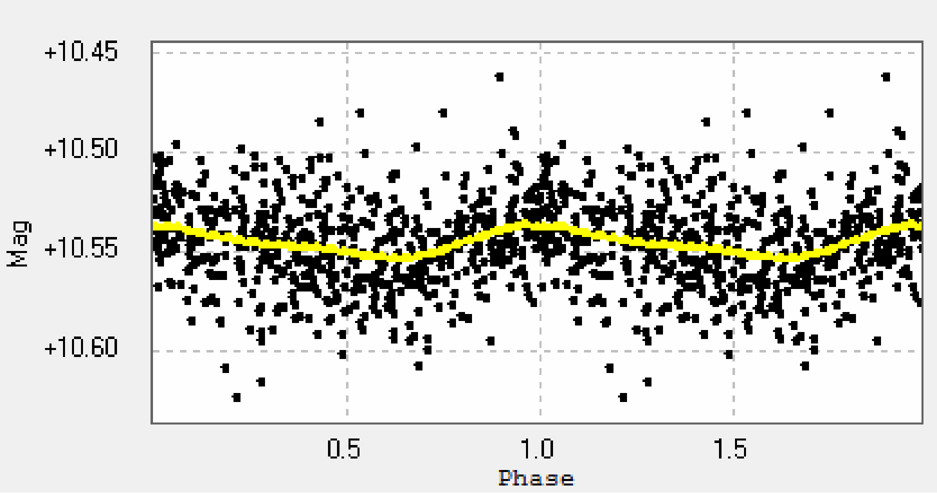


-0.02
-0.01
+0.00
+0.01
+0.02
Mag
0.5
1.0
1.5
Phase

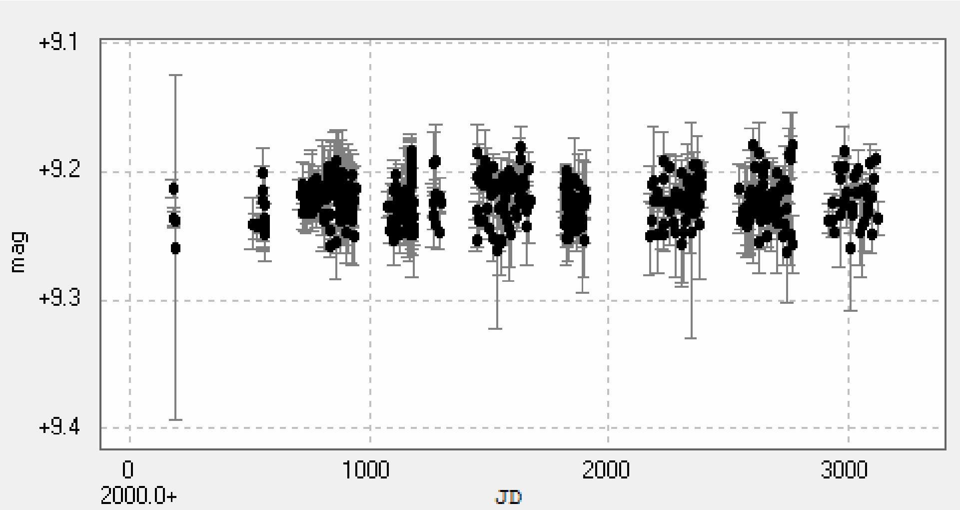
J18498-238

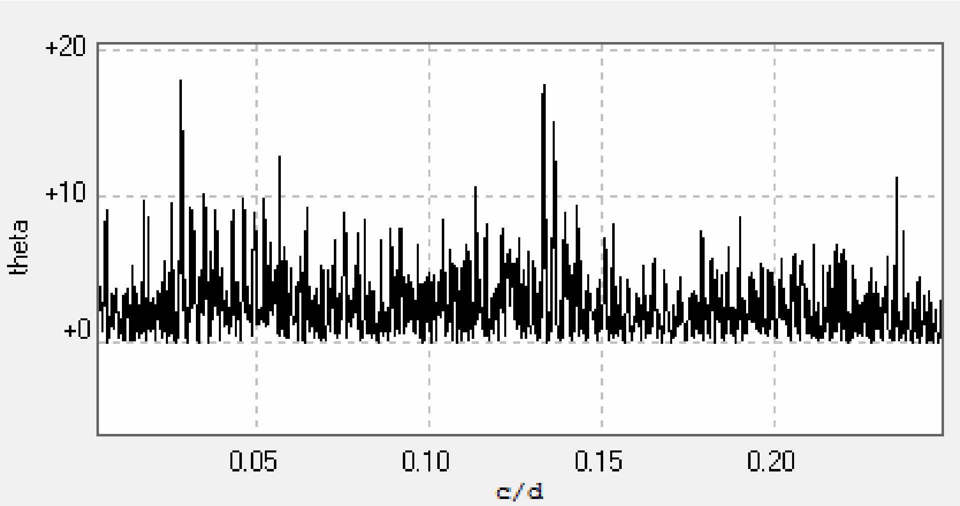

+10.5
+10.6
mag
0
1000
2000
3000
2000.0+
JD

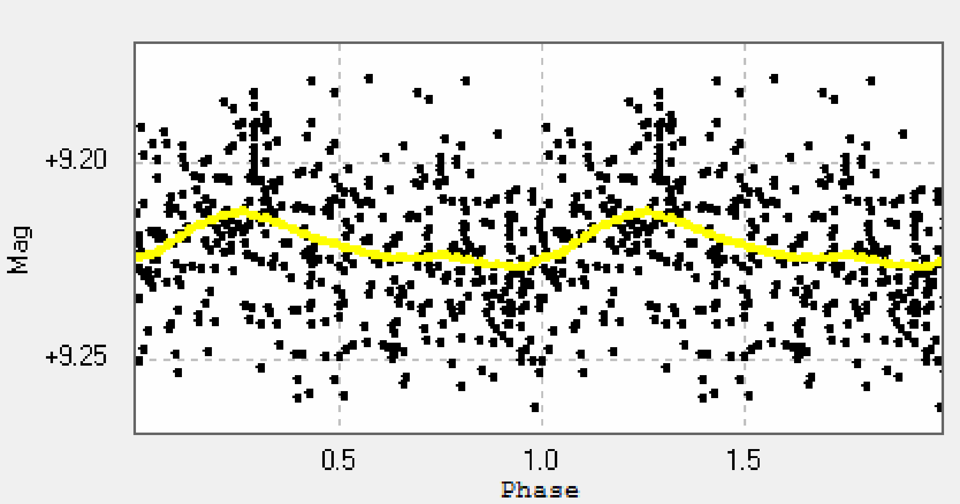

+20
+10
+0
theta
0.2
0.4
0.6
0.8
c/d


+10.45
+10.50
+10.55
+10.60
Mag
0.5
1.0
1.5
Phase

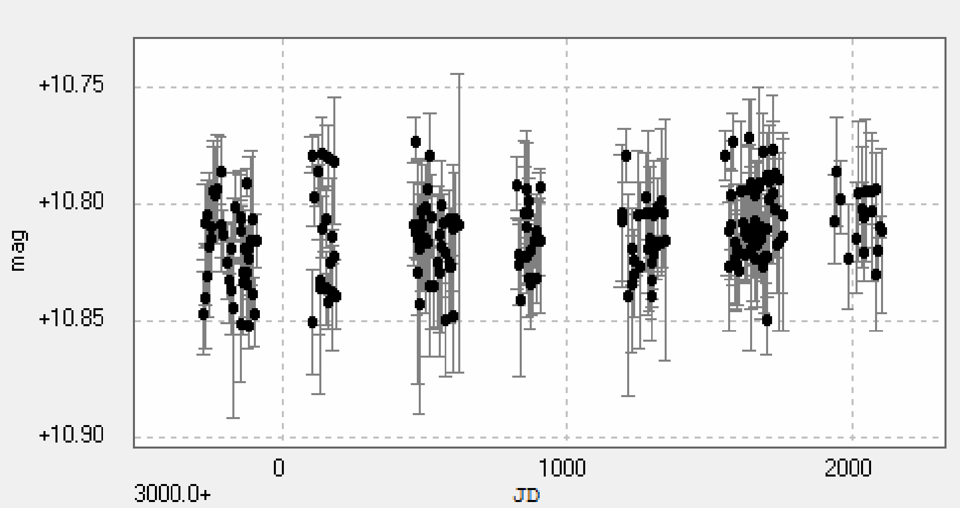
J18580+059


+9.1
+9.2
+9.3
+9.4
mag
0
1000
2000
3000
2000.0+
JD

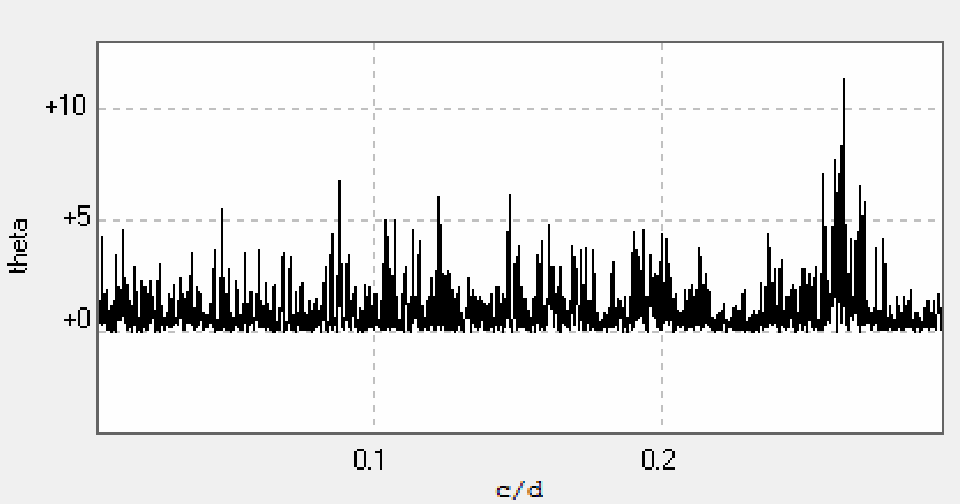

+20
+10
+0
theta
0.05
0.10
0.15
0.20
c/d


+9.20
+9.25
Mag
0.5
1.0
1.5
Phase

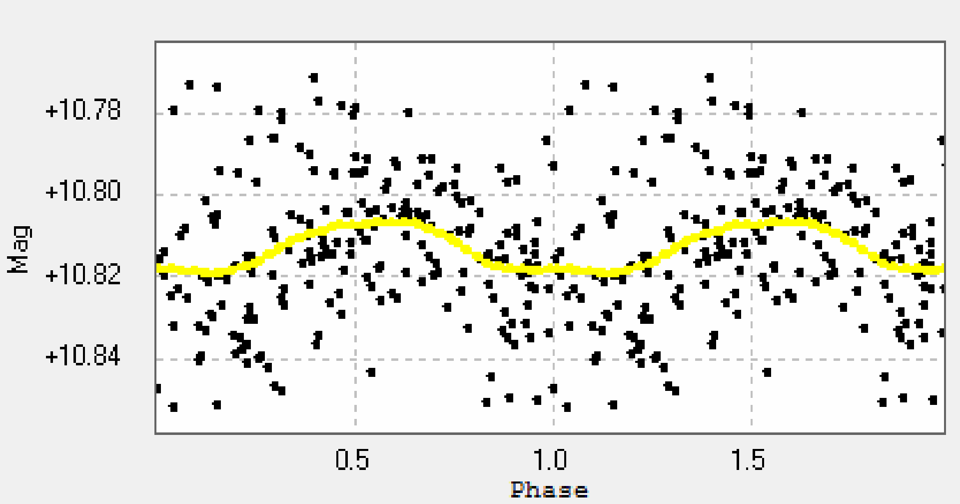
J19072+208 B



+10.75
+10.80
+10.85
+10.90
mag
0
1000
2000
3000.0+
JD

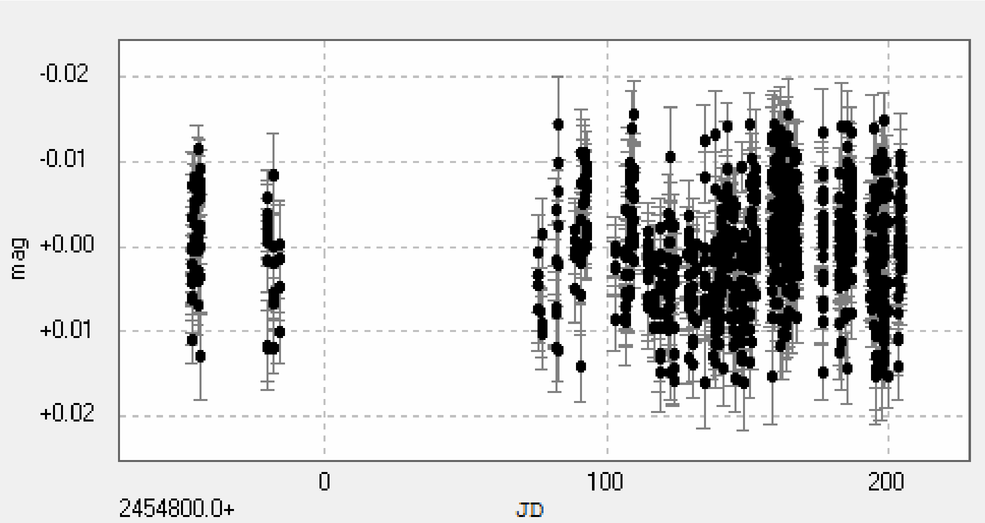


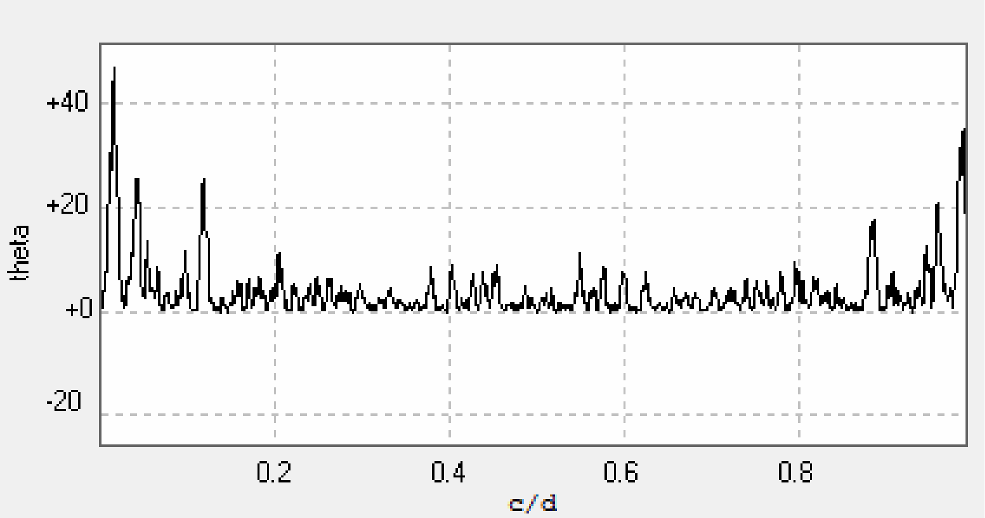
+10
+5
+0
theta
0.1
0.2
c/d

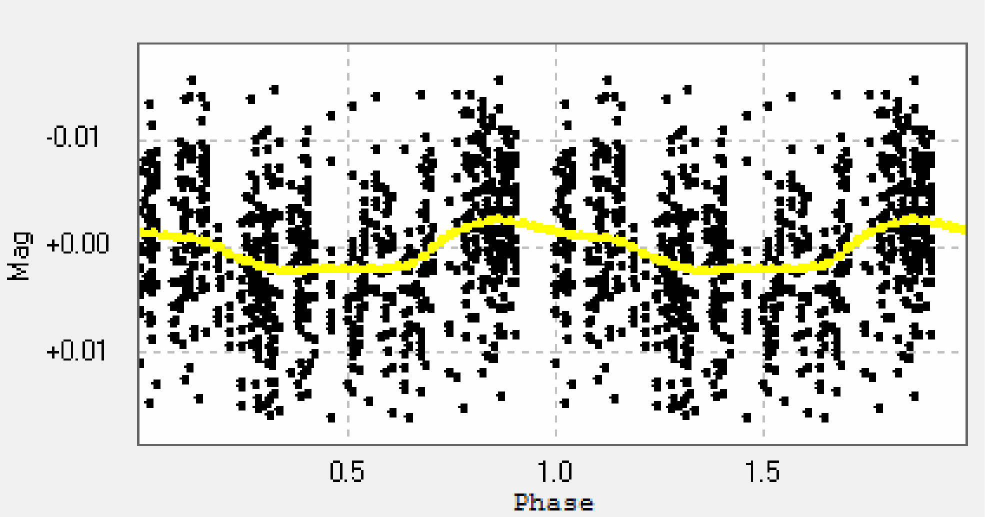


+10.78
+10.80
+10.82
+10.84
Mag
0.5
1.0
1.5
Phase

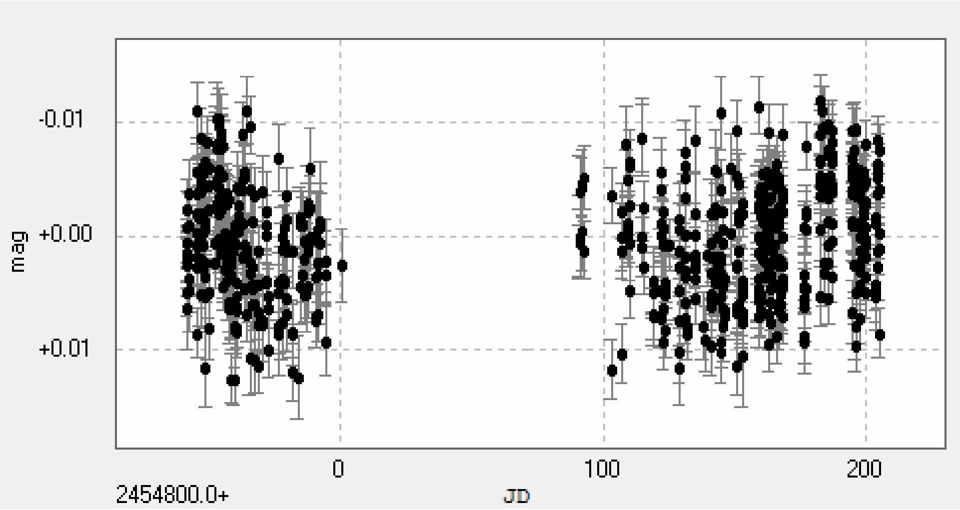
J19084+322

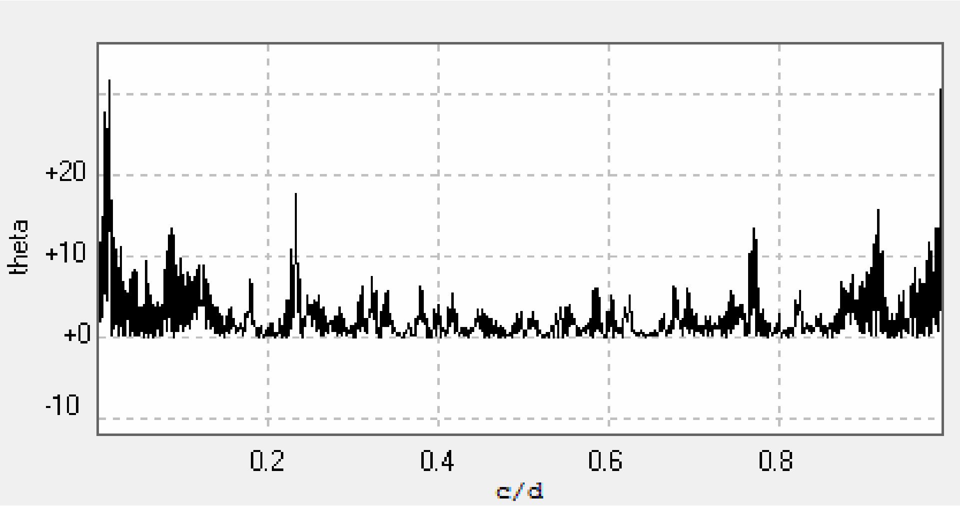

-0.02
-0.01
+0.00
+0.01
+0.02
mag
0
100
200
2454800.0+
JD

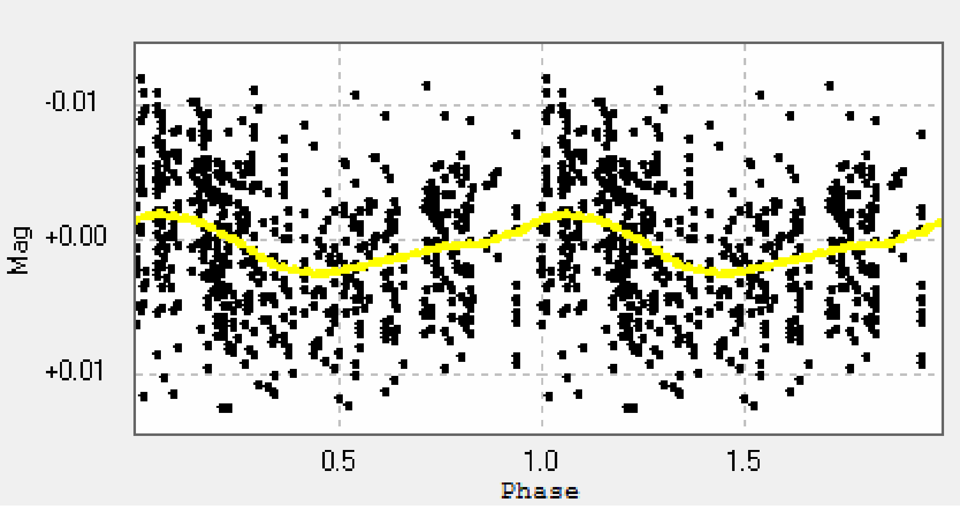

+40
+20
+0
-20
theta
0.2
0.4
0.6
0.8
c/d


-0.01
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

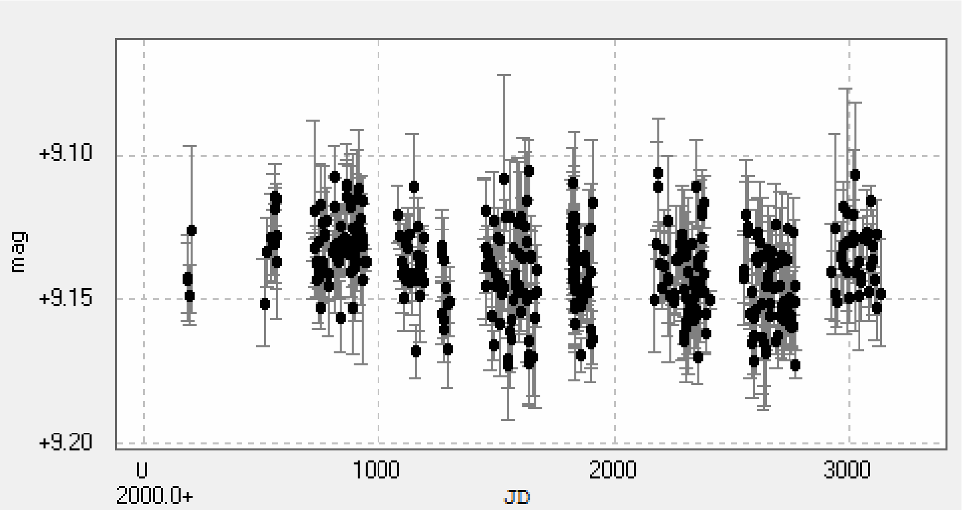
J19098+176


-0.01
+0.00
+0.01
mag
0
100
200
2454800.0+
JD

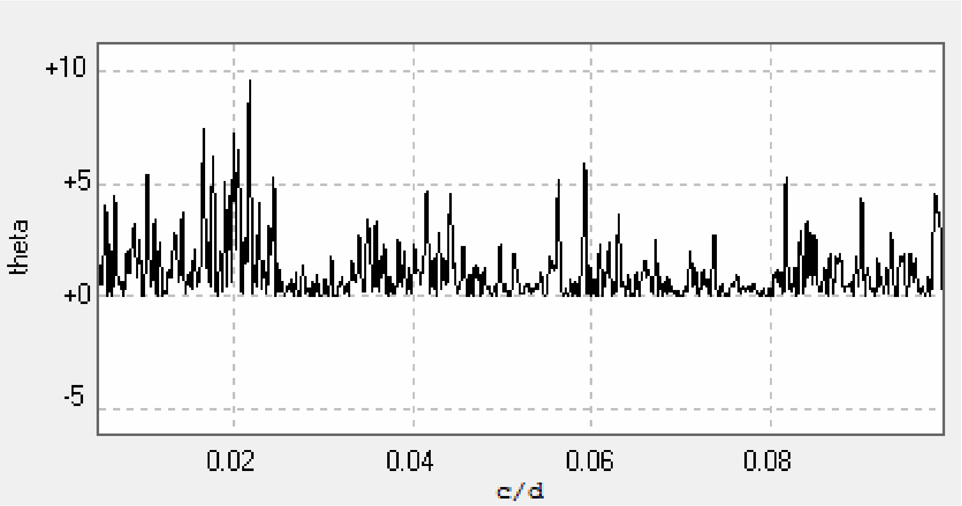

+20
+10
+0
-10
theta
0.2
0.4
0.6
0.8
c/d


-0.01
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

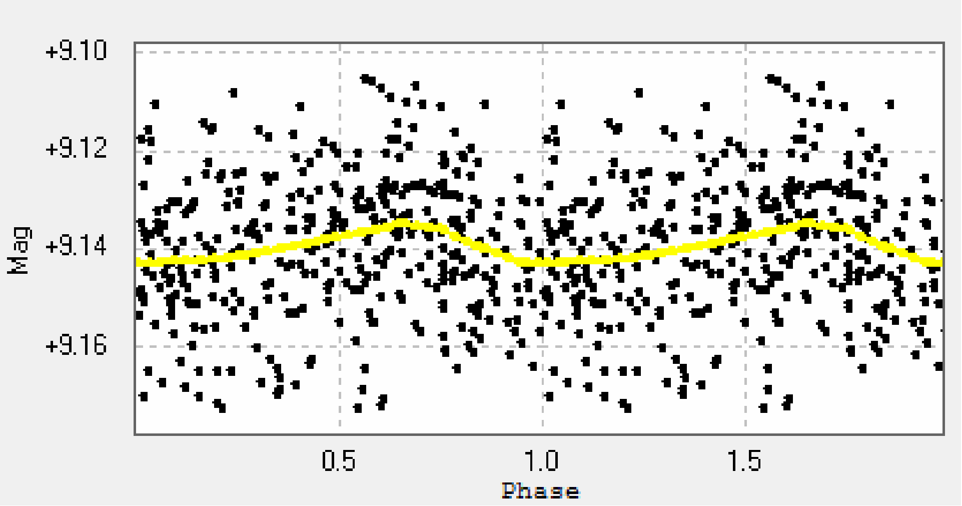
J19169+051N



mag
+9.10
+9.15
+9.20
0
2000.0+
1000
2000
3000
JD

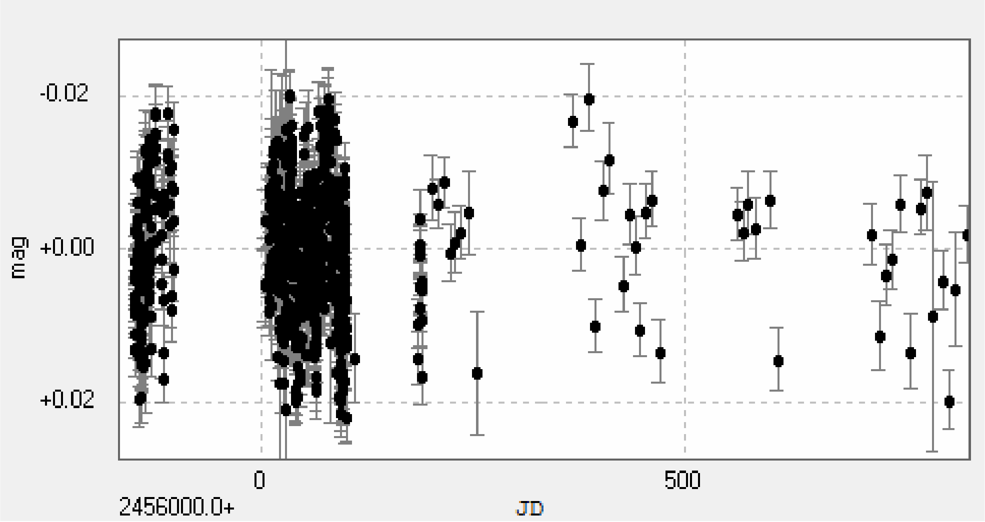


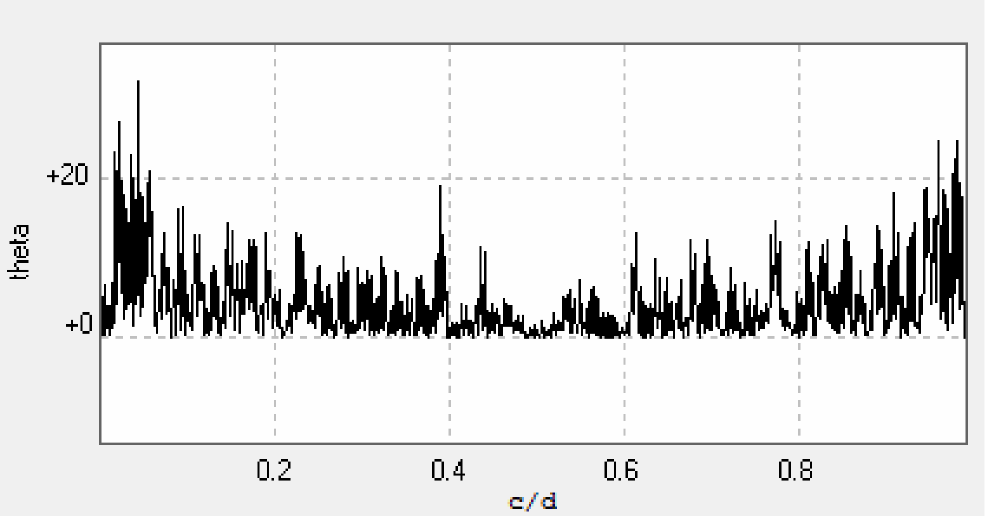
theta
+10
+5
+0
-5
0.02
0.04
0.06
0.08
c/d

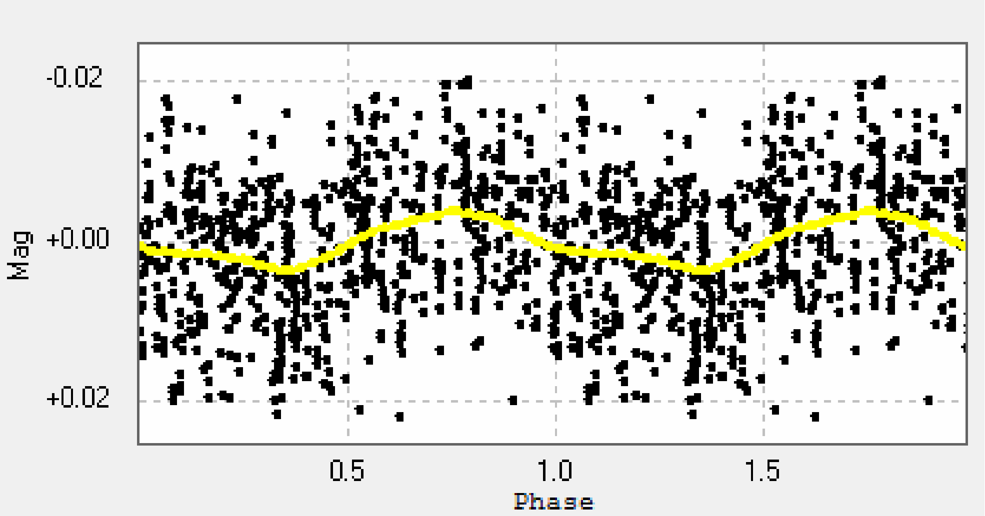


Mag
+9.10
+9.12
+9.14
+9.16
0.5
1.0
1.5
Phase

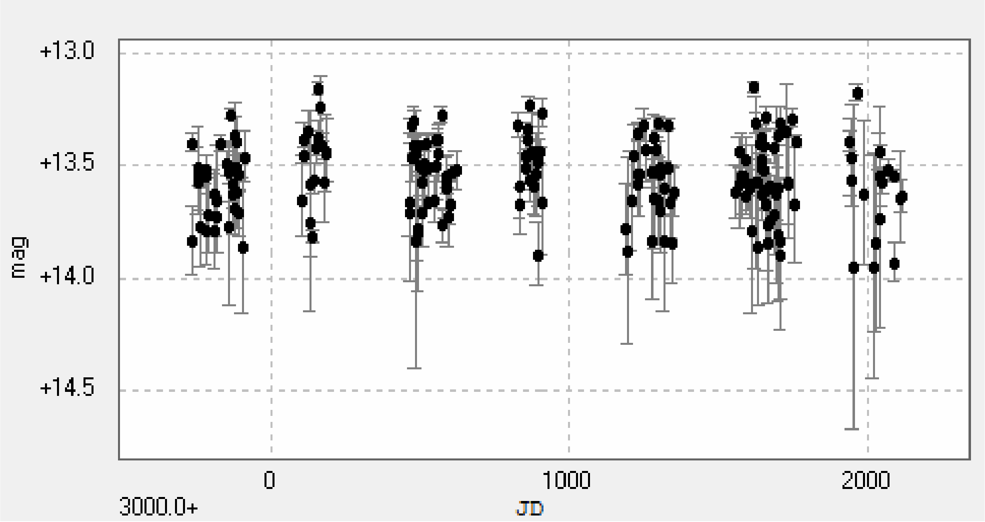
J19169+051S B

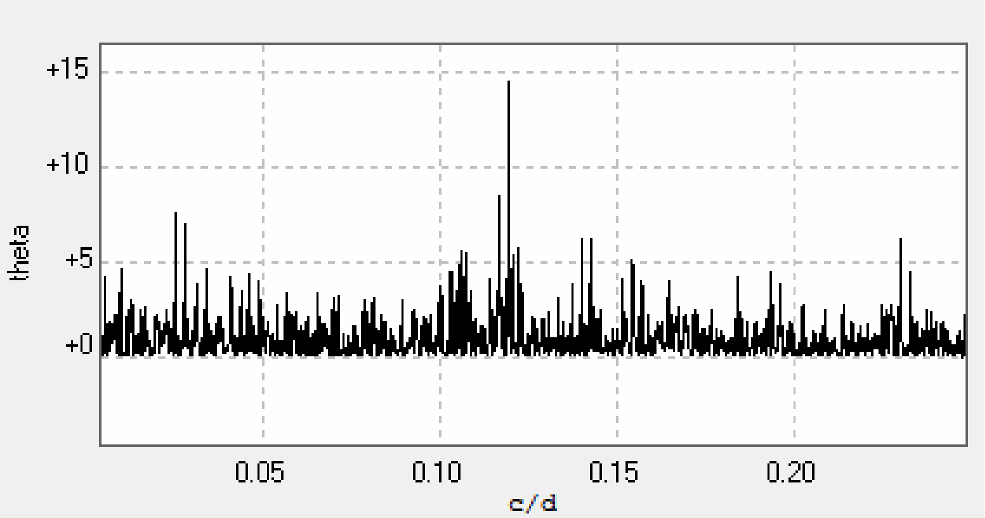


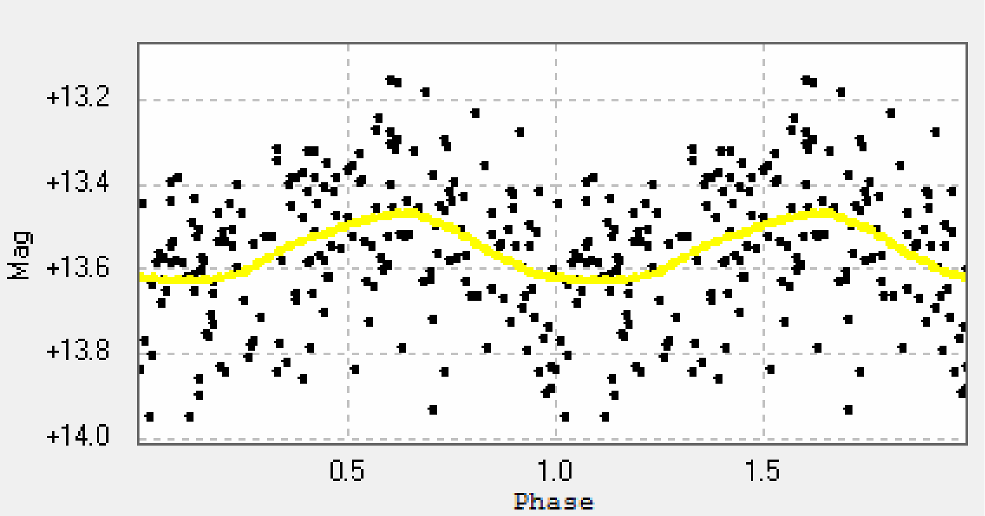




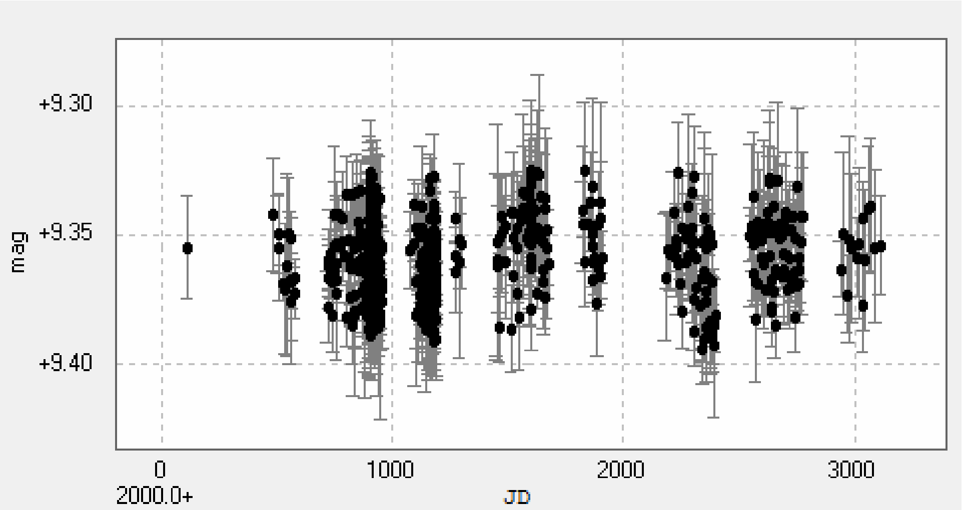
J19216+208


+13.0
+13.5
+14.0
+14.5
mag
0
1000
2000
3000.0+
JD

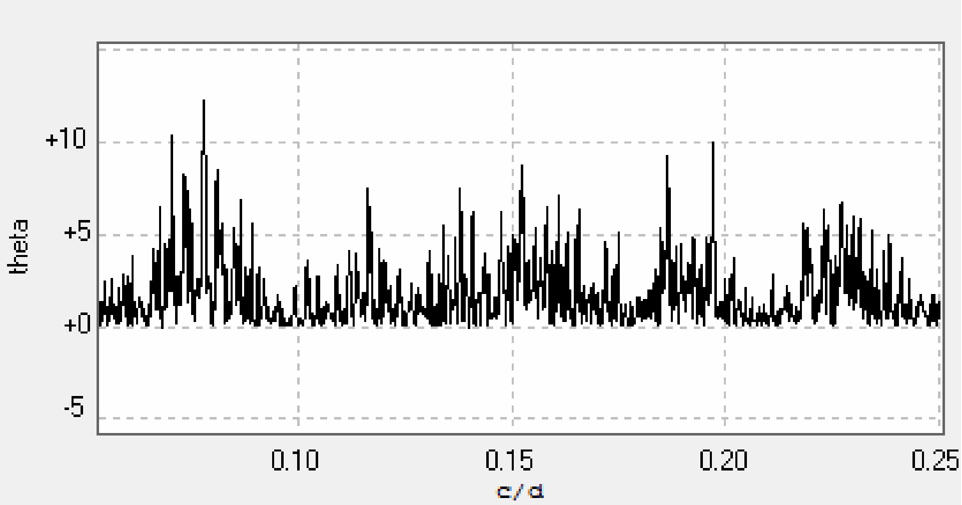

+15
+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d


+13.2
+13.4
+13.6
+13.8
+14.0
Mag
0.5
1.0
1.5
Phase

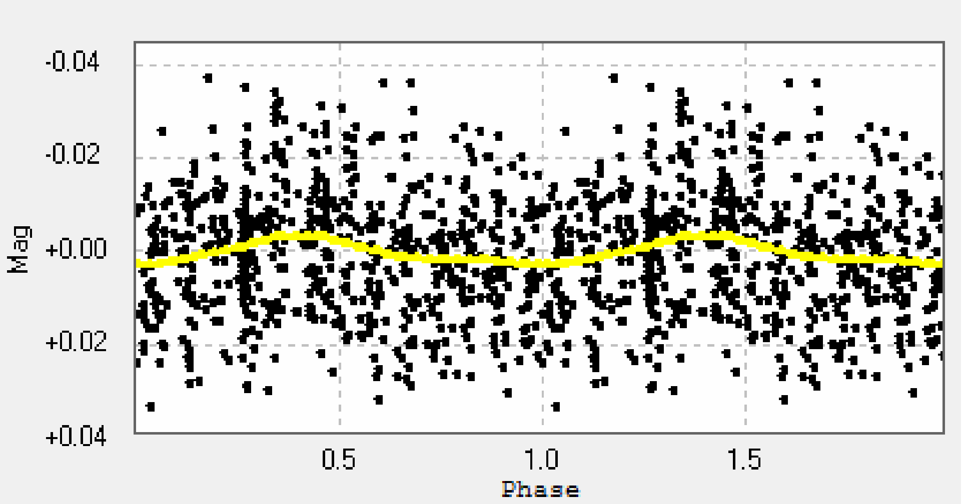
J19346+045



+9.30
+9.35
+9.40
mag
0
2000.0+
1000
2000
3000
JD

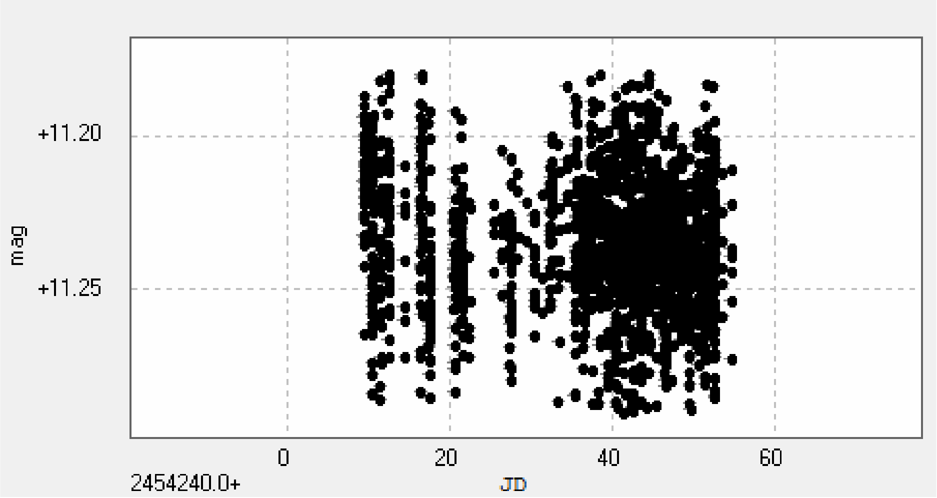


+10
+5
+0
-5
theta
0.10
0.15
0.20
0.25
c/d

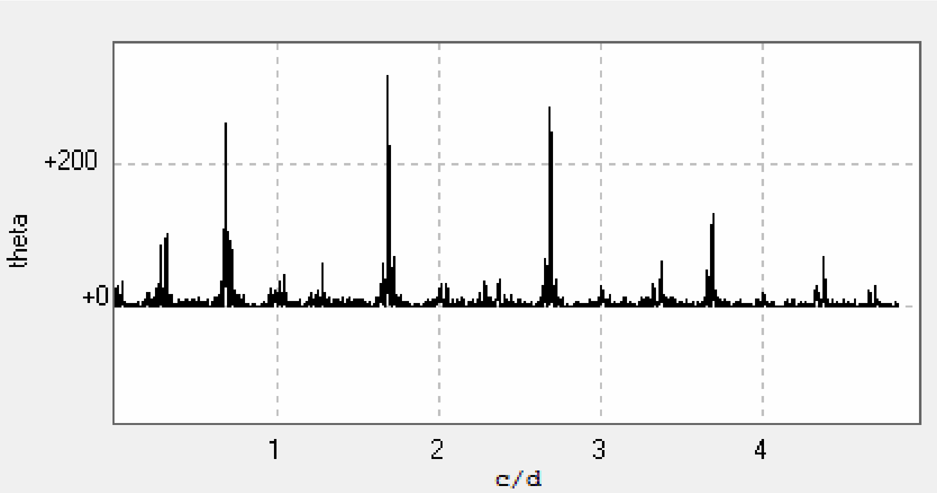


-0.04
-0.02
+0.00
+0.02
+0.04
Mag
0.5
1.0
1.5
Phase

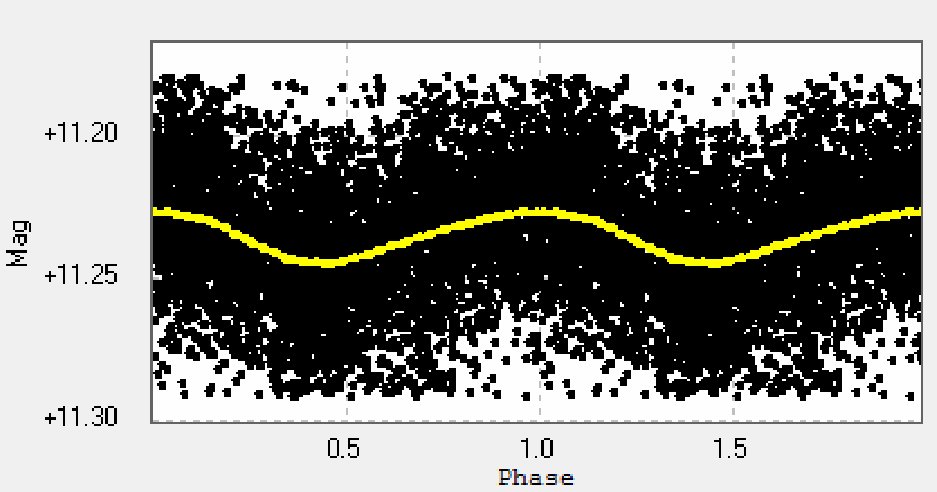
J19511+464



+11.20
+11.25
mag
0
20
40
60
2454240.0+
JD

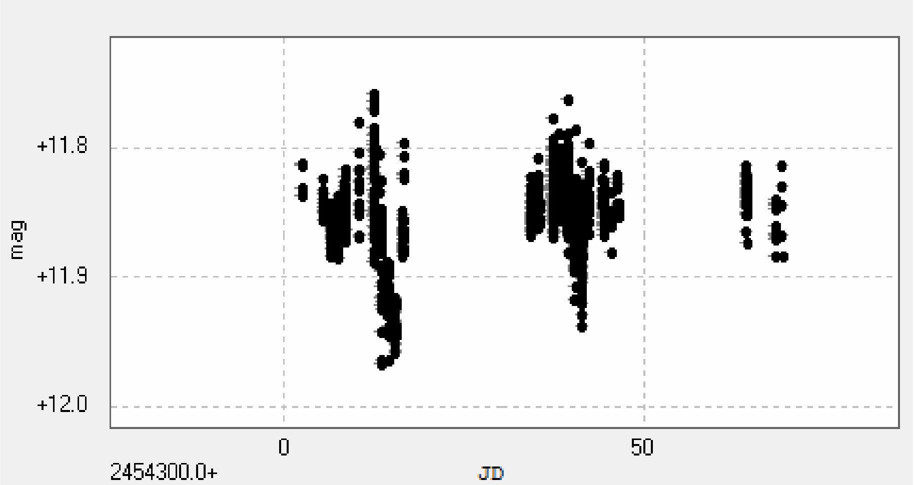


+200
+0
theta
1
2
3
4
c/d

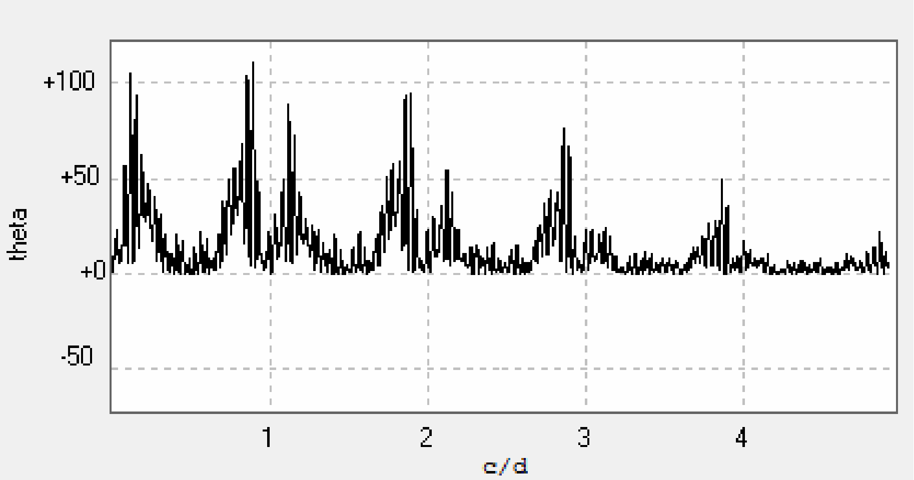


+11.20
+11.25
+11.30
Mag
0.5
1.0
1.5
Phase

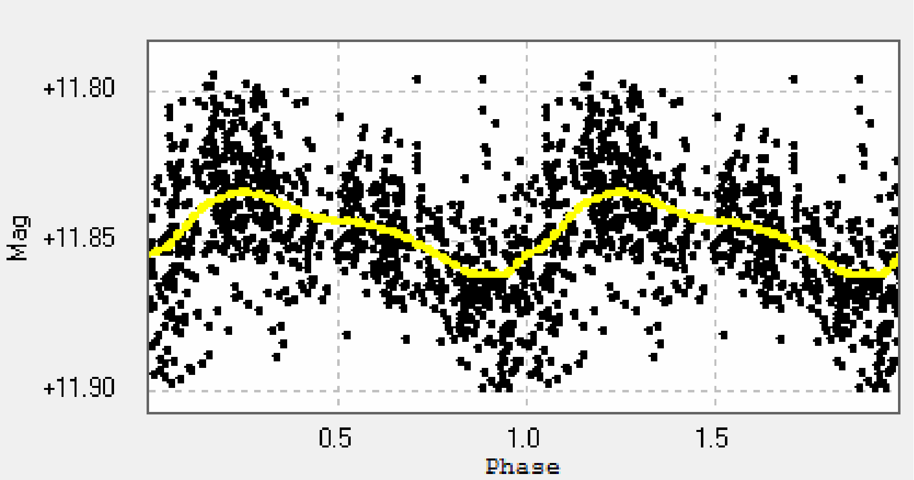
J20198+229



mag
+11.8
+11.9
+12.0
0
50
2454300.0+
JD

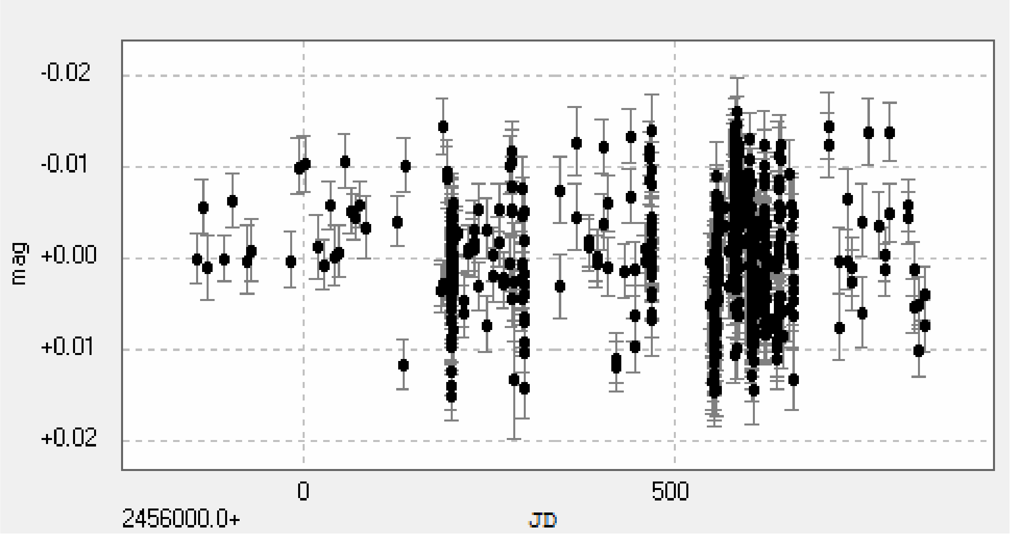


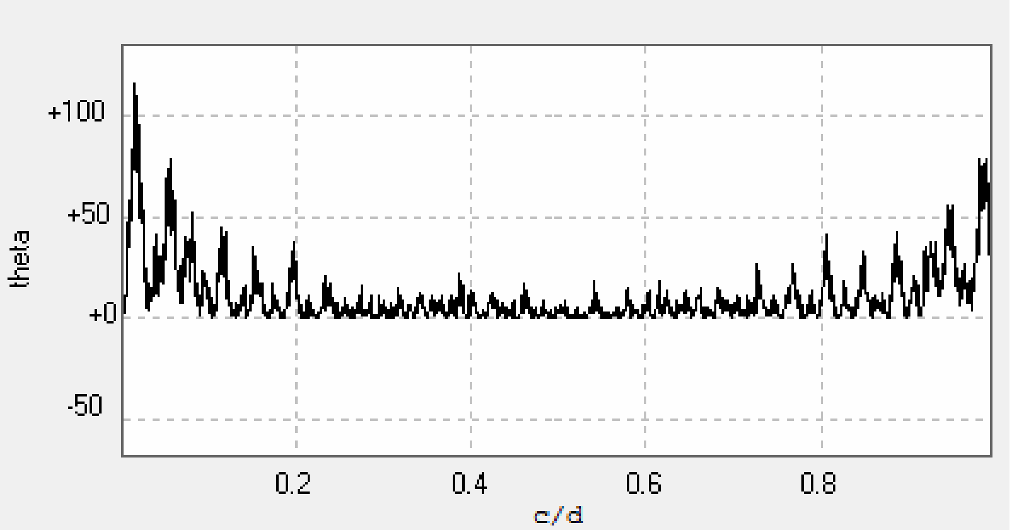
theta
+100
+50
+0
-50
1
2
3
4
c/d

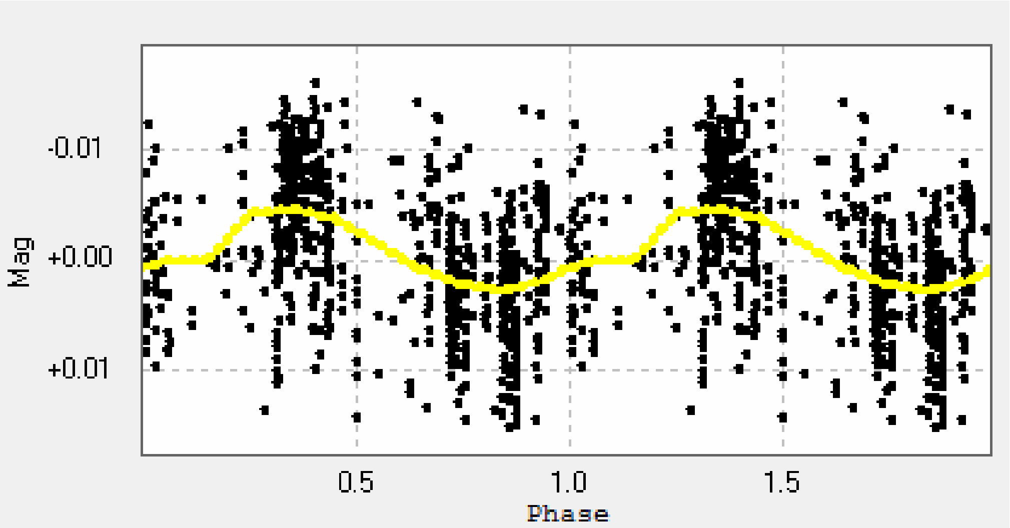


Mag
+11.80
+11.85
+11.90
0.5
1.0
1.5
Phase

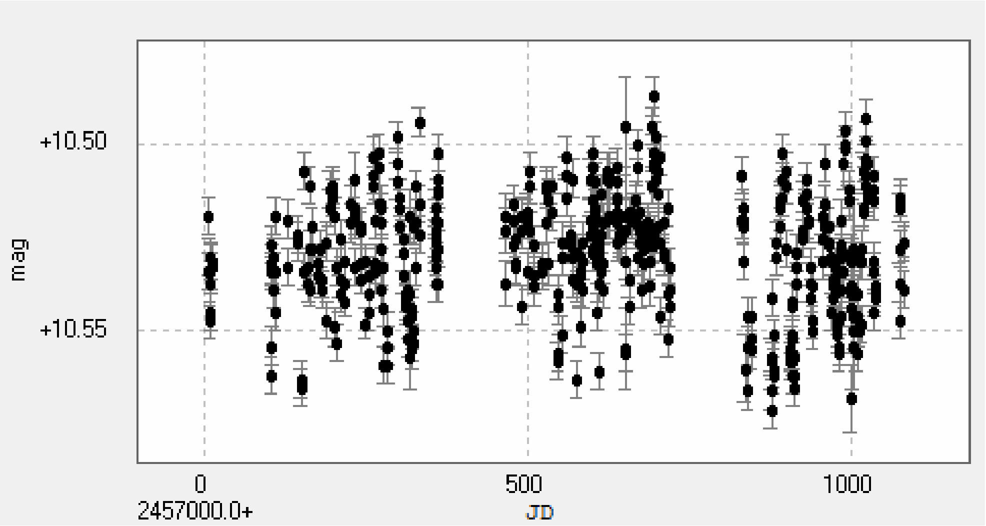
J20260+585

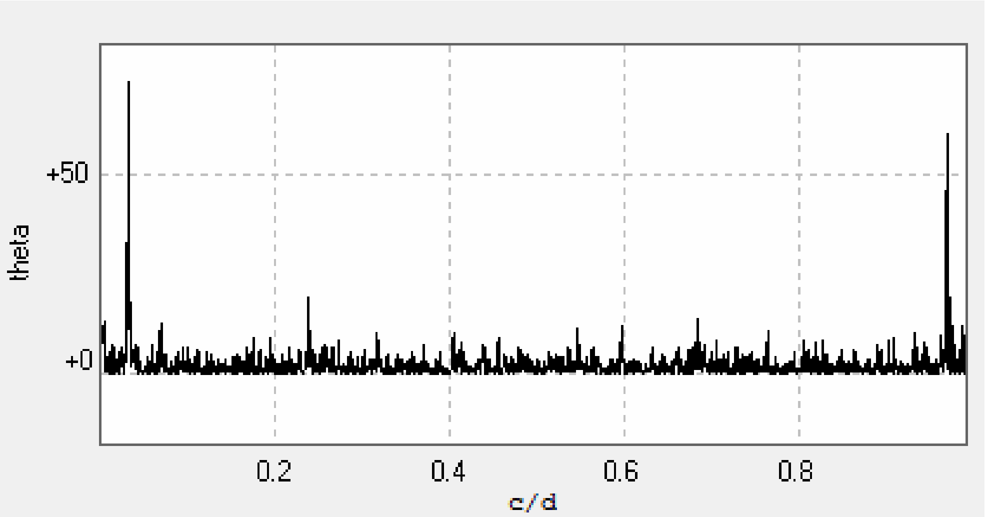

-0.02
-0.01
+0.00
+0.01
+0.02
mag
0
500
2456000.0+
JD

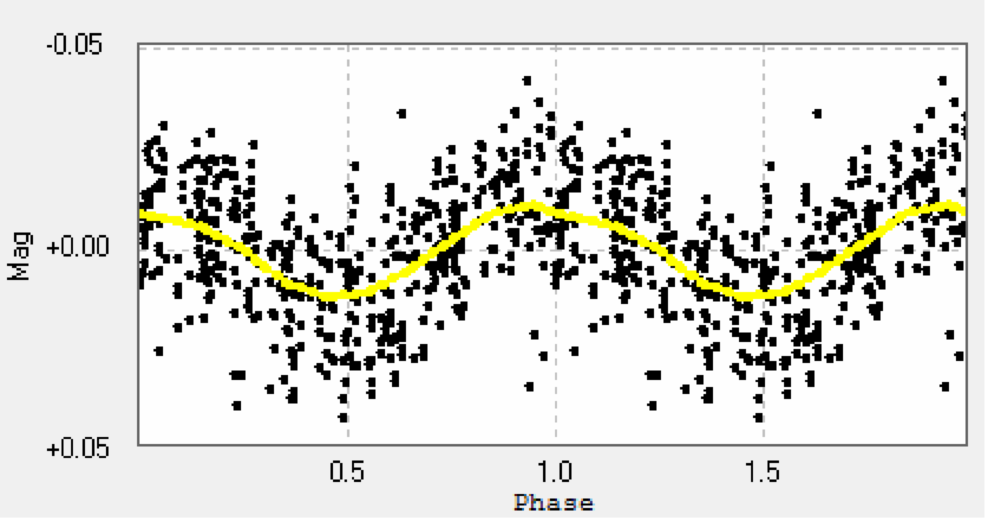

+100
+50
+0
-50
theta
0.2
0.4
0.6
0.8
c/d


-0.01
+0.00
+0.01
Mag
0.5
1.0
1.5
Phase

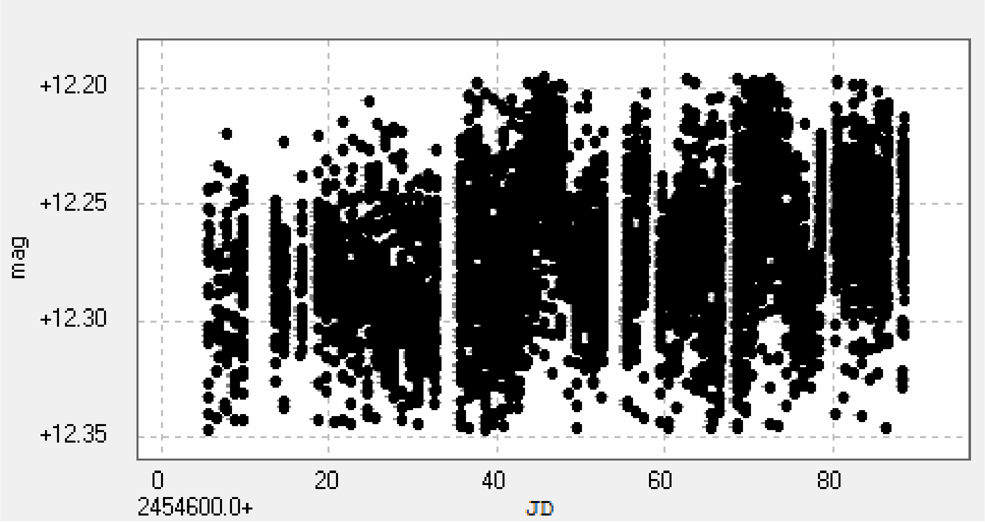
J20305+654

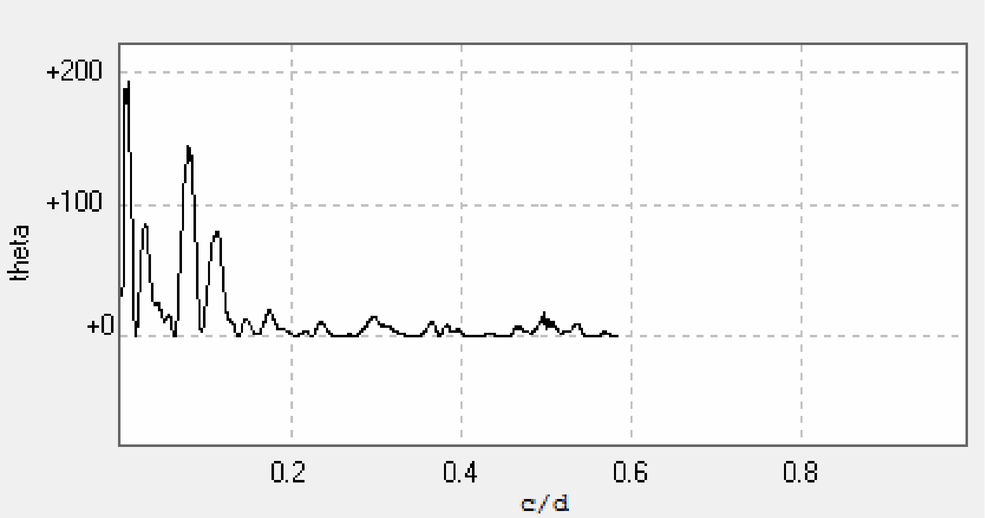

+10.50
+10.55
mag
0
500
1000
2457000.0+
JD

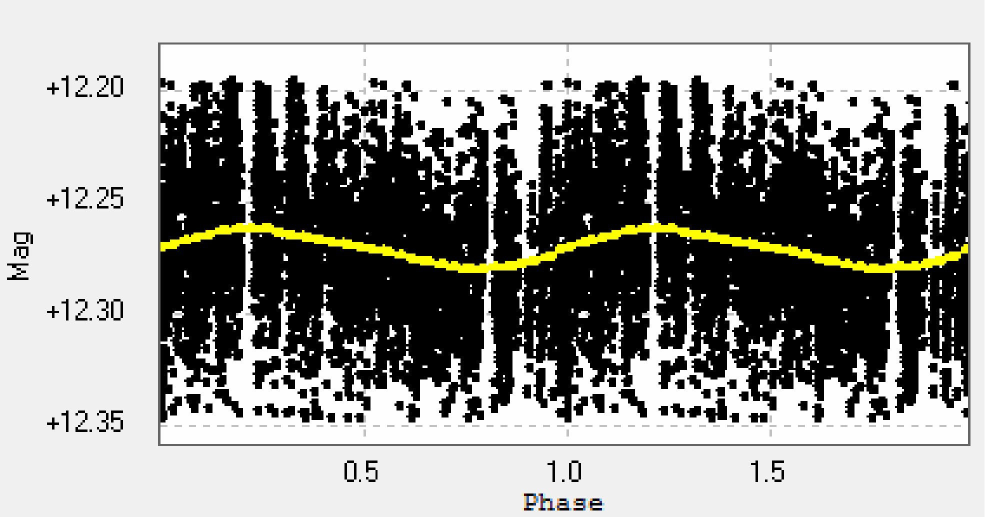

+50
+0
theta
0.2
0.4
0.6
0.8
c/d


-0.05
+0.00
+0.05
Mag
0.5
1.0
1.5
Phase

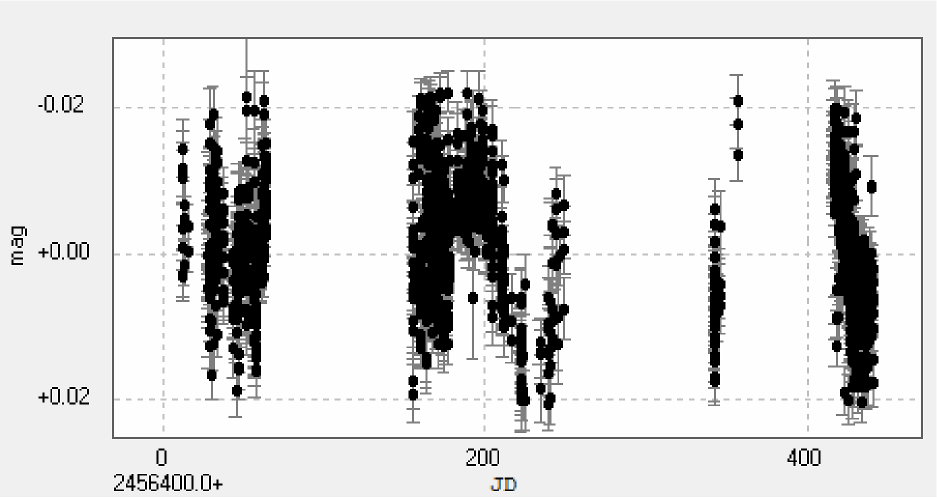
J20336+617


+12.20
+12.25
+12.30
+12.35
mag
0
20
40
60
80
2454600.0+
JD

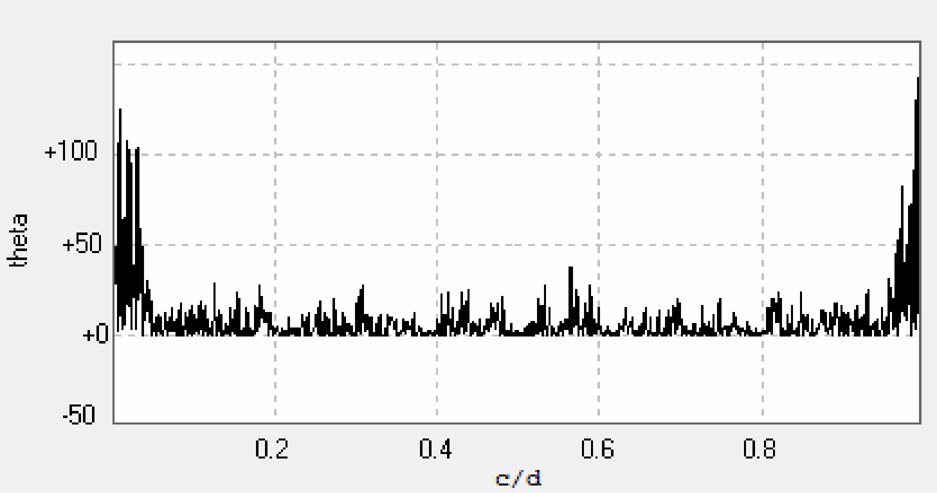

+200
+100
+0
theta
0.2
0.4
0.6
0.8
c/d


+12.20
+12.25
+12.30
+12.35
Mag
0.5
1.0
1.5
Phase

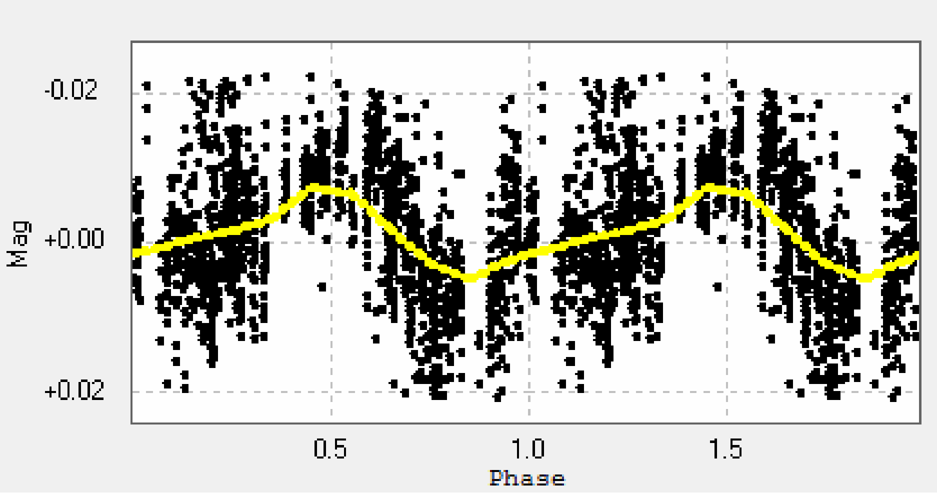
J20405+154



-0.02
+0.00
+0.02
mag
0
200
400
2456400.0+
JD

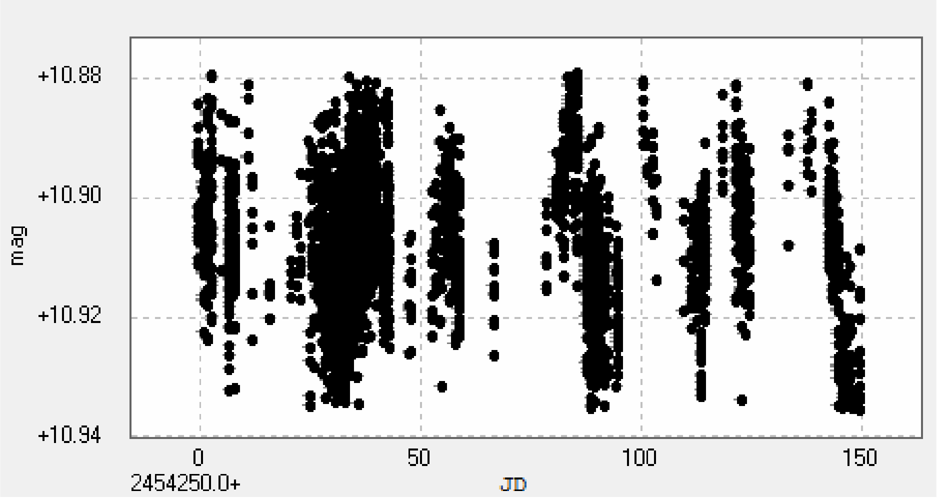


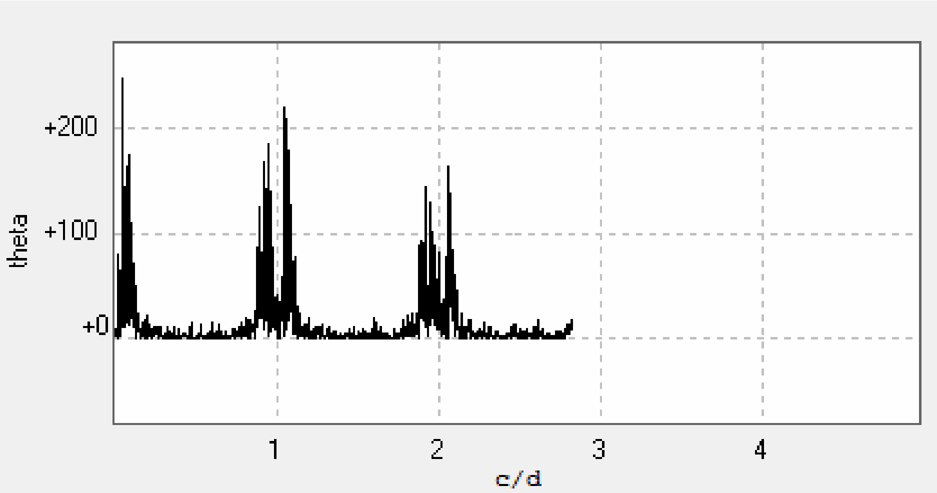
+100
+50
+0
-50
theta
0.2
0.4
0.6
0.8
c/d

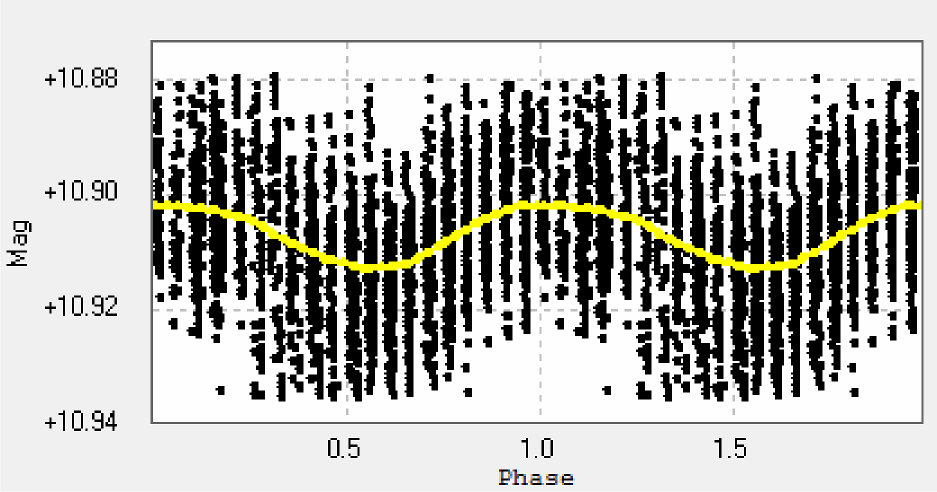


-0.02
+0.00
+0.02
Mag
0.5
1.0
1.5
Phase

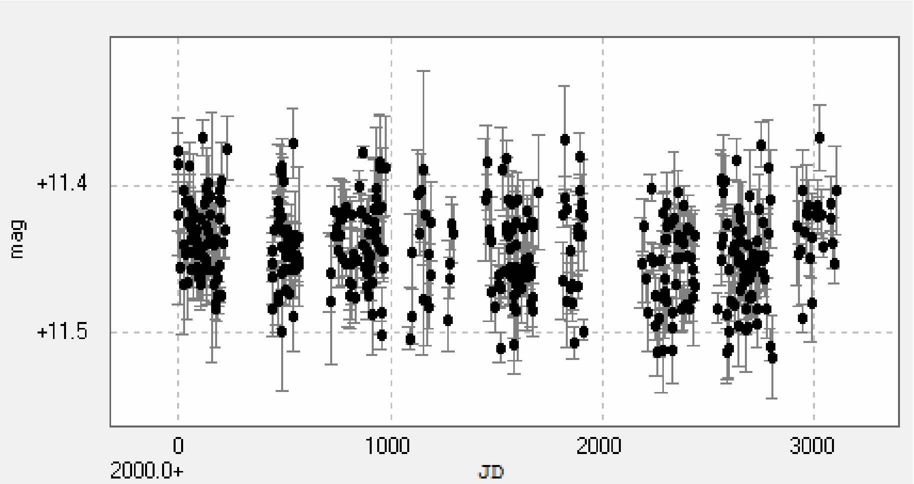
J20450+444

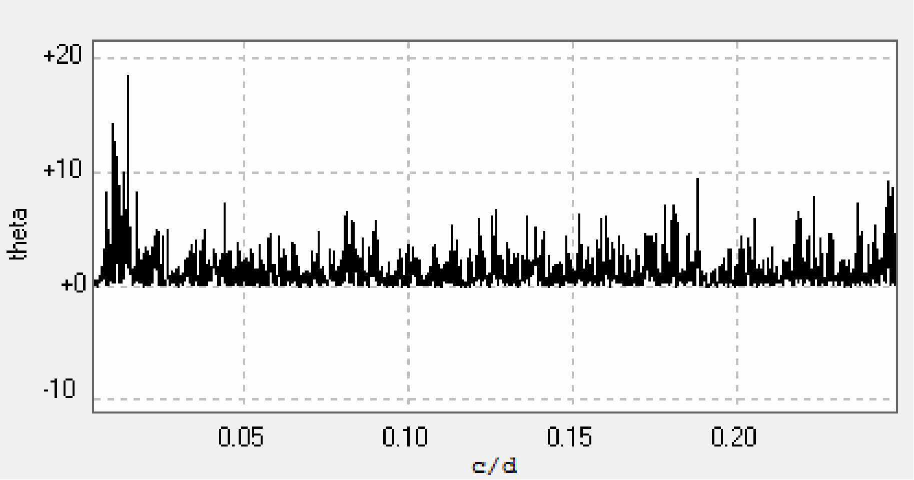

+10.88
+10.90
+10.92
+10.94
mag
0
50
100
150
2454250.0+
JD

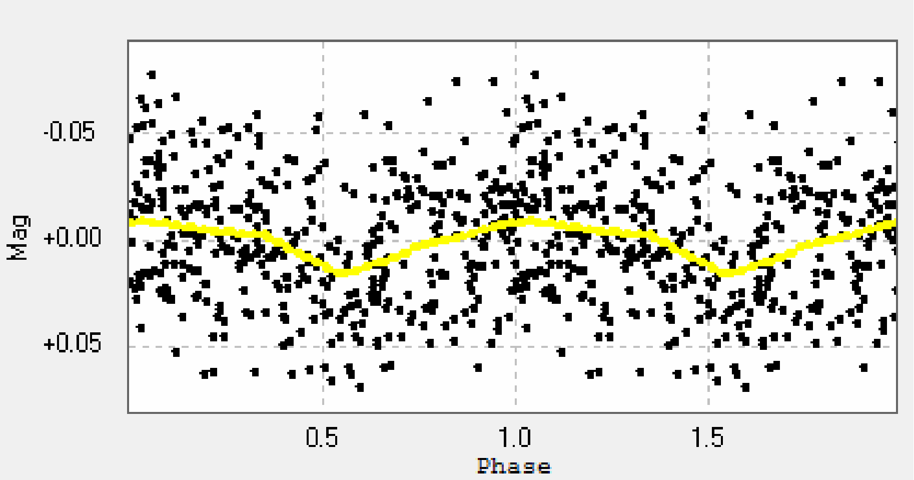

+200
+100
+0
theta
1
2
3
4
c/d


+10.88
+10.90
+10.92
+10.94
Mag
0.5
1.0
1.5
Phase

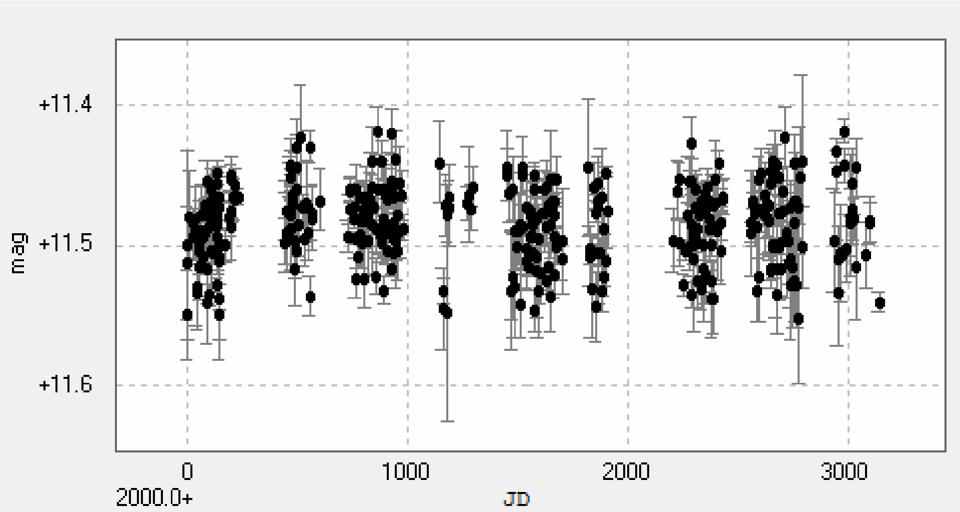
J20525-169


+11.4
mag
+11.5
0
1000
2000
3000
2000.0+
JD

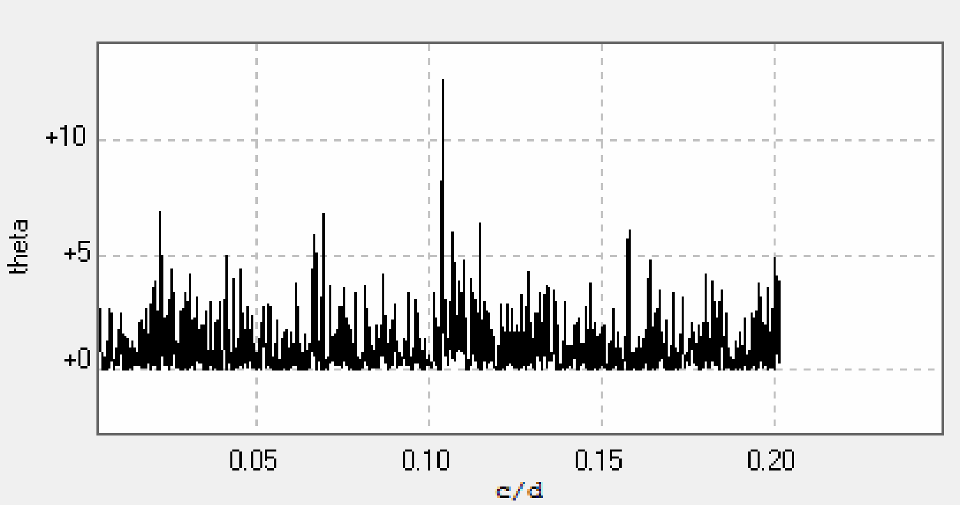

+20
+10
theta
+0
-10
0.05
0.10
0.15
0.20
c/d


-0.05
Mag
+0.00
+0.05
0.5
1.0
1.5
Phase

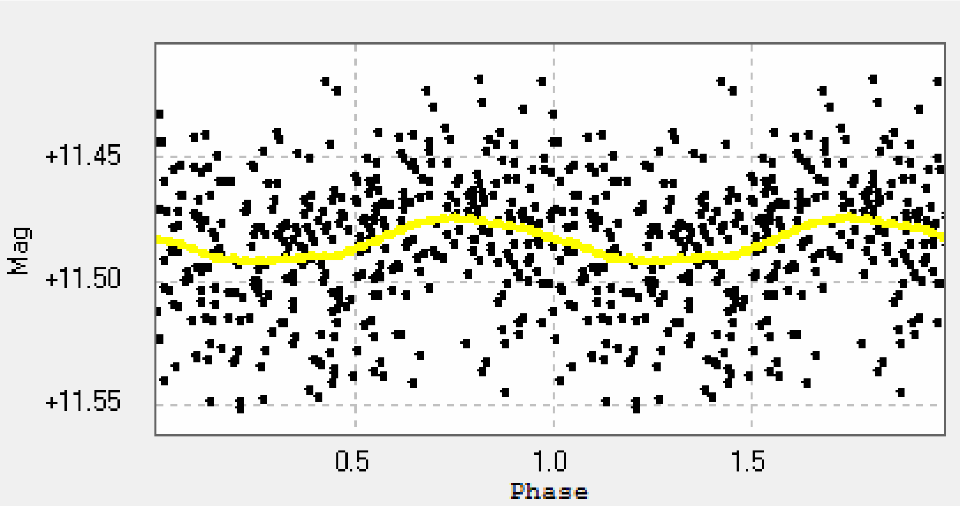
J20567-104



mag
+11.4
+11.5
+11.6
0
1000
2000
3000
2000.0+
JD

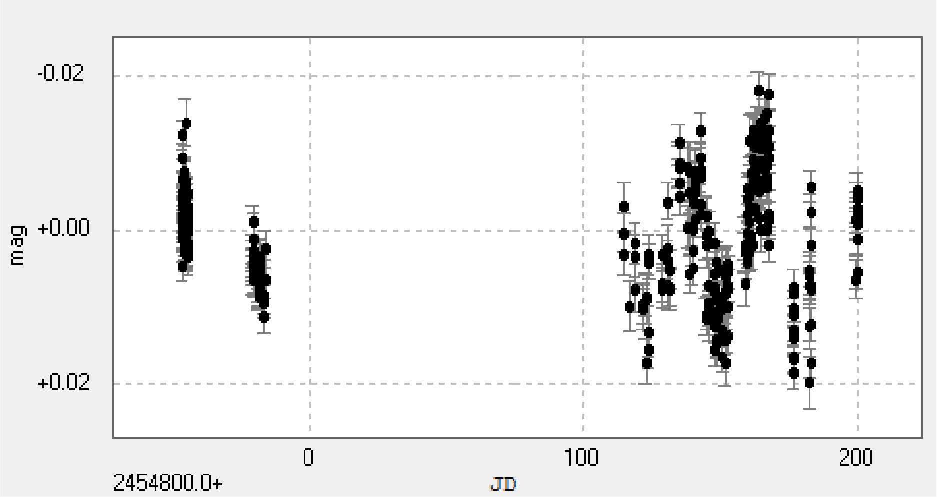


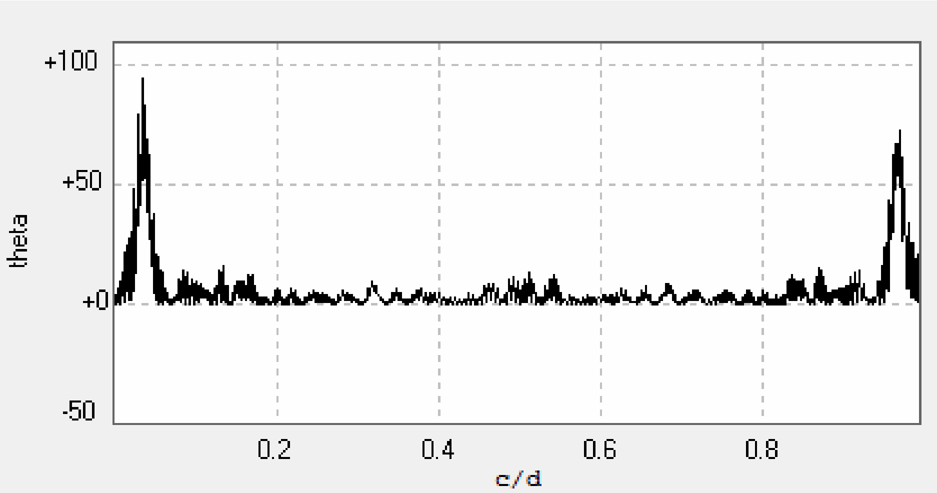
theta
+10
+5
+0
0.05
0.10
0.15
0.20
c/d

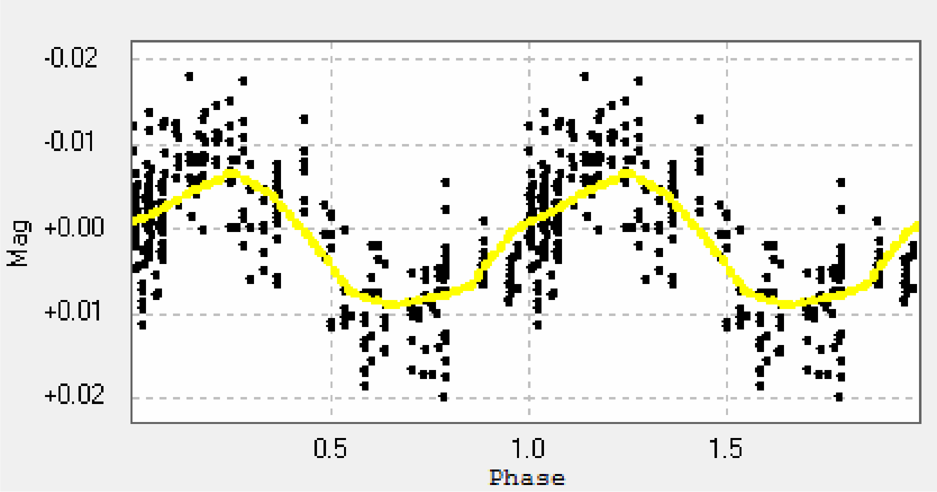


Mag
+11.45
+11.50
+11.55
0.5
1.0
1.5
Phase

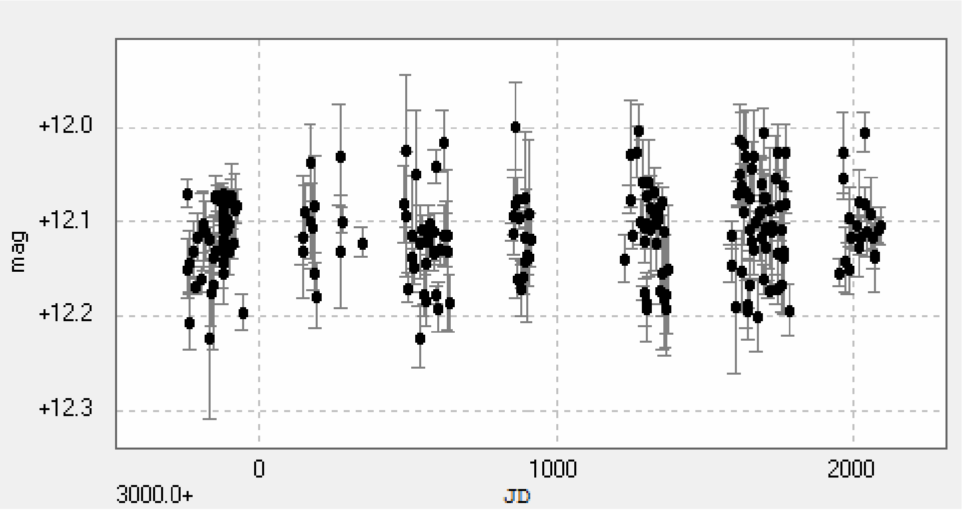
J21012+332


-0.02
+0.00
+0.02
mag
0
100
200
2454800.0+
JD

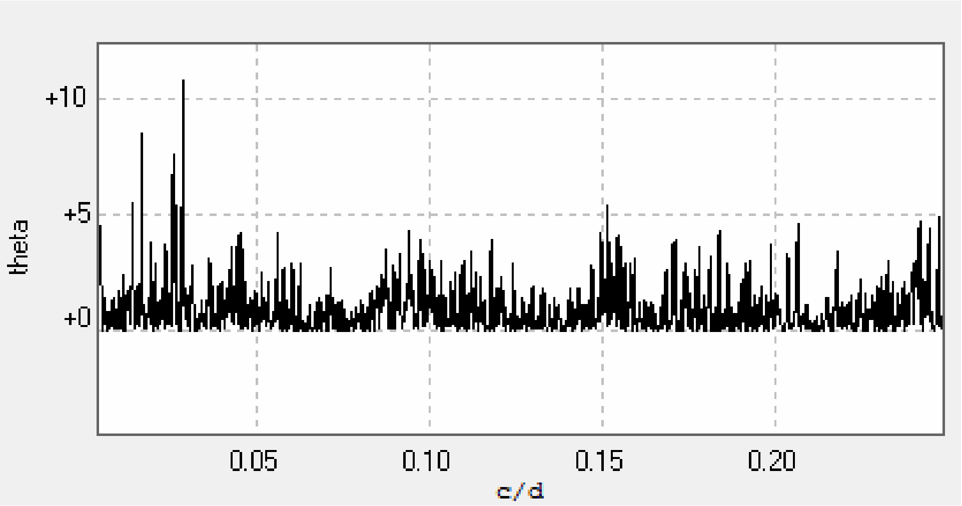

+100
+50
+0
-50
theta
0.2
0.4
0.6
0.8
c/d


-0.02
-0.01
+0.00
+0.01
+0.02
Mag
0.5
1.0
1.5
Phase

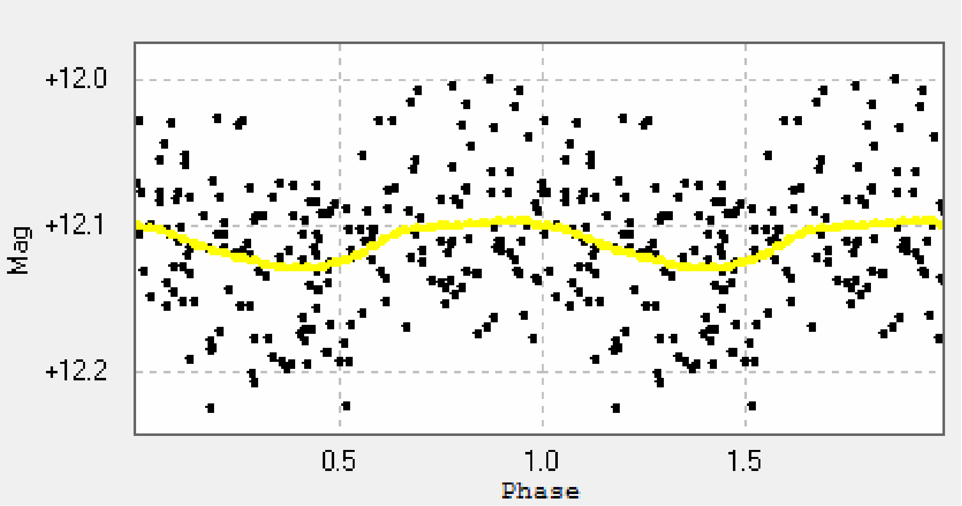
J21152+257



+12.0
+12.1
+12.2
+12.3
mag
0
1000
2000
3000.0+
JD

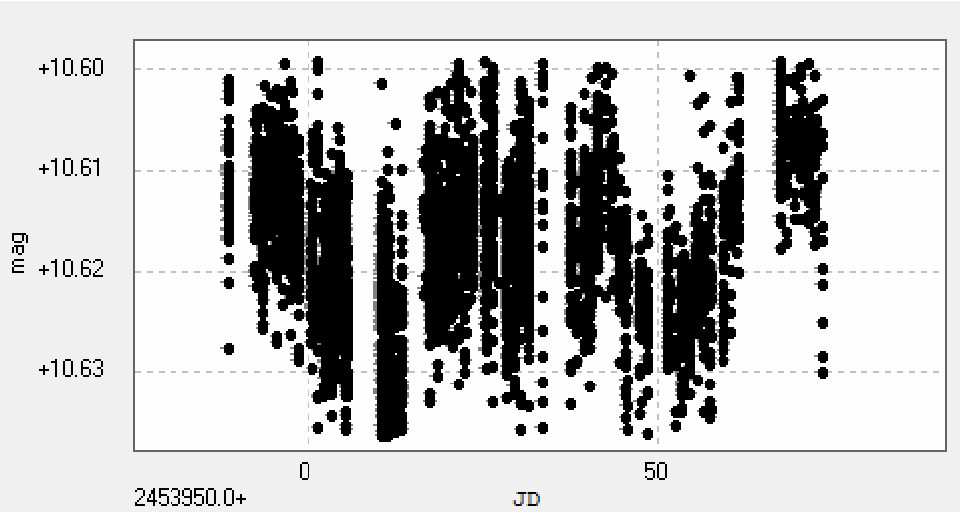


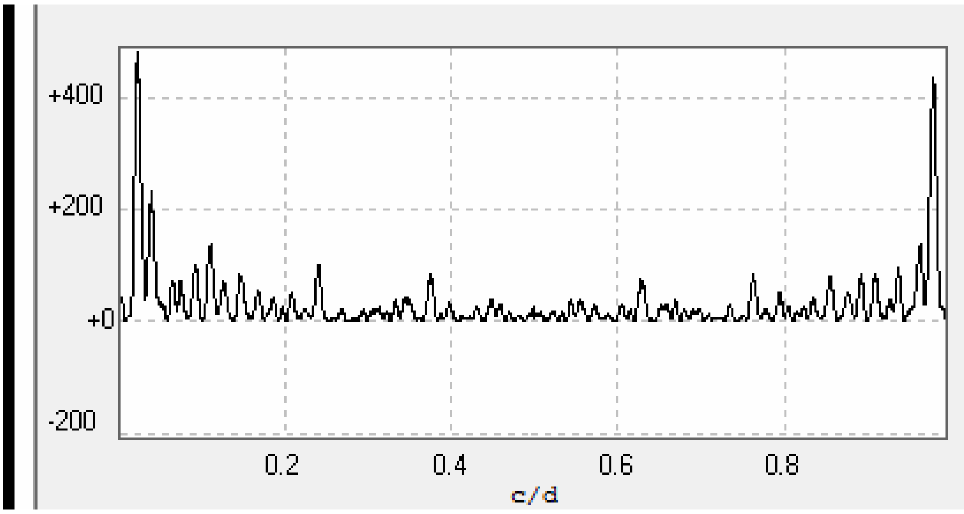
+10
+5
+0
theta
0.05
0.10
0.15
0.20
c/d

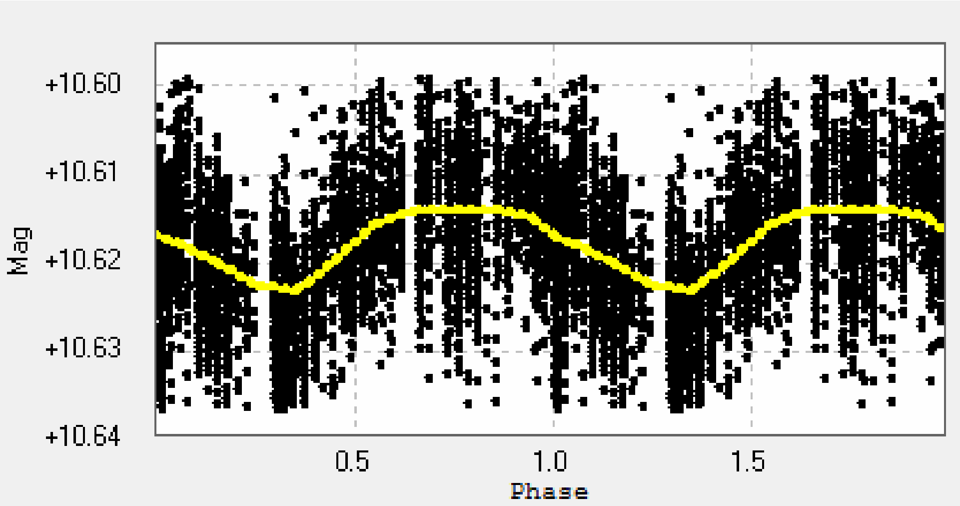


+12.0
+12.1
+12.2
Mag
0.5
1.0
1.5
Phase

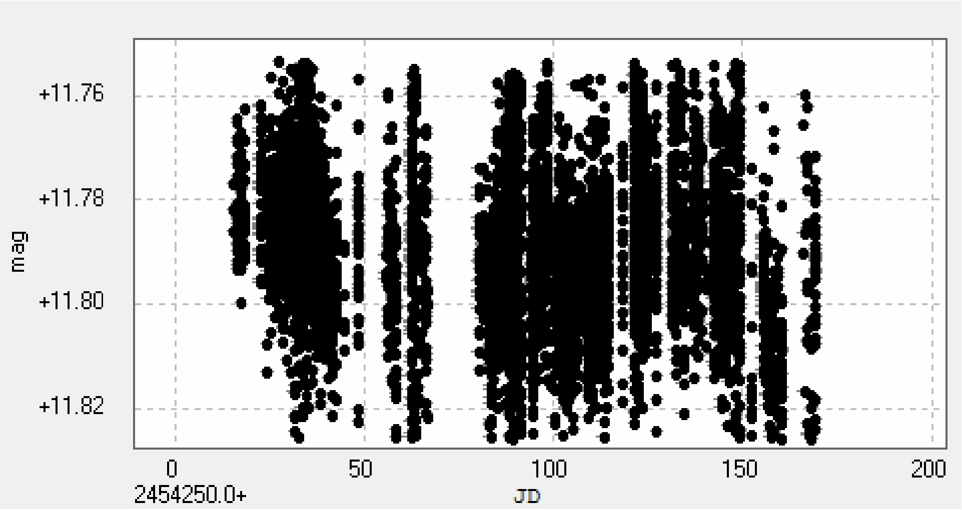
J21221+229

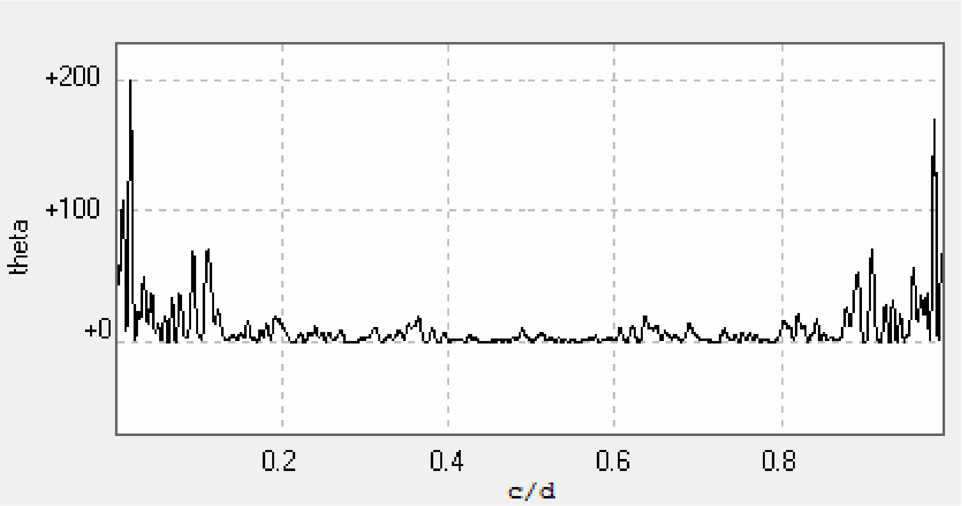

+10.60
+10.61
+10.62
+10.63
mag
0
50
2453950.0+
JD

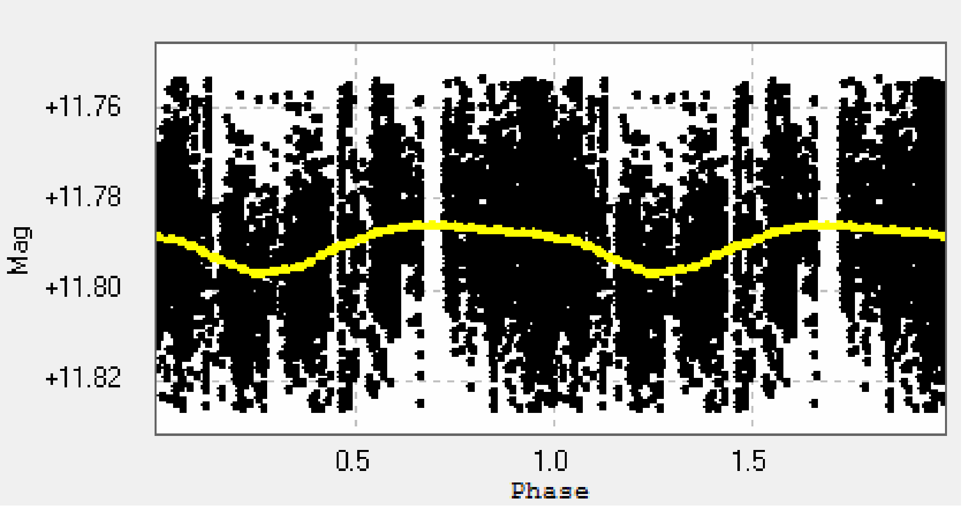

+400
+200
+0
-200
0.2
0.4
0.6
0.8
c/d


+10.60
+10.61
+10.62
+10.63
+10.64
Mag
0.5
1.0
1.5
Phase

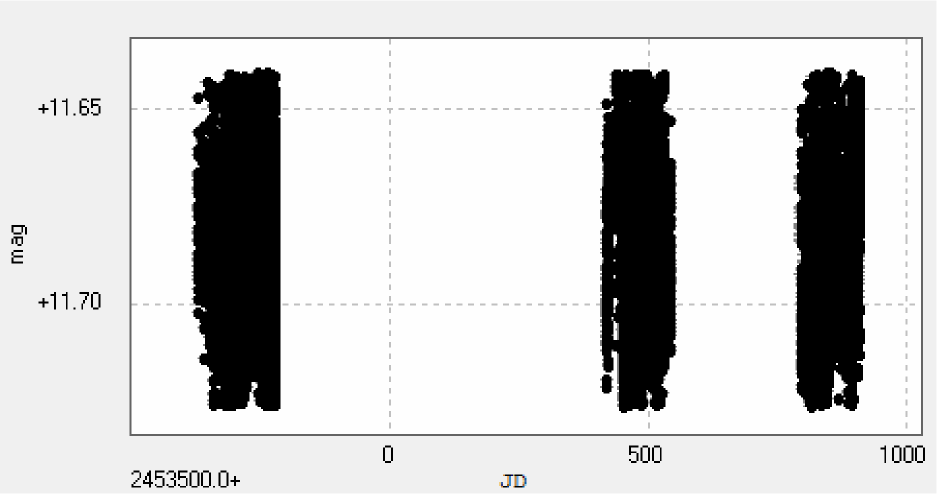
J21348+515

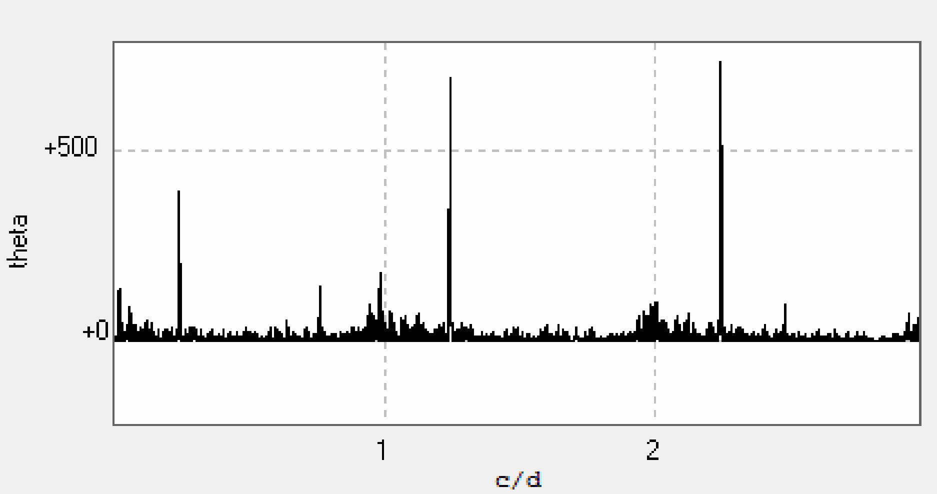

+11.76
+11.78
+11.80
+11.82
mag
0
50
100
150
200
2454250.0+
JD

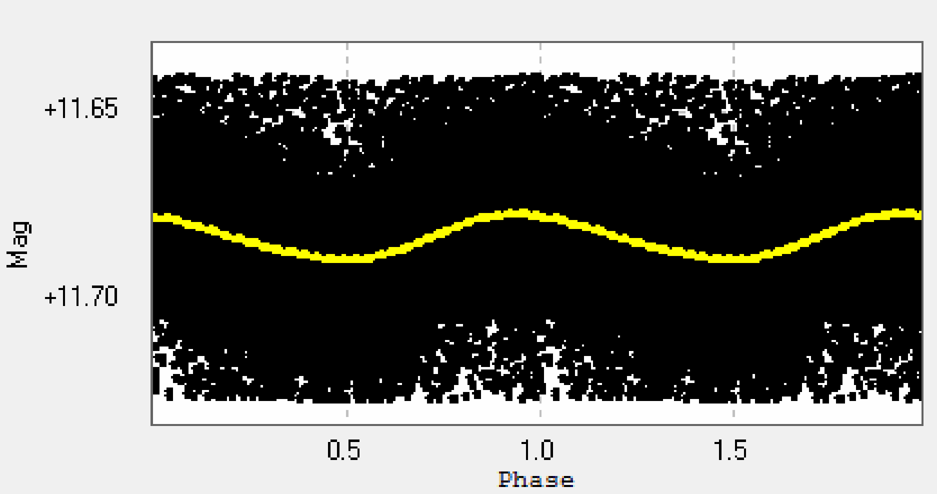

+200
+100
+0
theta
0.2
0.4
0.6
0.8
c/d


+11.76
+11.78
+11.80
+11.82
Mag
0.5
1.0
1.5
Phase

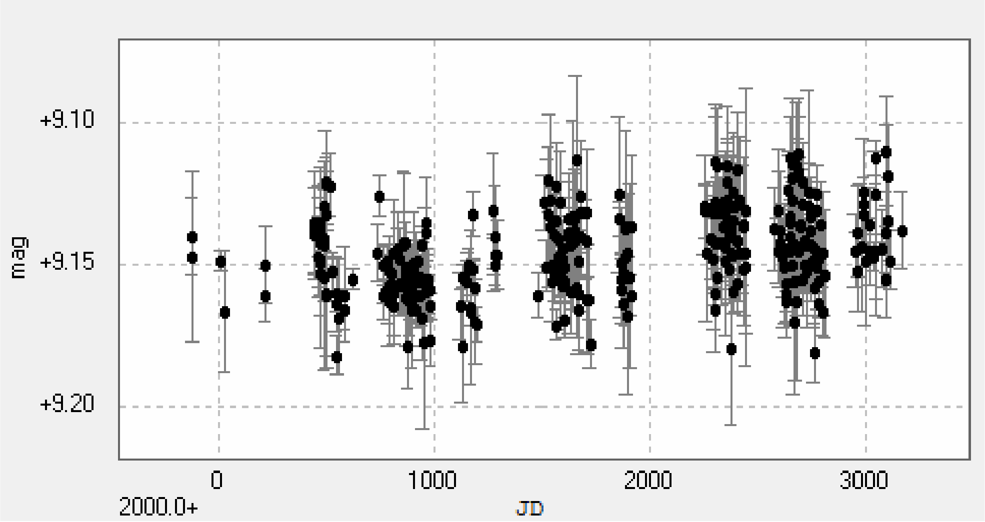
J22012+283

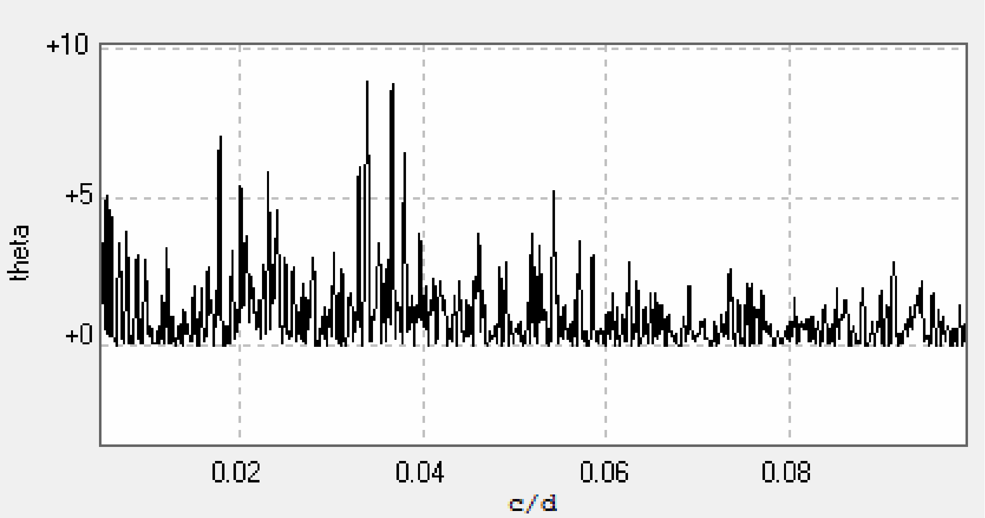

+11.65
+11.70
mag
0
500
1000
2453500.0+
JD

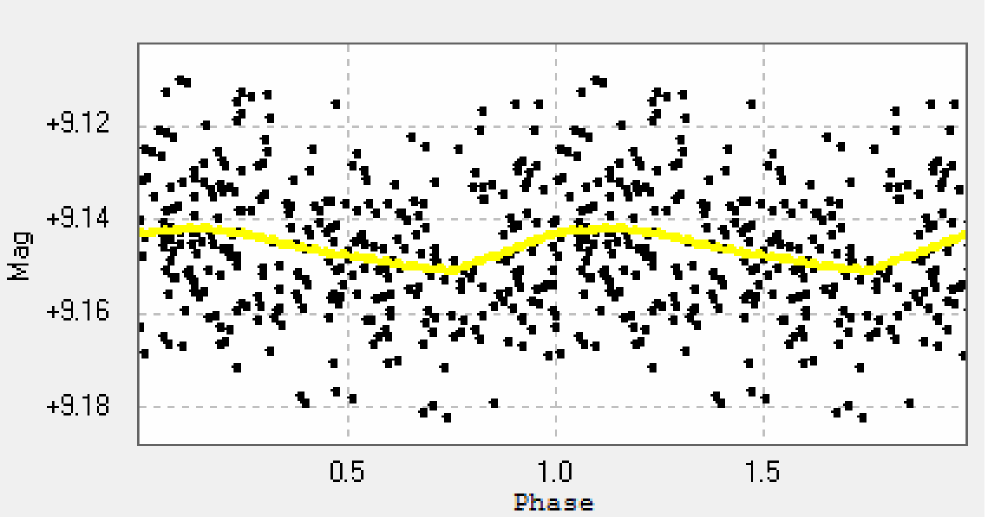

+500
+0
theta
1
2
c/d


+11.65
+11.70
Mag
0.5
1.0
1.5
Phase

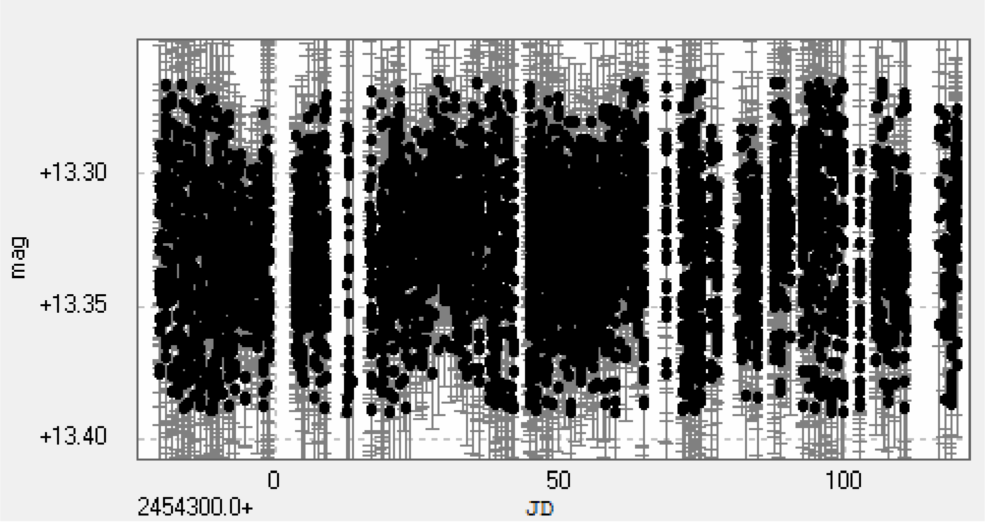
J22021+014

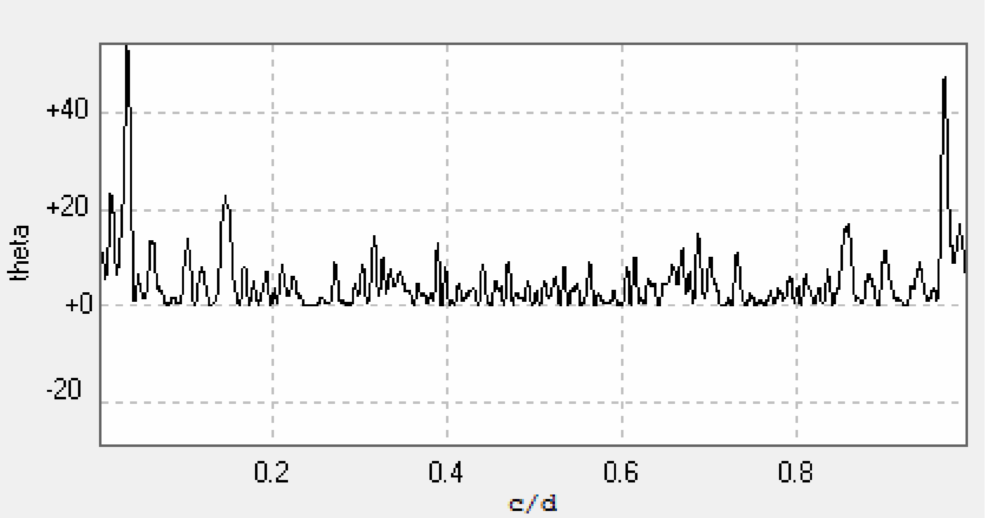

+9.10
+9.15
+9.20
mag
0
1000
2000
3000
2000.0+
JD

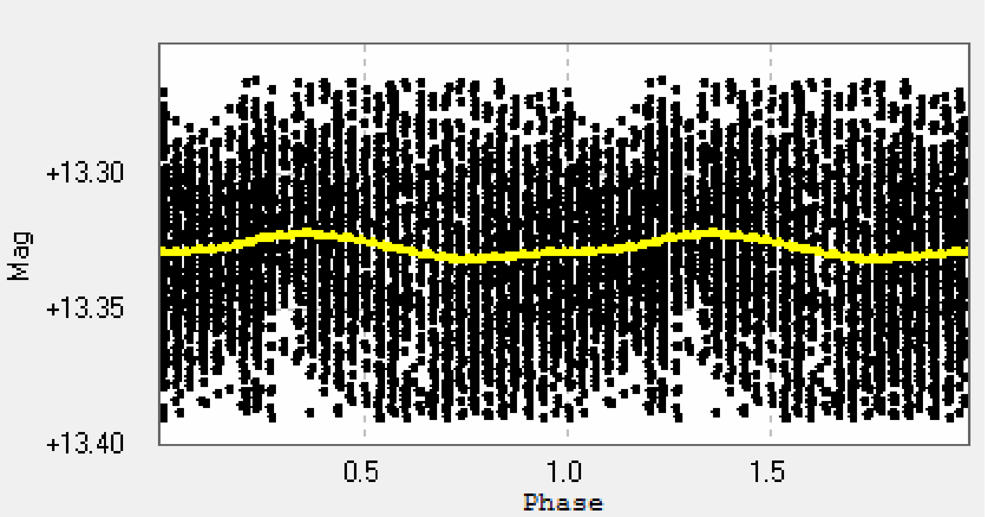

+10
+5
+0
theta
0.02
0.04
0.06
0.08
c/d


+9.12
+9.14
+9.16
+9.18
Mag
0.5
1.0
1.5
Phase

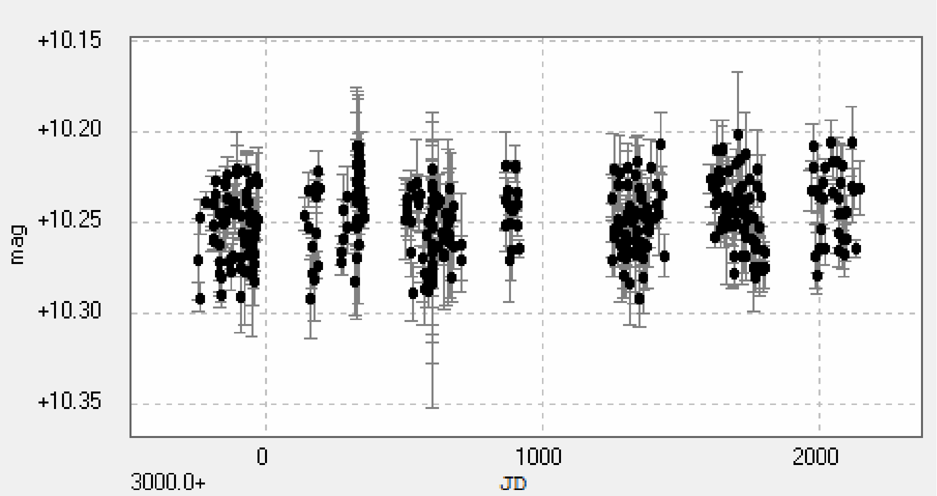
J22114+409

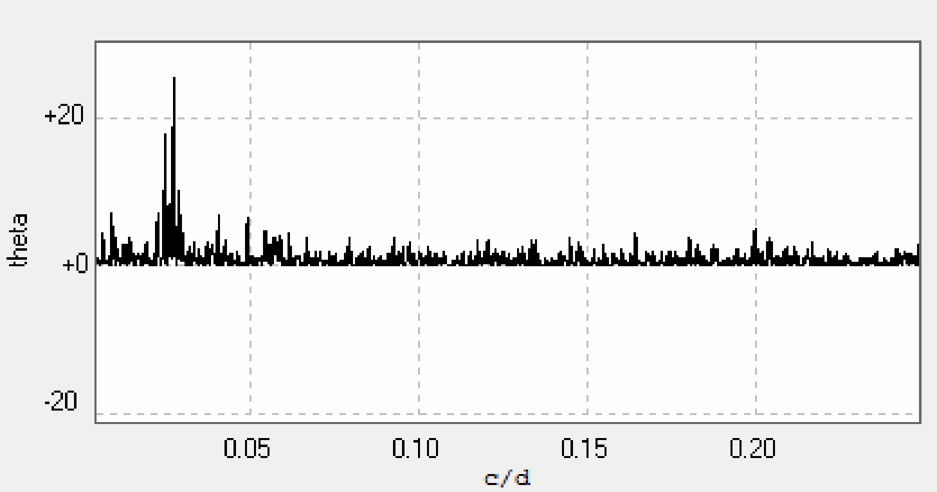

mag
+13.30
+13.35
+13.40
0
50
100
2454300.0+
JD

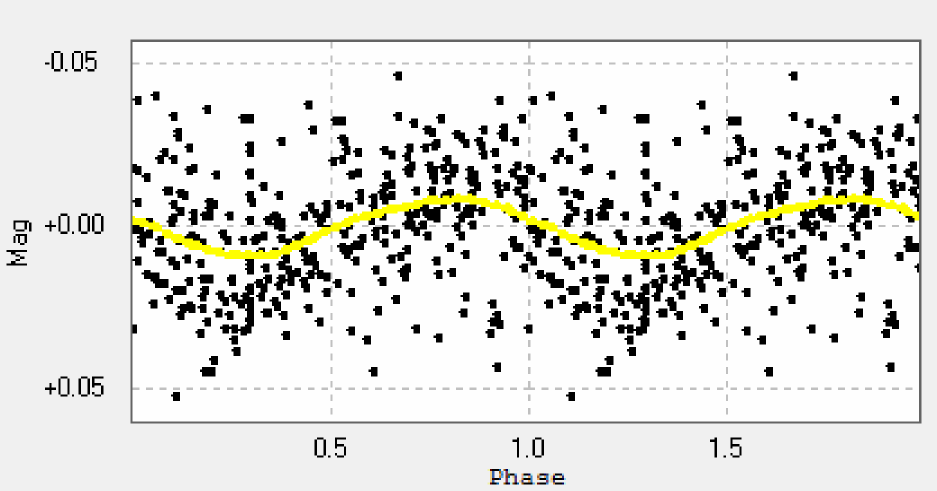

theta
+40
+20
+0
-20
0.2
0.4
0.6
0.8
c/d


Mag
+13.30
+13.35
+13.40
0.5
1.0
1.5
Phase

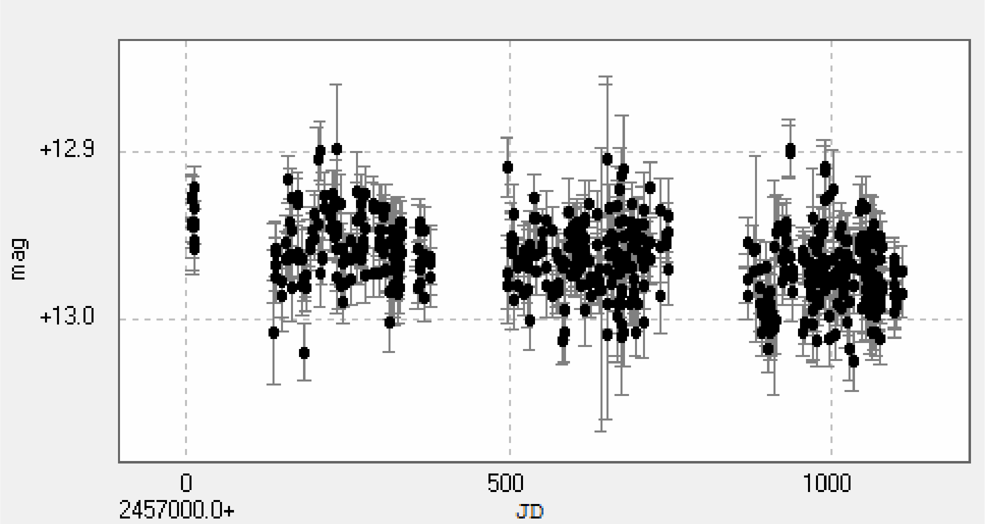
J22115+184


+10.15
+10.20
+10.25
+10.30
+10.35
mag
0
1000
2000
3000.0+
JD

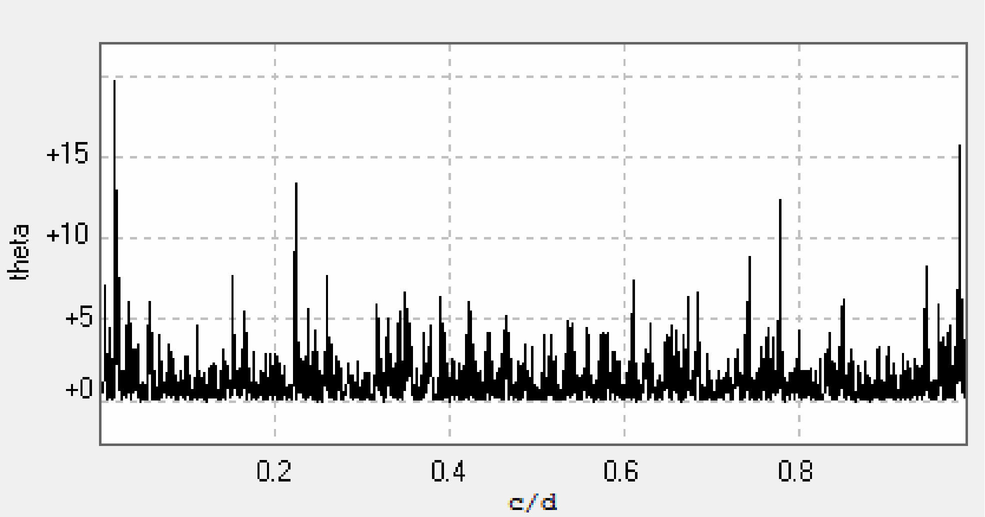

+20
+0
-20
theta
0.05
0.10
0.15
0.20
c/d


-0.05
+0.00
+0.05
Mag
0.5
1.0
1.5
Phase

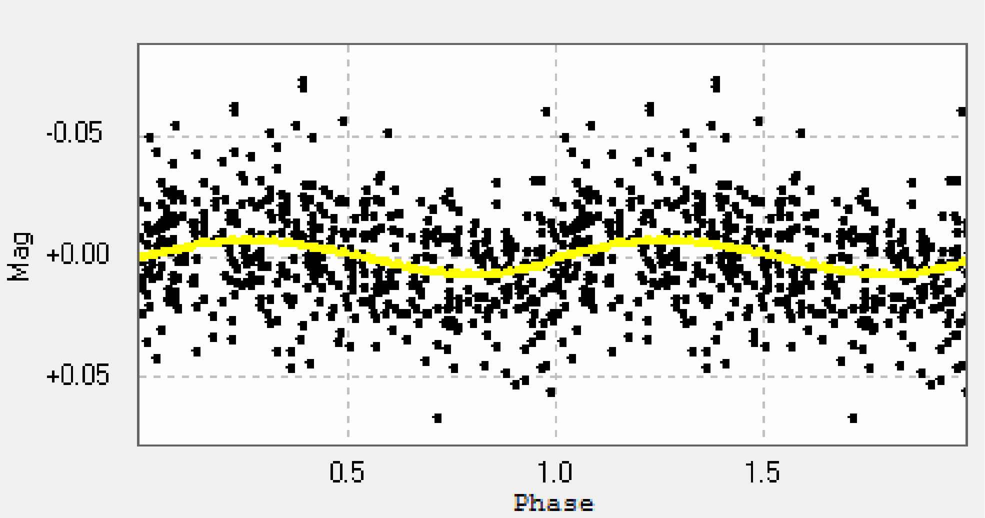
J 22252+594



+12.9
+13.0
mag
0
500
1000
2457000.0+
JD

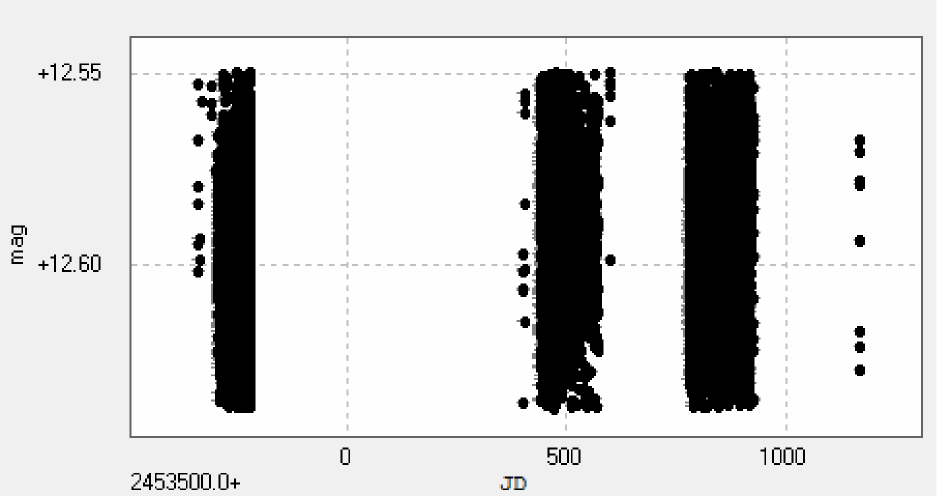


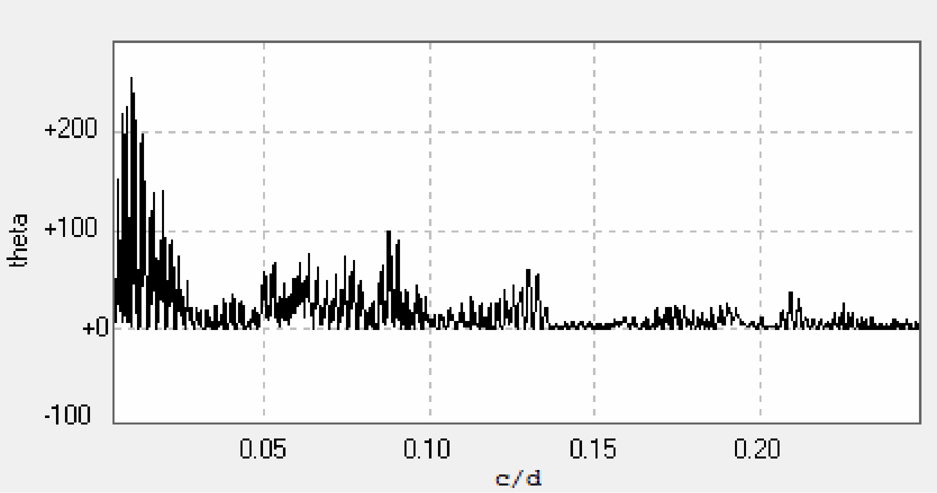
+15
+10
+5
+0
theta
0.2
0.4
0.6
0.8
c/d

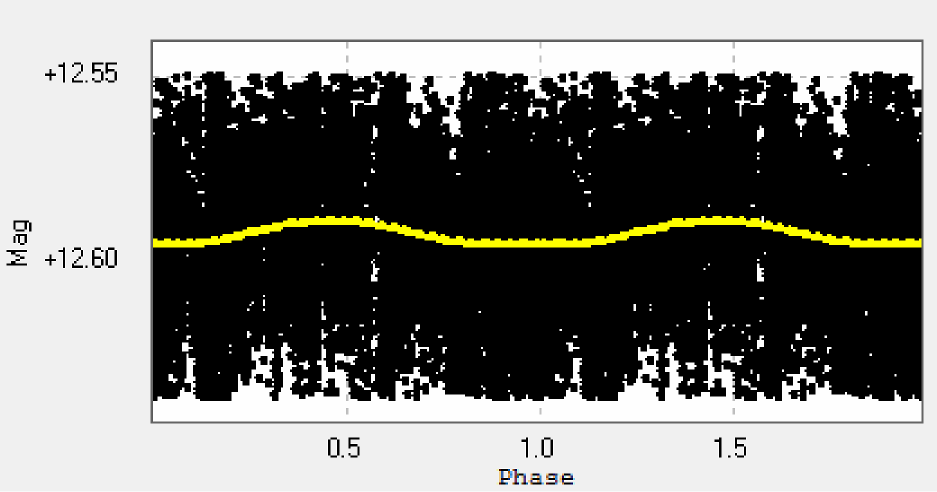


-0.05
+0.00
+0.05
Mag
0.5
1.0
1.5
Phase

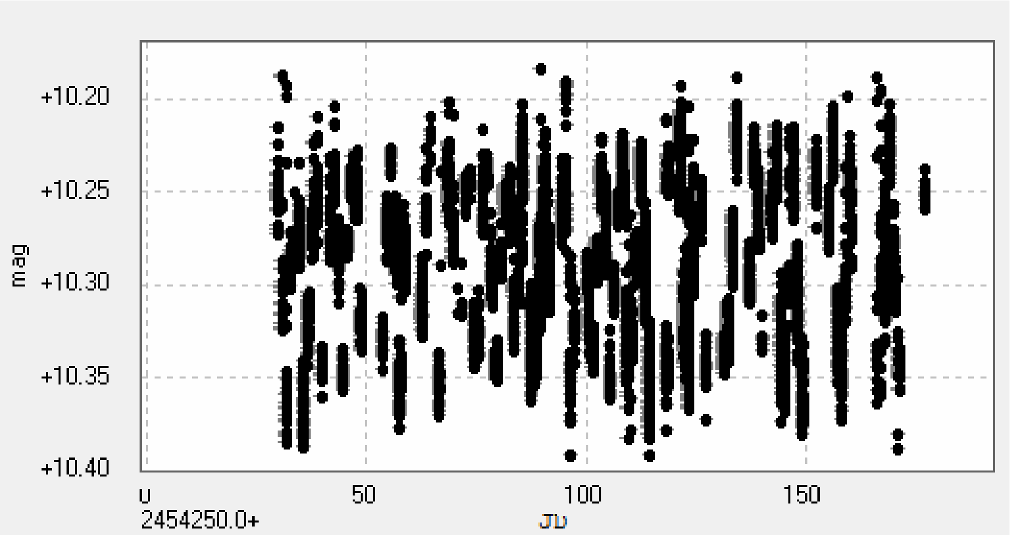
J22298+414


+12.55
+12.60
mag
0
500
1000
2453500.0+
JD

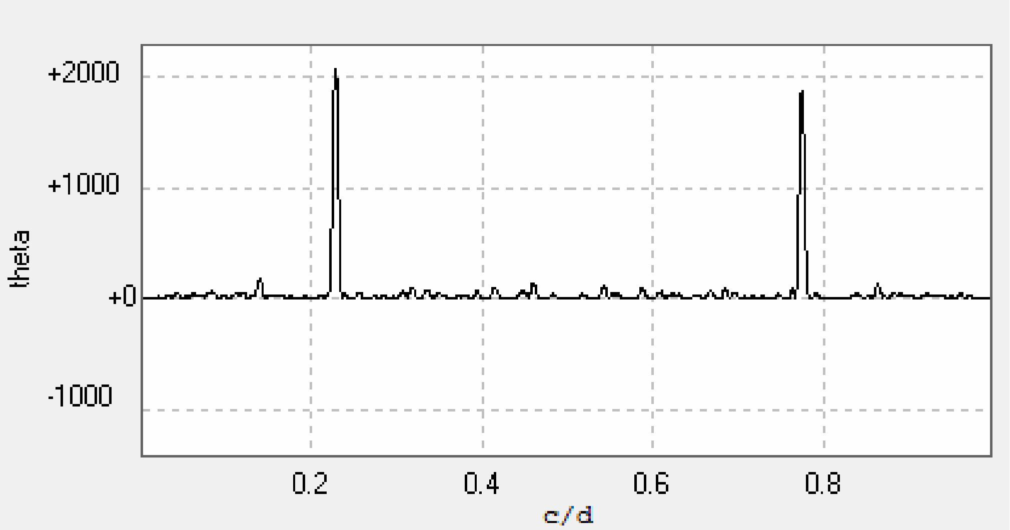

+200
+100
+0
-100
theta
0.05
0.10
0.15
0.20
c/d


+12.55
+12.60
Mag
0.5
1.0
1.5
Phase

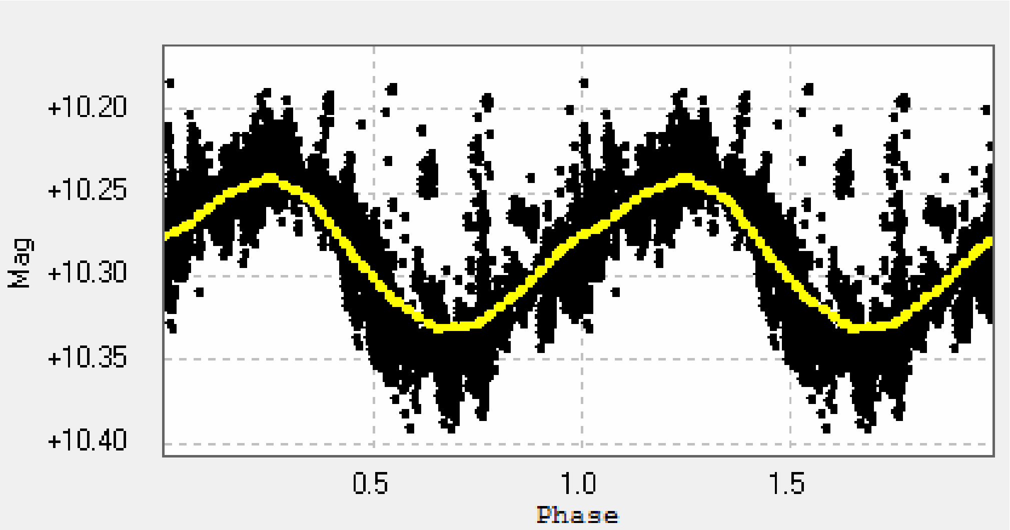
J22468+443



mag
+10.20
+10.25
+10.30
+10.35
+10.40
0
2454250.0+
50
100
150
JD

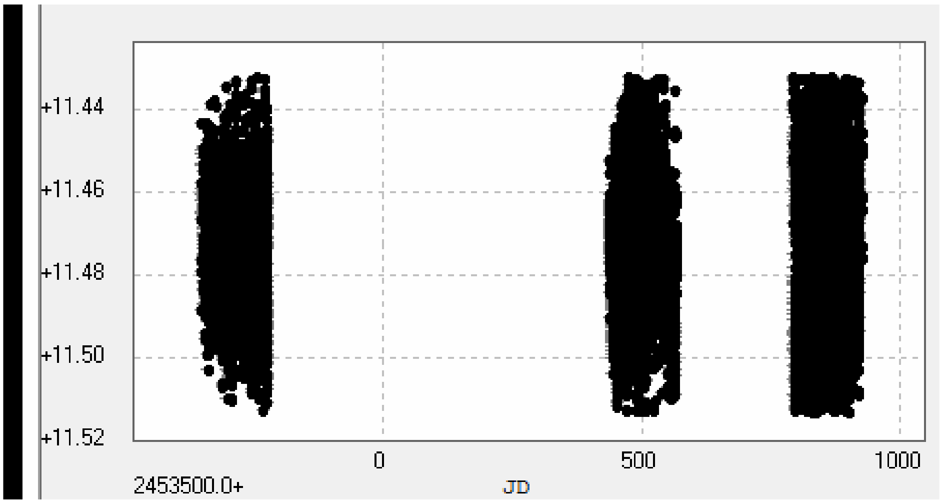


theta
+2000
+1000
+0
-1000
0.2
0.4
0.6
0.8
c/d

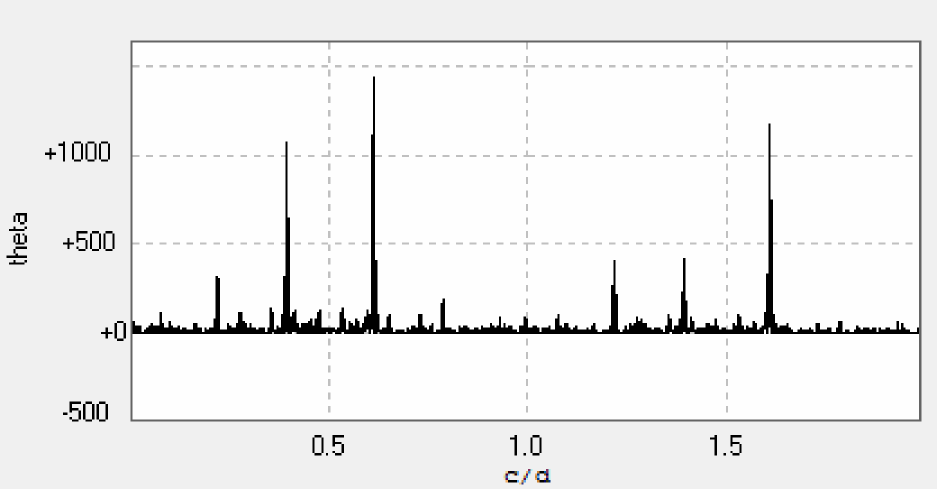


Mag
+10.20
+10.25
+10.30
+10.35
+10.40
0.5
1.0
1.5
Phase

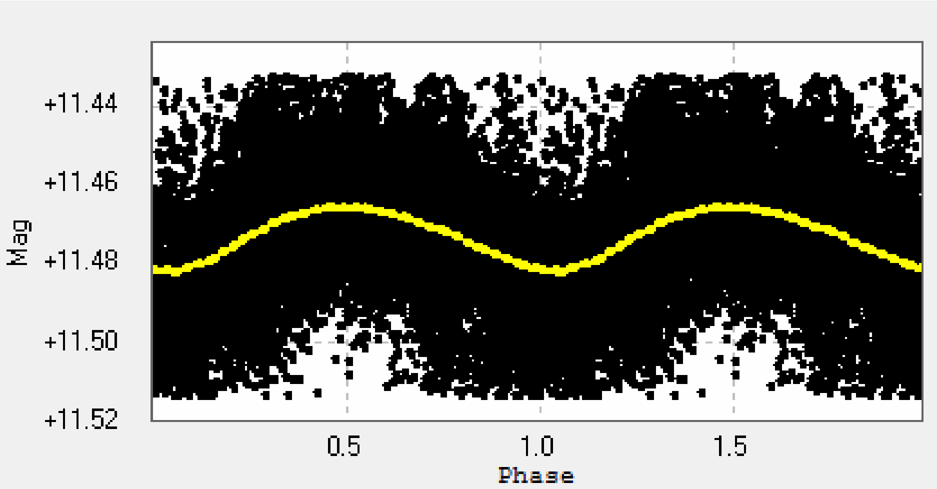
J22518+317



+11.44
+11.46
+11.48
+11.50
+11.52
0
500
1000
2453500.0+
JD

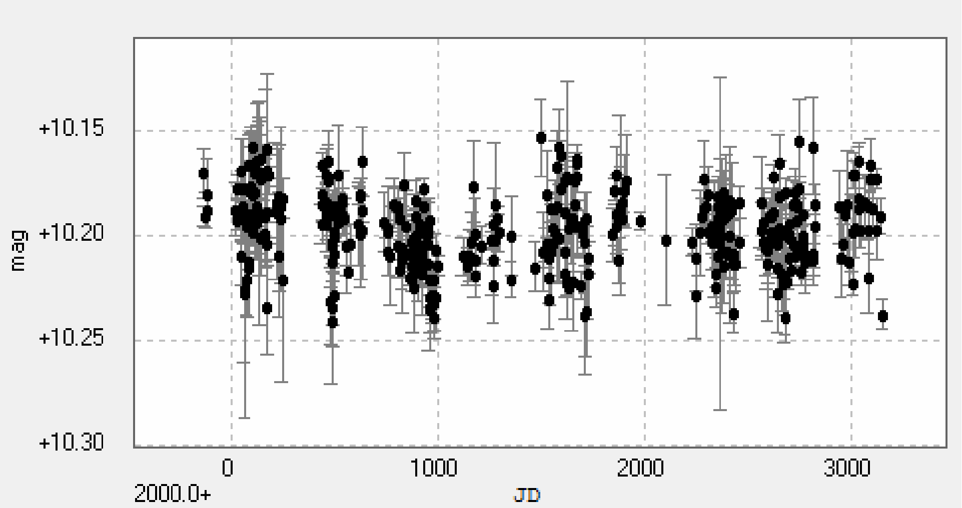


theta
+1000
+500
+0
-500
0.5
1.0
1.5
c/d

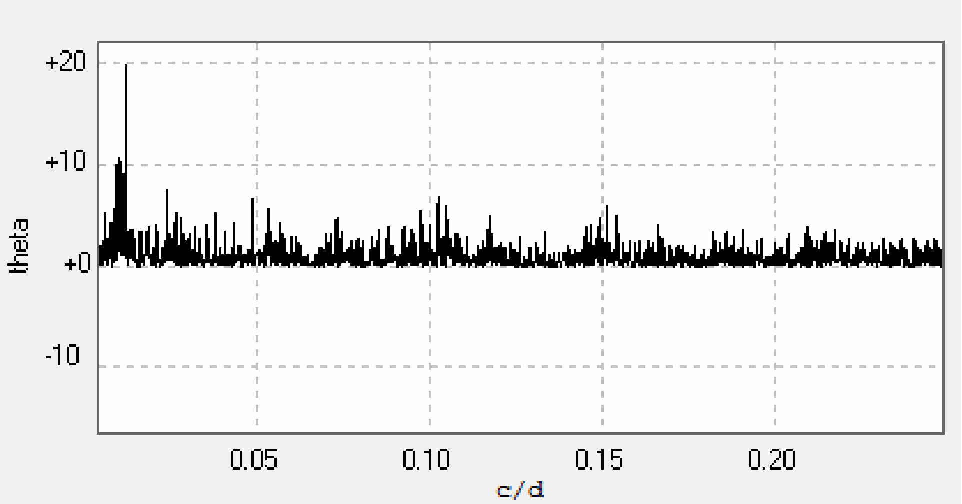


Mag
+11.44
+11.46
+11.48
+11.50
+11.52
0.5
1.0
1.5
Phase

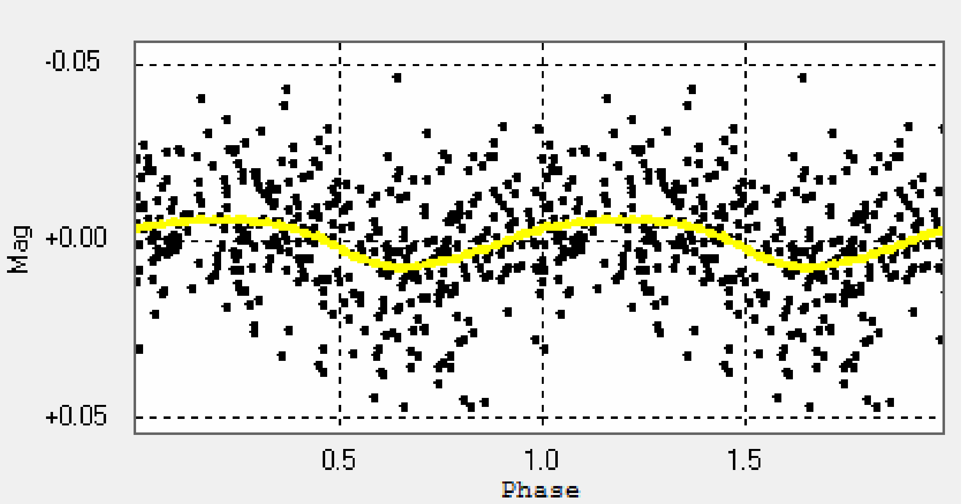
J22532-142



mag
+10.15
+10.20
+10.25
+10.30
0
1000
2000
3000
2000.0+
JD

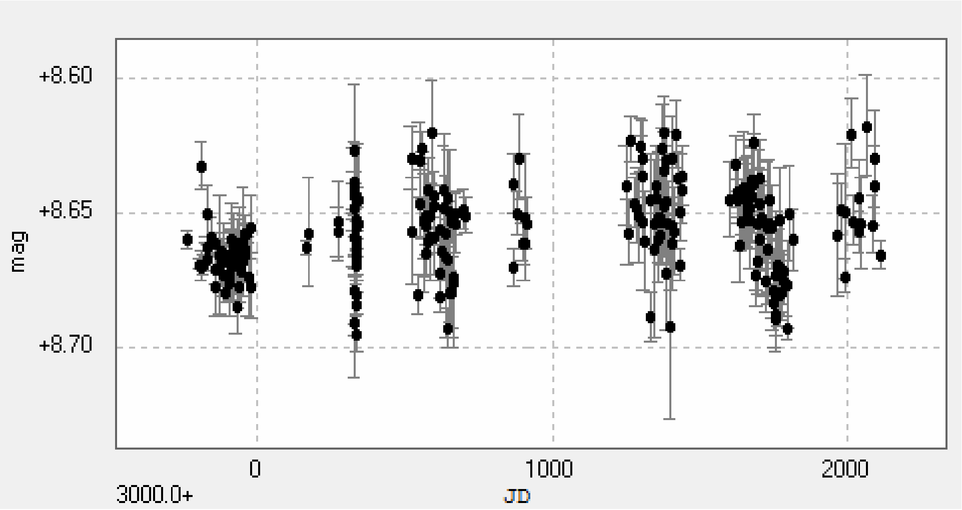


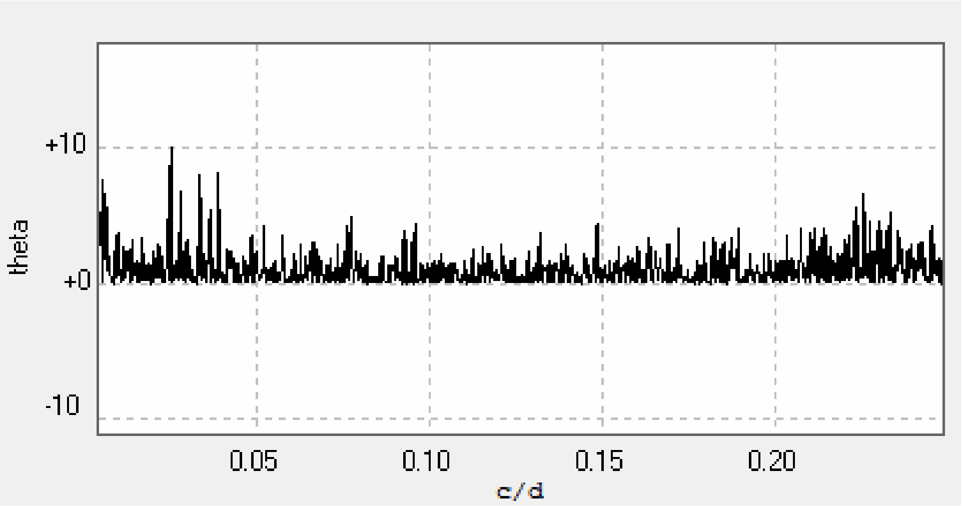
theta
+20
+10
+0
-10
0.05
0.10
0.15
0.20
c/d

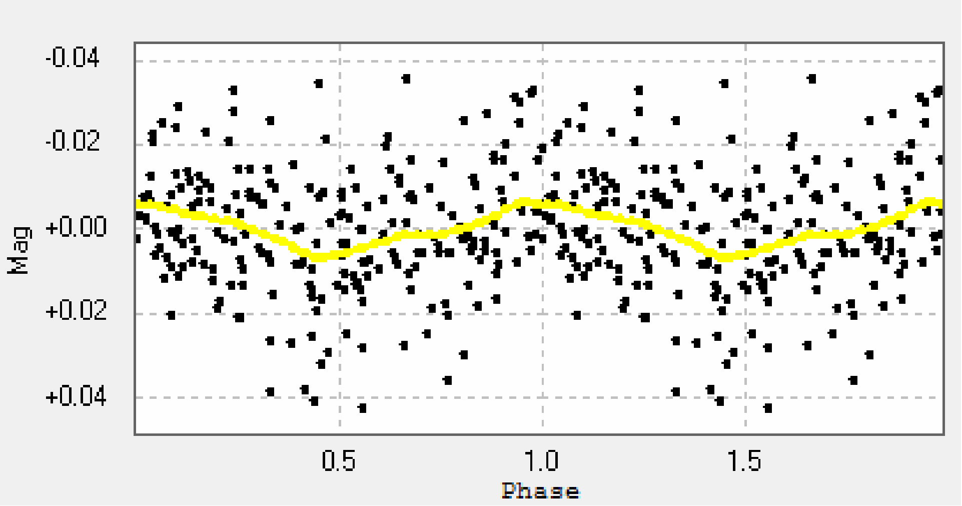


Mag
-0.05
+0.00
+0.05
0.5
1.0
1.5
Phase

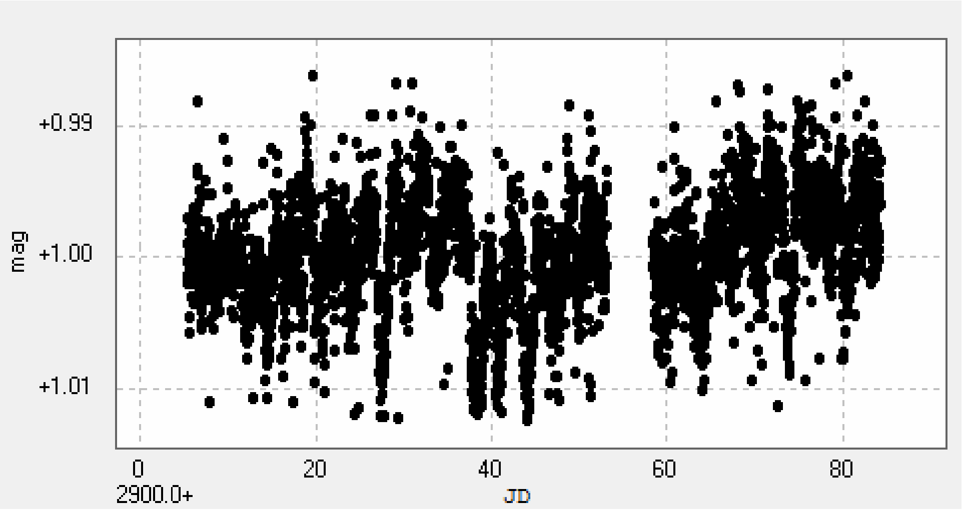
J22565+165


+8.60
+8.65
+8.70
mag
0
1000
2000
3000.0+
JD

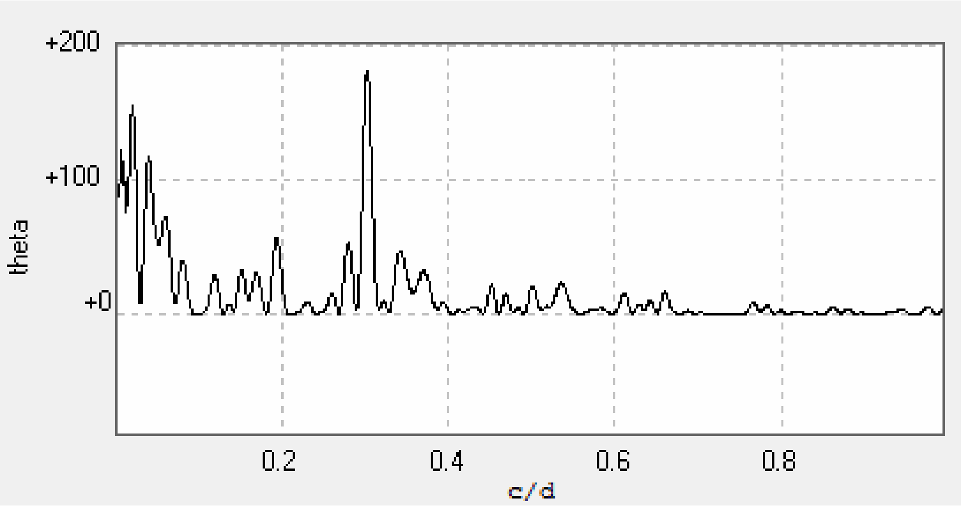

+10
+0
-10
theta
0.05
0.10
0.15
0.20
c/d


-0.04
-0.02
+0.00
+0.02
+0.04
Mag
0.5
1.0
1.5
Phase

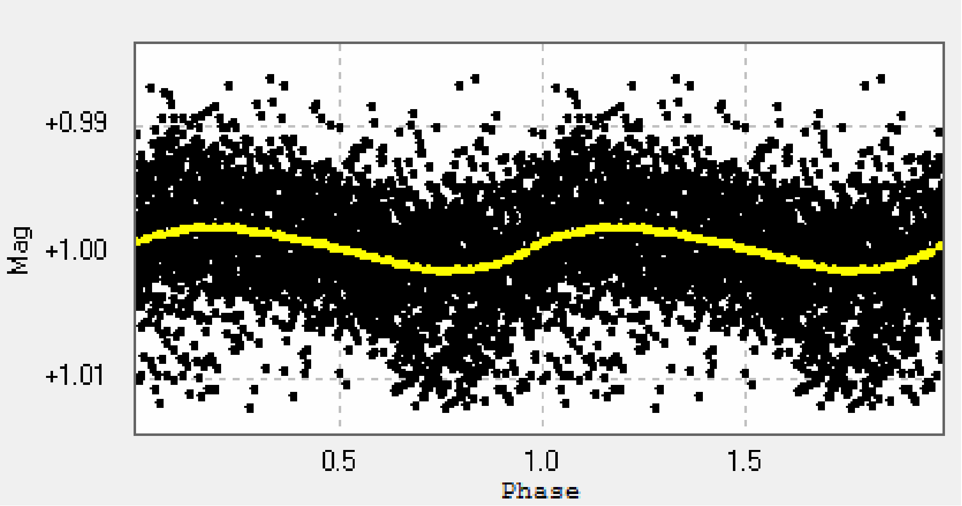
J23064-050



+0.99
+1.00
+1.01
mag
0
20
40
60
80
2900.0+
JD

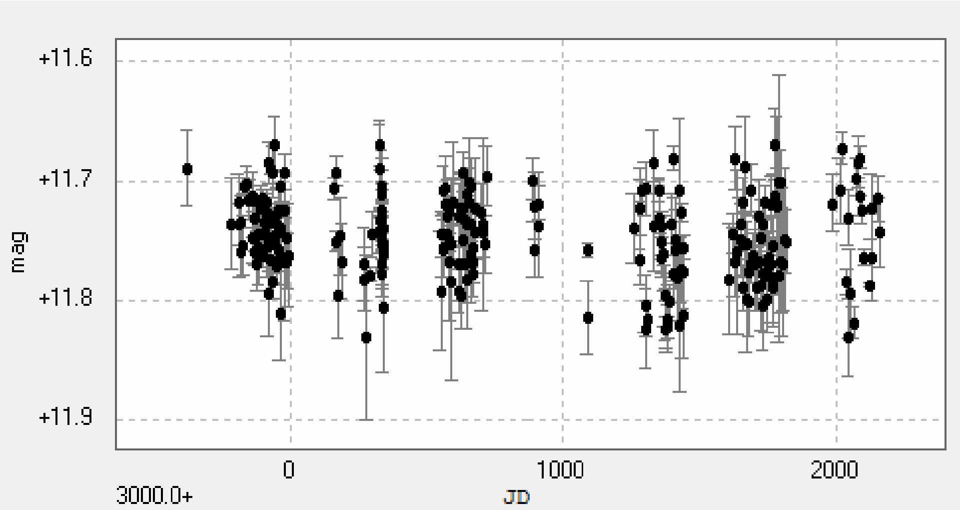


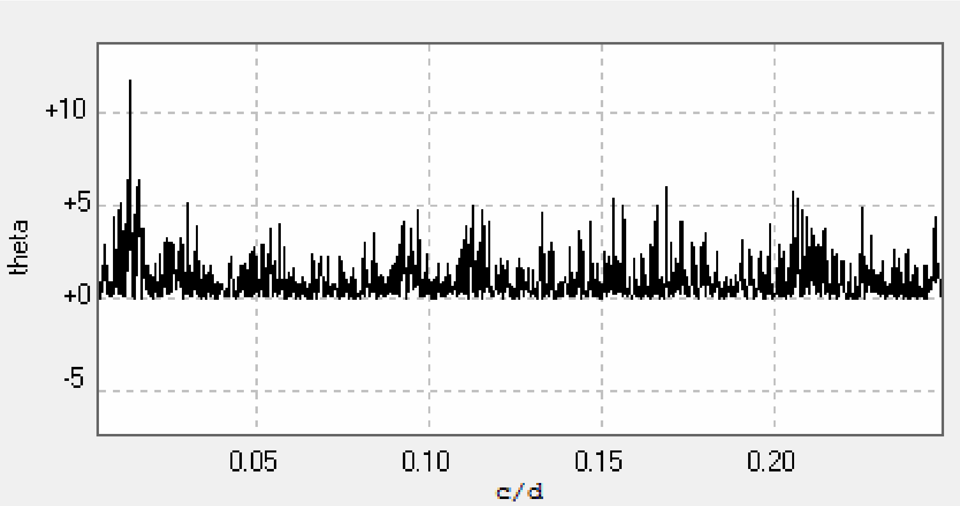
+200
+100
+0
theta
0.2
0.4
0.6
0.8
c/d

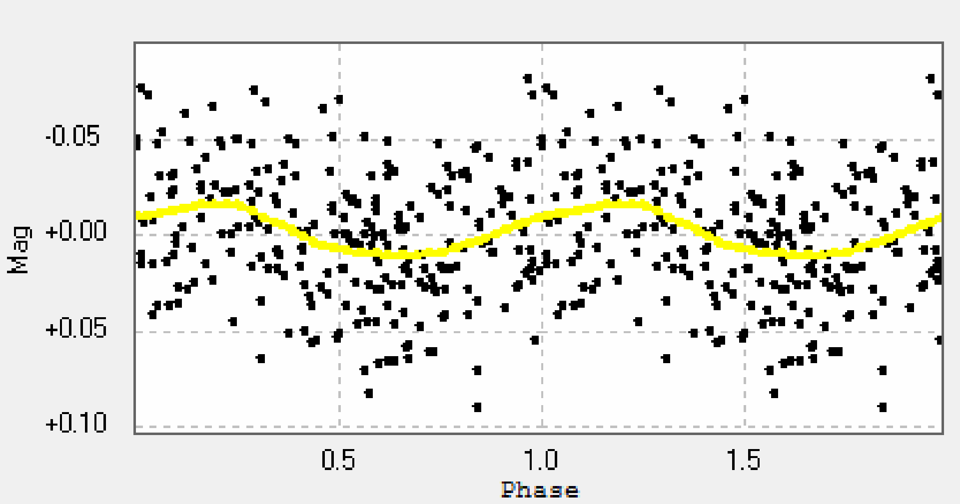


+0.99
+1.00
+1.01
Mag
0.5
1.0
1.5
Phase

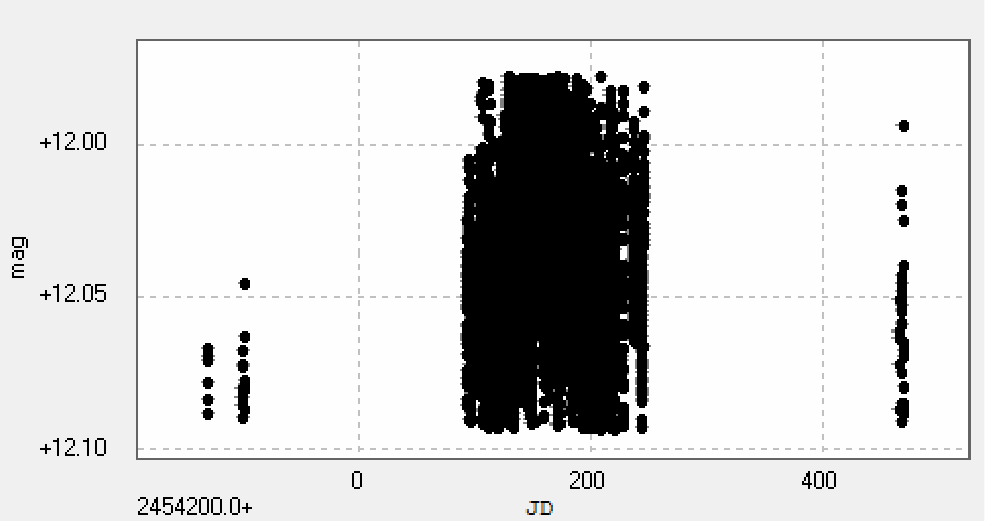
J23216+172

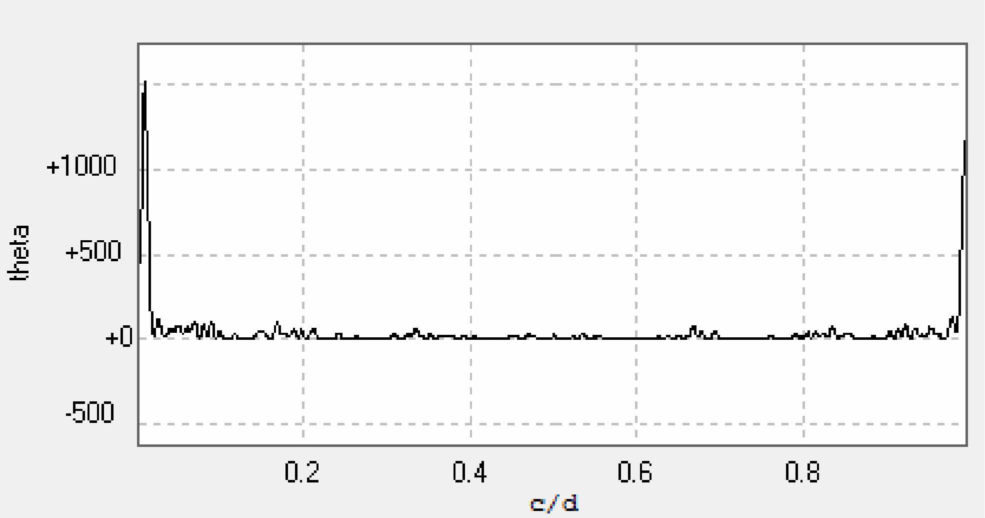

+11.6
+11.7
+11.8
+11.9
mag
0
1000
2000
3000.0+
JD

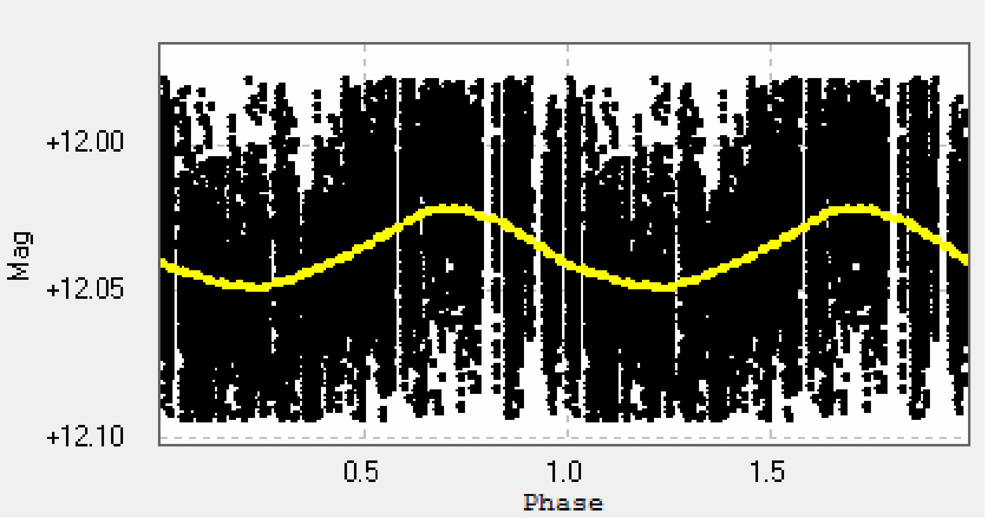

+10
+5
+0
-5
theta
0.05
0.10
0.15
0.20
c/d


-0.05
+0.00
+0.05
+0.10
Mag
0.5
1.0
1.5
Phase

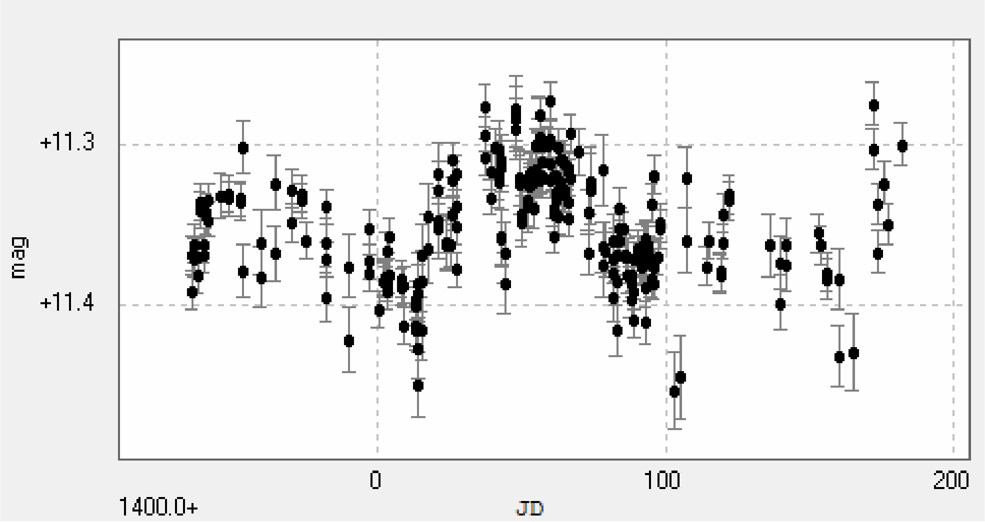
J23419+441

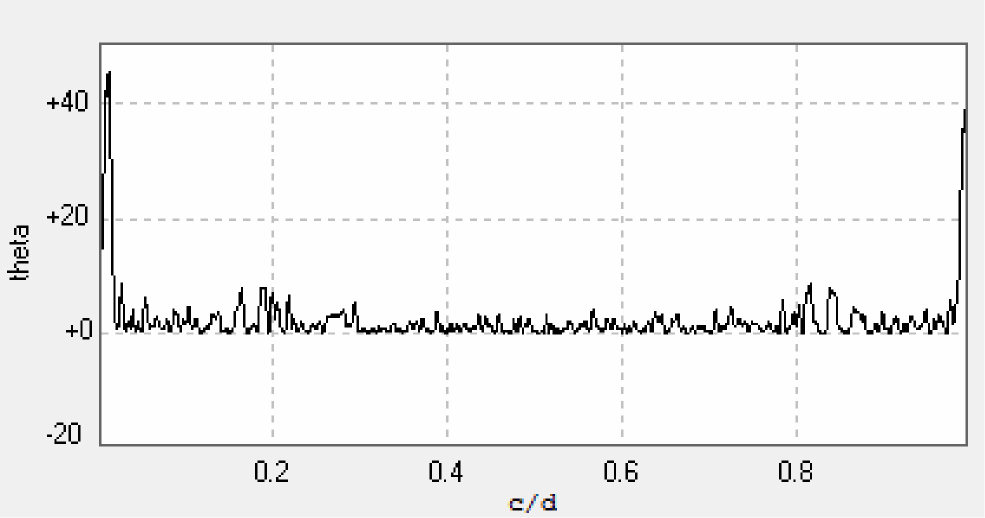

mag
+12.00
+12.05
+12.10
0
200
400
2454200.0+
JD

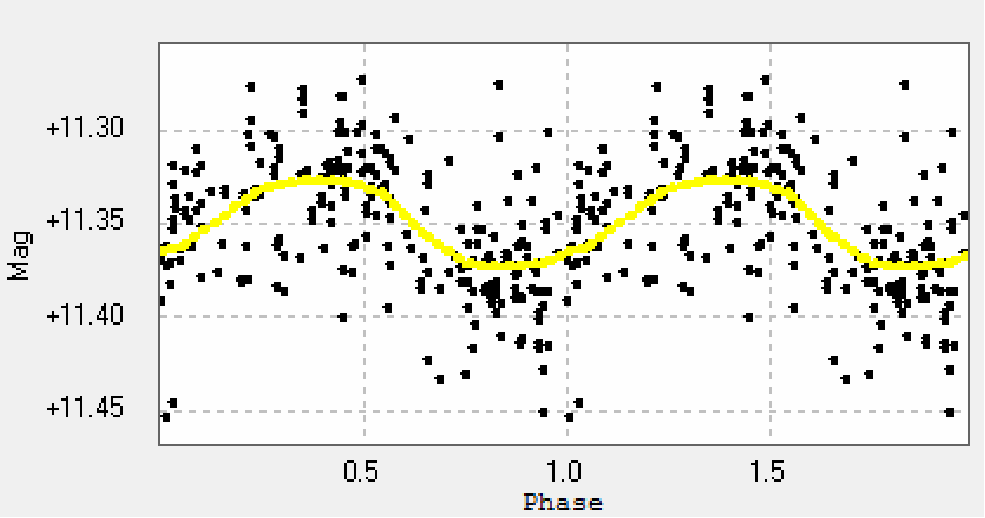

theta
+1000
+500
+0
-500
0.2
0.4
0.6
0.8
c/d


Mag
+12.00
+12.05
+12.10
0.5
1.0
1.5
Phase

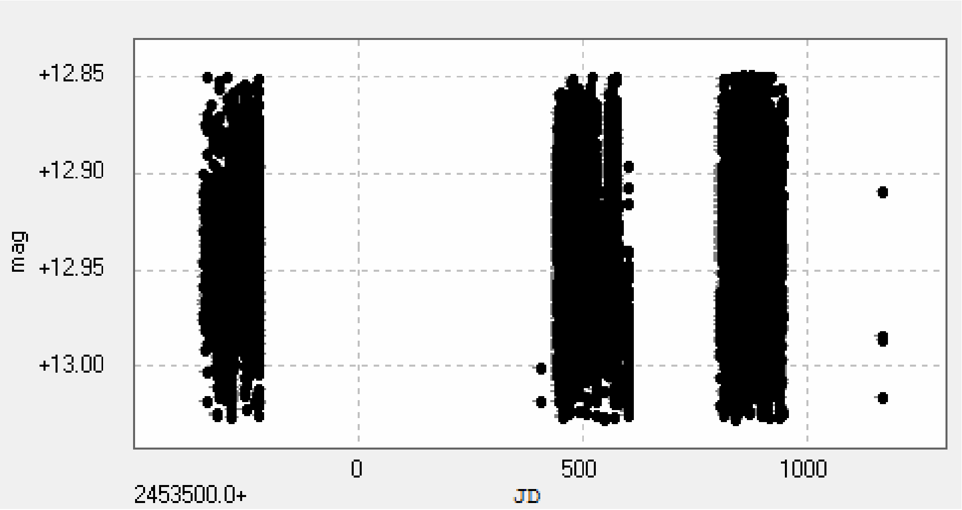
J23431+365

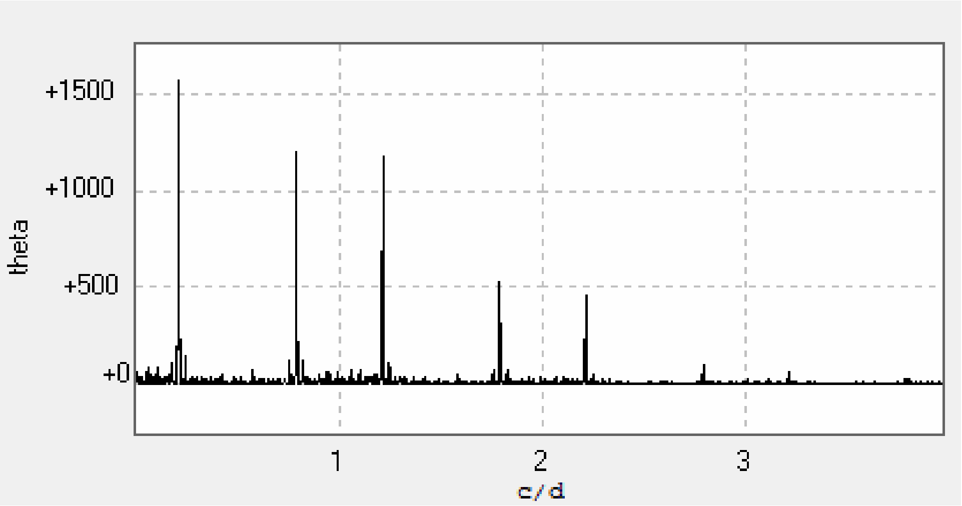

mag
+11.3
+11.4
0
100
200
1400.0+
JD


theta
+40
+20
+0
-20
0.2
0.4
0.6
0.8
c/d


Mag
+11.30
+11.35
+11.40
+11.45
0.5
1.0
1.5
Phase

J23548+385


+12.85
+12.90
+12.95
+13.00
mag
0
500
1000
2453500.0+
JD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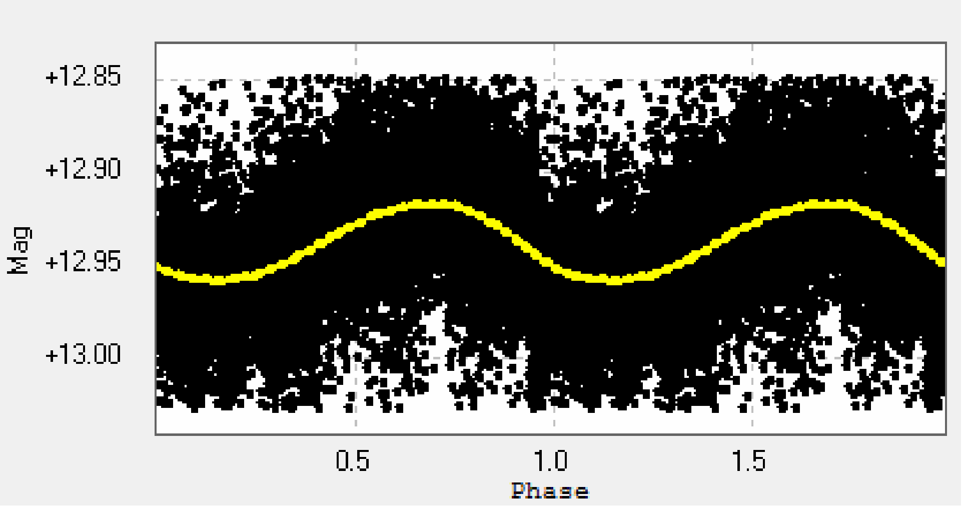
+1000
+500
+0
theta
1
2
3
c/d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+12.90
+12.95
+13.00
Mag
0.5
1.0
1.5
Phase

Apéndice C

Lista de publicaciones

C.1. Publicaciones de la tesis

1. E. Díez Alonso, J. A. Caballero, D. Montes, F. J. de Cos Juez, S. Dreizler, F. Dubois, S. Lalitha, R. Naves, S. Vanaverbeke, P. J. Amado, V. J. S. Bejar, M. Cortes-Contreras, E. Herrero, D. Hidalgo, S. V. Jeffers, M. Kuerster, L. Logie, A. Quirrenbach (2018). Carmenes input catalog of M dwarfs IV. New rotation periods from photometric time series. Astronomy & Astrophysis. Volume 621, A126, January 2019.

2. E. Díez Alonso, Suárez Gómez, S. L., González Hernández, J. I., Suárez Mascareño, A., González Gutiérrez, C., Velasco, S., … Rebolo, R. (2018). A system of three transiting super-Earths in a cool dwarf star. Monthly Notices of the Royal Astronomical Society: Letters, Volume 476, Issue 1, May 2018, Pages L50–L54.

3. E. Díez Alonso, Hernández, J. I. G., Suárez Gómez, S. L., Aguado, D. S., González Gutiérrez, C., Suárez Mascareño, A., … Rebolo, R. (2018). Two planetary systems with transiting Earth-size and super-Earth planets orbiting late-type dwarf stars. Monthly Notices of the Royal Astronomical Society: Letters, Volume 480, Issue 1, October 2018, Pages L1–L5.

4. E. Díez Alonso, J. I. González Hernández, B. Toledo–Padrón, S. L. Suárez Gómez, A. Suárez Mascareño, D. S. Aguado, C. González Gutiérrez,A. Cabrera-Lavers, J. Carballido–Landeira, L. Bonavera, F. J. de Cos Juez, R. Rebolo (2018). A transiting super-Earth close to the inner edge of the habitable zone of an M0 dwarf star. Monthly Notices of the Royal Astronomical Society: Letters. Published on 2018 December 24.

C.2. Publicaciones adicionales

1. Fuhrmeister, B. et al. The CARMENES search for exoplanets around M dwarfs. Period search in H, Na I D, and Ca II IRT lines. Astronomy & Astrophysics,623, A24.

2. Quirrenbach, A., Amado, P. J., Ribas, I., Caballero, J. A., Seifert, W., Aceituno, J., … Xu, W. (2018). CARMENES: high-resolution spectra and precise radial velocities in the red and infrared. In H. Takami, C. J. Evans, L. Simard (Eds.), Ground-based and Airborne Instrumentation for Astronomy VII (Vol. 10702, p. 32). SPIE.

3. Luque, R., Nowak, G., Pallé, E., Kossakowski, D., Trifonov, T., Zechmeister, M., … Schweitzer, A. (2018). The CARMENES search for exoplanets around M

dwarfs. The warm super-Earths in twin orbits around the mid-type M dwarfs Ross 1020 (GJ 3779) and LP 819-052 (GJ 1265). Astronomy & Astrophysics, 620, A171.

4. Baroch, D., Morales, J. C., Ribas, I., Tal-Or, L., Zechmeister, M., Reiners, A., … Seifert, W. (2018). The CARMENES search for exoplanets around M dwarfs: Nine new double-line spectroscopic binary stars. Astronomy & Astrophysics, Volume 619, id.A32, 17

5. Jeffers, S. V., Schoefer, P., Lamert, A., Reiners, A., Montes, D., Caballero, J. A., Sarmiento, L. F. (2018). CARMENES input catalogue of M dwarfs: III. Rotation and activity from high-resolution spectroscopic observations. Astronomy & Astrophysics, 614, A76.

6. Trifonov, T., Kürster, M., Zechmeister, M., Tal-Or, L., Caballero, J. A., Quirrenbach, A., … others. (2018). The CARMENES search for exoplanets around M dwarfs-First visual-channel radial-velocity measurements and orbital parameter updates of seven M-dwarf planetary systems. Astronomy & Astrophysics, 609, A117.

7. Reiners, A., Zechmeister, M., Caballero, J. A., Ribas, I., Morales, J. C., Jeffers, S. V, … others. (2018). The CARMENES search for exoplanets around M dwarfs-High-resolution optical and near-infrared spectroscopy of 324 survey stars. Astronomy & Astrophysics, 612, A49.

8. Reiners, A., Ribas, I., Zechmeister, M., Caballero, J. A., Trifonov, T., Dreizler, S., … others. (2018). The CARMENES search for exoplanets around M dwarfs-HD147379 b: A nearby Neptune in the temperate zone of an early-M dwarf. Astronomy & Astrophysics, 609, L5.

9. Kaminski, A., Trifonov, T., Caballero, J. A., Quirrenbach, A., Ribas, I., Reiners, A., … Udry, S. (2018). The CARMENES search for exoplanets around M dwarfs. A Neptune mass planet traversing the habitable zone around HD 180617. Astronomy & Astrophysics, 618, A115.

C.3. Publicaciones en congresos

1. Diez Alonso, E., Montes, D., de Cos Juez, F. J., Naves, R., de La Cuesta, F., Herrero, E., … others. (2017). Determination of rotation periods of M stars with photometric techniques. In Highlights on Spanish Astrophysics IX, Proceedings of the XII Scientific Meeting of the Spanish Astronomical Society held on July 18-22, 2016, in Bilbao, Spain, ISBN 978-84-606-8760-3. S. Arribas, A. Alonso-Herrero, F. Figueras, C. Hernández-Monteagudo, A. Sánchez-Lavega, S. Pérez-Hoyos (eds.), 2017, p. 502-503 (pp. 502–503).