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ECLIPSING BINARIES - PRECISE CLOCKS TO DISCOVER EXOPLANETS

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Abstract. Observational campaign Dwarf aimed at detection of circumbinary extrasolar planets using the timing of the minima of low-mass eclipsing binaries is presented. The observations are collected within an extensive network of $\sim$ 20 to 200 cm telescopes. The starting sample of the objects to be monitored contains (i) low-mass eclipsing binaries with M and K components, (ii) short-period binaries with a sdB or sdO component, and (iii) post-common-envelope systems containing a WD, which enable us to determine minima with high precision. Because the light-time effect amplitude caused by additional component to an eclipsing binary increases with its the orbital period, the timescale of the project is at least 5-10 years.

1. INTRODUCTION

Observing campaign Dwarf focuses at detection and characterization of extrasolar planets orbiting eclipsing binary stars (see the white paper of Pribulla et al., 2012). The only similar campaign, is the Polish project SOLARIS monitoring the Southern sky (Konacki et al. 2011). The presented project is a collaboration of more than 30 observatories including several well-equipped amateur astronomers.

The eclipses act as an accurate clock for detecting other objects revolving around the inner binary. The observations enable us to determine their orbital parameters from the *observed − calculated* residuals of minima times. The timing technique proved to be the most fruitful in detecting circumbinary planets. The exoplanet encyclopedia[1] lists (as of February 22, 2012) 12 planetary systems (15 planets/4 multiple planet systems) detected by timing.

In the past decade, the eclipse timing has been used to infer the existence of multiple low-mass planetary objects to a couple of binaries. A two-planet system orbiting HW Vir (sdB+M dwarf binary) was found by Lee et al. (2009). Recently, circumbinary planets were announced around a couple of post-common-envelope systems: two planets around NN Ser (Beuermann et al. 2010), two giant planets orbiting UZ For (Potter et al. 2011), a single planet around DP Leo (Qian et al. 2010), HU Aqr (Qian et al. 2011; Gozdziewski et al. 2012), and RR Cae (Qian et al. 2012).

[1]`http://www.exoplanet.eu/catalog.php`

Because the timing technique is sensitive to extrasolar planets on long-period orbits, the archival data play an important role. The major problem when using published timings is the inhomogeneity of the data mostly caused by different approaches to determine the minima. The original light curves (LCs) are usually hard to come by. The situation is exacerbated by many mistakes such as heliocentric correction missing, time shifted by one hour or typos. The minima uncertainties are often not available or underestimated.

2. TARGET SELECTION

Chances to discover a circumbinary substellar body depend primarily on three factors: (i) the precision and number of the minima which can be achieved; (ii) the semi-amplitude of the LITE caused by the body; (iii) the intrinsic variability of the binary causing noise in minima timings. The suitability of an object can be defined as the peak-to-peak amplitude of LITE caused by such a body, ΔT, divided by the theoretical precision of a single minimum timing, Δt. For systems with a triangular shape of the minima (i.e., binaries with partial eclipses and non-degenerate components) we have (see Sybilski et al., 2010; Pribulla et al., 2012):

$$\Delta t = \frac{D\sigma}{2d\sqrt{N}}, \tag{1}$$

where d is the depth and D the duration of the minimum, σ is the uncertainty of a single observational point, and N the number of observational points during the eclipse. It is clear, that the most precise are deep and narrow minima of bright objects. The sampling frequency and precision of observations primarily depend on the diameter of the telescope used and the brightness of the object. Assuming zero read-out times, it can be shown that (Pribulla et al., 2012):

$$\Delta t = \frac{1}{\sqrt{\tau F_\lambda}} 10^{0.2(m_\lambda + X\kappa_\lambda)} \frac{\sqrt{D}}{\sqrt{\pi} A d}. \tag{2}$$

where $\tau \in (0, 1)$ is the throughput of the observing system, F_λ is number of photons from a $m_\lambda = 0$ star per square meter and per second outside Earth atmosphere recorded through the filter used, X is airmass, κ_λ is the extinction coefficient, and A is the aperture or the diameter of the telescope. Because of several other sources of the noise (scintillation, read-out, sky background...) and non-negligible read-out times the minima uncertainties as estimated by the above relation should be regarded as the theoretical limits. The estimates, nevertheless, immediately show the suitability of the selected targets for the present project.

It can easily be shown, that the full amplitude (Max - Min or peak-to-peak) of the expected LITE changes caused by another body orbiting a binary on the edge-on ($i \sim 90°$) circular orbit ($e \sim 0$) is:

$$\Delta T \approx \frac{2M_3 G^{1/3}}{c} \left[\frac{P_3}{2\pi(M_1 + M_2)}\right]^{2/3}, \tag{3}$$

where M_1, M_2, M_3 are the masses of the components, G is gravitational constant, c is speed of light, and P_3 is orbital period of the third (substellar) component.

It is clear, that the most advantageous are low-mass eclipsing binaries orbited by massive sub-stellar companions on long-period orbits. The advantage of low-mass binaries is, on the other hand, offset by their surface activity causing noise and spurious periodicities in the timing data. Dark photospheric spots seen in the majority of the late-type systems cause LC asymmetries (O'Connell effect) and out-of-eclipse photometric wave(s). A spot seen by the observer close to or during the minimum of light shifts it from the spectroscopic conjunction. The maximum time shift caused by a single starspot can be estimated as follows (see Pribulla et al., 2012):

$$|\Delta t| = \frac{\pi}{4}\frac{A_{OCE}D^2}{dP}, \quad (4)$$

where A_{OCE} is peak-to-peak amplitude of the out-of-eclipse photometric wave, D is the duration of minimum, P is the orbital period, and d is the depth of eclipse. Pulsations of the sdB components are of much less concern (Kilkenny, 2011).

To get the highest possible accuracy and precision of the eclipse timings necessary to detect exoplanets, we selected low-mass eclipsing systems with sharp and deep minima. The following three groups of objects were included: (i) systems with K or/and M dwarf components, (ii) systems with a hot subdwarf (sdB or sdO) and a K or M dwarf component, (iii) post-common-envelope systems with a white dwarf (WD) component. Only detached binaries are considered. Because all observatories participating in the campaign are north of the 30th parallel, we excluded objects having DEC $< -10°$. To collect as many minima as possible, and to fully cover a minimum in one night from mid-latitudes we excluded objects with orbital periods longer than 10 days. The brightness range of our preliminary sample is R = 10-17 mag, which fits the possibilities of small telescopes with apertures of 20 to 200 cm equipped with a low-end CCD camera and at least the VRI filter set. The preliminary target list (Pribulla et al., 2012) is frequently being updated (see `http://www.ta3.sk/~pribulla/Dwarfs/`).

3. DATA REDUCTION AND ANALYSIS

The reduction of the CCD frames will be done using the standard approach. In the first step, the master dark and master flat-field frames will be produced for all exposure times, filters and CCD temperatures. To reduce effects of scattered light usually seen in sky flatfields the master flat fields will be box-car average divided to remove low-frequency variations while pixel-to-pixel sensitivity differences will be preserved. In the next step, the raw CCD frames will be dark and flatfield corrected. Then the WCS system will be determined using the GSC 2.3.3 online catalogue for reference[2]. Finally, aperture photometry of the target and suitable (stable) comparison star will be performed. The numerical aperture giving the smallest noise will be selected.

To secure uniform time basis for all observations, the data from individual observatories will be collected in geocentric JD based on UTC. The time will then be transformed to Barycentric Julian Date in Barycentric Dynamical Time (BJD-TDB). During the campaign we will attempt to quantify the shutter-delay effect which depends on the camera type and systematically shifts the observed timings.

The minima timings will be determined with a method similar to cross-corellation technique used to determine precise radial velocities. For each eclipsing binary (EB),

[2] `http://gsss.stsci.edu/webservices/GSC2/GSC2WebForm.aspx`

the fitting templates will be prepared to obtain the instant of conjunction (minimum) for any sufficiently long photometric sequence. In such a way, we will use not only the minima but also other LC segments where the brightness sufficiently changes. Due to the differences in filter transparencies and wavelength response of detectors, we will form a template LC for each filter separately. To obtain good fits of the template $T(x)$ to the observed LCs (and accurate timings), we constructed the following fitting function (see Pribulla et al. 2008):

$$F(x) = A + Bx + CT(x - D), \tag{5}$$

which would allow for shifting, scaling and 'slanting' of the template LC. Fixing of the parameters will be judged according to the appearance of individual LCs, e.g. in the case that only one branch was observed the vertical shift (A) would be fixed to zero. The minima uncertainties will be checked by a Monte Carlo simulation approach. To preserve the original shape and scatter of the data, the fitting function $F(x)$ in the instants of real observations will be replicated adding the Gaussian-distributed random noise. The standard deviation of the added noise will correspond to the standard deviation of the original data with respect to the original fit. Preliminary tests show that about 2000 replications of the LC are sufficient to arrive at the errors.

If an unseen third component revolves an EB, the residuals with respect to a linear (or quadratic) ephemeris will show a wavelike behavior in the (O-C) diagram because of the LITE. The observed times of minima then follow the relation below (see Irwin, 1959):

$$\begin{aligned} Min\ I = JD_0 + P \times E + Q \times E^2 + \\ + \frac{a_{12} \sin\ i}{c} \left[\frac{1 - e^2}{1 + e \cos\ \nu} \sin(\nu + \omega) + e \sin\ \omega \right], \end{aligned} \tag{6}$$

where a_{12} sin i is the projected semi-major axis (inclination cannot be derived from the LITE alone), e is the eccentricity, ω is the longitude of the periastron, ν is the true anomaly of the EB orbit around the common center of the mass of the whole system. $JD_0 + P \times E + Q \times E^2$ is the quadratic ephemeris of the minima of the EB and c is the velocity of light. To obtain the optimal fit and corresponding elements (JD_0, P, Q, $a \sin i$, e, ω, and also the epoch of periastron passage, T_0, and the period of the orbit of the three-body system, P_3) of the LITE orbit including errors, we use the differential corrections method (see Irwin 1959). Knowing the semi-amplitude of LITE, A, period of third-body orbit, P_3 and the total mass of the binary, $M_1 + M_2$, and assuming that $M_3 \ll M_1 + M_2$, we can determine the mass of the third component:

$$M_3^3 \sin^3 i \approx \frac{4\pi^2 (M_1 + M_2)^2}{G P_3^2} A^3 c^3 \tag{7}$$

where i is the inclination of the orbital plane, and G is the gravitational constant.

The analysis of the selected EBs timings will be performed in the following three steps: (i) period search in the (O-C) residuals with respect to a linear or quadratic ephemeris, (ii) fitting LITE orbits to most promising orbital periods, (iii) excluding possible spurious detections caused by, e.g. the Applegate's (1992) mechanism. Except CM Dra, which shows small orbital eccentricity, both types of minima can be simultaneously analyzed. A major problem in the timing analysis is matching our uncertainties with those listed for the published timings.

4. OBSERVING NETWORK AND STRATEGY

The targets (see Table 1 of Pribulla et al., 2012, for the preliminary list) will be observed at several observatories using 20-120 cm telescopes equipped mostly with low-end CCD cameras. In addition to the original list of observatories (Table 2 of Pribulla et al., 2012), a couple of well-equipped amateur astronomors decided to join. The role of smaller telescopes is mainly to characterize newly-detected eclipsing binaries, e.g. within NSVS or HAT networks. The first observations show that the true type of variability, the ephemeris or amplitude of the object are often different from those given in the original catalogue. The larger telescopes will concentrate on faint and short-period objects, mainly post-common-envelope binaries. The 2m telescope at the Rozhen observatory in Bulgaria will obtain medium-resolution spectroscopy of objects without any spectroscopy to infer the nature and spectral type of the components and to exclude systems with stellar third or multiple components.

To get the best S/N (and the highest precision of the timings) it is advisable to use the R or I filters for M or K EBs (see Section 2), and the V filter (or B in the case of back-illuminated CCDs) for the systems with sdB or WD components, where the eclipse depth quickly increases to the shorter wavelength range. Several faint or short-period objects will be observed without filter to provide more light. Using two or more filters would decrease the cadency of the photometry and decrease the duty cycle because of filter change overheads. For short-period systems it is advisable to cover both minima shoulders to see the LC asymmetry caused by the photospheric spots.

In addition to the observations focused on the exact timing, we will perform (much less extensive) multi-color $UBVRI$ photometry of the same fields to find the best comparison stars (to minimize the second-order extinction effects). The observations will also be focused to check possible out-of-eclipse and color brightness variations which would indicate the mechanism causing cyclic variations of the orbital period proposed by Applegate (1992).

Systematic CCD observations of the targets started at the Stará Lesná Observatory in February 2012. The precision of the data is good but still hardly approaching the theoretical limits discussed in Section 2. The best error estimates of 4 primary minima determined from the preliminary reduction (differential photometry with respect to one comparison) of the CCD photometry of NY Vir (March 16, 24, and 26, 2012) range between 1.7 and 3.5 seconds while the theoretically estimated limit is 0.6 seconds. This results from the red noise in the data (no autoguider available), possible variability of the comparison star (GSC 4966-00559), and read-out overheads.

5. CONCLUSION

The presented project is aimed at the detection of circumbinary extrasolar planets and brown dwarfs using minima timing variability of carefully selected EBs. Unlike more widespread techniques (RV or transit searches) to detect extrasolar planets, the minima timing does not require high-end and costly astronomical instrumentation.

Precise photometric observations of the brightest targets of our sample can be performed by well-equipped amateur astronomers. The chances to detect circumbinary bodies does not depend only on the precision of the individual timings but also on the number of participating institutions and devoted amateurs and number of targets monitored.

The theoretical estimates show that the timing technique enables to detect circumbinary planets down to Jupiter mass orbiting on a few-years orbits. The merit of an EB strongly depends on its brightness, depth, and width of the minima, less on the mass of the underlying eclipsing binary.

The observations within the project promise additional useful science such as: (i) the study of spot cycles in the RS CVn-like late-type binaries, detection of flares (see Pribulla et al., 2001), (ii) a more accurate characterization of recently-discovered detached eclipsing binaries, (iii) detection of new low-mass EBs which is crucial to better define the empirical lower main sequence, (iv) determination of absolute parameters of the components (in the case that spectroscopic orbits are available), (v) detection of EBs with pulsating component(s), (vi) detection and characterization of multiple systems with two systems of eclipses, (vii) detection of new variable stars in the CCD fields covered, (viii) photometric detection of transits of substellar components across the disks of the components of the eclipsing pair.

The LITE can always be regarded *only* as a very good indication of a substellar body in the system. In nearby systems with a sufficiently close visual companion (e.g., CU Cnc, GK Boo) the LITE on a long-period orbit could be possibly checked using the differential astrometry of the visual pair.

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