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Project DWARF – using eclipsing binaries for searching for exoplanets and brown dwarfs

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Project DWARF is a long-term observation campaign for about 60 selected eclipsing binaries aimed for detection of exoplanets or other objects (brown dwarfs) in low-mass detached binaries of different types (low-mass eclipsing binaries with M and K components, short-period binaries with sdB or sdO component, post-common-envelope systems containing a white dwarf). Existence of other bodies in systems are determined by analysing of O-C diagrams, constructed from observed minima times of binaries. Objects are selected with intention to determine minima with high precision. About 40 observatories are involved into the network at present time, mostly situated in Europe. The observations are made by small or middle class telescopes with apertures of $\sim 20-200$ cm. In this contribution we give information about current status of the project, we present main goals and results of 4 years observations.

Key words: stars: planetary systems, binaries: eclipsing

INTRODUCTION

Planetary companions to binary stars are defined in two types of hierarchical planet-binary configurations: (1) "S-type" planets which orbit just one of the stars, with the binary period being much longer than that of the planet; (2) "P-type" or circumbinary planets, where the planet simultaneously orbits both stars, and the planetary orbital period is much longer than that of the binary [8].

Simulations show either of above possibilities has a large range of stable configurations [1, 2, 12, 13]. Recent theoretical studies [14, 22, 23] predicted that P-type planets can form and survive over long timescales. Characterisation of such planets is potentially of great interest because they can lead to a better understanding of the formation and evolution of planetary systems around close binary stars, which can be rather different from the case of single stars. [7]. Hereafter we will consider the "P-type" or circumbinary planets only.

The substellar component and/or planet(s) in the binary system can be detected by timing variations of the binary system eclipses due to the finite velocity of light (light-time effect, hereafter LITE).

DWARF project [10] is a long-term observational campaign, focused at detection of extrasolar planets, brown dwarfs or other circumbinary objects orbiting binary stars using the timing of the minima of low-mass detached eclipsing binaries (EB).

TARGET SELECTION

To get the highest possible accuracy and precision of the eclipse timings necessary to detect exoplanets, we selected objects 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 hot subdwarf (sdB or sdO) and K or M dwarf components, (iii) post-common-envelope systems with a white dwarf (WD) component. Contact binaries will not be observed within this campaign because of the strong interaction of the components in the common envelope that introduces noise in their lightcurves. Moreover, their minima are normally broader and the ingress/egress phases less steep than in the previous class of EBs.

In addition to well-studied targets, we perform follow-up observations of recently discovered detached EBs based on the NSVS data [5], HAT network data [4], and ASAS data [15, 16, 17, 18, 19].

Because all observatories participating in the campaign are north of the 30th parallel, we limit the objects to systems northern than Dec = $-10°$. To collect as many minima as possible, and to fully cover a minimum within one night from mid-latitudes we excluded objects with orbital periods longer than 5 days. The brightness range of our sample is $R = 10^m - 17^m$, which fits the possibilities of small telescopes with apertures of 20–200 cm equipped with a low-end CCD camera and at least the VRI filter set. Such instrumentation allows us to extend the observing network to well-equipped amateur astronomers.

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CHANCES TO DISCOVER CIRCUMBINARY OBJECT

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 precision of the minimum time Δt (for a triangular shape of the minimum) can be determined from equation (see, e. g., [21])

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

where σ is the brightness uncertainty (in magnitudes) of a single observational point, D is the duration of the minimum, d is the depth (in magnitudes) and N is the number of observational points during the eclipse. The above relation shows that the precision of the minimum time increases with the number of data points taken in the minimum and their precision. The shape of the minimum also affects the precision of the timing – deep and narrow minima provide the best precision.

The full amplitude of the expected LITE changes caused by another body orbiting a binary on the edge-on ($i \sim 90^\circ$) circular orbit ($e \sim 0$) is:

$$\Delta T = \frac{2M_3G^{1/3}}{c}\left[\frac{P_3}{2\pi\left(M_1+M_2\right)}\right]^{2/3}, \qquad (1)$$

where M_1, M_2, M_3 are the masses of the components, G is the gravitational constant, c is the speed of light, and P_3 is the orbital period of the third (substellar) component. Eq. (1) shows that the semi-amplitude of the LITE changes is proportional to the mass of the third component and nearly proportional to its orbital period. In Table 1 we present values of LITE effect for Jupiter-mass companion on a 15-years orbit around selected binary system in our program, together with theoretical precision of minimum time for 50 cm telescope and detection sensitivity N= $\Delta T/\Delta t$.

Table 1: Expected LITE amplitude (ΔT) for Jupiter-mass companion on a 15-years orbit and theoretical precision (Δt) time of minima for 50 cm telescope. Detection sensitivity $N = \Delta T/\Delta t$.

Star	V	ΔT[s]	Δt[s]	N
DV Psc	10.6	4.5	1.1	4.1
BX Tri	13.4	5.4	4.2	1.3
V470 Cam	14.7	6.3	1.2	5.3
GSC 19411746	12.9	5.1	6.1	0.8
NY Vir	13.3	6.0	0.6	10.0
NSVS 02502726	14.0	4.3	3.9	1.1
NSVS 06507557	13.4	4.7	1.8	2.6
MR Del	11.0	3.7	1.4	2.7

In addition to the timing errors caused by the precision and accuracy of the data acquisition, the minima times are affected by the intrinsic variability of the binaries. The dominant cause of the intrinsic variability (and enhanced scatter) in the (O–C) diagrams are spots on the active late-type K or M dwarf components. Dark photospheric spots seen in the majority of the late-type systems cause lightcurve (LC) asymmetries (O'Connell effect) and out-of-eclipse photometric wave(s). The effects of starspots on the minimum timing of close eclipsing binaries were modelled and discussed in [20]. The authors found that a spot with a diameter of 20° migrating due to the differential rotation on surface of the contact binary AB And caused timing variations as large as 0.008 days. The effect of spot(s) on the precision of minima timing as well as other systematic errors in minima positions can be partially corrected by fitting of minimum with function

$$F\left(x\right) = A + Bx + CT\left(x - D\right),$$

where $T(x)$ is minimum template created by the average of many minima LCs, A, B and C describe shifting, scaling and "slanting" of the LC template, and D is shift in time to get exact time of minima. Fixing of the parameters are considered according to the appearance of individual LCs.

Because the goal of the project is going to be accomplished by the accurate (at a level of a few seconds) timing of the LC extrema (in our case minima), it is crucial to regularly synchronize the computer clock with the NTP-servers to provide the system time within 1 second off the UTC. UTC (or Coordinated Universal Time) is based on the atomic clocks but it is never allowed to differ from UT1 (based on the rotation of Earth) by more than 0.9 seconds. Therefore a leap second has to be included from time to time. The UTC, therefore, is discontinuous and not the best to use in timing analysis. Therefore we convert this time before all analyses to Barycentric Dynamical Time (TDB) which is a truly uniform time, and we also apply barycentric correction related to the Solar System Barycenter.

THE TIMING ANALYSIS AND ITS LIMITATIONS

If an unseen third component revolves an EB, the residuals with respect to a linear (or quadratic) ephemeris will show a wavelike behaviour in the (O – C) diagram because of the LITE. Although all our targets are well detached systems (where the mass transfer cannot occur), the orbital period can continuously decrease for two reasons: the magnetic braking in the case of systems with late-type components, and the radiation of gravity waves in the case of the systems with shortest orbital periods (< 0.1 d).

The (O – C) curve (due only to the inner binary) can be described by a linear (constant period) or quadratic ephemeris (linear period variation) and if a third body is orbiting the inner binary adding the LITE effect, the times of the minima can be computed as follows (a quadratic ephemeris added to the theoretical LITE given by formulae (2) and (3) of [6]):

$$\begin{aligned}\min I &= \mathrm{JD}_0 + P \times E + Q \times E^2 + \\ &+ \frac{a_{12}\sin i}{c}\left[\frac{1-e^2}{1+e\cos\nu}\sin(\nu+\omega) + e\sin\omega\right],\end{aligned}$$

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 centre of the mass of the whole system. $\mathrm{JD}_0 + P \times E + Q \times E^2$ is the quadratic ephemeris of the minima of the EB and c is the velocity of light. The parameter Q is the coefficient of the quadratic term, it gives the rate of the orbital period change of the EB. If a is the semi-major axis of the third (substellar) companion's orbit around the binary's mass centre, then:

$$a_{12} = \frac{aM_3}{M_1 + M_2 + M_3}.$$

To obtain the optimal fit and corresponding elements (JD_0, P, Q, $a\sin i$, e, ω, and also the epoch of periastron passage, *T0*, 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 [6]. The orbital elements determined above enable estimation of mass of the unseen companion. In the case we know the masses of the binary star components M_1, M_2 (or their sum), we can derive the mass function of the third body:

$$\begin{aligned}f\,(M_3) &= \frac{(M_3\sin i)^3}{M_1+M_2+M_3} = \\ &= \frac{4\pi^2}{G}\frac{(a_{12}\sin i)^3}{P_3^2} = \frac{4\pi^2}{G}\frac{A^3c^3}{P_3^2},\end{aligned}$$

where A is the semi-amplitude of LITE (in time units), i is the inclination of the orbital plane of the third body, M_1, M_2 are the masses of the eclipsing binary components, and M_3 is the mass of the third (substellar) companion, P_3 is the outer orbital period, and G is the gravitational constant.

Assuming that the mass of the substellar body is negligible compared to the total mass of the binary, $M_3 \ll M_1 + M_2$, its mass can be directly found as:

$$M_3^3\sin^3 i \approx \frac{4\pi(M_1+M_2)^2}{GP_3^2}A^3c^3. \qquad (2)$$

The analysis of the selected EBs timings will be performed in two 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. Orbital periods longer than the time span of the data will not be considered. A major problem in the timing analysis is matching our uncertainties with those listed for the published timings. Moreover, the minima uncertainties are often not given. This will complicate the relative weighting of the data points and cause additional uncertainty of the results.

CONCLUSIONS

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 EB (Eq. (1)). 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 [11],

(ii) a more accurate characterisation 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 if spectroscopic orbits are available),

(v) detection of EBs with pulsating component(s),

(vi) detection and characterisation of multiple systems with two systems of eclipses,

(vii) detection of new variable stars in the CCD fields covered,

(viii) photometric detection of substellar components transits across the disks of the eclipsing pair components [3],

(ix) detection of invisible massive components causing precession of the EB orbit and changes of the minima depth [9].

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 by the differential astrometry of the visual pair.

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