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The Dwarf project. First results.

T. Pribulla, M. Vaňko and the Dwarf team

Astronomical Institute of the Slovak Academy of Sciences
059 60 Tatranská Lomnica, The Slovak Republic, (E-mail: pribulla@ta3.sk)

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Abstract. First results of the observational campaign Dwarf aimed at detection of circumbinary extrasolar planets using the timing of the minima are presented. The campaign is focused on low-mass eclipsing binaries with M and K components, short-period binaries with an sdB or sdO component, and post-common-envelope systems, which enable us to determine minima with high precision. Because the light-time effect (LITE) amplitude caused by an additional component to an eclipsing binary increases with its the orbital period, the timescale of the project is at least 5-10 years.

Key words: eclipsing binaries, circumbinary planets

1. Introduction

The observing campaign Dwarf (Pribulla et al., 2012) focuses on detection of extrasolar planets orbiting eclipsing binary stars using accurate minima timing. Other similar campaign is the project SOLARIS (Konacki et al. 2012) and a quest for companions to post-common envelope binaries (Backhaus et al. 2012).

In the past decade, the eclipse timing has been used to infer the existence of multiple low-mass planetary objects to several of binaries. Circumbinary systems were announced around sdB+M dwarf binary HW Vir (Lee et al., 2009) and several post-common-envelope systems: NN Ser (Beuermann et al. 2010), UZ For (Potter et al. 2011), DP Leo (Qian et al. 2010), HU Aqr (Gozdziewski et al. 2012), and RR Cae (Qian et al. 2012).

2. Target selection

Chances to discover a circumbinary substellar body depend primarily on: (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. 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. In the case of triangular minima we have (see Pribulla et al., 2012):

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

where d is the depth and D the duration of the minimum, $\tau \in (0,1)$ is the total throughput of the telescope (the whole optical system), F_λ is number of photons from an $m_\lambda = 0$ star per square meter and per second outside the Earth's atmosphere recorded through the filter used, X is airmass, κ_λ is the extinction coefficient, and A is 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 above relation gives just the theoretical limits. It is clear that the most precise timings can be obtained for bright eclipsing binaries with deep and narrow minima. In the case that one component is a WD, the timing precision is determined by our ability to cover fast ingress and egress to the eclipse.

The 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:

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

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 component.

It is clear, that the most suitable 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 intrinsic variability. 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 bright ($R < 17$ mag) low-mass detached eclipsing systems with sharp and deep minima. To collect as many minima as possible, and to fully cover a minimum in one night from a single site at mid-latitudes, we excluded objects with orbital periods longer than 10 days.

3. Data reduction and analysis

In the first step, the master dark and master flat-field frames will be produced. In the next step, the raw CCD frames will be dark and flatfield corrected. Then the WCS system will be determined using the USNO B1 catalogue available in IRAF using the `adumpcat` task. Finally, aperture photometry of the target and suitable (stable) comparison(s) star will be performed. The numerical aperture giving the smallest noise of the differential photometry will be selected.

The data from individual observatories are being collected in geocentric JD based on UTC. The time will then be transformed to Barycentric Julian Date in Barycentric Dynamical Time (BJD-TDB).

The minima timings will be determined by cross-corelating the light curve (hereafter LC) with its best fitting model LC. Synthetic LCs will be produced using program *ROCHE* (Pribulla, 2012). For binaries with non-degenerate components the modelling will include proximity effects and assumes a tidally-deformed shape of the components. For systems with a WD component only its irradiation of the companion will be taken into account, while the spherical shapes of the components will be assumed.

Using an appropriate template LC will enable us to use any LC segment where the brightness sufficiently changes (see equation 1 of Pribulla et al. 2008). The "minima" uncertainties will be determined by a Monte Carlo simulation approach: a multitude of artificial data sets will be produced by adding the Gaussian-distributed random noise to the original data. The standard deviation of the added noise will correspond to the standard deviation of the original data with respect to the original fit.

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., Applegate's (1992) mechanism.

4. Observing network and strategy

The selected eclipsing binaries will be observed at several observatories using 20cm - 2m telescopes equipped mostly with low-end CCD cameras. In addition to the original list of observatories, several well-equipped amateur astronomers decided to join. The role of smaller telescopes is mainly to characterize newly-detected eclipsing binaries found in, e.g., NSVS or HAT surveys. The larger telescopes will concentrate on faint and short-period objects, mainly post-common-envelope binaries.

To get the best S/N it is advisable to use the R or I filters for M or K EBs, 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. For short-period systems both minima shoulders will be observed 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 on checking possible out-of-eclipse and color brightness variations which would indicate the mechanism causing cyclic variations of the orbital period proposed by Applegate (1992).

5. First results

Systematic CCD observations started at the Stará Lesná Observatory in February 2012. The first data release (from all observatories) of the extensive photometric campaign is still under preparation (Pribulla et al., 2014).

The precision of the data is good but it is still hardly approaching the theoretical limits discussed in Section 2. The best error estimates of 4 primary minima determined from the preliminary reduction of the CCD photometry (differential photometry with respect to one comparison) 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. The timing precision is well documented in the case of two short-period eclipsing binaries NSVS0786147 and SDSS J143547.87+373338.5 (Fig. 1).

A new sdB+M dwarf candidate star, VSX J075328.9+722424, was announced based on observations from several observatories within the project (Pribulla et al., 2013). The system is rather unusual: it is totally eclipsing, the primary minimum is about 3 mag deep and the orbital period, P=0.208 days, is the second longest among known eclipsing sd binaries. The system is rather faint, with $V_{\max}$ = 16.5.

Observations of systems with degenerate components (presently including PTFEB11.441, V471 Tau, CSS 41177, DE CVn, NN Ser, SDSS J1435.8+3734, and RX J2130.6+4710) showed that to obtain useful data requires at least 60cm telescope (see Fig. 2).

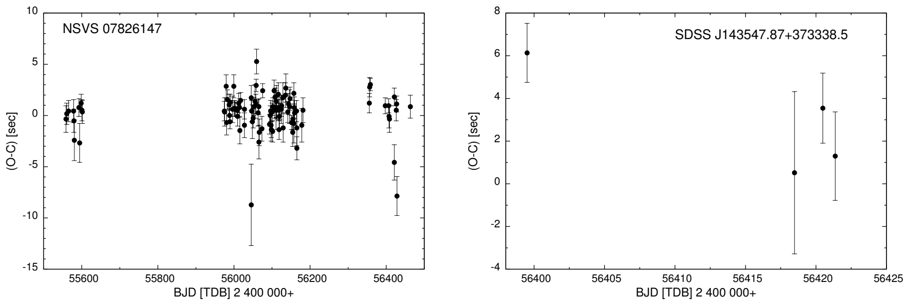

Figure 1. (O-C) diagrams of two short-period eclipsing binaries. NSVS0786147 is an sd+M dwarf system while SDSS J143547.87+373338.5 contains a late-type dwarf and a WD component. The minima have been determined from unpublished observations obtained within the Dwarf observing network

Extensive observations of more than 50 close eclipsing binaries[1] lead to determination of 606 minima times (as of October 2013). Eleven eclipsing binaries from the NSVS database (Hoffmann et al., 2008) were observed (mostly at the private observatory of Giorgio Corfini, San Lorenzo, Italy) and improved their light elements. Low dispersion spectroscopy of the NSVS eclipsing binaries is planned at the Stará Lesná observatory.

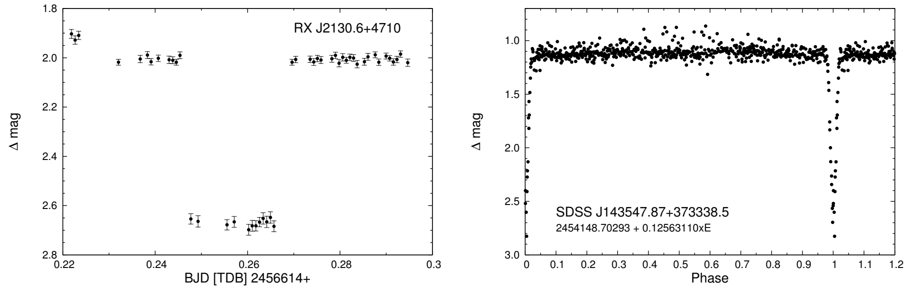

Figure 2. Light curve of RX J2130.6+4710 obtained in the *V* passband (left) and phase light curve of SDSS J143547.87+373338.5 obtained without a filter (right). Both light curves were obtained from observations with the 60-cm Cassegrain telescope at the Stará Lesná observatory of the Slovak Academy of Sciences.

6. 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. The chances to detect circumbinary bodies do 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 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)

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[1] for the details see `http://www.ta3.sk/~pribulla/Dwarfs/`

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 by the differential astrometry of the visual pair (see Kervella et al., 2013).

First observations show that it is feasible to obtain timing precision of about 1-3 seconds for eclipsing binaries with an sd or WD component.

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