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Evidence for planets in post-common envelope binaries

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Abstract. In the recent years, several circum-binary planets orbiting post-common envelope systems have been announced. Some of the derived planetary parameters have been questioned by others. We therefore present an investigation of the current status in this dynamically evolving field. False positive scenarios for the eclipse time variations are therefore discussed. We also present an update on new measurements on NN Ser and shortly address the quest for the frequency of planets in post-common envelope systems.

Key words. Binaries: eclipsing – Stars: planetary systems – Planets and satellites: detection – Planets and satellites: dynamical evolution and stability

1. Introduction

The database for extrasolar planets *exoplanet.eu* lists nearly 700 extrasolar planets by October 2011 which have been detected using various methods probing different regions of the planetary parameter space. These techniques also differ in their sensitivity with respect to the stellar parameters of the host stars. About three quarters of the detections are made with the radial velocity method, where the motion of the planet host star around the barycenter is measured via the Doppler shift. This method is especially successful for (slowly rotating, in-active) FGK main sequence stars (Mayor et al. 2011) and provided the first detection of a planet orbiting around a main sequence star another than the Sun (Mayor & Queloz 1995). With the advent of the KEPLER and CoRoT space missions the transit method, where the planet is detected as shallow eclipse in light curves, is catching up quickly regarding number of detections as well with regard to sensitivity for the detection of Earth-like planets.

The timing method, where the motion of the host star around the barycenter of its planetary system is detected via the light travel time effect (LTE), was, however, the first method to detect a planetary object outside our solar system (Wolszczan & Frail 1992). This method requires an intrinsically very precise clock, e.g. a pulsar (Wolszczan & Frail 1992), a pulsating star (Silvotti et al. 2007), or eclipsing binaries. In the latter case, post-common envelope (PCE) binaries have been investigated for circum-binary planets. Due to the short orbital periods these systems allow a frequent measurement of the eclipse times in order to search for eclipse time variations. Binaries with claimed detections of one or two planetary companions are HW Vir (Lee et al. 2009), DP Leo (Qian et al. 2008; Beuermann et al. 2011), HU Aqr (Schwarz et al. 2009; Qian et al. 2011), NN Ser (Qian et al. 2009;

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Beuermann et al. 2010), and UZ For (Dai et al. 2010; Potter et al. 2011), whereas V471 Tau (Guinan & Ribas 2001; Kamiński et al. 2007; Kundra & Hric 2011), QS Vir (Parsons et al. 2010), HS0705+6700 (Qian et al. 2009; Beuermann et al. 2011), and EM Cyg (Dai & Qian 2010) are suspected to harbor a brown dwarf as a third body. This compilation shows, that planets detect via the timing method probe quite exotic planetary systems, where the host stars have undergone violent phases of stellar evolution. These systems therefore allow probing the survival of planets and planetary systems in the course of stellar evolution or alternative formation scenarios as second or even third generation planets.

These interesting questions certainly deserve attention, from the observations this requires bona-fide planets in order to evaluate e.g. the frequency of planets in PCE binaries, or the properties of circum-binary planetary systems. Since some of the claimed detections have been challenged by celestial mechanics simulations (e.g. HU Aqr: (Qian et al. 2011) versus (Horner et al. 2011; Wittenmyer et al. 2011), others have undergone significant modifications of their orbital properties with more observations (e.g. NN Ser: (Qian et al. 2009) versus (Parsons et al. 2010; Beuermann et al. 2010). The motivation of this review therefore is to investigate the current situation with respect to false positive scenarios, and to present updates to NN Ser as well as first results for an estimate of the frequency of PCE binary planets.

2. False positive scenarios

Monitoring eclipse times of close binaries have already been performed for decades. Indeed, irregular, cyclic, or periodic eclipse time variations have been detected and intensively discussed in the cataclysmic variable community. For the detection of third bodies, it is clear that we are looking for periodic variations. Secular changes of the orbital period due to magnetic breaking or gravitational wave radiation cannot be confused with the signal of a planet, however, the secular changes have to be carefully taken into account when searching for periodic variations (see the case of HU Aqr discussed below).

A first illustrative example is UX Uma. Combining measurements from Mandel (1965) and Nather & Robinson (1974), Africano & Wilson (1976) presented a cyclic variation of eclipse times with a period of 29 years and with an amplitude of the order of 100 s (see Fig. 1 of Africano & Wilson 1976). In these papers on UX Uma, several scenarios for the cyclic variations were discussed, apsidal motion due to small eccentricity, mass transfer from the secondary, and the presence of a third, sub-stellar companion, while the scatter in the residuals were attributed to changes in the accretion disk. Rubenstein, Patterson, & Africano (1991) took new high-speed photometry and added data older back from the nineteen forties. The dataset now spanning a long baseline clearly shows an irregular eclipse time variation, eliminating the apsidal motion as well as the third body hypothesis. Instead, a magnetic cycle of the secondary and it's feedback on the orbital period, the process which has is known today as Applegate's mechanism (Applegate 1992), has been suggested as explanation.

Since the timing method is more sensitive for companions at long orbital period, the coverage of a sufficiently long baseline is a problem. In the case of UX Uma the irregularity in the eclipse time variations were only revealed when the base line was sufficiently longer then the coherence time of the variations. Another example, where too few measurements lead to a premature claimed detection is NN Ser. Qian et al. (2009) used a few own eclipse time measurement in combination with previous ones and fitted a circular orbit of a ten Jupiter mass planet in a 3.3 AU orbit. This solution was rejected by Parsons et al. (2010) using high-speed photometry obtained with ULTRACAM. With more measurements as well as with a reanalysis of a strategic measurement obtained with FORS at the VLT Haefner et al. (2004), Beuermann et al. (2010) were able to obtain a solution for two planets in a resonant orbit (see also next section), significantly different from the previously claimed detection.

The accretion process in cataclysmic variables may lead to false positive timing variation. Since an accretion disk or accretion spot typically outshines the accreting white dwarf, irregularities in the disk or spot will result in changes of eclipse times. In the case of UZ For, Potter et al. (2011) display eclipse profiles in their Fig. 1 obtained over two decades showing the varying contribution of the accretion spot. Since the spot may move over the white dwarf surface, this then leads to a pseudo-shift in eclipse times, if the contributions of the spot and the white dwarf to the eclipse profile are not resolved. Variation of the eclipse profile can therefore lead to false positive eclipse time variations. This is equivalent to the situation encountered in the radial velocity method, where stellar activity may lead to varying line profile distortions resulting in pseudo radial velocity shifts comparable to the effect from an orbiting planet. Since the effect of stellar activity on the spectral line profile changes with wavelength, stellar activity can be disentangled from a true stellar motion with a sufficient spectral coverage. Similarly, multi-color photometry may also indicate eclipse profile distortions.

HU Aqr reveals a case where even a good fit in the statistical sense with Keplerian orbits turns out to be un-physical. Qian et al. (2011) could fit the data with two planets, the large eccentricities, however, make the system dynamically unstable on very short time scales (Horner et al. 2011). Wittenmyer et al. (2011) investigated that case further and found that the pre-whitening of the data with a fit for a secular period change is problematic. Since the time baseline of the dataset is not much longer than the orbital period of the outer planetary candidate, a removal of the quadratic term influences the solution for that planet. Performing a simultaneous fit for two planets including a quadratic term in the ephemeris results in a different two-planet solution, which is however, dynamically unstable as well (Wittenmyer et al. 2011).

Potter et al. (2011) find a similar situation for UZ For, where the statistically best solution results in highly eccentric and therefore dynamically unstable orbits. Taking orbital stability as an additional criterion, a two-planet solution can be obtained, however, at a significantly higher χ^2. HU Aqr as well as UZ For therefore need more detailed investigations in order to resolve these discrepancies. These case also highlight the fact that caution is needed in interpreting even seemingly periodic eclipse time variations as indication for planetary companions.

3. Latest results on NN Ser

As mentioned above, a two-planet solution has been obtained for NN Ser (Beuermann et al. 2010). Two solutions with nearly equal χ^2 have been found. In both solution the two planets are in mean motion resonance, in 2:1 and 5:2, respectively. In both case the outer planet is more massive (0.4 or 0.54 M_{Jup}, respectively) while the inner planet has 0.27 or 0.38 MJup. The orbital periods are 16.73 and 6.69 years in the 2:1 resonance or 15.50 and 7.75 years in the 5:2 case. Eccentricities are small. The residuals of the fit are well below 1 s, the reduced $\chi^2 \approx 1$ indicates that this is clearly within the measurement uncertainties. It should be noted that both solutions are dynamically stable on time scales at least longer than the PCE time scale of the system.

With the caveats from above, it is certainly worthwhile to further monitor NN Ser in order to check the consistency of the previous results. Frequent observations in 2011 using our remotely-controlled MONET/North telescope at McDonald Observatory are fully consistent with the previous solution. When the new observations are taken into account for the fit, a solution within the uncertainties of the previous solution is obtained. In Fig. 1 and Fig. 2 we display the fit for the 2:1 as well as 5:2 mean motion resonance solution. With the additional data, the 2:1 solution is now statistically slightly better. Since we can now relax the restriction to circular orbits for the outer planet, further investigations are necessary.

4. Estimating the frequency of planets in PCE binaries

The detection of planets in PCE binaries is very fascinating. The binary system is the result of

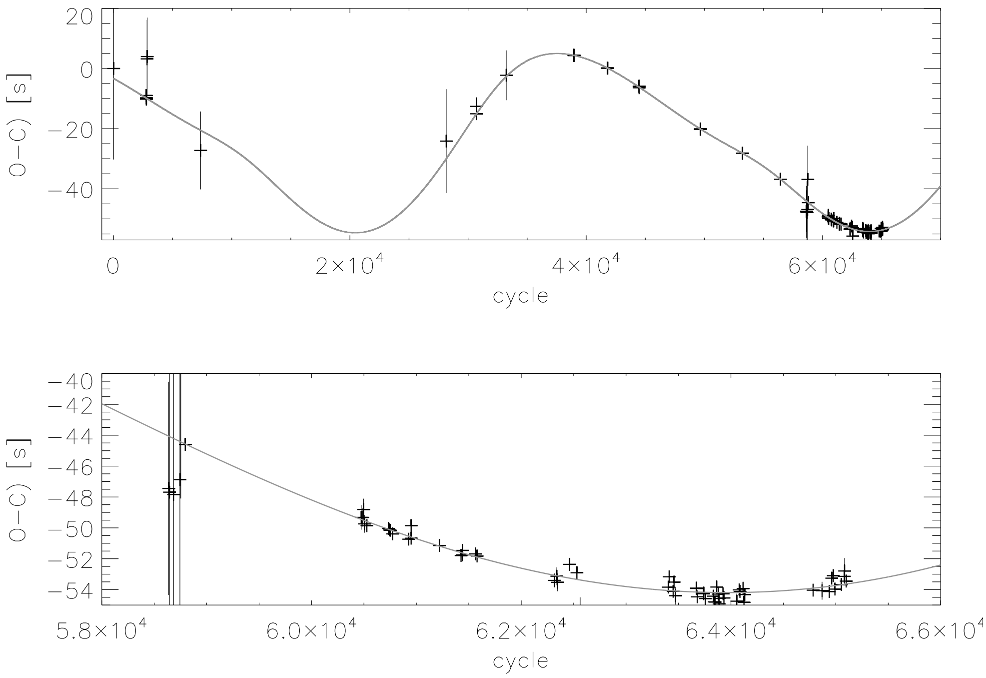

Fig. 1. Eclipse times of NN Ser compared to a fit with two Keplerian orbits for two planetary companions in 2:1 mean motion resonance. A quadratic term in the ephemeris is not required.

a dramatic evolution, where the primary lost a significant fraction of its mass on short time scales. For first generation planets, i.e. those which would have formed together with the binary at the beginning of the main sequence phase, the drastic loss of gravitational binding energy should lead to a drastic increase in orbital period. A potential first generation planetary system will, however, also be swelled with the mass lost during the common envelope phase. Depending on the concentration of the material in the orbital plane of the binary, the drag forces on the planets lead to a more or less shrinkage of the orbital period of the planets. It is an interesting question, but also a very challenging task, to simulate these two competing effect in order to evaluate the survival chance for first generation planets in binary systems. The density, temperature, and time scale of the common envelope shell also determines whether second generation planets could be formed.

The detection of planets in PCE systems is one interesting result, the non-detection is, however, as interesting in that context. An estimate of the frequency of PCE planets is required in order to allow discriminating between a first and second generation formation scenario. Started as a school project within Göttingen (Beuermann et al. 2009), the monitoring of eclipse times of PCE binaries has grown into the *PlanetFinder* project,which is a research project conducted by high-school teachers and their students in collaboration with professional astronomers. As a first result, Backhaus et al. (2011) present the result from the monitoring of a list of PCE binaries from the list of Drake et al. (2010). These twelve systems do not show any eclipse time variations. For tighter constraints on the non-detection, further monitoring is, however, necessary. Other non-detection. e.g. like in AA Dor (Kilkenny 2011) are equally interest-

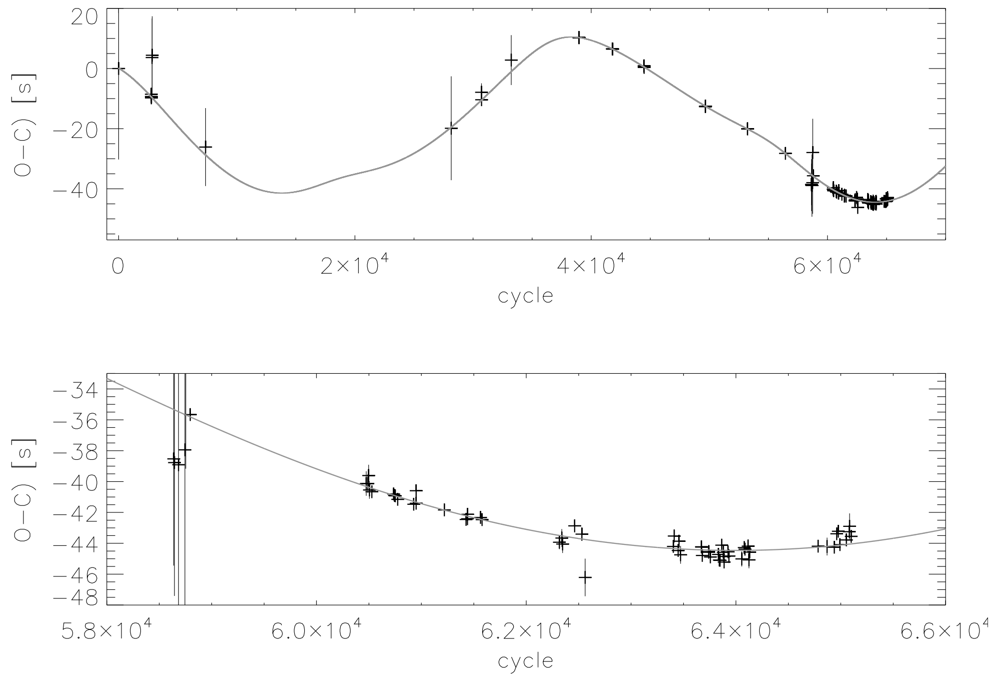

Fig. 2. Eclipse times of NN Ser compared to a fit with two Keplerian orbits for two planetary companions in 5:2 mean motion resonance. A quadratic term in the ephemeris is not required.

ing.It is, however, too early to provide an estimate of the frequency of circum-binary planets in PCE systems.

5. Conclusions

NN Ser might be regarded as the most reliable detection of planets in PCE binaries. It is a non-interacting system, the eclipse profile is therefore stable. This is reflected in the very low residuals of the two-planet fit. Our current solution is consistent with all data taken over the last two decades. Important ingredients are on the one hand the very precise measurements with ULTRACAM and on the other hand the very frequent measurements with MONET/North. Further monitoring will soon allow to discriminate between the two possible solutions, the 2:1 and the 5:2 mean motion resonance for the two planets and will allow to further tighten the determination of the planetary orbital parameters.

In other cases, like e.g. in HU Aqr and UZ For a dynamically stable solution providing a good fit to the eclipse time variations remains to be found. With the on-going accretion in these systems the situation is more difficult due to scatter introduced by eclipse profile variations. Further observations will therefore show whether the periodic variations are coherent or not.

In systems like e.g. DP Leo where only one planet is currently detected, the dynamical stability cannot be taken as an additional test. In the wide orbits, the feedback onto the binary itself is very small and irrelevant for the stability of the planetary system. We currently investigate, whether the feedback can have an influence on the orbital evolution of the binary and whether this could be detected.

The ultimate proof for the existence of PCE planets would be the detection with a second method. In the late nineties, the detection of the transit of one of the planets detected via the radial velocity method removed all doubts about the interpretation of radial velocity variations (Charbonneau et al. 2000; Henry et al. 2000). The chance for a transit in one of the PCE binary planets is very small due to the large orbital periods. This also makes the detection via the radial velocity method very challenging, since the timing and radial velocity are sensitive to large and small orbital separations respectively. The low number of spectral lines of the primary, the much larger radial velocity signal from the secondary and the long orbital periods make this a very difficult task. For direct imaging, the separation of the planets from the binary is, however, too low. A quick success for an independent confirmation of at least one of the PCE planets will therefore not be available.

Finally, it should be noted, that a circum-binary planet has now also been detected around a MS-MS binary (Kepler-16b, Doyle et al. 2011). With two M-stars, this system is not a direct progenitor of the PCE planetary systems, but it demonstrates that circum-binary planets already exist on the main sequence. The KEPLER mission certainly has the potential to find more circum-binary planets around MS pairs. Together with a growing number of bona-fide planets in PCE binaries and an estimate of the frequency of such systems it will be possible to study the evolution of planets and planetary systems from the main sequence phase of the host star up to late phases of stellar evolution including dramatic phases with significant mass loss.

6. Discussion

RAYMUNDO BAPTISTA: In CVs there are about 15 systems showing cyclical period changes. Systems above the period gap show 100-200s modulation amplitudes, while systems below the period gap show amplitudes that are lower by an order of magnitude. In a third body interpretation, how would the planets know they rotate around a CV above or below the period gap?

STEFAN DREIZLER: Not all period changes can be attributed to third bodies. I have shown e.g. the example of UX Uma. The presence of a third or fourth body has to be carefully investigated system by system. Some systems show non-coherent variations, but others like NN Ser show variations where Keplerian orbits can very well reproduce the observed O-C diagram. With very few well confirmed planets around post-common envelope binaries, the question of systematic differences for those above or below the period gap is too early.

DONALD W. HOARD: Have you observed enough systems to make a meaningful estimate of the frequency of circum-binary planets?

STEFAN DREIZLER: We prepare for it by observing a large sample within our *PlanetFinder* school project. A status report on this project will be published very soon (Backhaus et al. 2011).

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References

Africano J., Wilson J., 1976, PASP, 88, 8
Applegate J. H., 1992, ApJ, 385, 621
Backhaus U., et al. A&A, submitted
Beuermann K., et al., 2009, A&A, 507, 385
Beuermann K., et al., 2010, A&A, 521, L60
Beuermann K., et al., 2011, A&A, 526, A53
Beuermann K., et al., A&A, submitted
Charbonneau D., Brown T. M., Latham D. W., Mayor M., 2000, ApJ, 529, L45
Dai Z., Qian S.-B., 2010, PASJ, 62, 965
Dai Z.-B., Qian S.-B., Fernández Lajús E., Baume G. L., 2010, MNRAS, 409, 1195
Doyle L. R., et al., 2011, Sci, 333, 1602
Drake A. J., et al., 2010, arXiv, `arXiv:1009.3048`
Guinan E. F., Ribas I., 2001, ApJ, 546, L43
Haefner R., Fiedler A., Butler K., Barwig H., 2004, A&A, 428, 181
Henry G. W., Marcy G. W., Butler R. P., Vogt S. S., 2000, ApJ, 529, L41

Horner J., Marshall J. P., Wittenmyer R. A., Tinney C. G., 2011, MNRAS, 416, L11
Kamiński K. Z., et al., 2007, AJ, 134, 1206
Kilkenny D., 2011, MNRAS, 412, 487
Kundra E., Hric L., 2011, Ap&SS, 331, 121
Lee J. W., Kim S.-L., Kim C.-H., Koch R. H., Lee C.-U., Kim H.-I., Park J.-H., 2009, AJ, 137, 3181
Mandel O. E., 1965, PZ, 15, 474
Mayor M., Queloz D., 1995, Natur, 378, 355
Mayor M., Lovis C., Pepe F., Ségransan D., Udry S., 2011, AN, 332, 429
Nather R. E., Robinson E. L., 1974, ApJ, 190, 637
Parsons S. G., et al., 2010, MNRAS, 407, 2362
Potter S. B., et al., 2011, MNRAS, 416, 2202
Qian S.-B., et al., 2008, ApJ, 689, L49
Qian S.-B., et al., 2009, ApJ, 695, L163
Qian S.-B., et al., 2009, ApJ, 706, L96
Qian S.-B., Liao W.-P., Zhu L.-Y., Dai Z.-B., 2010, ApJ, 708, L66
Qian S.-B., et al., 2011, MNRAS, 414, L16
Rubenstein E. P., Patterson J., Africano J. L., 1991, PASP, 103, 1258
Schwarz R., et al., 2009, A&A, 496, 833
Silvotti R., et al., 2007, Natur, 449, 189
Wittenmyer R. A., et al., 2011, arXiv, arXiv:1110.2542
Wolszczan A., Frail D. A., 1992, Natur, 355, 145