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Planets Around White Dwarf Binaries

M.C.P. Bours,[1] T.R. Marsh,[1] and S.G. Parsons[2]

[1]*Department of Physics, University of Warwick, Coventry CV4 7AL, UK*

[2]*Departamento de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Avenida Gran Bretana 1111, Valparaíso, Chile*

Abstract. White dwarfs in eclipsing close binary stars enable very precise timing. Within the past decade the number of such systems has grown rapidly and we now know of more than 55 white dwarfs in eclipsing detached systems and over 130 in cataclysmic variables. Departures in eclipse times from constant period ephemerides of order 10 to over 100 seconds have been seen from eclipse timing in many of these systems. A possible explanation for the variations in orbital period is the presence of low-mass bodies in wide orbits around the binary. This explanation is still not proven and variations intrinsic to the binaries themselves are hard to rule out for certain. One test of the planetary hypothesis is to demonstrate that the orbits are dynamically stable, and that they correctly predict eclipse times of the systems. Using observations taken with the high-speed camera ULTRACAM and the RISE camera on the Liverpool Telescope, we fit the observed deviations from the expected eclipse times with models that include one or two planets. We investigate the orbital stability of the resulting systems. In the case of the star NN Serpentis we find that the planetary model appears to provide a good predictor of the timing behaviour, and its orbits are dynamically stable over the 1 million years since its formation. Both detached white dwarf binaries and semi-detached cataclysmic variables show increasingly convincing evidence for circumbinary planets.

1. White dwarfs in eclipsing binaries

Our targets are eclipsing binaries with typical orbital periods of 90 minutes to 12 hours. The primary, more massive, star is a white dwarf (WD) and the secondary star a low-mass, typically M dwarf (dM), star.

These white dwarf binaries come in two types. Firstly, the detached post common-envelope binaries (WD+dM), which offer extremely precise eclipse times, but are relatively rare. Secondly, the semi-detached cataclysmic variables (CVs), in which the WD accretes material from its companion. These binaries are much more numerous but more complicated systems. A third type of binary suitable for eclipse timing is the double white dwarf (WD+WD) system, but at present there are only 4 known eclipsing WD+WD binaries. For the other two types the number of known eclipsing binaries has grown explosively in recent years. In the last ten years the number of CVs has grown from 55 to 130 and in the last three years alone 50 of the currently known 57 detached WD+dM binaries have been discovered. This fast increase is largely due to surveys such as the Sloan Digital Sky Survey and the Catalina Sky Survey.

2. Observations

Most of our observations are done with the high-speed, portable camera ULTRACAM (Dhillon, V. S. and Marsh, T. R. and Stevenson, M. J., et al. 2007), which has been mounted on the William Herschel Telescope (4.2m), the Very Large Telescope (8.2m) and the New Technology Telescope (3.6m). We have supplemented this high precision data with observations from the RISE camera on the robotic Liverpool Telescope (2m)[1], which allows us to monitor binaries frequently over long periods of time.

Fig. 1 shows example light curves of both detached and semi-detached eclipsing white dwarf binaries. The main features in these light curves result from the small size of the white dwarf with respect to its companion. The ingress and egress features of the white dwarf's eclipse by the M dwarf are sharp and short, typically lasting for about 30 seconds (see the left hand side of Fig. 1), allowing for eclipse timing with an accuracy as small as 0.1 second. In semi-detached binaries the accretion stream, accretion disc and bright spot (where the accretion stream impacts the accretion disc) somewhat complicate the situation. However, if the eclipse of the white dwarf is clearly visible in the light curve, or if the white dwarf is magnetic eclipse timing can still be very accurate. In magnetic systems the accretion stream will start following the field lines and the material accretes at the magnetic poles of the white dwarf. This creates an extremely small and hot region, for which the ingress and egress last only a few seconds (see the right hand side of Fig. 1).

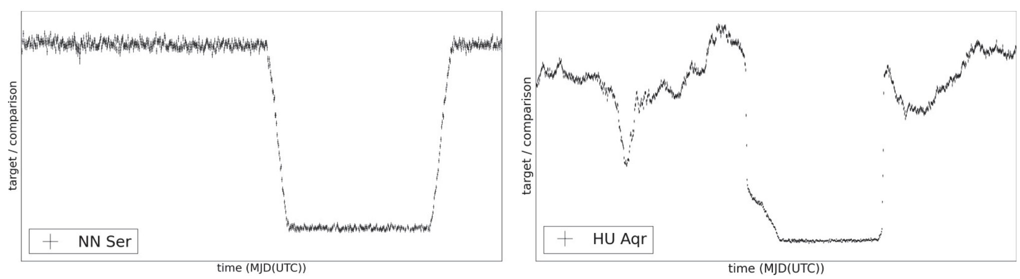

Figure 1. Left hand side: light curve of NN Serpentis, a detached WD+dM binary. The sharp features are the ingress and egress of the white dwarf when it moves behind its M dwarf companion. Right hand side: light curve of HU Aquarii, a CV, showing features of the accretion stream, the bright spot, the accretion disc and the hot spot where the matter after following the white dwarf's magnetic field lines accretes onto the white dwarf. Both targets were observed with ULTRACAM.

3. Orbital period variations

The sharp eclipse features allow very accurate determination of the eclipse times. We compare these observed times to expected eclipse times, as calculated with a linear ephemeris using a constant orbital period. The eclipse time T is given by

[1]http://telescope.livjm.ac.uk/Info/TelInst/Inst/RISE/

$$T = T_0 + P_{orb} \cdot E \tag{1}$$

where T_0 is a reference epoch at which the binary cycle number E is zero and P_{orb} is the binary's orbital period. An insightful way of comparing the observed (O) and calculated (C) eclipse times is an O-C diagram, shown in Fig. 2 for the detached white dwarf binary QS Vir. The large variations are non-linear in nature, indicating that the binary's orbital period is changing with time. These O-C variations are observed in most of the well-enough studied white dwarf binaries and could have several causes. Here we focus on two of these: Applegate's mechanism and circumbinary planetary companions.

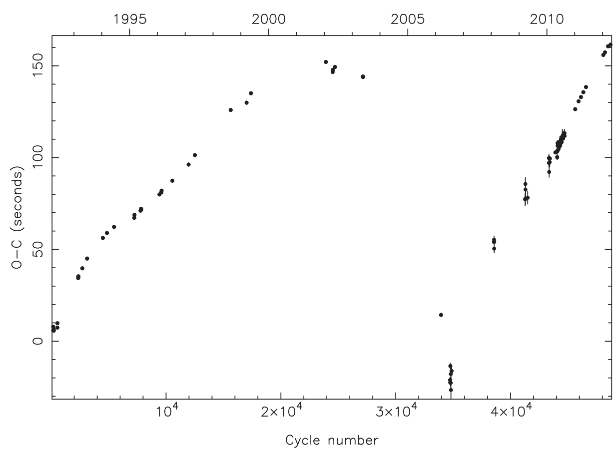

Figure 2. Observed minus calculated (O-C) in seconds as a function of the cycle number for QS Vir, a detached binary with an orbital period of $P_{orb} \simeq 0.150$ days. The observations span ~ 20 years and are a combination of ULTRACAM data, LT+RISE data and data from Parsons, S. G. and Marsh, T. R. and Copperwheat, C. M., et al. (2010), O'Donoghue, D. and Koen, C. and Kilkenny, D., et al. (2003), Kawka, A. and Vennes, S. and Koch, R., et al. (2002) and Qian, S.-B. and Liao, W.-P. and Zhu, L.-Y., et al. (2010).

3.1. Applegate's mechanism

One process that might cause semi-periodic variations in orbital period was first introduced by Applegate (1992). The mechanism is based on the presence of solar-like magnetic cycles in the M dwarf. These cause differential rotation within the star, changing the gravitational quadrupole moment which in turn leads to variations in the binary's orbital distance and speed. However, this process requires energy and one can do a quick calculation to see whether the energy required for the O-C variations is available in the low-mass main sequence star. Assuming that all the star's energy can be redirected into this process, an upper limit for the orbital period variations can be set. There are several cases known where Applegate's mechanism fails to be able to explain the orbital period variations (Brinkworth, C. S. and Marsh, T. R. and Dhillon, V. S., et al. 2006; Parsons, S. G. and Marsh, T. R. and Copperwheat, C. M., et al. 2010, Fig. 2).

3.2. Planetary companions

Another possible cause for the orbital period variations is the presence of planet-like bodies in wide circumbinary orbits around the binary. The principle is illustrated in Fig. 3, where the low-mass third companion slightly shifts the system's center of mass. Depending on the exact position of the binary in its orbit, the observed eclipse of the white dwarf will occur slightly earlier or later than was expected from a linear ephemeris and constant orbital period.

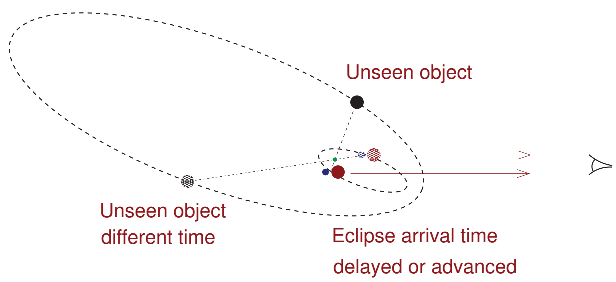

Figure 3. A compact binary accompanied by an unseen planet-like object. The observer is on the right hand side, seeing two eclipses at different times in the binary's orbit, induced by the third body. Due to the slight influence of this additional mass the eclipse of the white dwarf will occur earlier or later than expected from calculations using a linear ephemeris and constant orbital period.

In recent years the existence of circumbinary planets has been proven without a doubt. Using Kepler data several double main sequence star binaries have been observed in which one or more planets transit the binary stars (Armstrong, D. and Pollacco, D. and Watson, et al. 2012; Orosz, J. A. and Welsh, W. F. and Carter, J. A., et al. 2012; Orosz, J. A. and Welsh, W. F. and Carter, J. A., et al. 2012; Welsh, W. F. and Orosz, J. A. and Carter, J. A., et al. 2012; Doyle, L. R. and Carter, J. A. and Fabrycky, D. C., et al. 2011). However, these planets have much shorter periods than the hypothetical planets around evolved binaries. Although the existence of circumbinary planets around white dwarf binaries remains to be proven the behaviour of several white dwarf binaries strongly indicates that they are indeed accompanied by planets.

One good example is the binary NN Serpentis, a detached WD+dM binary with an orbital period $P_{\mathrm{orb}} = 3.122$ hours (Beuermann, K. and Hessman, F. V. and Dreizler, S., et al. 2010; Parsons, S. G. and Marsh, T. R. and Copperwheat, C. M., et al. 2010; Brinkworth, C. S. and Marsh, T. R. and Dhillon, V. S., et al. 2006). The white dwarf's temperature indicates that it is about 1 Myr old. Fig. 4 shows a part of the O-C diagram, covering the measured eclipse times from 2002 until the present. Eclipse times from before 2010 (left of the dashed line) were used to fit models which include two planets (Beuermann, K. and Hessman, F. V. and Dreizler, S., et al. 2010). These predicted a strong upturn in O-C values. Eclipse times from the last two years are in excellent agreement with this prediction and further constrain the model.

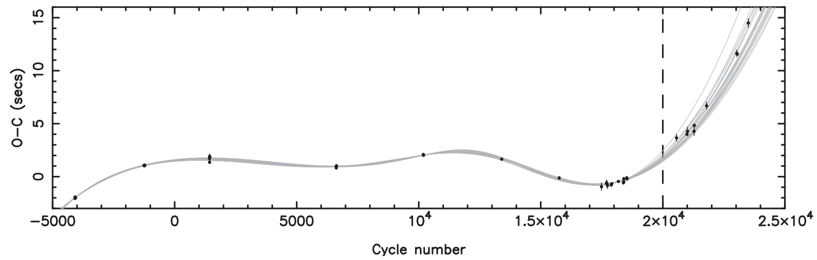

Figure 4. Eclipse times for the detached binary NN Ser, dating back to 2002 (almost entirely ULTRACAM data). The grey solid lines show Markov Chain Monte Carlo (MCMC) models including two planets based on the data to the left of the dashed line, the data to the right was not used to derive these orbital models. They predicted a very strong upturn in the O-C value and the data taken in the last two years (right of the dashed line) are clearly in good agreement with the models and constrains them further.

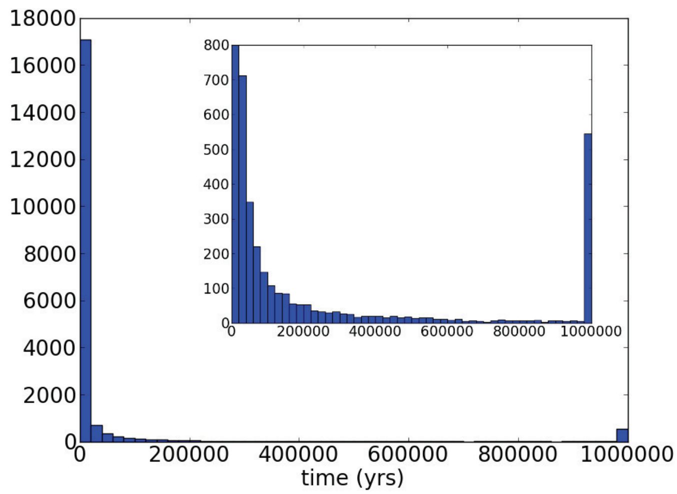

Figure 5. Stability histogram for the planetary MCMC models of NN Ser (Fig. 4). Each model was integrated using an N-body orbital integrator and ran until it reached the preset limit of 1 Myr or until it became unstable. The histogram indicates how long each model was integrated. The inset shows a zoom-in of the same plot.

4. Dynamical stability

A good fit to eclipse time data does not prove the existence of the planetary system under consideration. A crucial second step is to test the dynamical stability of the models by long-term N-body orbital integration. Fits to eclipse times (Qian, S.-B. and Liu, L. and Liao, W.-P., et al. 2011) have been proven to be extremely unstable (Wittenmyer, R. A. and Horner, J. and Marshall, J. P., et al. 2012; Hinse, T. C. and Lee, J. W. and Goździewski, K., et al. 2012) and therefore this step has to become an integral part of the data analysis and presentation. In the case of NN Ser we look for stability on a timescale of at least 1 Myr. A planetary system is considered to be unstable when planets collide with each other or the central object or when such a strong interaction occurs that a planet is ejected from the system and reaches a certain distance from the central object (much larger than the initial orbit of the outer planet). Fig. 5 shows a histogram for NN Ser indicating the time at which the planetary model considered becomes unstable during orbital integration. Although the large majority of models is unstable in the long run, several percent of them reaches the set limit of 1 Myr in a stable manner.

5. Summary and conclusions

- Almost all white dwarf binaries that have been well-enough studied over a long period of time show variations in their orbital period.
- Although intrinsic binary processes like Applegate's mechanism are difficult to rule out for certain, the evidence in favor of circumbinary planets around these binaries is accumulating.
- For NN Serpentis the planet hypothesis has succesfully predicted future eclipse times and long-term stable models exist.

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