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On the dynamical stability of the proposed planetary system orbiting NSVS 14256825

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ABSTRACT

We present a detailed dynamical analysis of the orbital stability of the two circumbinary planets recently proposed to orbit the evolved eclipsing binary star system NSVS 14256825. As is the case for other recently proposed circumbinary planetary systems detected through the timing of mutual eclipses between the central binary stars, the proposed planets do not stand up to dynamical scrutiny. The proposed orbits for the two planets are extremely unstable on time-scales of less than a thousand years, regardless of the mutual inclination between the planetary orbits.

For the scenario where the planetary orbits are coplanar, a small region of moderate stability was observed, featuring orbits that were somewhat protected from destabilization by the influence of mutual 2:1 mean-motion resonance between the orbits of the planets. Even in this stable region, however, the systems tested typically only survived on time-scales of the order of 1 Myr, far shorter than the age of the system.

Our results suggest that if there are planets in the NSVS 14256825 system, they must move on orbits dramatically different to those proposed in the discovery work. More observations are clearly critically required in order to constrain the nature of the suggested orbital bodies.

Key words: planets and satellites: dynamical evolution and stability – binaries: close – binaries: eclipsing – stars: individual: NSVS 14256825 – planetary systems.

1 INTRODUCTION

The intriguing possibility of circumbinary planets has been a feature of science-fiction for decades. Theoretical studies of planetary formation have shown that such systems are indeed possible (Quintana & Lissauer 2006; Gong, Zhou & Xie 2013), and that they can be dynamically stable (Kubala, Black & Szebehely 1993; Holman & Wiegert 1999), but their secure detection remained quite elusive, even in this present age of accelerating exoplanetary discovery. Finally, in late 2011, the first unambiguous example of a circumbinary planet was announced by the Kepler science team (Doyle et al. 2011). This discovery was quickly followed by the first multiple-planet circumbinary system, Kepler-34 (Orosz et al. 2012), and two additional circumbinary systems (Orosz et al. 2012; Welsh et al. 2012). These exciting results have yielded a first estimate that ∼1 per cent of close binary stars host such circumbinary planets.

In addition to the *Kepler* discoveries, there is a growing body of literature claiming the detection of circumbinary planets orbiting post-common-envelope host stars. Such objects can, in theory, be detected by light-travel-time variations: as the postulated planetary companions orbit the central stars, they cause those stars to move back and forth as they orbit around the system's centre of mass. As a result, the distance between the Earth and the host stars varies as a function of time, meaning that the light from the stars must sometimes travel further to reach us than at other times. This effect results in measurable variations in the timing of mutual eclipse events between the two stars that can be measured from the Earth. The stars proposed as hosts of circumbinary planets detected in this manner include cataclysmic variables (e.g. UZ For; Potter et al. 2011), pre-cataclysmic variables (NN Ser; Beuermann et al. 2010) and detached subdwarf-M dwarf (e.g. HW Vir; Beuermann et al. 2012b) or subdwarf-white dwarf (e.g. RR Cae; Qian et al. 2012) binaries. Zorotovic & Schreiber (2013) provide a complete summary of the 12 proposed post-common-envelope planetary systems in their table 2.

While the profusion of circumbinary planets claimed to orbit post-common-envelope binaries would suggest that such systems are extremely common, all is not as it seems. When subjected to rigorous dynamical testing, a great many of these proposed planetary systems have been found to be simply unfeasible. That is, the orbits of the proposed planets are such that, if they were truly planets, they would rapidly experience significant and ultimately catastrophic mutual interactions (ejections or collisions). Recently, several of the proposed circumbinary multiple-planet systems have

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Table 1. Data on the NSVS 1425 system from Almeida et al. (2012b).

Parameter	Inner planet	Outer planet
Eccentricity	0.0 ± 0.08	0.52 ± 0.06
ω (degrees)	11.4 ± 7	97.5 ± 8
Orbital period (yr)	3.49 ± 0.21	6.86 ± 0.25
Orbital radius (au)	1.9 ± 0.3	2.9 ± 0.6
$M \sin i$ ($M_{\rm Jup}$)	2.8 ± 0.3	8.0 ± 0.8

been tested in this manner. Highly detailed dynamical maps, showing the lifetimes of a wide range of orbital configurations for the planets in question, demonstrate that a number of these candidate systems are dynamically unstable on time-scales of $\lesssim 10^4$ yr. Some proposed circumbinary systems investigated in this way include HU Aqr (Horner et al. 2011; Hinse et al. 2012; Wittenmyer et al. 2012a), NN Ser (Horner et al. 2012b) and HW Vir (Horner et al. 2012a). The same dynamical mapping techniques have also been applied to multiple-planet systems discovered by radial velocity studies, in order to check their long-term stability (Wittenmyer et al. 2012b) and to assess the role of low-order resonances (Robertson et al. 2012a,b; Wittenmyer, Horner & Tinney 2012c).

NSVS 14256825 (hereafter NSVS 1425) is an eclipsing binary consisting of a subdwarf OB star and an M dwarf orbiting one another with a period of 0.110374 d (Almeida et al. 2012a). The combination of a hot subdwarf and a late-type dwarf produces significant reflection effects in the light curves, and such systems are known as 'HW Vir' systems, of which only 10 are currently known (Almeida, Jablonski & Rodrigues 2012b). Since its discovery in the Northern Sky Variability Survey (Woźniak et al. 2004), eclipse timings have been reported by Wils, di Scala & Otero (2007), Kilkenny & Koen (2012) and Beuermann et al. (2012a). A linear period change was noted by Kilkenny & Koen (2012), and Beuermann et al. (2012a) reported a cyclic period change, which they attributed to the presence of an $\sim 12\, M_{\rm Jup}$ planet with an unconstrained period $P \gtrsim 20$ yr. Most recently, Almeida et al. (2012b) presented additional eclipse timings and, by combining all available timings, fitted two periodicities which were then attributed to the influence of two unseen circumbinary planets. The reported parameters for the candidate planets are given in Table 1. In this work, we bring our well-tested dynamical mapping techniques (Section 2) to bear on the candidate NSVS 1425 planetary system. We determine the dynamical stability of the complete $\pm 3\sigma$ range of orbital parameters, and we test the effect of mutual inclinations between the two planets (Section 3). We discuss the results and make our conclusions in Section 4.

2 DYNAMICAL ANALYSIS

As in our previous work (e.g. Marshall, Horner & Carter 2010; Horner et al. 2011, 2012b), we used the Hybrid integrator within the N-body dynamics package MERCURY (Chambers 1999) to perform our integrations. We held the initial orbit of the inner planet fixed at its best-fitting parameters, as reported in Almeida et al. (2012b), and then created 126 075 test systems. In those test systems, the initial orbit of the outer planet was varied systematically in semimajor axis a, eccentricity e, periastron argument ω and mean anomaly M, resulting in a $41 \times 41 \times 15 \times 5$ grid of 'clones' spaced evenly across the 3σ range in those parameters (as given in Table 1). For the mean anomaly, not reported in Almeida et al. (2012b), we simply tested the entire allowed range 0°–360°. We assumed the central stars to be a single point mass, an acceptable approximation as the binary separation is ≪ orbital radius of the inner planet, with $M = 0.62\,{\rm M}_\odot$ (Beuermann et al. 2012a).[1] We assumed the planets were coplanar with each other and had masses equivalent to their minimum mass, $M \sin i$. We then followed the dynamical evolution of each test system for a period of 100 Myr, and recorded the times at which either of the planets was removed from the system. Planets were removed if they collided with one another, hit the central body or reached a barycentric distance of 10 au.

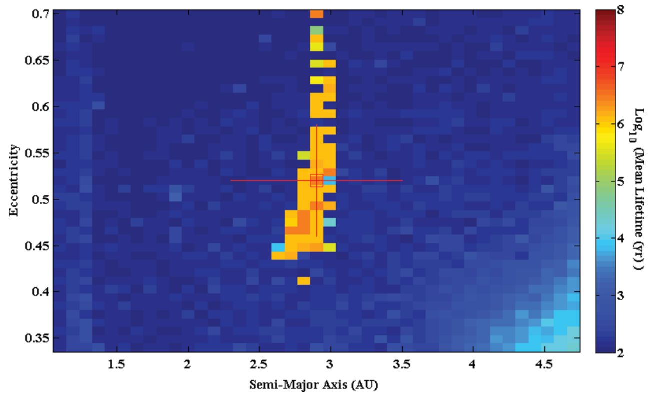

Figure 1. Dynamical stability of the NSVS 1425 system as proposed by Almeida et al. (2012b), as a function of the semimajor axis a and eccentricity e of the outer planet. The mean lifetime of the planetary system (in $\log_{10}$(lifetime/yr)) at a given a–e coordinate is denoted by the colour of the plot. The lifetime at each a–e location is the mean value of 75 separate integrations carried out on orbits at that a–e position (testing a combination of 15 unique ω values, and 5 unique M values). The nominal best-fitting orbit for the outer planet is shown as the small red square with $\pm 1\sigma$ error bars.

In addition to this highly detailed 'nominal' run, we examined the effects of mutual inclinations between the two planets by running further suites of simulations at lower resolution (e.g. Horner et al. 2011; Wittenmyer et al. 2012c). We varied the initial orbit of the outer planet as above, resulting in a $21 \times 21 \times 5 \times 5$ grid in a, e, ω and M, respectively (for a total of 11 025 test systems). We ran five such scenarios, with the inclination between the two planets set at 5°, 15°, 45°, 135° and 180° (the latter two corresponding to a retrograde orbit for the outer planet). Again, the 11 025 test systems were allowed to run for 100 Myr, or until the system was destabilized due to ejection or collision.

3 RESULTS

Fig. 1 shows the stability of the nominal orbits for the NSVS 1425 system as given in Almeida et al. (2012b). It is immediately apparent that the vast majority of the $\pm 3\sigma$ parameter space is extremely unstable, with mean lifetimes of less than 1000 yr. This result is not particularly surprising, given that the great majority of solutions tested place the two planets on mutually crossing orbits – meaning that close encounters between the two are a certainty.

The nominal best-fitting orbit of the outer planet does fall in a narrow strip of increased stability, featuring mean lifetimes $\sim 10^6$ yr. However, as the subdwarf B host star has evolved well off the main

[1] We note that Almeida et al. (2012a) recently determined a combined mass of 0.528 ± 0.074 for the central stars, 1.2σ smaller than our assumed value. This small difference would have no effect on the interactions *between* the planets, only on the overall *scale* of the system, and hence does not affect our results.

sequence, one would expect the system to be considerably older than this mean lifetime. While the ages of subdwarf B stars are highly uncertain (Hu et al. 2010), even an A-type progenitor would make the system ∼0.5 Gyr old. Population-synthesis models of the close binary progenitors of these post-common-envelope systems show that the initial mass distribution of primary stars that result in subdwarf B stars ranges from 1.0 to 1.8 $M_{\odot}$. The shortest lived (i.e. highest mass) progenitors would then evolve off the main sequence in $\sim 2 \times 10^{9}$ yr. Hence, any planets which existed before the common-envelope stage would be expected to demonstrate dynamical stability on a time-scale far longer than that exhibited by the NSVS 1425 system.

The observed strip of moderate stability is attributed to the protective influence of the mutual 2:1 mean-motion resonance between the two proposed planets. Such resonant protection is well known, both in our own Solar system (e.g. Horner & Lykawka 2010; Lykawka et al. 2011) and in exoplanetary science (e.g. Rivera et al. 2010; Robertson et al. 2012a,b). Indeed, it is interesting to compare our results with those obtained for the proposed planets around HU Aqr (e.g. fig. 1 of Horner et al. 2011). In both cases, the proposed outer planet lies on a highly eccentric best-fitting orbit ($e \sim 0.5$) that crosses that of the innermost planet and the two planets are close to mutual 2:1 mean-motion resonance. Additionally, the proposed system proves to be dynamically unstable on typical time-scales of hundreds or thousands of years.

We then considered the possibility of non-zero mutual inclinations between the two candidate planets in the NSVS 1425 system. For a significantly interacting planetary system, retrograde orbits can provide a dynamically stable configuration (e.g. Eberle & Cuntz 2010; Horner et al. 2011; Quarles, Cuntz & Musielak 2012; Morais & Giuppone 2012). To explore the dynamical stability of systems resulting from such non-coplanar scenarios, we performed a second suite of simulations at lower resolution, as described in Section 2. The results of the five mutually inclined scenarios are shown in Fig. 2, along with the nominal coplanar scenario from Fig. 1. We see that mutually inclined scenarios are even more unstable than

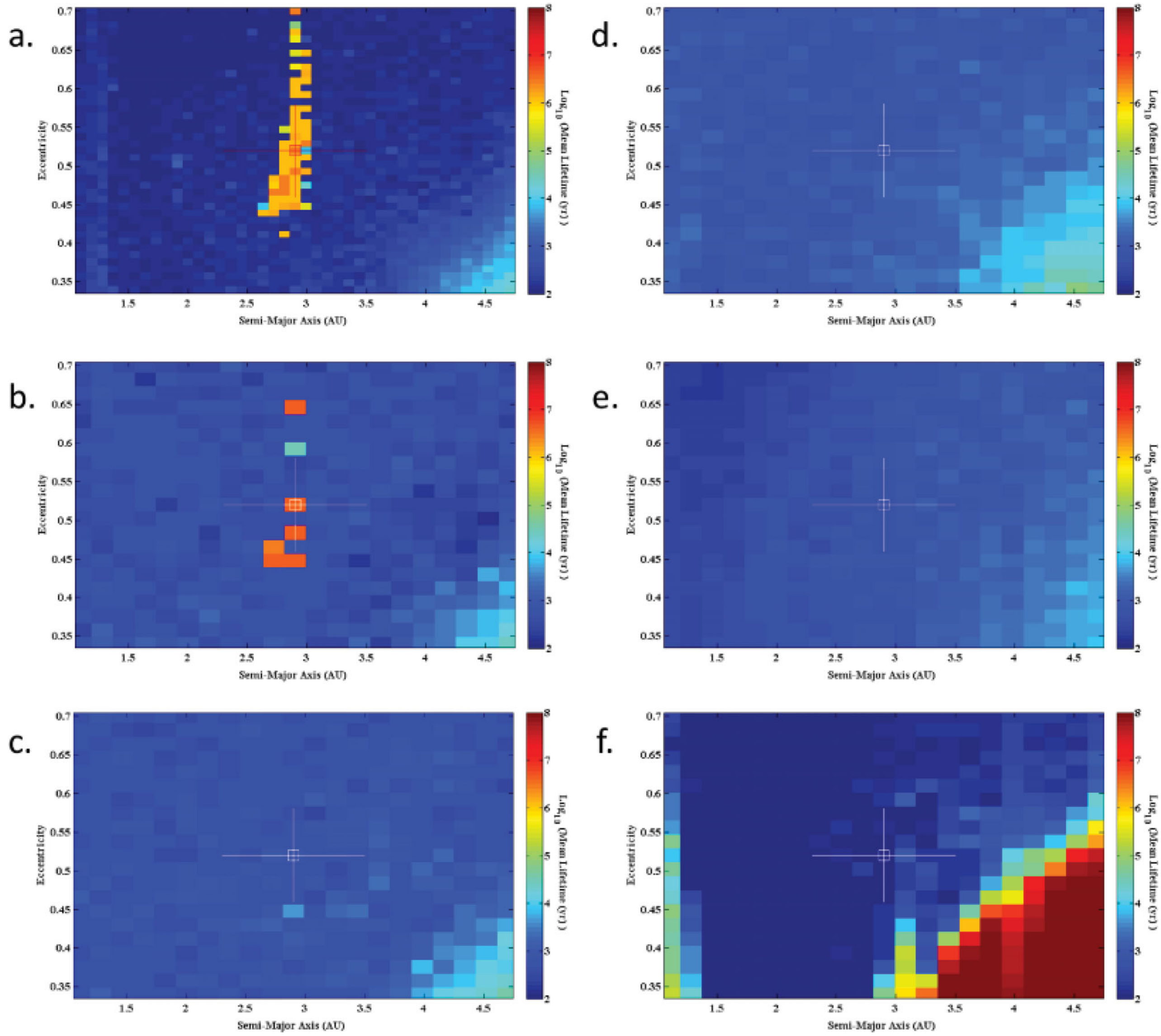

Figure 2. Dynamical stability for the NSVS 1425 system, for six values of inclination between the two planets. Panels (a) through (f) represent mutual inclinations of 0°, 5°, 15°, 45°, 135° and 180°, respectively. Panel (a) is a duplicate of Fig. 1, reprised here for ease of comparison. As in the previous figure, the colour bar represents the log of the mean survival time at each a–e position (testing a combination of five ω values and five M values).

the coplanar scenario. Even for the 180° configuration (i.e. retrograde and coplanar, panel f), the only region of stability appears in the lower right, at the lowest eccentricities and largest semimajor axis for the outer planet. As was the case for HU Aquarii (Horner et al. 2011), the highly stable region is restricted to orbits which have periastron distances of several Hill radii from the inner planet. However, this region lies well beyond the 1σ uncertainties of the orbits derived by Almeida et al. (2012b).

4 DISCUSSION AND CONCLUSIONS

We have shown that the two circumbinary planets proposed by Almeida et al. (2012b) are dynamically unfeasible in virtually any configuration within 3σ of their derived orbital parameters. Based on our results, a mechanism other than, or in addition to, one (or more) planets is needed to explain the observed period variations. Zorotovic & Schreiber (2013) note that about 90 per cent of eclipsing post-common-envelope binaries are reported to have timing variations, nearly all of which have been attributed to one or more orbiting circumbinary planets. Both avenues to such planetary systems – survival of the planets through the asymptotic giant branch (AGB) and planetary nebula phase, or secondary accretion from the ejected envelope of the primary star – are possible but highly uncertain (e.g. Postnov & Prokhorov 1992; Tavani & Brookshaw 1992; Phinney & Hansen 1993; Villaver & Livio 2007; Hansen, Shih & Currie 2009; Kunitomo et al. 2011; Veras et al. 2011; Mustill & Villaver 2012).

Zorotovic & Schreiber (2013) examined the formation and observational statistics of circumbinary planets in order to investigate the puzzling trend that fully 90 per cent of post-common-envelope eclipsing binaries appear to host planets. They note that observations of disc-bearing pre-main-sequence stars (Kraus et al. 2012) indicate that the circumbinary disc lifetime is too short ($\lesssim$1 Myr) to form giant planets by core accretion. Observational results from *Kepler* also point to a main-sequence circumbinary giant planet frequency of $\sim$1 per cent (Welsh et al. 2012). Wittenmyer et al. (2011) estimate the frequency of giant planets in 3–6 au orbits to be no more than 37 per cent, based on data on single main-sequence stars from the Anglo-Australian Planet Search. All of these strands of evidence led Zorotovic & Schreiber (2013) to the conclusion that 'virtually all close-compact binaries are unlikely to be explained by first-generation planets.'

Another potential solution to the near-ubiquitous presence of planets around evolved binaries is the formation of these companions in the post-main-sequence circumstellar envelope produced by the subdwarf OB progenitor as it evolves through its AGB phase. The amount of material cast off by an AGB star (up to 70 per cent of the stellar mass; Habing & Olofsson 2004) is comparable to that of the Minimum Mass Solar Nebula (Weidenschilling 1977) and the lifetime of the AGB phase is similar to that of gas-rich protoplanetary discs within which first-generation planet formation occurs (Hernández et al. 2007), lending plausibility to the idea of a second generation of planet formation. However, this second-generation planet formation scenario is highly speculative and requires further scrutiny (and detailed modelling) before it can be considered a viable answer (Akashi & Soker 2008; Perets 2010).

As was the case in earlier studies of proposed circumbinary planets in highly evolved systems (e.g. Horner et al. 2011, 2012a; Wittenmyer et al. 2012a), we find that the planetary system proposed in the evolved binary system NVSS 1425 is simply not dynamically feasible. Our results suggest that some mechanism other than planets must be responsible for the observed eclipse-timing variations, and once again highlight the critical importance of performing detailed dynamical analyses of potential new planetary systems in order to determine whether the proposed systems make sense.

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REFERENCES

Akashi M., Soker N., 2008, New Astron., 13, 157
Almeida L. A., Jablonski F., Tello J., Rodrigues C. V., 2012a, MNRAS, 423, 478
Almeida L. A., Jablonski F., Rodrigues C. V., 2012b, preprint (arXiv:1210.3055)
Beuermann K. et al., 2010, A&A, 521, L60
Beuermann K. et al., 2012a, A&A, 540, A8
Beuermann K., Dreizler S., Hessman F. V., Deller J., 2012b, A&A, 543, A138
Chambers J. E., 1999, MNRAS, 304, 793
Doyle L. R. et al., 2011, Sci, 333, 1602
Eberle J., Cuntz M., 2010, ApJ, 721, L168
Gong Y.-X., Zhou J.-L., Xie J.-W., 2013, ApJ, 763, L8
Habing H. J., Olofsson H., 2004, Asymptotic Giant Branch Stars. Springer, Berlin
Hansen B. M. S., Shih H.-Y., Currie T., 2009, ApJ, 691, 382
Hernández J. et al., 2007, ApJ, 662, 1067
Hinse T. C., Lee J. W., Goździewski K., Haghighipour N., Lee C.-U., Scullion E. M., 2012, MNRAS, 420, 3609
Holman M. J., Wiegert P. A., 1999, AJ, 117, 621
Horner J., Lykawka P. S., 2010, MNRAS, 405, 49
Horner J., Marshall J. P., Wittenmyer R. A., Tinney C. G., 2011, MNRAS, 416, L11
Horner J., Hinse T. C., Wittenmyer R. A., Marshall J. P., Tinney C. G., 2012a, MNRAS, 427, 2812
Horner J., Wittenmyer R. A., Hinse T. C., Tinney C. G., 2012b, MNRAS, 425, 749
Hu H., Glebbeek E., Thoul A. A., Dupret M.-A., Stancliffe R. J., Nelemans G., Aerts C., 2010, A&A, 511, A87
Kilkenny D., Koen C., 2012, MNRAS, 421, 3238
Kraus A. L., Ireland M. J., Hillenbrand L. A., Martinache F., 2012, ApJ, 745, 19
Kubala A., Black D., Szebehely V., 1993, Celest. Mech. Dyn. Astron., 56, 51
Kunitomo M., Ikoma M., Sato B., Katsuta Y., Ida S., 2011, ApJ, 737, 66
Lykawka P. S., Horner J., Jones B. W., Mukai T., 2011, MNRAS, 412, 537
Marshall J., Horner J., Carter A., 2010, Int. J. Astrobiol., 9, 259
Morais M. H. M., Giuppone C. A., 2012, MNRAS, 424, 52
Mustill A. J., Villaver E., 2012, ApJ, 761, 121
Orosz J. A. et al., 2012, Sci, 337, 1511
Perets H. B., 2010, preprint (arXiv:1001.0581)
Phinney E. S., Hansen B. M. S., 1993, Planets Around Pulsars, 36, 371
Postnov K. A., Prokhorov M. E., 1992, A&A, 258, L17
Potter S. B. et al., 2011, MNRAS, 416, 2202
Qian S.-B., Liu L., Zhu L.-Y., Dai Z.-B., Fernández L. E., Baume G. L., 2012, MNRAS, 422, L24
Quarles B., Cuntz M., Musielak Z. E., 2012, MNRAS, 421, 2930
Quintana E. V., Lissauer J. J., 2006, Icarus, 185, 1
Rivera E. J., Laughlin G., Butler R. P., Vogt S. S., Haghighipour N., Meschiari S., 2010, ApJ, 719, 890
Robertson P. et al., 2012a, ApJ, 749, 39

Robertson P. et al., 2012b, ApJ, 754, 50
Tavani M., Brookshaw L., 1992, Nat, 356, 320
Veras D., Wyatt M. C., Mustill A. J., Bonsor A., Eldridge J. J., 2011, MNRAS, 1332
Villaver E., Livio M., 2007, ApJ, 661, 1192
Weidenschilling S. J., 1977, Ap&SS, 51, 153
Welsh W. F. et al., 2012, Nat, 481, 475
Wils P., di Scala G., Otero S. A., 2007, Inf. Bull. Var. Stars, 5800, 1
Wittenmyer R. A., Tinney C. G., O'Toole S. J., Jones H. R. A., Butler R. P., Carter B. D., Bailey J., 2011, ApJ, 727, 102
Wittenmyer R. A., Horner J., Marshall J. P., Butters O. W., Tinney C. G., 2012a, MNRAS, 419, 3258
Wittenmyer R. A. et al., 2012b, ApJ, 753, 169
Wittenmyer R. A., Horner J., Tinney C. G., 2012c, ApJ, 761, 165
Woźniak P. R., Williams S. J., Vestrand W. T., Gupta V., 2004, AJ, 128, 2965
Zorotovic M., Schreiber M. R., 2013, A&A, 549, A95

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