The Astrophysical Journal, 706:L96–L99, 2009 November 20
doi:10.1088/0004-637X/706/1/L96

A SUBSTELLAR COMPANION TO THE WHITE DWARF–RED DWARF ECLIPSING BINARY NN Ser

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Received 2009 June 25; accepted 2009 October 15; published 2009 November 2

ABSTRACT

NN Ser is a short-period ($P = 3.12$ hr) close binary containing a very hot white dwarf primary with a mass of 0.535 $M_\odot$ and a fully convective secondary with a mass of 0.111 $M_\odot$. The changes in the orbital period of the eclipsing binary were analyzed based on our five newly determined eclipse times together with those compiled from the literature. A small-amplitude ($0\overset{d}{.}00031$) cyclic period variation with a period of 7.56 years was discovered to be superimposed on a possible long-term decrease. The periodic change was plausibly explained as the light-travel time effect via the presence of a tertiary companion. The mass of the tertiary companion is determined to be $M_3 \sin i' = 0.0107(\pm0.0017)\,M_\odot$ when a total mass of 0.646 $M_\odot$ for NN Ser is adopted. For orbital inclinations $i' \geqslant 49\overset{\circ}{.}56$, the mass of the tertiary component was calculated to be $M_3 \leqslant 0.014\,M_\odot$; thus it would be an extrasolar planet. The third body is orbiting the white dwarf–red dwarf eclipsing binary at a distance shorter than 3.29 AU. Since the observed decrease rate of the orbital period is about two orders larger than that caused by gravitational radiation, it can be plausibly interpreted by magnetic braking of the fully convective component, which is driving this binary to evolve into a normal cataclysmic variable.

Key words: binaries: close – binaries: eclipsing – stars: individual (NN Ser) – stars: low-mass, brown dwarfs – white dwarfs

1. INTRODUCTION

NN Ser (PG 1550+131) was discovered to be an eclipsing binary with an orbital period of ∼3.12 hr by Haefner (1989) who obtained a light curve that showed sine-shaped changes (∼0.6 mag) and very deep eclipses (>4.8 mag at $\lambda \sim 6500$ Å). However, because of the faintness of the binary system during eclipse, the true depth of the minimum could not be measured by him. A preliminary analysis by Haefner (1989) indicated that NN Ser is a detached progenitor of a cataclysmic binary. Because of the large temperature difference between the hot white dwarf and the cool red dwarf star, the binary shows strong reflection effect that was investigated by Wood & Marsh (1991) with the IUE spectra, and the white dwarf temperature was determined. Limits for the system parameters were also obtained by Haefner (1989). Later, by using phase-resolved blue and far red spectra, Catalan et al. (1994) derived radial velocities and improved the parameter of the system. However, since the true depth of the eclipse and the duration of the totality were unknown, the exact determination of the radii of the components was prevented. Recently, Haefner et al. (2004) and Parsons et al. (2009) determined more reliable parameters of the binary system by combining the VLT data together with earlier spectroscopy and photometry observations. Brinkworth et al. (2006) observed the secondary eclipse with the high speed CCD camera ULTRACAM, which revealed a high orbital inclination of $i \sim 88^\circ$.

The orbital period of NN ser was first determined by Haefner (1989), and the linear ephemeris of the binary was later revised by Pigulski & Michalska (2002) and Haefner et al. (2004). Brinkworth et al. (2006) reported that the orbital period of NN Ser decreased at a rate that was explained by angular momentum loss (AML) via magnetic braking (MB) of the fully convective component or the presence of a third body. More recently, analysis by Chen (2009) indicates that neither gravitational radiation nor MB can fully account for the period change of NN Ser. The tidal torques caused by the gravitational interaction between a circumbinary disk (CB) and the binary can efficiently extract the orbital angular momentum from the binary system and result in the period decrease (e.g., Chen et al. 2006). However, he found that the loss rates of angular momentum via the CB disk explain the period change observed in NN Ser only if the M dwarf has an ultra-high wind loss rate and a large fraction ($\delta \sim 10\%$) of wind loss is fed into the CB disk. Therefore, he pointed out that the presence of a third body in a long orbit around the binary might account for the changing period of NN Ser. To understand the properties of the variations in the orbital period of NN Ser, it has been monitored since 2009 May 20 with the 2.4 m telescope in the Lijiang station of the Yunnan Astronomical Observatory. Here we report the discovery of a cyclic change in the orbital period of NN Ser that reveals the presence of a tertiary companion, most likely a substellar companion, in this binary system.

2. NEW OBSERVATIONS AND THE ORBITAL PERIOD CHANGES OF NN Ser

The pre-cataclysmic variable, NN Ser, was monitored since 2009 May 20 by using the 2.4 m telescope in the Lijiang station of the Yunnan Astronomical Observatory. During the observation, a VersArray 1300B CCD camera was attached to the 2.4 m telescope. The integration time for each CCD image was 10 s. The light curves observed with the 2.4 m telescope on 2009 May 20 are displayed in Figure 1. The data outside the eclipse are of high quality, while those in the eclipse show large scatter. This may be caused by the fact that the binary system during eclipse is very faint. From our observations, five mid-eclipse times were obtained. They were measured by fitting three straight lines to the data around ingress (or egress) by the least-squares method. The first line was fitted to the out-of-eclipse observations, the second line with zero slope was fitted to the section in totality just after ingress (or before egress),

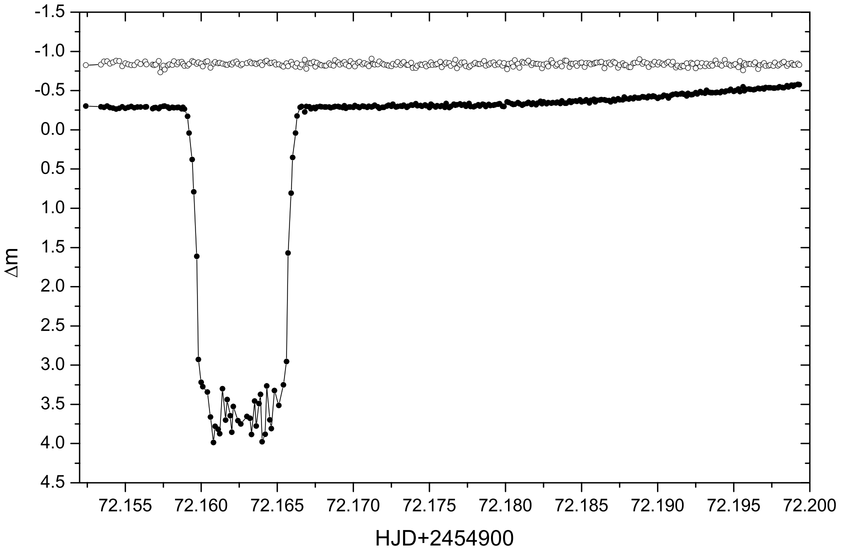

Figure 1. Light curve of NN Ser with no filters obtained with the 2.4 m telescope on 2009 May 20. The coordinates of the comparison and the check stars are $\alpha_{2000} = 15^{\mathrm{h}}52^{\mathrm{m}}58\overset{\mathrm{s}}{.}4$ and $\delta_{2000} = +12^\circ54'50\overset{\prime\prime}{.}3$ for the comparison and $\alpha_{2000} = 15^{\mathrm{h}}53^{\mathrm{m}}00\overset{\mathrm{s}}{.}6$ and $\delta_{2000} = +12^\circ54'02\overset{\prime\prime}{.}2$ for the check star. Solid dots refer to the magnitude differences between NN Ser and the comparison star, while open circles to the magnitude differences between the comparison star and the check star.

Table 1

New CCD Mid-Eclipse Times for NN Ser

J.D. (Bar.) +2400000 (days)	Errors (days)	Min.	Filters
47344.52466347	±0.0050000	I	Unknown
47703.54574409	±0.0000020	I	*UBVIR*
47703.67584114	±0.0000060	I	*UBVIR*
47704.71646600	±0.0000030	I	*UBVIR*
47705.62702779	±0.0000030	I	*UBVIR*
47705.75712450	±0.0000070	I	*UBVIR*
47712.78159377	±0.0001500	I	*UBVIR*
47713.82224430	±0.0001500	I	*UBVIR*
48301.91420304	±0.0001500	I	*UBVIR*
51006.54055320	±0.0002000	I	*UBVIR*
51340.71594081	±0.0002000	I	*V*
51667.47788233	±0.0004000	I	*V*
52412.44705640	±0.0000020	I	g'
52412.57713850	±0.0000020	I	g'
52413.48769770	±0.0000030	I	g'
52414.52833940	±0.0000030	I	g'
52415.56898100	±0.0000025	I	g'
52779.53316960	±0.0000021	I	g'
52781.61445130	±0.0000015	I	g'
52782.65509290	±0.0000021	I	g'
52784.47621510	±0.0000022	I	g'
53129.44867780	±0.0000070	I	g'
53129.57875970	±0.0000027	I	g'
53129.70883560	±0.0000050	I	g'
53130.48932290	±0.0000050	I	g'
54972.16349710	±0.00008	I	Clear
54973.07405535	±0.00010	I	Clear
54978.14717907	±0.00012	I	Clear
54986.08207887	±0.00012	I	Clear
54987.12283592	±0.00013	I	Clear

and the third straight line was fitted to the ingress (or egress) section. The time of mid-ingress (or egress) was taken to be the time when the third line crossed the average levels of the first two lines, and the mid-eclipse timings are the average value of the mid-ingress and mid-egress times. The errors listed in Table 1 are the standard deviation values.

Since Barycentric Dynamical Time (BJD) is a precise time system, which can differ from Heliocentric Julian Date (HJD) by up to 30 s, the 12 previous eclipse times, published by several investigators, i.e., Haefner (1989), Wood & Marsh (1991), Pigulski & Michalska (2002), Haefner et al. (2004), and our new five mid-eclipse times are converted to BJD. Moreover, the 13 recent eclipse times in BJD published by Brinkworth et al. (2006) are in units of modified Julian date, which differs from Julian date by $0\overset{\mathrm{d}}{.}5$. Thus, all the corrected data including the new five eclipse times in BJD are listed in Table 1, and an available linear ephemeris is needed for further analysis.

In order to match with BJD eclipse times, the ephemeris derived by Haefner et al. (2004) should be converted to BJD, which is

$$\mathrm{Min.\ I} = \mathrm{BJD}\,2447344.524617 + 0.1300801195 \times E. \qquad (1)$$

The converted ephemeris is used to calculate all 30 $O-C$ values of NN Ser. The corresponding $(O-C)_1$ diagram is shown in the upper panel of Figure 2, where our 5 new minimum times and the other 25 mid-eclipse times collected from the sources noted above were used.

As shown in Figure 2, the variation of the $(O-C)_1$ is more complex than that considered by Brinkworth et al. (2006). Since there may exist a cyclic variation and a long-term change as well, a sinusoidal term is added to a quadratic ephemeris to give a good description to the $(O-C)_1$ curve. By using the least-squares method, we determined,

$$\begin{aligned}\mathrm{Min.\ I} = {} & 2447344.52443(\pm0.00005) + 0\overset{\mathrm{d}}{.}1300801969\\ & \times (\pm0.0000000033) \times E - 3.92(\pm0.59) \times 10^{-13}\\ & \times E^2 + 0.00031(\pm0.00003)\sin[0\overset{\circ}{.}01698(\pm0.00002)\\ & \times E + 252\overset{\circ}{.}0(\pm6\overset{\circ}{.}8)],\end{aligned} \qquad (2)$$

with variance $\sigma = 9\overset{\mathrm{d}}{.}15 \times 10^{-5}$. To describe the quality of the fit between Equation (2) and our data, the χ^2 value is calculated to be ~1.0, which is unity and far less than the χ^2 value of linear fit 4.9 and of quadratic fit 3.8. According to the F-test proposed by Pringle (1975), we calculated the statistic system parameter $\lambda_1 = 37.06$ and $\lambda_2 = 39.05$ for Equation (2)

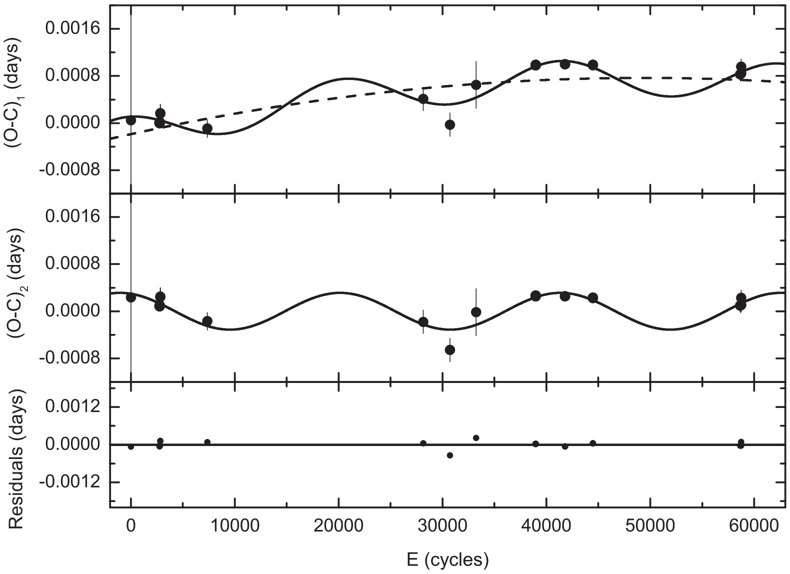

Figure 2. Upper panel: plot of the $(O - C)_1$ diagram of NN Ser with respect to the linear ephemeris given by Haefner et al. (2004). The solid line in the panel suggests a combination of a cyclic change and a long-term period decrease, while the dashed line refers to the period decrease. The $(O - C)_2$ curve of NN Ser with respect to the quadratic ephemeris in Equation (2) is shown in the middle panel where the periodic variation can be seen more clearly. After all period variations were removed, the residuals are shown in the lower panel where no changes can be traced.

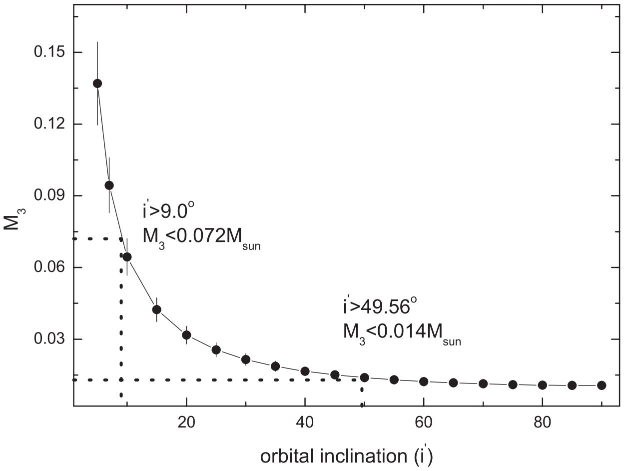

Figure 3. Relation between the mass M_3 $(M_\odot)$ and the orbital inclination i' of the tertiary component in the NN Ser system. The tertiary companion should be an extrasolar planet when the orbital inclination is larger than $49\overset{\circ}{.}56$.

compared to the linear fit and the quadratic fit, respectively, which indicate that a sinusoidal plus quadratic ephemeris is significant well above the 99.99% level. Thus, the best fit of the $O-C$ diagram for NN Ser is a cyclical modulation with a period of ~7.56 yr and an amplitude of $\sim 0\overset{\mathrm{d}}{.}00031$ superimposed on a secular orbital period decrease at a rate of $dP/dt = -6.0(\pm 0.9) \times 10^{-12}$ s/s $= -2.2(\pm 0.3) \times 10^{-9}$days yr^{-1}. The $(O - C)_2$ values that calculated the quadratic ephemeris in Equation (2) are plotted in the middle panel of Figure 2 where the cyclical change is seen more clearly. After both the continuous decrease and the periodic change were subtracted from the $(O - C)_1$ curve, the residuals are displayed in the lowest panel where no variations can be found implying that Equation (2) gives a good fit to the $(O - C)_1$ curve.

3. DISCUSSIONS AND CONCLUSIONS

The cyclic period changes in close binaries containing at least one cool component could be explained by the solar-type magnetic activity cycles (i.e., the Applegate mechanism; Applegate 1992). In the mechanism, a certain amount of angular momentum is assumed to be periodically exchanged between the inner and the outer parts of the convection zone, and therefore the rotational oblateness and thus the orbital period will vary when the cool component goes through its activity cycles. As in the cases of HW Vir, HU Aqr, and Z Cha (Qian et al. 2008a; Schwarz et al. 2009; Dai et al. 2009), the fully convective secondary in NN Ser rotates mainly as a rigid body, and lacks the thin interface layer between a radiative core and a convective envelope, where dynamo processes are thought to concentrate at for solar-type stars (e.g., Barnes et al. 2005). Analyses for the four systems indicated that the required energies are much larger than the total radiant energy of the M-type components (Qian et al. 2008a; Schwarz et al. 2009; Brinkworth et al. 2006; Dai et al. 2009), suggesting that the mechanism of Applegate cannot explain the cyclic period variations of the four binary systems. Moreover, as discussed by Qian et al. (2008a, 2008b) and Dai et al. (2009), a more general explanation of the cyclic period changes in close binaries would be the light-travel time effect via the presence of a tertiary companion.

Therefore, we analyzed NN Ser for the light-time effect that arises from the gravitational influence of a third body. We assumed the orbit of the third body to be circular by considering that the sine fit seems quite good. With the absolute parameters determined by Parsons et al. (2009), we derived the mass function and the mass of the third body as $f(m) = 2.78(\pm 0.93) \times 10^{-6}\,M_\odot$ and $M_3 \sin i' = 0.0107(\pm 0.0017)\,M_\odot$, respectively. The relation between the mass M_3 and the orbital inclination i' is displayed in Figure 3. When the orbital inclination of the third body is larger than $49\overset{\circ}{.}56$, the mass of the tertiary component corresponds to $M_3 \leqslant 0.014\,M_\odot$. In this case, the third body should be an extrasolar planet. Therefore, with 44.9% probability, the tertiary component is an extrasolar planet (by assuming a random distribution of orbital plane inclination). In addition, when $i' \geqslant 9\overset{\circ}{.}0$, the mass of the tertiary component is less than the upper limit on the mass of brown dwarf, $0.0072\,M_\odot$. This suggests that the third body at least is a substellar object instead of a low-mass, stellar companion with a higher possibility of ∼90.0%. The orbital radius d_3 of the tertiary component is about 3.29 AU and its mass M_3 is about 11.1 $M_{\rm jupiter}$ when the orbital inclination equals 90°. Substellar objects orbiting white dwarfs are rare. To date, only a few companions to white dwarf or white dwarf binaries were found (e.g., Becklin & Zuckerman 1988; Farihi & Christopher 2004; Dobbie et al. 2005; Burleigh et al. 2006; Maxted et al. 2006; Guinan & Ribas 2001; Lee et al. (2009); Qian et al. 2009a). The detection of a brown dwarf tertiary companion in the white dwarf–red dwarf binary NN Ser will provide us more knowledge on the formation and evolution of substellar objects.

NN Ser is formed through a common-envelope (CE) evolution after the more massive component star in the original system evolves into a red giant. The ejection of CE removed a large amount of the angular momentum, and results in the present, white dwarf–red dwarf binary system (e.g., Paczynski 1976; Iben & Livio 1993). The distance between the tertiary component and the central binary d_3 is about 3.29 AU. The detection of a substellar companion in NN Ser at this distance could give some constraints on the stellar evolution and the interaction between red giants and their companions. This situation is similar to that of HS 0705+6700 where a tertiary brown dwarf companion at a distance of 3.6 AU to the central sdB-type binary was found (Qian et al. 2009b).

As shown in the upper panel of Figure 2, apart from cyclic period changes, there may exit a long-term period decrease in NN Ser. This binary is a detached system, the period decrease cannot be explained by mass transfer between the two components. The contribution of the gravitational radiation to the period decrease was computed by using the following equation (e.g., Kraft et al. 1962; Faulkner 1971),

$$\frac{\dot{P}_{\rm GR}}{P} = -3\frac{32G^3}{5c^5}\frac{M_1M_2(M_1+M_2)}{d^4}, \qquad (3)$$

where P is the orbital period, M_1 and M_2 are the masses of the primary and secondary, d is the distance between both components, G is the gravitational constant, and c is the speed of light. The result is $\dot{P}_{\rm GR} = -4.48 \times 10^{-14}$ s/s, which is two orders smaller than the observed value. Therefore, a plausible explanation of the period decrease is the secular AML via MB of its fully convective component. Therefore, NN Ser will evolve into normal cataclysmic variables through the AML via MB as those post-CE binary stars (e.g., Shimansky et al. 2006). However, to check whether the long-term period decrease is true or not, more times of light minimum are required in the future.

This work is partly supported by the Chinese Natural Science Foundation (No.10973037, No.10573032, and No. 10778718), the National Key Fundamental Research Project through grant 2007CB815406, the Yunnan Natural Science Foundation (No. 2008CD157), and by the Special Foundation of the President and the West Light Foundation of the Chinese Academy of Sciences. New CCD photometric observations of the system were obtained with the 2.4 m telescopes in the Lijiang station of Yunnan Observatory.

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