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CIRCUMBINARY PLANETS ORBITING THE RAPIDLY PULSATING SUBDWARF B-TYPE BINARY NY Vir

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ABSTRACT

We report here the tentative discovery of a Jovian planet in orbit around the rapidly pulsating subdwarf B-type (sdB-type) eclipsing binary NY Vir. By using newly determined eclipse times together with those collected from the literature, we detect that the observed–calculated ($O-C$) curve of NY Vir shows a small-amplitude cyclic variation with a period of 7.9 yr and a semiamplitude of 6.1 s, while it undergoes a downward parabolic change (revealing a period decrease at a rate of $\dot{P} = -9.2 \times 10^{-12}$). The periodic variation was analyzed for the light-travel-time effect via the presence of a third body. The mass of the tertiary companion was determined to be $M_3 \sin i' = 2.3(\pm 0.3) M_{\rm Jupiter}$ when a total mass of 0.60 $M_\odot$ for NY Vir is adopted. This suggests that it is most probably a giant circumbinary planet orbiting NY Vir at a distance of about 3.3 astronomical units (AU). Since the rate of period decrease cannot be explained by true angular momentum loss caused by gravitational radiation or/and magnetic braking, the observed downward parabolic change in the $O-C$ diagram may be only a part of a long-period (longer than 15 years) cyclic variation, which may reveal the presence of another Jovian planet ($\sim$2.5 $M_{\rm Jupiter}$) in the system.

Key words: binaries: close – binaries: eclipsing – planetary systems – stars: individual (NY Vir) – subdwarfs

1. INTRODUCTION

HW-Vir-like eclipsing binaries are a group of detached binary systems that consists of a very hot subdwarf B-type (sdB) primary and a fully convective M-type secondary with periods shorter than 4 hr (e.g., Menzies & Marang 1986; Kilkenny et al. 1998; Drechsel et al. 2001; Ostensen et al. 2007, 2010; Polubek et al. 2007; Wils et al. 2007; For et al. 2010). The hot sdB components in this group of systems are on the extreme horizontal branch (EHB) of the Hertzsprung–Russell diagram burning helium in their cores and having very thin hydrogen envelopes (e.g., Heber 2009). Theoretical investigations have shown that they are formed through a common envelope (CE) evolution (e.g., Han et al. 2003) and will evolve into normal cataclysmic variables (CVs; e.g., Shimansky et al. 2006). The discovery of circumbinary substellar objects orbiting these peculiar binaries has very important implications for several outstanding problems in astrophysics, e.g., the formation of sdB stars and the fates of low-mass companion systems. To date, three substellar companions have been found in the HW Vir and HS0705+6700 systems to be circumbinary brown dwarfs and planets (Lee et al. 2009; Qian et al. 2009).

As for substellar objects in orbits around single sdB-type stars, Silvotti et al. (2007) discovered a giant planet with a mass of 3.2 $M_{\rm Jupiter}$ and an orbital separation of 1.7 AU around the hot sdB star V391 Peg. Geier et al. (2009) later announced the detection of a close substellar companion to the hot sdB star HD 149382 with a short period of 2.391 days. However, Jacobs et al. (2011) found no evidence for the presence of the claimed substellar object by analyzing He lines. Recently, Geier et al. (2011) detected a brown dwarf companion to the hot subdwarf SDSS J083053.53+000843.4 with a very short period of 0.096 days and a mass of 0.045–0.067 $M_\odot$. Here, we report the tentative discovery of a Jovian planet with a mass of $\sim$2.3 $M_{\rm Jupiter}$ around the HW-Vir-like binary star NY Vir. The planet has the lowest mass among the substellar objects discovered before orbiting sdB stars. Moreover, evidence may show that there is another circumbinary planet companion in the system.

2. NEW OBSERVATIONS AND CHANGES OF THE $O-C$ DIAGRAM

NY Vir (=PG 1336-018) was discovered as an sdB star by the Palomar-Green survey (Green et al. 1986) and was later found to be an HW-Vir-like eclipsing binary by Kilkenny et al. (1998). It is a short-period detached system with a period between 2 and 3 hr. The sdB primary is also a rapid pulsator and the secondary is an M_5-type star. The detailed photometric and spectroscopic investigation was carried out by Kilkenny et al. (1998) who determined a mass ratio of 0.3. They also found effective temperatures $T_1 = 33{,}000$ K and $T_2 = 3000$ K. A multisite (WET) campaign identified 28 pulsation frequencies in the sdB star and found that the amplitudes of at least the strongest frequencies were varying on timescales of days (Kilkenny et al. 2003).

Thirty-eight times of light minimum of NY Vir were published by using the telescopes in South African Astronomical Observatory (SAAO; Kilkenny et al. 1998, 2000; Kilkenny 2011). Linear ephemerides,

$$\mathrm{Min.\,I(HJD)} = 2450223.36142 + 0.1010174 \times E \qquad (1)$$

and

$$\mathrm{Min.\,I(HJD)} = 2450223.36134 + 0.101015999 \times E, \qquad (2)$$

were determined by Kilkenny et al. (1998, 2000), where E is the cycle number. A recent period investigation of NY Vir (Kilkenny 2011) suggests that its period is decreasing at a rate of

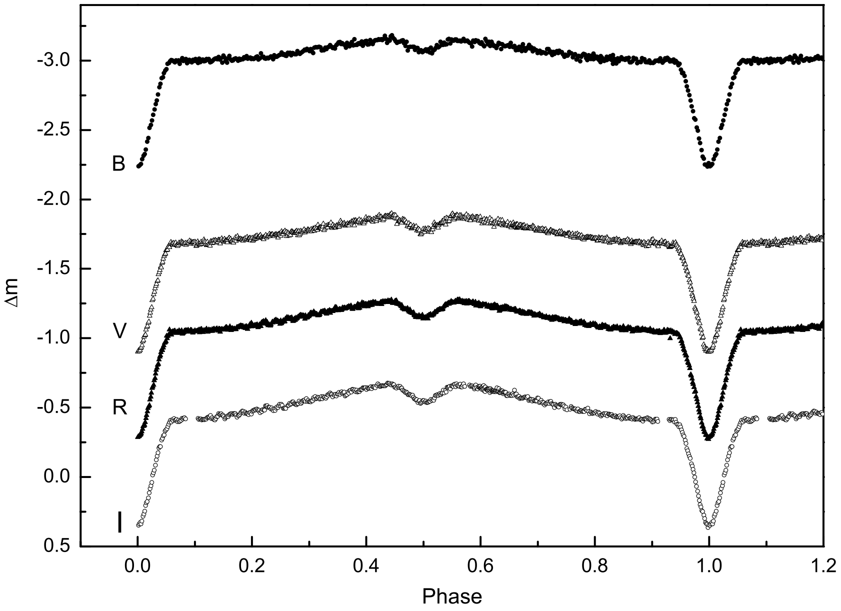

Figure 1. Light curves of NY Vir in the B, V, R, and I bands observed in the time interval from 2011 May 28 to 31. Phases of the observations were calculated with the linear ephemeris: Min. I = HJD 2455711.65991 + 0.101015999 × E.

Table 1
New CCD Times of Light Minimum of NY Vir

BJD (days)	Errors (days)	Min.	Filters	E	Telescopes
2454211.16991	0.00007	I	R	39477	The 1.0 m telescope
2455709.64037	0.00001	I	I	54311	The 2.15 m telescope
2455709.69102	0.00004	II	I	54311.5	The 2.15 m telescope
2455711.55967	0.00001	I	R	54330	The 2.15 m telescope
2455711.61016	0.00004	II	R	54330.5	The 2.15 m telescope
2455711.66070	0.00001	I	V	54331	The 2.15 m telescope
2455711.71125	0.00006	II	V	54331.5	The 2.15 m telescope
2455712.56984	0.00002	I	B	54340	The 2.15 m telescope
2455712.62042	0.00005	II	B	54340.5	The 2.15 m telescope

$\dot{P} = -11.2 \times 10^{-13}$ days per orbit. The mechanism that causes this decrease is unknown. To get more data for this binary star, it was observed with the 1.0 m telescope in Yunnan observatory on 2007 April 20. Then, after reading the paper by Kilkenny (2011), we monitored it again in the time interval from 2011 May 28 to 31 with the 2.15 m "Jorge Sahade" telescope in Argentina. During the observation, a Versarray 1300B CCD camera was used. The complete light curves in the B, V, R, and I bands were obtained and are displayed in Figure 1. By using those photometric data, nine eclipse times were determined. In order to obtain high data precision, we applied a standard time system Barycentric Julian Dynamical Date (BJD), which are converted using the code of Stumpff (1980) to all eclipse timings and orbital period analysis. The derived eclipse times in BJD are listed in Table 1.

With all of the available times of light minimum, the linear ephemeris published by Kilkenny et al. (1998, 2000) was revised as

$$\mathrm{Min.\,I(BJD)} = 2450223.362213(8) + 0.1010159673(2) \times E, \tag{3}$$

where BJD 2450223.362213 is the initial epoch and 0.1010159673 is the revised period. The variance is derived as 1.7×10^{-4} days. The $(O - C)_1$ values with respect to the linear ephemeris were calculated. The corresponding $(O - C)_1$ diagram is plotted in Figure 2. As shown in the figure, a downward parabolic fit (dashed line in Figure 2) cannot describe well the general trend of the $(O - C)_1$ curve. This indicates that, to describe the general $(O - C)_1$ trend satisfactorily, a combination of a downward parabolic change and a cyclic oscillation is required. Using the least-squares method, we determined

$$\begin{aligned}(O - C)_1 = &-0.000073(\pm 0.00002) + 2.7(\pm 0.2) \times 10^{-8} \times E \\ &- 4.6(\pm 0.4) \times 10^{-13} \times E^2 \\ &+ 0.000071(\pm 0.000017) \sin[0\overset{\circ}{.}0126(\pm 0.0007) \\ &\times E + 312\overset{\circ}{.}1(\pm 20\overset{\circ}{.}1)],\end{aligned} \tag{4}$$

with a variance of 3.8×10^{-5} days and $\chi^2 \approx 1.2$. Using the F-test as discussed by Pringle (1975) to assess the significance of the quadratic and sinusoidal terms in Equation (4), the parameter λ can be derived to be 180, which indicates that it is well significant above 99.99% level. The rate of the orbital period decrease is close to that determined by Kilkenny (2011). Considering that the influence of the pulsations on the minima time measurements is a plausible reason for the observed season scatters shown in Figures 2 and 3, we average over the eclipse times within one year as a window of time. The averaged points obey our fitting curve in a long base line well. Thus, we believed that the variation in the $O - C$ diagram should be real.

After the downward parabolic variation was removed, the $(O - C)_2$ curve is plotted in the upper panel of Figure 3 where a cyclic change is seen more clearly. The cyclic variation has an amplitude of 6.1 s and a period of 7.9 yr. As pointed out by Kilkenny (2011), eclipsing times for NY Vir are less accurate than for AA Dor because of the pulsation. However, errors introduced should be of the order of 0.00005 days or less (Kilkenny 2011) and essentially random. The mean values of $(O - C)_2$ suggest that the systematically cyclic variation in the $(O - C)_2$ diagram is true. After all of the changes were removed, the residuals are shown in the lower panel of Figure 3. It can be seen in the panel that the scatter of the residuals is indicating in a random way that the scatter may be caused by the pulsation of the sdB star. Moreover, no systematic changes can be traced

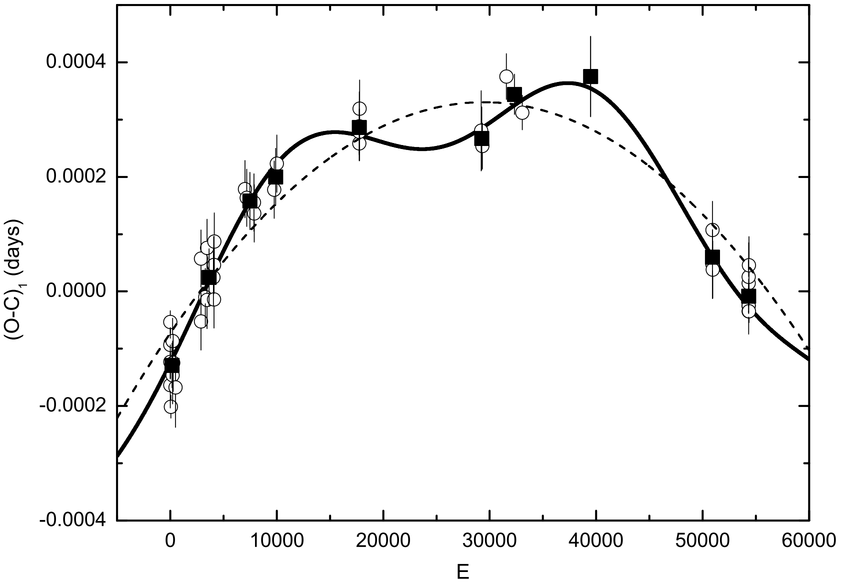

Figure 2. $O - C$ diagram of the sdB-type eclipsing binary NY Vir with respect to Equation (3). The solid line refers to the best fit of the $O - C$ curve by a combination of a periodic variation with a small amplitude of 6.1 s and a period of 7.9 yr and a downward parabolic change (the dashed line). Open circles refer to the original data points, while solid squares to their averaged values.

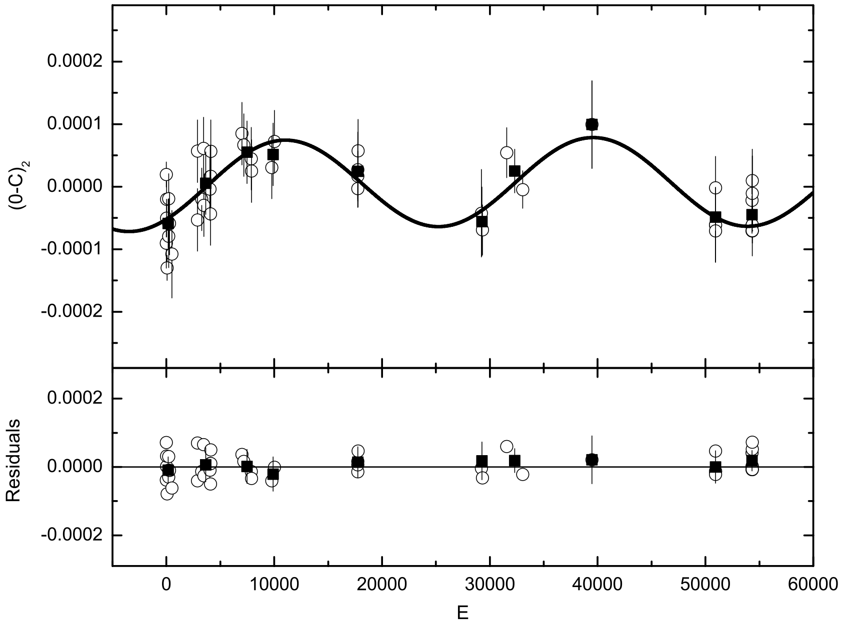

Figure 3. Cyclic variation of NY Vir (the light-travel-time effect via the presence of the giant circumbinary planet) after the downward parabolic change is subtracted from the $(O - C)_1$ diagram. Symbols are the same as those in Figure 2. The mean values follow the general $(O - C)_2$ trend, which suggests that the cyclic variation is real.

there, which suggests that Equation (4) can give a good fit to the observations.

3. DISCUSSIONS AND CONCLUSIONS

Investigations of several authors (e.g., Qian et al. 2008; Brinkworth et al. 2006) showed that the magnetic activity cycles of a fully convective component star (i.e., the Applegate mechanism; Applegate 1992) cannot explain the observed cyclic variations in the $O - C$ diagrams of close binaries because of the problem of energy. Moreover, a recent statistical study by Liao & Qian (2010) suggests that light-travel-time effect is the most probable mechanism causing cyclic changes in the $O - C$ diagrams of close binary stars. Therefore, we analyzed NY Vir for the light-travel-time effect that arises from the gravitational influence of a tertiary companion. The possible presence of a companion object produces the relative distance changes of the eclipsing pair as it orbits the barycenter of the triple system.

By considering a typical mass of $M_1 = 0.46\,M_\odot$ for sdB-type stars and using the mass ratio of $q = 0.3$ determined by Kilkenny et al. (1998), the mass of the secondary is estimated as $M_2 = 0.14\,M_\odot$. Then, the mass function and the mass of the possible tertiary companion were derived by using the following equation:

$$\begin{aligned} f(m) &= 4\pi^2(a_{12}\sin i')^3/GT^2 \\ &= (M_3\sin i')^3/(M_1+M_2+M_3)^2, \end{aligned} \tag{5}$$

where M_3 is the mass of the third body, G is the gravitational constant, and T is the period of the $(O-C)_2$ oscillation. $a_{12}\sin i'$ can be determined by

$$a_{12}\sin i' = A \times c, \tag{6}$$

where A is the semi-amplitude of the $(O-C)_2$ oscillation and c is the speed of light. The results are $f(m) = 3.0(\pm 0.4) \times 10^{-8}\,M_\odot$ and $M_3 \sin i' = 2.3(\pm 0.3) M_{\mathrm{Jupiter}}$. When the orbital inclination of the third body is larger than $9^{\circ}.6$, the mass of the tertiary component corresponds to $2.3\,M_{\mathrm{Jupiter}} \leqslant M_3 \leqslant 14\,M_{\mathrm{Jupiter}}$. In this situation, as a few good cases have been made for circumbinary planets (e.g., Lee et al. 2009; Beuermann et al. 2010; Qian et al. 2010, 2011), it should be a planetary object. The orbital separation d_3 of the Jupiter-like planet candidate is about 3.3(±0.8) AU.

The downward parabolic change in the $O-C$ diagram (the dashed line in Figure 2) implies a period decrease at a rate of $\dot{P} = -9.2 \times 10^{-12}$ (or 1 s in about 3447 years). This corresponds to $\dot{P} = -3.36 \times 10^{-9}$ days yr^{-1}, which is close to the value obtained in literature (Kilkenny 2011). The orbital separation of the two component stars in NY Vir is estimated as $0.77\,R_\odot$. By using the equation given by Kraft et al. (1962) and Faulkner (1971),

$$\frac{\dot{P}_{\mathrm{GR}}}{P} = -3\frac{32G^3}{5c^5}\frac{M_1 M_2 (M_1 + M_2)}{d^4}, \tag{7}$$

where P is the orbital period and d is the distance between both components, the contribution of gravitational radiation (GR) to the period decrease can be computed as $\dot{P}_{\mathrm{GR}} = -0.026 \times 10^{-9}$ days yr^{-1}. This is about two orders smaller than the observed value indicating that it cannot be caused by GR. This decrease can be explained by magnetic braking (MB) as in the case of HW Vir (Qian et al. 2008; Lee et al. 2009). However, it is more widely accepted that MB is stopped for fully convective stars (Rappaport et al. 1983; Spruit & Ritter 1983).

Therefore, as in the case of HU Aqr, the more plausible reason for the observed long-term period decrease is that it is only a part of a long-period cyclic variation (longer than 15 years), revealing the possible presence of another planet in the planetary system. This is the same as that of HU Aqr where a planetary system is orbiting the eclipsing polar (Qian et al. 2011). We estimate that the mass of the second planet is about $2.5\,M_{\mathrm{Jupiter}}$. Some investigators (e.g., Horner et al. 2011) think that the serious problem for the presence of the fourth body is the dynamical stability of the circumbinary planetary system. However, the three-dimensional dynamic-aware analysis of the stability of circumbinary orbits by Doolin & Blundell (2011) reveals that these orbits are surprisingly stable throughout binary mass-fraction–eccentricity parameter space.

If the cyclic variations in the $O-C$ diagram are caused by the light-travel-time effects via the presence of planetary objects, they should be strictly periodic. To check the existence of the planetary system, more eclipse times are needed in the future. Moreover, at the maximum point of the $O-C$ curve, the central eclipsing binary NY Vir is at the farthest position of the orbit, while the circumbinary planet is closest to the observer. If the tertiary companion is coplanar to the central binary, the circumbinary planet should be in the light of the eclipsing binary and transit the binary component stars. Therefore, searching for the transits of the binary components by the circumbinary planets at the $O-C$ maxima can ascertain the planetary system. More recently, a Saturn-like planet transits an M-type eclipsing binary reported by Doyle et al. (2011), which provides the first direct evidence for the presence of a circumbinary planet.

As in the cases of other HW Vir like binary stars, NY Vir was evolved through a CE 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 the present EHB star with a low-mass stellar companion in a short-period binary was formed. The distance between the central EHB binary and the circumbinary planet is about 3.3 AU. By assuming that the mass of the main-sequence (MS) progenitor of the EHB star is $M_{\mathrm{MS}} = 1.0 M_\odot$, the orbital separation of the planet around the MS progenitor is estimated as (e.g., Bear & Soker 2011) $a_0 \cong (M_{\mathrm{EH}} + M_2)/(M_{\mathrm{MS}} + M_2) \approx 1.74$ AU (by ignoring tidal interaction). When the primary star evolved to a red giant branch star before the system entered a CE, it has reached a radius of $\sim 100\,R_\odot \sim 0.5$ AU. Therefore, the secondary should be at a distance that is a little large, say 0.8 AU. Can a system of two stars ($M_1 = 1.0\,M_\odot$ and $M_2 = 0.14\,M_\odot$) at an orbital separation of 0.8 AU have a planet at 1.74 AU in a stable orbit? The three-dimensional numerical simulations by Doolin & Blundell (2011) indicate that the orbit is stable. A system with two M-type stars ($M_1 = 0.69\,M_\odot$ and $M_2 = 0.20\,M_\odot$) at an orbital separation of 0.22 AU was reported to have a Saturn-like planetary companion at a distance of 0.7 AU (Doyle et al. 2011). If the detection of a planetary companion to NY Vir at an orbital separation of 3.3 AU is true, it can give some constraints on the stellar evolution and the interaction between red giants and their planetary companions. Moreover, it is interesting to point out that the orbital separations between the central binaries and the inner substellar objects in the three systems, i.e., HW Vir (Lee et al. 2009), HS 0705+6700 (Qian et al. 2009), and NY Vir, are all in the small range of 3.3–3.6 AU. It is unclear whether these agreements are fortuitous or there are physical reasons.

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