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EVIDENCE OF A MASSIVE BLACK HOLE COMPANION IN THE MASSIVE ECLIPSING BINARY V PUPPIS

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ABSTRACT

Up to now, most stellar-mass black holes have been discovered in X-ray–emitting binaries, in which the black holes are formed through a common-envelope evolution. Here we give evidence for the presence of a massive black hole candidate as a tertiary companion in the massive eclipsing binary V Puppis. We found that the orbital period of this short-period binary ($P = 1.45$ days) shows a periodic variation while it undergoes a long-term increase. The cyclic period oscillation can be interpreted by the light-travel time effect via the presence of a third body with a mass of no less than 10.4 $M_\odot$. However, no spectral lines of the third body were discovered, which indicates that it is a massive black hole candidate. The black hole candidate may correspond to the weak X-ray source close to V Pup, discovered by the *Uhuru*, *Copernicus*, and *ROSAT* satellites, produced by accreting materials from the massive binary via a stellar wind. The circumstellar matter with many heavy elements around this binary may have been formed by the supernova explosion of the progenitor of the massive black hole. All of the observations suggest that a massive black hole is orbiting the massive close binary V Pup with a period of 5.47 yr. Meanwhile, we found that the central close binary is undergoing a slow mass transfer from the secondary to the primary star on a nuclear timescale of the secondary component, revealing that the system has passed through a rapid mass transfer stage.

Subject headings: binaries: close — binaries: eclipsing — black hole physics — stars: evolution — stars: individual (V Puppis)

1. INTRODUCTION

With an orbital period of 1.4545 days and two B-type component stars (spectral types B1 and B3), V Puppis (HR 3129 and HD 65818) is one of a few massive semidetached eclipsing binaries in which the less massive components are filling their Roche lobes (e.g., Andersen et al. 1983; Bell et al. 1987a, 1987b; Terrell et al. 2005). According to the theory of binary evolution (e.g., Sybesma 1986), these systems were formed through case A mass transfer (mass transfer occurring when hydrogen is burning in the core). Since the discovery of V Pup more than a century ago, it has been extensively investigated photometrically and spectroscopically (e.g., Andersen et al. 1983 and references therein). A weak X-ray source in the field of V Pup (e.g., Giacconi et al. 1974; Groote et al. 1978; Bahcall et al. 1975) and a significant amount of circumstellar matter around the binary (e.g., York et al. 1976; Koch et al. 1981) make it a very interesting binary to study.

Because of its stable light curve and its deep and sharp eclipsing minima (e.g., Andersen et al. 1983), the times of light minimum of V Pup can be determined precisely. Thus, the variations of the orbital period can, in principle, be derived with high precision by analyzing the $O - C$ (observed minus calculated) diagram. In the present paper, the orbital period changes of V Pup are investigated. Then, on the basis of the period variations, the presence of a massive black hole companion and the evolutionary state of the system are discussed.

2. ANALYSIS OF THE ORBITAL PERIOD CHANGES

Epochs and orbital periods of V Pup have been given by several authors (e.g., Andersen et al. 1983). Kreiner & Ziółkowski (1978) did not detect any period change for the binary, whereas Andersen et al. (1983) pointed out that the period of V Pup is variable. However, since the early eclipse times were mainly observed photographically or visually, conclusions on the period change are not reliable. For the present analysis, we only use photoelectric (“Pe”) and charge-coupled device (CCD) observations. Most of the data were collected by Kreiner et al. (2001). Two new CCD times of light minimum were obtained on 2007 November 2 and 2008 March 24 with the Virpi S. Niemela 0.8 m telescope at La Plata Observatory (see Table 1). During the observation, the *V* filter was used. The $(O - C)_1$ values of all available Pe and CCD times of light minimum were computed with the linear ephemeris given by Kreiner et al. (2001, p. 1914):

$$\text{Min. I} = \text{HJD } 2{,}428{,}648.2837 + 1.45448686E, \qquad (1)$$

where HJD 2,428,648.2837 is the time of the conjunction, 1.45448686 days is the constant ephemeris period P_e, and E is the cycle. The $(O - C)_1$ values are listed in the sixth column of Table 1 and are represented graphically against E in the top panel of Figure 1.

If the orbital period of a binary varies linearly in time, the $O - C$ diagram should have a parabolic shape, as observed in other eclipsing binaries (e.g., Qian & Zhu 2006). As for V Pup, a simple second-order polynomial does not give a satisfactory fit (see the dashed line in the top panel of Fig. 1). Therefore, a sinusoidal term was added to a quadratic ephemeris in order to give a good fit to the $(O - C)_1$ curve. A least-squares solution leads to the following ephemeris:

$$\begin{aligned}\text{Min. I} = {} & \text{HJD } 2{,}428{,}648.2960(\pm 0.0045)\\ & + 1.45448114(\pm 0.00000091)E\\ & + \left[4.18(\pm 0.44) \times 10^{-10}\right]E^2\\ & + 0.0163(\pm 0.0016)\\ & \times \sin[0.2621^\circ(\pm 0.0011^\circ)E + 44.3^\circ(\pm 3.9^\circ)]. \qquad (2)\end{aligned}$$

The sinusoidal term suggests an oscillation with a period of about $T = 5.47$ yr and an amplitude of about $A = 0.0163$ days, which suggests a cyclic period oscillation with a period of 5.47 yr (Fig. 1,

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TABLE 1

All Available Photoelectric and CCD Times of Light Minimum for V Puppis

HJD (2400000+) (1)	Error (days) (2)	Method (3)	Minimum (4)	E (5)	$(O-C)_1$ (days) (6)	$(O-C)_2$ (days) (7)	Residual (days) (8)	Refs. (9)
31917.957	±0.0010	Pe	I	2248	−0.0132	−0.0147	−0.0004	1
31965.952	±0.0010	Pe	I	2281	−0.0162	−0.0176	−0.0046	1
39869.6264	±0.0010	Pe	I	7715	−0.0234	−0.0164	−0.0011	1
41791.0113	±0.0002	Pe	I	9036	−0.0157	−0.0104	+0.0065	2
42537.9043	±0.0001	Pe	II	9549.5	−0.0017	+0.0026	−0.0042	2
42561.9044	±0.0005	Pe	I	9566	−0.0006	+0.0036	−0.0044	2
43124.8032	±0.0002	Pe	I	9953	+0.0118	+0.0151	−0.0001	2
43148.8024	±0.0002	Pe	II	9969.5	+0.0119	+0.0151	+0.0014	2
43151.7111	±0.0002	Pe	II	9971.5	+0.0117	+0.0149	+0.0014	2
45367.6063	±0.0002	Pe	I	11495	−0.0039	−0.0056	−0.0022	2
45383.6052	±0.0001	Pe	I	11506	−0.0043	−0.0061	−0.0014	2
48391.5025	±0.0010	CCD	I	13574	+0.0142	+0.0026	+0.0021	3
48425.6868	±0.0007	CCD	II	13597.5	+0.0180	+0.0063	+0.0044	3
48500.5947	±0.0050	Pe	I	13649	+0.0198	+0.0078	+0.0025	4
49821.2500	±0.0050	Pe	I	14557	+0.0011	−0.0164	−0.0003	4
54456.7420	±0.0010	CCD	I	17744	+0.0435	+0.0012	−0.0024	5
54550.5667	±0.0010	CCD	II	17808.5	+0.0538	+0.0109	+0.0028	5

References.—(1) Kreiner & Ziółkowski 1978; (2) Andersen et al. 1983; (3) M. J. Kreiner 2006, private communication; (4) Stickland et al. 1998; (5) this work.

top). Although the $(O-C)_1$ data do not cover a whole cycle, as shown in Figure 1, the minimum, the maximum, and the period of the cyclic variation are all well constrained, indicating that the period changes are reliable. The quadratic term in equation (2) reveals a continuous period increase at a rate of $dP/dt = 2.10\times10^{-7}$ days yr^{-1}, corresponding to a period increase of 1.8 s per century.

3. DISCUSSION OF THE ORBITAL PERIOD VARIATION

3.1. *The Presence of a Massive Black Hole Companion*

Both components of V Pup are B-type stars containing a convective core and a radiative envelope, which is different from the Sun. Hence, the period oscillation cannot be explained as solar-type magnetic activity cycles (i.e., the Applegate mechanism; Applegate 1992). Therefore, the simplest explanation of the cyclic period oscillation is a wobble of the binary's barycenter due to the presence of a tertiary companion. The $(O-C)_2$ values calculated from the quadratic ephemeris in equation (2) are shown in the seventh column of Table 1. The corresponding $(O-C)_2$ diagram is plotted against the epoch number E in the middle panel of Figure 1. By considering a general case with an elliptical orbit, the following equation was used to describe those $(O-C)_2$ residuals:

$$(O-C)_2 = a_0 + \sum_{i=1}^{2}[a_i \cos(i\Omega E) + b_i \sin(i\Omega E)]. \quad (3)$$

The results were obtained with the same value of Ω (0.2621°) as that used in equation (2) (see the solid line in the middle panel of Fig. 1). We computed the orbital parameters of the tertiary companion using the formulae derived by Kopal (1959, p. 112):

$$a'_{12} \sin i' = c\sqrt{a_1^2 + b_1^2}, \quad (4)$$

$$e' = 2\sqrt{\frac{a_2^2 + b_2^2}{a_1^2 + b_1^2}}, \quad (5)$$

$$\omega' = \arctan\frac{(b_1^2 - a_1^2)b_2 + 2a_1a_2b_1}{(a_1^2 - b_1^2)a_2 + 2a_1b_1b_2}, \quad (6)$$

$$\tau' = t_0 - \frac{T}{2\pi}\arctan\frac{a_1b_2 - b_1a_2}{a_1a_2 + b_1b_2}, \quad (7)$$

where c is the speed of light and a'_{12}, i', e', ω', and τ' are the semimajor axis, the orbital inclination, the eccentricity, the longitude of the periastron from the ascending node, and the time of the periastron passage, respectively. The solutions are displayed in Table 2. With the following well-known equations,

$$f(m) = \frac{4\pi^2}{GT^2}(a_{12}\sin i')^3, \quad (8)$$

$$f(m) = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2}, \quad (9)$$

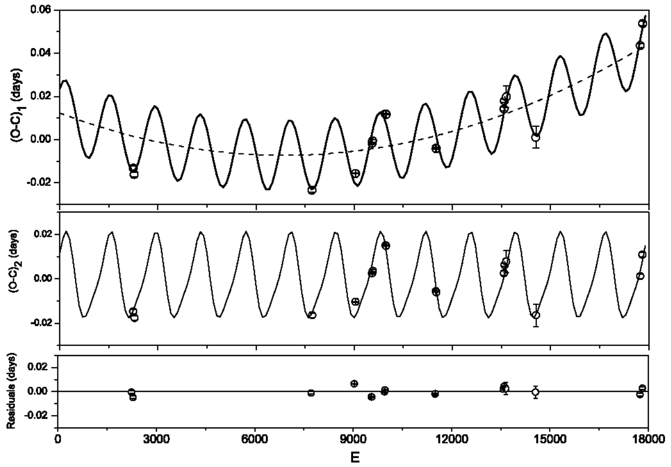

Fig. 1.—Plot of the $(O-C)_1$ curve of V Pup with respect to the linear ephemeris given by Kreiner et al. (2001). The solid line in the top panel suggests the combination of a long-term period increase and a cyclic change, while the dashed line refers to the continuous increase of the orbital period. The middle panel shows the plot of the $(O-C)_2$ residuals of the eclipse timings, based on the quadratic ephemeris in eq. (2). The solid line in the middle panel indicates the theoretical orbit of a massive black hole candidate with an eccentricity of 0.45. The residuals after subtracting all effects of period change are displayed in the bottom panel, and no variations can be traced there.

TABLE 2

Calculated Orbital Parameters of the Tertiary Companion in V Puppis

Parameter	Value	Error
a_0	-0.0005	±0.0001
a_1	$+0.0142$	±0.0012
b_1	$+0.0113$	±0.0012
a_2	-0.0031	±0.0019
b_2	$+0.0026$	±0.0004
$a'_{12} \sin i'$ (AU)	3.14	±0.21
e'	0.45	±0.16
ω' (deg)	-63.0	±18.9
τ' (days)	2428213	±101
$f(m)$ ($M_\odot$)	1.03	±0.21
M_3 (i' = 90°)	10.40	±0.87
M_3 (i' = 70°)	11.25	±0.96
M_3 (i' = 50°)	14.74	±1.33
M_3 (i' = 30°)	27.44	±2.87
d_3 (i' = 90°)	6.82	±0.73
d_3 (i' = 70°)	6.80	±0.73
d_3 (i' = 50°)	6.28	±0.70
d_3 (i' = 30°)	5.56	±0.66

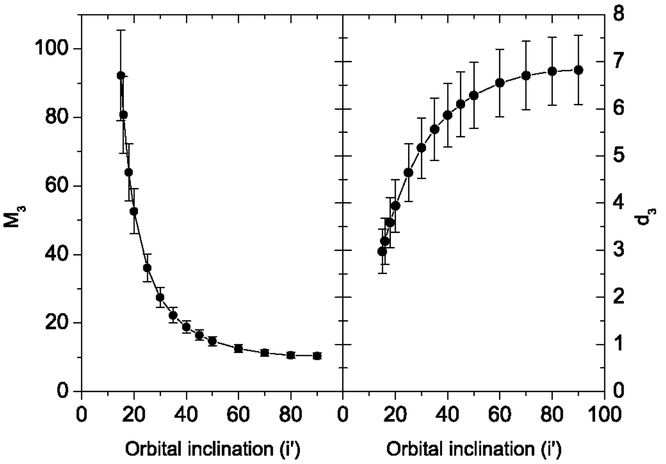

Fig. 2.—Relations between the mass, M_3 (in units of $M_\odot$), and the orbital radius, d_3 (in units of AU), of the tertiary component and its orbital inclination i' in the V Pup system. The tertiary companion should be more massive than the secondary component and thus may be a black hole candidate.

we calculated the mass function, the mass, and the radius of the third body, using the absolute parameters determined by Andersen et al. (1983). In equations (8) and (9), M_1, M_2, and M_3 are the masses of the two bodies in the eclipsing pair and the third body, respectively; G is the gravitational constant; and T is the period of the $O - C$ oscillation. For different values of the orbital inclination, the masses and orbital radii of the tertiary component are displayed in Table 2. The corresponding relations between the mass and the radius of the third body and its orbital inclination are shown in Figure 2.

The lowest mass of the tertiary companion is 10.4 $M_\odot$; i.e., larger than the mass of the secondary component. If the tertiary component were a normal star, we would see its spectral lines not changing with the orbital phase of the binary. However, this has not been reported (e.g., York et al. 1976; Koch et al. 1981; Andersen et al. 1983). Moreover, if the third body is more massive than the secondary component ($M_2 = 7.76\ M_\odot$) in the central binary, it should be very luminous and should contribute a large amount of third light to the total system, unless it is not a normal main-sequence star. Therefore, we suspect that the tertiary component is a compact object and a probable black hole candidate. This situation resembles that in the triple system HR 2876, where a compact object (possibly a white dwarf star) with a mass excess of 1.0 $M_\odot$ was found to be orbiting a B-type close binary star (B3.5 V + B6 V; $P = 15$ days; Burleigh & Barstow 1998; Vennes 2000). The main differences between the two systems are that the tertiary companion in the V Pup system is much more massive and that the central eclipsing binary in the V Pup system has a much tighter orbit and shows strong interaction between both components.

A weak X-ray source (3U 0750−49) with a count rate of 9.4 ± 2.3 counts s^{-1} was detected by the *Uhuru* satellite (Giacconi et al. 1974). The counterpart of this X-ray source has been a puzzling problem for astronomers since the 1970s. V Pup was initially listed in the 3U catalog as a possible candidate by Giacconi et al. (1974). However, another bright star, HD 64740, close to the source (within the 90% confidence error box) was also considered as a possible candidate (Groote et al. 1978). By analyzing the X-ray data of V Pup and HD 64740 from the *Copernicus* satellite, Bahcall et al. (1975) concluded that the weak X-ray source must almost certainly be closer to V Pup than to HD 64740, but most probably neither V Pup nor HD 64740 was the candidate. More recently, V Pup was also discovered to be a X-ray source by *ROSAT*, with a count rate of 0.08 counts s^{-1} (in the X-ray 50 Å, 250 eV band; e.g., Lampton et al. 1997). Our study indicates that the tertiary companion may correspond to the weak X-ray source. There are two mechanisms that could produce the X-ray emission in the V Pup system. If the massive tertiary companion is a normal star, the X-ray emission could be caused by the colliding winds from the eclipsing pair and the tertiary companion, resembling those observed in other massive binary systems (e.g., Stevens et al. 1992; Pittard & Stevens 2002). If the third body is a massive black hole, the X-ray source could be caused by the accretion of material from the massive binary via a stellar wind, as observed in X-ray–emitting binaries (e.g., Prestwich et al. 2007). However, the former mechanism can be ruled out, because no spectral lines of the tertiary component were found.

Another interesting feature of V Pup is the existence of a significant amount of circumstellar matter, which was deduced from the optical spectra and ultraviolet observations obtained by the *International Ultraviolet Explorer* (*IUE*) spacecraft and the *Copernicus* satellite (e.g., York et al. 1976; Koch et al. 1981; Andersen et al. 1983). Numerous interstellar spectral lines, especially those of many types of heavy elements (e.g., Mg II, Si I, Si II, Si III, C I, O I, Fe II, and Fe III) were found in the H II region around V Pup, in which strong lines of Si III and Fe III are remarkable (e.g., York et al. 1976; Koch et al. 1981). The formation of the circumstellar matter around V Pup is an unsolved problem. Considering that V Pup has undergone mass exchange, one may think that the circumstellar matter results from the binary evolution. However, we question why the other systems (e.g., AI Cru) that resemble V Pup do not have the same significant amount of circumstellar matter (Bell et al. 1987b). The most probable reason for the formation of the circumstellar matter around V Pup is that it was formed by the supernova explosion of the progenitor of the tertiary black hole companion (e.g., Woosley & Weaver 1995; Zhang et al. 2008). This can produce the heavy elements in the circumstellar matter and results in the formation of the H II region around the eclipsing binary.

3.2. *The Slow Mass Transfer of V Puppis*

V Puppis is a semidetached binary system in which the secondary component fills the critical Roche lobe (e.g., Andersen et al. 1983). The long-term period increase can be explained by the mass transfer from the secondary to the primary component. By using the equation

$$\tau_N = 10^{10} M_2/L_2, \tag{10}$$

where M_2 and L_2 are the mass and the luminosity of the less massive component, we calculate the nuclear timescale of the secondary to be $\tau_N = 7.1 \times 10^6$ yr. This value is close to the timescale of the period change, $\tau_P = P/\dot{P} = 6.9 \times 10^6$ yr, which reveals that V Pup is now undergoing a slow mass transfer evolutionary stage on the nuclear timescale of the less massive component. This suggests that V Pup was formed via case A evolution and has passed through a rapid mass transfer stage. These results are in agreement with the prediction from the theory of massive binary evolution (e.g., Sybesma 1986). If we assume a conservative mass transfer, the well-known equation

$$\frac{\dot{P}}{P} = 3\dot{M}\left(\frac{1}{M_2} - \frac{1}{M_1}\right) \tag{11}$$

yields a rate of mass transfer of $dM/dt = 7.82 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. However, since the nuclear timescale of the secondary is slightly longer than the timescale of the period change, the slow mass transfer is insufficient to cause the observed period increase. This suggests that the stellar wind from the massive component of the binary should contribute to the period increase. This situation resembles that of AI Cru (S.-B. Qian et al. 2008, in preparation).

With the consideration of conservative mass and angular momentum, the calculation by Plavec (1968) suggests that, to produce a case A mass transfer of massive binaries, the initial orbital period should be less than 1.8 days. One may ask, what causes the origin of the initially short-period detached system? It is possible that the massive tertiary companion has played an important role for the origin and evolution of the inner binary by removing angular momentum from the central system via Kozai oscillation (Kozai 1962) or a combination of the Kozai cycle and tidal friction (e.g., Fabrycky & Tremaine 2007). This causes the inner eclipsing pair to have a lower angular momentum and a shorter initial orbital period.

4. CONCLUSIONS

The cyclic change of the orbital period, the presence of a weak X-ray source near V Puppis, and the significant amount of circumstellar matter around the binary star all support the conclusion that a massive black hole is orbiting the massive close binary V Pup with a period of 5.47 yr. Several massive stellar black hole candidates have been discovered recently (e.g., Greiner et al. 2001; Orosz et al. 2007), but all of the candidates have been found to be a component in a binary system. We conclude here that we have provided observational evidence for the first massive stellar black hole candidate as a tertiary companion of a massive close binary star. Theoretical investigations have shown that the formation of black hole binaries should experience a common-envelope phase, with the spiraling in of the companion in the envelope causing the ejection of the envelope (e.g., Taam & Sandquist 2000; Podsiadlowski et al. 2003). The mean distance between the black hole candidate and the eclipsing pair is about 5.5 AU. During the supergiant phase, the radius of the precursor of the black hole companion in V Pup may have reached to several AU. The survival of V Pup in this evolutionary stage suggests that the tertiary black hole companion must have been formed through an evolutionary process that is different from that of the black holes in X-ray binaries (e.g., Woosley & Weaver 1995; Zhang et al. (2008) and that it could give some constraints to the evolution of single massive stars and the formation of isolated black holes.

From the present investigation, we deduce that the progenitor of V Pup was a triple system that was composed of a short-period detached B-type eclipsing binary and a much more massive tertiary companion. By drawing angular momentum from the inner binary through Kozai oscillation (Kozai 1962) or a combination of the Kozai cycle and tidal friction (e.g., Fabrycky & Tremaine 2007), the massive tertiary companion may have played an important role in the origin of the central system, causing the inner eclipsing binary to have a very short initial orbital period. In the triple system, the massive tertiary companion evolved faster, and it finally evolved into a massive black hole via a supernova explosion (e.g., Woosley & Weaver 1995; Zhang et al. 2008). At the same time, the originally more massive component of the eclipsing pair evolved to fill its critical Roche lobe. Then the binary underwent a rapid mass transfer stage, and after the mass ratio was reversed, the central binary finally reached its present semidetached configuration, with a slow secondary-to-primary mass transfer on the nuclear timescale of the currently less massive star. Supergiant stars have recently been found to be tertiary companions of OB-type close binaries in the triple systems HD 167971 and FR Sct (e.g., Leitherer et al. 1987; Davidge & Forbes 1988; Pigulski & Michalska 2007). They resemble the progenitor of V Pup, with the tertiary supergiant companion evolving into a compact object. As for V Pup, the existence of the black hole in the outer orbit poses strong constraints on the formation of the black hole, the mass loss in the supernova that led to the formation of the black hole, and the magnitude of the kick received by the black hole, all of which make this object a much more interesting system for future study.

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