

Detection of a planetary system orbiting the eclipsing polar HU Aqr

S.-B. Qian,^{1,2,3*} L. Liu,^{1,2,3} W.-P. Liao,^{1,2} L.-J. Li,^{1,2,3} L.-Y. Zhu,^{1,2,3} Z.-B. Dai,^{1,2}
J.-J. He,^{1,2} E.-G. Zhao,^{1,2} J. Zhang^{1,2,3} and K. Li^{1,2,3}

¹National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, PO Box 110, 650011 Kunming, China

²Key Laboratory of the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, PO Box 110, 650011 Kunming, China

³Graduate University of the Chinese Academy of Sciences, Yuquan Road 19, Sijingshang Block, 100049 Beijing, China

Accepted 2011 March 7. Received 2011 March 3; in original form 2011 January 11

ABSTRACT

Using the precise times of mid-egress of the eclipsing polar HU Aqr, we discovered that this polar is orbited by two or more giant planets. The two planets detected so far have masses of at least 5.9 and 4.5 M_{Jup} . Their respective distances from the polar are 3.6 and 5.4 au with periods of 6.54 and 11.96 yr, respectively. The observed rate of decrease of period derived from the downward parabolic change in the observed – calculated (O – C) curve is a factor of 15 larger than the value expected for gravitational radiation. This indicates that it may be only a part of a long-period cyclic variation, revealing the presence of one more planet. It is interesting to note that the two detected circumbinary planets follow the Titus–Bode law of solar planets with $n = 5$ and 6. We estimate that another 10 yr of observations will reveal the presence of the predicted third planet.

Key words: binaries: close – binaries: eclipsing – stars: individual: HU Aqr – planetary systems – white dwarfs.

1 INTRODUCTION

With an orbital period of 2.08 h, HU Aqr is a member of the AM Her subclass (also called polars because of their highly polarized optical emission) of cataclysmic variables (CVs) with the magnetic field of the white dwarf primary strong enough to prevent materials from the main-sequence companion from forming an accretion disc (Warner 1995). It is the brightest among the 15 known eclipsing polars at both optical and X-ray wavelengths (Schwope, Thomas & Beuermann 1993; Schwope et al. 2001). Since the discovery by *ROSAT* in 1993, it has become one of the most comprehensively observed polars in various wavelength bands (Schwope et al. 1993, 2001; Harrop-Allin et al. 1999; Bridge et al. 2002; Schwarz et al. 2009).

Using the 2.4-m optical telescope in Lijiang station of Yunnan Astronomical Observatory, we monitored HU Aqr for nearly one year (from 2009 May 20 to 2010 May 17) and 10 eclipse profiles were obtained. We discovered that the ingress shapes of those eclipses are variable, whereas the profiles of the eclipse egress were as stable as those observed at other wavelengths (e.g. X-ray). It is therefore possible to register very small differences in the arrival times of the mid-egress photons at various wavelengths, allowing the detection of extremely low mass circumbinary objects through the analysis of the observed – calculated (O – C) diagram ('O' refers to the observed times of the eclipse egress, whereas 'C' refers to

those computed with a linear ephemeris). This method is similar to the radio approach used to detect planets around pulsars (e.g. Backer, Foster & Sallmen 1993), and has been used to find giant planets orbiting the other eclipsing polar DP Leo (Qian et al. 2010; Beuermann et al. 2011a), the extreme horizontal branch pulsating star V391 Peg (Silvotti et al. 2007) and the others listed by Silvotti et al. (2010).

2 NEW MID-EGRESS TIMES AND THE CHANGES OF THE O – C DIAGRAM

The orbital period of the brightest eclipsing polar HU Aqr was first noted to be variable by Schwope et al. (2001). 72 times of accretion spot egress in optical, UV and X-rays were measured and collected (Schwarz et al. 2009). It is shown that the O – C diagram of the observed accretion spot eclipse timings reveals complex deviations from a linear trend, and a constant or cyclic period change or a combination thereof cannot describe the general O – C trend. To understand the properties of the O – C variation, HU Aqr was monitored from 2009 May 20 using a VersArray 1300B CCD camera mounted on the 2.4-m telescope at Lijiang station of Yunnan Astronomical Observatory. During the observation, no filters were used. In all, 10 complete eclipses were observed. Examples of these eclipses are displayed in Fig. 1.

The no-filter light curves displayed in Fig. 1 show a number of features that are characteristic of an eclipsing polar system. The eclipse starts with the limb of the secondary star (the red dwarf component) eclipsing the accretion region, and the white dwarf is

*E-mail: qsb@ynao.ac.cn

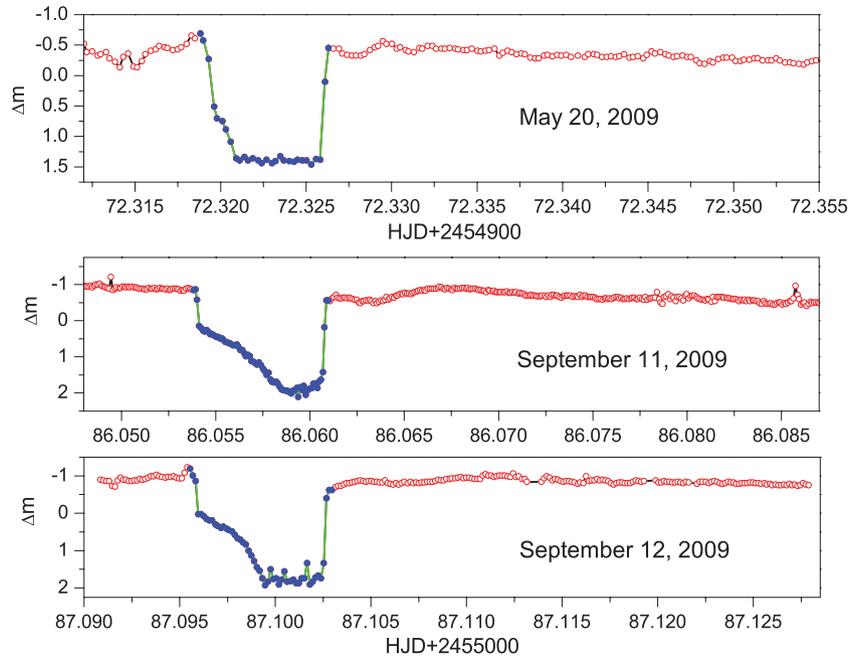


Figure 1. No-filter light curves of HU Aqr obtained with the 2.4-m telescope from 2009 May 20 to September. Blue solid dots are results obtained during an eclipse, whereas red circles denote results obtained outwith each eclipse occurrence.

also eclipsed nearly at the same time. Then the accretion stream is the dominant source of brightness with a small contribution from the red dwarf component, and finally only the secondary star is visible and provides a constant contribution. The sequence of the egress is approximately reversed. As shown in Fig. 1, the profiles of the ingress vary from one to another, whereas those of the egress are very stable. When we started to monitor the binary on 2009 May 20, it was entering into a high-accretion state and was in a high state on 2009 September 11 and 12. Since the profiles of the egress are very stable, the times of mid-egress can reliably be used for period investigation. Moreover, HU Aqr is one of the brightest eclipsing polars at optical and X-ray wavelengths. These properties make HU Aqr the most suitable binary system for determining high-precision period changes.

We defined the egress times with half-intensity (mid-egress), as done by Schwarz et al. (2009). The integration time for each CCD image was 5 s, and the readout time of the VersArray 1300B CCD camera was about 1.8 s. Therefore, the time resolution of the photometric data is about 6.8 s. We estimate that the error of the timings of mid-egress is about half of the time resolution, i.e. 3.4 s or 0.000 039 d. Since coordinated universal time (UTC) is affected by the fluctuations of the Earth’s rotation and is not uniform, the determined eclipse egress times have been converted to Barycentric Dynamical Time (TDB). The BJDs listed in Table 1 are barycentrically corrected TDB, whereas HJDs are the heliocentric UTC times. Therefore, their differences are close to 60 s (e.g. Eastman, Siverd & Gaudi 2010).

Those mid-egress times collected by Schwarz et al. (2009) are in BJED, the barycentrically corrected ephemeris time (ET). Since 1984 January 1, ET was replaced by Terrestrial Dynamical Times (TDT) and the difference between TDT and TDB is no more than 0.0017 s. Therefore, BJEDs are actually the same as BJDs. In order to compare with the O – C diagram published by Schwarz et al. (2009), the same linear ephemeris,

$$\text{BJD} = 244\,9102.920\,1788 + 0.086\,820\,406\,12E, \quad (1)$$

Table 1. New eclipse egress times of the eclipsing polar HU Aqr.

E	HJD (d)	BJD (d)	Errors (d)
67604	245 4972.326 050	245 4972.326 789	0.000 039
68914	245 5086.060 739	245 5086.061 477	0.000 039
68926	245 5087.102 611	245 5087.103 349	0.000 039
69328	245 5122.004 406	245 5122.005 145	0.000 039
69490	245 5136.069 318	245 5136.070 057	0.000 039
69800	245 5162.983 604	245 5162.984 342	0.000 039
69812	245 5164.025 454	245 5164.026 193	0.000 039
69823	245 5164.980 456	245 5164.981 195	0.000 039
69915	245 5172.967 933	245 5172.968 672	0.000 039
71785	245 5335.322 021	245 5335.322 762	0.000 039

used by them was applied to calculate the O – C values. To construct the diagrams, 72 eclipse egress times from the literature (blue) and 10 new ones (red) were used. The corresponding O – C diagram is displayed in the top panel of Fig. 2. The investigation by Schwarz et al. (2009) revealed that a long-term decrease or a cyclic change or a combination of them cannot describe the general O – C trend well. Therefore, it seems that there are two cyclic variations in the O – C curve that are caused by a pair of light traveltime effects via the presence of two companions [HU Aqr (AB)b and HU Aqr (AB)c]. To describe the O – C curve well, a combination of a quadratic ephemeris and two additional periodic terms is required:

$$O - C = \Delta T_0 + \Delta P_0 E + \frac{\beta}{2} E^2 + \tau_A + \tau_B, \quad (2)$$

where ΔT_0 and ΔP_0 are the revised epoch and period with respect to the ephemeris values in equation (1), β is the rate of the linear period decrease and τ_A and τ_B are the two cyclic changes.

Our best fit to the O – C diagram (the solid magenta line in the top panel of Fig. 2) reveals that the orbit of HU Aqr (AB)b is circular, whereas that of HU Aqr (AB)c is eccentric (e.g. Irwin

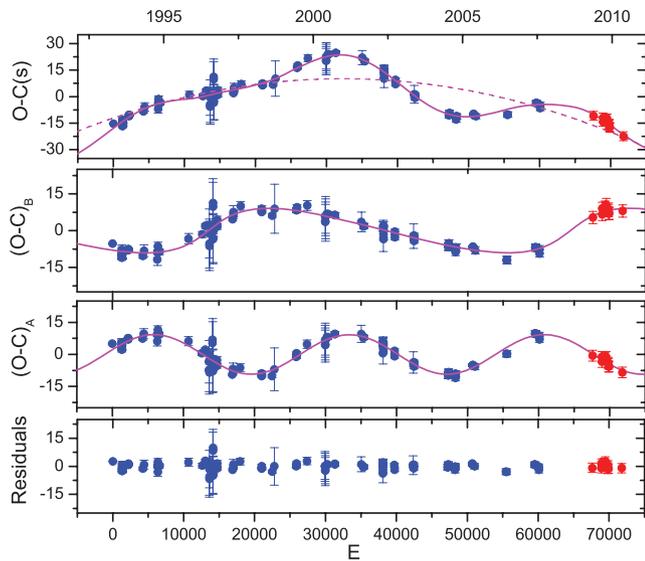


Figure 2. O – C diagrams of the eclipsing polar HU Aqr. Blue dots refer to the data compiled from the literature, whereas red ones refer to our new observations. It is shown in the top panel that a combination (solid magenta line) of two cyclic variations and a linear decrease (dashed magenta line) can give a good fit to the general trend of the O – C data. The two cyclic changes (Case A: $P_A = 6.54$ yr and $K_A = 9.25$ s; Case B: $P_B = 11.96$ yr and $K_B = 10.54$ s) are displayed in the middle panels. After all of the variations were removed, the residuals are displayed in the lowest panel where no variations can be traced.

1952), i.e.

$$\tau_A = K_A \sin\left(\frac{2\pi}{P_A} E + \varphi\right) \quad (3)$$

and

$$\begin{aligned} \tau_B &= K_B \left[\frac{(1 - e^2) \sin(\nu + \omega)}{1 + e \cos \nu} + e \sin \omega \right] \\ &= K_B [\sqrt{1 - e^2} \sin E^* \cos \omega + \cos E^* \sin \omega], \end{aligned} \quad (4)$$

where ν is the true anomaly, E^* is the eccentric anomaly, $K_A = (a_A \sin i_A)/c$ and $K_B = (a_B \sin i_B)/c$ ($a_A \sin i_A$ and $a_B \sin i_B$ are the projected semimajor axes and c is the speed of light). In solving τ_B , the two correlations

$$N = E^* - e \sin E^* \quad (5)$$

and

$$N = 2\pi(t - T)/P_B \quad (6)$$

were used, where N is the mean anomaly and t is the time of mid-egress. The other parameters and the derived values are described in Table 2. The light traveltime effect amplitudes of HU Aqr (AB)b and HU Aqr (AB)c are 9.2 and 10.5 s, respectively. The derived orbital periods are 6.54 yr for HU Aqr (AB)b and 11.96 yr for HU Aqr (AB)c.

3 THE MULTIPLE PLANETARY SYSTEM ORBITING HU Aqr

To interpret cyclic period variations in close binaries containing at least one late-type star, a physical mechanism based on solar-type activity cycles was proposed (Applegate 1992). In this mechanism, a certain amount of angular momentum is periodically exchanged between the inner and the outer parts of the convection zone, and therefore the rotational oblateness of the partly convective solar-like star, and thus the orbital period, will vary while it goes through its active cycles. The secondary star (with a mass of $0.2 M_\odot$, where M_\odot is the solar mass) in HU Aqr is a fully convective cool star. It has no differential rotation and it rotates mainly as a rigid body. Magnetic field in this type of stars is mainly the axisymmetric large-scale stable field (Donati et al. 2006, 2008). Applegate mechanism in such kind of cool stars is generally too weak to explain the observed amplitudes (e.g. Brinkworth et al. 2006). The most plausible explanation for the two periodic changes is wobbles in the system's barycentre due to the presences of low-mass companion objects (e.g. Qian et al. 2008; Beuermann et al. 2011a). As the eclipsing polar moves around the barycentre of the system, it is periodically closer to or more distant from the sun and the time of mid-egress is cyclically advanced or delayed.

Adopting the parameters $M_{\text{WD}} = 0.88 M_\odot$ and $M_2 = 0.2 M_\odot$ for the white dwarf primary and the red dwarf secondary (Schwarz et al. 2009), we obtain $d_A = 3.6$ au and $M_A \sin i_A = 5.9 M_{\text{Jup}}$ for HU Aqr (AB)b and $d_B = 5.4$ au and $M_B \sin i_B = 4.5 M_{\text{Jup}}$ for HU Aqr (AB)c, where d_A and d_B are the companion–binary separations and 1 au is the mean distance between the Earth and the Sun. When the orbital inclinations (i_A and i_B) are low, the companion objects may be a brown dwarf (for $4.6^\circ \lesssim i_A \lesssim 23.6^\circ$ and $3.5^\circ \lesssim i_B \lesssim 17.8^\circ$) or even a low-mass star (for $i_A \lesssim 4.6^\circ$ and $i_B \lesssim 3.5^\circ$), but these situations have a very low possibility. Moreover, circumbinary planets were

Table 2. Orbital parameters of the planetary system in HU Aqr.

Parameters	Values	
Revised epoch, ΔT_0 (d)	$-1.40(\pm 0.56) \times 10^{-4}$	
Revised period, ΔP_0 (d)	$+1.59(\pm 0.41) \times 10^{-8}$	
Rate of the linear decrease, β (d cycle $^{-1}$)	$-4.9(\pm 1.0) \times 10^{-13}$	
Longitude of the periastron passage [HU Aqr (AB)c], ω (deg)	$3.4(\pm 0.5)$	
Periastron passage [HU Aqr (AB)c], T (BJD)	$245\,0299.4(\pm 104.1)$	
Orbital phase [HU Aqr (AB)c], φ (deg)	$13.8(\pm 0.6)$	
Parameters	HU Aqr (AB)b	HU Aqr (AB)c
Light traveltime effect amplitude, K_A and K_B (d)	0.000 107(17)	0.000 122(14)
Eccentricity, e_A and e_B	0.0	0.51(± 0.15)
Orbital period, P_A and P_B (yr)	6.54(± 0.01)	11.96(± 1.41)
d_A and d_B ($i_A = i_B = 90^\circ$) (au)	3.6(± 0.8)	5.4(± 0.9)
Mass function, $f(m_A)$ and $f(m_B)$ (M_\odot)	$1.49(\pm 0.32) \times 10^{-7}$	$0.66(\pm 0.13) \times 10^{-7}$
Projected masses, $M_A \sin i_A$ and $M_B \sin i_B$ (M_{Jup})	5.9(± 0.6)	4.5(± 0.5)

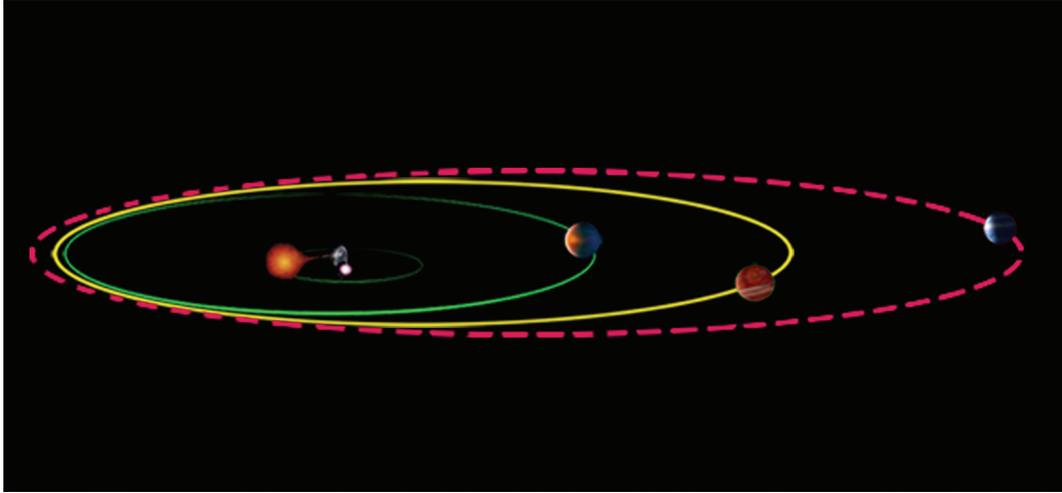


Figure 3. Sketch of the eclipsing polar HU Aqr and its circumbinary planetary system. The inner planet [HU Aqr (AB)b] is orbiting in a circular orbit, whereas the outer planet [HU Aqr (AB)c] is in an elliptical orbit with eccentricity 0.51. The distances of the two planets from the central binary are 3.6 and 5.4 au, respectively. The red dashed line refers to the orbit of the predicted third circumbinary planet [HU Aqr (AB)d].

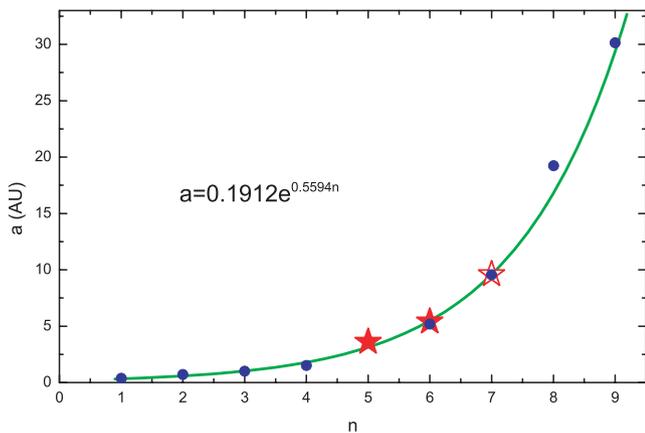


Figure 4. Titus–Bode relation for the Solar system planets (the green line). The blue dots refer to the positions of the solar planets, whereas the red solid stars are two detected circumbinary giant planets in HU Aqr. It is found that the two planets follow the Titus–Bode law of solar planets with $n = 5$ and 6 , corresponding to the positions of the belt of asteroids and Jupiter. If the predicted third extrasolar planet in HU Aqr system follows the same law ($n = 7$, the position of soil–planet), its orbital distance from the central binary should be 9.6 au (the red open star); another 10 yr of observations will form the full light traveltime effect orbit of the third circumbinary planet.

expected theoretically, at least initially, to have a nearly coplanar orbit with the central binary (e.g. Bonnell & Bate 1994). Therefore, by assuming that the companions are coplanar to the eclipsing polar ($i_A = i_B = 85^\circ:0$) (e.g. Bridge et al. 2002), they should be giant planets. From our best fit, HU Aqr (AB)b is moving around the polar in circular orbit, whereas HU Aqr (AB)c is in an elliptical orbit with eccentricity of 0.51. A sketch of the eclipsing polar HU Aqr and its circumbinary planetary system is displayed in Fig. 3.

4 DISCUSSIONS AND CONCLUSIONS

It is well known that there is a Titus–Bode law for solar planets deduced from the known distances of the main planets (e.g. Poveda & Lara 2008). Although the law predicts that there should be a planet

between Mars and Jupiter, this planet does not exist. It is interesting to point out that the planet–binary distances of the two planets of HU Aqr follow the Titus–Bode law of solar planets with $n = 5$ and 6 . As shown in Fig. 4, HU Aqr (AB)b is at the position of the belt of asteroids, whereas HU Aqr (AB)c corresponds to the position of Jupiter. It is unclear whether these agreements are fortuitous or there are physical reasons. Although substellar-object systems were reported to be orbiting two post-red giant branch binary stars, i.e. HW Vir (Lee et al. 2009) and NN Ser (Beuermann et al. 2011b), the circumbinary planetary system in HU Aqr is the first one orbiting a polar.

The quadratic term in the O – C diagram (dashed magenta line in the top panel of Fig. 2) implies a period decrease at a rate of $\dot{P} = -0.56 \times 10^{-11}$ (or 1 s in about 5700 yr), which is half the value obtained by Schwarz et al. (2009). If the observed period decrease reflects a true angular momentum loss, it would be a factor of 15 larger than the value expected for gravitational radiation. This decrease can be explained by magnetic braking (MB; Schwarz et al. 2009), but it is widely accepted that MB is stopped for fully convective stars (Rappaport, Verbunt & Joss 1983; Spruit & Ritter 1983). Moreover, the strong magnetic field of the white dwarf primary may suppress magnetic stellar wind braking in most polars (King et al. 1994; Wickramasinghe & Wu 1994). Therefore, the most plausible reason for the observed long-term period decrease is that it is only a part of a long-period cyclic variation, revealing the presence of a third planet [HU Aqr (AB)d] in the planetary system. We estimate that the planet–binary distance is about 9.6 au with an orbital period of 27.1 yr. A complete light traveltime effect orbit of the third circumbinary planet could be obtained in about 10 more years of monitoring.

It is generally proposed that non-magnetic CVs (normal CVs with an accreting disc) and polars like HU Aqr were formed through a common-envelope (CE) evolution where the secondary star orbits inside the red giant photosphere of the white dwarf progenitor (King et al. 1994; Kolb 1995). The circumbinary planetary system in HU Aqr may have been formed in a protoplanetary disc and then survived over long time-scales including the CE evolution phase. It is possible that the HU Aqr system may have been born with a considerable number of planets orbiting a star like the Sun. The inner

planets spiralled in the CE after the original central star evolves into a red giant. During the CE phase, the less massive the spiralled object is, the longer will be the time-scale of the CE evolution. Therefore, if one of the spiralled planets survived, it will have enough time to accrete so much material to form a low-mass companion. At the same time, the masses of the other planets were increased due to accreting. Finally, a polar system with a few relic giant planets was formed. Similar physical mechanism has been proposed to explain the formation of the low-mass companions in the two very hot subdwarf stars HW Vir and AA Dor (Rauch 2000; Heber 2009).

To date, over 30 multiple exoplanet systems were discovered after the first detection 18 yr ago (Wolszczan & Frail 1992). Most of them are orbiting around single solar-type stars (e.g. Wright 2010). It is possible that some will evolve into polar-planetary systems. The observational fact that the inner planet [HU Aqr (AB)b] is more massive than the outer one [HU Aqr (AB)c] supports this formation process. Moreover, the two planets following the Titus-Bode law of solar planets appear to be further evidence. Therefore, most probably, HU Aqr is an offspring of a single-stellar multiple planetary system. However, it should be pointed out that a WD mass of $0.88 M_{\odot}$ in HU Aqr suggests a progenitor much more massive than the Sun. From the initial-to-final mass relation, the mass of the progenitor should be about $5 M_{\odot}$ (Weidemann 2000; Catalán et al. 2008a,b). The two planets in HU Aqr and the one in the other polar DP Leo are more massive than the solar planets (Qian et al. 2010; Beuermann et al. 2011a). They may have accreted a large amount of material during the evolution of the CE. The question is that it is unclear on which conditions a planet will survive and gain mass. Another possibility is that the circumbinary planets in HU Aqr are the second generation planets that originated from a disc formed in the ejected envelope, as discussed by Perets (2010).

ACKNOWLEDGMENTS

This work is partly supported by the Chinese Natural Science Foundation (Nos 10973037, 10903026 and 11003040), the National Key Fundamental Research Project through grant 2007CB815406, the Yunnan Natural Science Foundation (No. 2008CD157) 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 telescope in the Lijiang station of Yunnan Astronomical Observatory. The authors thank the referee for the useful comments and suggestions that helped to improve the original manuscript.

REFERENCES

- Applegate J. H., 1992, *ApJ*, 385, 621
 Backer D. C., Foster R. S., Sallmen S., 1993, *Nat*, 365, 817
 Beuermann K. et al., 2011a, *A&A*, 526, 53
 Beuermann K. et al., 2011b, *A&A*, 521, L60
 Bonnell I. A., Bate M. R., 1994, *MNRAS*, 269, L45
 Bridge C. M. et al., 2002, *MNRAS*, 336, 1129
 Brinkworth C. S., Marsh T. R., Dhillon V. S., Knigge C., 2006, *MNRAS*, 365, 287
 Catalán S., Isern J., García-Berro E., Ribas I., 2008a, *MNRAS*, 387, 1693
 Catalán S., Ribas I., Isern J., García-Berro E., 2008b, *A&A*, 477, 901
 Donati J.-F., Forveille T., Cameron A. C., Barnes J. R., Delfosse X., Jardine M. M., Valenti J. A., 2006, *Sci*, 311, 633
 Donati J.-F. et al., 2008, *MNRAS*, 390, 545
 Eastman J., Siverd R., Gaudi B. S., 2010, *PASP*, 122, 935
 Harrop-Allin M. K., Cropper M., Hakala P. J., Hellier C., Ramsay T., 1999, *MNRAS*, 308, 807
 Heber U., 2009, *ARA&A*, 47, 211
 Irwin J. B., 1952, *ApJ*, 116, 211
 King A. R., Kolb U., de Kool M., Ritter H., 1994, *MNRAS*, 269, 907
 Kolb U., 1995, in Buckley D. A. H., Warner B., eds, *ASP Conf. Ser. Vol. 85, Cape Workshop on Magnetic Cataclysmic Variables*. Astron. Soc. Pac., San Francisco, p. 440
 Lee J. W., Kim S.-L., Kim C.-H., Koch R. H., Lee C.-U., Kim H.-I., Park J.-H., 2009, *AJ*, 137, 3181
 Perets H. B., 2010, *ApJ*, submitted (arXiv:1001.0581)
 Poveda A., Lara P., 2008, *Rev. Mex. Astron. Astrofis.*, 34, 49
 Qian S.-B., Dai Z.-B., Zhu L.-Y., Liu L., He J.-J., Liao W.-P., Li L.-J., 2008, *ApJ*, 689, L49
 Qian S.-B., Liao W.-P., Zhu L.-Y., Dai Z.-B., 2010, *ApJ*, 708, L66
 Rappaport S., Verbunt F., Joss P. C., 1983, *ApJ*, 275, 713
 Rauch T., 2000, *A&A*, 356, 665
 Schwarz R., Schwöpe A. D., Vogel J., Dhillon V. S., Marsh T. R., Copperwheat C., Littlefair S. P., Kanbach G., 2009, *A&A*, 496, 833
 Schwöpe A. D., Thomas H. C., Beuermann K., 1993, *A&A*, 271, L25
 Schwöpe A. D., Schwarz R., Sirk M., Howell S. B., 2001, *A&A*, 375, 419
 Silvotti R. et al., 2007, *Nat*, 449, 189
 Silvotti R., Szabo R., Degroote P., Ostensen R. H., Schuh S., 2011, *AIP Conf. Ser. Vol. 1331, Planetary Systems Beyond the Main Sequence*. Am. Inst. Phys., Melville, NY, p. 133
 Spruit H. C., Ritter H., 1983, *A&A*, 124, 267
 Warner B., 1995, *Cambridge Astrophys. Ser. Vol. 28*. Cambridge Univ. Press, Cambridge
 Weidemann V., 2000, *A&A*, 363, 647
 Wickramasinghe D. T., Wu K., 1994, *MNRAS*, 266, L1
 Wolszczan A., Frail D. A., 1992, *Nat*, 355, 145
 Wright J. T., 2010, *EAS Publ. Ser.*, 42, 3

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.