DETECTION OF A TERTIARY BROWN DWARF COMPANION IN THE sdB-TYPE ECLIPSING BINARY
HS 0705+6700

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ABSTRACT

HS 0705+6700 is a short-period ($P = 2.3$ hr), close binary containing a hot sdB-type primary and a fully convective secondary. We have monitored this eclipsing binary for more than two years and as a result, 32 times of light minimum were obtained. Based on our new eclipse times together with those compiled from the literature, it is discovered that the observed–calculated curve of HS 0705+6700 shows a cyclic variation with a period of 7.15 years and a semiamplitude of 92.4 s. The periodic change was analyzed for the light–time effect that may be due to the presence of a tertiary companion. The mass of the third body is determined to be $M_3 \sin^3 i = 0.0377(\pm 0.0043) M_\odot$ when a total mass of 0.617 $M_\odot$ for HS 0705+6700 is adopted. For orbital inclinations $i' \geq 32.8^\circ$, the mass of the tertiary component would be below the stable hydrogen-burning limit of $M_3 \sim 0.072 M_\odot$, and thus it would be a brown dwarf. The third body is orbiting the sdB-type binary at a distance shorter than 3.6 AU. HS 0705+6700 was formed through the evolution of a common envelope after the primary becomes a red giant. The detection of a substellar companion in HS 0705+6700 system at this distance from the binary could give some constraints on stellar evolution in such systems and the interactions between red giants and their companions.

Key words: binaries: close – binaries: eclipsing – stars: individual (HS 0705+6700) – stars: low-mass, brown dwarfs – subdwarfs

1. INTRODUCTION

HS 0705+6700 (= GSC 4123−265) was listed as a dwarf candidate from the Hamburg Schmidt survey (Hagen et al. 1995). Follow-up spectroscopy by Heber et al. (1999) and Edelmann et al. (2001) revealed that its effective temperature lies in the predicted pulsational instability. Therefore, in order to search for pulsations, this star was included in a photometric monitoring programme at the Nordic Optical Telescope (see Ostensen et al. 2001a, 2001b). The observations indicated that it was an eclipsing binary (Drechsel et al. 2001). A detailed photometric and spectroscopic investigation was carried out by Drechsel et al. (2001) who discovered that HS 0705+6700 is a detached, short-period eclipsing binary. Absolute parameters of both components were determined suggesting the primary is a subluminous B (sdB) star, while the secondary is a cool stellar object that does not contribute to the total optical light apart from a strong reflection effect. These detections reveal that HS 0705+6700 is the third one of a small group of HW Vir-like eclipsing binary stars that consist of a very hot sdB type primary component and a fully convective M-type secondary with a period between 2 and 3 hr. Up to now, only six of this type of binaries have been discovered (e.g., Menzies & Marang 1986; Kilkenny et al. 1998; Drechsel et al. 2001; Ostensen et al. 2007; Polubek et al. 2007; Wils et al. 2007). The hot sdB components in this group of binaries are on the extreme horizontal branch of the Hertzsprung–Russell diagram, they burn helium in their cores, and have very thin hydrogen envelopes. They are formed through a common-envelope evolution (e.g., Han et al. 2003) and will evolve into normal cataclysmic variables (CV) (e.g., Shimansky et al. 2006).

As pointed out by Qian et al. (2008a), because of the compact structures and large temperature differences between the components, light curves of this group of binaries show a strong reflection effect with very sharp primary and shallow secondary minima. Therefore, eclipse times can be determined with a high precision (e.g., Kilkenny et al. 1994, 2000), and very small-amplitude orbital period variations could be detected by analyzing the observed–calculated (O–C) diagram. Orbital period variations of HW Vir, the prototype of this group of systems, were discovered (e.g., Kilkenny et al. 1994; Qian et al. 2008a; Lee et al. 2009), which show a combination of a cyclic variation and a long-term period decrease. The cyclic variation suggests the presence of a brown dwarf tertiary companion in the system, while the continuous decrease can be explained as secular angular momentum loss via magnetic braking of the fully convective component star or as a part of another long-period cyclic change via the existence of another companion. To search for the variations in the orbital period of HS 0705+6700, it has been monitored since 2006. Here we report the discovery of a cyclic change in the orbital period of HS 0705+6700 that reveals the presence of a tertiary, most likely a brown dwarf companion in this system.

2. NEW OBSERVATIONS AND THE ORBITAL PERIOD CHANGE OF HS 0705+6700

Drechsel et al. (2001) published 13 times of light minimum of HS 0705+6700 and obtained the first linear ephemeris,

$$\text{Min.} I = \text{HJD} 2451822.75982 + 0.09564665 \times E, \tag{1}$$

where HJD 2451822.75982 is the initial epoch and 0.09564665 is the orbital period. Later, some eclipse times were derived by Niarchos et al. (2003), Németh et al. (2005), and Kruspe et al. (2007). To search for the variations in the orbital period of HS 0705+6700, it was monitored from 2006 December to

L163
from the (O–C)1 values of all available times of minima were calculated by using the ephemeris from Equation (1). The corresponding (O–C)1 diagram is shown in Figure 1, where our 38 new minima times and the other 31 eclipse times collected from the sources noted above.

As shown in Figure 1, the linear component of the orbital period of HS 0705+6700 needs revision and it appears that there is a cyclic variation as well. To describe the general (O–C)1 trend satisfactorily, a new linear ephemeris is required (dashed line in Figure 1) with additional cyclic variations superimposed. Using the least-squares method, we determined

\[
\text{Min.} = 2451822.76090(\pm 0.00007) \\
+ 0.095646625(\pm 0.000000003) \times E \\
+ 0.00107(\pm 0.00007) \times \sin[0.0132(\pm 0.0001)] \\
\times E + 237.2(\pm 3.6)].
\]

The derived orbital period is slightly shorter than that determined by Drechsel et al. (2001). The cyclic oscillation has an amplitude of 92.4 s and a period of 7.15 years. During the analysis, two timings of light minima, HJD 2451957.5274 and HJD 2454706.5040, were not used because their (O–C)1 values show large scatter when compared with the general trend formed by the other data points. Actually, the eclipse minimum, HJD 2451957.5274, has been deleted by Drechsel et al. (2001) too, in their analysis.

The (O–C)2 values calculated with the new linear ephemeris are plotted in the upper panel of Figure 2 where the cyclic change is seen more clearly. After the periodic change was subtracted from the (O–C)2 curve, the residuals are displayed in the lower panel where no variations can be found indicating that Equation (2) gives a good fit to the (O–C)1 curve.

3. DISCUSSIONS AND CONCLUSIONS

One cause of cyclic period change could be the magnetic activity cycles of the fully convective component (i.e., the Applegate mechanism; Applegate 1992). It is assumed in the mechanism that a certain amount of angular momentum is

![Figure 1. Plot of the (O–C) diagram of HS 0705+6700 with respect to the linear ephemeris given by Drechsel et al. (2001). The solid line suggests a combination of a revised linear ephemeris and a cyclic change, while the dashed line refers to the revision of the orbital period.](image1)

![Figure 2. (O–C) curve of HS 0705+6700 with respect to the new linear ephemeris in Equation (2) is shown in the upper panel where the periodic variation can be seen more clearly. After the small-amplitude period oscillation was removed, the residuals are shown in the lower panel where no changes can be traced.](image2)
companion as: With the absolute parameters determined by Drechsel et al. (2001), the fully convective secondary in HS 0705+6700 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). The analyses for HW Vir and NN Ser indicated that the required energies are much larger than the total radiant energy of the M-type components, suggesting, that the mechanism of Applegate cannot interpret the cyclic period variations of the two systems. Moreover, as discussed by Qian et al. (2008a, 2008b), a more general explanation of the cyclic period changes in close binaries would be the light-travel time effect via the presence of a third body.

Therefore, we analyzed HS 0705+6700 for the light-time effect that arises from the gravitational influence of a third companion. The presence of a tertiary body produces the relative distance changes of the eclipsing pair as it orbits the barycenter of the triple system. Since the sine fit seems quite good, we assumed the orbit of the third body to be circular. With the absolute parameters determined by Drechsel et al. (2001), we derived the mass function and the mass of the tertiary companion as: $f(m) = 1.25(\pm0.24) \times 10^{-5} M_\odot$ and $M_3 \sin i = 0.0377(\pm0.0043) M_\odot$, respectively. The relations between the mass $M_3$ and the orbital radius $d_3$ of the tertiary component and its orbital inclination $i'$ are displayed in Figure 3. When the orbital inclination of the third body is larger than $32.8^\circ$, the mass of the tertiary component corresponds to $0.0377 M_\odot \leq M_3 \leq 0.072 M_\odot$. In this case, the tertiary component cannot undergo a stable hydrogen burning in the core, and it should be a brown dwarf. Therefore, with 63.6% probability, the third body is a substellar object (by assuming a random distribution of orbital plane inclination). However, depending on the unknown orbital inclination of the third body, a low-mass, stellar companion cannot be totally excluded but with a lower possibility of 36.4%.

HS 0705+6700 has passed through the phase of a common envelope (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, short-period sdB-type binary has been formed. As it is shown in Figure 3, the orbital radius $d_3$ of the tertiary component is smaller than 3.6 AU. The detection of a brown dwarf or a very low-mass stellar companion in HS 0705+6700 at this distance, could give some constraints on the stellar evolution and the interaction between red giants and their companions.

Apart from cyclic period changes, a long-term period decrease was discovered in HW Vir which can be plausibly explained by secular angular momentum loss via magnetic braking of its fully convective component (Qian et al. 2008a; Lee et al. 2009). If this is true, a long-term period decrease could be discovered in HS 0705+6700. Actually, as displayed in Figure 1, the $(O-C)_1$ diagram can also be described by a combination of a cyclic change and a long-term period decrease. To check whether a long-term period decrease exists or not, more times of light minimum are required in the future.

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Figure 3. Relations between the mass $M_3 (M_\odot)$ and the orbital radius $d_3$ (AU) of the tertiary component and its orbital inclination $i'$ in the HS 0705+6700 system. The tertiary companion should be a brown dwarf when the orbital inclination is larger than $32.8^\circ$, while the orbital radius $d_3$ of the tertiary component is always less than 3.6 AU.

No. 2, 2009 DETECTION OF A TERTIARY BROWN DWARF COMPANION L165