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SDSS J0926+3624, the first eclipsing AM CVn star, as seen with ULTRACAM

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Abstract. We present light curves of SDSS J0926+3624, the first eclipsing AM CVn star, observed with the high-speed CCD camera ULTRACAM on the WHT. We find unusually that the accreting white dwarf is only partially eclipsed by its companion. Apart from this, the system shows the classic eclipse morphology displayed by eclipsing dwarf novae, namely the eclipse of a white dwarf and accretion disc followed by that of the bright spot where the mass transfer stream hits the disc. We are able to fit this well to find masses of the accretor and donor to be $M_1 = 0.84 \pm 0.05\,\mathrm{M}_\odot$ and $M_2 = 0.029 \pm 0.02\,\mathrm{M}_\odot$ respectively. The mass of the donor is significantly above its zero temperature value and it must possess significant thermal content.

1. Introduction

The AM CVn stars are hydrogen-deficient interacting binaries. They have orbital periods which range from 10 to 65 minutes, only possible because the absence of hydrogen in their donor stars allows them to reach the high densities required at short orbital periods. The accreting objects in these stars are white dwarfs, and they are sometimes called "double degenerates" as the high densities of their mass donors implies degeneracy pressure is important. It would be a mistake however simply to regard these stars as two white dwarfs, as has sometimes happened in the past, because it is quite possible for the donor stars to have significant thermal content, and indeed the extent of this is one of the major questions concerning these objects (Deloye & Bildsten 2003). For a recent review of AM CVn stars, see Nelemans (2005).

The origin of the AM CVn stars is uncertain. Three possible paths are under debate. First is the merger of two white dwarfs under gravitational radiation (Nelemans et al. 2001). This requires a mass ratio well below one for stability

(Nelemans et al. 2001; Marsh et al. 2004). The main uncertainty about this route is its rate (Marsh et al. 2004). Second, is mass transfer from a core helium burning star, e.g. an sdB star (Iben & Tutukov 1991) although some degree of fine tuning seems necessary to terminate the helium burning early enough that there is no significant build-up of carbon. Third are cataclysmic variables with donor stars that have left the main-sequence and built up a significant helium core (Podsiadlowski et al. 2003). Here the problem seems to be that one would often expect to see hydrogen. The second two paths reach a minimum period of about 10 minutes, whereas double white dwarfs merge at periods of 1 or 2 minutes, a difference which is particularly significant in the context of the gravitational wave observatory *LISA* (Nelemans et al. 2004).

The donor stars in semi-detached binaries have a fixed density at any given period. Completely degenerate, zero temperature stars obey a specific mass-radius relation, and thus they can only fill their Roche lobe for a unique mass at any one period. A star of finite entropy is always less dense than a zero temperature star of the same mass, and therefore for a given orbital period, finite entropy donors must be more massive than their degenerate counterparts. The completely degenerate case therefore sets a lower limit to the mass of the donor. Since mass transfer in AM CVn stars is thought to be driven by gravitational radiation, then completely degenerate donors give the lowest mass, least gravitational radiation, and lowest mass transfer rates. All this shows the importance of mass measurements in these systems. We have made efforts to measure masses for these reasons (Roelofs et al. 2006), but the measurements are reliant on several assumptions which are hard to verify. Eclipsing systems always offer the most direct way to measure masses, unfortunately, until recently not a single eclipsing AM CVn had been discovered.

This changed with the discovery of SDSS J0926+3624 by Anderson et al. (2005). SDSS J0926+3624, discovered through its colour and spectrum, turned out to be an eclipsing system with a period of 28 min. We therefore acquired photometry of this object with the aim of carrying out an analysis similar to that applied to hydrogen-dominated cataclysmic variables in the 1980s (e.g. Wood et al. 1986).

2. Observations

We observed SDSS J0926+3624 on the nights of 1 to 3 March 2006 using the high-speed CCD camera ULTRACAM mounted on the 4.2m WHT in La Palma. ULTRACAM is a triple-beam camera and we observed through the filters u', g' and r'. On each night we attempted to stay on the target for long, uninterrupted runs to monitor both the eclipses and the out-of-eclipse modulations. Table 1 shows a log of the observations.

We used an exposure time of 3 sec for the majority of our observations; dead time was 0.024 sec for our frame transfer CCDs. The data were reduced with standard aperture photometry. Observations of a standard star showed that SDSS J0926+3624 had $g' \approx 19.3$ out of eclipse, as observed by Anderson et al. (2005).

Date start	Time start	 end	Comment
01 Mar 2006	22:28	04:48	Poor weather at start
02 Mar 2006	20:04	04:49	Seeing ~ 1 – 1.5”, clear
03 Mar 2006	19:57	03:59	Variable seeing, 1.2 – 2.0”

Table 1. Log of the observations.

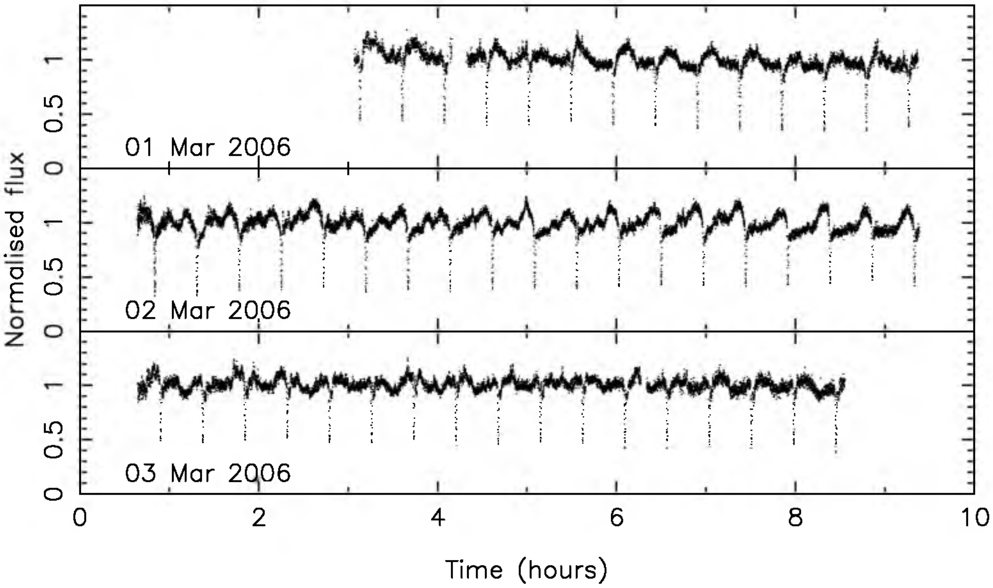

Figure 1. The light-curves of SDSS J0926+3624 (u', g' and r' combined) over the three nights of our run. The mean level outside eclipse has been normalised to one.

3. Results

Fig. 1 shows all the data from the run, and covers 50 eclipses of SDSS J0926+3624. The eclipse depth is variable, but is as much as 70% of the out-of-eclipse flux. There is marked variability outside eclipse which changes character from night to night. This is caused by what are known as “superhumps”, periodic flaring of the accretion on a period slightly longer than the orbital period, and thought to be caused by a tidally-driven instability of discs in extreme mass ratio systems (Whitehurst 1988).

We removed most of the effect of the superhump by fitting and subtracting a sinusoid to the data outside eclipse. We then folded the first and last nights' data, which have a similar morphology, on the orbital period to obtain the data plotted in Fig. 2. The data show a relatively narrow eclipse, lasting approximately from phase -0.02 to $+0.02$, or a little over one minute in time. It is no coincidence that it is centred on phase zero as this feature was used to define the conjunction phase as we believe it is the white dwarf. A remarkable feature is that it is round-bottomed, indicating that we are seeing the *partial* eclipse of the accretor in this system.

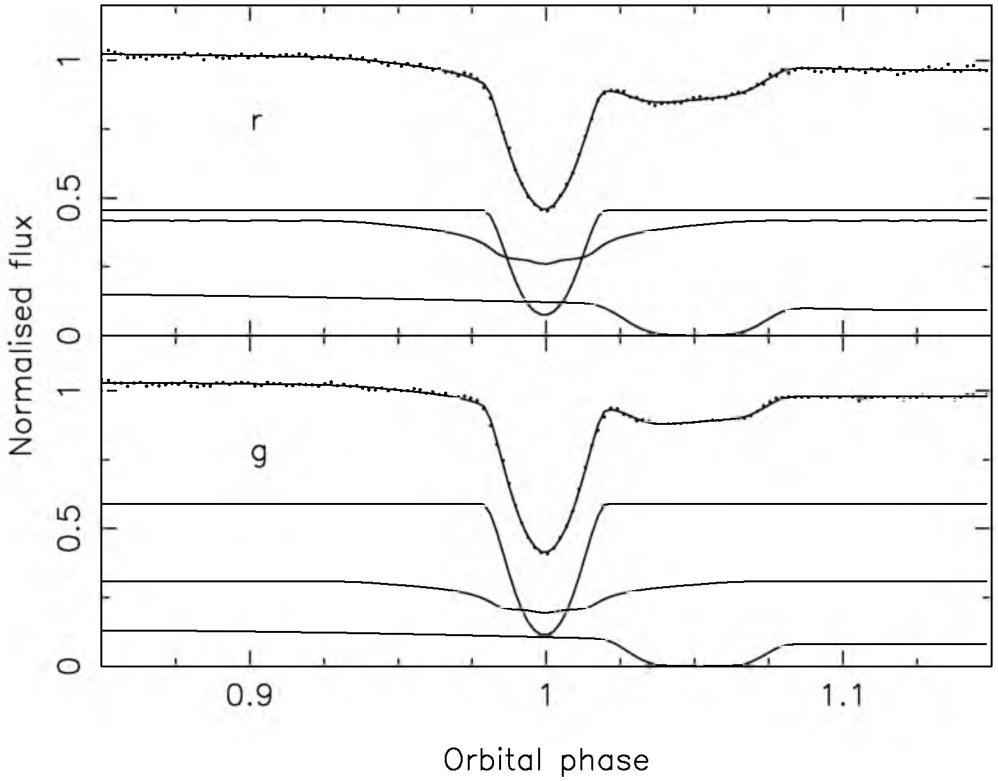

Figure 2. The phase-folded light-curves of SDSS J0926+3624 in g' and r' based upon the first and last nights' data. Solid lines show calculations of the eclipse of the white dwarf (narrowest), the bright-spot (offset from phase zero) and the accretion disc (shallowest) as well as the sum of all three.

Following the narrow eclipse, there is another, broader feature. This is the eclipse of the bright spot where the mass transfer stream hits the disc. Its extreme displacement from the white dwarf eclipse such that its ingress starts after the white dwarf's egress is a sign that the system is of extreme mass ratio because in such systems, the high angular momentum of the transferred gas deflects it far in advance of the mass donor's orbit as it moves towards the accretor. The bright spot is eclipsed totally, but its eclipse is not flat-bottomed because of the eclipse of a third component, the accretion disc. This is coming out of eclipse during the eclipse of the bright spot, and hence the increasing flux at this time.

We modelled all these features with a light-curve fitting program which sets element grids over all components and computes their mutual occultations (Fig. 3), accounting for the Roche-distorted geometry. The parameters were then adjusted to obtain the best fit using Levenberg-Marquart minimisation of χ^2. The results from this are plotted in Fig. 2, confirming the partial eclipse of the white dwarf and total eclipse of the bright spot. The fit was obtained for a mass ratio $q = M_2/M_1 = 0.035 \pm 0.002$, an inclination $i = 83.1 \pm 0.1^\circ$ and a relative radius of the accretor of $R_1/a = 0.033 \pm 0.002$. Using a zero-temperature relation for the mass-radius relation of the donor (which will be improved upon

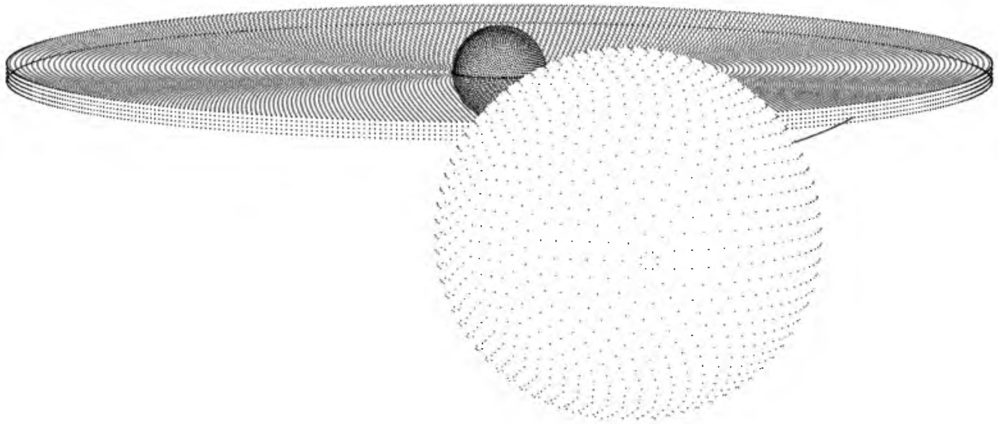

Figure 3. A visualisation of the relative sizes of the components used to model the light-curves of Fig. 2. The line leading from the right of the donor star (closest to us) is the mass transfer stream showing that the spot where it hits the disc has yet to be eclipsed at this phase when the accretor has almost emerged from eclipse. Note that the accretor and donor stars are not that different in size, which is a feature of these very compact binary stars.

in the future) leads to $M_1 = 0.84 \pm 0.05\,\mathrm{M}_\odot$ and $M_2 = 0.029 \pm 0.02\,\mathrm{M}_\odot$ for the accretor and donor respectively. The uncertainties are preliminary, nonetheless we believe that these are the most secure masses for any AM CVn star. We note that accounting for the finite temperature of the accretor will lead to a small increase in the masses.

The mass of the donor is of particular interest. Had it been completely degenerate, it should have had a mass close to $0.020\,\mathrm{M}_\odot$. Instead it is substantially higher than this indicating a significant level of thermal energy (Deloye & Bildsten 2003). The implications of this for the evolution of the binary need to be worked out.

An interesting point from our model of the light-curve is that the white dwarf contributes most of the optical flux in this system. This is comparable to quiescent dwarf novae. However, unlike the great majority of quiescent dwarf novae, SDSS J0926+3624 shows obvious superhumps in this state. Superhumps in dwarf novae are normally associated with outburst bright states. A likely explanation for this lies in the extreme mass ratio of the system, although there have not been any reports as far as we are aware of superhumps in similar AM CVn stars in their low state.

We finish by showing the times of the eclipses in Fig. 4. The mean eclipse time has an uncertainty of $\approx 0.2\,\mathrm{sec}$, which shows that it should be possible to detect period changes of plausible magnitude. Gravitational radiation, for example, should cause $\sim 5\,\mathrm{sec}$ departure from linearity over 10 years.

4. Conclusions

We have presented high-speed light curves of the first eclipsing AM CVn star, SDSS J0926+3624 which we find to display the usual form of eclipse light curve displayed by eclipsing dwarf novae. Modelling of the light curve leads to an

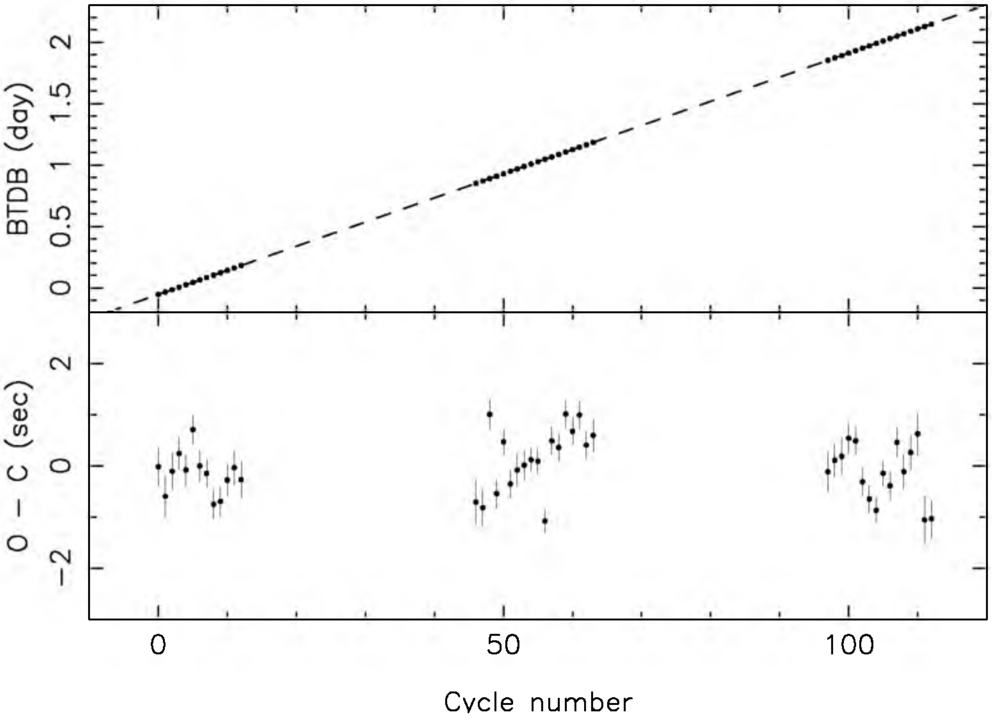

Figure 4. Eclipse times based upon our model of the light curve. Systematics in the residuals in the middle night are likely the result of the superhumps.

extreme mass ratio of $q = 0.035 \pm 0.002$, as expected for these systems and a donor mass 50% above the mass expected for pure degeneracy indicating that thermal pressure is significant.

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