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# The nature of the close magnetic white dwarf + probable brown dwarf binary SDSS J121209.31+013627.7*

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**ABSTRACT**

Optical time series photometry of the short-period magnetic white dwarf + probable brown dwarf binary SDSS J121209.31+013627.7 reveals pulse-like variability in all bands from $i'$ to $u'$, increasing towards bluer wavelengths and peaking at $u'$. These modulations are most likely due to a self-eclipsing accretion hot spot on the white dwarf, rotating into view every 88.43 min. This period is commensurate with the H$\alpha$ radial velocity period of ≈90 min, and consistent with the rotation period of the accretor being equal to the binary orbital period. We combine our observations with other recently reported results to provide an accurate ephemeris. We also detect the system in X-rays with *Swift*, and estimate the accretion rate at $\approx 10^{-13}$ M$_\odot$ yr$^{-1}$. We suggest that SDSS J121209.31+013627.7 is most likely a magnetic cataclysmic variable in an extended state of very low accretion, similar to the well-studied polar EF Eri. Alternatively, the putative brown dwarf is not filling its Roche lobe and the system is a detached binary in which the white dwarf is efficiently accreting from the wind of the secondary. However, it is unclear whether an L dwarf wind is strong enough to provide the measured accretion rate. We suggest further observations to distinguish between the Roche lobe overflow and wind accretion scenarios.

**Key words:** stars: low-mass, brown dwarfs – novae, cataclysmic variables – white dwarfs.

## 1 INTRODUCTION

Brown dwarf companions to white dwarfs are rare (Farihi, Becklin & Zuckerman 2005). Proper motion surveys and searches for infrared (IR) excesses have so far found only three confirmed examples: GD 165 (DA+L4; Becklin & Zuckerman 1988), GD 1400 (DA+L6/7; Farihi & Christopher 2004; Dobbie et al. 2005) and WD 0137−349 (DA+L8; Burleigh et al. 2006; Maxted et al. 2006). GD 165 is a widely separated system (120 au) and the separation of the components in GD 1400 is currently unknown, but WD 0137−349 is a close ($P = 116$ min), detached (non-interacting) binary. The L8 companion must have survived a phase of common envelope (CE) evolution during which the orbit decayed to near the current period.

There is no confirmed brown dwarf secondary in a cataclysmic variable (CV). Many are strongly suspected to contain such very low mass companions, but the secondaries are difficult to certify (Littlefair, Dhillon & Martin 2003). For example, the claimed direct detection of the $L\,4/5$ secondary in the magnetic CV (polar) EF Eri (Howell & Ciardi 2001) has subsequently been called into question through evidence for IR cyclotron emission (Harrison et al. 2003). Recent radial velocity measurements also support a substellar mass for the secondary in EF Eri, although the unknown white dwarf mass still allows for a stellar companion (Howell et al. 2006).

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SDSS J121209.31+013627.7 (hereafter SDSS 1212) was identified by Schmidt et al. (2005b) from the Sloan Digitized Sky Survey as a $g' \approx 18$, $T_{\rm eff} \approx 10\,000$ K, $B \approx 13$ MG magnetic DA white dwarf. Optical spectra display the characteristic Zeeman split H$\alpha$ and H$\beta$ absorption lines and also a weak, narrow H$\alpha$ 6563 Å emission line, which is variable both in radial velocity and flux. This emission line is interpreted as arising from the irradiated face of a cool secondary star in a close orbit with the white dwarf. The radial velocity variations show a ≈90 min periodicity, which is most likely the orbital period of the system. Despite a photometric measurement at 1.2 μm ($J$ band), the cool secondary was not detected by Schmidt et al. (2005b), limiting its absolute magnitude to $M_J > 13.4$, equivalent to a brown dwarf of spectral type L5 or later ($T_{\rm eff} < 1700$ K).

The lack of evidence for ongoing accretion led Schmidt et al. (2005b) to conclude that SDSS 1212 is most likely a detached binary. As with WD 0137−349, the cool companion would always have been a brown dwarf and, therefore, must have survived a previous phase of CE evolution. In this picture, SDSS 1212 would be a precursor of a magnetic CV (a pre-polar), and the first known magnetic white dwarf with a cool secondary (Liebert et al. 2005). Alternatively, Schmidt et al. (2005b) suggested that SDSS 1212 is a magnetic CV in an extended low state, similar to that experienced by EF Eri between 1996 and early 2006.

SDSS 1212 is clearly an important new binary requiring more detailed study. Therefore, we obtained time series optical photometry of the system to search for variability to: (a) better determine the orbital period; (b) investigate the effects of irradiation on the putative brown dwarf; (c) to search for a possible short (<5 min) eclipse of the white dwarf, which would yield a radius for the cool companion; and (d) to search for non-radial pulsations, since the temperature of the white dwarf is close to the range occupied by the ZZ Ceti stars. Our surprising results prompted us to then obtain X-ray observations with the *Swift* space observatory, which provide further insight into the nature of the system.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 Faulkes Telescope North and Isaac Newton Telescope

SDSS 1212 was remotely observed on 2006 January 3 (MJD 53738) for 1 h with the 2-m robotic Faulkes Telescope North (FTN), located at the Haleakala Observatory on Maui, Hawaii. The observations were made through a Bessell $V$ filter with 45-s exposures obtained approximately every 2 min. The debiased and flat-fielded data were downloaded and differential aperture photometry was performed with respect to three comparison stars in the 4.6 × 4.6 arcmin$^2$ field of view, using the Starlink software package PHOTOM. Once we had checked the comparison stars for variability, they were added together and divided into the target to give the differential photometry. The resultant light curve is shown in Fig. 1 (top). The target is clearly variable at the ≈ 3 per cent level, consistent with the ≈90 min radial velocity period reported by Schmidt et al. (2005b).

Although the FTN data revealed for the first time that SDSS 1212 is photometrically variable, the data did not cover the entire radial velocity period and were of relatively poor quality. Therefore, two of us (MRB and SLC) obtained further time series photometry with the Wide Field Camera (WFC) on the 2.5-m Isaac Newton Telescope (INT) in La Palma on 2006 February 4 (MJD 53771). The target was observed continuously for 3 h through a Sloan $r'$ filter, with 60-s exposures. The readout speed meant that exposures were obtained every ≈1.5 min. The weather was clear and photometric throughout the observations, with seeing ≈1 arcsec. The data were reduced with the WFC pipeline reduction software at the Cambridge Astronomical Survey Unit, Institute of Astronomy, Cambridge. Differential photometry was performed in the same manner as the FTN data, although four different non-variable comparison stars were utilized. The light curve is also shown in Fig. 1 (bottom).

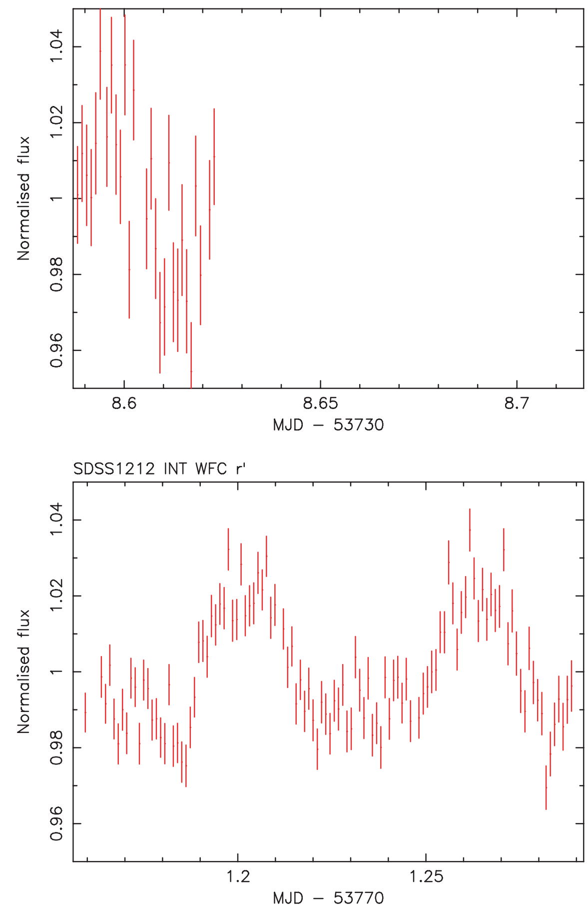


**Figure 1.** Top panel: 1-h $V$-band light curve of SDSS 1212 obtained with the 2-m robotic Faulkes Telescope North on 2006 January 3 (MJD 53738), revealing variability at the ≈3 per cent level. Bottom panel: 3-h $r'$ light curve of SDSS 1212 obtained with the INT WFC on 2006 February 4 (MJD 53771). The time axes have been scaled to match for ease of comparison.

### 2.2 ULTRACAM on the William Herschel Telescope

SDSS 1212 was independently observed by three of us (TRM, VSD and SPL) on the nights of 2006 March 11 and 12 (MJD 53805 & MJD 53806) using the multiband high-speed CCD camera ULTRACAM (Dhillon & Marsh 2001) mounted on the 4.2-m William Herschel Telescope (WHT) in La Palma. We observed simultaneously in $i'$, $g'$ and $u'$ with exposure times of 10 s (with only 25 ms of dead time between each frame) for a total of 3.6 h on the first night (during gaps in the main programme) and for 2 h on the second night. The weather was clear throughout the observations, but the seeing which was ≈1 arcsec on the first night, deteriorated to 2–3 arcsec on the second night. The seeing combined with a bright Moon meant that the first night's data were superior. The data were reduced with the ULTRACAM data reduction pipeline software. The reduced, normalized differential light curves from the first night are shown in Fig. 2. Note that the 10-s exposures have been binned to 90 s in this plot.

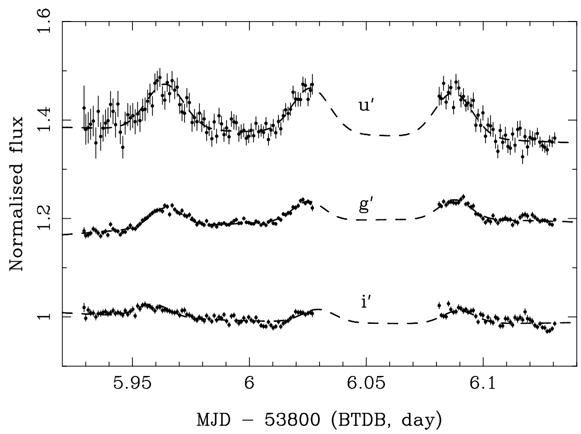


**Figure 2.** Simultaneous $i'$, $g'$ and $u'$ light curves of SDSS 1212 obtained with ULTRACAM on the WHT on 2006 March 11 (MJD 53805). The original 10-s exposures have been binned to 90 s per data point. The $g'$ and $u'$ data sets have been arbitrarily offset for clarity. The fitted model consists of parabolas plus three Gaussians; the fit to the $g'$ data yields a period of 88.43 min.

### 2.3 *Swift* observations

The primary scientific objective of the *Swift* space observatory is to detect and obtain follow-up multiwavelength observations of gamma-ray bursts (GRBs). In addition to a gamma-ray detector (Burst Alert Telescope; BAT), *Swift* carries an X-ray telescope (XRT) and an ultraviolet and optical telescope (UVOT). During periods when GRBs and their afterglows are not being observed, these instruments can be used to observe other interesting astronomical targets. Following our discovery of the unusual optical light curves of SDSS 1212 (discussed in detail below), we requested and were awarded such ‘fill-in’ time with *Swift* to search for X-ray emission. These observations were carried out in late 2006 April and May (Table 1). SDSS 1212 was observed on 11 separate occasions for ≈1 ks per observation.

#### 2.3.1 *Swift XRT data reduction*

The *Swift* XRT PC mode event lists were processed using the standard XRT data reduction software XRTPIPELINE version 0.9.4, within FTOOLS v6.0.3, screening for hot and flickering pixels, bad columns and selecting event grades 0–12, giving a total on-source exposure time of 10.7 ks.

An X-ray source is clearly detected at 8$\sigma$ close to the position of SDSS 1212, at $12^{\rm h}12^{\rm m}09\overset{\rm s}{.}7$, $+01^\circ36'25\overset{''}{.}8$ (J2000), with an error radius of 5.2 arcsec (90 per cent containment), and has a mean X-ray count rate of $2.6 \pm 0.6 \times 10^{-3}$ count s$^{-1}$ in the 0.3–10 keV range. We note that no X-ray source was detected at this position in the *ROSAT* all-sky survey.

**Table 1.** Journal of *Swift* observations.

| Obs. ID | Start time (UT) | Start time (MJD) | Exp. (s) |
|---|---|---|---|
| 00030391001 | 2006-04-20 01:01:01 | 53845.0423727 | 794.4 |
| 00030391002 | 2006-04-23 01:41:00 | 53848.0701389 | 956.9 |
| 00030391003 | 2006-04-25 00:18:00 | 53850.0125000 | 794.3 |
| 00030391004 | 2006-04-27 21:14:00 | 53852.8847222 | 985.9 |
| 00030391005 | 2006-04-30 10:27:01 | 53855.4354282 | 966.8 |
| 00030391006 | 2006-05-02 12:23:30 | 53857.5163194 | 531.8 |
| 00030391007 | 2006-05-04 16:56:01 | 53859.7055671 | 797.3 |
| 00030391009 | 2006-05-11 21:26:00 | 53866.8930556 | 810.5 |
| 00030391011 | 2006-05-16 13:52:01 | 53871.5777893 | 872.1 |
| 00030391012 | 2006-05-18 04:18:01 | 53873.1791782 | 1237.5 |
| 00030391013 | 2006-05-20 06:13:01 | 53875.2590394 | 2030.3 |

## 3 DATA ANALYSIS AND RESULTS

### 3.1 Optical light curves

Although the FTN *V*-band data from 2006 January revealed the photometric variability of SDSS 1212, the pulse-like behaviour is not due to the variations in flux of the weak H$\alpha$ emission line reported by Schmidt et al. (2005b). The INT, WFC and WHT ULTRACAM multiband data sets (Figs 1–3) reveal that the variability is larger in the ultraviolet (UV) and blue compared to the red, and that in all bands the light curve consists of a broad Gaussian peak rising from an underlying steady continuum level. The source of the variability is most likely a hot spot on the surface of the white dwarf, which is self-eclipsed every time the star rotates. This type of variability is commonly observed in polars (e.g. Stockman et al. 1994; Gänsicke, Beuermann & de Martino 1995).

To determine the rotation period of the white dwarf from this hot spot, we fit the ULTRACAM $g'$-band light curve from 2006 March with a model consisting of a parabola (allowing for any general trend during the observations, due to colour-dependent extinction effects) plus three Gaussians (two for the second night), which are constrained to have the same width and height but are otherwise free. We then extended our model to include the 2006 February INT WFC data, and to include the very recently reported data of Koen & Maxted (2006), who observed SDSS 1212 on several occasions in white light, *V* and *R* filters for a total 27 h between 2006 March 23 (MJD 53823) and 2006 April 26 (MJD 53851).

The pulse times for all these observations are given in Table 2. All times are barycentric corrected. We find no ambiguity in the cycle identifications, and from a linear fit to the pulse times we determine the following ephemeris:

$$\text{MJD (BTDB)} = T_0 + PE = 53798.5953(2) + 0.061\,4081(7)\,E.$$

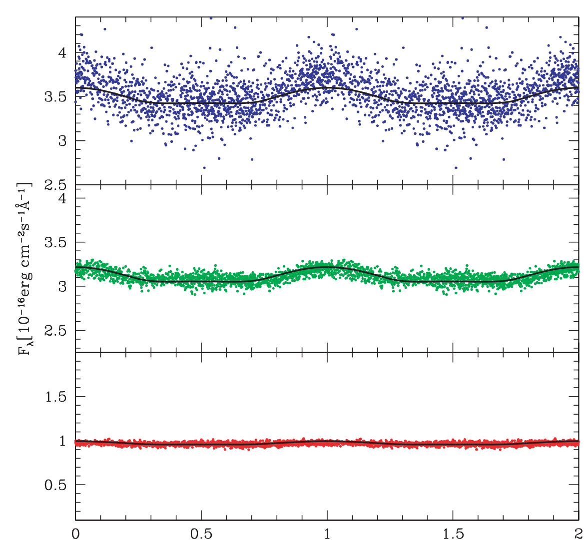


**Figure 3.** Model fits to the (from top to bottom) ULTRACAM $u'g'i'$ light curves to derive the parameters of the hot spot, as described by Gänsicke et al. (1998) and Gänsicke et al. (2006). The parameters are given in Table 3.

**Table 2.** Pulse times from model fits to the 2006 March ULTRACAM observations, the 2006 February INT observations and the recent results of Koen & Maxted (2006).

| Data set | Cycle ($E$) | Time MJD (BTDB) | Uncertainty $1\sigma$ |
|---|---|---|---|
| INT/WFC $r'$ | −446 | 53771.20735 | 0.000 51 |
| INT/WFC $r'$ | −445 | 53771.26823 | 0.000 52 |
| WHT/ULTRACAM $g'$ | 120 | 53805.96444 | 0.000 32 |
| WHT/ULTRACAM $g'$ | 121 | 53806.02519 | 0.000 51 |
| WHT/ULTRACAM $g'$ | 122 | 53806.08779 | 0.000 41 |
| WHT/ULTRACAM $g'$ | 137 | 53807.00771 | 0.001 03 |
| Koen & Maxted | 398 | 53823.0375 | 0.0025 |
| Koen & Maxted | 412 | 53823.8946 | 0.0025 |
| Koen & Maxted | 413 | 53823.9567 | 0.0025 |
| Koen & Maxted | 414 | 53824.0188 | 0.0025 |
| Koen & Maxted | 430 | 53825.0000 | 0.0025 |
| Koen & Maxted | 446 | 53825.9842 | 0.0025 |
| Koen & Maxted | 447 | 53826.0452 | 0.0025 |
| Koen & Maxted | 462 | 53826.9621 | 0.0025 |
| Koen & Maxted | 851 | 53850.8522 | 0.0025 |
| Koen & Maxted | 852 | 53850.9101 | 0.0025 |

The zero-point $T_0$ was chosen to minimize the correlation coefficient between it and the period $P$. The errors on the last two digits are given in parentheses and are $1\sigma$ uncertainties. $E$ is the number of cycles since $T_0$.[1] The rotation period of $88.428 \pm 0.001$ min compares favourably with the $93 \pm 2$ min H$\alpha$ radial velocity period estimated by Schmidt et al. (2005b), the $88 \pm 1$ min $K_s$-band variability recently reported by Debes et al. (2006) (presumably due to cyclotron emission) and the similar 88.43-min optical photometric period reported by Koen & Maxted (2006). Since the H$\alpha$ emission line originates on the secondary star, while the photometric variability is due to a hot spot on the white dwarf, we conclude that the binary is synchronously rotating, at least within the large uncertainty on the spectroscopic period, and has most likely evolved to this state through magnetic locking.

We also fit the simultaneous $i'$-, $g'$- and $u'$-band light curves obtained by ULTRACAM on 2006 March 11 and 12 (Fig. 2) with the same model to determine the pulse heights in each case. We find the height of the pulse is $2.6 \pm 0.1$ per cent at $i'$, $4.0 \pm 0.1$ per cent at $g'$ and $9.2 \pm 0.4$ per cent at $u'$.[2] The formal uncertainties on these fits may underestimate the systematic uncertainties, particularly at $i'$.

Assuming the pulses originate solely from a hot spot on the white dwarf, we can model the ULTRACAM $u'g'i'$ light curves of SDSS 1212 and estimate the temperature of the spot (Fig. 3). We used the code described by Gänsicke et al. (1998) and Gänsicke et al. (2006), and find the spot has a temperature $T_{\rm spot} \simeq 14\,000$ K. The self-eclipse of the spot constrains its size, although the inclination is somewhat of a guess; the large radial velocity amplitude measured by Schmidt et al. (2005b) suggests it cannot be particularly low, and the system is not eclipsing so it cannot be higher than $\approx 75°$. We estimate the fractional area of the spot is $\approx 5$ per cent of the white dwarf surface, in good agreement with the values found in other systems (e.g. A M Her; Gänsicke et al. 2006). We also estimate the luminosity of the hot polar cap at $\approx 1.6 \times 10^{29}$ erg s$^{-1}$.

[1] By extrapolating back to the 2006 January FTN observation, we can use this ephemeris to verify that the peak in those data is at phase 0 (cycle number −977).

[2] Note that Schmidt et al. (2005b) give the magnitudes of SDSS 1212 in these bands as $i' = 18.24 \pm 0.02$, $g' = 17.99 \pm 0.02$ and $u' = 18.43 \pm 0.03$.

**Table 3.** Hot spot parameters derived from model fits to the ULTRACAM $u'g'i'$ light curves, for a white dwarf of radius $8 \times 10^8$ cm.

| Parameter | Value |
|---|---|
| $T_{\rm WD}$ | 9500 K |
| Distance | 120 pc |
| $T_{\rm spot}$ | 14 000 K |
| Spot opening angle | 50° |
| Colatitude of spot | 75° |

While an eyeball fit of a non-magnetic model spectrum to the SDSS 1212 spectrum suggests $T_{\rm eff} \approx 11\,000$ K, a fit to the lower envelope of the ULTRACAM light curves gives $T_{\rm eff} \approx 9500$ K (Table 3). For this temperature, and assuming a radius of $8 \times 10^8$ cm for a $\approx 0.6\,{\rm M}_\odot$ white dwarf, the distance is $\approx 120$ pc.

Schmidt et al. (2005b) report that the H$\alpha$ emission line disappears at one phase, and conclude that the system is likely viewed at high inclination. However, we find no evidence for eclipses. The white dwarf also lies near the edge of the ZZ Ceti instability strip for (non-magnetic) H-rich degenerates, but we see no non-radial pulsations in our optical photometry. This suggests its temperature is most likely below the lower edge of the instability strip, assuming that the boundaries are the same for magnetic and non-magnetic white dwarfs.

We also note that Koen & Maxted (2006) believed that they had found a secondary pulse between the maxima in the optical light curves, possibly caused by a second pole. Although there is some slight evidence for such features in Figs 1 and 2, our data are inadequate to support such a claim.

### 3.2 *Swift* XRT observations

The XRT count rate is too low to detect any X-ray variability on the orbital period, but sufficient to construct an X-ray spectrum (Fig. 4).

For the spectral extraction, we specified a 20-pixel radius circular aperture centred on the X-ray position. For the background, we chose an annular region of inner radius 30 pixel, outer radius 50 pixel, centred on the same position. Source and background spectra were extracted from the cleaned event lists using XSPEC11, using the appropriate ancillary response files and response matrices as

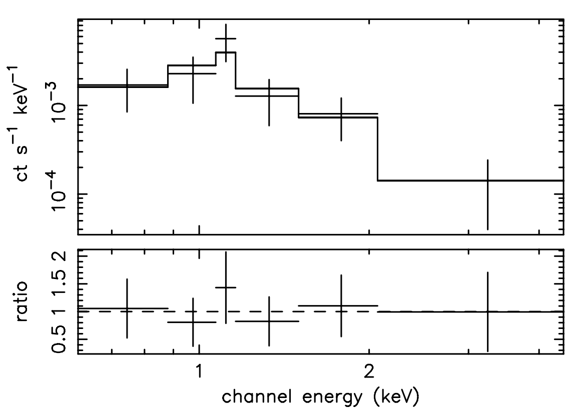


**Figure 4.** *Swift* XRT X-ray spectrum of SDSS 1212. The fit is for the single-temperature thermal plasma model described in the text.



 

defined in the latest release of the *Swift* CALDB (version 24). Due to the small number of source counts, the XRT spectrum was grouped to a minimum of 5 counts per bin and model fits were minimized using Cash statistics (C-stat).

We attempted a number of model fits to the extracted spectrum: an absorbed blackbody, an absorbed bremsstrahlung and an absorbed one-temperature thermal plasma (the MEKAL model in XSPEC). Since the X-ray count rate and signal/noise are low, we initially fixed the hydrogen (H) column density in each model at a number of values between $10^{18}$ and $10^{20}$ atoms cm$^{-2}$. This is a reasonable assumption for the distance and Galactic latitude and longitude of SDSS 1212 (Frisch & York 1983; Paresce 1984).

The blackbody fit gives a temperature $kT_{\rm BB} = 0.36$ keV for $N_{\rm H} = 10^{18}$ atoms cm$^{-2}$ (C-stat = 4.1 for 4 degrees of freedom), and $kT_{\rm BB} = 0.35$ keV for $N_{\rm H} = 10^{20}$ atoms cm$^{-2}$ (C-stat = 4.6). The unabsorbed flux for these models is $\approx 9 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (between 0.3 and 10 keV in all these calculations).

Perhaps a more physically plausible model is a bremsstrahlung spectrum, again with excess hydrogen column density. Free–free (bremsstrahlung) radiation is expected to dominate the cooling of the gas in the post-shock region, where accreting gas impacts the white dwarf atmosphere. For a fixed column density $N_{\rm H} = 10^{18}$ atoms cm$^{-2}$, the temperature $kT_{\rm Br} = 1.64$ keV (C-stat = 4.6 for 4 degrees of freedom). The fit improves slightly as the H column density increases. In fact, if the H column density is included as a free parameter in the fit, we find that the best-fitting bremsstrahlung model has a temperature $kT_{\rm Br} = 0.92$ keV, and $N_{\rm H} = 2 \times 10^{21}$ atoms cm$^{-2}$ (C-stat=3.7 for 3 degrees of freedom). For this model, the absorbed and unabsorbed fluxes are $8.9 \times 10^{-14}$ and $2.0 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, respectively.

The best fit to the data is given by the single-temperature thermal plasma model. We find $kT = 1.9$ keV (C-stat = 0.94 for 4 degrees of freedom), and the fit is very insensitive to the assumed H column density. In particular, this model matches the flux at 1.1 keV, which is underpredicted in the blackbody and bremsstrahlung models. This model fit is shown in Fig. 4. The unabsorbed flux given by the single-temperature thermal plasma model is $1.2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

Using the unabsorbed flux from the best-fitting single-temperature thermal plasma model, and assuming a distance of 120 pc, we then estimate the X-ray luminosity $L_{\rm x} = 2 \times 10^{29}$ erg s$^{-1}$. Assuming this X-ray luminosity is entirely due to accretion, we can estimate the accretion rate from

$$L_{\rm x} = \frac{G M_{\rm WD} \dot{M}}{R_{\rm WD}}. \qquad (1)$$

Assuming a canonical mass for the white dwarf $M_{\rm WD} = 0.6\,{\rm M}_{\odot}$, $R_{\rm WD} = 8 \times 10^{8}$ cm and $d = 120$ pc, we obtain an accretion rate of $\dot{M} \approx 3 \times 10^{-14}$ M$_{\odot}$ yr$^{-1}$. For a distance of 145 pc (Schmidt et al. 2005b), $L_{\rm x} = 3 \times 10^{29}$ erg s$^{-1}$ and $\dot{M} \approx 5 \times 10^{-14}$ M$_{\odot}$ yr$^{-1}$.

Given the X-ray accretion rate estimated here, and the optical/UV luminosity estimated in Section 3.1, the total accretion rate for SDSS 1212$\dot{M}_{\rm total} \approx 10^{-13}$ M$_{\odot}$ yr$^{-1}$.

## 4 DISCUSSION

Multiband optical photometry of the magnetic white dwarf + probable brown dwarf close binary SDSS 1212 reveals a hot spot on the surface of the white dwarf, which rotates into view every 88.4 min. This is in addition to the weak, narrow and variable (in radial velocity and strength) H$\alpha$ emission line observed by Schmidt et al. (2005b) in optical spectra, which most likely arises from the warm irradiated face of the probable brown dwarf secondary. If the system is synchronously rotating, then the orbital period is the same as the 88.43-min rotation period of the white dwarf.

The large hot spot on the white dwarf is directly linked to magnetically funnelled accretion. A likely hypothesis for the heating of the white dwarf surface in this spot is irradiation with cyclotron radiation and/or thermal bremsstrahlung (Gänsicke et al. 1995), although remnant heat from a previous high state (Gänsicke et al. 2006), or heating by direct accretion cannot be excluded. This hypothesis is confirmed by the detection of the system in X-rays. A $\approx$10 000 K white dwarf photosphere does not have any emission in this waveband. These results strongly suggest that SDSS 1212 is in fact a magnetic CV in a low accretion state, in which the brown dwarf secondary fills its Roche lobe during periods of active accretion. We note that although Schmidt et al. (2005b) concluded that SDSS 1212 was in their view more likely a detached binary, they also suggested that it could be a low accretion rate polar (LARP). The optical light curves presented here are similar to those seen in other polars in low states, e.g. EF Eri (Harrison et al. 2003), further strengthening the polar identification.

The comparison with EF Eri is appropriate for a number of reasons. That system was first identified as an active X-ray source in 1978 and appeared in a high state every time it was observed either in the optical or in X-rays until it almost entirely switched off in 1996. It only reappeared as an actively accreting CV early in 2006. This decade-long low state shows that polars can efficiently hide from discovery. Beuermann et al. (2000) modelled the optical low-state spectrum of EF Eri entirely in terms of emission from the white dwarf with a temperature $T_{\rm eff} = 9500$ K at a distance of $\approx$130 pc. Based on the non-detection of TiO absorption bands in the *I*-band, the authors suggested the spectral type of the donor star to be later than L1. Howell & Ciardi (2001) later suggested that they had directly detected the secondary in a near-IR spectrum, but Harrison et al. (2003) showed that, for EF Eri at least, cyclotron emission due to low-level accretion spoils the chances of a direct detection in this waveband.

The detection of a heated polar cap on SDSS 1212 lends strong support to the polar scenario. The first evidence for a relatively large moderately heated spot on white dwarfs in polars was derived by Heise & Verbunt (1988) for the prototype system AM Herculis on the basis of *International Ultraviolet Explorer* UV spectra. This hot spot has been quantitatively modelled by Gänsicke et al. (1995) in terms of a heated cap near the magnetic pole of the white dwarf. The luminosity of the polar cap in AM Her could be explained either by heating through ongoing accretion, or as a remnant from deep localized heating of the envelope during a previous high state. The best-documented evidence for a heated spot on AM Her during the low state is based on *Hubble Space Telescope*/*FUSE* data (Gänsicke et al. 2006). Evidence for heated polar caps has been found in low-state observations of many systems: V834 Cen shows a strong modulation in the *U* band (Ferrario et al. 1992), DP Leo in the UV (Stockman et al. 1994). Spectroscopic signatures of heated polar caps have been found in V1043 Cen (RX J1313.2−3259; Gänsicke et al. 2000), and in V834 Cen, MR Ser and BL Hyi (Araujo-Betancor et al. 2005).

From modelling the observed UV cyclotron emission of the high-field polar AR UMa in low state, Gänsicke et al. (2001) derived an accretion rate of $\dot{M} \approx 2 \times 10^{-13}$ M$_{\odot}$ yr$^{-1}$. For the same system, Szkody et al. (1999) determined a low-state X-ray luminosity of $\approx 2 \times 10^{29}$ erg s$^{-1}$. These measurements are comparable to our estimates of the X-ray luminosity and accretion rate of SDSS 1212, supporting the low state, magnetic CV scenario.

Debes et al. (2006) recently detected cyclotron emission in the $K_s$ band, also indicating that the white dwarf is accreting material from its very low mass companion. By comparing their ephemeris to our optical ephemeris, we note that the cyclotron hump is coincident with the optical peak, as expected if the emission is from the same spot. While it is unclear whether cyclotron emission is responsible for all the near-IR excess reported by Debes et al. (2006), they use the *H*- and $K_s$-band minimum fluxes to place an upper limit of L7 on the secondary spectral type.

The 88.43-min orbital period, well outside the CV minimum period of 80–82 min, combined with the evidence for a very low mass secondary, and the cool temperature of the white dwarf primary, suggests that SDSS 1212 could be a candidate for a period bouncer, i.e. a CV that has evolved through and beyond the period minimum. These highly evolved binaries are predicted by population models to be the most abundant species of CVs (Kolb 1993), but have so far been elusive despite intensive searches. Patterson, Thorstensen & Kemp (2005) present evidence for a number of such systems among non-magnetic dwarf novae. In this scenario, the probable brown dwarf secondary may have evolved to that state through mass loss, and could plausibly have originally evolved through the CE phase as a higher mass main-sequence M dwarf.

An alternative possibility is that the secondary does not fill its Roche lobe, and accretion is occurring via efficient capture of almost all of the stellar wind (Li, Wu & Wickramasinghe 1994). Schmidt et al. (2005a) discuss the evolutionary status of six low accretion rate ($\dot{M} \lesssim 10^{-13}$ M$_{\odot}$ yr$^{-1}$) binaries with cool ($T_{\rm eff} < 14\,000$ K) magnetic ($B \approx 60$ MG) white dwarf primaries, termed as LARPs by Schwope et al. (2002). The first, HS 1023+3900, was discovered by Reimers, Hagen & Hopp (1999). These binary periods are all $\gtrsim$2.5 h, and Schmidt et al. (2005a) suggest that the secondaries are too late in spectral type to fill their Roche lobes. If they are not in contact, these binaries can be considered as post-CE, pre-polar systems. Such binaries are also of interest because the accretion of the stellar wind by the primary could lead to diminution of the wind-driven angular momentum loss which usually drives the period evolution of these systems. However, all of the claimed pre-polar binaries were discovered through optical cyclotron emission features, which lie in the IR for SDSS 1212. All the claimed pre-polars are also faint in X-rays ($L_x \lesssim 10^{29}$ erg s$^{-1}$; Szkody et al. 2004), and none contains a substellar secondary. If SDSS 1212 is a wind-accreting pre-polar, then it would be the first to be discovered without optical cyclotron lines.

The wind accretion scenario requires a strong brown dwarf wind. Webbink & Wickramasinghe (2005) suggest that coronal M dwarf X-ray luminosities $\approx 10^{29}$ erg s$^{-1}$ can drive several $10^{-13}$ M$_{\odot}$ yr$^{-1}$ of material, which is then siphoned over and accreted by the magnetic white dwarf in LARPs. Young ($\lesssim$0.1 Gyr) brown dwarfs, which have spectral types M5–M9, have been detected in X-rays with luminosities $L_x \approx 10^{27}$ erg s$^{-1}$ (Stelzer 2004; Preibisch et al. 2005). However, no L dwarf has been detected in X-rays, limiting their quiescent X-ray luminosities to $L_x \lesssim 10^{23}$ erg s$^{-1}$ (Stelzer et al. 2006). This large suppression in X-ray luminosity between young and old brown dwarfs is almost certainly due to the transition to a largely neutral atmosphere (Stelzer et al. 2006). It is likely that the rotation period of the brown dwarf in SDSS 1212 is the same as the orbital period, i.e. 88.4 min. Field brown dwarfs typically rotate with periods of the order of 2–20 h (Bailer-Jones 2004). Thus, the brown dwarf in SDSS 1212 might have been spun up by a factor of 10 during and after the CE phase. Adopting the rotation–activity relation for field dwarfs allows us to place upper limits on the likely X-ray flux, assuming the activity is not saturated. A spin up of factor of 10 gives a two orders of magnitude increase in X-ray luminosity (Pizzolato et al. 2003). The largest X-ray flux we might then expect from the companion is $L_x \lesssim 10^{25}$ erg s$^{-1}$, too small by a factor of $\sim 10^4$ to drive the material being accreted by the white dwarf.

For similar reasons, we are not persuaded that the X-ray flux detected by *Swift* is due to intrinsic activity on the brown dwarf. Even if the L dwarf was an unlikely source of at least some of the X-ray emission seen by *Swift*, the detection of cyclotron emission in the near-IR by Debes et al. (2006) proves that accretion is taking place. However, Rottler et al. (2002) point out that the H$\alpha$ emission from the K dwarf in the pre-CV binary V471 Tau disappeared between 1985 and 1992. Therefore, it cannot be due to irradiation. They also point out that the temperatures of the white dwarfs in many pre-CV binaries do not seem high enough to account for irradiation-induced H$\alpha$ emission. A combination of irradiation and chromospheric activity may be needed to account for the H$\alpha$ emission lines from the secondaries in these systems. The $T_{\rm eff} \approx 10\,000$ K white dwarf in SDSS 1212 may also not be hot enough to produce the H$\alpha$ emission seen by Schmidt et al. (2005b) through irradiation, and the L dwarf may be intrinsically active (but not necessarily a detectable X-ray source). Indeed, Howell et al. (2006) claim that the radial velocity variable H$\alpha$ emission line observed from the putative substellar companion in EF Eri is due to intrinsic activity rather than irradiation.

Despite the Sloan Digitized Sky Survey more than doubling the numbers of known white dwarfs with detached cool companions (Silvestri et al. 2006) and the numbers of magnetic white dwarfs (e.g. Vanlandingham et al. 2005), Liebert et al. (2005) noted that there was zero overlap between these two samples. In contrast, an estimated 25 per cent of accreting CVs have a magnetic white dwarf primary (Wickramasinghe & Ferrario 2000). If SDSS 1212 is a polar in a low state, then the lack of magnetic white dwarfs in detached binaries remains. Liebert et al. (2005) discuss a number of explanations, and suggest that the presence of the companion and the likely large mass and small radius of the magnetic white dwarf (relative to non-magnetic degenerate dwarfs) may provide a selection effect against the discovery of such binary systems.

More observations are needed before the nature of SDSS 1212 can be fully confirmed. Detailed modelling of the magnetic white dwarf's optical spectrum will better determine its temperature, surface gravity, mass, radius, field strength and configuration and cooling age. Further optical spectroscopy is necessary to obtain a better radial velocity curve and place the spectroscopy and photometry on to a single ephemeris. Near- and mid-IR spectroscopy will lead to a detailed model of the cyclotron emission and may help to reveal the spectral type of the secondary. A direct detection of the brown dwarf would also allow investigation of the effects of irradiation. Finally, UV light curves may help to distinguish between the low-state polar and wind accretion models, since different accretion spot geometries might be expected in each case. Recent *Galaxy Evolution Explorer (GALEX)* observations of EF Eri reveal a large amplitude modulation in the far- and near-UV, which Szkody et al. (2006) attempted to fit with a white dwarf plus heated polar cap. While their simplistic model using blackbodies rather than model atmospheres remains inconclusive, it is clear that UV observations of SDSS 1212 have the potential to constrain the hot spot temperature and geometry.

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## REFERENCES

Araujo-Betancor S., Gänsicke B. T., Long K. S., Beuermann K., de Martino D., Sion E. M., Szkody P., 2005, ApJ, 622, 589
Bailer-Jones C. A. L., 2004, A&A, 419, 703
Becklin E. E., Zuckerman B., 1988, Nat, 336, 656
Beuermann K., Wheatley P., Ramsay G., Euchner F., Gänsicke B. T., 2000, A&A, 354, L49
Burleigh M. R., Hogan E., Dobbie P. D., Napiwotzki R., Maxted P. F. L. 2006, MNRAS, 373, L55
Debes J. H., Lopez-Morales M., Bonanos A. Z., Weinberger A. J., 2006, ApJ, 647, L147
Dhillon V. S., Marsh T. R., 2001, New Astron. Rev., 45, 91
Dobbie P. D., Burleigh M. R., Levan A. J., Barstow M. A., Napiwotzki R., Holberg J. B., Hubeny I., Howell S. B., 2005, MNRAS, 357, 1049
Farihi J., Christopher M., 2004, AJ, 128, 1868
Farihi J., Becklin E. E., Zuckerman B., 2005, ApJS, 161, 394
Ferrario L., Wickramasinghe D. T., Bailey J., Hough J. H., Tuohy I. R., 1992, MNRAS, 256, 252
Frisch P., York D., 1983, ApJ, 271, L59
Gänsicke B. T., Beuermann K., de Martino D., 1995, A&A, 303, 127
Gänsicke B. T., Hoard D. W., Beuermann K., Sion E. M., Szkody P., 1998, A&A, 338, 933
Gänsicke B. T., Beuermann K., de Martino D., Thomas H.-C., 2000, A&A, 354, 605
Gänsicke B. T., Schmidt G. D., Jordan S., Szkody P., 2001, ApJ, 555, 380
Gänsicke B. T., Long K. S., Barstow M. A., Hubney I., 2006, ApJ, 639, 1039
Harrison T. E., Howell S. B., Huber M. E., Osborne H. L., Holtzman J. A., Cash J. L., Gelino G. M., 2003, AJ, 125, 2609
Heise J., Verbunt F., 1988, A&A, 189, 112
Howell S. B., Ciardi D. R., 2001, ApJ, 550, L57
Howell S. B., Walter F. M., Harrison T. E., Huber M. E., Becker R. H., White R. L., 2006, ApJ, in press (astro-ph/0607140)
Koen C., Maxted P. F. L., 2006, MNRAS, 371, 1390
Kolb U., 1993, A&A, 149, 271
Li J. K., Wu K. W., Wickramasinghe D. T., 1994, MNRAS, 268, 61
Liebert J. et al., 2005, AJ, 129, 2376
Littlefair S. P., Dhillon V. S., Martin E. L., 2003, MNRAS, 340, 264
Maxted P. F. L., Napiwotzki R., Dobbie P. D., Burleigh M. R., 2006, Nat, 442, 543
Paresce F., 1984, AJ, 89, 1022
Patterson J., Thorstensen J. R., Kemp J., 2005, PASP, 117, 427
Pizzolato N., Maggio A., Micela G., Sciortino S., Ventura P., 2003, A&A, 397, 147
Preibisch T. et al., 2005, ApJS, 160, 582
Reimers D., Hagen H.-J., Hopp U., 1999, A&A, 343, 157
Rottler L., Batalha C., Young A., Vogt S., 2002, A&A, 392, 535
Schmidt G. D. et al., 2005a, ApJ, 630, 1037
Schmidt G. D., Szkody P., Silvestri N. M., Cushing M. C., Liebert J., Smith P. S., 2005b, ApJ, 630, L173
Schwope A. D., Brunner H., Hambaryan V., Schwarz R., Staude A., Szokoly G., Hagen H.-J., 2002, in Gänsicke B. T., Beuermann K., Reinsch K., eds, ASP Conf. Ser. Vol. 261, The Physics of Cataclysmic Variables and Related Objects. Astron. Soc. Pac., San Francisco, p. 31
Silvestri N. M. et al., 2006, AJ, 131, 1674
Stelzer B., 2004, ApJ, 615, L153
Stelzer B., Micela G., Flaccomio E. R. N., Jayawardhana R., 2006, A&A, 448, 293
Stockman H. S., Schmidt G. D., Liebert J., Holberg J. B., 1994, ApJ, 430, 323
Szkody P., Vennes S., Schmidt G. D., Wagner R. M., Fried R., Shafter A. W., Fierce E., 1999, ApJ, 520, 841
Szkody P. et al., 2004, AJ, 128, 2443
Szkody P., Harrison T. E., Plotkin R. M., Howell S. B., Siebert M., Bianchi L., 2006, ApJ, 646, L147
Vanlandingham K. M. et al., 2005, AJ, 130, 734
Webbink R. F., Wickramasinghe D. T., 2005, in Hameury J.-M., Lasota J.-P., eds, ASP Conf. Ser. Vol. 330, The Astrophysics of Cataclysmic Variables and Related Objects. Astron. Soc. Pac., San Francisco, p. 137
Wickramasinghe D. T., Ferrario L., 2000, PASP, 112, 873

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