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Optical/Infrared spectroscopy and photometry of the short period binary RX J1914+24 ⋆

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ABSTRACT

We present observations of the proposed double degenerate polar RX J1914+24. Our optical and infrared spectra show *no* emission lines. This, coupled with the lack of significant levels of polarisation provide difficulties for a double degenerate polar interpretation. Although we still regard the double degenerate polar model as feasible, we have explored alternative scenarios for RX J1914+24. These include a double degenerate algol system, a neutron star-white dwarf pair and an electrically powered system. The latter model is particularly attractive since it naturally accounts for the lack of both emission lines and detectable polarisation in RX J1914+24. The observed X-ray luminosity is consistent with the predicted power output. If true, then RX J1914+24 would be the first known stellar binary system radiating largely by electrical energy.

Key words: Accretion, Cataclysmic variables, X-rays: stars, Stars: individual: RX J1914+24.

1 INTRODUCTION

RX J1914+24 was discovered during the course of the *ROSAT* all-sky survey and was found to show a modulation in X-rays on a period of 9.5 min (Motch et al 1996). In further observations, Cropper et al (1998) detected only the 9.5 min period which they suggested was the binary orbital period. This implied a very small binary dimension. This together with the X-ray light curve, which was consistent with zero for half the 9.5 min period, led them to propose that the system is a polar (those magnetic cataclysmic variables – mCVs – in which the accreting white dwarf has a magnetic field strong enough to synchronise its spin period with the binary orbital period). This would imply that the 9.5 min period seen in X-rays was both the spin period of the accreting white dwarf and also the binary orbital period. For an orbital period this short the secondary star could not be a main sequence star as in the case of ordinary mCVs. It could, however, be a He white dwarf. If confirmed, RX J1914+24 would be the first binary system in which both components are white dwarfs and magnetically synchronised – a double degenerate polar. Furthermore, its orbital period would be the shortest of any known stellar binary system.

Observations by Ramsay et al. (2000) gave supporting evidence for the double degenerate polar interpretation. These include: discovery of the optical counterpart (in the I band) in which only one period was seen (the 9.5 min period seen in X-rays); no periods other than the 9.5 min period in further X-ray data; an X-ray spectrum which is very soft and typical of polars; large variations in its long-term X-ray light curve which are typical of polars, and infrared colours which are not consistent with that of a main-sequence star. Ramsay et al. (2000) also found that the peak intensity in the X-ray and I band light curves were approximately anti-phased. They interpreted the X-ray flux as originating from the accretion region on the white dwarf, while the I-band flux originated from the irradiated face of the mass donating white dwarf. This was consistent with the observation that the I-band flux was not polarised.

In this paper we present further observations of RX J1914+24. We discuss these results in relation to the double degenerate polar model of Cropper et al (1998) and

⋆ Based (in part) on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

Ramsay et al (2000). We also consider several alternative models for RX J1914+24.

2 OPTICAL/INFRARED IMAGING

2.1 J-band imaging using Subaru

RX J1914+24 was observed on 1999 June 6 in the J band using the 8-m Subaru telescope on Hawaii and the Cooled Infrared Spectrograph and Camera (CISCO) in its imaging mode. Each exposure was 5 sec in duration, and after every 12 exposures an offset was applied to the telescope so that a flat field could be obtained. The observation lasted $\sim$1 hour. Conditions were good and the seeing was $\sim$0.4 arc sec. An image using all the frames (each frame was shifted in position so the stellar images were coincident) is shown in Figure 1.

To make an accurate determination of the position of the optical counterpart of RX J1914+24, we matched the positions of stars in the Subaru image with those in the Digitised Sky Survey. The accurate positions of these stars were then taken from the USNO A1.0 catalogue. We then determined the position of RX J1914+24 using the astrometry package ASTROM (Wallace 1998): $\alpha_{2000} = 19^h\ 14^m\ 26.1^s$, $\delta_{2000} = +24^\circ\ 56'\ 43.6''$. The uncertainty on this position is $0.4''$. It is consistent with the X-ray position reported by Cropper et al. (1998).

Aperture photometry was performed on the images using PHOTOM (Eaton, Draper & Allan 1999). Differential photometry was obtained using various comparison stars in the field. Figure 2 shows the differential light curve of the optical counterpart to RX J1914+24 binned and folded on the ephemeris of Ramsay et al. (2000). (The ephemeris of Ramsay et al. (2000) is sufficiently precise to phase the Subaru data with the original X-ray and I data to within 0.02 cycles). The shape and phasing of the light curve is similar to that of the I-band light curve shown in Ramsay et al. (2000) (and also shown here for comparison) although the rise to maximum is less rapid. The amplitude is greater in J (0.16 mag peak-to-peak) compared to I (0.07 mag). By comparison, the J-band data obtained using UKIRT (Ramsay et al. 2000) was of too low a signal to noise for a significant modulation to be apparent.

2.2 $BVRI$ imaging using NOT

Observations were obtained on the nights 1999 July 6–8 using the 2.5-m Nordic Optical Telescope (NOT) on La Palma, and the Andalucia Faint Object Spectrograph (ALFOSC) was used in its imaging mode. The conditions were photometric on the first two nights. The seeing was typically $1''$. To obtain circular polarimetry data a 1/4-waveplate was inserted into the optical path: this split the light into both polarised beams on the Loral 2k×2k CCD so that 2 images of each star were recorded. The instrument was orientated in such a way that images of field stars did not overlap with any of the stars of interest. The images were bias-subtracted and flat-fielded in the usual way. On the first night images were mainly taken in the R band (20-sec exposures) and the second night the V band (40-sec exposures). The CCD was windowed to reduce the readout time.

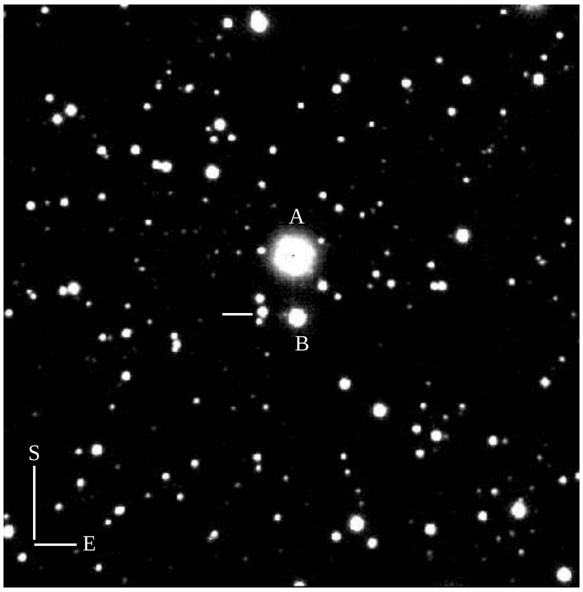

Figure 1. A 60-min J-band image of the field of RX J1914+24 taken using the 8-m Subaru telescope on Hawaii. Stars A & B are shown in the images of Motch et al. (1996) and Ramsay et al. (2000) and are separated by 7 arcsec. Star A has V $\sim$15.5 (from data obtained at the NOT) and J $\sim$12.1 (from UKIRT data, Ramsay et al. 2000) and was saturated in each 5-sec exposure. The optical counterpart of RX J1914+24 is shown by the white marker.

In addition to the extended sequence of V- and R- band images, we also made a sequence of B, V, R and I images and a standard star at the beginning of each night. This allowed us to deduce magnitudes for RX J1914+24 across the broad optical/infrared band – see Table 1. In the I band RX J1914+24 was found to be $\sim$4.8 mag fainter than star 'A' – the same as it was when observed in June 1998 (Ramsay et al. 2000).

Profile fitting photometry was carried out on stars in the field using DAOPHOT (Stetson 1992). Since the profiles of the two polarised beams were different, two point spread functions had to be constructed We show the V and R differential light curves (using one of the polarised beams) of the optical counterpart of RX J1914+24 folded and binned on the ephemeris of Ramsay et al. (2000) in Figure 2. Both light curves resemble those in the I and J bands with their peak intensities occurring $\sim$0.3–0.4 cycles before the maximum in X-rays. The peak to peak amplitude is greatest in V: 0.13 mag in V, 0.10 in R and 0.07 in I.

We note the presence of a dip at ϕ $\sim$0.85 which is seen in the V, R and J bands. (The time resolution of the I band data is poorer than the other bands, which probably prevents us detecting it in this band). We would not regard this dip as significant if observed in only one band, but its presence in 3 bands (taken at different epochs) suggests that it is indeed significant.

The presence of a 1/4 waveplate and calcite block in the optical path allowed us to search for circular polarisation in RX J1914+24. The instrumental polarisation was found to depend on the position of the stellar image on the CCD. To make a first order correction for instrumental polarisation we made the assumption that star 'A' has no intrinsic circular

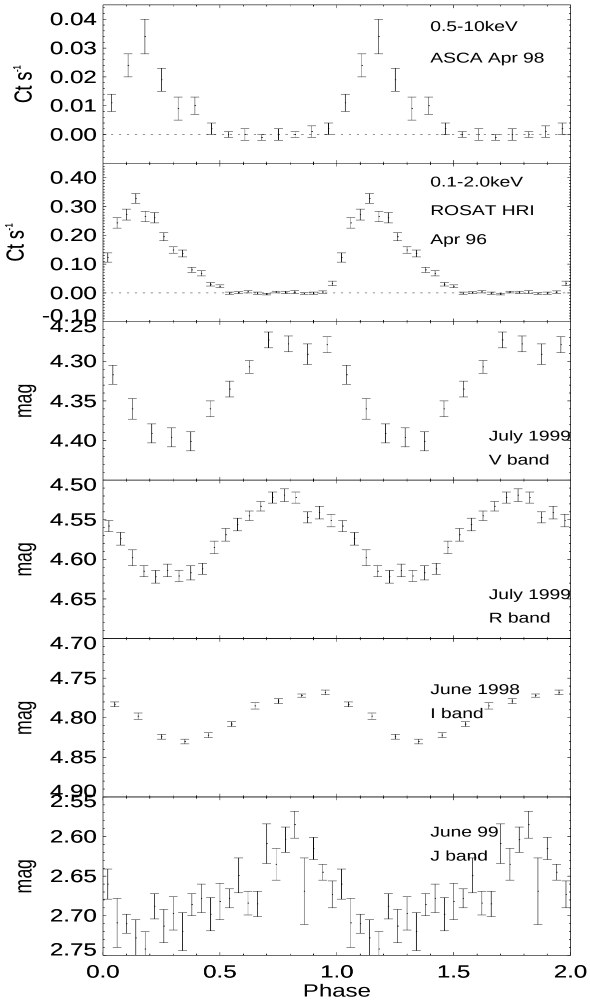

Figure 2. The light curve of RX J1914+24 as a function of energy folded on the 9.5 min period.

polarisation (cf. Figure 1). We applied this correction to the polarised light curves of star 'B' and RX J1914+24 and then folded them on the ephemeris of Ramsay et al. (2000). No significant polarisation was found in RX J1914+24 in either the V or R bands. To test that the instrument could detect polarisation, observations of the polar QQ Vul were made at the end of the first and second nights. It was found that significant circular polarisation was detected, with the same polarity and similar degree of polarisation detected in the observations of Cropper (1998).

3 SPECTROSCOPY

3.1 The optical spectrum

Central to their double degenerate polar interpretation, Cropper et al. (1998) noted that the shortest orbital period a binary system could have with a main sequence secondary is ∼80 min (see Ritter 1986). However, with a He degenerate secondary, the binary orbital period could lie in the range ∼6–50 min. A crucial test is the characteristics of the optical/infrared spectrum of RX J1914+24 – if hydrogen lines were to be detected, then this would cast considerable doubt upon the double degenerate polar interpretation.

Band	Mean Magnitude	Dereddened Magnitude	Dereddened Flux erg cm^{-2} s^{-1} Å^{-1}
B	21.1±0.15	16.9	$1.1\pm0.2 \times 10^{-15}$
V	19.9±0.10	16.9	$6.3\pm0.9 \times 10^{-16}$
R	19.2±0.10	17.0	$3.6\pm0.3 \times 10^{-16}$
I	18.6±0.10	17.2	$1.6\pm0.1 \times 10^{-16}$
J	17.3±0.10	16.5	$8.3\pm0.8 \times 10^{-17}$
H	17.4±0.15	16.9	$2.0\pm0.3 \times 10^{-17}$
K	17.1±0.15	16.8	$7.8\pm1.2 \times 10^{-18}$

Table 1. The apparent and dereddened magnitudes and fluxes of RX J1914+24 assuming an extinction of $A_V = 3.0$ mag. The B, V, R, I estimates were made in July 1999 while the J, H, K magnitudes were made in July 1998 (when the I magnitude was within 0.1 mag of that in July 1999). The error on the mean magnitudes includes the error in placing them onto the standard system. The error on the dereddened flux does not include the uncertainty on the interstellar extinction.

Spectra were taken with the 2.3-m telescope at Steward Observatory at Kitt Peak on the nights of 1998 Sep 24 and 1998 Nov 15, under conditions of moderate ($\sim 1.0 - 1.5''$) seeing with a slit of 3" and 2" width, respectively. The object could be discerned from surrounding nearby stars on the guider TV. The total exposure time was 5400 sec, using the CCD spectropolarimeter developed by Schmidt et al. (1992). Resolution was about 12 Å. The resulting spectrum (Figure 3) is very red and, remarkably, *no* emission lines are detected. The only possible line is an absorption line at ∼5200Å which could be due to Mg I (5173/5184 Å). This feature was only observed on one of the two nights so this feature must be regarded as tentative.

For the data taken in Sept 1998, the instrument was configured for circular spectropolarimetry. Using the whole spectral range we find a formal result of V/I = 0.14 percent +/- 0.29 percent (1 sigma), for a 3 sigma upper limit of 0.9 percent. This is consistent with our imaging polarimetry data. There are no significant polarization features in the spectrum from 4000–8000 Å.

3.2 The K-band Infrared Spectrum

We obtained a K-band infrared spectrum of RX J1914+24 on 1999 August 14 using UKIRT on Hawaii as part of the service program. The detector was CGS4. A 30-sec exposure was taken at each detector position, then the detector was moved by half a pixel over a distance of 2 pixels. Each frame was therefore a total of 120 sec. The combined exposure was 104 min in total. The bright star BS7280 was observed to correct for telluric features. The images were reduced in the standard manner using `FIGARO` procedures. Because of variations in the seeing and water content in the atmosphere during the observations, it is not possible to obtain reliable flux calibrated spectra, and therefore the flux scale is arbitrary. The resulting spectrum is shown in Figure 4. Although the signal to noise is low, no obvious emission lines of either H or He are present.

In the 1.9–2.4-μm wavelength range, several emission lines have been observed in the spectra of mCVs with red-dwarf secondaries (Dhillon & Marsh 1995; Dhillon et al. 1997; Dhillon 1998; Dhillon et al. 2000). These include the

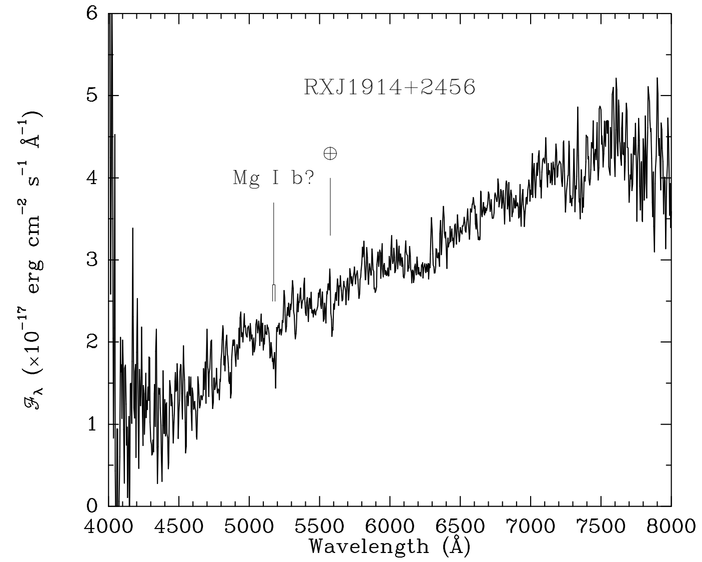

Figure 3. The optical spectrum of RX J1914+24 taken with the 2.3-m telescope at Steward Observatory at Kitt Peak, no correction for reddening has been applied. No significant emission lines are detected.

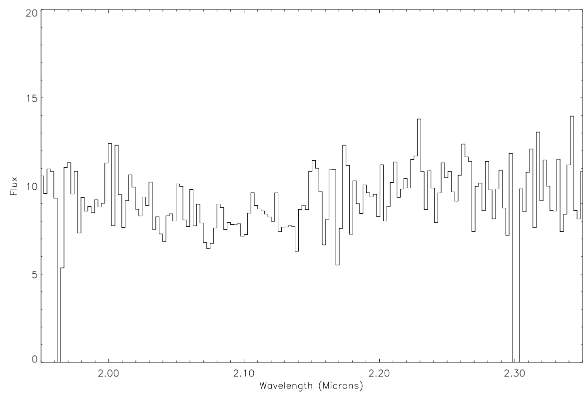

Figure 4. The K-band infrared spectrum of RX J1914+24 taken with the UKIRT telescope. The flux scale is arbitrary.

prominent emission lines He I (2.059μm) and Bracket γ (2.166μm). Dhillon et al. (2000) also show the spectrum of the non-magnetic, double degenerate system, GP Com, which exhibits the prominent He I line at 2.059 μm. These spectra were also obtained using UKIRT and CGS4. Although there is no known K-band magnitude for GP Com in the literature, its V-band magnitude is $\sim$16, compared to $\sim$20 when we observed RX J1914+24 in July 1999 (the month previous to our UKIRT spectrum). The exposure of the GP Com spectra (24 min) is a factor of 4.3 shorter than that of our RX J1914+24 spectrum, which is equivalent to reaching 1.6 mag fainter. If the V-band magnitude difference between GP Com and RX J1914+24 is roughly comparable in the K band, this would suggest that the lines may be hidden in the noise.

4 THE EXTINCTION TOWARDS RX J1914+24

Haberl & Motch (1995) fitted the *ROSAT* X-ray spectrum of RX J1914+24 with an absorbed blackbody spectrum and obtained a column density of $1.0{\pm}0.1\times10^{22}$ cm^{-2}. From this they derived an extinction of A_V=5.6 using the N_H, E_{B-V} relationship (eg Predehl & Schmitt 1995) and $A_V = 3E_{B-V}$. Using this value for the extinction, Ramsay et al (2000) found that the extinction corrected $I, J, K,$ & H fluxes could not be well fitted with a blackbody. We now have observations extending down to the B band which allows us to re-examine the extinction towards RX J1914+24.

The $BVRI$ band data shown in Table 1 were taken on 6–8 July 1999 while the JHK were taken in 2–3 July 1998. In addition I band data were taken on 25–27 June 1998 which show that RX J1914+24 was approximately the same magnitude in June 1998 as July 1999 (to within $\sim$0.1 mag). This suggests that we can combine the $BVRIJHK$ data with a reasonable degree of confidence.

We fitted a blackbody to the optical-infrared data assuming an area of a Roche lobe filling secondary (a $0.08M_\odot$ white dwarf) and one which just underfills its Roche lobe (a $0.1M_\odot$ white dwarf). We caution that for such low masses, the reliability of the Nauenberg (1972) mass-radius relationship for white dwarfs is not known. The free parameters were the temperature of the blackbody; the extinction and the normalisation (or distance). For the extinction we take the interstellar reddening law given in Zombeck (1990). We show in Figure 5 the confidence contours in the Temperature–E_{B-V} and Temperature–normalisation planes.

We find that a wide range of temperatures are consistent with the data. Single DA white dwarfs have a mean temperature of $\sim$10000K, while accreting white dwarfs usually have photospheric temperatures in the range $\sim$10000–30000K (Sion 1998). For a temperature of 10000K, $E_{B-V} \sim 0.85, A_V = 2.6$, while for a temperature of 30000K, $E_{B-V} \sim 1.25, A_V = 3.9$. For a temperature in the range 10000–30000K the distance is $\sim$200–500pc. To match the extinction derived by Haberl & Motch (1995), the temperature would have to be much greater than 50000K. From similar arguments, Ramsay et al (2000) estimate a distance of 100–400pc.

For an extinction of A_V=3.0, the implied unabsorbed luminosity over the 4000–25000 Å range is $\sim 2\times10^{31} d_{100}^2$ ergs s^{-1}where d_{100}^2 is the distance in units of 100pc.

Since we derive a lower absorption than Haberl & Motch (1995) we extracted the *ROSAT* PSPC spectrum from the data archive. Rather than binning the spectrum into 6 bins, we binned it into 52 bins. We fitted the spectrum with an absorbed blackbody and find that the temperature and absorption column is closely correlated and the absorption is not closely constrained. We find that if we fix the extinction at A_V=3.0 (=5.4×10^{21} cm^{-2}) we obtain a good fit: χ^2_ν=1.05 (50 dof), kT =56eV. This is consistent with the fits to the *ASCA* SIS spectrum (Ramsay et al 2000). The phased-averaged bolometric X-ray luminosity is $1.2^{+4.1}_{-0.3}\times10^{33}d_{100}^2$ ergs s^{-1}.

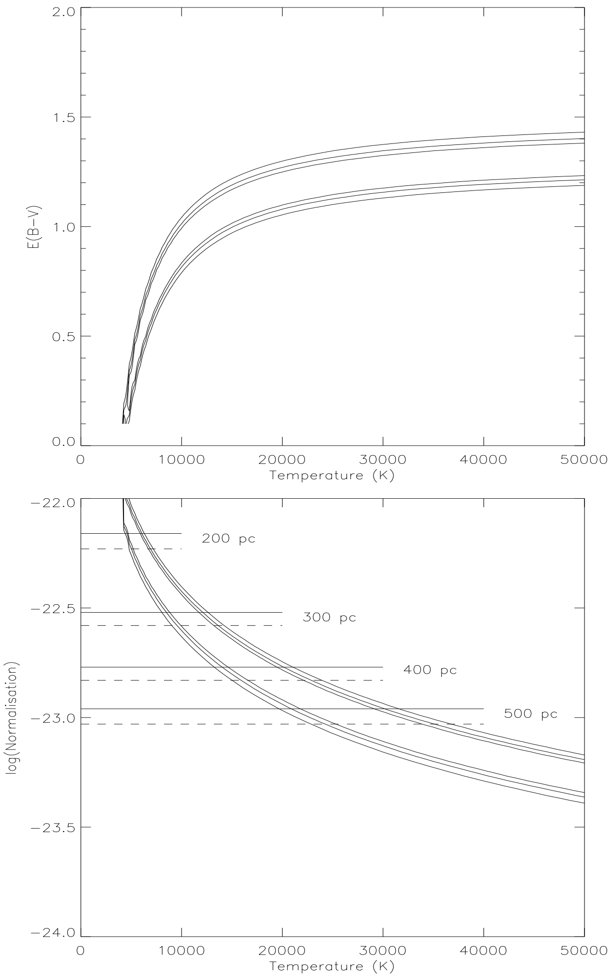

Figure 5. The temperature, extinction and normalisation (=Area white dwarf/2distance^2) derived using a blackbody fit to the *BVRIJHK* data. The 68, 90 and 99 per cent confidence contours are shown. The solid lines are for a white dwarf of radius appropriate for a Roche lobe filling secondary (a $0.08M_\odot$white dwarf) and the dashed lines are for a slightly underfilling its Roche lobe (a $0.1M_\odot$white dwarf).

5 AMPLITUDE VARIATIONS IN OPTICAL/INFRARED

In Figure 2 we show the V, R, I, J photometry folded and binned on the 9.5 min orbital period. The peak to peak amplitude variation is 0.13, 0.10, 0.07 and 0.16 mag respectively. In the double degenerate model of Ramsay et al (2000) the optical/infrared modulation is due to the secondary star which is irradiated by the accretion sites on the primary. We can make a very crude estimate of the temperature difference between the irradiated and non-irradiated hemispheres of the secondary star, if we assume they have equal areas and the emission can be approximated by a blackbody. In reality neither assumption is likely to be an accurate approximation, as the emission is probably characterised by a blackbody component together with another component which is due to irradiation. Other effects, such as limb darkening will also complicate matters. Assuming a mean temperature for the secondary of T=20000K we find that the observed amplitude variations require a temperature difference of ~1000–2000K between the irradiated and non-irradiated parts of the secondary.

6 THE NATURE OF THE SHORT DIP SEEN IN THE OPTICAL

In §2.2 we concluded that the short dip seen at phase ϕ ~0.85 was significant. Using the J-band data, which has the highest time resolution, we find that the width of the dip is $\Delta\phi$ ~0.03 cycles. The phasing of the optical/infrared light curve with respect to the X-ray curve suggests that it could be due to a stream which partially obscures the irradiated surface of the secondary. Since the dip is so narrow, the stream should have a small diameter.

Suppose RX J1914+24 consists of a magnetic white dwarf accreting material from its companion. For a dipole magnetic field, one can define a magnetospheric radius, r_μ, at which point the magnetic pressure balances the ram pressure of the accretion flow. The magnetospheric radius takes the form:

$$r_\mu \; = \; 5.1 \times 10^8 M_1^{-1/7} \dot{M}_{16}^{-2/7} \mu_{30}^{4/7} \text{ cm} \qquad (1)$$

which gives $r_\mu = 1.2 \times 10^{10}$ cm for M_1=$1.0M_\odot$(giving R_1 = 5.5×10^8 cm), B =5 MG and $\dot{M}$=$1{\times}10^{16}$ g s^{-1}. This is comparable to the binary separation of $a \sim 1.1 \times 10^{10}$ cm for the same orbital parameters. This suggests that the stream gets coupled by the magnetic field very close to the L_1 point.

The azimuthal angular span of the accretion stream is approximately constant from the L_1 point towards the primary and hence the width of the dip seen in the optical can be estimated if we can determine the radius of the stream at the L_1 point. The radius of the stream at the L_1 point, r_{L1}, is roughly given by

$$r_{\rm L1} \sim \sqrt{HR_2} \qquad (2)$$

where H is the scale height of the unperturbed atmosphere, given by

$$H \sim \frac{kT_2R_2^2}{\mu_m m_H G M_2} \;, \qquad (3)$$

and T_2 is the surface temperature of the secondary star, μ_m is the mean molecular mass, M_2 is the mass of the secondary (Pringle 1985). In our double degenerate polar interpretation, we have M_2=$0.08M_\odot$, giving $R_2 = 2 \times 10^9$ cm from the Nauenberg (1972) mass-radius relationship for white dwarfs. For a helium atmosphere, μ_m=4 and for $T_2 = 10^4$ K, we obtain $r_{\rm L1} = 1.1 \times 10^7$ cm. This would result in a dip lasting $\sim 2\pi/1000$ ~0.006 cycles which is of the right order of magnitude for the observed duration of the dip.

7 UNSOLVED MYSTERIES

Cropper et al. (1998) suggested that RX J1914+24 is a double degenerate polar to explain the lack of a second period in the *ROSAT* data and the shape of the X-ray light curve. The more extensive study of Ramsay et al. (2000), added weight to this argument: the X-ray spectrum is typical of polars; a main sequence secondary star was found to be inconsistent with the infrared colours; and a more detailed search of the X-ray and optical data continued to reveal only a single period.

At this point it maybe useful to briefly summarise the arguments that support the presence of mass transfer in RX J1914+24. The fact that we observe a modulation in X-rays and the optical is not by itself indicative of mass transfer: for instance, a modulation is seen in the non-interacting white dwarf RE J0317−853 due to its rotation (Barstow et al. 1995). On the other hand, since the optical and X-ray light curves are out of phase (Figure 2) it is much more likely that it is indeed an interacting binary. Further, Ramsay et al. (2000) found a large variation in the long-term X-ray light curve which can be explained in terms of mass-transfer variations. These features support the double degenerate polar model. However, in this model we would also expect to detect optical polarisation and emission lines – which we do not detect. We now go on to address these issues.

7.1 The problem of no polarisation

I-band polarimetry by Ramsay et al. (2000) failed to detect significant circular polarisation in the system. The anti-phasing of the I-band and X-ray light curves indicates that the optical flux is unlikely to originate from cyclotron emission. Ramsay et al. (2000) concluded that the magnetic field of the primary must be sufficiently high for the cyclotron emission to peak in the UV, or sufficiently low for it to be at infrared wavelengths. Alternatively, they suggested that no shock formed owing to the small dimensions of the system. Our V band polarimetric and spectropolarimetric observations presented in this paper extend the non-detection of circular polarisation to shorter wavelengths, so that the high-field option above can be considered less tenable. Unfortunately no infrared circular polarimetry is available to test the low field option.

7.2 The problem of no emission lines

A second difficulty with the double degenerate polar model is that we find that *no* detectable emission lines. A general (indeed almost defining) feature of accreting binary stars is the presence of emission lines. In the case of AM CVn systems (non-magnetic interacting double-degenerate binary systems) the donor is a low-mass helium white dwarf. In these systems, no hydrogen lines are visible, but strong helium lines are present (eg Marsh, Horne & Rosen 1991).

If mass transfer does occur, the lack of emission lines may be due to continuum emission from the heated face of the secondary which far exceeds the flux from any line emission from the accretion stream. Assuming the temperatures of the heated secondary and the accretion stream are approximately similar, then the flux ratio from the secondary and the stream is simply proportional to the relative emitting areas. For the secondary, the area is $\pi R_2^2 \sim 10^{19}$ cm^2. Crudely, the projected area of the stream is $\sim ra$ where r is the radius of the stream and a the orbital separation. In §6 we estimate the radius of the stream as $\sim 10^7$ and $a = 10^{10}$ cm (Ramsay et al 2000), giving an area of 10^{17} cm^2. The flux ratio is therefore ∼100. For a hot accretion stream, say $T >$30000 K, line emission would be suppressed and therefore the flux ratio of 100 must be regarded as a lower limit. Although the double degenerate polar model predicts weak optical emission lines to be present, we will require a spectrum of much higher signal to noise than the spectra obtained in §2 to test this.

8 ALTERNATIVE MODELS

Despite the success of the double-degenerate polar model in explaining many of the characteristics of the system, the absence of both detectable circular polarisation and line emission requires some explanation. The arguments discussed earlier indicate that it is possible to explain the absence of these features, but only by adopting particular values for the magnetic field and that the emission lines are so weak that we did not detect them in our relatively low signal to noise spectra. We have therefore explored whether there may be alternative models for RX J1914+24 which would explain its characteristics more naturally. We consider below three alternatives: a double-degenerate algol model, a neutron star-white dwarf pair and an electrically driven model.

8.1 Double-degenerate Algol Model

In normal Algol systems, the accretor is an early main sequence star, the donor either a late type giant or sub-giant star. For relatively short period systems (less than ∼6 days), the radius of the primary, R_1, is large enough compared to the minimum distance between the stream and the center of the primary ($R_{\rm min}$), that the accretion stream will impact directly onto the primary without forming an accretion disc.

Here we consider the case when both the primary and secondary are white dwarfs with negligible magnetic fields. We show in Figure 6, for a range of combinations of M_1, $R_{\rm min}$ and R_1. We also show for interest, the radius from the primary at which a disc starts to form – the circularisation radius $R_{\rm circ}$. Figure 6 shows that for $M_1 < 0.5 M_\odot$ the stream will impact directly onto the primary.

This model has the advantage that it would naturally account for the lack of optical polarisation. In addition, if the accretion stream flow impacts with the primary over a range of azimuth, it is likely that the brightness of the accretion site would not be uniform. This would result in a non-symmetric X-ray light curve: this is consistent with the X-ray light curves shown in Figure 2. However, as with the double degenerate polar model, emission lines (possibly weak) would be expected to be observed in optical spectra.

After we submitted this paper, we became aware of a paper by Marsh & Steeghs (2002) who also propose this double-degenerate Algol model for RX J1914+24.

8.2 Neutron star-white dwarf pair

We now consider a second alternative, that of a neutron star primary and a white dwarf secondary. A number of accreting neutron stars are known. These include low mass X-ray binary systems or isolated neutron stars which accrete from the interstellar medium. The luminosity of an accreting neutron star depends on the accretion rate, $\dot{M}$. For an isolated neutron star the accretion rate is determined by the proper motion of the star, and the gas density in the interstellar

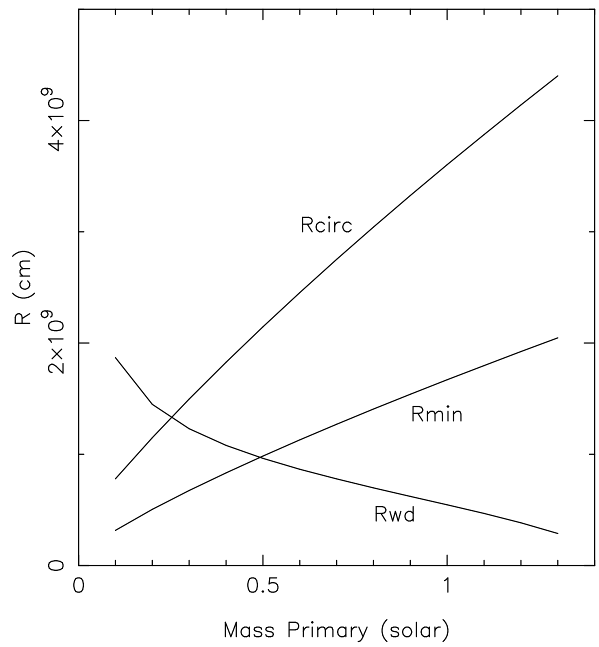

Figure 6. For a range of masses for the white dwarf primary we show the radius of the primary (R_{wd}), the circularisation radius (R_{circ}) and the distance of minimum approach of the stream to the primary (R_{min}). For $R_{wd} > R_{min}$ the stream will impact directly onto the primary as in the case for short period Algol systems.

medium. (eg Treves et al 2000). Assuming a number density of interstellar gas $\sim 0.1 - 1$ cm^{-3} and a gas temperature of $10^3 - 10^4$ K, typical of the solar neighbourhood, $\dot{M} \sim 10^{11} - 10^{12}$ g s^{-1}, implying that the luminosity of an accreting isolated neutron star would be $\lesssim 10^{32}$ erg s^{-1}.

Our estimate for the X-ray luminosity (§4) is a factor ~10 greater than this. However, if the neutron star is accreting at a low rate, say from material located in the binary system which maybe the remnants of a previous evolutionary phase, then the predicted luminosity could equal the observed luminosity.

We conclude that a neutron star-white dwarf model for RX J1914+24 is only viable if the neutron star is accreting material which has been left over from a previous phase of binary evolution. This scenario is attractive in the sense that we would not expect to observe significant levels of polarisation in the optical band. Further, we would not necessarily expect to observe optical line emission if the neutron star was accreting spherically. In addition, if accretion was occurring onto one of the magnetic poles of the neutron star the X-ray light curve could match the observed X-ray profile for a wide range of geometries. As in the double degenerate polar interpretation the hot polar cap could irradiate the secondary white dwarf and cause a phase shift in the X-ray/optical data.

8.3 Unipolar-Inductor Model

In our double degenerate polar model the less massive degenerate star, the secondary, must fill its Roche-lobe in order to facilitate the mass-transfer process. Suppose that the companion is now slightly denser and unable to fill its Roche lobe. The companion is still tidally locked into synchronous rotation with the orbit, while the magnetic primary may not be in perfect synchronism. The secondary will then traverse the magnetic field of the primary. Because white dwarfs are highly conductive, a large e.m.f. will be induced across the secondary. If the space between the two white dwarfs is filled with plasma, current loops can be set up (closed circuits), and the system acts like a unipolar inductor. Dissipation occurs mainly in the atmospheres of the white dwarfs, where the resistance is highest. We now consider an alternative to our accretion driven scenarios.

One example of a cosmic unipolar inductor is a planet-moon system. A well known example is the Jupiter-Io system, of which a bright trail of foot-points of the magnetic-field lines traversed by Io are observed on the surface of Jupiter (Clarke et al 1996). Another type of unipolar inductor is a white dwarf-planet system. For such a system with an orbital period of 10 hrs, electrical energy with a power $\sim 10^{29}$ erg s^{-1} (Li, Ferrario & Wickramasinghe 1998) can be generated. A double-degenerate unipolar inductor can produce a large emf because of the strong magnetic field of primary dwarf and the large diameter of the secondary white dwarf. Thus the electrical current and hence the power that it generates should be significantly larger than a planet-moon or a white dwarf-planet system. The details of the unipolar-inductor model for double-degenerate star are presented in Wu et al. (2002).

This model predicts X-ray emission from both magnetic poles. We would expect the emission from each foot-point to result in light curves which were 'top-hat' in appearance. The X-ray light curves shown in Figure 2 are consistent with a combination of two such light curves. Further, if the foot-points of the current carrying field-lines remain fixed with respect to the secondary (as in the Jupiter-Io system, Clarke et al 1996) then asynchronous rotation will not manifest itself in orbital period changes. The stability of the X-ray light curves is consistent with this scenario.

Further, a luminosity of 10^{33} erg s^{-1} (cf §4) can be produced if the system deviates sufficiently from synchronism (eg 1/1000; Wu et al, 2002). As there is no accretion column and no accretion shock, no strong emission lines or circular polarisation are expected. Thus, the unipolar inductor can naturally account for the two main difficulties with the accretion models.

9 CONCLUSIONS

We have presented optical and infrared spectra of RX J1914+24: no strong emission lines are present. Further, there is no evidence for significant levels of polarisation. In the double degenerate polar model, emission lines and detectable levels of polarisation are expected. It is, however, possible that the emission lines are too faint to have been detected in our spectra. We have also explored other alternative models: a double degenerate Algol, a neutron star-white dwarf pair and a cosmic unipolar inductor. The latter model is attractive in that the non-detection of polarisation and emission lines is a natural consequence of this model. It can also account for the X-ray luminosity if the system has a small degree of asynchronism.

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