Discovery of the high-field polar RX J1724.0+4114*

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ABSTRACT

We report the discovery of a new AM Herculis binary (polar) as the optical counterpart of the soft X-ray source RX J1724.0+4114 detected during the ROSAT all-sky survey. The magnetic nature of this $V \sim 17$ mag object is confirmed by low-resolution spectroscopy showing strong Balmer and He II emission lines superimposed on a blue continuum, which is deeply modulated by cyclotron humps. The inferred magnetic field strength is $50 \pm 4$ MG (or possibly even $\approx 70$ MG). Photometric observations spanning $\sim 3$ yr reveal a period of 119.9 min, directly below the period gap. The morphology of the optical and X-ray light curves, which do not show eclipses by the secondary star, suggests a self-eclipsing geometry. We derive a lower limit on the distance of $d \geq 250$ pc.

Keywords: accretion, accretion discs – stars: individual: RX J1724.0+4114 – stars: magnetic fields – novae, cataclysmic variables.

1 INTRODUCTION

Cataclysmic variables (CVs) are interacting binary stars consisting of a primary white dwarf and a low-mass main-sequence secondary that fills its Roche lobe. The common feature of these objects is the accretion of matter from the secondary on to the white dwarf. A detailed description of this class is given by Warner (1995). In 1977, Tapia reported the detection of (10 per cent) polarized emission in the nova-like variable AM Herculis indicating that the white dwarf in this CV has a strong magnetic field. Two decades later a well-established group of about 60 members form an intriguing subclass of CVs: the AM Herculis binaries or polars. The magnetic field strength in these systems as measured by Tapia (1977) and his successors using polarimetry, Zeeman and cyclotron spectroscopy ranges from 7 to 230 MG, and thus is strong enough to lock the rotation of the primary to the orbital motion and channel the accreted matter to a small area near one or both magnetic poles. This direct, magnetic accretion leads to the release of hard and soft X-rays as well as (partially) polarized cyclotron radiation. Owing to their high $F_X/F_{opt}$ ratio most of the polars were discovered by X-ray missions. It was in particular the ROSAT all-sky survey (RASS) which more than doubled the number of known systems (Watson 1993; Beuermann & Burwitz 1995). The source presented here was found in a systematic survey for supersoft X-ray sources within the RASS data base (Greiner 1996) which revealed a large number of CVs and single white dwarfs. The first polar identified from this sample was V844 Herculis = RX J1802.1+1804 (Greiner, Remillard & Motch 1995). In this paper we present photometric, spectroscopic and X-ray observations (summarized in Table 1) which led to the discovery of another AM Herculis system, RX J1724.0+4114 (henceforth referred to as RX J1724).

2 X-RAY OBSERVATIONS

The field of RX J1724 was scanned during the ROSAT all-sky survey for four days in 1990 August. The source was detected (using the EXSAS reduction package provided by MPE Garching; Zimmermann et al. 1994) with a mean count rate of $0.245 \pm 0.005$ count s$^{-1}$ at a best-fitting position of $\alpha_{2000} = 1\rlap{.}^h 24\rlap{.}^m 05\rlap{.}^s 4$ and $\delta_{2000} = 41\rlap{.}^\circ 14\rlap{.}^\prime 08\rlap{.}^\prime\prime$ (using only channels 25–50 for the position determination). The X-ray emission is very soft as indicated by the hardness ratio $HR_{1} = -0.97 \pm 0.03$, where $HR_{1}$ is defined as $(H - S)/(H + S)$, with $H$ ($S$) being the counts above (below) 0.4 eV.

The X-ray flux shows 100 per cent modulation with a peak count rate of $\sim 1.5$ count s$^{-1}$ and a pronounced faint-phase where the X-ray flux is practically zero (formal count rate of $-0.02 \pm 0.10$ count s$^{-1}$). The RASS light curve folded over the photometric ephemeris as derived in Section 4 is shown together with the light curves obtained from further pointed observations with the PSPC in 1993 March and the High Resolution Imager (HRI) in 1995 August (PI: Burwitz) in the three upper panels of Fig. 1. Although the achieved phase coverage is poor in each observation, we can constrain the X-ray bright phase from $\phi \sim 0.5$ to $\phi = 0$, where $\phi = 0$ marks the end of the bright phase observed in the optical. The pointed Position Sensitive Proportional Counter (PSPC) observation covers just the end of the bright phase and the faint-phase intensity is again zero ($0.00094 \pm 0.002$ count s$^{-1}$). In the HRI
Table 1. Log of all observations of RX J1724.0+4114.

| Telescope       | Date        | Instrument | Spectral range | N(1) | Duration (h) | T_int (sec) |
|-----------------|-------------|------------|----------------|------|--------------|-------------|
| ROSAT XRT       | 90 Aug 24/28| PSPC-C     | 0.1–2.4 keV    | 320  | 0.36         | 7–32        |
| ROSAT XRT       | 93 Mar 8/11 | PSPC-B     | 0.1–2.4 keV    | 72   | 1.65         |             |
| ROSAT XRT       | 95 Aug 5/8  | HRI        | 0.1–2.4 keV    | 90   | 3.58         |             |
| Calar Alto 3.5 m| 92 Oct 1    | Cassegrain | 3800–7100 Å    | 1    | 1            | 3600        |
| Sonneberg 0.6 m | 94 Jun 15   | EEV–CCD    | R              | 62   | 2.34         | 120         |
| Sonneberg 0.6 m | 94 Jun 19   | EEV–CCD    | R              | 65   | 2.89         | 120         |
| Sonneberg 0.6 m | 94 Jul 1    | EEV–CCD    | R              | 61   | 2.51         | 120         |
| Sonneberg 0.6 m | 94 Jul 2    | EEV–CCD    | R              | 46   | 2.06         | 120         |
| Sonneberg 0.6 m | 94 Jul 11   | EEV–CCD    | R              | 50   | 2.47         | 120         |
| Potsdam 0.7 m   | 97 Apr 1    | TEK–CCD    | WL             | 157  | 5.50         | 120         |
| Potsdam 0.7 m   | 97 May 28   | TEK–CCD    | WL             | 90   | 3.05         | 120         |

(1) Number of images for photometry or number of X-ray counts for ROSAT data.

The exposure lasted one hour corresponding to approximately half of the binary orbit, and was centred on HJD 244 8897.30923 which corresponds to $\phi = 0.619$ of the ephemeris given by equation (2). Hence the spectrum covers equally ~50 per cent of the faint and bright phase. The original spectrum is shown in Fig. 3. It is dominated by intense emission lines of the Balmer series, He II λ4686 Å, and He i superimposed on a blue continuum. The inverted Balmer decrement and the strength of the He II λ4686 Å line point to a magnetic CV classification.

This is directly confirmed by the cyclotron lines seen at λλ4500 and 5700. According to

$$\lambda_u = \frac{10710}{n} \left( \frac{10^8}{B(G)} \right) \mu \text{m}$$

the separation of the two observed cyclotron humps allows for an interpretation as the 3rd/4th or 2nd/3rd harmonics of the cyclotron fundamental. If we identify these as the 3rd and 4th harmonics, the (minimum) implied field strength is $50 \pm 4$ MG depending on the plasma temperature and the viewing angle. A corresponding cyclotron model for a 20 keV plasma, a polar angle of $70°$ and a plasma parameter log A = 3.5 is shown in Fig. 3. The high polar angle is thought to be a reasonable assumption owing to the accretion geometry (see below) and the fact that the exposure of the spectrum covers the rise of the spot over the limb. In the case of an interpretation of the observed cyclotron humps as the 2nd and 3rd harmonics the implied field strength is of the order of 70 MG. Further low-resolution spectroscopy extending to the near-infrared is needed to clarify this ambiguity.

3 A LOW-RESOLUTION SPECTRUM

Within the programme of the optical identification of all new ROSAT supersoft X-ray sources we obtained a low-resolution (FWHM ~12 Å) spectrum of RX J1724 on 1992 October 1 with the 3.5-m telescope at Calar Alto, Spain. We used the Cassegrain spectrograph equipped with a RCA CCD as detector covering the optical wavelength range from 3800–7100 Å. The observation was obtained under stable photometric conditions and accompanied by measurements of the standard star Feige 110 which was used to calibrate the flux with an accuracy of ~20 per cent (using standard MIDAS procedures). By convolving the original spectrum with functions representing the MIDAS calibrate the flux with an accuracy of ~20 per cent (using standard measurements of the standard star Feige 110 which was used to obtained under stable photometric conditions and accompanied by optical wavelength range from 3800-7100 Å. The observation was $V = 17.6$ mag, $R = 17.1$ mag and $B = 17.6$ mag for RX J1724.

4 PHOTOMETRIC OBSERVATIONS

RX J1724 was photometrically monitored during seven nights in 1994 and 1997 with the 0.6-m reflector at Sonneberg Observatory and the 0.7-m reflector at the Astrophysical Institute Potsdam (both Germany). Observational details are listed in Table 1. During all runs no standard stars were observed, so that we are restricted to differential photometry, which was computed with respect to star 'A' marked in Fig. 2. We used the profile-fitting scheme of the DOPHOT reduction package (Mateo & Schechter 1989) to achieve high accuracy. The individual light curves are characterized by a faint phase showing only little variability followed by a pronounced bright phase with an amplitude of 0.7 mag. In order to derive an
Figure 2. R-band CCD image of RX J1724.0+4114 obtained with the Sonneberg 60-cm telescope. North is top and east to the left. The size of the field is ≈ 8 × 8 arcmin². The uncertainty of the X-ray position is given by the 95 per cent confidence error circle (10 arcsec) which is based on the HRI observation. The position of the optical counterpart is α2000 = 17h 24m 06.2s and δ2000 = 41°44'09.1" (± 1 arcsec). Star ‘A’ is used for differential photometry (Fig. 1) and star ‘B’ for the evaluation of the long-term behaviour on the Sonneberg astrographic patrol plates (Section 5).

Table 2. Results of three different spectral fits of RASS data of RX J1724.0+4114 with the sum of a blackbody and thermal bremsstrahlung model. Parameters marked with a * have been fixed during the respective fit: the second line for adopting the Galactic absorbing column and the third line for fixing the blackbody temperature to the canonical value of polars.

| N_H (10²⁰ cm⁻²) | kT (eV) | Norm (ph/cm²/s/keV) | Norm (ph/cm²/s/keV) |
|------------------|---------|---------------------|---------------------|
| 1.9±0.5          | 58±20   | 1.4×10⁻²            | 1.9×10⁻⁶            |
| 2.7*             | 51±20   | 2.8×10⁻²            | 6.5×10⁻⁶            |
| 5.6±0.5          | 25*     | 240×10⁻²            | 20.5×10⁻⁶           |

ephemeris we carried out a period search using the analysis-of-variance method (Schwarzenberg-Cerny 1989) and a least squares calculation applied to the heliocentric timings defining the end of the bright phase as compiled in Table 3. The resulting periodograms (Fig. 4) reveal a period of 0.90832837. Cycle aliases caused by the ∼2.8-yr separation of the data sets are quite prominent. However, they lead to a significant phase displacement of the observation on 1997 May 28. Moreover, for both neighbouring alias periods the X-ray bright and faint phases as observed in the three X-ray observations do not align. We therefore are confident that the alias periods can be ruled out. Then, the accuracy is sufficient to connect all the data from 1990 August to 1997 May with an uncertainty of δφ ~ 0.029. The linear ephemeris for the times of end bright phase derived from the optical data is

\[ T_{\text{end}}(\text{HJD}) = 244 9519.4721(14) + 0.083 283 88(8)E, \]

where the numbers in brackets give the uncertainty in the last digits. In Fig. 1 we present a collection of light curves folded over the ephemeris given by equation (2). The bright phases observed in the optical and X-ray bands coincide.

5 DISCUSSION AND CONCLUSIONS

We have identified the X-ray source RX J1724 as a new magnetic CV. The combination of extreme soft X-ray spectrum, a strong magnetic field of \( B = 50 \pm 4 \text{ MG} \) (or possibly even \( \approx 70 \text{ MG} \)), an inverted Balmer decrement and strong He II lines provide strong
Figure 3. Left: low-resolution optical spectrum of RX J1724 obtained on 1992 October 1. Main emission lines are indicated. The solid line represents a homogeneous cyclotron model for a magnetic field of 50 MG assuming $kT = 20$ keV, $\log A = 3.5$ and $\theta = 70^\circ$. Right: phase-averaged RASS X-ray spectrum of RX J1724 unfolded with a blackbody plus thermal bremsstrahlung spectrum (see text for details). The lower-right panel shows the residuals of the fit in units of $\sigma$.

Table 3. Heliocentric Julian dates of the end of the bright phase (estimated error of 180 s) together with the epoch and deviation from phase zero implied by the ephemeris of equation (2).

| $T_{\text{end}}$ (HJD 2440000+) | O-C (sec) | Epoch | Filter |
|-------------------------------|----------|-------|--------|
| 49519.4735                    | 72       | 0     | R      |
| 49523.4690                    | 21       | 48    | R      |
| 49536.4615                    | 49       | 204   | R      |
| 49545.4567                    | -28      | 312   | R      |
| 50540.4467                    | -217     | 12259 | WL     |
| 50540.5325                    | 108      | 12260 | WL     |
| 50540.6153                    | -163     | 12261 | WL     |
| 50597.4158                    | 150      | 12943 | WL     |
| 50597.5010                    | 86       | 12944 | WL     |

evidence for the polar nature although no polarimetry has been obtained. The observed values for $B$ and $F_{\text{bbd}}/F_{\text{body}}$ obey well the proportionality relation between these quantities found for other polars (Beuermann & Burwitz 1995).

The period derived from the optical and X-ray light curves is 119.9 min, directly below the lower edge of the period gap. No other periodicities have been found, so that RX J1724 appears to be synchronized over the observed time-scale.

The coincidence in phase of the bright phase in X-ray and optical bands as well as the lack of X-ray emission during the optical faint phase resemble the behaviour of self-eclipsing polars like ST LMi or VV Pup (Cropper & Warner 1986; Cropper 1986) where the accretion region passes behind the limb of the white dwarf and is out of sight. The duration of the faint phase $\gamma$ gives a constraint on possible geometries. Assuming a point-like accretion spot the inclination $i$ and the colatitude $\beta$ are related via

$$\cos \gamma \pi = \cot i \cot \beta.$$  

\( \gamma \)

Figure 4. Results of the period search using the $\chi^2$ calculation of the minima given in Table 3 (upper panel, units of the ordinate are $10^4$ $d^{-2}$) and the analysis of variance (lower panel). The adopted period is marked with a tick.

The lack of eclipses implies $i < 78^\circ$. The duration of the bright phase is $\approx 0.5$ for most of the observations consistent with $i > 90^\circ$, i.e., an accretion region located on the hemisphere of the white dwarf facing away from the observer ("southern hemisphere"). The light curves obtained on 1994 June 19 and July 2 show a much more extended bright phase. This might indicate that the location of the accretion spot might have changed or a second accreting pole was active.

The observed X-ray intensity during the HRI pointing in 1995 is considerably smaller than the intensity seen during the RASS 5
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years earlier, thus implying variable mass transfer to the white dwarf. We note, however, that the observed count rate is an extremely sensitive function of the temperature: depending on the exact absolute temperature and the model used, the count rate is proportional to $T^{5-16}$ (Heise et al. 1994). Thus, a reduction of the temperature $T$ by about 30 per cent can account already for the observed count rate difference. It is therefore impossible to quantify the difference in mass transfer rates.

Additional evidence for changes in the transfer rate comes from the discovery of substantial ($> 1$ mag) long-term optical variations using photographic patrol plates. RX J1724 is covered by the M 92 field (taken with the GB 40/190-cm instrument) of the Sonneberg Observatory astrographic patrol (although it is very near the edge of the field of view). A check of the available $\sim 100$ plates reveals RX J1724 sometimes (e.g. 1976 April until September, 1987 June 30, 1993 August 13–15) as bright as comparison star B (labelled in Fig. 2; note that owing to its colour star B is notably fainter than star A in the blue band). At other times it is invisible even on very deep plates (fainter than 17.5 $m_{pg}$) such as 1982 April/May, 1983 June 6/7, 1984–1985 and 1992 (including the time of the spectroscopic observation). Unfortunately, the data are too spotty to derive a meaningful light curve. As a result of its clear variability this object is assigned the number S 10946 in the series of variable stars detected at Sonneberg Observatory.

The density of a Roche-lobe filling secondary with $P = 2$ h is $28 \pm 0.5$ g cm$^{-3}$, only weakly depending on the mass–ratio $q$. Assuming that a mass–radius relationship for main-sequence stars is valid for RX J1724 (e.g. Patterson 1984) we find $M_2 = 0.16 M_\odot$ and $R_2 = 0.2 R_\odot$. The spectral type of a star with that mass is M 4–4.5 (Kirkpatrick & McCarthy 1994). We do not see any spectral signature of the late-type companion in our spectrum. Assuming a contribution of the secondary to the total mean optical light of $\leq 10$ per cent in the V band ($V \approx 20.1$ mag) and using $M_V = 13.1$ mag (Kirkpatrick & McCarthy 1994) we find a lower limit on the distance of RX J1724 of $d \geq 250$ pc. This is consistent with the $N_H$ found in the X-ray spectral fit and the Galactic latitude of RX J1724 of $b = 33^\circ 3$.

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