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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 $V \sim 17^{\rm m}$ object is confirmed by low-resolution spectroscopy showing strong Balmer and HeII emission lines superimposed on a blue continuum which is deeply modulated by cyclotron humps. The inferred magnetic field strength is 50 ± 4 MG (or possibly even ≈ 70 MG). Photometric observations spanning ~ 3 years reveal a period of 119.9 min, right 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 $d \gtrsim 250$ pc.

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

1 INTRODUCTION

Cataclysmic variables (CVs) are interacting binary stars consisting of a primary white dwarf and a low-mass main-sequence secondary which fills its Roche lobe. The common feature of these objects is the accretion of matter from the secondary onto the white dwarf. A detailed description of this class is given by Warner (1995). In 1977, Tapia reported the detection of (10%) polarised 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 Megagauss, 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) polarised cyclotron radiation. Due to their high $F_{\rm X}/F_{\rm opt}$ 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 database (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 and Motch 1995). In this paper we present photometric, spectroscopic and X-ray observations (summarized in Tab. 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 August 1990. 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 ± 0.005 cts/s at a best-fit position of $\alpha_{2000} = 17^{\rm h}24^{\rm m}05\overset{\rm s}{.}4$ and $\delta_{2000} = 41°14'08''$ (using only channels 25–50 for the position determination). The X-ray emission is very soft as indicated by the hardness ratio $HR1 = -0.97\pm0.03$, where $HR1$ is defined as (H–S)/(H+S), with H (S) being the counts above (below) 0.4 keV.

The X-ray flux shows 100% modulation with a peak count rate of $\sim$1.5 cts/s and a pronounced faint-phase where the X-ray flux is practically zero (formal count rate of -0.02 ± 0.10 cts/s). 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 March 1993 and the HRI in August 1995 (PI: Burwitz) in the three upper panels of

* Partly based on observations collected at the German-Spanish Astronomical Centre, Calar Alto, operated by the MPI für Astronomie, Heidelberg, jointly with the Spanish National Commission for Astronomy.

Table 1. Log of all observations of RX J1724.0+4114.

Telescope	Date	Instrument	Spectral range	#(1)	Duration (h)	$T_{\rm int}$ (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.

Fig. 3. 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 PSPC observation covers just the end of the bright-phase and the faint-phase intensity is again zero (0.00094 ± 0.002 cts/s). In the HRI observation RX J1724 is covered over nearly all phases. The mean intensity during the bright phase (0.02 cts/s) is about a factor of 10 lower than during the RASS; note that due to the soft X-ray spectrum the conversion factor between PSPC and HRI count rates is 7.5 (Greiner *et al.* 1996).

The HRI observation allows for an improved X-ray position ($\pm 10''$) determination as compared to the original RASS error circle (see Fig. 1): $\alpha_{2000} = 17^{\rm h}24^{\rm m}06\overset{\rm s}{.}2$, $\delta_{2000} = 41^\circ 14' 11''$. This confirms the earlier (1992) identification of RX J1724 based on the optical spectroscopy.

Only the RASS data are suited for a spectral investigation since the other PSPC observation only covers the faint phase interval (Fig. 3). Adopting a blackbody plus thermal bremsstrahlung model and fixing the temperature of the latter component to 20 keV gives the values reported in Tab. 2. The temperature of the blackbody component is about 50 eV and the absorbing column in the free fit (see Fig. 2) about 2/3 of the total galactic absorbing column in this direction (Dickey and Lockmann 1990). We also have performed fits with fixing either the absorbing column to the galactic value (2.7×10^{20} cm^{-2}) or the blackbody temperature to the canonical value of 25 eV. In both cases the fit is considerably worse.

With the parameters of the free fit and considering only the X-ray bright phase, the unabsorbed fluxes of the two model components in the ROSAT band (0.1–2.4 keV) are $F_{\rm bbdy} = 1.3 \times 10^{-11}$ erg/cm^2/s and $F_{\rm thbr} = 2.8 \times 10^{-14}$ erg/cm^2/s, giving a flux ratio of $F_{\rm thbr}/F_{\rm bbdy} = 0.0022$. The mean luminosity (of both components) during the X-ray bright phase is $L_{\rm X} = 1.5 \times 10^{31}$ (D / 100 pc)^2 erg/s.

3 A LOW RESOLUTION SPECTRUM

Within the program of the optical identification of all new ROSAT supersoft X-ray sources we obtained a low resolution (FWHM $\sim$ 12 Å) spectrum of RX J1724 on October 1, 1992 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 $\sim$ 20% (using standard MIDAS procedures). By convolving the original spectrum with functions representing the BVR bandpasses we arrive at $V = 17\overset{\rm m}{.}6$, $R = 17\overset{\rm m}{.}1$ and $B = 17\overset{\rm m}{.}6$ for RX J1724.

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.

$N_{\rm H}$ (10^{20} cm^{-2})	kT (eV)	blackbody Norm (ph/cm^2/s/keV)	bremsstrahlung Norm (ph/cm^2/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}

The exposure lasted one hour corresponding to approximately half of the binary orbit, and was centered on HJD 244 8897.30923 which corresponds to $\phi = 0.619$ of the ephemeris given by Eq. 2. Hence the spectrum covers equally $\sim$ 50 % of the faint and bright phase. The original spectrum is shown in Fig. 2. It is dominated by intense emission lines of the Balmer series, He II λ4686Å, and He I superimposed on a blue continuum. The inverted Balmer decrement and the strength of the He II λ4686Å line point to a magnetic CV classification.

This is directly confirmed by the cyclotron lines seen at λ4500 and λ5700. According to

$$\lambda_n = \frac{10710}{n} \left(\frac{10^8}{B({\rm G})} \right) \quad \text{Å} \tag{1}$$

the separation of the two observed cyclotron humps allows for an interpretation as the 3rd/4th or 2nd/3rd harmonics

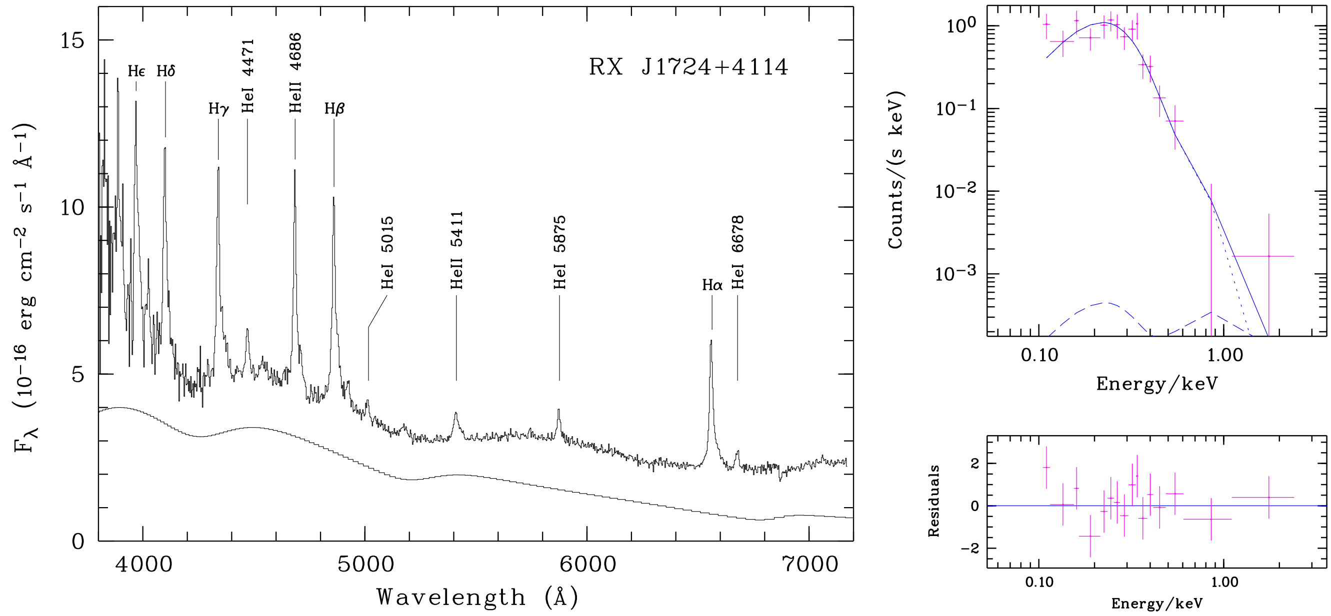

Figure 2. Left: Low resolution optical spectrum of RX J1724 obtained on October 1, 1992. Main emission lines are indicated. The solid line represents a homogeneous cyclotron model for a magnetic field of 50 MG assuming $kT = 20$ keV, $\log \Lambda = 3.5$ and $\theta = 70°$. **Right:** Phase-averaged 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 residua of the fit in units of σ.

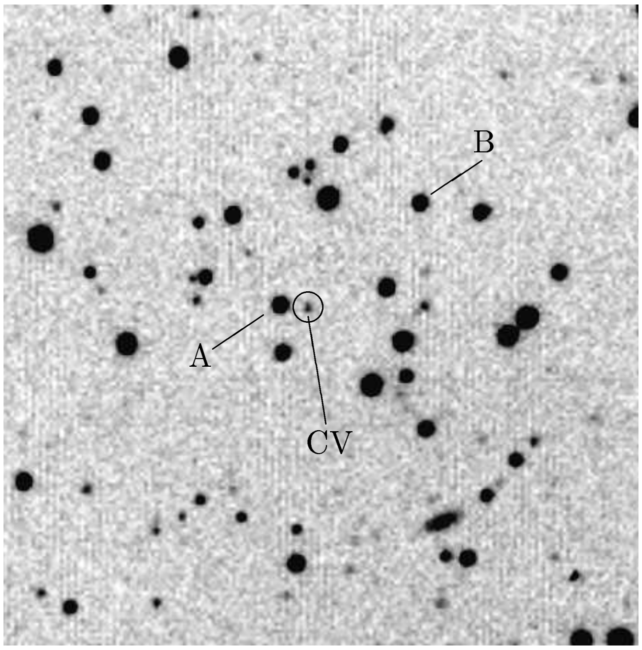

Figure 1. *R*-band CCD image of RX J1724.0+4114 obtained with the Sonneberg 60 cm telescope. North is top and East to the left. The size of the field is $\approx 8' \times 8'$. The uncertainty of the X-ray position is given by the 95% confidence error circle ($10''$) which is based on the HRI observation. The position of the optical counterpart is $\alpha_{2000} = 17^{\mathrm{h}}24^{\mathrm{m}}06\overset{\mathrm{s}}{.}2$ and $\delta_{2000} = 41°44'09''$ ($\pm 1''$). Star 'A' is used for differential photometry (Fig. 3) and star 'B' for the evaluation of the long-term behaviour on the Sonneberg astrographic patrol plates (paragr. 5).

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 Eq. 2.

T_{end} (HJD 2400000+)	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

of the cyclotron fundamental. If we identify these as the 3rd and 4th harmonics, the (minimum) implied field strength is 50±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 $\log \Lambda = 3.5$ is shown in Fig. 2. The high polar angle is thought to be a reasonable assumption due 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.

4 PHOTOMETRIC OBSERVATIONS

RX J1724 was photometrically monitored during 7 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 Tab. 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. 1. We used the profile-fitting scheme of the DoPhot reduction package (Mateo & Schechter 1989) to achieve high accuracy. The individual light curves are characterised 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 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 Tab. 3. The resulting periodograms (Fig. 4) reveal a period of $0\overset{\mathrm{d}}{.}0832843$. Cycle aliases caused by the $\sim$ 2.8 year separation of the data sets are quite prominent. However, they lead to a significant phase displacement of the observation on May 28, 1997. 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 August 1990 to May 1997 with an uncertainty of $\delta\phi \sim 0.029$. The linear ephemeris for the times of end bright phase derived from the optical data is

$$T_{\mathrm{end}}(\mathrm{HJD}) = 244\,9519.4721(14) + 0.08328388(8)E, \qquad (2)$$

where the numbers in brackets give the uncertainty in the last digits. In Fig. 3 we present a collection of light curves folded over the ephemeris given by Eq. 2. The bright phases observed in the optical and X-ray bands coincide.

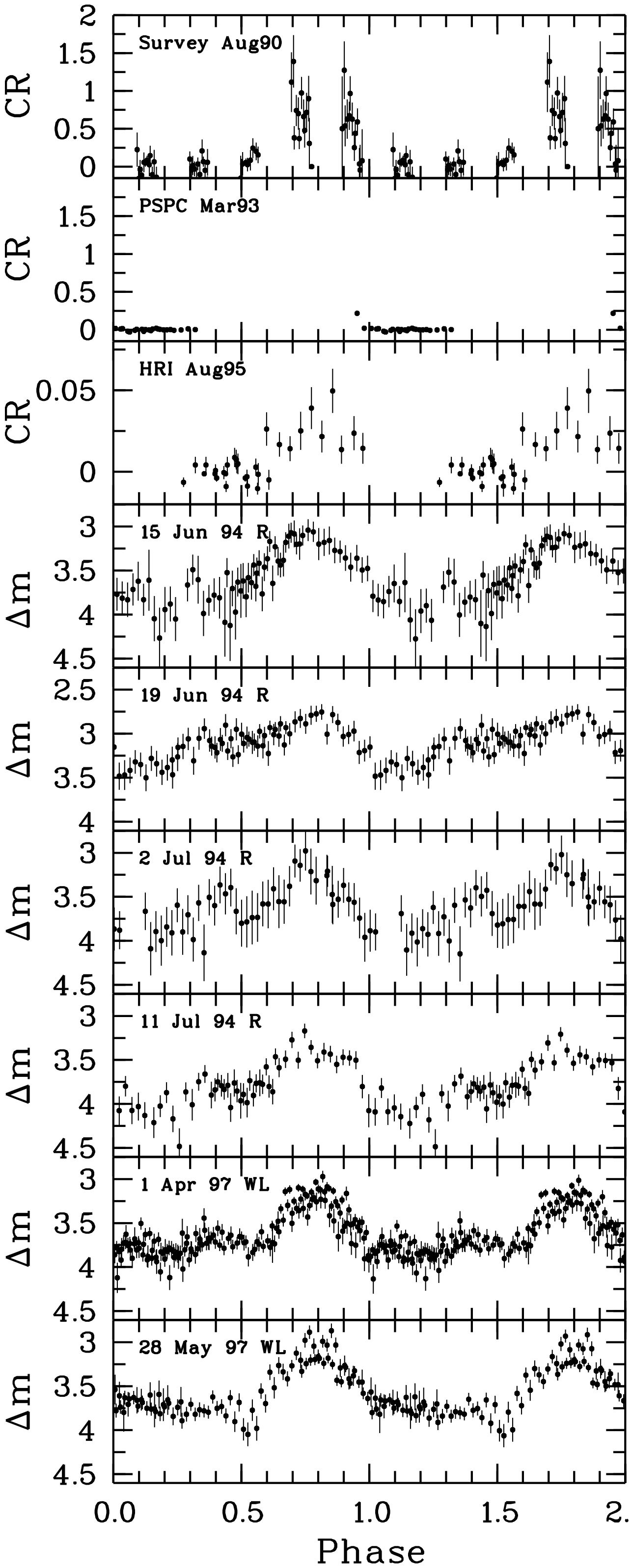

Figure 3. Optical and X-ray light curves of RX J1724 plotted as a function of ephemeris Eq. 2. Data are plotted twice for clarity and units are cts/s in the corresponding X-ray detector for the upper three panels and relative magnitudes with respect to star A (Fig. 1) elsewhere.

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±4 MG (or possibly even ≈70 MG), an inverted Balmer decrement and strong He II lines provide strong evidence for the polar nature though no polarimetry has been obtained. The observed values for B and $F_{\mathrm{thbr}}/F_{\mathrm{bbdy}}$ 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, right below the lower edge of the period gap. No other periodicities have been found, so that RX J1724 appears to be synchronised over the observed timescale.

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 γ gives a constraint on possible geometries. Assuming a point-like accretion spot the inclination i and the colatitude β are related via

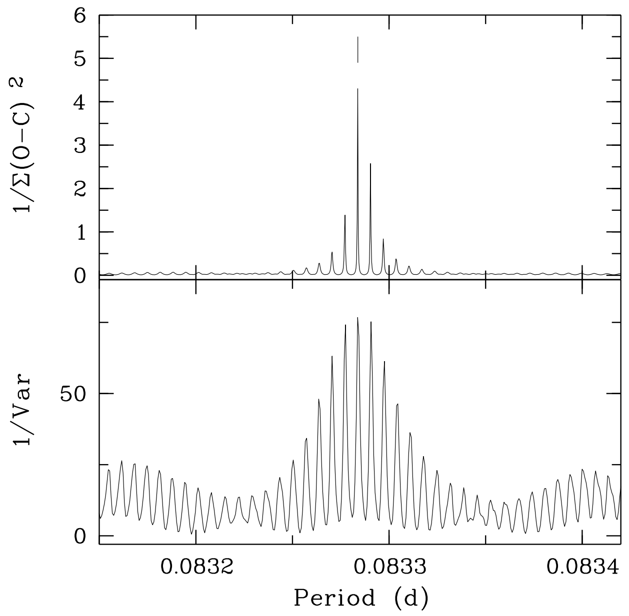

Figure 4. Results of the period-search using the χ^2 calculation of the minima given in Tab. 3 (upper panel, units of the ordinate are $10^4 \mathrm{d}^{-2}$) and the analysis-of-variance (lower panel). The adopted period of is marked with a tick.

$$\cos\gamma\pi = \cot i \cot\beta. \qquad (3)$$

The lack of eclipses implies $i < 78°$. The duration of the bright phase is ≤ 0.5 for most of the observations consistent with $\beta > 90°$, 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 June 19 and July 2 1994 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 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% 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 (though very near the edge of the field of view). A check of the available ≈100 plates reveals RX J1724 sometimes (e.g. 1976 Apr. until Sep., 1987 June 30, 1993 Aug. 13–15) as bright as comparison star B (labeled in Fig. 1; note that due 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 $\mathrm{m_{pg}}$) such as 1982 Apr./May, 1983 Jun. 6/7, 1984–1985 and 1992 (including the time of the spectroscopic observation). Unfortunately, the data are too spotty to derive a meaningful lightcurve. Due to 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 ± 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 $M_2 = 0.16$ $\mathrm{M_\odot}$ and $R_2 = 0.2$ $\mathrm{R_\odot}$. 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 $\lesssim$10% in the V band ($V \gtrsim 20\overset{\mathrm{m}}{.}1$) and using M_V=13.1 mag (Kirkpatrick & McCarthy 1994) we find a lower limit on the distance of RX J1724 of $d \gtrsim 250$ pc. This is consistent with the N_H found in the X-ray spectral fit and the galactic latitude of RX J1724 of $\mathrm{b^{II}} = 33\overset{\circ}{.}3$.

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