

1RXS J062518.2+733433: A bright, soft intermediate polar[★]

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Abstract. We present the results of 50 hours time-resolved *R*-band photometry of the ROSAT all-sky survey source 1RXS J062518.2+733433. The source was identified by Wei et al. (1999) as a cataclysmic variable. Our photometry, performed in 10 nights between February 11, 2003, and March 21, 2003, reveals two stable periodicities at 19.7874 and 283.118 min, which are identified as probable spin and orbital periods of the binary. We therefore classify 1RXS J062518.2+733433 as an intermediate polar. Analysis of the RASS X-ray observations reveal a variability of 100% in the X-ray flux and a likely soft X-ray excess. The new IP thus joins the rare group of soft IPs with only four members so far.

Key words. stars: individual: 1RXS J062518.2+733433 – binaries: close – novae, cataclysmic variables

1. Introduction

1RXS J062518.2+733433 (RX06 in the following) was discovered during an AGN search in the ROSAT All-Sky Survey (RASS) by Wei et al. (1999) and identified as a cataclysmic variable star (CV). Wei et al. selected their sources for an optical identification program according to a high ratio of X-ray to optical flux (F_X/F_{opt}). Most of their objects are indeed emission line AGNs, however, four CVs are among them. The optical spectrum of RX06 showed a blue continuum with bright emission lines of hydrogen and helium, both neutral and ionized, thus making the object a candidate magnetic CV.

New magnetic CVs were found numerously in the RASS, most of them are polars (AM Herculis stars). The strong magnetic fields in these systems channel the accreted matter to rather small regions at the footpoints of accreting field lines, where a soft X-ray engine is located. As a result of the RASS and several identification programs the total number of polars has increased from a dozen or so pre-ROSAT ones to about 70 now. Progress for the cousins with weaker magnetic fields, the DQ Herculis stars or intermediate polars (IPs), was much slower. Today only about 23 confirmed systems are known. This is mainly due to their relative hard X-ray spectra, preventing their detection in large number in the RASS or the EUVE all sky survey.

IPs were traditionally thought to have accretion disks truncated by the magnetic field in the inner regions. They accrete from the disk via an azimuthally extended accretion curtain. Although the processes of energy release at the foot points

of the accretion curtain are similar to polars, the classical IPs lack detection of a soft X-ray component. This was usually explained by a too low temperature of the soft component or by high photoelectric absorption in the accretion curtain. ROSAT has discovered a small number of weakly absorbed, so called soft IPs (Mason et al. 1992; Haberl et al. 1994, 2002) with relatively high magnetic field strength and corresponding high collimation of the accretion flow. Here we present the discovery of a new, soft IP. The classification rests on extended optical photometry and an analysis of the RASS X-ray data.

2. Optical photometry

Our photometric observations were performed with the 0.7 m-telescope of the AIP in Potsdam and the 0.8 m-telescope of the Universität München at the Wendelstein in the period between February 11, 2003 and March 21, 2003. The Potsdam telescope is equipped with a cryogenic Photometrics CCD, using a thinned SITE 1k × 1k chip. The telescope at Mount Wendelstein was operated with the MONICA CCD camera system (Roth 1990). All observations were performed using a broad-band *R* filter. Details are shown in Table 1.

The brightness of the object was measured with respect to a brighter comparison star (marked “C” in Fig. 1), for which we determined an apparent *R*-magnitude of 12.^m89 from standard-star measurements on February 24 and March 18, 2003.

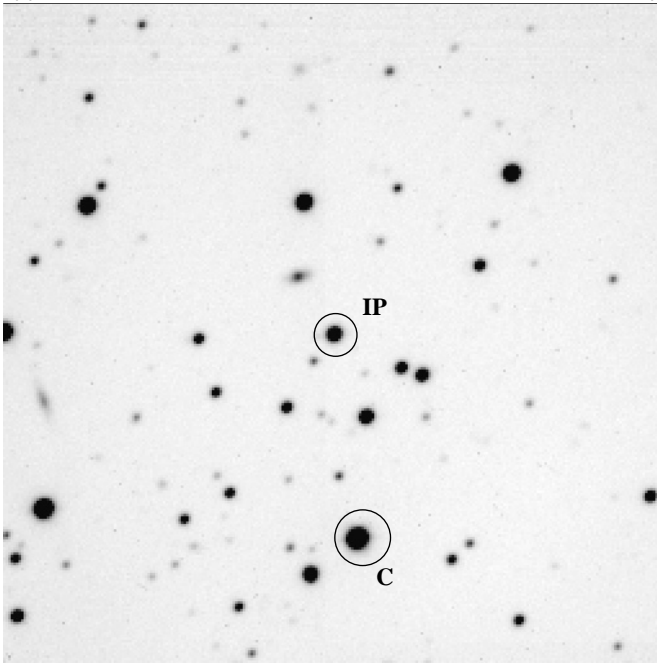
Figure 2 shows all our observations. Obviously there is the superposition of brightness variations on two different time-scales: short-term oscillations with a period of ~20 min and broad humps with a periodicity of ~5 hours. In addition the overall brightness level does vary on a night-to-night basis by about 0.2 mag.

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[★] Partly based on observations collected at the Wendelstein observatory, operated by the Universitäts-Sternwarte München.

Table 1. Log of observations.

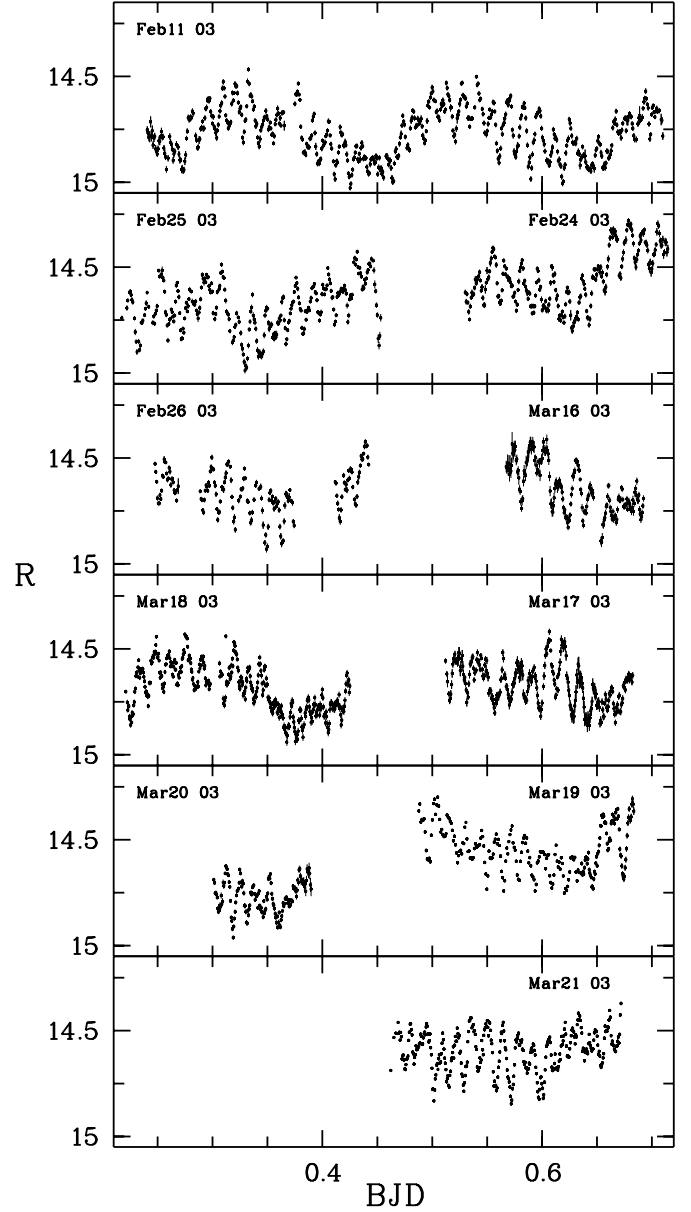
Date	Telescope	Filter	Duration	Exp. time
2002/02/11	AIP 0.7m	R	11.34 h	60 s
2002/02/24	AIP 0.7m	R	4.42 h	60 s
2002/02/25	AIP 0.7m	R	5.67 h	60 s
2002/02/26	AIP 0.7m	R	4.67 h	60 s
2002/03/16	UM 0.8m	R	3.02 h	35 s
2002/03/17	UM 0.8m	R	4.09 h	35 s
2002/03/18	UM 0.8m	R	4.90 h	35 s/25 s
2002/03/19	UM 0.8m	R	4.50 h	65 s/35 s
2002/03/20	UM 0.8m	R	2.13 h	35 s
2002/03/21	UM 0.8m	R	5.03 h	35 s

**Fig. 1.** *R*-band image of RX06 taken with the AIP 0.7 m-telescope ($\sim 6' \times 6'$). North is on top and East is left. The object and the comparison-star (“C”) are marked.

3. Period analysis

For determining the periodicities we applied the analysis-of variance method (AoV, Schwarzenberg-Cerny 1989) on the combined data set including all nights. Beforehand the individual data sets were normalised to the mean brightness level, in order to account for the night-to-night variations.

The resulting periodogram (Fig. 3) is dominated by two most significant periods at 19.7877 min (72.774 cyc/d) and 283.117 min (5.086 cycle/d), which we interpret as spin and orbital period of a DQ Herculis system, respectively. Other significant peaks in the periodogram include the inevitable alias periods due to sampling, a series of sub-harmonics of the spin period as well as the first sub-harmonic of the orbital signal. In the raw periodogram any of the side-band periods commonly detected in the intermediate polars are hidden in

**Fig. 2.** All light curves used for the period determination in this paper. The brightness is given in *R*-magnitudes, time in fractions of barycentric JD. The light curves of Feb. 25, March 18 and 20 have been offset horizontally by -0.25 days.

the complicated alias structure. When repeating the analysis after removal of the two main signals from the light curves, a clear signal at 21.2737 min becomes evident. If our assignment of spin and orbital period were correct, this detection would represent the $\omega - \Omega$ side-band frequency.

The accuracy of the spin period (FWHM of the peak) is sufficient to establish an unequivocal cycle count in our data. Individual barycentric timings of the pulse maxima for each night of observation were determined from fitting a sinusoid to our smoothed light curves and are listed in Table 2. They obey a linear relation yielding a spin ephemeris

$$\text{BJD}(\text{max}) = 2\,452\,682.4181(5) + E \times 0.01374128(16) \quad (1)$$

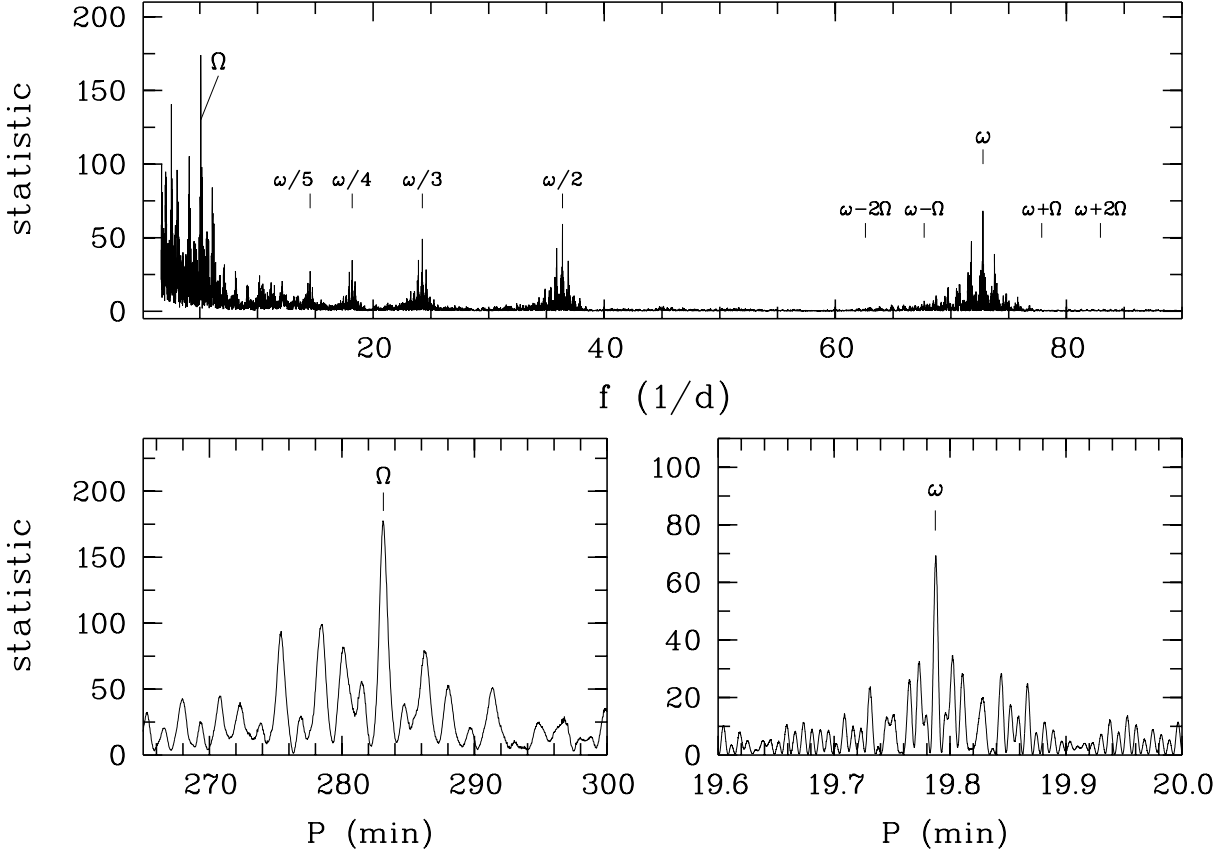


Fig. 3. The results of the period analysis. *top*: full-range periodogram, *left*: around 283 min, *right*: around 19.8 min.

Table 2. Timings of the pulse maxima.

T_{\max} (BJD 2 450 000+)	Cycle	OMC (s)
2682.41805	0	-11
2695.55464	956	-17
2696.51701	1026	23
2697.34144	1086	19
2715.63071	2417	-12
2716.56483	2485	-37
2717.52629	2555	-74
2718.55801	2630	22
2719.57546	2704	74
2720.56402	2776	4

where the number in brackets denote the uncertainties in the last digits as given by the linear regression. The scatter of the measured values is in general in agreement with the formal errors of our sine-fitting.

In case of the orbital modulation the sharp rise from minimum provided the best marker for defining the zero point of our orbital ephemeris,

$$\text{BJD}(\text{orb}) = 2\,452\,682.464(3) + E \times 0.19661(27) \quad (2)$$

while the period and its uncertainty were taken from the peak value in the periodogram. Other orbital minima, possibly useful for defining a future long-baseline ephemeris, were measured at barycentric Julian dates 2 452 682.65, 2 452 695.633, 2 452 696.58, 2 452 717.619, 2 452 718.644 and 2 452 719.614. Given the irregular shape of the minima these timings are not accurate to better than 5 min.

In order to determine the waveform of the spin and orbital modulations, we normalised all available data to the nightly mean and subtracted the competing signal, e.g. the mean orbital variation in case of the spin pulse. The resulting data folded over spin and orbital period given by Eqs. (1) and (2) are shown in Fig. 4. The spin pulse is almost a sine-wave and has a semi-amplitude of 0.07 mag, comparable to other DQ Her stars with similar spin periods. In principle the actual spin period may also be twice the observed value, and the pulse should then be double peaked, with unequal maxima or minima as seen in the few double pulsed IPs (e.g. V405 Aur, Skillman 1996). To check this possibility the data were also folded using twice the spin period (39.57 min). Contrary to the known double pulsed IPs there are no evident asymmetries between the two pulses and we conclude that 19.7874 min is the true spin period of the white dwarf in RX06.

Another supporting argument that our spin period is correct comes from the probable detection of the beat frequency at $(\omega - \Omega)$. In contrast, a double-peaked pulse would imply that this signal corresponds to a frequency at $(\omega/2) - \Omega$, which has not been observed in IPs yet.

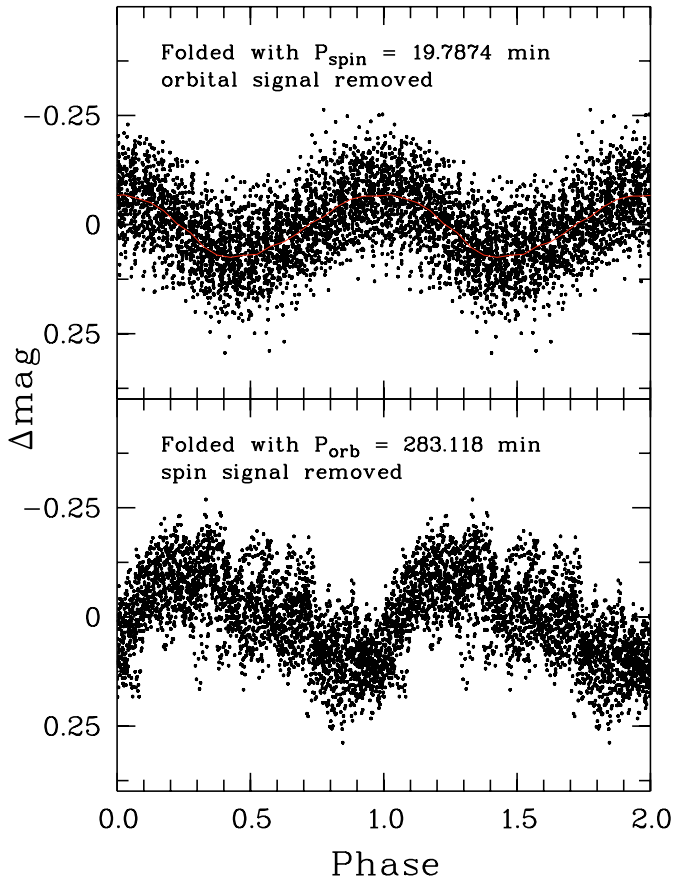


Fig. 4. 2865 photometric measurements folded with the spin (upper panel) and orbital ephemeris (lower panel) given by Eqs. (1) and (2). The data have been normalised and the competing signal (e.g. the orbital signal in case of the spin folded data) has been subtracted. Two cycles shown for clarity.

The orbital wave form is quite asymmetric with a sharp rise and smoother decline, similar to the behaviour of BG CMi (Patterson & Thomas 1993). Such orbital variations in intermediate polars are in general thought to be the result of X-ray heating of either the secondary star, or/and the bright spot at disk rim. In order to observe such an effect with a peak-to-bottom amplitude of 0.2 mag, the inclination of RX06 is probably not very low, i.e. $\gtrsim 30^\circ$.

4. ROSAT all-sky survey observations

RX06 was scanned during the RASS 29 times and got a total exposure of 462 s. The ROSAT Bright Source Catalogue (Voges et al. 1999) lists the source with a mean count rate of 0.18 s^{-1} , and hardness ratios $\text{HR1} = -0.32 \pm 0.11$ and $\text{HR2} = -0.02 \pm 0.20$. X-ray photons of the field of RX06 were extracted from the ROSAT data archive at MPE. A light curve of RX06, mean count rate per individual scan, was generated by subtracting the background signal measured in concentric circles from the source photons and dividing by the duration of individual scans. This light curve shows 100% variability of the X-ray source with maximum count rate of 0.6 s^{-1} . Folding of the light curve over both, the spin and the orbital periods, does

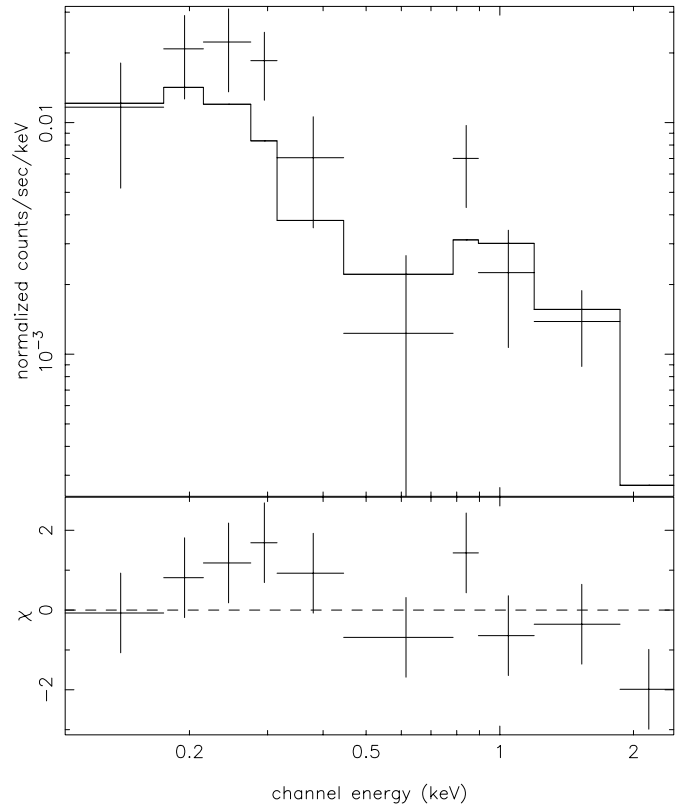


Fig. 5. Spectrum of the RASS X-ray data. They were fitted with a single bremsstrahlung component of temperature corresponding to $kT_{\text{tb}} = 15 \text{ keV}$. The residuals show excess emission in the soft band between 0.2 and 0.4 keV.

not yield an obvious periodic pattern of variability, clearly due to the short exposure.

The observed hardness ratio HR1 indicates a rather soft X-ray spectrum. An X-ray spectrum of RX06 was built from the 83 source photons detected in the RASS. It was fitted with a hard bremsstrahlung model ($kT_{\text{tb}} = 15 \text{ keV}$ fixed, plus interstellar cold absorption), with a pure black-body model (kT_{bb} free, plus interstellar absorption), and with a combined black-body/bremsstrahlung model (bb/tb). The absorbed black-body could not represent the spectrum at all and is clearly ruled out. The 15 keV bremsstrahlung spectrum with zero interstellar absorption gives a marginal good fit to the data. The reduced χ^2 of the fit is 1.6 for 8 degrees of freedom (d.o.f.) and the null hypothesis probability is 12%. The fit and the residuals are shown in Fig. 5 and indicate an excess of soft photons between 0.2 and 0.4 keV. Taking into account some absorption, the soft excess increases. This makes a combined bb/tb model very likely. Such a fit with $kT_{\text{tb}} = 15 \text{ keV}$ (fix) gives $N_{\text{H}} = (2.8 \pm 0.9) \times 10^{20} \text{ cm}^{-2}$, $kT_{\text{bb}} = 43 \pm 9 \text{ eV}$, at reduced $\chi^2 = 1.00$ for 6 d.o.f. We regard the presence of a soft component as very likely.

5. Discussion and conclusions

RX06 is likely to be a cataclysmic variable of DQ Her-type, an intermediate polar. It exhibits the defining criterion of these systems: two stable and coherent periodicities in the optical

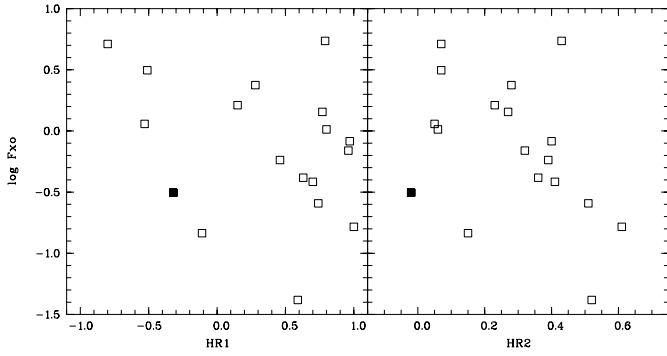


Fig. 6. Logarithm of the X-ray to optical flux ratio as a function of RASS hardness ratios of all confirmed IPs. The new IP RX06 is indicated by the filled square.

photometry of 19.7874 min and 283.118 min which we tentatively regard as the spin and orbital periods of the binary. The orbital and spin modulation of RX06 closely resemble those of other well-known intermediate polars like e.g. BG CMi (e.g. Patterson & Thomas 1993). The absence of any obvious eclipse-like feature limits the orbital inclination to less than 75 degrees.

With our measured spin period of $P_{\text{spin}} \simeq 0.1P_{\text{orb}}$ and an orbital period above the period gap, the system has parameters similar to most previously known classical DQ Her stars (see Patterson 1994; Hellier 1996, 1999, 2001). Other hallmarks of magnetic CVs observed in RX06 include an optical spectrum with a continuum steeply increasing towards the blue with H, HeI and HeII emission lines superposed, X-ray variability by 100%, and an X-ray spectrum likely consisting of a hard (bremsstrahlung-like) and a soft (bb-like) component. The optical emission likely originates from the hot accretion disk and the magnetically channelled accretion stream or curtain. The presence of the HeII line is a clear additional indication of a soft X-ray component in the system.

In Fig. 6 we put RX06 in context with other confirmed IPs. These were drawn from the compilation of K. Mukai (<http://lheawww.gsfc.nasa.gov/users/mukai/iphome/iphome.html>). In the figure we plot the ratio of X-ray to optical flux as a function of the RASS hardness ratios HR1 and HR2. Five out of 23 IPs were not discovered in the RASS. The X-ray and optical fluxes were computed using the relations $F_X = 10^{-11} \times CR_{\text{RASS}}$ and $F_{\text{opt}} = 10^{(-0.4V-5.44)}$. The diagram has limited analytic power, since optical and X-ray data were not obtained simultaneously. However, compared with the other IPs, RX06 has a rather low flux ratio F_X/F_{opt} , and a very soft X-ray spectrum. The three systems with smaller value of HR1 than that of RX06 (PQ Gem, V405 Aur = 0558+53, and UU Col = 0512–32), are well established soft IPs, i.e. systems with a hard plasma cooling component of typical temperature 10–30 keV, and a soft bb-like component similar to the spectra of the strongly magnetic AM Herculis binaries. RX06 has the smallest HR2 of all the IPs, which supports the classification as soft IP.

The presently available data are too sparse in order to discern between the possible accretion modes, stream-fed, disk-fed or a mixture of both. There is also the possibility that

Table 3. Timings of the pulse maxima from the data of Araujo-Betancor et al.

T_{max} (BJD 2 450 000+)	Cycle	OMC (s)
2617.66847	−4712	−70
2623.55025	−4284	−25
2624.51353	−4214	94
2637.49760	−3269	−30
2638.51519	−3195	33
2639.68290	−3110	7

the short-term variations do not trace the spin but a side-band period, as seen for example in V1223 Sgr (Warner 1986). Both issues should be clarified by a dedicated X-ray observation of RX06.

Note added in proof: After submission of this paper we became aware of an independent photometric and spectroscopic study of RX06 by Araujo-Betancor et al. (2003) that confirms the likely white dwarf spin and orbital periods. The authors kindly provided us with plots of their photometric data. We measured the times of the maxima of the spin variation in their data and used the additional data points listed in Table 3 for the determination of an improved spin ephemeris (Eq. (3)).

$$\text{BJD}(\text{max}) = 2\,452\,682.4181(5) + E \times 0.01374127(5). \quad (3)$$

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