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A new cataclysmic variable RX J0757.0+6306: candidate for the shortest period intermediate polar

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Abstract. A new cataclysmic variable is identified as the optical counterpart of the faint and hard X-ray source RX J0757.0+6306 discovered during the ROSAT all-sky survey. Strong double-peaked emission lines bear evidence of an accretion disc via an S–wave which varies with a period of 81 ± 5 min. We identify this period as the orbital period of the binary system. CCD photometry reveals an additional period of 8.52 ± 0.15 min. which was stable over four nights. We suggest that RX J0757.0+6306 is possibly an intermediate polar, but we cannot exclude the possibility that it is a member of the SU UMa group of dwarf novae.

Key words: stars: individual: RX J0757.0+6306 – stars: novae, cataclysmic variables – X-rays: stars

1. Introduction

Within a project for the optical identification of a complete sample of 674 northern ROSAT All-Sky Survey (RASS) X-ray sources (which is a collaboration between the Max-Planck-Institut für extraterrestrische Physik, Garching, the Landessternwarte Heidelberg, Germany, and the Instituto Nacional de Astrofísica, Optica y Electronica, Mexico) several new cataclysmic variables were identified. A detailed description of the project is given by Zickgraf et al. (1997). The full catalogue with all identifications is published in Appenzeller et al. (1998). Here we report the identification of the RASS X-ray source RX J0757.0+6306 (= 1RXS J075700.5+630602).

Cataclysmic variables (CVs) are close binary systems with a white dwarf primary accreting matter supplied by a late type main-sequence secondary star via an accretion disc or along magnetic field lines of the white dwarf. Magnetic CVs, where the white dwarf has a sufficiently strong magnetic field to affect the accretion trajectory, form two distinctive subclasses: the high-field polars, and the low-field intermediate polars (IPs). These subclasses are characterized by well-defined observational properties (Cropper 1990; Patterson 1994; Warner 1995). The polars are usually soft X-ray emitters and have near synchronously rotating WD, the IPs are harder X-ray sources and show a second periodicity due to the asynchronously rotating WD. In some cases a third period is observable, which is interpreted as the beat period between orbital and spin periods.

Besides differences in the flux distribution and variability, the orbital period distribution of the various subclasses of CVs were also noticed to be different (Kolb 1995). Polars tend to cluster below the period gap (2 h $< P_{orb} <$ 3 h), while IPs are preferentially above the gap. Non-magnetic CVs are distributed almost equally. All subclasses however show deficiency of systems in the period gap and a short-period cutoff at $\mathrm{P_{min}} = 80$ min (the minimum period). The statistically significant properties of the period distribution are presumed to have an evolutionary origin (Verbunt & Zwaan 1981, Verbunt 1984, King 1988, Kolb and Ritter 1992). The rapidly increasing number of magnetic CVs discovered from the ROSAT data has a significant impact on the above mentioned distribution and its consequences.

2. Observations

RX J0757.0+6306 was scanned in the RASS between Sep. 28–30, 1990 for a total exposure time of 420 sec. RX J0757.0+6306 is found as a source with a total of 55 photons, which corresponds to a vignetting corrected count rate of 0.13±0.02 cts/s. No strong variability in the X-ray intensity is seen at this level. The spectrum, as derived from these 55 photons is rather hard, extending up to 2.4 keV (the upper bound of the PSPC) as ev-

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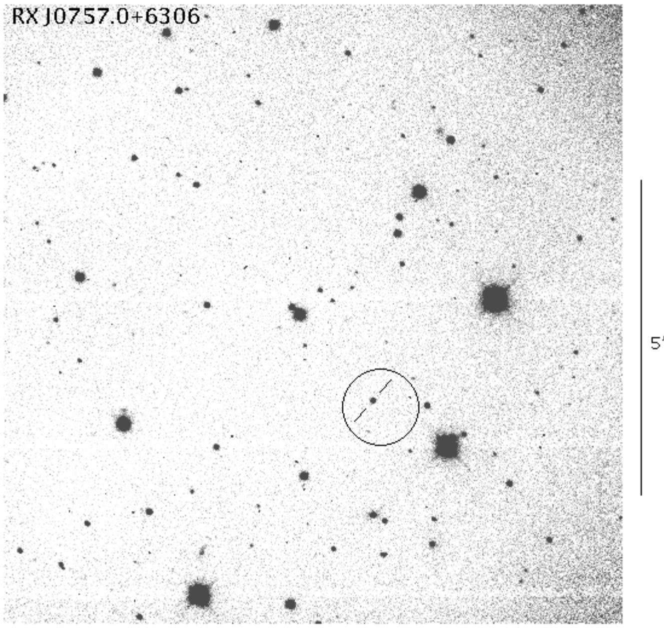

Fig. 1. Image of the field around the X-ray source RX J0757.0+6306 (centroid position with a 40″ (3σ) error circle). The cataclysmic variable is marked by two dashes.

idenced by the hardness ratios HR1 = 0.80±0.08 and HR2 = 0.42±0.13. The best fit X-ray position is (equinox 2000.0): RA = $07^{\rm h}57^{\rm m}00^{\rm s}.3$, Decl. = +63°05′56″ (bII=+31.°3).

RX J0757.0+6306 was observed by the Extreme Ultraviolet Explorer Satellite (EUVE) on 3 Oct 1997 UT. A 50 ksec observation was performed and data collected in both the EUV spectrographs ($70 - 800$Å wavelength coverage) and in the Deep Survey Instrument (a EUV imager with peak sensitivity near 90Å). The source was not detected in either detector.

The original optical identification observations were carried out at the 2.1 m telescope operated by INAOE at Cananea, Sonora, Mexico. The optical counterpart of the X-ray source was identified with an emission line star using a low-resolution multiobject spectrograph. Further detailed study of the object, and its identification as a new CV, was done at the 2.1 m telescope of the Observatorio Astronómico Nacional de San Pedro Mártir, Mexico. The Boller & Chivens Spectrograph with a 600 l/mm grating was used to obtain spectra in the $3600 - 5700$Å range with 4.5Å FWHM resolution. Exposure times of 300 sec were chosen in order to be able to derive the orbital period of the system. Later we observed the object alternating between $4200 - 6300$Å and $4600 - 6700$Å wavelength ranges with the same spectral and time resolution.

We obtained eight spectra at the Astrophysical Research Consortium (ARC) 3.5-m telescope at Apache Point Observatory. The double-beam spectrograph (DIS) was employed in high-resolution (3Å) mode set in two wavelength regions $4200-5100$Å and $7900-8900$Å. Due to weather problems we covered only about one orbital period with a time-resolution of 8 min.

Optical photometry was performed during four nights in April 1996 at the Sonneberg Observatory 600/1800 mm reflector, equipped with a 385×578 pixel EEV CCD. Exposure times were 40–60 sec with overall time resolution of about 80–120 sec using a Johnson B filter. In February 1997, one more night of photometric observations were performed with the same settings.

Additional optical photometry was performed at the Red Buttes Observatory of the University of Wyoming. The object was observed on the nights of 9 and 10 Feb 1997 UT using the RBO 24” telescope equipped with ST-6 CCD. All integration times were 150 seconds and a ”clear” filter was employed in order to obtain the highest possible time resolution. The ”clear” filter is simply using the ST-6 in an unfiltered mode, thus the bandpass approximates the QE curve of the CCD itself, similar to a broad R+I bandpass.

Infrared observations were made using the University of Wyoming 2.3 m IR telescope (WIRO) on the night of 09 Feb 1997. The observations were made using the Aerospace camera, a LN2 cooled Nicmos IR array imaging camera. The JHK observations were 30 sec integrations over an 90 min period. The filters were rotated so successive filter observations are about 2.5 min apart.

The combined log of all optical observations is presented in Table 1.

The spectra were reduced using standard IRAF routines. The optimal extraction method was used to retrieve the spectra. Wavelength calibration was done using He-Ar arc spectra at the beginning and end of each set of spectra except for ARC spectra which were calibrated using a single arc spectrum obtained prior to the object. Flux calibration was possible, although slit width limitations and non-alignment to the parallactic angle makes these results less reliable.

3. Results

3.1. Identification and position

The sequence of spectra of the emission line object taken with the 2.1 m telescope shows strong emission lines of the Balmer series, HeI and HeII on top of a blue continuum. It is the brightest and only object reachable for spectrophotometry in the 40″ error box of the ROSAT ASS. We measured the position of the optical counterpart of RX J0757.0+6306 as (equinox 2000.0) R.A. = $07^{\rm h}57^{\rm m}00^{\rm s}.5$, Dec. = 63°06′02″(±1″). Fig. 1 shows a finding chart with the cataclysmic variable marked.

3.2. Spectroscopy

A typical Balmer series accompanied by HeI and HeII lines in emission (see Fig. 2) identifies the magnetic CV nature of RX J0757.0+6306 fairly well . Details of the spectra are given in Tab 1. The spectra from each night are summed and flux calibrated. The two channels overlap around Hβ and have continuum fluxes which differ by no more than 0.2 mag.

The emission lines are double-peaked due to the contribution from a strong accretion disc. In addition, the spike correspond-

Table 1. Log of optical observations

Date	JD	Telescope + Equip.	Filter Wavelength	Duration min.	Exp. sec.	Site
1996 April 10	2450183	2.1m, B&Ch sp.	3600–5700	120	300	SPM
1997 February 09	2450489	3.5m, DIS sp.	4200–5200	70	480	APO
1997 February 09	2450489	3.5m, DIS sp.	7900–8900	70	480	APO
1997 March 02	2450509	2.1m, B&Ch sp.	4200–6300	180	300	SPM
1997 March 03	2450510	2.1m, B&Ch sp.	4600–6700	90	300	SPM
1996 April 16	2450190	0.6m, CCD	B	150	40	Sonneberg
1996 April 17	2450191	0.6m, CCD	B	150	40	Sonneberg
1996 April 18	2450192	0.6m, CCD	B	70	40	Sonneberg
1996 April 20	2450194	0.6m, CCD	B	155	60	Sonneberg
1997 February 01	2450481	0.6m, CCD	B	225	60	Sonneberg
1997 February 09	2450489	0.6m, CCD	R+I	120	150	RBO
1997 February 09	2450489	2.3m, NICMOS	J,H,K	90	30	WIRO
1997 February 10	2450490	0.6m, CCD	R+I	120	150	RBO

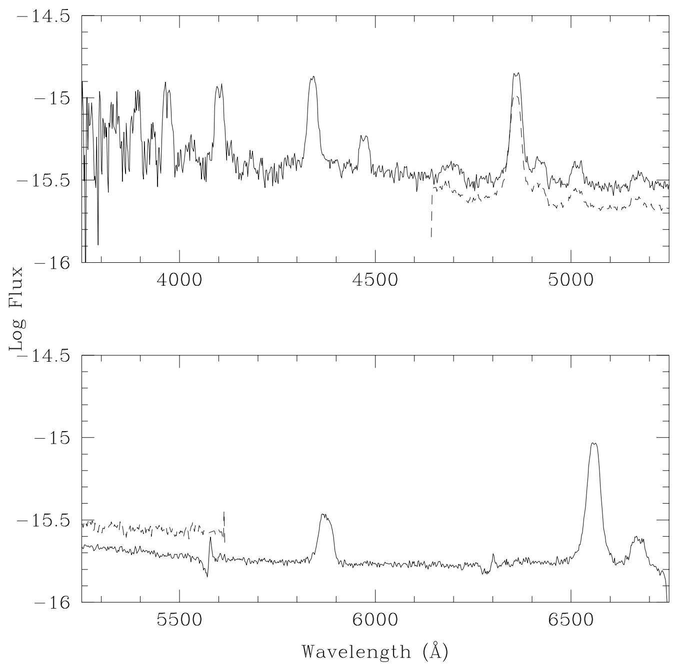

Fig. 2. The optical spectrum of RX J0757.0+6306. Two integrated spectra from different epochs are presented.

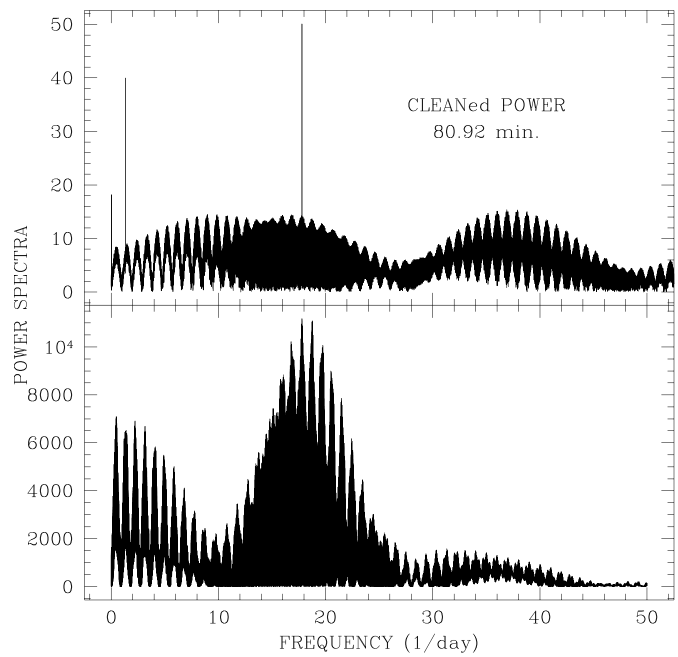

Fig. 3. The power spectrum of radial velocity measurements of RX J0757.0+6306.

ing to the S–wave component is clearly visible at most phases, moving back and forth inside the lines. We used the double-Gaussian deconvolution method suggested by Schneider and Young (1980), and Shafter (1985) in order to measure radial velocity variations. The method is especially designed to measure line wing variations by varying the separation and FWHM of double Gaussians, thus taking into account different parts of the wings. A wide range of Gaussian half–separations (250 – 2000 km/sec) was used. However, reasonable radial velocity curves were obtained only in the narrow range between 450 to 650 km/sec, which actually corresponds to the central parts of the line, where the S–wave dominates. This method assumes that the orbital period is known well enough to measure precise radial velocities in the application of diagnostics, as described in the above mentioned papers. Instead, since the period was not known, we used the radial velocity measurements for the period search.

It is known from the study of various systems that the S–wave is caused by the bright spot on the outher edge of the disc, where inflowing matter strikes the disc (Smak 1976; Young et al. 1981; Shafter & Szkody 1984). WZ Sge is the classical example of such a system (Hack & la Dous, 1993; Kaitchuk et al. 1994). The orbital motion is often seen as a radial velocity variation of the outer parts of the line wings. However, the amplitude of these variations is smaller than that of the bright spot. Usually the radial velocity curve of the primary is phase shifted rela-

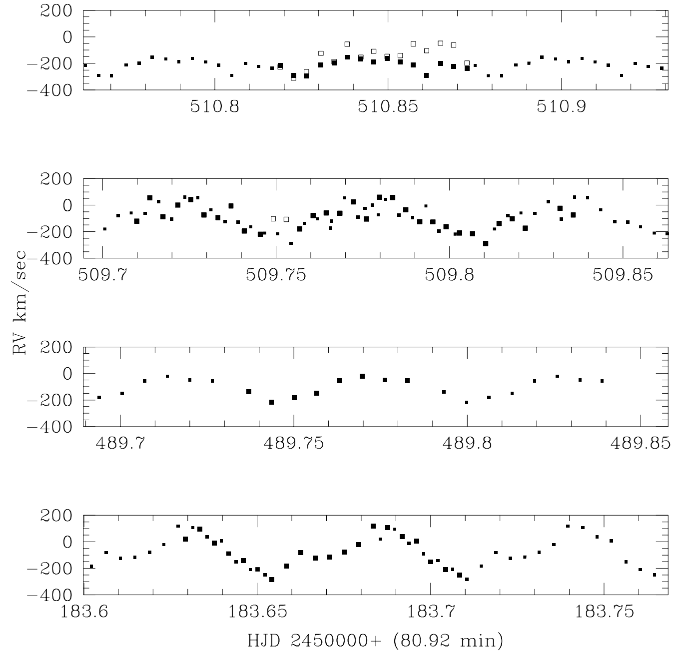

Fig. 4. The radial velocity measurements folded by the best period. Each night is shown on separate panel. In the first three panels from the bottom the radial velocities of Hβ are presented. In the third panel two points out of three rejected are shown by open symbols (see text), the third point drops out of the boundaries of the graph. In the fourth (top) panel measurements of Hα are presented by the filled symbols, while open symbols are of Hβ. In all panels the points are repeated one phase shifted back and forth.

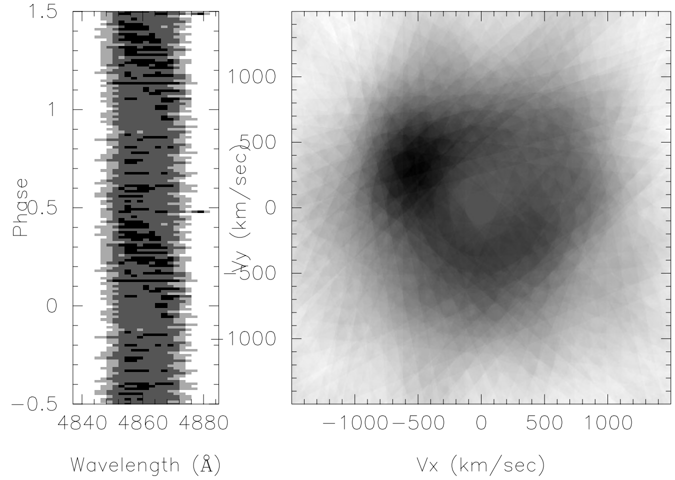

Fig. 5. The velocity map of RX J0757.0+6306. The phase is chosen arbitrarily, so is the location of the hot spot on the figure seen as a darker spot on a ring corresponding to the accretion disc.

tive to the S–wave by almost 180°. We barely can see the line variations corresponding to the WD primary. We fitted single Gaussians with centers corresponding to the S–wave component with different widths and subtracted them from actual line profiles, but still we were unable to see any substantial (measurable) period variations in the rest of the lines. However, the clear waveform RV curve emerged at all measured Balmer lines at a separation of double Gaussians between 450–650 km/sec. So we selected 550 km/sec half-separation Gaussians for analysis because that choice produced the smoothest waveform and it lies in the center of the range of waveform variations.

Our analysis involves mainly the measurements of Hβ. The Hγ and Hα lines were also measured and checked for consistency against Hβ. The period search revealed equally strong (1 day aliased) peaks at 86, 81 and 76 min periods. A search on a nightly basis tends to a higher frequencies than on the combined data. The 76 min peak was dominant in the April 96 observations covering almost 1.5 orbital periods (Tovmassian et al. 1997).

Three measurements were rejected (from a total of 77) after thorough inspection of each spectrum in the combined set of data, because the line profiles were affected by cosmic rays. The combined power spectrum was also affected by the data corresponding to the fourth night when the quality of spectra were the poorest and the spectral range was centered toward Hα. Since we had more signal at Hα, we replaced the RV measurements of Hβ on the fourth night by corresponding measurements of Hα. The resulting power spectrum shows competitive peaks at 81 and 76 min respectively, with 81 min being slightly stronger. Next we performed the CLEAN algorithm (Roberts, Lehár & Dreher 1987) on the Hβ measurements and on the combined Hβ + Hα data. Both resulted in a single strong peak around 81 min estimation. The CLEANed spectra are presented in the top panel of Fig. 3. In the bottom panel an unCLEANed power spectrum of data incorporating the Hβ and Hα is presented. The RV curves folded at 81 min period are shown (each night on the separate panel) in the Fig. 4. Larger symbols in Fig. 4 correspond to the actual measurements. Smaller symbols are actual measurements which have been shifted back and forth in phase by one for clarity. In the top panel, measurements of Hα are designated by filled symbols while those of Hβ are open.

The RV curve of Fig. 4 looks smoother than the curves folded at aliased periods. We favor the 81 min period over the two others. Nevertheless, we cannot completely exclude the other periods as alternative solutions. Therefore, we must include a 5 min uncertainty, although our estimation of the peak is precise to 0.014 min. By comparison to similar systems, we assume that this period is the orbital period of the binary. However, the ephemerides of the stellar components remain unknown. We can also assume that the system is at a very low inclination so that we see it face on. We applied the Doppler tomography method (backprojection method by Marsh and Horne 1988) to constrain the velocity map of the system. The Hβ line from the first two nights were used. The 81 minute period was assumed to be the orbital period and phase was picked arbitrarily. Thus, the location of the dense spot on the velocity map (see Fig. 5) corresponding to the hot spot is also arbitrary, but it is evidence for the presence of a large accretion disc (donut structure) with the prominent hot spot on its edge.

We measured fluxes and equivalent widths of the majority of the visible lines. We checked the measured values (they are

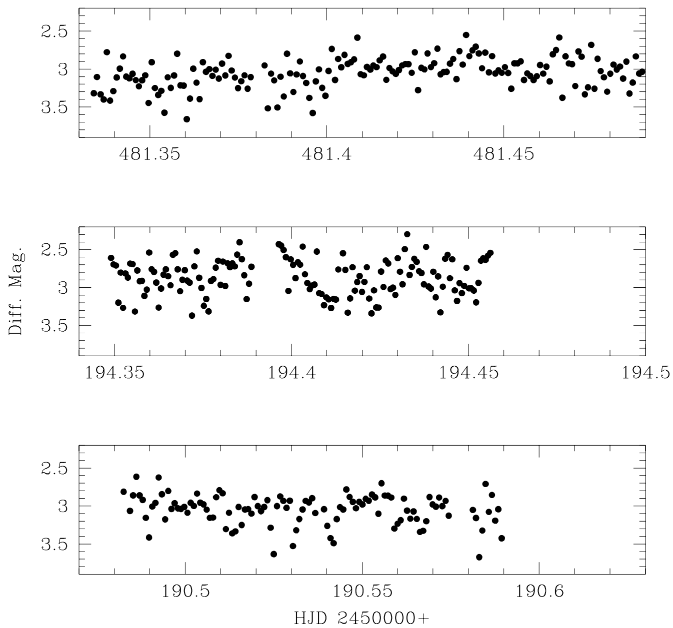

Fig. 6. Light curves of three separate nights. The x-axes have the same scale.

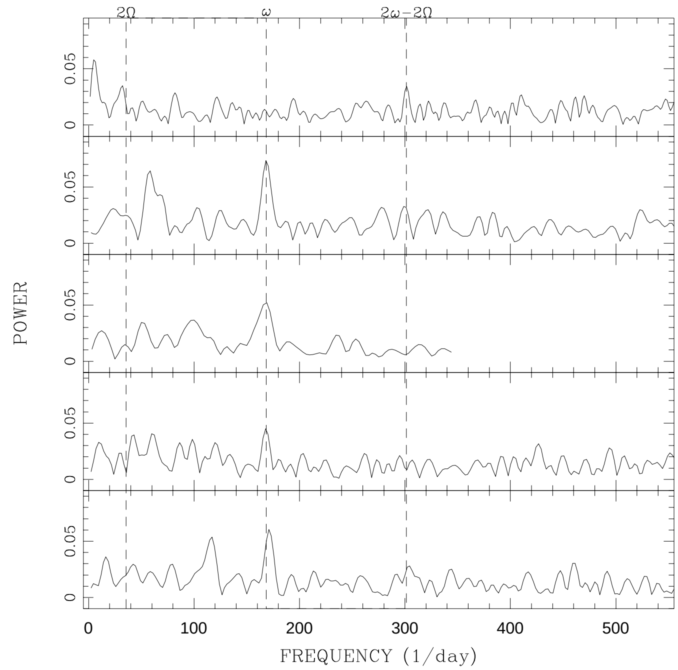

Fig. 7. The power spectra of each night of B photometry of RX J0757.0+6306. The frequencies corresponding to the orbital period, possible spin period and their harmonics are marked by vertical lines.

Table 2. Measurements of spectral lines

Emission Line	Equivalent Width Å	Flux($\times 10^{-14}$) (erg/cm^2/s)	Relative Flux	Range of Fluxes[1]
Hα	-150(5)	3.7	103	91-188
Hβ	-118(4)	3.6	100	100
Hγ	-90(4)	3.4	94	72–119
Hδ	-70(3)	2.7	75	53–114
Hϵ	-45(4)	1.9	52	–
He I 5876	-38(4)	0.65	25	12–31
He I 5015	-14(2)	0.37	10	11–14
He I 4922	-18(3)	0.55	15	6–17
He I 4471	-21(1)	0.72	20	17–31
He I 4026	-14(1)	0.50	15	9–20
He II 4686	-16.7(1.5)	0.50	14	15–34

presented in Table 2) with other CVs[1] since the system lies near the lower limit of orbital periods for hydrogen-composition cataclysmic variables. No abnormalities were detected. The He I strength is within the limits for normal dwarf novae. The He II 4686 Å line is present, but its strength does not indicate anything definite though in many CVs it often correlates with the magnetic field strength of the WD primary.

3.3. Optical photometry

The light curves of the three longer CCD photometry runs are presented in Fig. 6. The light curve demonstrates large amplitude flickering. However, no eclipses or modulations with the spectroscopic period were observed. This fits well with the spectroscopic results, namely that the system has a low inclination and a large accretion disk. Nevertheless, we conducted a period search on the photometric data. The period search on time series from separate nights revealed one repetitive peak around 169 cy/day at the first four nights. The amplitude varies from night to night, but the significance of the peak is almost the same on each night and does not exceed the noise level by more than 10–15%. We combined the data of those nights and obtained similar results. The separate night peaks coincide with an accuracy of $\pm$4 sec, while the precision of the determination is about 9 sec. The fifth night of data, which is separated by ≈ 400 day lag from the first four, does not show any signal at the above mentioned frequency. However there is a small peak which perfectly coincides with the $2(\omega - \Omega)$ frequency where Ω is the spectroscopic (orbital) period and ω is the frequency obtained on the previous nights. The power spectra of separate nights are presented in Fig. 7. The first night is in the lower panel, the fifth night is in the top. The mentioned periods are indicated by vertical lines. We replaced the actual data from the first four nights with random numbers spread exactly by the same range of magnitudes as the observed. We repeated the period search on the simulated random data and found no peaks at the 169 cy/day frequency or any other repetitive or significant signal. So we are confident that the peaks in the power spectra of the original data are not caused by the temporal distribution of the exposures. The 169 cy/day frequency corresponds to 8.52 min, which constitutes about 10% of the orbital period. Although no conclusive dependence was found between the spin and orbital periods of intermediate polars, most of them tend to have spin periods of approximately 1/10 of the orbital.

[1] according to Williams & Ferguson (1982)

Thus, RX J0757.0+6306 probably belongs to the family of intermediate polars. If confirmed, the ultra–short orbital period makes this system unique within this class.

3.4. Infrared data

The near infrared spectra which we obtained with the red chip of the DIS spectrograph at the ARC 3.5 m telescope does not show any interesting features, particularly any absorption lines from the secondary star. That is not surprising, because the latter is expected to be a low–luminous late M dwarf while radiation of the system is strongly dominated by the disc. Extrapolating the dependence of the spectral type on the orbital period, presented by Patterson (1984), we estimate that the secondary should be of spectral type M8 V for the orbital period of RX J0757.0+6306. We note that there are a few exceptions in which the period-secondary relation does not seem to work well for short period systems, and therefore types M4-6 could be possible too.

Through the use of IR standard stars, we found mean magnitudes for RX J0757.0+6306 of J=19.0±0.3 mag, H=18.5±0.3 mag, and K=18.1±0.3 mag. An M8 V star should have an absolute K magnitude of $M_K \sim 10$ mag according to Kirkpatrick et al. (1993). Thus, if we assume that the radius of the secondary is similar to that of a normal field dwarf and that all of the K flux is contributed solely by the secondary, we find a distance to RX J0757.0+6306 of $D \sim 400$ pc. These assumptions are extreme (including that of the spectral type), but since they push the limits in opposite directions we find the estimate to be quite reasonable.

The weather was photometric for all these observations except that of 10 February 1997. Differential time-series light curves were produced for each night/filter combination consisting of 2 hour runs in the optical and 1.4 hour runs in the IR. The photometric behavior of RX J0757.0+6306 in the IR showed constant brightness light curves (within the errors) and no indication of any short period (few minutes) oscillations. The near IR data showed more modulation with an almost constant flickering-type behavior. The February 10 data was interrupted for about half its length by clouds and is therefore not very useful for short-period analysis. The February 9 data showed a constant value with flickering for about two-thirds of the time and then a rapid increase (5 min) in brightness of 0.2 mags, but with no change in the flickering amplitude. Period searches of the single short February 9 photometric dataset yielded no conclusive periods.

3.5. Archival photographic data

We conducted a limited search in the all-sky patrol plates of Sonneberg Observatory. We looked through 194 photographic plates (blue sensitive) from the years 1958–1965 (these are in general the best plates available, because later air pollution degrades the sensitivity). We found one outburst of RX J0757.0+6306 from these plates. It was seen on only one plate taken on 9 December 1964. Another plate one hour later was not as deep and the nearest other plates were taken on 9 November 1964 and 9 February 1965 in which the object was not visible, definitely being fainter than it was on 9 December 1964.

4. Discussion

A new cataclysmic variable is discovered with interesting features:

1. The orbital period of 81 ± 5 min puts RX J0757.0+6306 near the hydrogen burning period minimum where CVs experience a turning point of their evolution. Large flickering in the optical light curve and the observed spectral features of the object certainly show the presence of an accretion disc.
2. The limited search in the Sonneberg all-sky patrol plates revealed that the system undergoes outburst activity. Another outburst was recorded (vsnet-alert No. 1379) shortly after the object's discovery was announced through the VSNET (vsnet-chat No 662). From the plate statistics we can assume that the system has rather frequent outbursts. The amplitude of the outbursts of about 4 mag are typical for dwarf novae systems, but not as large as in SU UMa superoutbursts or the so called TOADs (tremendous outburst amplitude dwarf novae; Howell et al. 1995).
3. There are periodic light variations with a period of 8.5 min in the light curve of the RX J0757.0+6306. We observed them directly on four out of five occasions. In the fifth night a periodic signal with a side-band frequency was detected in the power spectrum. Very recently, the 8.5 min period was confirmed by R. Fried (vsnet-alert No 1387) from more prolonged observations.

Thus, RX J0757.0+6306 shows mixed characteristics, making its type classification uncertain. From purely spectroscopic characteristics one may conclude that the new CV is a dwarf nova. Its short orbital period suggests that instead it may belong to the SU UMa class or TOADs. But the repetitive detection of high-frequency pulses with a clearly fixed period indicates that it deserves a classification as an intermediate polar. This still needs to be confirmed by checking the coherency of the photometric pulses and by the detection of X-ray pulses. Intermediate polars are CVs with the primary white dwarf rotating asynchronously due to its moderate magnetic field. Column accretion onto the magnetic poles results in the emission of high-energy radiation. This radiation is reprocessed elsewhere in the system into optical light which is modulated at periods shorter than the orbital period. The optical modulation can track the spin and/or the spin/orbit beat period of the binary (see the review by Patterson 1994).

The presence of X-ray emission in the quiescent state of RX J0757.0+6306 along with the moderate He II 4686 Å emission also argue in favor of a magnetic nature. The survey of non-magnetic CVs by van Teeseling et al. (1996) shows that the majority of X-ray emitting dwarf novae are of the SU UMa type, but they all are softer sources (HR1≤ 0.7) than RX J0757.0+6306. There are a few long-period objects classified as non-SU UMa variables that are as hard as RX J0757.0+6306. These belong to the VY Scl, Z Cam, and UX UMa subclasses. We do not have any evidence which support a classification of RX J0757.0+6306 as any of these types. Hence, since the rest of the CVs which are X-ray sources are magnetic, we conclude that RX J0757.0+6306 is most probably magnetic.

Only two IPs have been detected with EUVE and only a few dwarf novae, all of the latter during outburst. AM Herculis stars, particularly those with high magnetic fields are detected using EUVE. Thus, the non-detection of RX J0757.0+6306 with EUVE does not prove that it is not an IP. It may indicate that RX J0757.0+6306 could have a weak magnetic field (B < 8 MG), but given that only two IPs have EUVE detections and because of the rather large distance of RX J0757.0+6306 the non-detection is not considered unusual. On the other hand, the intensity of the He II emission is not high enough to unambiguously classify it as a magnetic system. Silber (1992) set the following criteria for magnetic CVs: $20 <$EW (Hβ) < 40Å and HeII/H$\beta > 0.4$. In our case, if the larger equivalent width could be attributed to a shorter orbital period, the HeII/Hβ ratio is definitely below this criterium (≈ 0.15).

The existence of outbursts and the short orbital period of the system is in some discordance with the IP classification. Most IPs cluster above the 2–3 hour period gap, while short period magnetic CVs are usually polars. However, a weak field IP will remain an IP even when it evolves towards shorter periods. In IPs, accretion outside of the Alfven radius remains in the form of a disc, while accretion inside the Alfven radius is dominated by flow along magnetic field lines. Outburst activity is uncommon since the inner part of the disc is disrupted by the magnetic field.

Nevertheless, neither outburst activity nor short orbital period exclude the possibility of RX J0757.0+6306 to be classified as an IP. In addition, the presence of a large disc in a short period magnetic CV suggests that the magnetic field is weak. Otherwise it would be a polar. For such a weak field case it may not be surprising that RX J0757.0+6306 appears to be an IP with some properties (i.e. outbursts) similar to non-magnetic CVs, yet the evidence that it is a magnetic CV is compelling. Therefore, we offer RX J0757.0+6306 as a candidate for the shortest period intermediate polar.

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