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LETTER

Letter to the Editor

RX J0439.8-6809: a double-degenerate supersoft X-ray source? ⋆

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Abstract. We present optical CCD photometry of the supersoft X-ray source RX J0439.8-6809. The absence of significant X-ray and optical variability (3σ peak-to-peak $\Delta V < 0.07$) and the optical faintness ($V \sim 21.6$) put severe constraints on a possible binary nature. Without rather unusual assumptions, a main-sequence donor star seems to be ruled out. All of the available information suggests that RX J0439 is either a double-degenerate supersoft X-ray source with a predicted orbital period of a few minutes or an extremely hot single pre-white dwarf. In either case, it is an extraordinarily rare and interesting object.

Key words: accretion – stars: individual: RX J0439.8-6809 – stars: post-AGB – white dwarfs – X-rays: stars

1. Introduction

The most popular model for close-binary supersoft X-ray sources is that these systems contain a white dwarf which accretes at a sufficiently high rate ($\gtrsim 10^{-7} M_\odot\,\mathrm{yr}^{-1}$) to have steady-state shell burning of the accreted hydrogen (Van den Heuvel et al. 1992) or which accretes at a lower rate and is in a phase of residual-hydrogen burning after a shell flash (cf. Iben 1982; Sion & Starrfield 1994). As a result, these sources appear as persistent or transient X-ray sources with almost all detectable radiation below ~ 0.5 keV and a bolometric luminosity near the Eddington luminosity of a solar-mass star. Excluding the classical novae and the long-period symbiotic binaries, only 10 sources are presently known which may be tentatively classified as close-binary supersoft X-ray sources; either because their orbital periods have been detected or because they show transient behaviour. For a recent collection of papers on supersoft X-ray sources, see Greiner (1996).

The persistent supersoft X-ray source RX J0439.8-6809 (hereafter RX J0439) is probably located in the outskirts of the LMC, and was discovered during the Rosat All-Sky Survey (Greiner et al. 1994). Based on the accurate Rosat HRI position, Van Teeseling et al. (1996) (hereafter Paper I) identified the optical counterpart of RX J0439 as a very blue object with $B \sim 21.5$. Among the optically identified supersoft X-ray sources, RX J0439 has the smallest ratio of optical to X-ray flux. In Paper I, we could not find any significant X-ray or optical variability, with 3σ upper limits to long-term X-ray variability of $\sim 20\%$ and to random B variability of ~ 0.2 mag. Without any evidence that RX J0439 is an accreting binary, we noted that the optical continuum could be explained as the Rayleigh-Jeans tail of the soft X-ray component. Thus, RX J0439 resembles an extremely hot $\sim 1 M_\odot$ pre-white dwarf, though it would have to be the hottest pre-white dwarf known. However, this interpretation has its problems: such objects have very short evolutionary time scales (e.g. Vassiliadis & Wood 1994) and would normally be hidden in a young planetary nebula.

Schmidtke & Cowley (1996) presented photometry of RX J0439 and claimed that the source is variable on a time scale less than a day with a peak-to-peak amplitude of $\Delta V \sim 0.15$. They found a 90% significant period of 0.1403 days. We were rather sceptical about their results for two reasons: first, with a similar variability in B, the probability to obtain the B light curve presented in Paper I is only $\sim 3\%$; second, the tabulated V magnitudes of Schmidtke & Cowley are consistent with a Gaussian distribution with a standard deviation of 0.07 mag, which is only slightly larger than the quoted error of a typical measurement of ~ 0.06 mag.

In this *Letter*, we present follow-up CCD photometry to settle these contradicting results about variability. In Sect. 2, we present the observations and the results. In Sect. 3, we summarize all available observations and discuss their implications for the nature of RX J0439.

2. Observations and results

We obtained 34 10 min V exposures with EFOSC-2 at the ESO/MPI 2.2m telescope at La Silla. The recently installed UV-flooded 2048 × 2048 Loral/Lesser CCD #40 has a factor

⋆ Based in part on observations collected at the European Southern Observatory, La Silla, Chile: ESO N^o 58.D-0275

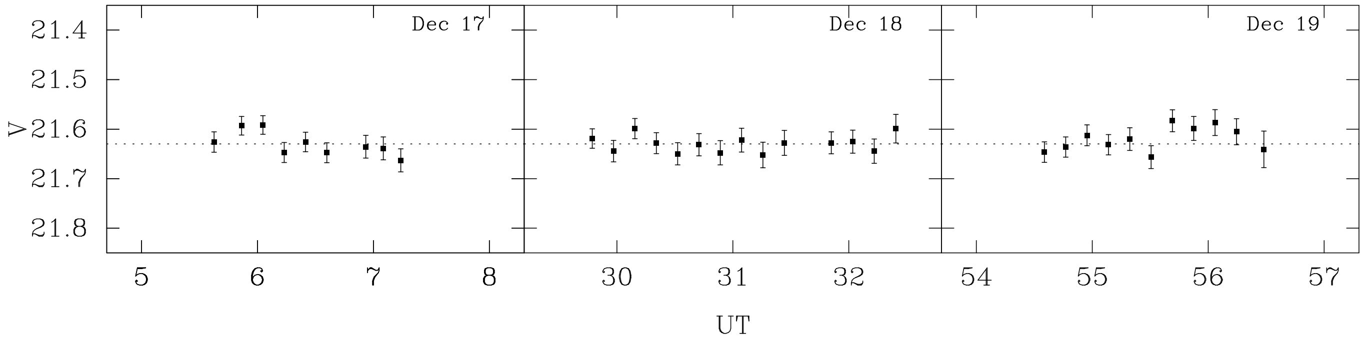

Fig. 1. V light curve of RX J0439.8-6809 observed with the 2.2m telescope at La Silla in December 1996. Time is measured in hours from 0 UT on JD 2 450 434. The ~ 0.15 mag variability claimed by Schmidtke & Cowley (1996) has a period approximately corresponding to the sizes of the boxes

of 2 increased sensitivity in V compared to the CCD we used previously. The observations were obtained during three subsequent nights from December 16 to 19, 1996. During all observations, the sky was photometric and the seeing was always $\sim 1''$ (1 pixel $\widehat{=}$ $0.262''$).

We obtained relative fluxes of RX J0439 and several comparison stars by integrating the measured intensities within apertures centered on the star and with 4-pixel radii ($\sim 1''$). The typical error in the resulting differential V magnitudes of RX J0439 is ~ 0.02 mag. We find that RX J0439 is not significantly variable in V with a 3σ upper limit to random variability of ~ 0.07 mag (peak-to-peak). Each night, we also measured the total intensities (within larger apertures) of RX J0439 and the standard stars in several Landolt fields (Landolt 1992) from which we determined one average offset for the total light curve. For RX J0439, we find $V = 21.63 \pm 0.03$. Figure 1 shows the resulting V light curve. If RX J0439 is located in the LMC this corresponds to an absolute visual magnitude of $M_{\rm v} \sim 2.8$.

3. Discussion

The results in the previous section exclude variability with a peak-to-peak amplitude of $\Delta V \sim 0.15$ and strengthen our suspicion that the variability found by Schmidtke & Cowley (1996) is not real. We cannot exclude that the source changes its behaviour, but we consider this unlikely in view of the arguments given in the Introduction.

To test the significance of the periods quoted by Schmidtke & Cowley, we took their published photometry and calculated a periodogram with the ‘Analysis of Variance’ method (Schwarzenberg-Czerny 1989). This is a phase-dispersion-minimization method with well-defined statistical properties and so does not require Monte-Carlo simulations in order to judge the significance of potential periods. Although our periodogram resembles that of Schmidtke & Cowley, the highest peak is only significant at the 80% (rather than the quoted 90%) level.

We note that - if RX J0439 is not variable - its optical identification is only based on the Rosat HRI position and the very blue optical colour. In this section, we summarize all available

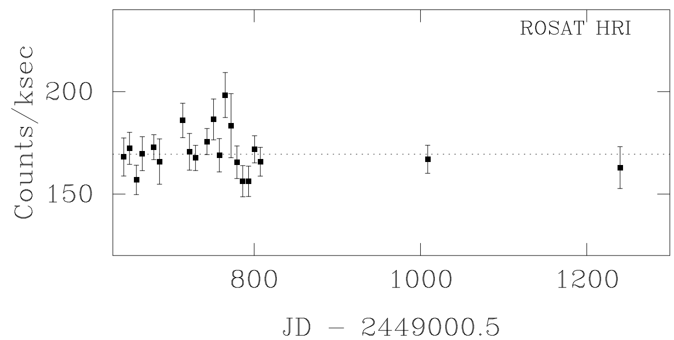

Fig. 2. X-ray light curve of RX J0439.8-6809 obtained with the Rosat HRI

information and investigate its implications for a possible binary nature of RX J0439.

3.1. X-ray variability

On October 18, 1995, and June 5–6, 1996, we obtained two additional monitoring observations of RX J0439 with the High Resolution Imager on Rosat with 3701 s and 1613 s accepted exposures, respectively. As shown in Fig. 2, the count rates during these observations were consistent with the count rate during previous HRI observations. There is also no significant variability in the HRI data on shorter time scales. Since its discovery in November 1990 during the Rosat All-Sky Survey, RX J0439 has been extremely constant in X-rays.

Greiner et al. (1994) mention that the source shows X-ray variability of about 50% on time scales down to a few seconds. We re-analysed the pointed PSPC observation and confirm that on time scales of less than 10 seconds the number-of-counts distribution deviates significantly from a Poisson distribution, but only because there are statistically too many bins with zero or one counts. With an on-axis PSPC observation, it is difficult to determine whether this is due to intrinsic source variability or due to instrumental effects like e.g. obscuration of the source by the PSPC window support structure. That the short-term X-ray variability of RX J0439 may not be real, is supported by the fact that other sources with comparable count rate and PSPC spectrum (e.g. the PG 1159 star RX J0122.9-7521) show a similar deviation in their number-of-counts distribution. We conclude that there is no unambiguous evidence for significant X-ray variability, although X-ray variability on very short time scales as short as a few seconds may exist.

3.2. Comparison with other close-binary SXS

Van Paradijs & McClintock (1994) showed that for low-mass X-ray binaries there is a correlation between the absolute visual magnitude $M_{\rm v}$ and $\Sigma = L_{\rm x}^{1/2} P^{2/3}$, where $L_{\rm x}$ is the X-ray luminosity in units of the Eddington luminosity and P the orbital period in hours. Because this correlation can be explained with reprocessing of X-rays by the accretion disk, a similar (but quantitatively different) correlation may hold for close-binary supersoft X-ray sources. Unfortunately, reliable estimates of the absolute visual magnitudes and the orbital periods exist for only five close-binary supersoft X-ray sources. Because the true luminosities of the accreting stars are uncertain, we use for $L_{\rm x}$ the bolometric luminosities (in units of 10^{38}erg s^{-1}) determined with LTE white-dwarf model atmospheres and the absorption fixed to the total galactic absorption in the direction of the source. In spite of the uncertainty in $L_{\rm x}$, the five sources are well correlated with $M_{\rm v} = 0.83(\pm 0.25) - 3.46(\pm 0.56) \log \Sigma$. In Fig. 3, we extrapolate this relation to $M_{\rm v} = 2.8$ for RX J0439. If the accreting star in RX J0439 contributes significantly to the visual flux, then this extrapolation overestimates the inferred orbital period. Therefore, assuming that the above relation holds for close-binary supersoft X-ray sources, including RX J0439, we find that the orbital period of RX J0439 (with $L_{\rm x} > 3\,10^{37}$ erg s^{-1}) must be less than $\sim$ 35 minutes.

3.3. $M_{\rm v}$ and an irradiated accretion disk

A similar argument as made above can be made on a more theoretical basis. If RX J0439 contains an accretion disk, the visual flux from this disk would be dominated by reprocessing of soft X-ray and extreme-ultraviolet radiation. Assuming that the accreting white dwarf is a slightly expanded, $1 M_\odot$ 350 000 K white dwarf with a radius of 2.5×10^9 cm, we have calculated the visual magnitude of a flat irradiated disk using the model described by Reinsch et al. (1996). This simple model appears to explain the optical flux of the supersoft X-ray source RX J0513.9-6951 reasonably well. We further assume that the donor star is a Roche-lobe filling main-sequence star with $(R/R_\odot) = (M/M_\odot)^{0.88}$ (Patterson 1984) and that the accretion disk fills 70% of the white-dwarf Roche lobe. Because approximating the reprocessed radiation as blackbody radiation overestimates the visual flux, we have adopted an effective reprocessing factor of 70%. Finally, we have calculated a lower limit for the orbital inclination by demanding that the observed visual magnitude of the disk at 50 kpc must be larger than 21.6. Figure 4 shows this lower limit as a function of donor star mass. For a main-sequence donor star, the inclination of RX J0439 must be $\gtrsim 75°$ if an irradiated accretion disk is present. However, for an inclination $\gtrsim 75°$ the donor star would eclipse the accreting star and X-ray eclipses and/or optical dips would be expected. Because there is no evidence for an optical or X-ray eclipse, a very high inclination is unlikely. A lower inclination implies that the accretion disk must be significantly fainter than calculated here.

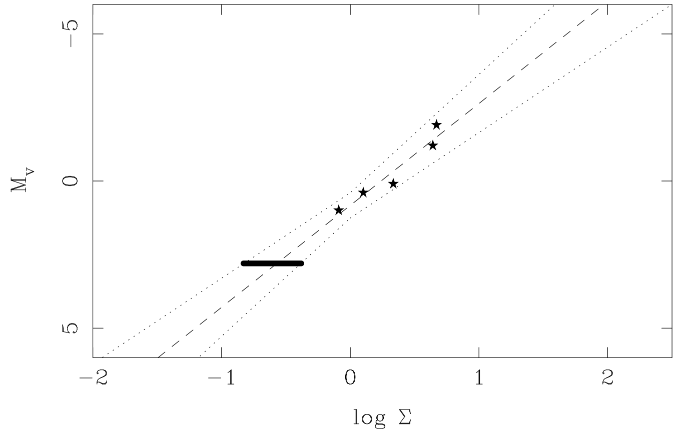

Fig. 3. Relation between the absolute visual magnitude $M_{\rm v}$ and $\Sigma = L_{\rm x}^{1/2} P^{2/3}$ for supersoft X-ray binaries. The dashed line represents an unweighted least-squares fit (because the errors in $L_{\rm x}$ are difficult to estimate, we have given all points equal weights and assume a good fit). The dotted lines bound the 1σ range. Part of the scatter must be due to differences in orbital inclination (cf. Van Paradijs & McClintock 1994). The thick line shows the cross section of $M_{\rm v} = 2.8$ with the 1σ area

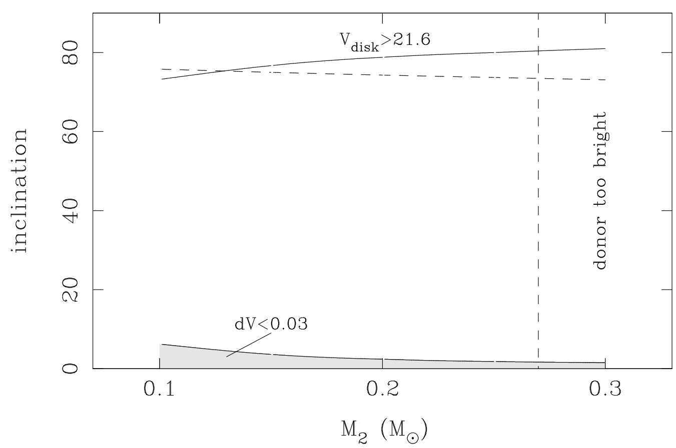

Fig. 4. The upper line shows the lower limit for the orbital inclination of RX J0439 if it contains a main-sequence donor star with mass M_2 and an irradiated accretion disk. The almost horizontal dashed line indicates above which inclination the donor star would eclipse the accreting star. The lower line shows the upper limit for the inclination of RX J0439 if it contains an irradiated main-sequence donor star that is not shielded by a thick accretion disk. For $M_2 \gtrsim 0.27 M_\odot$, the irradiated donor star would be brighter than RX J0439. See Sect. 3.3&3.4 for details

3.4. Optical variability and an irradiated donor star

The observed standard deviation in the V light curve limits the amplitude of a sinusoidal light curve to $\sim$ 0.03 mag. If for some reason, RX J0439 does not contain a bright irradiated accretion disk which almost completely shields the donor star from the accreting primary, the changing aspect of the irradiated donor star would show up as a sinusoidal modulation in the optical light curve. With the same assumptions as above, we have calculated the visual light curve with the Wilson-Devinney code (Wilson & Devinney 1971) for eclipsing binaries. The accreting, slightly expanded white dwarf would contribute significantly to the visual flux. The remaining visual flux would come from the irradiated secondary and an accretion disk which must be much fainter than calculated in Sect. 3.3. We have calculated an upper limit for the inclination by demanding that the observed amplitude must be $\Delta V < 0.03$, which is shown in Fig. 4 as a function of donor star mass. An irradiated main-sequence donor with a mass in excess of $\sim 0.27 M_{\odot}$ would be brighter than RX J0439 at a distance of 50 kpc. The absence of an orbital modulation with $\Delta V > 0.03$ would imply an inclination $\lesssim 10°$. We conclude that if RX J0439 is a semi-detached binary with a main-sequence donor star, it must either have a very high inclination with an almost completely shielded donor star or a (temporarily) absent bright accretion disk and a very low inclination. In the first case, with the exception of a very small region in parameter space with $M_2 \sim 0.1 M_{\odot}$ and $i \sim 75°$, it is remarkable that no X-ray dip or eclipse has been detected so far. In the last case, it would be an ironic freak of nature that the optically faintest supersoft X-ray source would also be the one with the lowest inclination. Different assumptions about e.g. the white dwarf or the mass-radius relation for the donor star would change the numbers slightly, but would not affect the basic results (the most important parameters, the radius and luminosity of the accreting white dwarf, are constrained by the X-ray spectrum).

3.5. Double-degenerate supersoft X-ray sources

All available observational information summarized above would be explained if RX J0439 is an accreting double-degenerate binary. Yungelson et al. (1996) discuss possible evolutionary channels for the formation of binary supersoft X-ray sources. They note that very tight binaries may be formed consisting of a carbon-oxygen white dwarf which accretes helium from a low-mass helium white dwarf. Under certain conditions, and with an orbital period of a few minutes, the mass accretion rate may be sufficiently high to maintain stable He shell burning on the accreting white dwarf, and the binary would appear as a supersoft X-ray source (see also Tutukov & Yungelson 1996). Typical masses of the stars would be $\sim 0.6 M_{\odot}$ for the CO white dwarf and $\sim 0.13 - 0.2 M_{\odot}$ for the He white dwarf.

Because the irradiated He white dwarf would be practically invisible, there would be no optical variability with an amplitude $\Delta V \gtrsim 0.02$ for an orbital inclination $\lesssim 60°$. When the inclination is $\gtrsim 60°$, mutual eclipses would appear as X-ray and optical dips of a few seconds. Optical dips of a few seconds are presently unobservable, and evidence for X-ray variability on time scales of a few seconds is, unfortunately, ambiguous (see Sect. 3.1). However, if this X-ray variability is real, it would support the double-degenerate nature of RX J0439. The very small or even absent accretion disk would explain the optical faintness of RX J0439. A He donor would be consistent with the absence of hydrogen features in the optical spectrum (Paper I), which have been observed in all other optically identified close-binary supersoft X-ray sources. The absence of He II λ4686 could be explained if this line originates mainly on the accretion disk or in an accretion-disk wind.

4. Conclusions

Rosat observations and CCD photometry in the V band of RX J0439 show no unambiguous evidence for significant X-ray or optical variability (peak-to-peak $\Delta V < 0.07$). It is difficult to explain the optical faintness of RX J0439 *and* the absence of orbital modulation with $\Delta V \gtrsim 0.03$ with an accreting binary with a main-sequence donor star.

In Paper I, we noticed that RX J0439 could be a very hot single pre-white dwarf. There is no new evidence against this rather extreme possibility, whereas an accreting binary with a main-sequence donor star seems to be inconsistent with the observations. It is still possible that RX J0439 is an accreting binary, although also in this case RX J0439 would be a rather extreme object: it may be the first known double-degenerate supersoft X-ray source. With an orbital period of only a few minutes, it would have the shortest orbital period among all known accreting binaries. However, such a short period might be difficult to detect in the near future.

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