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LETTER

Letter to the Editor

A limit-cycle model for the binary supersoft X-ray source RX J0513.9-6951

K. Reinsch[1], **A. van Teeseling**[1], **A.R. King**[2], **and K. Beuermann**[1]

[1] Universitäts-Sternwarte, Geismarlandstrasse 11, 37083 Göttingen, Germany (reinsch@uni-sw.gwdg.de)
[2] University of Leicester, Astronomy Group, Leicester LE1 7RH, U.K.

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Abstract. We present new results of our X-ray monitoring of the transient binary supersoft X-ray source RX J0513.9–6951 in the LMC and of our re-analysis of optical light curves obtained during the MACHO project. We have covered a complete X-ray outburst cycle with the ROSAT HRI detector. From the amplitude and timescale of the soft X-ray variability, tight limits are derived for the temporal behaviour of the white-dwarf radius and the effective temperature of its envelope. A limit-cycle model is proposed to explain the observed optical and X-ray variability, the characteristic timescales of the durations of the X-ray on and off states, and those of the transitions between both states. Our observations confirm that the radius changes of the white-dwarf envelope occur on the Kelvin-Helmholtz timescale. The duration of the X-ray on and off states is compatible with the viscous timescales of the inner and outer accretion disk, respectively.

Key words: accretion, accretion disks – stars: binaries: close – stars: binaries: spectroscopic – stars: individual: RX J0513.9–6951 – stars: novae, cataclysmic variables – X-rays: stars

1. Introduction

Luminous supersoft X-ray sources (SSS) have been established as a new and distinct class of objects which are observationally distinguished by their very soft X-ray spectra with temperatures on the order of 30 eV and luminosities of $10^{36} - 10^{38}$ erg s^{-1} (for recent reviews see Kahabka & van den Heuvel 1997; van Teeseling 1998). Several SSS have been identified as accreting close binaries with orbital periods of $\sim$ 1 day or less. The most popular interpretation of these systems involves a white dwarf which accretes matter via Roche-lobe overflow and an accretion disk at a rate of $\sim 1 - 4 \times 10^{-7} M_{\odot}$/yr, sufficient to permit stable quasi-steady nuclear shell-burning in the surface layers of the white dwarf, either because of thermal timescale mass transfer from a more massive (slightly evolved) main sequence companion (van den Heuvel et al. 1992) or because of wind-driven mass transfer from a low-mass irradiated companion (van Teeseling & King 1998).

2. The transient binary SSS RX J0513.9–6951

The luminous transient soft X-ray source RX J0513.9–6951 (henceforth RX J0513) discovered in the ROSAT all-sky survey (Schaeidt et al. 1993) has been optically identified as a high mass-transfer accreting binary system in the LMC (Cowley et al. 1993; Pakull et al. 1993) with an orbital period of 0.76 days (Crampton et al. 1996). Optical monitoring has revealed that RX J0513 undergoes recurrent low states at quasi-regular intervals, in which the optical brightness drops by $\sim$ 1 magnitude (Reinsch et al. 1996; Southwell et al. 1996). The optical low-states are accompanied by a turn-on of the system in the soft X-ray range (Reinsch et al. 1996; Schaeidt 1996).

The optical low states last for $\sim$ 40 days and repeat about every 140–180 days. Such short time scales cannot be explained by the limit-cycle behaviour sketched by van den Heuvel et al. (1992) or by recurrent burning models (Fujimoto 1982). Within the framework of a shell-burning white dwarf an alternative explanation has been suggested by Pakull et al. (1993): The rather sudden changes in the soft X-ray flux are the result of the direct response of the white dwarf to slight changes in the mass transfer rate. On the horizontal shell-burning branch, a small increase of the accretion rate may significantly affect the effective radius of the white dwarf envelope (Kato 1985). An increase of the photospheric radius by e.g. a factor of 4 implies that the effective temperature drops by a factor of 2. Given the extreme sensitivity of the ROSAT PSPC and HRI count rates on temperature, this in turn implies that the source may become undetectable although the bolometric luminosity remains roughly the same (e.g. Heise et al. 1994). In this model of an expanding and contracting envelope the sudden drop of the optical flux, the colour variation, and the temporarily increased soft X-ray flux can be quantitatively described by variations in the effective temperature of the hot central star and variations in the irradiation of the accretion disk (Reinsch et al. 1996).

This model is supported by an independent estimate of the neutral hydrogen column density obtained with recent HST UV spectroscopy which constrains the X-ray luminosity during the on-state of RX J0513 to $(2.5 - 9) \times 10^{37}$ erg s^{-1}, i.e. somewhat below the Eddington limit, and confirms that the radius of the

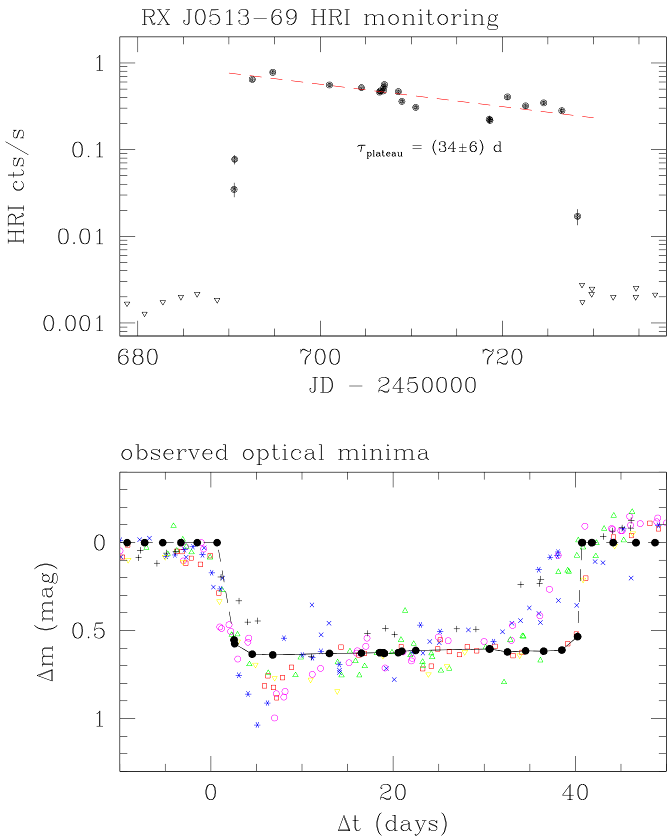

Fig. 1. X-ray and optical variability of the transient binary RX J0513. Upper panel: ROSAT HRI detected (filled circles) and upper limit count rates (triangles) of RX J0513 during a complete outburst cycle. Lower panel: light curves of different optical minima determined from CCD images taken for the MACHO project. Filled circles predicted optical light curves calculated from our X-ray data (see text).

soft X-ray source is consistent with the radius of a non-expanded white dwarf (Gänsicke et al. 1998).

3. X-ray and optical monitoring

In order to obtain tight limits for the temporal development of the radius and the effective temperature of the photosphere, we have monitored RX J0513 with the ROSAT HRI detector at intervals of about two days covering one complete X-ray outburst cycle (Fig. 1, upper part). The source remained undetectable during the X-ray off state and showed a sudden increase of the soft X-ray flux by a factor of > 100 at the end of August 1997, reaching maximum flux after ~ 5 days. The X-ray outburst lasted ~ 40 days and ended with a steep flux decline by again a factor of > 100 to non-detectability within 2 days. The slow flux variation during the X-ray outburst can be approximated by an exponential decline with a time constant of (34 ± 6) days.

Detailed light curves of several optical low states are available from regular monitoring of RX J0513 as a serendipitous source on CCD images taken for the MACHO project (Southwell et al. 1996). In Fig. 1 (lower part) the light curves of different observed optical minima are shifted in time such that the onset of the optical decline occurs at $\Delta t = 0$. MACHO data obtained quasi-simultaneously with our HRI monitoring indicate that the steep onset of the X-ray outburst occurred within 1–2 days after the beginning of the optical decline (W. Sutherland, private communication).

The shape of the optical low states repeats fairly well with an uncertainty of some 5 days in the duration of the low state. Within this uncertainty, its length coincides with the duration of the X-ray outburst. Both, the X-ray and the optical light curves show a similar small flux gradient before the final fast transition to the X-ray off/optical high state occurs.

4. Light curve modelling

To test whether the model of a contracting and expanding white dwarf can quantitatively explain both the X-ray light curve and the dips in the optical light curve we have calculated a predicted optical light curve from our X-ray data. First we used LTE white dwarf model atmosphere spectra (van Teeseling et al. 1994) to determine the photospheric radius as a function of the HRI count rate, where we assumed a distance of 50 kpc, a bolometric luminosity of 10^{38} erg s^{-1}, and an absorption column of $n_{\rm H} = 6 \times 10^{20}$ cm^{-2} (Gänsicke et al. 1998). Then we used the binary light curve code BINARY++ (van Teeseling et al. 1998) to calculate the orbital average optical magnitude as a function of the photospheric radius R_1 of the white dwarf. Since this code self-consistently calculates the amount of irradiation from an extended white dwarf on the accretion disk and companion, including all possible shielding effects, this calculation is more accurate than the semi-analytic approach we used in Reinsch et al. (1996) and allows us to investigate how the results depend on the various parameters. We assume a mass ratio of $M_2/M_1 = 2$, an orbital separation $a = 3.8 \times 10^{11}$ cm as appropriate for a quasi-main-sequence donor star and an orbital period $P = 0.76$ days, an orbital inclination of 10°, a disk filling 80% of the average Roche-lobe radius, a uniform irradiation reprocessing efficiency of $\eta = 0.5$, a secondary temperature of 9000 K, and an accretion rate of $3.4 \times 10^{-7}\, M_\odot$.

Fig. 2 shows the resulting total absolute V magnitude as a function of R_1, and individual magnitudes of the disk, the companion star and the white dwarf. For $R_1/a > 0.13$ or $R_1 \gtrsim 5 \times 10^{10}$ cm, the expanded white dwarf is the dominant optical light source. With increasing R_1 the disk first becomes brighter because of more effective irradiation, but becomes fainter again for $R_1 \gtrsim 2 \times 10^{10}$ cm because an increasing part of the inner disk disappears inside the white dwarf envelope.

In Fig. 1, we have plotted the predicted optical light curve over the combined MACHO light curve. For data points with only an upper limit for the X-ray count rate, we assume a radius $R_1 \sim 4.5 \times 10^{10}$ cm, which correctly reproduces the amplitude of the dip in the MACHO light curve. The 3σ X-ray upper limit of 0.00014 cts/s for the X-ray off state requires a radius of $R_1 \gtrsim 1 \times 10^{10}$ cm (using $L = 10^{38}$ erg s^{-1}, $T \lesssim 185000$ K, $n_{\rm h} = 6 \times 10^{20}$ cm^{-2}) during the optical bright state. Our calculations show that it is relatively easy to reproduce the observed optical dips from the X-ray data, with the correct amplitude

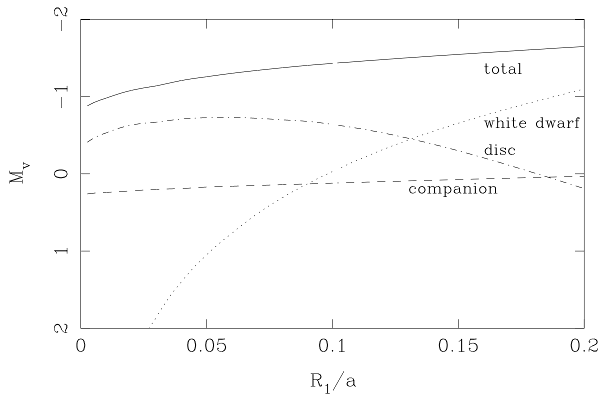

Fig. 2. Absolute V magnitude as a function of the white dwarf photospheric radius R_1 for the disk, the companion star, the white dwarf, and their sum.

and surprisingly accurate absolute magnitudes. It also illustrates that when the X-rays become detectable, the white dwarf photosphere has almost reached its minimum size and the optical light curve has almost reached the level of the faint phase plateau. The difference between the observed and predicted optical light curve immediately after the optical decline could be explained by the initial lack of an optically thick inner disk after the white dwarf envelope has contracted to its minimal proportions.

5. A limit-cycle model for RX J0513

The X-ray and optical light curves of RX J0513 suggest that the system follows a kind of a limit cycle behaviour with four typical time-scales: the ~ 140 days of the optical high/ X-ray off state, the rapid transition ($\lesssim 4$ days) to the X-ray on/ optical low state, the ~ 30 days duration of this state, and, again, the rapid transition ($\lesssim 2$ days) to the optical high/ X-ray off state.

We propose here that this behaviour results from expansion of the white dwarf photosphere in response to enhanced accretion onto the white dwarf, together with the reaction of the disk to increased irradiation by this expanded photosphere while the mass transfer from the companion star remains constant. At the (arbitrary) start of the cycle (Fig. 3(d)), let us assume we have an accretion disk supplying matter to a white dwarf with its non-expanded radius $R_1 \sim 10^9$ cm. Because the mass supply rate is close to the Eddington critical accretion rate $\dot{M}_{\rm crit}$ (Fujimoto 1982; Kato 1985), the white dwarf radius begins to expand (Fig. 3 (d)–(e)), as explained in Sect. 2 above. This will, in turn, influence the disk temperature. An extended central source with radius $R_1 \gg H$, where H is the scale height of the disk, produces a surface temperature $T_{\rm irr}$ at disk radius R in an optically thick disk (e.g. Adams et al. 1988) given by

$$\left(\frac{T_{\rm irr}}{T_1}\right)^4 = \frac{\eta}{\pi}\left[\arcsin\rho - \rho(1-\rho^2)^{1/2}\right]. \quad (1)$$

Here $\rho = R_1/R$, T_1 is the temperature of the white dwarf photosphere, limb-darkening has been neglected, and η is the reprocessing efficiency of the disk surface. Increasing R_1 has two effects: (i) at given radius R, the disk temperature rises

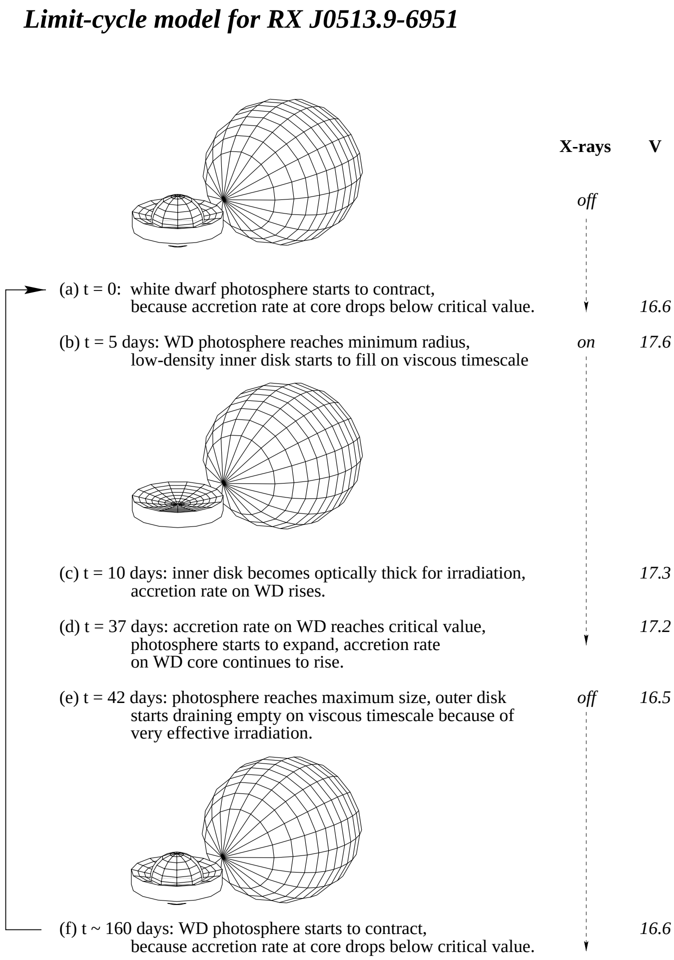

Fig. 3. Limit-cycle model for RX J0513 (see text).

approximately as $T_{\rm irr}^4 \propto R_1\, R^{-3} \propto R_1$, and (ii) the inner disk disappears in the hot envelope of the star (see also Sect. 4 above).

The increase in disk temperature raises the mass-flow rate in the disk, since the disk viscosity coefficient $\nu = \alpha c_{\rm S} H$ is increased. Here $c_{\rm S}$ is the sound speed, and $H = c_{\rm S} R^{3/2}/(2GM)^{1/2}$ is the scale height of the disk. The disk is now no longer in a steady state, since the mass-flow rate within it exceeds the mass supply rate from the companion star at its outer edge. Its mass is therefore gradually drained onto the white dwarf on a viscous timescale

$$t_{\rm visc,d} = \frac{R_d^2}{\nu} = \frac{R_d}{\alpha}\frac{R_d}{c_{\rm S}H}$$
$$\sim 130 \left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{R_d}{10^{11}{\rm cm}}\right) \text{ days}, \quad (2)$$

where 10^{11} cm is a characteristic disk radius (the radius of the Roche lobe is about 1.5×10^{11} cm), $H/R_{\rm d} \simeq 0.03$, $c_{\rm S} \simeq 3 \times 10^6\,{\rm cm\,s^{-1}}$ for $T_{\rm irr} \simeq 30\,000$ K, and $\alpha \simeq 0.1$ is a typical value of the viscosity parameter. With the disk being drained, the accretion rate onto the white dwarf eventually drops below $\dot{M}_{\rm crit}$, and the white dwarf reverts to its unexpanded state, the disk becomes cooler, and the system enters an optical low and X-ray on state (Fig. 3(a)–(b)). The collapse of the expanded

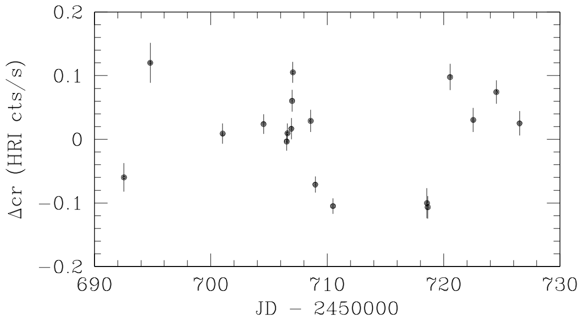

Fig. 4. Observed variability of the soft X-ray flux of RX J0513 during the X-ray on-state after subtraction of the exponential long-term flux decline shown in Fig. 1.

stellar envelope leaves the accretion disk with an inner hole of approximately the envelope radius which is gradually refilled by accretion from the outer disk. The disk temperature at a given radius R decreases as $T_{\rm irr}^4 \propto R_1\,R^{-3}$, but with $R_1 \sim 10^9$ cm in the optical low state the temperature at the edge of the hole ($R_{\rm h} \simeq 3 \times 10^{10}$ cm) becomes $\sim 32\,000$ K, similar to the outer disk temperature in the optical high state. The viscous time scale for refilling the hole, assuming again $H/R_{\rm h} \simeq 0.03$ and $c_{\rm S} \simeq 3 \times 10^6$ cm s^{-1} then is

$$t_{\rm visc,h} = \frac{R_{\rm h}^2}{\nu} = \frac{R_{\rm h}}{\alpha}\,\frac{R_{\rm h}}{c_{\rm S}H} \sim 40\,\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{R_{\rm h}}{3\times10^{10}{\rm cm}}\right)\,{\rm days}. \qquad (3)$$

This picture predicts a long X-ray off state and a shorter X-ray on state, with rapid (thermal-timescale) transitions between them, in quantitative agreement with what is observed.

6. Short-term variability

Besides the exponential decline, the soft X-ray flux of RX J0513 shows significant variations of $\sim \pm 0.1$ HRI counts/s on timescales of hours to days (Fig. 4). A time-series analysis of the detrended HRI count rates, however, reveals no clear periodicity in the range 0.1–10 days. The strongest signal is found at $P = 0.4075$ days but corresponds only to a 2σ detection. We have arbitrarily phase-folded the residual fluxes on the suggested orbital period of $\sim$0.76 days but find no obvious modulation of the light curve neither using the spectroscopic ephemeris (Crampton et al. 1996) nor using the better defined photometric ephemeris (Alcock et al. 1996).

Although our analysis shows that variability on the orbital and possibly shorter timescales may be present, our data coverage is not sufficient to decide whether the flux variations are truly periodic or not.

7. Conclusions

The ROSAT HRI monitoring of a complete X-ray outburst of the transient SSS RX J0513 has shown that the transition between the X-ray on and off states occurs with a change of the soft X-ray flux by a factor of > 100 within 2–4 days. In the model of an expanding and contracting white dwarf envelope this implies that the decrease of the effective radius by a factor of > 7 and the increase of the effective temperature by a factor of $\gtrsim 3$ occur on the same time-scale during the X-ray turn-on and vice versa during the X-ray turn-off.

The steepest intensity variations in the optical occur on a similar time-scale as the soft X-ray flux variations. This is consistent with our model that the optical variability is caused by the varying contribution of the accretion disk illumination by the expanding and contracting envelope of the white dwarf.

The existence of typical time-scales of the optical high/ X-ray off state, of the optical low/ X-ray on state, and of the transition phases, and the fairly accurate repetition of the optical lightcurve suggests that the observed variability is driven by limit-cycle behaviour. A possible self-maintained mechanism is the periodic change of the accretion disk viscosity in response to changes of the irradiation by the hot central star. In this scenario, the mass-flow rate at the surface of the white dwarf varies while the mass-transfer rate from the companion star remains constant. Our model can qualitatively explain the observed time-scales and requires no external mechanism like the episodic occurrence of star spots near the L_1 point to trigger the transition between the X-ray on and off states.

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