Relation between Supersoft X-ray sources and VY Scl stars

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Abstract. In a recent ROSAT observation, taken during its optical low state, we found that the VY Scl star V751 Cyg was a highly luminous source of soft X-rays. The ROSAT HRI count rate of V751 Cyg was a factor of 10–20 higher than upper limits obtained with ROSAT during previous observations, during which V751 Cyg happened to be in the optical high state. Analysis of the X-ray spectrum suggests a very low temperature ($kT_{\rm bb} \approx 15$ eV) and a bolometric luminosity of $5{\times}10^{36}$ (D/500 pc)^2 erg/s. These values are characteristic of supersoft X-ray sources. Based on the supersoft nature of V751 Cyg and the similarity of the variability pattern of VY Scl stars and the supersoft transient source RX J0513.9–6951 we hypothezise a relation between VY Scl stars and supersoft X-ray sources. It is conceivable that VY Scl stars are all supersoft binaries (SSB), that they form an extension of the previously known class of SSBs towards lower white dwarf masses and lower temperatures. In this case SSBs must be even more numerous than previously thought.

1. Introduction

Supersoft X-ray binaries (SSB) were established as a new class of astronomical objects during the early years of this decade (Trümper *et al.* 1991, Greiner *et al.* 1991, Kahabka & van den Heuvel 1997) and are thought to contain white dwarfs accreting mass at rates high enough to allow quasi-steady nuclear burning of the accreted matter (van den Heuvel *et al.* 1992). The sources are highly luminous ($L_{bol} \sim 10^{36} - 10^{38}$ ergs s^{-1}), but since their characteristic temperatures are on the order of tens of eV, much of the energy is radiated in the far ultraviolet or soft X-ray region of the spectrum, where the radiation is easily absorbed by the interstellar medium. Because of this, only 2 close-binary Galactic supersoft sources are known although there should be about 1000 in the Milky Way (Di Stefano & Rappaport 1994). The quest to find new SSBs has inspired several projects.

Here we report on the discovery of a new SSB. We have taken and analyzed ROSAT data that verify that the binary V751 Cyg is indeed a luminous supersoft X-ray source. Because of the importance of being able to identify additional SSBs, we also report on the reasoning that led us to suspect that V751 Cyg was likely to be a transient SSB.

VY Scl stars are a subclass of nova-like, cataclysmic variables which are bright most of the time, but occasionally drop in brightness by several magnitudes at irregular intervals (Warner 1995). The transitions between the brightness levels occur on timescales of days to weeks. These variables have large mass transfer rates $\dot{M}$ (of the order of 10^{-8} $M_\odot$/yr), and thus are thought to be steady accretors with hot disks. Livio & Pringle (1994) proposed a model for the group of VY Scl stars in which the brightness drop is due to a reduced mass transfer rate which in turn may be caused by a magnetic spot temporarily covering the L_1 region.

V751 Cyg (= EM* LkHA 170 = SVS 1202) was discovered by Martynov (1958), showing irregular variations and occasional fadings down to about 16$^{\rm m}$ (Martynov & Kholopov 1958). Now-a-days V751 Cyg is classified as a nova-like variable based on the observed rapid flickering and the complete similarity to VY Scl (Robinson *et al.* 1974). The orbital period of V751 Cyg is not well known, but estimated to $P \approx 6$ hrs (Bell & Walker 1980).

2. ROSAT, IUE and optical observations

Full details of the observations of V751 Cyg will appear elsewhere (Greiner *et al.* 1998), so we only summarize the relevant information here. The distinct lightcurve of RX J0513.9–6951 and its similarity to VY Scl stars led us to decide to monitor the light curves of the 14 known VY Scl stars. When V751 Cyg started to drop in brightness somewhere between 1 March and 11 March 1997 (Fig. 1) we performed a target-of-opportunity ROSAT HRI observation (4660 sec) on 3 June 1997. We discovered a new X-ray source, RX J2052.2+4419, within 1$''$ of V751 Cyg, at a mean count rate of 0.015 cts/s. During a second ROSAT HRI observation on Dec. 2–8, 1997 the count rate and X-ray spectrum are nearly identical to the June values.

In contrast, V751 Cyg was not detected during the ROSAT all-sky survey on Nov. 19/20, 1990 giving a 3σ

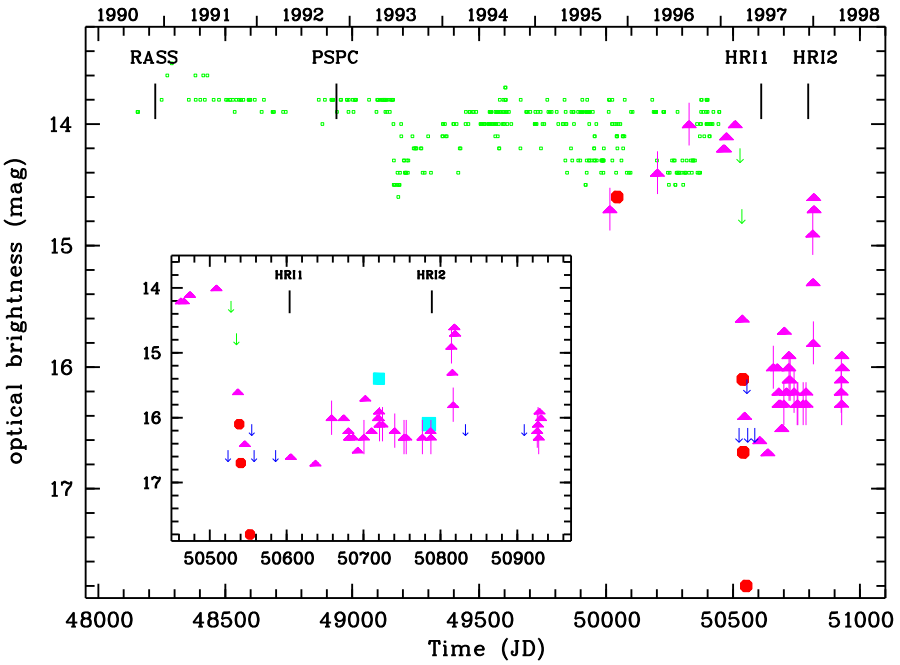

Fig. 1. Optical light curve of V751 Cyg over the last 8 years: small (gray) squares denote measurements as reported to AFOEV and triangles denote measurements as reported to VSNET (uncertain measurements are plotted with an error bar while the error of the certain measurements is about the size of the symbol sign). Large filled circles are CCD measurements of the Ouda team (also taken from VSNET). Arrows denote upper limits. At the top the times of the ROSAT observations are marked. V751 Cyg is detected in X-rays only during the optical low state. The inset shows a blow-up of the optical low-state together with the times of the two HRI observations. The two squares in the inset represent the mean brightness on Sep. 29/30, 1997 as derived from our spectra and our Dec. 3 1997 photometry (at the time of the 2nd HRI observation).

upper limit of 0.019 cts/s in the PSPC. In addition, it was also not detected during a serendipituous pointing on Nov. 11, 1992 providing an upper limit of 0.0058 cts/s in the PSPC. On both occasions V751 Cyg was in its optical bright state. We therefore find evidence for an anti-correlation of optical and X-ray intensity in V751 Cyg.

Using a new method (Prestwich *et al.* 1998) to extract reliable spectral information from HRI data, we crafted a response matrix which takes into account both the gain state of the detector at the time of the observation and the "wobble" of the HRI during the detection. Fits using this response matrix to all the source photons of V751 Cyg show that simple black-body models with kT of a few tens of eV are consistent with the data, whereas higher temperature models (0.5 keV) can be ruled out (Fig. 2).

An IUE observation performed in 1985 (also during an optical high state) was used to derive the extinction towards V751 Cyg based on the broad absorption centered at 2200 Å. The best result is obtained with a value of $E(B-V) = 0.25 \pm 0.05$. With the intrinsic color being near zero, this implies a visual extinction of $A_{\rm V} = 0.82 \pm 0.17$. Using a mean extinction law of $A_{\rm V} = 1.9$ mag/kpc (Allen 1973) we derive a distance to V751 Cyg of 430±100 pc, while using that from Neckel & Klare (1980) gives d=610±30 pc. Using the absorbing column derived from IUE, $N_{\rm H} = 1.1{\times}10^{21}$ cm^{-2}, the best-fit blackbody model gives $kT = 5$ eV and extremely high luminosity, so we adopt $kT = 15^{+15}_{-10}$ eV in the following (see Fig. 2).

At this temperature, the bolometric luminosity on 3 June 1997 is $6.5{\times}10^{36}$ (D/500 pc)^2 erg/s. Thus, during its optical low state, V751 Cyg was emitting soft X-rays with a temperature and luminosity which confirm that it is a transient supersoft X-ray source.

3. V751 Cyg as a supersoft X-ray binary

The following picture emerges. During optical low states V751 Cyg exhibits transient soft X-ray emission thus revealing itself as a supersoft X-ray binary. The appearance of He II 4686 Å emission in optical spectra taken in Sep. 1997 also indicates the presence of >54 eV photons. V751 Cyg, like the other members of the VY Scl star group, accretes at a few times $10^{-8} M_\odot$ yr^{-1}. If the mass of the white dwarf in V751 Cyg is small, this may allow nuclear burning, as the high X-ray luminosity suggests. It is worth emphasizing that recent calculations of hydrogen-accreting carbon-oxygen white dwarfs have shown that the accretion rate for low mass white dwarfs (0.5–0.6 $M_\odot$) can be as low as 1–3×10^{-8} $M_\odot$/yr (Sion & Starrfield 1994, Cassisi *et al.* 1998) while still maintaining shell burning (consistent with Fujimoto 1982). The V751 Cyg values of $M_{\rm V}^{\rm max} = 3.9$ and $\log\Sigma = (L_x/L_{\rm Edd})^{1/2} P_{\rm orb}^{2/3}\,(hr) = -0.23$ are consistent, within the uncertainties of L_x and $P_{\rm orb}$, with the relation $M_{\rm V} = 0.83(\pm0.25) - 3.46(\pm0.56)\log\Sigma$ found for 5 SSB (van Teeseling *et al.* 1997) implying that, if nuclear burning is the correct interpretation of the X-ray flux during the optical low state, then nuclear burning may continue during the optical high state.

There is ample evidence in some VY Scl stars that during the optical low state the accretion disk has vanished. Though we have no optical observations to provide direct evidence for this in V751 Cyg, the disk is certainly optically thin, thus drastically reducing the efficacy of reprocessing. This would cause some difference between the optical spectra of V751 Cyg and the SSBs in which the optical light is dominated by reprocessed light from the accretion disk (Popham & DiStefano 1996).

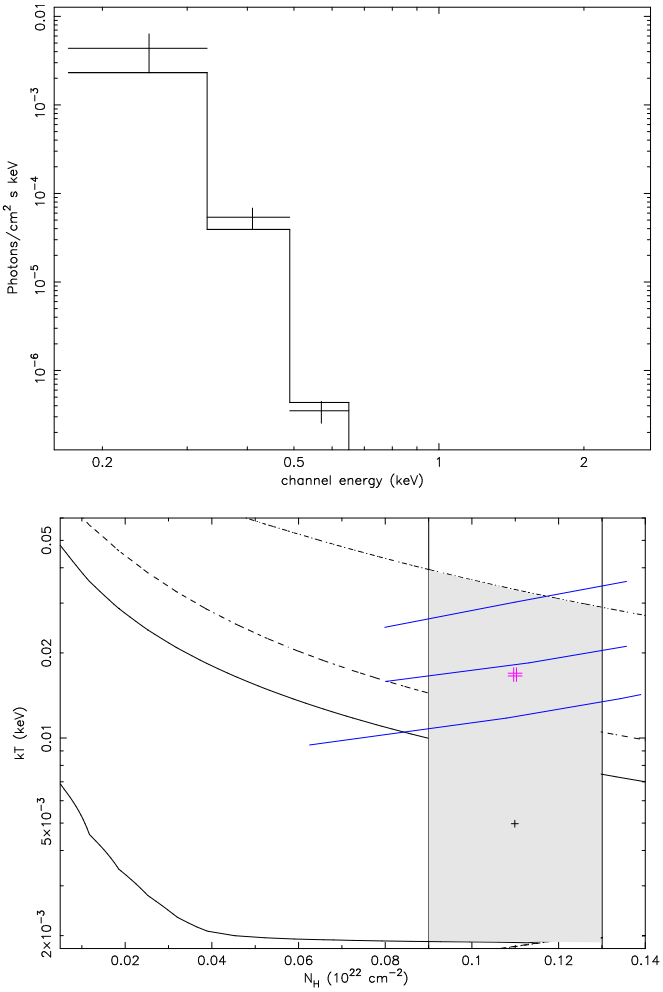

Fig. 2. Spectral fit result of the June 1997 observation of V751 Cyg: **Top:** The photon spectrum deconvolved with a blackbody model with $N_{\rm H}$ fixed at the value derived from the IUE spectrum. **Bottom:** Confidence contours of the blackbody fit in the $kT - N_{\rm H}$ plane: 68% (solid line), 90% (long-dashed line), 99% (short-dashed line). The two vertical lines denote the $N_{\rm H}$ range allowed by the IUE data ($(1.1\pm0.2)\times10^{21}$ cm^{-2}), and the vertical extent of the hatched region marks the 99% confidence region of the blackbody temperature. The three solid lines crossing the hatched region mark contours of constant luminosity (at an assumed distance of 500 pc) of 10^{34}, 10^{36} and 10^{38} erg/s (from top to bottom), respectively. The cross denotes the best fit-value of kT=5 eV and the double cross the parameter pair used in the discussion (see sect. 2).

Our discovery that V751 Cyg is a transient supersoft X-ray source arose from the similarity in the optical light curve of RX J0513.9–6951 and VY Scl stars. RX J0513.9–6951 (Schaeidt *et al.* 1993, Pakull *et al.* 1993) shows ∼4 week optical low states which are accompanied by luminous supersoft X-ray emission (Reinsch *et al.* 1996, Southwell *et al.* 1996). It is generally assumed that the white dwarf accretes at a rate slightly higher than the burning rate, and thus is in an inflated state during the optical high state. Changes in the irradiation of the disk caused by the expanding/contracting envelope around the white dwarf have been proposed as explanation for the 1 mag intensity variation in RX J0513.9–6951 (Reinsch *et al.* 1996, Southwell *et al.* 1996). Note, that the white dwarf itself varies drastically as it expands/contracts, and in fact a flaring disk had to be assumed for RX J0513.9–6951 to reduce the theoretically possible amplitude down to only 1 mag (Hachisu & Kato 1998).

The explanation of the X-ray/optical variability of V751 Cyg could be similar to RX J0513.9–6951 (Pakull *et al.* 1993, Reinsch *et al.* 1996, Southwell *et al.* 1996): $\dot{M}$variations change both the photospheric radius and the disk spectrum. If the white dwarf has a small mass, than photospheric radius expansion is reached at 1×10^{-7} $M_\odot$/yr (Cassisi *et al.* 1998).

A major difference between the optical light curves of RX J0513.9–6951 and VY Scl stars is the amplitude between low and high states, i.e. 1 mag (RX J0513.9–6951) versus 3–6 mag for VY Scl stars (4 mag for V751 Cyg). Note that the ≈15 eV blackbody model derived as the best fit for V751 Cyg corresponds to a m_V ≈20 mag, i.e. several magnitudes fainter than the observed optical low-state intensity (Fig. 1). Indeed, an amplitude of 4 mag can be easily accommodated by a white dwarf when expanding from R_{WD} to 5 R_{WD}. Thus, the observed large amplitudes in VY Scl stars could be due to a combination of both the disk disappearance and the white dwarf contraction.

4. Are other nova-like variables also SSBs?

4.1. VY Scl stars

The discovery of luminous, supersoft X-ray emission during the optical low state of V751 Cyg naturally leads to the question of whether other VY Scl stars may also be SSBs. It turns out that the basic properties of VY Scl stars correspond surprisingly well to an extension of the SSB class (see Tab. 1): (i) In all thouroughly observed VY Scl stars, optical emission line studies indicate that the *donor* has a mass smaller than 0.5 $M_\odot$. In addition, the *mass ratio* (between the donor and the white-dwarf accretor) seems to be close to unity in some systems. (ii) The *white dwarf mass* in VY Scl systems may be systematically smaller than generally considered in models for SSBs. We therefore may be seeing an extension of the CO-nuclear-burning white dwarf scenario which has formed the basic model for most SSBs so far. The low white dwarf mass may lead to a larger effective radii (Vennes *et al.* 1995) and thus lower temperatures. (iii) The orbital periods of VY Scl stars range from ∼ 3.2 hours to 6 hours, with the longest period associated with V751 Cyg. These periods are compatible with the orbital periods of some other SSBs, most notably 1E 0035.4–7230 with its 4.1 hr orbital period (Schmidtke *et al.* 1996). However, such 3–4 hr orbital periods are significantly lower than those required in the canonical van den Heuvel *et al.* (1992) model for supersoft sources in which a possibly slightly evolved

donor more massive than the white dwarf provides a mass transfer on a thermal timescale. However, it has recently been shown that the strong X-ray flux in supersoft sources should excite a strong wind ($\dot{M}_{\rm wind} \sim 10^{-7}\ M_\odot$/yr) from the irradiated companion which in short-period binaries would be able to drive Roche lobe overflow at a rate comparable to $\dot{M}_{\rm wind}$ (van Teeseling & King 1998). (iv) The value of $\dot{m}$ typically adopted in VY Scl systems (Warner 1987) is $\dot{m} \sim 10^{-8} M_\odot$ yr^{-1}. Interestingly enough, these values may be compatible with quasi-steady burning on white dwarfs with the low masses that seem to be indicated in some VY Scl systems.

Thus, the conjecture that all VY Scl stars are SSBs is viable. Should it be verified, even for a subset of systems, then VY Scl stars may represent an extension of the class of SSBs as discussed above and summarized in Tab. 1. Even if the underlying mechanisms in SSB and V751 Cyg are completely different, the somewhat similar anticorrelations between X-ray and optical have proved useful to identify V751 Cyg as a transient supersoft X-ray source.

4.2. V Sge stars

It has recently been suggested (Steiner & Diaz 1998; Patterson *et al.* 1998) V Sge (and possibly also WX Cen, V617 Sge and HD 104994) have properties very similar to SSBs. These suggestions are based on the following characteristics, shared by these four stars but rare or even absent among canonical cataclysmic variables: (1) the presence of both O VI and N V emission lines, (2) a He II λ4686/Hβ emission line ratio $\gtrsim 2$, (3) rather high absolute magnitudes and very blue colours, and (4) orbital lightcurves which are characterized by a wide and deep eclipse. A detailed comparison of the optical states of V Sge and archival ROSAT observations has shown that during optical bright states, V Sge is a faint hard X-ray source, while during optical faint states ($V \gtrsim 12$ mag), V Sge is a 'supersoft' X-ray source (Greiner & Teeseling 1998). Spectral fitting confirms that V Sge's X-ray properties during its soft X-ray state may be similar to those of supersoft X-ray binaries, although a much lower luminosity cannot be excluded. It is possible to explain the different optical/X-ray states of V Sge by a variable amount of extended uneclipsed matter, which during the optical bright states contributes significantly to the optical flux and completely absorbes the soft X-ray component (Greiner & Teeseling 1998). We note that our strategy of finding new, transient SSB by measuring the X-ray emission during optical low states would have worked also for V Sge.

Although there is certainly a lot of work to be done we are encouraged that the method of finding new SSB based on variability analysis seems capable to expand the realm of known SSB.

Table 1. Comparison of SSB and VY Scl group properties

	SSBs	VY Scl stars
Mass of WD ($M_\odot$)	~ 1	$\sim$0.5
Mass of Donor ($M_\odot$)	$\sim 1 - 2$	$\sim$0.5 – 0.7
Period (hrs)	6 – 70	3 – 6
kT (eV)	20 – 50	10 – 20
Accretion rate ($M_\odot$/yr)	10^{-7}	10^{-8}
M_V (mag)	–2 – +1	3 – 5
log L (erg/s)	37–38	36
Number in Galaxy (obs)	2	15
Number in Galaxy (mod)	1000–3000	??

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