V751 Cyg and V Sge as transient supersoft X-ray sources

Jochen Greiner[a]

[a] *Astrophysikalisches Institut Potsdam,*
14482 Potsdam, An der Sternwarte 16, Germany

Abstract

I review the observational evidence for luminous, soft X-ray emission during optical low-states in the two cataclysmic variables V751 Cyg and V Sge, and discuss the possible link to the canonical supersoft X-ray sources.

1. Introduction

Supersoft X-ray sources (SSS) 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 (Motch et al. 1994, Beuermann et al. 1995), though there should be about 1000 in the Milky Way (Di Stefano & Rappaport 1994). The situation is further complicated by the fact that supersoft X-ray binaries are highly time variable, both at X-ray and optical wavelengths (Greiner 1995). The greatest number are known in the Magellanic Clouds, but they are difficult to study because of their distance. The quest to find new SSBs has inspired several projects including comprehensive studies of deep ROSAT pointings. So far, these were not generally successful, however.

Recently, two other approaches to search for further members of the SSS class have been attempted: (1) Using a unique variability pattern: Although most SSS are variable in their X-ray and/or optical emission, the behaviour of several systems is distinctive. Data collected during the MACHO team's monitoring of the LMC has shown that the seemingly sporadic X-ray bright states of RX J0513.9–6951, a well-known supersoft X-ray binary in the LMC (Schaeidt et al. 1993, Pakull et al. 1993), are correlated with short-lived optical low states (Pakull et al. 1993, Reinsch et al. 1996, Southwell et al. 1996). As first suggested by Brian Warner, the birthday of whom we are celebrating here, at the SSS workshop in Garching in 1996, the 3 year MACHO light curve (Southwell et al. 1996) suggests a strong similarity to the VY Scl stars. 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 (Bond 1980, Warner 1995). (2) Searching among unusual cataclysmic variables: One possible Galactic source, V Sagitae, has been suggested by studying the properties of several unusual cataclysmic variables (Patterson et al. 1998). Steiner & Diaz (1998) note the similarity of 3 other Galactic systems to V Sge.

In the following, I will describe both strategies and review the evidence for transient, luminous supersoft X-ray emission in the two cataclysmic variables (CVs) V751 Cyg and V Sge during their optical low states.

2. V751 Cyg

Full details of the correlated X-ray and optical observations of V751 Cyg have appeared elsewhere (Greiner et al. 1999), 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 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. A new X-ray source, RX J2052.2+4419, was discovered 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 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. This suggests an anti-correlation of optical and X-ray intensity in V751 Cyg.

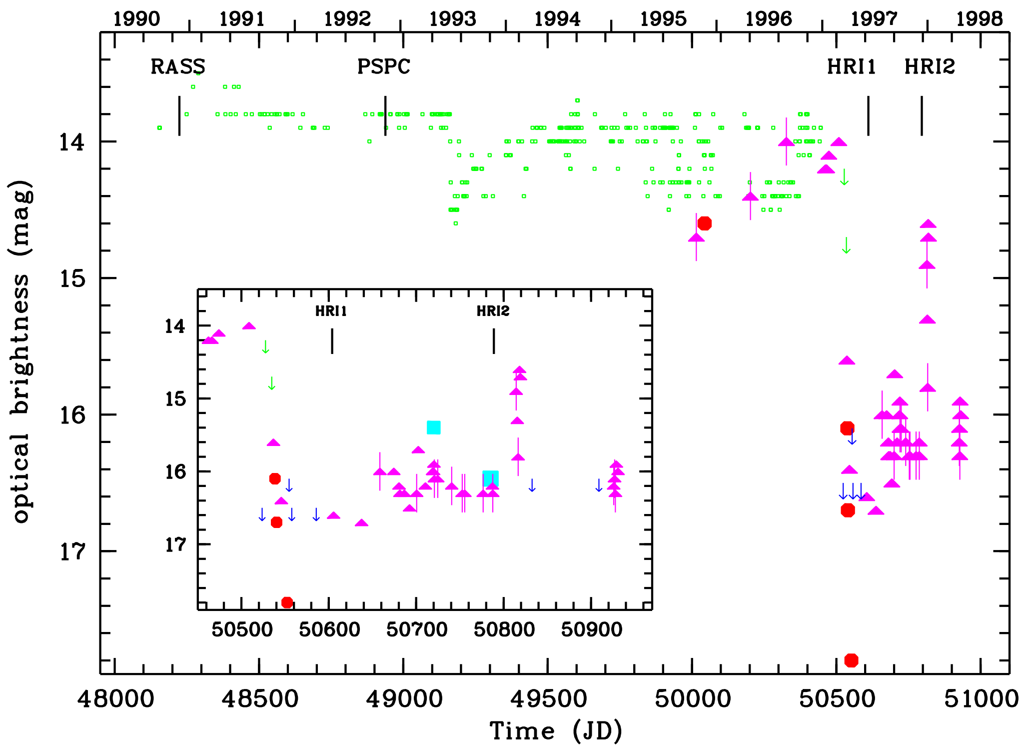

Fig. 1. Optical light curve of V751 Cyg over 8 years: small (gray) squares denote measurements as reported to AFOEV and triangles denote measurements as reported to VSNET. Large filled circles are CCD measurements of the Ouda team (also taken from VSNET). Arrows denote upper limits. At the top the times of the ROSAT observations are marked. V751 Cyg is detected only in the HRI observations 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 spectra and Dec. 3, 1997 photometry (at the time of the second HRI observation) (from Greiner et al. 1999).

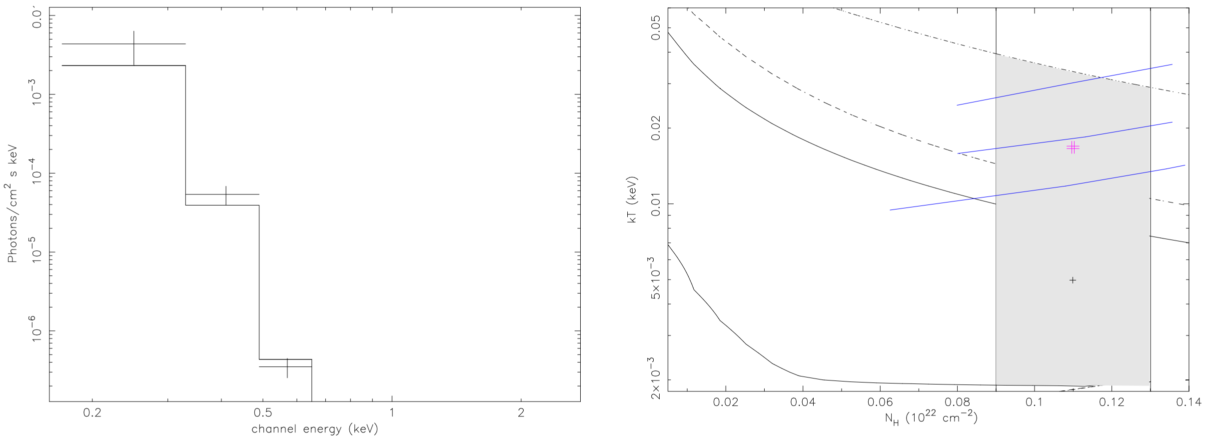

Fig. 2. Spectral fit result of the June 1997 ROSAT observation of V751 Cyg: **Left:** The photon spectrum deconvolved with a blackbody model with $N_{\rm H}$ fixed at the value as derived from the IUE spectrum. **Right:** Confidence contours of the blackbody fit in the $kT - N_{\rm H}$ plane: 68% (solid line), 90% (long-dashed line), 99% (short-dashed line). The two vertical lines denote the $N_{\rm H}$ range allowed by the IUE data ($(1.1{\pm}0.2){\times}10^{21}$ 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 (top to bottom). The double cross denotes the parameter pair used in the text.

A new method (Prestwich et al. 1999) to extract reliable spectral information from HRI data allowed to craft a response matrix for a given observation. 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 (during an optical high state) was used to derive the extinction towards V751 Cyg based on the broad absorption centered at 2200 Å: $E(B-V) = 0.25 \pm 0.05 \equiv N_{\rm H} = 1.1{\times}10^{21}$ cm^{-2}. This implies a distance of the order of 500 pc. With this $N_{\rm H}$ the X-ray spectral fitting gives $kT = 15^{+15}_{-10}$ eV (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. 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. 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 $M_{\rm V} = 0.83(\pm 0.25) - 3.46(\pm 0.56) \log \Sigma$ 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.

The 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 (Reinsch et al. 1996, Southwell et al. 1996). The explanation of the X-ray/optical variability of V751 Cyg could be similar to RX J0513.9–

6951: $\dot{M}$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).

The explanation for the character of the optical and UV observations is not yet clear, but it seems certain that the illumination of the donor and disk play important roles in determining what we see. If the X-ray source during the optical low state indeed is very luminous one may expect a strong heating effect on the secondary as well as on the accretion disk. The heating of the secondary in V751 Cyg is probably comparable to that in SSS because the illumination depends on the ratio of companion radius and binary separation which is similar in both kind of systems. Unfortunately, no photometry has been obtained during the optical low state to immediately test for this effect in V751 Cyg though it is anyway not expected to produce a strong modulation due to the low orbital inclination.

The question of the illumination of the accretion disk has to be addressed separately for optical low and 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 direct evidence for this in V751 Cyg due to the lack of optical observations, the disk is certainly optically thin thus drastically reducing the efficancy of illumination. In the optical high state the illumination depends on whether hydrogen burning stops or whether it continues on an inflated white dwarf at a temperature below the sensitivity range of ROSAT: If the burning stops then there are no soft X-rays which could be reprocessed. If the nuclear burning continues, reprocessing may still not be strong because the amount of reprocessing depends on the size of the accretion disk (orbital period) and only for large disks also on the flaring of the disk. For V751 Cyg the disk is so small that any flaring is probably insignificant compared to the angle which the white dwarf subtends with respect to the disk. Even if flaring were significant, reprocessing of the radiation from the white dwarf will begin to have a dominant effect on the local disk temperature (King 1997, Knigge & Livio 1998) if the white dwarf luminosity $L_{\rm WD} \gtrsim 2.5 L_{\rm acc}(1-\beta)^{-1}$ (where β is the albedo of the disk surface). That is, a disk around a 1 $M_\odot$ white dwarf accreting at 10^{-8} $M_\odot$/yr will be dominated by reprocessing only if the white dwarf temperature is $>2\times10^5$ K $\equiv$ 17 eV. This is seemingly just a value between the temperatures of SSS (30–50 eV) and V751 Cyg (15 eV). Thus, one difference of the systems could be that the disk in V751 Cyg is not flared and therefore not dominated by reprocessing while the SSS disks are flared and dominated by reprocessing and thus are optically much brighter than the VY Scl disks.

3. V Sge

It has recently been suggested (Steiner & Diaz 1998; Patterson et al. 1998) that 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 >2, (3) rather high absolute magnitudes and very blue colours, and (4) orbital lightcurves which are characterized by a wide and deep eclipse.

V Sge has been the target of three dedicated pointed PSPC and HRI observations (one of these splits into 3 separate observation intervals), and in addition is in the field of view of another PSPC observation. 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 ($V > 12$ 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.

The model that has been suggested for RX J0513.9–6951 cannot explain the observational data of V Sge. First, the optical brightness changes of V Sge are very rapid: both the faint-/bright-state transitions as well as the succession of different faint states may occur on timescales of $\lesssim$1 day (compared to the

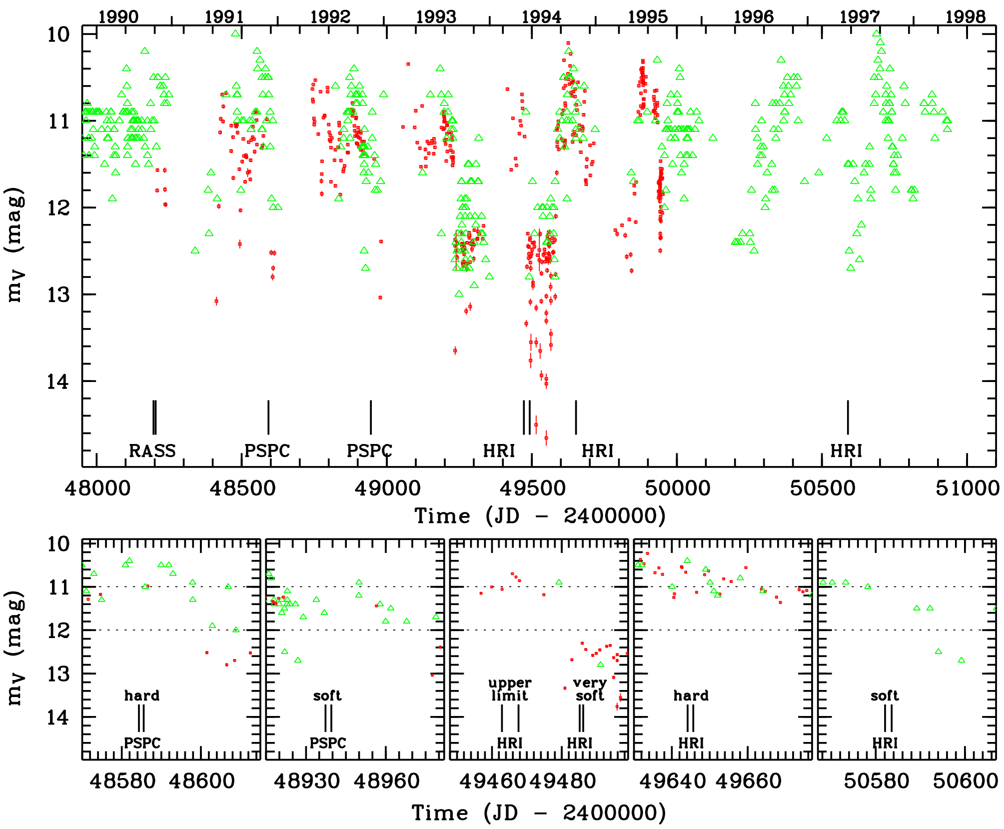

Fig. 3. Optical light curve of V Sge with data from Robertson (et al. 1997 and unpublished; red dots) and VSOLJ (Web; green triangles). Vertical dashes mark the times of ROSAT observations. The lower panels show blow-ups around the ROSAT observations (two vertical lines mark the start and the end of each ROSAT exposure). The dotted lines denote the boundaries of the three optical states. (From Greiner & Teeseling 1998)

smooth decline of several days in RX J0513.9–6951). Such very rapid changes are only possible if the white dwarf envelope expands and contracts on the Kelvin-Helmholtz timescale and the mass of the expanding envelope is rather small ($M_{\rm env} \sim 10^{-9}$ M$_{\odot}$). Such a small envelope mass is difficult to accept for a white dwarf with stable shell burning (e.g. Prialnik & Kovetz 1995). Second, the expected optical eclipse would become deeper when the system becomes brighter, opposite to what has been observed (Patterson et al. 1998).

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). A simple wind model for the recently observed radio flux density of V Sge implies a mass-loss rate of the order of 10^{-6} M$_{\odot}$/yr (Lockley et al. 1997). With their (assumed) terminal velocity of 1500 km/s this wind zone is completely opaque for X-rays up to 0.7 keV, even if the wind is assumed to be circumbinary instead of arising from one component. Since the radio measurement has been obtained during optical high state, it supports the above described scenario.

4. Discussion and Conclusion

As shown above, both strategies to search for new SSS were successful. This is very promising, and opens up the way to use optical observation strategies besides X-ray observations to identify new SSS. The surprising part of this development is that both, V751 Cyg and V Sge, are short-period CVs, and if true, their transient supersoft source nature would establish a direct link between classical CVs and canonical SSS which typically have orbital periods inthe 0.5–3 days range.

For both sources, V751 Cyg and V Sge, the estimates for their X-ray luminosity (under reasonable assumptions on $N_{\rm H}$) are $\sim 10^{36}...10^{37}$ erg/s. This is at the lower end of the stable burning region. Two issues are relevant in this respect: (1) As for most CVs, the available evidence for VY Scl stars suggests that the white dwarfs have a low mass. At these low masses the accretion rate necessary for steady-state burning (consistent with Fujimoto 1982) is 1–3×10^{-8} $M_\odot$/yr (Sion & Starrfield 1994, Cassisi 1998), and correspondingly the luminosity is lower than the canonical values for SSS. (2) Even at rates below the steady-state burning level there could be a range where the hydrogen flashes are rather mild. A recent study of this parameter space has shown that the luminosity between the flashes remains at the surprisingly high value of ~10%–30% of the burning luminosity (Rappaport 1999).

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