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LETTER

*Letter to the Editor*

# On the X-ray properties of V Sge and its relation to the supersoft X-ray binaries

**Jochen Greiner**[1] **and André van Teeseling**[2]

[1] Astrophysical Institute Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany
[2] Universitäts-Sternwarte Göttingen, Geismarlandstrasse 11, D-37083 Göttingen, Germany

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**Abstract.** We investigate the ROSAT X-ray properties of V Sge, which has been proposed to be related to supersoft X-ray binaries. 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. 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 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. An additional, perhaps permanent, hard X-ray component, such as a bremsstrahlung component with a 0.1–2.4 keV luminosity of $\sim 10^{30}$ erg s$^{-1}$, must be present to explain the X-ray properties during the optical bright/hard X-ray state.

**Key words:** accretion disks – cataclysmic variables – eclipsing binaries – X-rays: stars – stars: individual: V Sge

## 1. Introduction

V Sge is a blue star with a mean brightness around 11 mag which has been shown to vary between 9.6–14.7 mag since its discovery in 1902. It shows wide eclipses at a period of $0\overset{d}{.}51419$, a small secondary eclipse, and complex emission line behaviour (Herbig et al. 1965). Extinction estimates vary between $E_{\rm B-V} = 0.4$ (Herbig et al. 1965) and $E_{\rm B-V} = 0.15$ (Verbunt 1987) implying a distance of 0.7–2.7 kpc.

Supersoft X-ray binaries (SSB; see Greiner 1996 and references therein; van Teeseling 1998) were established as a new class of accreting binaries during the early 90ies with ROSAT (Trümper et al. 1991; Greiner et al. 1991) and are thought to contain white dwarfs accreting mass at rates sufficiently high to allow stable nuclear surface burning of the accreted matter (van den Heuvel et al. 1992). SSB have luminosities of $L_{\rm bol} \sim 10^{36}$–$10^{38}$ ergs s$^{-1}$, but their characteristic temperatures of 20–40 eV imply strong attenuation by the interstellar medium. Thus, most of the known SSB are located in external galaxies (e.g. Greiner 1996) making detailed optical observations difficult. It is therefore of great interest to identify galactic SSB.

It has recently been suggested (Steiner & Diaz 1998; Patterson et al. 1998) that V Sge has spectroscopic and photometric properties which are very similar to those of SSB. This suggestion is based on characteristics which are typical for SSB, but are rare or even absent among canonical cataclysmic variables: (1) the presence of both O VI and N V emission lines, (2) a He II $\lambda 4686$/H$\beta$ 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.

The suggestion of the similarity of V Sge to SSB is almost entirely based on optical and ultraviolet data. In this paper, we investigate the archival ROSAT data of V Sge and discuss them in the context of the long-term optical behaviour of V Sge. Hoard et al. (1996) reported the detection of V Sge as a soft X-ray source in the Nov. 1992 ROSAT observation, but did not perform a spectral fit. Verbunt et al. (1997) already reported the non-detection of V Sge during the ROSAT all-sky survey.

## 2. ROSAT Observations

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 (Table 1). The results of these observations are quite diverse: V Sge has not been detected during the ROSAT all-sky survey in 1990 and a long ROSAT HRI pointing in April 1994, but has been detected during all other observations, even in a much shorter HRI observation. Thus, V Sge shows strong X-ray variability with an amplitude of a factor of 140. In addition, the X-ray spectral characteristics during two ROSAT PSPC pointings obtained 1 yr apart show a remarkable difference: at one occasion V Sge has a 'supersoft' X-ray spectrum, at another occasion the spectrum is very hard.

The diversity of X-ray measurements looks more ordered when it is compared with the optical brightness of V Sge. This binary system is included in the RoboScope program of automatic long-term monitoring the results of which led to the classification of three distinct optical states: bright state (V<11 mag), intermediate state (V$\sim$11–12 mag) and faint

*Send offprint requests to*: J. Greiner (e-mail: jgreiner@aip.de)

**Table 1.** ROSAT observations of V Sge

| Date | Obs-ID$^{(1)}$ | $T_{exp}$ (sec) | offaxis angle | CR$^{(2)}$ (cts/s) | HR1$^{(3)}$ | HR2$^{(3)}$ | X-ray state | optical state | D$^{(4)}$ |
|---|---|---|---|---|---|---|---|---|---|
| Oct. 19–31, 1990 | – | 50 | 0–55′ | <0.054 | – | – | – | bright | – |
| Nov. 23/24, 1991 | 400155P | 10 235 | 0.′39 | 0.0011±0.0004 | 1.0±0.7 | 0.2±0.4 | hard | bright | 16″ |
| Nov. 10–12, 1992 | 300182P | 27 745 | 30.′9 | 0.0091±0.0010 | –0.64±0.15 | –0.13±0.39 | soft | intermediate | 28″ |
| Apr. 19–24, 1994 | 300311H | 24 610 | 0.′18 | <0.00044 | – | – | – | bright | – |
| May 12–13, 1994 | 300311H | 4 700 | 0.′18 | 0.0199±0.0021 | – | – | very soft | faint | 1″ |
| Oct. 18/19, 1994 | 300311H-1 | 18 440 | 0.′17 | 0.0011±0.0003 | – | – | hard | bright | 5″ |
| May 12/13, 1997 | 300582H | 15 700 | 0.′17 | 0.0025±0.0004 | – | – | soft | intermediate | 1″ |

(1) The letter after the observation ID number gives the ROSAT detector: P = PSPC, H = HRI.
(2) Count rates in the corresponding detector in the 0.1–2.4 keV range (PSPC: channels 11–240). Upper limits are $3\sigma$ confidence level. Note the different PSPC to HRI count rate conversion factors of 2.7:1 and 7.8:1 for hard and soft spectrum sources.
(3) Hardness ratios with HR1 = $(B-A)/(B+A)$ and HR2 = $(D-C)/(D+C)$, where $A(0.1-0.4\,\mathrm{keV})$, $B(0.5-2.0\,\mathrm{keV})$, $C(0.5-0.9\,\mathrm{keV})$, and $D(0.9-2.0\,\mathrm{keV})$ are the counts in the given energy range.
(4) Distance between best-fit X-ray and optical position. For the optical position $\alpha$(2000.0)=20$^{\mathrm{h}}$20$^{\mathrm{m}}$14.$^{\mathrm{s}}$7, $\delta$(2000.0)=+21°06′10″ has been used as determined from the second generation DSS. This position differs from the SIMBAD position by $\triangle\alpha$=12″ and $\triangle\delta$=4″.

state (V>12 mag) (Robertson et al. 1997). We have combined the optical lightcurve obtained by these observations with data collected in the VSOLJ database (www.kusastro.kyoto-u.ac.jp/vsnet/) and plotted these in Fig. 1 together with the times of the ROSAT observations. This suggests that during optical bright state V Sge is a hard, but rather faint X-ray source, while during optical faint state V Sge is a more luminous and very soft X-ray source. During the intermediate optical state also the X-ray spectrum is intermediate with respect to the very soft and hard spectrum.

To obtain an idea about the X-ray spectral parameters during the soft X-ray state, we fit the Nov. 1992 PSPC spectrum with a solar-abundance LTE $\log g = 9$ white dwarf atmosphere model (Van Teeseling et al. 1994). The $\chi^2$ contours are shown in Fig. 2. The $1\sigma$ contour suggests a temperature $T_{\rm eff} > 500\,000$ K and a bolometric luminosity $L \lesssim 10^{33}$ erg s$^{-1}$ (with $d = 1$ kpc), but lower temperatures and higher luminosities are still acceptable within the 90% confidence contour. If we require that the soft X-ray absorbing column is at least $n_{\rm H} \sim 8 \times 10^{20}$ cm$^{-2}$ as derived from the 2200 Å absorption dip ($E(B-V) \sim 0.15$; Verbunt 1987), we find $T_{\rm eff} < 800\,000$ K and $L > 10^{32}$ erg s$^{-1}$. With $n_{\rm H} \sim 10^{21}$ cm$^{-2}$, only for $T_{\rm eff} \lesssim$200 000 K a luminosity of $L > 10^{36}$ erg s$^{-1}$ is reached. It is possible, however, that because of the very high orbital inclination the soft X-ray absorption is much larger than the ultraviolet absorption. A similar discrepancy is known for CAL 87 (cf. Hutchings et al. 1995; Parmar et al. 1997). If we relax the absorption constraint and assume that V Sge is a SSB with $L > 10^{36}$ erg s$^{-1}$, we find $T_{\rm eff} < 500\,000$ K and a radius $R > 2 \times 10^{8}$ cm consistent with a white dwarf. However, because of a very high orbital inclination, the white dwarf may be completely obscured from view by the accretion disk rim, in which case the observable luminosity (from X-rays scattered into the line of sight) may be much less than $10^{36}$ erg s$^{-1}$. We note that there is no significant modulation of the soft X-rays on the orbital period.

A factor of 45 increase in HRI count rate occurred within less than three weeks in April/May 1994 during which the optical brightness decreased and V Sge eventually became a very soft X-ray source. Though the ROSAT observations during this optical state transition have been performed with the HRI, the grossly different spectral shapes are easy to recognize (Fig. 2, bottom).

## 3. Discussion

The anti-correlation of soft X-ray emission with optical brightness is reminiscent of the behaviour of the SSB RX J0513.9–6951 (Reinsch et al. 1996; Southwell et al. 1996). RX J0513.9–6951 turns on as a supersoft X-ray source only during $\sim 1$ mag optical dips, which occur every 100–200 days and last about $\sim 30$ days. This behaviour has been explained by assuming that the shell-burning white dwarf in RX J0513.9–6951 has normally expanded to a few $10^{10}$ cm and radiates its luminosity in the extreme-ultraviolet. During the optical faint states, the white dwarf contracts with almost constant bolometric luminosity to $\sim 10^{9}$ cm, and radiates in the soft X-ray band.

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 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).

Before we speculate on a possible explanation for the observed X-ray properties of V Sge, we note the similarity of the V Sge behaviour to that of VY Scl stars (as has been noted with respect to the optical behaviour also by Robertson et al. 1997). In a recent survey of the available ROSAT data of VY Scl stars

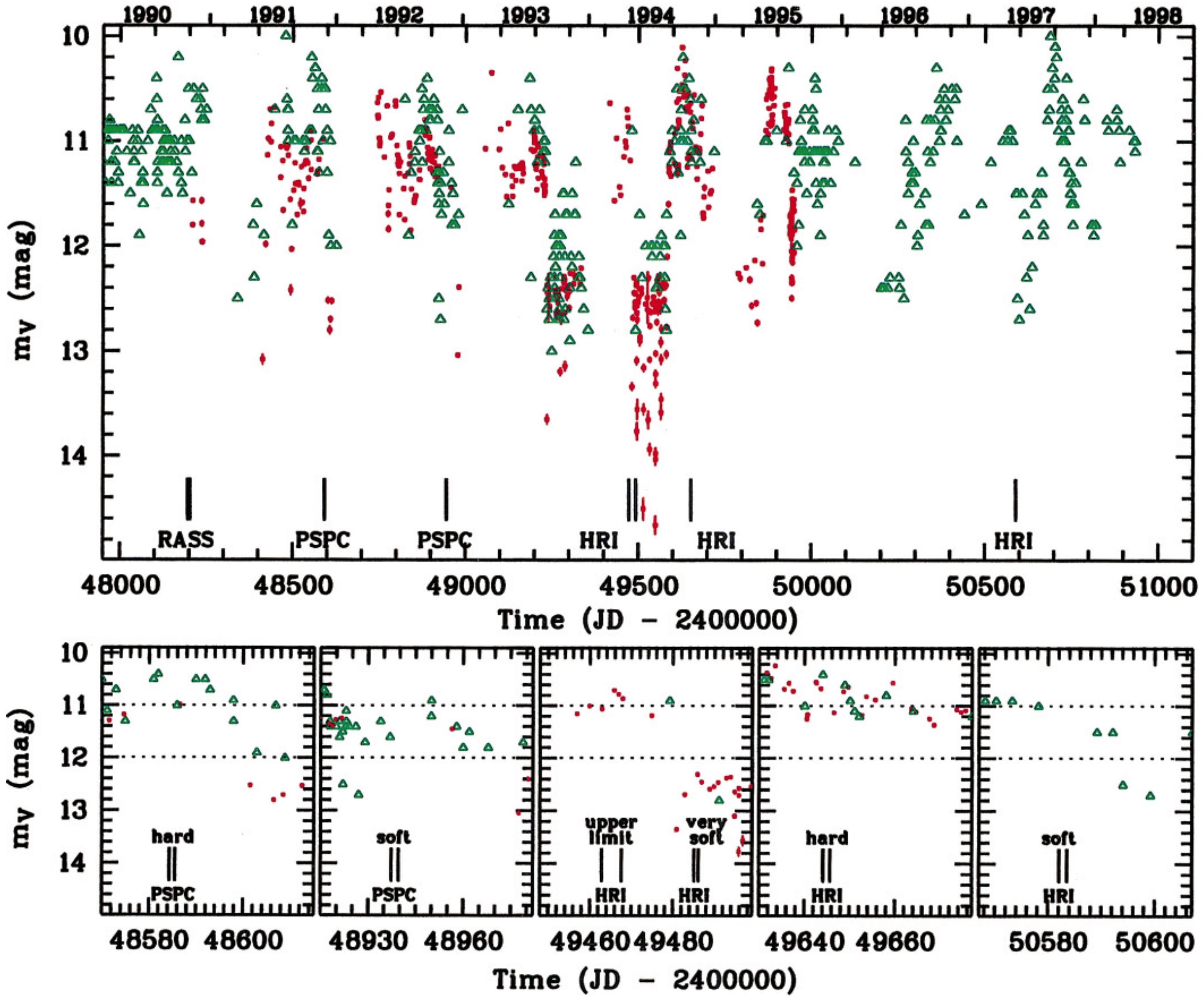


**Fig. 1.** Optical light curve of V Sge with data from Robertson et al. 1997 (red dots) and VSOLJ (Web; green triangles). Vertical dashes mark the times of ROSAT observations. The lower panels show blow-ups around the ROSAT observations which are characterized by two vertical lines marking the start and the end of the ROSAT exposure. The dotted lines denote the boundaries of the three optical states.

(Greiner 1998) a relatively hard X-ray spectrum was found for VY Scl stars during optical bright state (see also van Teeseling et al. 1996). Moreover, observations of the VY Scl star V751 Cyg during its 1997 optical faint state have revealed luminous and very soft X-ray emission (Greiner et al. 1998), similar to that of V Sge in its faint state.

Inspection of the change in eclipse depth from faint to bright state (e.g. Fig. 5 in Patterson et al. 1998) shows that it is possible to reproduce this change by an increase of uneclipsed flux, while the eclipsed light (presumably from the irradiated accretion disk) remains almost constant. If the flux from the irradiated disk (and therefore also from the irradiated secondary) remains unchanged, this would suggest that a brightening of V Sge is caused by an increasing amount of extended luminous (outflowing?) matter. This would also be consistent with the emission lines, which only show partial eclipse effects, and which increase in strength when V Sge brightens (e.g. Herbig et al. 1965), indicating either an increasing amount of line emitting matter or an increasing amount of ionizing flux. (Mauche et al. (1997) note that the He II $\lambda1640$/C IV $\lambda1550$ and N V $\lambda1240$/C IV $\lambda1550$ line ratios decrease when V Sge brightens.)

Additional extended gas could increase the amount of soft X-ray absorption and make the soft X-ray component fainter and harder and make it even completely undetectable. Because it is impossible to produce the hardness ratios *and* count rate observed in Nov. 1991 by simply adding more absorption to an absorbed hot-white-dwarf spectrum, we conclude that in Nov. 1991 an additional harder X-ray component was present. The hardness ratios and count rate of the Nov. 1991 PSPC observation can be explained perfectly with a thermal bremsstrahlung spectrum, absorbed with $n_{\rm H} \gtrsim 10^{21}\,{\rm cm}^{-2}$, a temperature of a few keV, and a 0.1–2.4 keV luminosity of $\sim 10^{30}\,{\rm erg\,s}^{-1}$

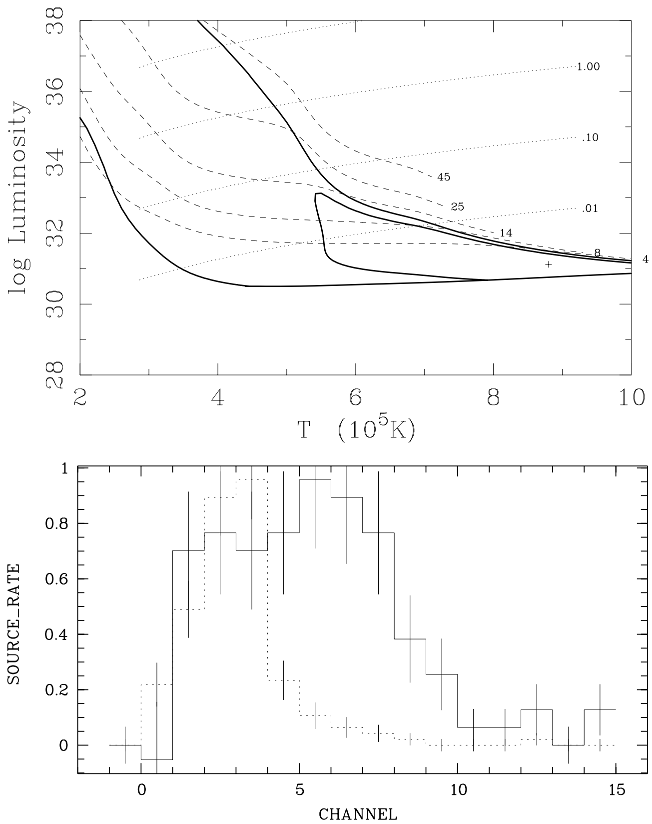


**Fig. 2. Top:** $1\sigma$ and 90% confidence contours (solid lines) of a $\chi^2$ fit of solar-abundance LTE $\log g = 9$ model spectra to the Nov. 1992 ROSAT PSPC spectrum, when V Sge was in an intermediate optical state and had a very soft X-ray spectrum. Dashed lines denote contours of constant absorbing column $n_{\rm H}/10^{20}\,{\rm cm}^{-2}$, dotted lines indicate white dwarf radii in units of $10^8$ cm. The radius and luminosity have been scaled to a distance of 1 kpc. **Bottom:** Comparison of the normalized HRI channel distribution of the photons during the May 1994 (dotted line; soft state) and Oct. 1994 (solid line; hard state) observations.

(at 1 kpc). The same bremsstrahlung component may also have been present during the soft X-ray state in Nov. 1992 without significantly affecting the confidence intervals in Fig. 2 of the spectral parameters of the soft component. We note that such a bremsstrahlung component is not inconsistent with the X-ray flux of an evolved secondary in a 12 hr binary (cf. Dempsey et al. 1993).

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. We note that the colliding wind scenario as discussed in Lockley et al. (1997) would predict a positive correlation between optical and X-ray emission, contrary to our finding. Vitello & Shlosman (1993) have modeled the UV line shapes of V Sge assuming a biconical accretion disk wind, and need high mass-loss rates to explain the observations, while they did not consider the possibility of a luminous shell-burning white dwarf. We also note that irradiation-induced winds with a rate of $10^{-7}$–$10^{-6}$ M$_\odot$/yr are expected in SSB (Van Teeseling & King 1998).

We conclude that it is possible to explain the optical and X-ray behaviour of V Sge by assuming a variable amount of extended uneclipsed matter which contributes significantly in the optical (by reprocessing of soft X-rays?) and may completely absorb the 'supersoft' X-ray component during the optical bright/hard X-ray state. The X-ray properties of V Sge, in any case, support the presence of a hot luminous white dwarf, possibly with hydrogen shell-burning, and do not hinder the addition of V Sge to the class of supersoft X-ray binaries. More detailed modelling of the changing optical light curves and ultraviolet and optical spectra are necessary to test this scenario.

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