Astron. Astrophys. 343, 183–196 (1999)

ASTRONOMY AND ASTROPHYSICS

Transient supersoft X-ray emission from V 751 Cygni during the optical low-state

J. Greiner[1], **G.H. Tovmassian**[2], **R. Di Stefano**[3], **A. Prestwich**[3], **R. González-Riestra**[4], **L. Szentasko**[5], **and C. Chavarría**[2]

[1] Astrophysical Institute Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany
[2] Observatorio Astronomico Nacional, Instituto de Astronomía, UNAM, AP 877, 22860, Ensenada, B.C., México Harvard-Smithonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[3] Laboratorio de Astrofísica Espacial y Física Fundamental, P.O. Box 50727, E-28080 Madrid, Spain
[4] Budapest, Hungary

Received 27 July 1998 / Accepted 23 November 1998

Abstract. We have observed V 751 Cyg with the ROSAT HRI in a target-of-opportunity mode during its recent optical low state and clearly detect it at a count rate of 0.015 cts s^{-1}. The X-ray intensity is a factor of 7–19 (depending on the exact X-ray spectral shape) higher than the upper limit obtained with the ROSAT PSPC during the optical high state, thus suggesting an anti-correlation of X-ray and optical intensity. Spectral investigations suggest a very soft X-ray spectrum. We investigate archival IUE data of V 751 Cyg and derive a distance of V 751 Cyg of d≈500 pc based on the extinction estimate of $E(B-V)$=0.25±0.05. This implies that the X-ray emission is very luminous, on the order of 10^{34}–10^{36} erg s^{-1}.

We have obtained quasi-simultaneous optical photometry and spectroscopy. The spectrum during the optical low-state is characterized by a very blue continuum and the presence of strong emission lines of the Balmer series and HeI. Also, HeII 4686 Å is clearly detected.

We establish that V 751 Cyg is a transient supersoft X-ray source and speculate that other VY Scl stars may also be of similar type.

Key words: accretion, accretion disks – stars: individual: HD 199178 – stars: individual: V 751 Cyg – stars: novae, cataclysmic variables – X-rays: stars

1. Introduction

Supersoft X-ray binaries (SSBs) have been established as a new class by ROSAT observations over the past several years (e.g. Greiner 1996 and references therein). Supersoft X-ray binaries are characterized by luminous (10^{36}–10^{38} erg s^{-1}) emission with typical temperatures of 20–40 eV, and are thought to contain white dwarfs accreting mass at rates sufficiently high to allow quasi-steady nuclear burning of the accreted matter (van den Heuvel et al. 1992). Although the estimated Galactic population is large (Di Stefano & Rappaport 1994), only a few sources in the Milky Way are known, because of the effect of interstellar absorption. Indeed, most of the known supersoft X-ray binaries (SSB) are located in external galaxies making detailed optical observations difficult.

The long-term monitoring of the transient supersoft X-ray source RX J0513.9-6951 (Schaeidt et al. 1993) has revealed quasi-periodic optical intensity dips of about 4 weeks duration (Reinsch et al. 1996, Southwell et al. 1996) which occur simultaneously to the X-ray on states. The similarity of the optical behaviour of this supersoft transient with that of VY Scl stars led us to speculate that some of the VY Scl stars may indeed be hitherto unrecognized supersoft transients. If true, this would allow us to search for and find new supersoft X-ray sources independent of X-ray surveys. This is important since the estimated population in the Galaxy is large (Di Stefano & Rappaport 1994), but only few systems are known. We have therefore systematically checked the 14 known VY Scl stars for their optical state over the last two years in order to carry out soft X-ray observations once a VY Scl star enters an optical low state. In this paper we report on the results of some of these observations, which indicate that at least one VY Scl star, V 751 Cyg, is a supersoft X-ray binary.

We begin below with a brief introduction to the properties of VY Scl stars in general, and V 751 Cyg in particular. We then go on in Sect. 2 and Sect. 3 to describe, respectively, our observations (Tables 1, 2) and results. In Sect. 4 we discuss V 751 Cyg, and address in Sect. 5 the question of whether other VY Scl stars may also be SSBs. In Sect. 6 we summarize our conclusions (see also Greiner & Di Stefano 1998).

VY Scl stars (or sometimes called anti-dwarf novae) are bright most of the time, but occasionally drop in brightness at irregular intervals by 2–8 magnitudes. The transitions between the brightness levels take place on a time scale of days to weeks. During the optical low states the optical Balmer emission lines become very narrow and show recombination ratios, the UV emission lines disappear and occasionally the infrared spectrum reveals the signatures of the cool donor star (see e.g. Warner 1995). These observations suggest that most or even all of the accretion disk disappears during the low state. VY Scl variables are typically found at $P > 3$ hrs (i.e. exclusively

Send offprint requests to: J. Greiner (jgreiner@aip.de)

Table 1. Log of ROSAT observations of V 751 Cyg

Date	JD	Detector	Exposure (sec)	Offaxis Angle (′)	CR[1] (cts s^{-1})	Opt. State
Nov. 19/20, 1990	2448216	PSPC	370	0–55	< 0.019	high
Nov. 3, 1992	2448930	PSPC	3637	52	< 0.0058	high
Jun. 3, 1997	2450603	HRI	4663	0.3	0.015±0.002	low
Dec. 2–8, 1997	2450788	HRI	10814	0.2	0.010±0.001	low

(1) The values for the two PSPC observations are 3σ upper limits. Note that the 0.015 HRI cts s^{-1} correspond to a PSPC rate of 0.039–0.11 cts s^{-1} (see Sect. 3.5).

Table 2. Log of optical observations

Date	JD	Telescope + Equip.	Filter/Wavelength	Duration (min)	Exp. (sec)	Site
Sep. 28, 1997	2450719	2.1m, B&Ch sp.	3600–7500 Å	60	600	SPM
Sep. 29, 1997	2450720	2.1m, B&Ch sp.	4290–8385 Å	30	600	SPM
Sep. 30, 1997	2450721	2.1m, B&Ch sp.	5460–8530 Å	80	1200	SPM
Sep. 30, 1997	2450721	1.5m, Danish Phot.	*uvby*-β	5	10	SPM
Dec. 03, 1997	2450785	1.5m, CCD direct	UBVRI	80	180–300	SPM

above the period gap), and with large mass transfer rate $\dot{M}\sim 10^{-8}\ M_{\odot}$/yr in the optical high state (upper right corner of the $P_{\rm orb}-\dot{M}$ diagram of Osaki 1995), and thus are thought to be steady accretors (or dwarf novae in a state of continuous eruption as suggested by Kraft 1964) with hot disks. Their disks are thus assumed to be thermally and tidally stable.

V 751 Cyg (= EM* LkHA 170 = SVS 1202) was discovered by Martynov (1958) and originally classified as an R Coronae Borealis star due to its irregular variations between 13.5–14.0 mag (pg) and the occasional fading down to about 16 mag (pg) (Martynov & Kholopov 1958). Further observations revealed additional strong fading events (Wenzel 1963), but spectroscopic results, most notably the lack of absorption lines and the continuous and very blue spectrum (Herbig 1958, Herbig & Rao 1972, Downes et al. 1995), are clearly inconsistent with the interpretation of a carbon-rich, pulsating late supergiant. Nowadays V 751 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).

V 751 Cyg has poorly determined binary parameter properties, though its classification as a VY Scl star is beyond doubt (Wenzel 1963, Robinson et al. 1974, Downes et al. 1995). Both the small reddening implied by the blue colors ($U-B\approx-1.02, B-V\approx-0.12$; see Burrel & Mould 1973, Munari et al. 1997) and the projected vicinity to both IC 5070 (920 pc) and the ^{13}CO cloud #34 (Dobashi et al. 1994; 800 pc) suggest that V 751 Cyg is at 800 pc distance at maximum. With these assumptions, i.e. no extinction and $d<920$ pc it has been deduced that V 751 Cyg is fainter than $M_{\rm V}\approx+4.8$ at maximum light, and fainter than $M_{\rm V}\approx+7.0$ at minimum light (Robinson et al. 1974). The orbital period of V 751 Cyg is not well known, the only report being that of Bell & Walker (1980) on $P\approx0\overset{\rm d}{.}25$.

Livio & Pringle (1994) proposed a model for the group of VY Scl stars in which optical low states are associated with a reduced mass transfer rate caused by a magnetic spot covering temporarily the L_1 region. This mechanism works predominantly at short orbital periods because the level of magnetic activity increases with the rotation rate of the star (which in turn is coupled to the orbit).

The above described model to explain VY Scl star low states may also work for supersoft X-ray sources (Alcock et al. 1997) with their longer periods because the magnetic activity actually scales like $P_{\rm rot}/\tau_{rmc}$ (= Rossby number) with τ_{rmc} being the convective overturn time in the envelope (Schrijver 1994). And τ_{rmc} is longer for stars with a deeper convective envelope, precisely what is expected for the evolved secondaries in supersoft X-ray sources according to the standard model (van den Heuvel et al. 1992, DiStefano & Rappaport 1994).

2. Observations

2.1. X-ray observations

After notification of the fading of V 751 Cyg in March 1997 we performed a target-of-opportunity HRI observation (after the opening of the ROSAT observing window) for a total of 4660 sec on June 3, 1997. We detect 12 X-ray sources above 4σ in the whole HRI field of view (Table 3) one of which coincides within 1″ with V 751 Cyg. This X-ray source, RX J2052.2+4419, is detected at a mean count rate of 0.015 cts s^{-1}, thus giving a total of 67 photons.

A second ROSAT HRI observation was performed on Dec. 2–8, 1997 in order to follow-up on this surprising detection. V 751 Cyg was again detected at a mean rate of 0.010 cts s^{-1} during this 10.8 ksec observation, yielding a total of 108 photons.

Table 3. List of X-ray sources found during the two HRI observations

	HRI pointing 1		HRI pointing 2				
Name	R.A. Decl. (2000.0)	CR[(1)] (10^{-3} cts s^{-1})	R.A. Decl. (2000.0)	CR[(1)] (10^{-3} cts s^{-1})	offaxis angle	D[(2)] ($''$)	Ident. (Type)
RX J2052.1+4426		<0.76	$20^h52^m09^s.2$ $+44^\circ26'04''$	1.5±0.4	$6'.9$	4.3	HD 198931 (B1V)
RX J2051.9+4425		<0.53	$20^h51^m59^s.0$ $+44^\circ25'44''$	1.5±0.4	$6'.9$	7.9	LkHA 164 (EM*)
RX J2053.2+4423	$20^h53^m15^s.2$ $+44^\circ23'17''$	7.4±1.4	$20^h53^m14^s.5$ $+44^\circ23'14''$	6.8±0.9	$12'.0$	1.4	HR 8001 (B5V)[(3)]
RX J2053.9+4423	$20^h53^m54^s.1$ $+44^\circ23'09''$	531±12	$20^h53^m53^s.7$ $+44^\circ23'11''$	412±7	$18'.7$	2.6	HD 199178 (G2V)
RX J2050.8+4421		<1.59	$20^h50^m51^s.5$ $+44^\circ21'47''$	2.4±0.8	$14'.6$		
RX J2052.2+4419	$20^h52^m12^s.9$ $+44^\circ19'26''$	14.6±1.8	$20^h52^m12^s.3$ $+44^\circ19'24''$	10.2±1.0	$0'.3$	0.9	V 751 Cyg (VY Scl)
RX J2052.4+4417		<0.75	$20^h52^m26^s.6$ $+44^\circ17'04''$	0.6±0.3	$3'.4$		
RX J2052.2+4415	$20^h52^m13^s.3$ $+44^\circ15'30''$	1.1±0.5		<0.36	$3'.7$		
RX J2052.7+4414	$20^h52^m44^s.2$ $+44^\circ14'35''$	1.5±0.6		<0.65	$7'.4$		
RX J2051.0+4411	$20^h51^m04^s.2$ $+44^\circ11'34''$	3.6±1.2	$20^h51^m02^s.8$ $+44^\circ11'39''$	3.2±0.8	$14'.3$		
RX J2053.4+4410		<1.79	$20^h53^m25^s.1$ $+44^\circ10'32''$	3.0±0.9	$15'.7$		
RX J2051.4+4408	$20^h51^m25^s.6$ $+44^\circ08'19''$	11.8±1.9	$20^h51^m24^s.7$ $+44^\circ08'16''$	13.9±1.4	$13'.7$	4.6	BD+43 3744(G5)
RX J2052.9+4407	$20^h52^m58^s.4$ $+44^\circ07'18''$	31.4±2.9	$20^h52^m58^s.0$ $+44^\circ07'16''$	121±3.6	$14'.5$		
RX J2051.4+4404	$20^h51^m27^s.3$ $+44^\circ04'26''$	7.2±1.7	$20^h51^m28^s.1$ $+44^\circ04'11''$	3.8±1.2	$16'.8$		

(1) Upper limits are 3 σ confidence level.
(2) Distance between best-fit X-ray position and optical position of presumed counterpart (the better of the two X-ray positions).
(3) The measured flux is consistent with being no X-ray emission, but solely UV emission of this $m_{\rm B}$=4.6 mag star due to the UV leak of the HRI (Berghöfer 1997).

The area around V 751 Cyg had been scanned during the ROSAT all-sky survey in Nov. 1990 for a total of 370 sec. No X-ray emission is detected from V 751 Cyg during the PSPC scans, giving a 3σ upper limit of 0.019 cts s^{-1}.

The location of V 751 Cyg was serendipituously observed in a pointed PSPC observation of the supernova remnant G84.2–00.8 (PI: Pfeffermann) on Nov. 11, 1992. Again, no X-ray emission is detected from V 751 Cyg. Though located at an off axis angle of 49$'$ in the ROSAT PSPC, the derived 3σ upper limit of 0.0058 cts s^{-1} is more stringent than that of the all-sky survey due to the larger exposure time.

A summary of all X-ray observations with ROSAT of the V 751 Cyg location is given in Table 1. Note that the count rates refer to the specific detector, and that the HRI is considerably less sensitive than the PSPC.

2.2. Archival IUE observations

While searching the available archival data on V 751 Cyg we became aware of unpublished IUE observations on April 25, 1985. The object appears in the observing log as A2050+455, and its coordinates coincide within 2$''$ with the position of V 751 Cyg. We have checked the position of the aperture, from the coordinates of the guide stars, and it coincides with the position of V 751 Cyg within a few arcsec. The magnitude, as given by the Fine Error Sensor onboard IUE was 14.2 mag. The absence of any other closeby object and the coincidence of the measured magnitude with the AFOEV (Association Francaise des Observateurs d'Etoiles Variables) database (m $\approx$ 13.8) confirm the identification. V 751 Cyg was therefore at or close to optical maximum at the time of the IUE observation.

The object was observed in low dispersion through the large aperture in both wavelength ranges: 1200–1950 Å (65 min; SWP25774) and 1800–3300 Å (47 min; LWP05819).

The spectra have been extracted from the bi-dimensional files with the ESA-INES system (Rodríguez–Pascual et al. 1998).

2.3. Optical observations

2.3.1. Photometric observations

V 751 Cyg is monitored by a number of amateur astronomers around the world, among them, one of us (LS). A collection of brightness estimates over the last 8 yrs is plotted in Fig. 1 showing V 751 Cyg to vary irregularly between 13.6 and 14.5 mag most of the time, consistent with earlier observations (Wenzel 1963). However, starting somewhere between March 1 and March 11, 1997, V 751 Cyg dropped in brightness to as low as $\approx$17.8 mag. Only recently, V 751 Cyg has started to recover from this low state.

We obtained photometric observations on two occasions. First, we observed V 751 Cyg on September 30, 1997 (coincident with the end of our spectroscopic runs; see below) with the Danish photometer installed at the 1.5 m telescope of the Observatorio Astronómico Nacional de San Pedro Mártir, Mexico (OAN-SPM). It was set-up to allow observations in the Strömgren photometric system. Three measurements of V 751 Cyg were taken together with standard stars. In addition, for the time of the second HRI observation we performed multicolor photometry with the 1.5 m telescope of OAN-SPM to ensure broad-band coverage in the Johnson UBVRI system.

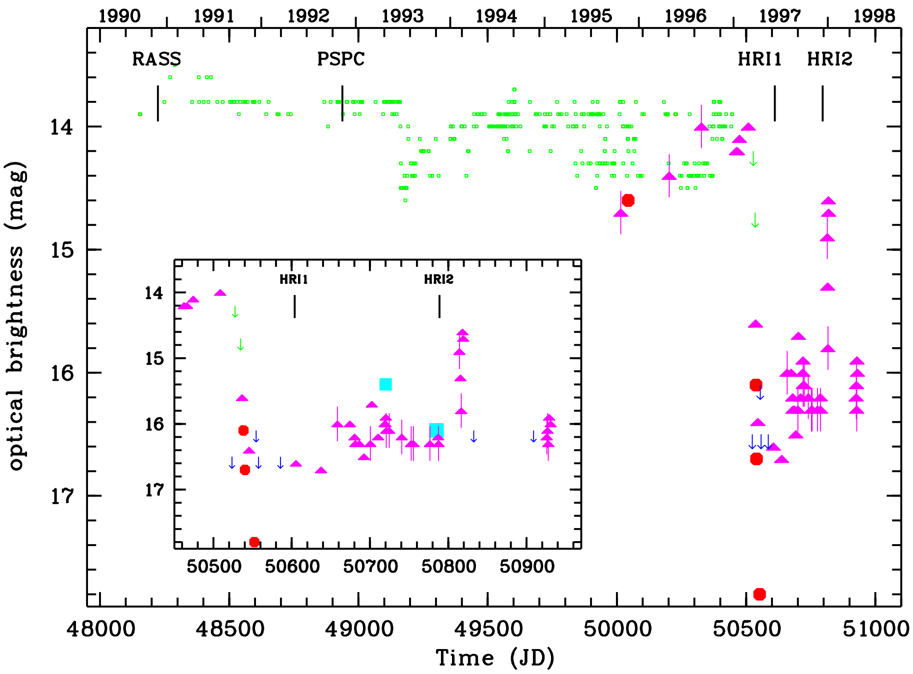

Fig. 1. Optical light curve of V 751 Cyg over the last 8 years: small (gray) squares denote measurements as reported to AFOEV and triangles denote measurements as reported to VSNET (uncertain measurements are plotted with an error bar while the error of the certain measurements is about the size of the 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. V 751 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 our spectra and our Dec. 3, 1997 photometry (at the time of the second HRI observation).

Standard fields PG2213-00.6 and RU 149 from Landolt (1992) were observed in the same night.

2.3.2. Spectroscopic observations

After the X-ray detection of V 751 Cyg we obtained optical spectra on the nights of September 28–30, 1997 at the 2.1 m telescope of OAN-SPM (Figs. 8, 9). The Boller & Chivens spectrograph was used with a 300 l/mm (400 l/mm in the last night) grating, thus covering the 3600–7500 Å (5500–8500 Å) range. In combination with a 2″ slit a 8 (6) Å FWHM resolution is reached. Exposure times of 600 sec (1200 sec during last night) were chosen. The spectrophotometric standard stars BD 284211 and G191-B2B were observed with the same settings as V 751 Cyg for flux calibration. During the last night the slit was inclined to accommodate a nearby star for tracing the flux variations, since the weather was not very good and tiny clouds were passing by.

The observational data were reduced using the IRAF package DAOPHOT and the corresponding routines for long slit spectroscopy. The optimal extraction method was used for extraction of the spectra from the two-dimensional images.

3. Results

3.1. Identification of the X-ray source with V 751 Cyg

In order to ensure a correct identification of the detected X-ray emission with V 751 Cyg, we have investigated several alternatives: (1) Check of the attitude solution: There are no indications of any anomaly in the guide star acquisition. Next, from the 14 X-ray sources in the HRI field of view, five sources in addition to V 751 Cyg have rather secure optical identifications based on the positional coincidence, spectral type and the $L_{\rm X}/L_{\rm opt}$ ratio. Also, a few sources have been detected during the all-sky survey with positions which are consistent within their errors to those derived from our pointings, i.e. #4 ≡ 1RXS J205353.7+442308, #12 (detected with a count rate of 0.018±0.07 cts s^{-1} (just below the count rate threshold for inclusion in the 1RXS catalog) at R.A. = $20^{h}51^{m}28\overset{s}{.}2$, Decl. = 44°08′02″) and #13 ≡ 1RXS J205257.8+440716. Finally, 9 out of the 14 sources are detected in both of the two independent pointings, including V 751 Cyg. (2) Mis-identification: Given the correct attitude solution and the fact that there is no optical object brighter than about 20th mag (due to some nebulosity associated with the Cyg T1 association) within the 10″ X-ray error box (see Fig. 2), we consider a mis-identification as very improbable. (3) Background source: Due to the very soft X-ray spectrum a variable X-ray source located along the line of sight towards V 751 Cyg must have a distance smaller than the molecular clouds at 800–920 pc. Such a source, if it were not V 751 Cyg, cannot be excluded, but its peculiar properties (X-ray intensity amplitude; no accompanied optical variability) are unlike any known variable X-ray source population.

3.2. Relation of optical and X-ray intensity

Combining the optical monitoring data with the X-ray upper limits and detection of V 751 Cyg (Fig. 1) reveals that the two X-ray non-detections occurred during the optical high state whereas the X-ray detections occurred during the optical low state. We therefore find evidence supporting an anti-correlation of optical and X-ray intensity in V 751 Cyg.

3.3. The extinction towards and distance of V 751 Cyg

The UV spectrum shows a broad absorption centered at 2200 Å which is the typical signature of interstellar absorption. The reddening toward V 751 Cyg has been estimated by remov-

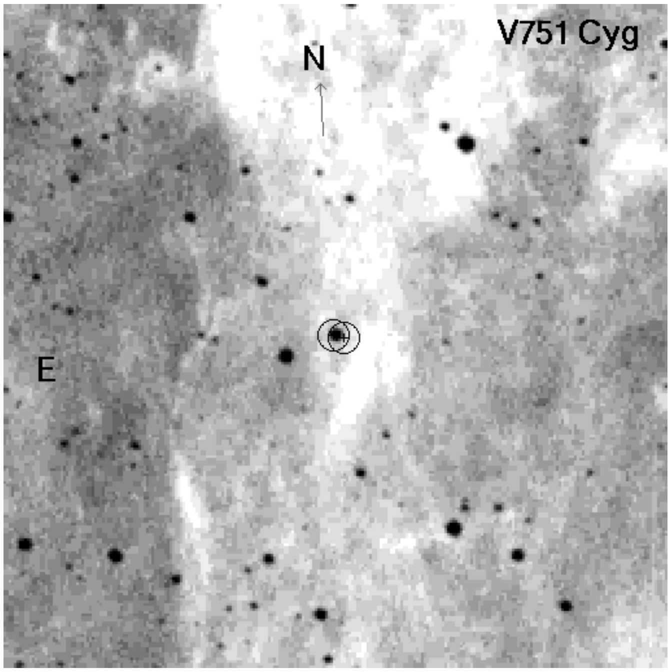

Fig. 2. A $7' \times 7'$ digitized sky survey image with the $10''$ X-ray error radii of the two HRI observations overplotted. V 751 Cyg is the only visible optical source down to $\approx 20^{\mathrm{m}}$. The grey colors are due to the diffuse, nebular optical emission in this region.

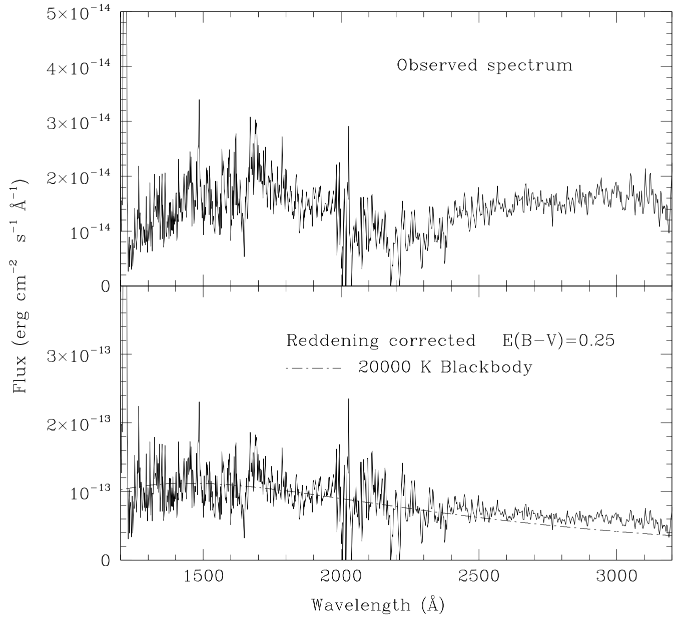

Fig. 3. Archival, observed IUE spectrum of V 751 Cyg (*top*) taken on April 25, 1985. The two peaks near 1480 and 2020 Å are cosmic rays affecting the spectrum. The spectrum corrected for extinction of $E_{\mathrm{B-V}}$=0.25 is shown in the *bottom panel* together with a blackbody model of 20000 K.

ing this feature by using a standard galactic interstellar absorption law and different values of the color excess. The best result is obtained with $E(B-V) = 0.25 \pm 0.05$. No assumption about the intrinsic spectral shape of the spectrum has been made to evaluate the correction.

With the intrinsic color $(B-V)$ being near zero, the above color excess implies a visual extinction of $A_{\mathrm{V}} = 0.82 \pm 0.17$. Using a mean extinction law of 1.9 mag/kpc (Allen 1973) we derive a distance to V 751 Cyg of 430±100 pc (the error being solely due to the error in $E(B-V)$). Alternatively, using the extinction distribution as estimated by Neckel & Klare (1980) results in d $\approx$ 610±30 pc. Because of the global nature of the extinction determination in both cases and the possibility that circumbinary extinction cannot be excluded (which would reduce the derived distance), we will adopt d=500 pc in the following. We mention that this is consistent with the previous upper limit of 800 pc (Dobashi et al. 1994). For the sake of ease in the later sections (describing the X-ray spectral fits) we note that the above A_{V} corresponds to a neutral hydrogen column density of N_{H} = (1.1±0.2)×10^{21} cm^{-2}, using the relation A_{V} = 17/23× N_{H} [10^{21} cm^{-2}] as derived by Predehl & Schmitt (1995). The above values and a maximum and minimum brightness of $m_{\mathrm{V}}^{max} = 13.2$ mag (Martynov 1958) and $m_{\mathrm{V}}^{min} = 17.8$ mag (Ouda team CCD photometry, from VSNET) imply absolute magnitudes of $M_{\mathrm{V}}^{max} = 3.9$ mag and $M_{\mathrm{V}}^{min} = 8.5$ mag.

Even after the reddening correction, we do not see a rising continuum toward the shorter wavelengths which could be attributed to the presence of a hot white dwarf in this binary system.

The UV spectrum (Fig. 3) has a low S/N and it is nearly featureless, except for a prominent absorption near 1640 Å, which can be ascribed to HeII. Other features, as the emissions near 1590 Å and 3200 Å, are cosmic rays affecting the spectrum. No other emission line can be unambiguously identified. In particular, there is not any noticeable feature near the positions of the N V 1243 Å, Si IV 1400 Å, C IV 1550 Å, or MgII resonance lines which are seen in other VY Scl stars during high state (see e.g. LX Ser; Szkody 1981, MV Lyr, Szkody & Downes 1982, or TT Ari, Shafter et al. 1985; PX And, Thorstensen et al. 1991; BH Lyn, Hoard & Szkody 1997). UV spectra of VY Scl stars at different brightness levels are shown in la Dous (1993). In particular, the spectrum described here resembles most that of TT Ari in high state, although the spectral features are less marked in the case of V 751 Cyg.

3.4. The inclination of the V 751 Cyg binary

La Dous (1991) has shown in her study of a large number of IUE spectra of dwarf novae and nova-like stars, that there exists a clear relation between the inclination of the system and the equivalent width of some UV lines. Her sample includes nine VY Scl stars. The VY Scl sample follows the same trend as other nova-like stars: for high values of inclination ($\gtrsim$70°), the lines are in emission, with large equivalent widths, and for lower inclinations the equivalent widths decrease so that for nearly face-on systems the lines are in absorption.

The lack of evident emission lines in the spectrum of V 751 Cyg (Fig. 3) therefore points to a low inclination. Although the S/N ratio of the IUE spectrum is low, we have estimated the equivalent widths of some lines, namely Si IV 1400 Å (EW 2.7 Å), C IV 1550 Å (13 Å), the blend Al III+Fe III 1860 (5.5 Å) and Mg II 2800 Å (0.7 Å) (note that in la Dous' not tion positive equivalent widths mean absorption lines). A com parison with the equivalent widths of the VY Scl systems wi known inclination (taken from the compilation of Greiner 1998 results in a value for the orbital inclination of V 751 Cyg i=30±20°. In any case, it can be said conservatively that t inclination of the system is <50°.

3.5. *The X-ray spectrum and luminosity of V 751 Cyg*

Given the sensitivity dependence of the HRI to the X-ray spe tral shape (soft vs. hard spectrum), the comparison of the PSP and HRI count rates/upper limits requires some knowledge the X-ray spectrum of V 751 Cyg during the HRI observation. Before discussing this below, we note that the conversion factors for the two extremes are 2.7:1 and 7.8:1 (Greiner et al. 1996) for a very hard and a very soft spectrum, respectively. Thus, the HRI count rate of 0.0146 cts s^{-1} translates into a corresponding PSPC count rate between 0.039 and 0.11 cts s^{-1}.

The need to quantify the X-ray spectral shape has motivated us to study the pulse height distribution in more detail. The CsI-coated micro-channel plates of the HRI provides some crude spectral sensitivity, and we have used two approaches to determine the spectral characteristics. First, we have compared the pulse height distribution of the V 751 Cyg observation with other, on-axis observations of sources with known (from PSPC observations at about the same time) soft X-ray spectra in order to derive a rough idea for the interpretation of the shape of the pulse height distribution of V 751 Cyg. Based on the description of the temporal gain changes of the HRI as described in the recent HRI calibration report (David et al. 1997), in particular their Fig. 20, we have then shifted the pulse height distributions of these selected observations to match the gain status of our HRI observation on June 3, 1997. The result is shown in Fig. 4 and suggests that the V 751 Cyg spectrum is neither an unabsorbed supersoft spectrum nor a strongly absorbed hard spectrum, but similar to RX J0927.7–4758, i.e. a soft source suffering some absorption.

In a second step, we make use of new software developed to allow improved spectral analysis of HRI data (Prestwich et al. 1998). The CsI coating on the microchannel plates means that the HRI has two-color energy resolution above and below 0.62 keV. We have used this spectral response to study the pulse height distribution of V 751 Cyg in more detail. Full details of the HRI spectral calibration will be given in a separate paper (Prestwich et al. 1998); here we give a summary of the calibration procedure. A spatial gain map and spectral response matrix (for the center of the detector) were produced from ground calibration data. However, this response matrix cannot be used for in-flight data because the gain changes slowly with time throughout the mission, with occasional "jumps" when the gain is adjusted from the ground. To solve these problems, the spatial and temporal gain variations have been tracked using the Bright Earth (BE) data. The BE data is dominated by scattered solar

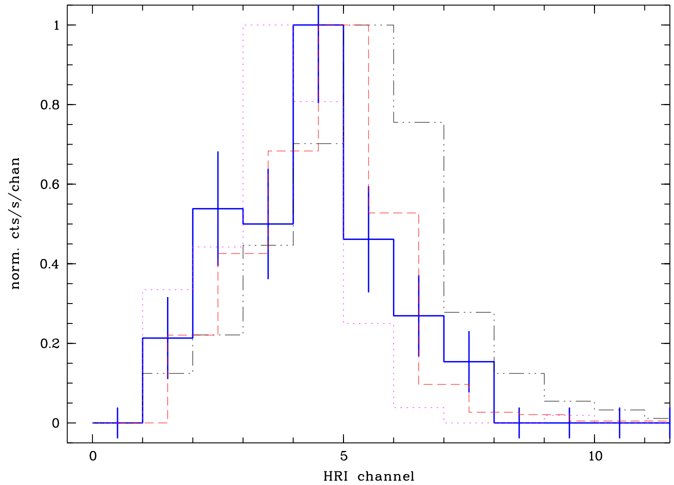

Fig. 4. Comparison of the HRI pulse height distribution of V 751 Cyg (thick line) with those of an extremely absorbed hard X-ray source (GRS 1915+105 – dash-dot-dot line), an moderately absorbed supersoft source (RX J0925.7–4758 – dashed line) and a slightly absorbed supersoft source (AG Dra – dotted line). All sources have been observed on-axis, and the temporal gain change between the observations (distributed over three years) has been taken into account (corrected to the June 1997 observation of V 751 Cyg).

X-rays: the dominant feature is the oxygen Kα line at 525 eV. It is effectively a monochromatic flat field, and is used to monitor gain changes throughout the mission. Using the BE data and other calibration sources it is possible to shift the response matrix derived from ground-based observations to the gain state of any given observation. There is, however, one further complication: the HRI is "wobbled" and as the source is moved across the detector the gain may change. Hence it is important to derive a response matrix weighted by livetime for a given source position. This is done by de-applying the aspect solution to calculate the detector position and gain of a source versus time.

The observation of V 751 Cyg on June 3, 1997 is on axis and was obtained very shortly after the HRI gain was increased on May 13 1997. Analysis of BE data obtained after the change indicate that the maximum of the BE gain function lies at HRI PHA channel 4.5, requiring a shift in the ground-based response matrix of approximately 0.6 channels. Fits using this response matrix to the photons extracted from a 15-pixel radius around the position of V 751 Cyg and background subtracted from a circular ring region of 8 pixel width result in the confidence contour map shown in Fig. 5. From this figure it is clear 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.

Since the absorbing column cannot be constrained from the X-ray data, we fix the absorbing column at $N_{\rm H}$ = 1.1×10^{21} cm^{-2} as derived from the IUE spectrum (Sect. 3.3). The best-fit temperature of the blackbody model is 5 eV, and the formal 90% confidence error is about $^{+10}_{-5}$ eV (see the confidence contours in Fig. 5).

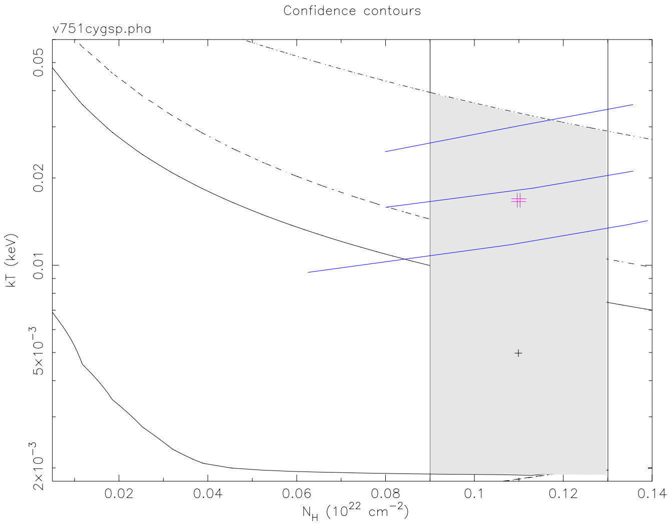

Fig. 5. Spectral fit result of the June 1997 ROSAT observation of V 751 Cyg: Confidence contours of the blackbody fit in the $kT - N_{\rm H}$ plane: 68% (solid line), 90% (long-dashed line), 99% (short-dashed line). The two vertical lines denote the $N_{\rm H}$ range allowed by the IUE data ((1.1±0.2)×10^{21} 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^{-1} (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 following discussion (see text).

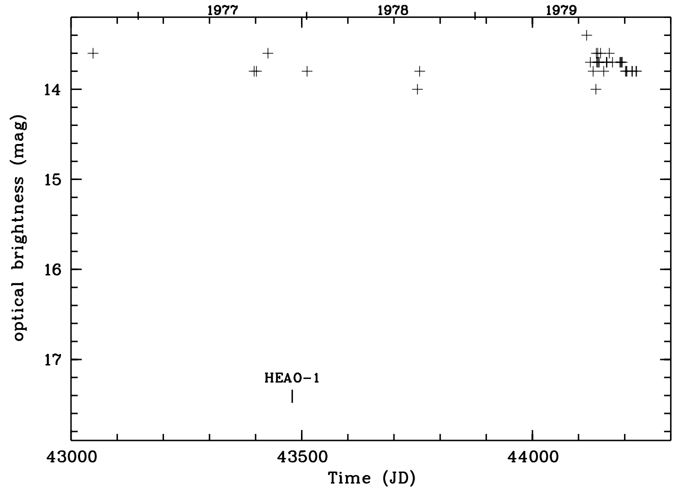

Fig. 6. Optical light curve of V 751 Cyg (data from AAVSO) around the time of the HEAO-1 A2 observation in 1977. Though the coverage is sparse, it seems justified to assume that V 751 Cyg was in its optical high (normal) state during that X-ray observation.

The luminosity determination of V 751 Cyg is a delicate problem because of the softness of the emission (we measure just the very end of the Wien tail), the uncertainties given by the detector response at these very soft energies, and the intercorrelation of spectral shape and absorbing column. In addition, the deduced luminosity also depends on the applied model with white dwarf atmosphere models giving typically a factor of 10–100 lower luminosity than a blackbody model. Though for simplicity we applied a blackbody model (also justified by the poor spectral energy resolution) we took several steps in order to determine a minimal luminosity. As a first step, we minimized the effect of the absorbing column by fitting a gaussian line with a width that corresponds to the energy resolution of the detector and without applying any absorbing column. This results in a best-fit centroid of 9 eV and a luminosity of 2×10^{31} erg s^{-1} in the 0.1–2.4 keV range. As the next step, we introduce absorption, i.e. fit an absorbed gaussian line with the absorbing column fixed at an amount as derived from the IUE data. The result is a centroid energy of 2 eV (at the fixed $N_{\rm H}$=1.1×10^{21} cm^{-1}), and the luminosity in the ROSAT band (0.1–2.4 keV) alone is 5×10^{33} (D/500 pc)^2 erg s^{-1}. Considering the full flux under the gaussian, e.g. adding up the flux below 0.1 keV, rises the luminosity to 7×10^{33} (D/500 pc)^2 erg s^{-1}. We consider this the absolutely minimal flux which can be accomplished by the IUE-derived extinction and the HRI detection, since any other model will have a wider shape than a gaussian function. Since the best-fit value derived with the blackbody model implies extremely high luminosity, we adopt $kT = 15^{+15}_{-10}$ eV in the following (and $N_{\rm H}$=1.1×10^{21} cm^{-1} from the IUE spectrum). At this temperature the bolometric, unabsorbed luminosity is $L = 6.5 \times 10^{36}$ (D/500 pc)^2 erg s^{-1}.

The HRI pointing on Dec. 3, 1997 shows V 751 Cyg to be in the same intensity and spectral state as during the June 1997 observation. This suggests that the soft X-ray emission is present throughout the whole optical low state.

3.6. *Re-assessment of the HEAO-1 detection of V 751 Cyg*

V 751 Cyg has been listed as the only detected VY Scl star besides MV Lyr within the HEAO-1 A2 survey of more than 200 cataclysmic variables (Cordova et al. 1981). This survey used data of one of the low-energy detectors (LED1), a proportional counter sensitive in the 0.18–2.8 keV range (Rothschild et al. 1979). The field of view was collimated to 1$.\!\!^\circ$5 (FWHM) in and 3° (FWHM) perpendicular to the scan direction. V 751 Cyg was scanned during Nov. 25–Dec. 2, 1977 and is reported with an upper limit of <2.56 cts/sec at 0.18–0.48 keV and a detection at 3.95±0.90 cts/sec in the 0.48–2.8 keV band (Cordova et al. 1981). Using a thermal bremsstrahlung spectrum with kT = 10 keV and $N_{\rm H}$ = 1×10^{20} cm^{-2} Cordova et al. (1981) give a conversion rate of 3×10^{-11} erg/cm^2 s^{-1} per LED1 cts/sec in the 0.48–2.8 keV band. Though the absorbing column to V 751 Cyg is larger than this assumption, the effect on the absorption corrected flux is not large. Thus, the detected count rate corresponds to 1.2×10^{-10} erg/cm^2 s^{-1} in the 0.48–2.8 keV band.

This flux corresponds to a ROSAT PSPC count rate of 16 cts s^{-1}, much higher than any of our ROSAT measurements of V 751 Cyg. The reported HEAO-1 A2 count rate is also a factor of 5 larger than that of MV Lyr (Cordova et al. 1981), the second brightest VY Scl star at X-rays (Greiner 1998). This motivated us to check the optical state of V 751 Cyg during the HEAO-1

A2 observation as well as to investigate the possibility of misidentification of the X-ray emission detected with HEAO-1 A2.

Data from the AAVSO database (courtesy J. Mattei) indicate (though the coverage is poor) that V 751 Cyg was seemingly in the optical high state during the HEAO-1 A2 observation. Given the same optical state during the HEAO-1 A2 and the ROSAT PSPC observations but the huge difference in X-ray intensity, it is extremely unlikely that the identification of the HEAO-1 A2 X-ray source (with a position uncertainty of 1°.5–3°) with V 751 Cyg is correct.

We therefore have attempted to identify a better candidate counterpart for the HEAO-1 A2 X-ray source. The ROSAT all-sky survey data reveal more than a dozen X-ray sources within 3° of V 751 Cyg, the brightest of which is the FK Com star (spectral type G2V) HD 199178 (Bopp & Stencel 1981). However, it has a quiescent count rate of 1.6 cts/sec, a factor of 10 too low to account for the emission seen with HEAO-1 A2. Even adding up the fluxes of all ROSAT sources which potentially could have been within the collimated LED1 field of view would give about 4 cts s^{-1}, still a factor 4 below the HEAO-1 A2 rate. On the other hand, HD 199178 was around maximum of its 9 yr activity cycle at the end of 1977 (Jetsu et al. 1990), and it is thus conceivable that it was observed with HEAO-1 A2 during a flare. While this possibility can be checked by a temporal analysis of the HEAO-1 A2 data, we propose tentatively that HD 199178 (which is only 18′.5 away from V 751 Cyg) is a better counterpart candidate than V 751 Cyg to the X-ray source detected with HEAO-1 A2.

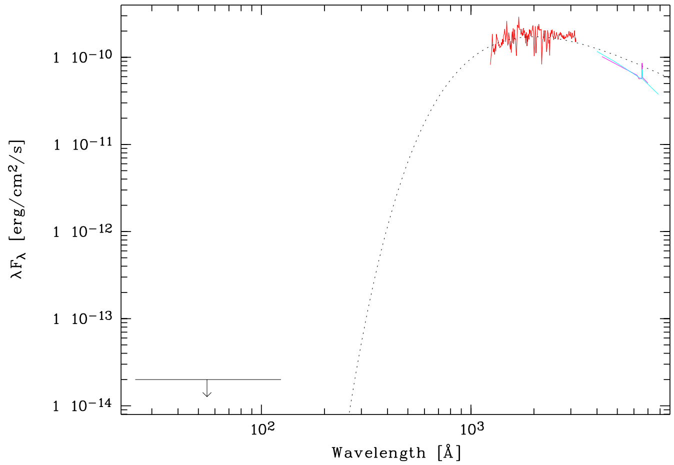

Fig. 7. Broad-band energy spectral distribution of V 751 Cyg during the optical high-state. Combined are observations of different epochs, but all during optical high-state: The ROSAT upper limit from Nov. 1992, the IUE spectrum from April 1985, the optical spectra (both at $m_V = 14.3$) from May 1986 (Downes et al. 1995) and Oct. 1994 (Munari et al. 1997). Overplotted is a 3×10^4 K accretion disk spectrum demonstrating that the UV/optical emission can be well reproduced by optically thick emission.

3.7. The optical emission

The Strömgren photometry performed on September 30, 1997 yields the following results for V 751 Cyg: v=16.28±0.06, b-y=0.17±0.02, m1=0.16±0.02, c1=–0.14±0.03, β=3.95±0.02 (including systematic uncertainties). The narrow Strömgren u, b and y filters measure mostly continuum in cataclysmic objects, although HeII 4686 Å contributes in the b band. The v and β filters are dominated by Hγ and Hβ, respectively. Thus, the c_1 index c_1=(u-v)-(v-b) is a reflection of the Balmer discontinuity (it is negative, when the Balmer jump is in emission), while m_1= (v-b)-(b-y) is a more complex index. For the possible interpretation of the above mentioned magnitudes we refer to the survey of dwarf novae by Echevarria et al. (1993). The comparison of the obtained values shows that V 751 Cyg at the moment of the observation was occupying an extreme place in the range presented by dwarf novae, but with some reservations could be fitted in between quiescent systems and systems in rise, which actually corresponds to the optical state of V 751 Cyg during this time. The most extreme value is that of β which is much higher than most of the systems caught in the maximum or rise. This could partially be due to the contribution of the nebular background emission, but it also is consistent with a reduced mass transfer rate and low intensity contribution of the disk.

The broad band photometry on Dec. 3, 1997 has found V 751 Cyg at U=15.53±0.02, B=16.17±0.01, V=16.08±0.01, R=15.58±0.01, I=15.36±0.01. These errors are according to the accuracy of the aperture photometry and do not include systematic uncertainties (see Fig. 9) and the magnitudes are corrected for the air mass by interpolation of the observed standard fields. However, extinction coefficients were not calculated in accordance to the generally adopted technique, so in Fig. 9, the error bars reflect possible deviations of magnitudes due to the extinction. In general, there is good agreement between the September spectrophotometry and the December broad band photometry which was conducted simultaneously with the second HRI observation.

In the September 1997 spectroscopy we detect strong and relatively narrow emission lines of the Balmer series up to H9, and many strong HeI emission lines (see a sample spectrum in Fig. 8). The high-excitation He II 4686 Å line is moderately strong while C III/N III 4640–4650 Å is present but very weak. The Balmer decrement is very shallow. The mean ratio of Hδ:Hγ:Hβ:Hα is 0.65:0.8:1.0:1.6, thus implying a rather high electron density and temperature. According to Drake & Ulrich (1980) the electron densities N_e would range from $10^{13} - 10^{14}$ cm^{-3} with relatively low optical depth in Lα of the order of 10^3–10^4 and a relatively weak ground-state photoionization rate of 3×10^{-2} s^{-1}. The Balmer decrement is less sensitive to the effective temperature and fits to the narrow range of temperatures $(2–4) \times 10^4$ considered by Drake & Ulrich (1980). The FWHM of the Hα line varies between 12 and 17 Å along with significant variations of the continuum level and slope of the spectrum. Since we used a narrow slit (but did not orient it along the parallactic angle), and atmospheric conditions were far from perfect, we calibrated the last night observations by a field star which was placed in the slit. For V 751 Cyg we detected significant variations of continuum intensity and slope of the spectra, especially from one night to the other which hardly

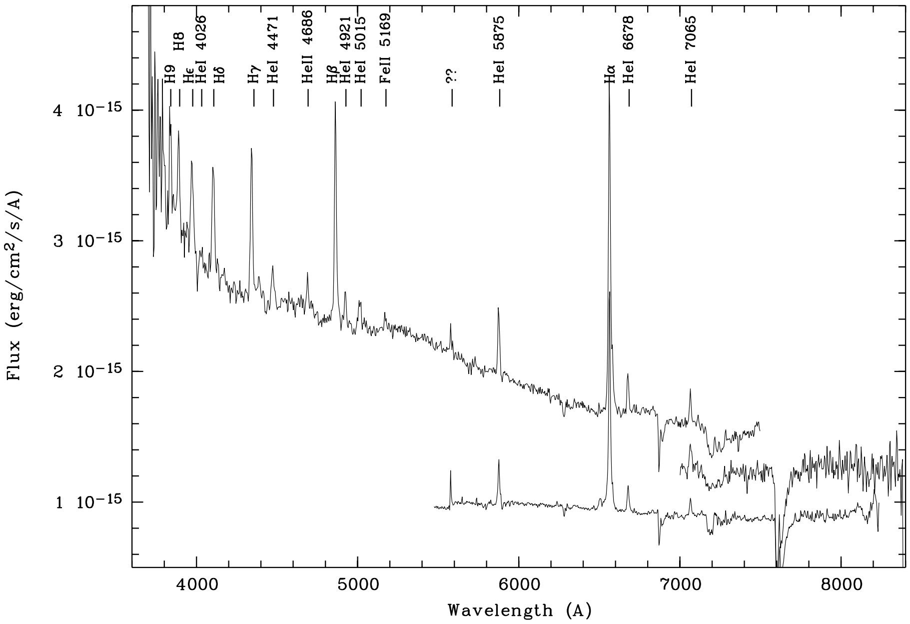

Fig. 8. Composite of a blue- and red-arm spectrum of V 751 Cyg taken on Sep. 30, 1997 (JD = 2450722). The continuums intensity around 5500 Å corresponds to $m_V \approx$ 15.4 mag. The spectra have not been reddening corrected.

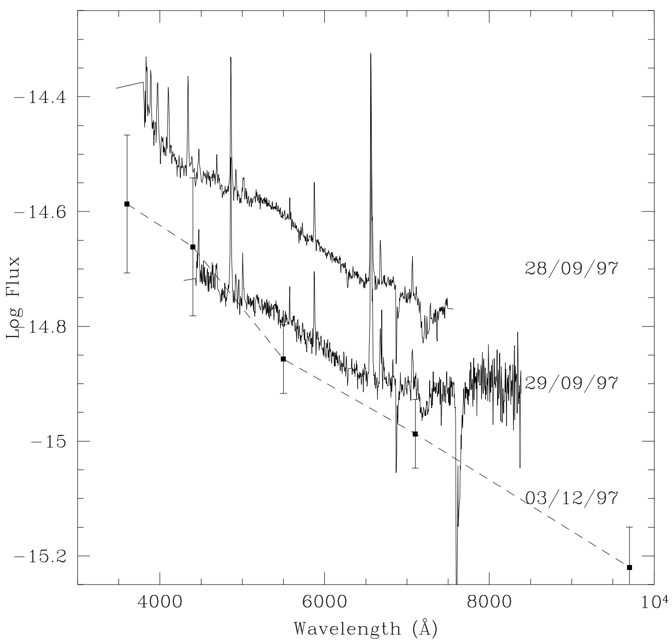

Fig. 9. Comparison of the variability of the global shape of the optical spectrum within a few days. For Dec. 3, 1997 (the time of the second ROSAT HRI observation) we have connected our UBVRI photometry by a dashed line to visualize the global shape. The error bars reflect both the errors of transformation and extinction uncertainty.

can be accounted for imperfection of our observing/reduction techniques and probably are due to the intrinsic variations of the V 751 Cyg. However, we do not find continuous variations of intensity or radial velocity with the suspected orbital period of 6 hrs (though the observations covered only 4 hrs). Extreme cases of spectra at different nights are shown in Fig. 8.

The emission line spectrum could be interpreted as arising from the wind of the secondary or alternatively as an optically thin accretion disk. The lines are not very broad (half widths at the base of ∼1200 km s^{-1}), probably due to orbital and/or turbulent motion in the low inclination disk. Also, the high-excitation line He II 4686 Å is clearly detected though not as strong as in magnetic cataclysmic variables or supersoft X-ray binaries. Finally, the shallow Balmer decrement of V 751 Cyg is similar (though somewhat steeper) to that observed in some other VY Scl stars at intermediate brightness levels (e.g. in Sep. 1980 in MV Lyr; Fig. 5 in Robinson et al. 1981). In contrast, the VY Scl star low state spectra have very narrow and fainter emission lines which have been interpreted to arise in the heated chromosphere of the secondary. Based on these three facts and a $m_V \approx 15.4$ (i.e. at least 2 mag brighter than during the low-state) deduced from a line-free region of our spectra around 5500 Å we conclude that V 751 Cyg was observed in an intermediate state. It is, however, difficult to assess whether the accretion disk disappeared in the early phase of the low state and had been reestablished by September or whether a residual disk always remained.

The detection of the high-excitation He II 4686 Å line during our intermediate state spectroscopic observations in September 1997 is in line with the X-ray detections in June and December 1997, since its ionization implies the presence of E>54 eV photons. This confirms the conclusion drawn from the December 1997 HRI observation that seemingly the soft, luminous X-ray emission is "on" throughout the optical low state and not just a short-lived, temporary event. We therefore may anticipate that the He II emission is even stronger during the low state, and that its intensity declines together with that of the X-ray emission as the optical brightness rises towards maximum.

We do not detect any signature of the companion in the red part of the spectrum. This is compatible with the expectation of a M0–1 main-sequence star according to a $P \approx 6$ hrs binary and the mass-radius relation of Patterson (1984) which would have $m_V \approx 18$ mag at 500 pc. We note that an early- to mid-F type companion as suggested by Downes et al. (1993) is far too bright to be consistent with our spectra and $d \lesssim 1$ kpc.

4. V 751 Cyg

4.1. V 751 Cyg as a supersoft X-ray binary

The following picture emerges. During optical low states V 751 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 nearly simultaneous with the ROSAT HRI data also indicates the presence of photons with energy >54 eV. V 751 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 V 751 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 V 751 Cyg values of $M_{\rm V}^{\rm max} = 3.9$ (see Sect. 3.3) and $\log\Sigma = \log(L_x/L_{\rm Edd})^{1/2} P_{\rm orb}^{2/3}(hr) = -0.23$ 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.

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 V 751 Cyg is probably comparable to that in supersoft X-ray binaries because the illumination depends on the ratio of companion radius and binary separation which is similar in both kind of systems. In addition, second order effects are competing against each other, e.g the mass ratio dependence of the illumination would imply larger heating in supersoft X-ray binaries while the flared disks in these systems are also thought to occult the donor near the equatorial plane from illumination. Unfortunately, no photometry has been obtained during the optical low state to immediately test for this effect in V 751 Cyg though it is anyway not expected to produce a strong modulation due to the low inclination (see Sect. 3.3).

The question of the illumination of the accretion disk has to be addressed separately for optical low and high state. As mentioned above, there is 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 V 751 Cyg due to the lack of optical observations, the disk is certainly optically thin thus drastically reducing the effectivity 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 flaring of the accretion disk. As was first shown by King (1997) and later argued by Knigge & Livio (1998), reprocessing of the radiation from the white dwarf will begin to have a dominant effect on the local disk temperature 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 >2×10^5 K ≡ 17 eV. This is seemingly just a value between the temperatures of SSS (30–50 eV) and V 751 Cyg (15 eV), implying that one difference of the systems could be that the disk in V 751 Cyg (if burning continues during the optical high state) 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.

4.2. Comparison of V 751 Cyg to RX J0513.9–6951

Our discovery of V 751 Cyg as a transient supersoft X-ray source arose from the similarity in the optical light curve of RX J0513.9–6951 and VY Scl stars. In this section we discuss the similarities and differences between these two systems. We note that, even if the underlying mechanisms are completely different, the somewhat similar anticorrelations between X-ray and optical have proved useful.

RX J0513.9–6951 shows ∼4 week optical low states which are accompanied by luminous supersoft X-ray emission. 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 of the 1 mag intensity variation in RX J0513.9–6951 (Southwell et al. 1996, Reinsch et al. 1996). Larger amplitudes are difficult to explain in this scenario. However, 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 main features of the X-ray/optical variability of V 751 Cyg could be explained by the same scenario as proposed for 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). If one approximates the contraction time scale by the duration of the mass-ejection phase (Livio 1992) then the ≈50 days transition time of V 751 Cyg into the low state implies a white dwarf mass of ≈0.8 $M_{\odot}$.

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 V 751 Cyg). Note that the

≈15 eV blackbody model derived as the best fit for V 751 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.

5. Are other VY Scl systems also SSBs?

The finding of luminous, supersoft X-ray emission during the optical low state of V 751 Cyg naturally leads to the question on how the properties of the VY Scl star group as a whole fit into the scenario of a SSB interpretation. After a short recollection of the X-ray properties of VY Scl stars we consider the mass ratios, orbital periods, and other system properties of VY Scl stars. These characteristics yield some clues as to why V 751 Cyg is a SSB and whether any other members of the VY Scl stars may also be SSBs. The tentative interpretation we will make is that V 751 Cyg and possibly other VY Scl systems may represent an extension of the close-binary supersoft source model (van den Heuvel et al. 1991, Di Stefano & Nelson 1996) that appears to apply to other SSBs.

5.1. X-ray emission of VY Scl stars at optical high state

Not much is known about the systematics of the X-ray behaviour of VY Scl stars. In a recent survey of available ROSAT data on all known VY Scl stars (Greiner 1998) their X-ray emission properties during optical high states were found to be limited to a very narrow range of temperature and luminosity. Blackbody models gave the best fits to the X-ray spectra, resulting in temperatures of 0.25–0.5 keV and luminosities in the 10^{30}–10^{32} erg s^{-1} range. While the emission process and location is not clear, the surprise is twofold in that VY Scl stars show a homogeneous X-ray spectral shape during their optical high state, and that their X-ray spectra are distinct from other non-magnetic cataclysmic variables (see also van Teeseling et al. 1996).

The upper limits derived for V 751 Cyg during the optical high-state ($L_X < 10^{31}$ erg s^{-1}) would allow for the existence of such a 0.25–0.5 keV blackbody. If, however, such a 0.25–0.5 keV blackbody existed in V 751 Cyg during the optical high state at the same intensity level as observed in most VY Scl stars then it must have vanished during the transition to the optical low state and has been replaced by the extremely soft emission of ≈15 eV.

5.2. Are all VY Scl stars supersoft X-ray binaries?

5.2.1. Group properties of VY Scl stars and how they fit the supersoft X-ray binary scenario

Donor masses and the mass ratio: In 11 of the 14 VY Scl stars, optical emission line studies indicate that the donor has a mass smaller than $0.5\ M_\odot$. In addition, the ratio between the donor's mass and that of the white-dwarf accretor seems to be close to unity in some systems. Although there is no spectral information about the donor in any SSB, and only indirect evidence about the mass of the white-dwarf accretor, the mass of the donor and the mass ratio are both typically assumed to be larger, by factors ∼2. These larger values emerge largely from theoretical models, and are needed to produce a mass transfer rate, $\dot{m}$, large enough ($\sim 10^{-7}\ M_\odot$/yr) to allow the accreting matter to burn steadily on a white dwarf.

Mass of the accreting white dwarf: If the mass of the donor is small, and the mass ratio is close to, or even smaller than unity, then the white dwarfs in VY Scl systems may be less massive than generally considered in models for SSBs. In fact, in several cases, the estimated lower limit on the mass of the white dwarf is low enough to be consistent with a He white dwarf. Therefore, if the lower limit is correct in any of these cases, we may be seeing an extension (Sion & Starrfield 1994) 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 temperature.

White dwarf temperatures White dwarf temperature estimates in VY Scl stars have been proved difficult, and only for four systems temperatures indeed have been suggested ranging around 50 000 K. It has been argued by Warner (1995) that if true the "high temperatures" of these few VY Scl stars as compared to other cataclysmic variables are not due to "simply radiating their original core energies". A detailed look at the four systems gives the following picture: (1) DW UMa: The temperature may be incorrect because the primary may be obscured by the disk (Warner 1995). (2) V 794 Aql: the temperature goes back to the fit of a Wesemael white dwarf model to "a hint of Ly-alpha absorption", and is "consistent with a high temperature" (Szkody et al. 1988). (3) MV Lyr and TT Ari: the temperatures are derived from a fit of a Wesemael white dwarf model to the UV continuum, and "is compatible with a hot (T>50 000 K) white dwarf" (Szkody & Downes 1982, Shafter et al. 1985). For TT Ari, Gänsicke et al. (1998) recently re-analyzed the available data and derive 39 000±5 000 K. Thus, there is evidence – though weak – that the white dwarfs in VY Scl stars are indeed higher than in other cataclysmic variables, though it is presently not clear whether the temperatures are high enough for the H burning hypothesis.

Orbital periods: The orbital periods of VY Scl stars range from ~ 3.2 hours to 6 hours, with the longest period associated with V 751 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 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

Table 4. Comparison of SSB and VY Scl group properties. Uncertain values are marked with a "?".

	SSBs	VY Scl stars
Mass of WD ($M_\odot$)	$\sim$ 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^{-1})	37–38	36
Number in Galaxy (obs)	2	15
Number in Galaxy (mod)	1000–3000	??

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). The important point to note here is that even among the generally accepted, optically identified supersoft binaries there are sources which due to their short orbital periods are very unlikely to operate according to the thermal-timescale mass transfer scenario of van den Heuvel et al. (1992). Whether or not the above described scenario (van Teeseling & King 1998) to explain the low-mass donor supersoft systems also applies to V 751 Cyg (or other VY Scl stars) remains to be seen.

Accretion rates: The value of $\dot{m}$ typically adopted in VY Scl systems (Warner 1987) is $\dot{m} \sim 10^{-8} M_\odot$ yr^{-1}. This is derived (using various methods) from the observed values of $M_{\rm V}$ during the optical high state. 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. We note that if the disks in VY Scl stars were flared, reprocessing of the white dwarf radiation may dominate the viscous luminosity of the disk, thus implying accretion rates lower than the above value.

Thus, the conjecture that all VY Scl stars are SSBs is viable. Should it be verified, then it is likely that VY Scl stars represent an extension of the class of SSBs in several respects as discussed above and summarized in Table 4. In addition, independent of the value of the white dwarf mass, the evolution of thermal-timescale, close SSBs (those with orbital periods $\lesssim$ 1 day) predicts an epoch in which the masses have equalized, and the accretion rate declines (Di Stefano & Nelson 1996). The discovery of VY Scl stars as SSBs may represent the first detections of this more quiescent phase of the evolution of close-binary SSBs.

5.3. Accretion disk during optical state transitions

It is not clear what happens to the disk during the low state in VY Scl stars. Optical spectroscopy of VY Scl stars during the very lowest states, most notably of V 794 Aql (Honeycutt & Schlegel 1985, Szkody et al. 1988), TT Ari (Shafter et al. 1985) and MV Lyr (Robinson et al. 1981), also being in line with our low state spectra of V 751 Cyg (Fig. 8), have revealed very narrow (FWHM $\sim$ 150 km s^{-1}), strong Balmer emission and fainter HeI and HeII emission. In the case of TT Ari it could be shown that the phasing of these emission lines is shifted by 180° to that at optical high state, suggesting that in the very low state (1) the emission lines are due to irradiation of the secondary, (2) there is no dominating disk emission anymore, and (3) the presence of HeII emission lines points to >54 eV photons. Our low-state spectra reveal a FWHM $\sim$700–800 km s^{-1} for V 751 Cyg, i.e. somewhat larger than in the above mentioned VY Scl stars during the very lowest state.

As an alternative possibility it had been proposed that the state transition is due to a transition from the optically thick, high $\dot{M}$ disk in the optical high state into an optically thin disk in the optical low state due to reduced mass transfer from the donor. While this can explain the large optical amplitude between high and low state, a simple reduction in mass transfer rate from the secondary is not sufficient because then, after the transition to a cool state, the disk should show outbursts like in dwarf novae (King & Cannizzo 1998). This has never been observed in VY Scl stars, and it has been argued that all disk mass must be accreted during the transition to the optical low state. Leach et al. (1999) have shown that the inner disks can be kept in a hot state by irradiation by hot (T$\gtrsim$ 30000 K) white dwarfs. The latter are known to be hot in VY Scl stars, either due to accretion heating or due to hydrogen burning as proposed here.

5.4. Detectability of VY Scl systems in UV/EUV surveys

We have shown that V 751 Cyg is a very soft X-ray/EUV emitter during optical low states. We have therefore considered the question whether any of the known VY Scl stars have been detected during the EUVE survey. We have checked the second EUVE survey catalog (Bowyer et al. 1996) for an entry on any of the 14 VY Scl stars but did not found any. We also checked the catalog of the cross-correlations of ROSAT all-sky survey and EUVE detections (Lampton et al. 1997) which includes sources detected in both surveys but at lower significance in the EUVE survey as compared to the second EUVE catalog. These non-detections are somewhat surprising at first glance, but quite obvious when considering the foreground absorbing columns towards the VY Scl stars. For nearly all of the VY Scl stars IUE spectra have been taken, and estimates of the extinction are available. We have used the ROSAT count rates of the detected VY Scl stars (Greiner 1998) and their $E(B-V)$ values ($E(B-V)$<0.05 implying $N_{\rm H} < 2 \times 10^{20}$ cm^{-2} for V 794 Aql, TT Ari, V 425 Cas, VZ Scl, VY Scl, LX Ser, DW UMa, BZ Cam, MV Lyr and $E(B-V)$=0.05 for KR Aur, $E(B-V)$=0.2 for V 442 Oph) and estimated the predicted count rates for the 100 Å band EUVE survey LEXB band. In a second step we used the best-fit blackbody model of V 751 Cyg as a template and applied the individual absorbing columns of the VY Scl stars to estimate LEXB count rates. In both cases the derived count rates are well below the sensitivity of the EUVE survey and the non-detection with EUVE of any VY Scl star is not in contradiction to our suggestion of VY Scl stars possibly harboring white dwarfs with H shell burning.

The location of the emission peak in the UV implies that other sources of similar kind but at possibly smaller distance and/or less extinction should be strong EUV sources. Several ROSAT WFC and EUVE sources are known which so far could not be identified with hot white dwarfs or main-sequence stars which constitute the major population of EUV sources (Maoz et al. 1997). In particular, in analyzing deep multicolor imaging and utilizing both color-magnitude diagrams as well as ROSAT all-sky survey data, Maoz et al. (1997) conclude that these unidentified EUV sources are either X-ray quiet cataclysmic variables or a new class of objects. Given the observational result of V 751 Cyg being an X-ray quiet cataclysmic variable during optical high state we propose that nearby, hitherto unknown VY Scl stars (during optical low state) are good candidates for these unidentified EUV sources.

An estimate of the number of unidentified EUV sources which could be VY Scl stars depends on several poorly known parameters such as the space density of VY Scl stars, the duty cycle of low states, and the distance out to which EUV could detect emission despite interstellar absorption. There are 4–5 known VY Scl stars within 200 pc of the Sun (Earth) while at larger distance both the distribution perpendicular to the galactic plane as well as absorption introduces very strong selection biases. An even stronger selection bias is the fact that nearly all VY Scl stars have been discovered while searching variable stars on sky patrol plates, and thus only very few systems are known for which the bright state is fainter than 14 mag. Given the fact that most of the known VY Scl stars during their optical bright state are in the 12–14 mag range, one may expect that there is at least a similar number of VY Scl stars in the 14–16 mag range (during bright state), and thus the true number of VY Scl stars is higher by a factor of 2–3, implying a space density of VY Scl stars of 3–5$\times 10^{-7}$ pc^{-3}. Based on the long-term optical light curves available for many VY Scl stars we estimate that they spend about 5–10% of their time in the low state. Given the high luminosity of the UV emission it is reasonable to assume that EUV could detect sources out to about 200 pc in the galactic plane and even further out at high galactic latitudes. It thus seems possible that 1–3 of the unidentified EUV sources could be VY Scl stars.

6. Conclusions

We have observed the VY Scl star V 751 Cyg with ROSAT during the optical low-state in 1997. The X-ray spectrum is very soft and the bolometric luminosity is very high, showing that V 751 Cyg exhibits episodes of supersoft X-ray emission. The anti-correlation of the X-ray and optical intensity in V 751 Cyg resembles the behaviour of the transient supersoft X-ray source RX J0513.9–6951.

The optical spectra taken in the optical low state are similar to those of other VY Scl stars suggesting an optically thin emission region. However, we note the clear appearance of the high-excitation He II 4686 Å line during the optical low and intermediate states. This is independent evidence for an ionization source in the system with $>$54 eV photons.

An IUE spectrum taken during an optical high-state in 1985 has a similar shape as compared to other VY Scl stars in the same state but lacks strong emission lines. From the 2200 Å absorption dip we derive an extinction of $E(B-V)$ =0.25±0.05 and consequently estimate a distance of d≈500 pc. The lack of noticeable UV emission lines as well as the optical spectrum showing no strong orbital-phase-dependent line changes during the low-state spectroscopy suggest that V 751 Cyg is viewed at a low inclination angle of i = 30°±20°.

The absolute magnitudes in the low and high state of V 751 Cyg are in good agreement with the expected (Warner 1987) $M_{\rm V}$(secondary) = 16.7–11.1 log P(hrs) = 8.1 mag of a Roche-lobe filling main-sequence secondary and the luminosity of the accretion disk $M_{\rm V}$(disk) = 5.74–0.259 $\times$ P(hrs) = 4.2 mag when adopting the (uncertain) period of 6 hrs (Bell & Walker 1980).

Our finding that V 751 Cyg is a transient Galactic SSB suggests that other VY Scl stars may be also SSBs. We are therefore continuing to monitor all the known VY Scl systems, in hope of detecting luminous soft-X-ray emission from some of the other systems during optical low states. Also other nova-like variables should be considered potential candidates because of their high $\dot{M}$ amd low white dwarf masses similar to VY Scl stars. Detection of X-rays from these systems, however, might turn out to be difficult because, if they behave like RX J0513.9–6951, would be in an expanded state always, and thus predominantly emit in the UV band.

At this stage of our investigations, it is important to keep an open mind about whether VY Scl stars are SSBs, and also about the physical explanation for SSB behavior and variability in whatever systems definitively exhibit it. The conjecture that VY Scl stars are SSBs should now be subjected to further tests. First, if more-or-less steady nuclear burning is responsible for their luminous supersoft X-ray emission, then during the optical high state, the bolometric luminosity, which can be measured by a concerted multiwavelength campaign, using e.g. EUVE for some sources, should be as high as it is in the optical low state. Second, the known VY Scl stars should be monitored closely for their optical behaviour in order to perform further X-ray observations during optical low states. This will allow to determine whether other VY Scl stars also exhibit luminous supersoft X-ray emission or whether V 751 Cyg is an exception among VY Scl stars. In addition, there are implications such as the fact that such low mass, low temperature white dwarfs are difficult to detect in external galaxies (e.g. M 31), and the presence of one (or more, maybe 14) near us in the Galaxy may mean that previous estimates of the size of the population (Di Stefano & Rappaport 1994) need to be revised upward. This would also require a re-examination of the effect of SSBs on their environment.

Whatever the outcome of these investigations, the opportunity to study a larger population of local SSBs will surely shed light on the fundamental nature of these enigmatic sources.

Acknowledgements. JG thanks Prof. J. Trümper for granting ROSAT TOO time which made this investigation only possible. We are extremely grateful to J. Mattei for providing very useful AAVSO data, in particular from the 1976–1979 span. We appreciate the efforts of John Silverman and Jonathan McDowell over the last years in developing the code to compute the HRI detector response matrices. We thank the referee for a thorough reading and helpful comments which substantially improved this paper. JG is supported by the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF/DLR) under contract No. FKZ 50 QQ 9602 3, and GT acknowledges funding by CONACYT grant 25454-A. The *ROSAT* project is supported by BMBF/DLR and the Max-Planck-Society. This research has made use of the Simbad database, operated at CDS, Strasbourg, France. Fig. 2 is based on photographic data of the National Geographic Society – Palomar Observatory Sky Survey (NGS-POSS) obtained using the Oschin Telescope on Palomar Mountain. The NGS-POSS was funded by a grant from the National Geographic Society to the California Institute of Technology. The plates were processed into the present compressed digital form with their permission. The Digitized Sky Survey was produced at the Space Telescope Science Institute under US Government grant NAG W-2166.

References

Alcock C., Allsman R.A., Alves D., et al. 1997, MNRAS 286, 483
Allen C.W., 1973, Astrophysical Quantities. Athlone Press, London
Bell M., Walker M.F., 1980, BAAS 12, 63
Berghöfer Th., 1997, (priv. comm.)
Bopp B.W., Stencel R.E., 1981, ApJ 247, L131
Bowyer S., Lampton M., Lewis J., et al., 1996, ApJS 102, 129
Burrell J.F., Mould J.R., 1973, PASP 85, 627
Cassisi S., Iben I.Jr., Tornambe A., 1998, ApJ 496, 376
Cordova F.A., Jensen K.A., Nugent J.J., 1981, MNRAS 196, 1
David L.P., Harnden F.R., Kearns K.E., Zombeck M.V., 1997, The ROSAT HRI Calibration Report. Available from the URL addresses http://heawww.harvard.edu/rosat/rsdc_www/HRI_CAL_REPORT/hri.html
DiStefano R., Rappaport S., 1994, ApJ 437, 733
Di Stefano R., Nelson L.A., 1996, In: Greiner J. (ed.) Supersoft X-ray Sources. Lecture Notes in Phys. 472, Springer, p. 3
Dobashi K., Bernard J.-P., Yonekura Y., Fukui Y., 1994, ApJS 95, 419
Downes R., Hoard D.W., Szkody P., Wachter S., 1995, AJ 110, 1824
Drake S.A., Ulrich R.K., 1980, ApJS 42, 351
Echevarria J., Costero R., Michel R., 1993, A&A 275, 201
Fujimoto M.Y., 1982, ApJ 257, 767
Gänsicke B., Sion E.M., Beuermann K., et al. 1998, A&A (to be subm.)
Greiner J. (Ed.), 1996, Supersoft X-ray Sources. Lecture Notes in Phys. 472, Springer
Greiner J., Schwarz R., Hasinger G., Orio M., 1996, A&A 312, 88
Greiner J., 1998, A&A 336, 626
Greiner J., Di Stefano R., 1998, In: Aschenbach B., et al. (eds.) Highlights in X-ray Astronomy. Garching, June 1998, MPE Report (in press) (astro-ph/9810019)
Hachisu I., Kato M., 1998, ApJ (in press)
Herbig G.H., 1958, ApJ 128, 259
Herbig G.H., Rao N.K., 1972, ApJ 174, 401
Hoard D.W., Szkody P., 1997, ApJ 481, 433
Honeycutt R.K., Schlegel E.M., 1985, PASP 97, 1189
Jetsu L., Huovelin J., Tuominen I., et al., 1990, A&A 236, 423
King A.R., 1997, MNRAS 288, L16
King A.R., Cannizzo J.K., 1998, ApJ 499, 348
Knigge C., Livio M., 1998, MNRAS 297, 1079
Kraft R.P., 1964, In: Luyten W.J. (ed.) First Conf. on Faint Blue Stars. Univ. of Minnesota, Minneapolis, p. 100
la Dous C., 1991, A&A 252, 100
la Dous C., 1993, In: Hack, La Dous (eds.) Cataclysmic variables and Related Objects. NASA SP-507, p. 107
Lampton M., Lieu R., Schmitt J.H.M.M., et al., 1997, ApJS 108, 545
Landolt A.U., 1992, AJ 104, 340
Leach R., Hessman F.V., King A.R., Stehle R., Mattei J., 1999, MNRAS (in press)
Livio M., 1992, ApJ 393, 516
Livio M., Pringle J.E., 1994, ApJ 427, 956
Maoz D., Ofek E.O., Shemi A., 1997, MNRAS 287, 293
Martynov D.Y., 1958, Perem. Zvezdy 11, 170
Martynov D.Y., Kholopov P.N., 1958, Perem. Zvezdy 11, 222
Munari U., Zwitter T., Bragaglia A., 1997, A&AS 122, 495
Neckel Th., Klare G., 1980, A&AS 42, 251
Osaki Y., 1996, PASP 108, 39
Pakull M.W., Motch C., Bianchi L., et al. 1993, A&A 278, L39
Patterson J., 1984, ApJS 54, 443
Predehl P., Schmitt J.H.M.M., 1995, A&A 293, 889
Prestwich A.H., Silverman A., McDowell J., Callanan P., Snowden S., 1998, (in prep.); see also the URL address http://heasarc.gsfc.nasa.gov/docs/rosat/hrispec.html
Reinsch K., van Teeseling A., Beuermann K., Abbott T.M.C., 1996, A&A 309, L11
Robinson E.L., Nather R.E., Kiplinger A., 1974, PASP 86, 401
Robinson E.L., Barker E.S., Cochran A.L., Cochran W.D., Nather R.E., 1981, ApJ 251, 611
Rodríguez-Pascual P., Schartel N., Wamsteker W., Pérez A., 1998, In: González-Riestra, et al.(eds.) UV Astrophysics beyond the IUE Final Archive. ESA SP-413, p. 731
Rothschild R., Boldt E., Holt S., et al. 1979, Space Sci. Instr. 4, 269
Schaeidt S., Hasinger G., Trümper J., 1993, A&A 270, L9
Schmidtke P.C., Cowley A.P., McGrath T.K., Hutchings J.B., Crampton D., 1996, AJ 111, 788
Schrijver C.J., 1994, In: Caillault J.-P. (ed.) Cool Stars, Stellar Systems and the Sun. ASP Conf. Ser. 64, ASP, San Francisco, p. 328
Shafter A.W., Szkody P., Liebert J., et al., 1985, ApJ 290, 707
Sion E.M., Starrfield S.G., 1994, ApJ 421, 261
Southwell K.A., Livio M., Charles P.A., O'Donoghue D., Sutherland W.J., 1996, ApJ 470, 1065
Szkody P., 1981, PASP 93, 456
Szkody P., Downes R.A., 1982, PASP 94, 328
Szkody P., Downes R.A., Mateo M., 1988, PASP 100, 362
Thorstensen J.R., Ringwald F.A., Wade R.A., Schmidt G.D., Norsworthy J.E., 1991, AJ 102, 272
van den Heuvel E.P.J., Bhattacharya D., Nomoto K., Rappaport S.A., 1992, A&A 262, 97
van Teeseling A., Beuermann K., Verbunt F., 1996, A&A 315, 467
van Teeseling A., Reinsch K., Hessman F.V., Beuermann K., 1997, A&A, L41
van Teeseling A., King A.R., 1998, A&A 338, 957
Vennes S., Fontaine G., Brassard P., 1995, A&A 296, 117
Warner B., 1987, MNRAS 227, 23
Warner B., 1995, Cataclysmic Variable Stars. Cambridge Astrophys. Ser. 28, Cambridge Univ. Press
Wenzel W., 1963, Mitt. Ver. Sterne Nos. 754 and 755
Wheatley P.J., van Teeseling A., Watson M.G., Verbunt F., Pfeffermann E., 1996, MNRAS 283, 101