

*Letter to the Editor***HST/STIS ultraviolet spectroscopy  
of the supersoft X-ray source RX J0439.8–6809\***A. van Teeseling<sup>1</sup>, B.T. Gänsicke<sup>1</sup>, K. Beuermann<sup>1</sup>, S. Dreizler<sup>2</sup>, T. Rauch<sup>2</sup>, and K. Reinsch<sup>1</sup><sup>1</sup> Universitäts-Sternwarte Göttingen, Geismarlandstrasse 11, 37083 Göttingen, Germany<sup>2</sup> Institut für Astronomie und Astrophysik, Waldhäuser Strasse 64, 72076 Tübingen, Germany

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**Abstract.** We present ultraviolet observations of the supersoft X-ray source RX J0439.8–6809 obtained with the Hubble Space Telescope Imaging Spectrograph. The ultraviolet spectrum is a very blue continuum overlaid with interstellar absorption lines. The observed broad Ly $\alpha$  absorption line is consistent with an interstellar column density of neutral hydrogen  $N_{\text{HI}} = (4.0 \pm 1.0) \times 10^{20} \text{ cm}^{-2}$ . The light curve obtained from the time-tagged dataset puts a  $3\sigma$  upper limit of 0.04 mag on the ultraviolet variability of RX J0439.8–6809 on time scales between 10 s and 35 min. The long-term X-ray light curve obtained from our three-year ROSAT HRI monitoring of RX J0439.8–6809 shows the source with a constant count rate, and implies that the temperature did not change more than a few 1000 K. If RX J0439.8–6809 is a massive extremely hot pre-white dwarf on the horizontal shell-burning track, opposed to the alternative possibility of a very compact double-degenerate supersoft X-ray binary, its constant temperature and luminosity are a challenge to stellar evolution theory. Interestingly, RX J0439–6809 is found close to the theoretical carbon-burning main-sequence.

**Key words:** accretion, accretion disks – stars: individual: RX J0439.8–6809 – stars: novae, cataclysmic variables – stars: white dwarfs – X-rays: stars

**1. Introduction**

Among the optically identified persistent supersoft X-ray sources, RX J0439.8–6809 (hereafter RX J0439) has the largest X-ray luminosity, but is also the faintest one in the visual light. After its discovery with ROSAT (Greiner et al., 1994) and its optical identification with a faint blue star in the LMC (van Teeseling et al., 1996), we are still puzzled by its exotic

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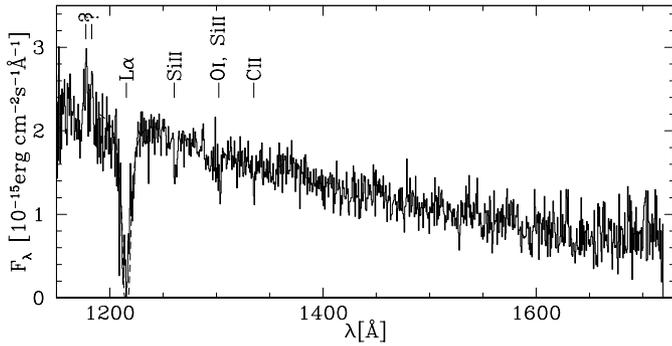
nature. The ROSAT X-ray spectrum of RX J0439 is consistent with an object in the LMC with a radius of a few times  $10^9 \text{ cm}$ , an effective temperature of  $3 \times 10^5 \text{ K}$ , and a luminosity of  $\sim 10^{38} \text{ erg s}^{-1}$ . These parameters suggest that RX J0439 is a shell-burning white dwarf or pre-white dwarf. Two scenarios have been suggested by van Teeseling et al. (1997) that could explain the observed characteristics of RX J0439.

(a) RX J0439 is a supersoft X-ray binary, and the high X-ray luminosity is powered by stable nuclear shell burning. The absence of any X-ray or optical variability in RX J0439, combined with its optical faintness, excludes the presence of a quasi-main-sequence companion. If RX J0439 belongs to the supersoft X-ray binaries, it must be a double-degenerate system containing two semi-detached white dwarfs, with an orbital period of a few minutes only. In this case, binarity is extremely hard to prove: with no or only a tiny accretion disc and a faint degenerate companion, the flux is dominated by the accreting shell-burning white dwarf. This model could explain the absence of strong emission lines which have been observed in all other known supersoft X-ray binaries (see e.g. overview by van Teeseling 1998), as well as the fact that the optical spectrum of RX J0439 is consistent with the Rayleigh-Jeans tail of the X-ray component.

(b) RX J0439 is an exceptionally hot pre-white dwarf on the horizontal shell-burning track. In this case, RX J0439 would be the hottest star of this type known so far. However, to match the observed X-ray luminosity, such a pre-white dwarf would have to be rather massive, with accordingly short evolution times.

**2. HST/STIS observations**

HST/STIS ultraviolet observations of RX J0439 were carried out on 1998 November 17. Due to the faintness of the object, the target acquisition was performed on a nearby bright star, and RX J0439 was positioned in the  $52'' \times 0.5''$  slit with a subsequent offset. A 2100 s exposure far-UV spectrum (FUV, 1150–1730 Å) and a 1700 s near-UV spectrum (NUV, 1600–3200 Å) were obtained with the G140L and G230L gratings, respectively. Using the MAMA detectors in the time-



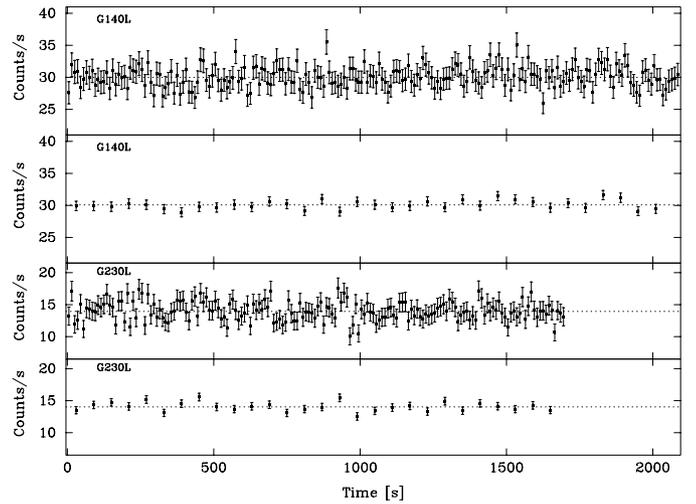
**Fig. 1.** The interstellar  $\text{Ly}\alpha$  absorption line in the G140L spectrum of RXJ 0439. Plotted as a dashed line is a Lorentzian fit to the observed line with a column density of  $N_{\text{HI}} = 4 \times 10^{20} \text{ cm}^{-2}$ . The absorption lines of Si II, C II, and O I are likely of interstellar origin. Two unidentified possible emission features at  $\approx 1178 \text{ \AA}$  and  $\approx 1184 \text{ \AA}$  are indicated

tagged mode, we have obtained in addition to the ultraviolet spectra two photon event files which contain an entry  $(t, x, y)$  for each photon, with  $t$  the arrival time at a  $125 \mu\text{s}$  time resolution and  $x, y$  the detector coordinates. In order to extract light curves of RX J0439 from the two observations we proceeded as follows. Two-dimensional raw FUV and NUV detector images were obtained by summing up all photons registered in each individual pixel  $(x, y)$ . FUV source+background counts were extracted within a box 35 pixel wide in cross-dispersion direction and covering  $1230 \text{ \AA} \lesssim \lambda \lesssim 1720 \text{ \AA}$ , excluding the strong geocoronal  $\text{Ly}\alpha$  emission (but including the weak O I  $\lambda 1302$  airglow). Background counts were extracted from two adjacent empty regions on the detector with the same wavelength coverage as the source spectrum. From the NUV photon event file, we extracted source+background and background counts covering the entire observed wavelength range in a similar way.

### 3. The ultraviolet spectrum

The ultraviolet spectrum of RX J0439 is a blue continuum which contains a broad  $\text{Ly}\alpha$  absorption line and weak absorption features at  $\sim 1260 \text{ \AA}$ ,  $\sim 1300 \text{ \AA}$ , and  $\sim 1335 \text{ \AA}$ , which we identify as interstellar absorption of Si II  $\lambda 1260$ , O I  $\lambda 1302$ /Si II  $\lambda 1304$ , and C II  $\lambda 1335$  (Fig. 1). Some spurious structure remains in the  $\text{Ly}\alpha$  profile and around  $1300 \text{ \AA}$  after the subtraction of the airglow  $\text{Ly}\alpha$  and O I emission. The observed  $\text{Ly}\alpha$  absorption is centred at  $\approx 1217 \text{ \AA}$ . Due to the offset target acquisition, RX J0439 might not have been perfectly centred in the aperture, which could account for the error in the wavelength zero point. The equivalent widths measured from the three metal absorption features,  $750 \pm 300 \text{ m\AA}$ ,  $450 \pm 200 \text{ m\AA}$ , and  $500 \pm 200 \text{ m\AA}$ , respectively, are compatible with just the galactic foreground absorption (e.g. Gänsicke et al. 1998) and make it plausible that RX J0439 is located relatively far in the outskirts of the LMC (van Teeseling et al., 1996).

Interpreting the observed  $\text{Ly}\alpha$  profile as interstellar absorption, we have estimated the neutral hydrogen column density along the line of sight towards RX J0439. Using a pure damping profile we find  $N_{\text{HI}} = (4 \pm 1) \times 10^{20} \text{ cm}^{-2}$ . This value



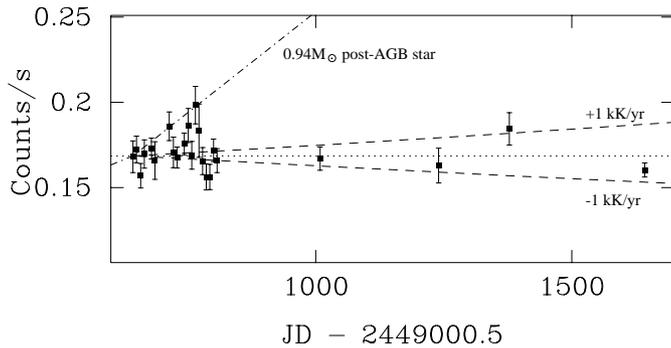
**Fig. 2.** Count rate of RXJ0439 during the STIS G140L and G230L observations in 10 s and 60 s bins

is lower than those found for CAL 83 and RX J0513.9–6951 (Gänsicke et al., 1998) and is consistent with the estimated galactic foreground column density of  $N_{\text{HI}} = 4.5 \times 10^{20} \text{ cm}^{-2}$  (Dickey & Lockman, 1990). As for the interstellar metal lines, there can be no significant  $\text{Ly}\alpha$  absorption by interstellar or circumstellar material in the LMC. The upper limit on the reddening derived from the G230L spectrum,  $E_{B-V} \lesssim 0.1$ , is consistent with the  $N_{\text{HI}}$  column density. The derived value for  $N_{\text{HI}}$  is also consistent with the relatively low absorption column found from the ROSAT X-ray spectrum (van Teeseling et al., 1996), and we will use  $N_{\text{HI}} = 4 \times 10^{20} \text{ cm}^{-2}$  for the total hydrogen column towards RX J0439 throughout the rest of this paper.

The absence of N V  $\lambda 1240$  and He II  $\lambda 1640$  emission, which has been observed in CAL 83, CAL 87, and RX J0513.9–6951 (Gänsicke et al., 1998; Hutchings et al., 1995), reminds of the pure continuum spectra observed in the optical. However, the rather noisy blue end of the G140L spectrum of RX J0439 contains two possible emission features, which are centred at  $\approx 1178 \text{ \AA}$  and  $\approx 1184 \text{ \AA}$  and are detected at a  $2-3\sigma$  level. Possible identifications are C III  $\lambda 1175.7$  and C IV  $\lambda 1184.7$ , even though two reasons argue against these transitions. (1) If C IV were present in the atmosphere of RX J0439, the resonance line C IV  $\lambda 1550$  should be much stronger than C IV  $\lambda 1184.7$ . (2) C III is increasingly less populated for temperatures in excess of  $120\,000 \text{ K}$ , which is much lower than the temperature derived below from the overall spectrum. Such a low temperature, however, could be found on the irradiation-heated surface of an accretion disc or degenerate secondary star in the case of a (so far unproven) binary nature of RX J0439.

### 4. The absence of ultraviolet variability

Fig. 2 shows the background subtracted count rate of RX J0439 binned in 10 s and 60 s intervals for both gratings. Neither observation shows significant variability. To determine the upper limit to any random variability we have performed a Monte Carlo simulation using the observed errors: The G140L obser-



**Fig. 3.** Long-term X-ray light curve of RX J0439 obtained with the ROSAT HRI. The dashed lines show the expected change in count rate with a secular change of  $\pm 1\,000\text{ K yr}^{-1}$  at constant bolometric luminosity and with an effective temperature close to  $270\,000\text{ K}$ . The steeply rising dash-dotted line shows the evolutionary change of a  $0.94M_{\odot}$  pre-white dwarf with roughly the correct temperature and luminosity (Blöcker, 1995), corresponding to a change of  $\sim 10\,000\text{ K yr}^{-1}$  at nearly constant bolometric luminosity

variation gives with a  $3\sigma$  upper limit of  $1.0\text{ count s}^{-1}$  (corresponding to  $0.04\text{ mag}$ ) the strongest constraint on possible ultraviolet variability. The G230L observation gives a  $3\sigma$  upper limit of  $1.7\text{ count s}^{-1}$  (corresponding to  $0.13\text{ mag}$ ).

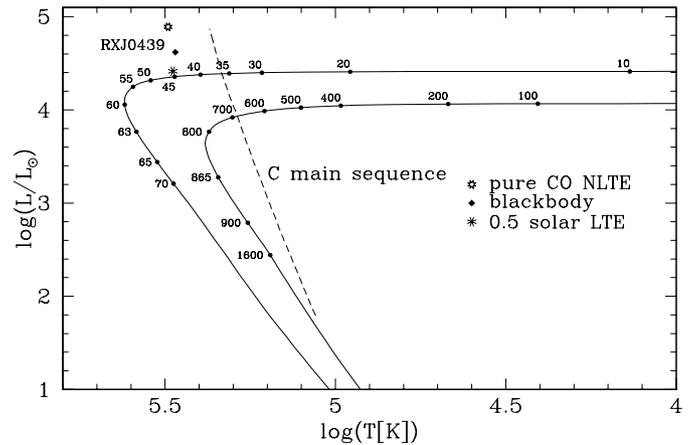
The upper limit of  $0.04\text{ mag}$  in the ultraviolet is even more stringent than the  $3\sigma$  upper limit of  $0.07\text{ mag}$  in the optical (van Teeseling et al. 1997). Combined with a visual magnitude of  $V = 21.6$ , the absence of any optical or ultraviolet variability excludes an irradiated companion with the size of a main-sequence star. Although the flux in a double-degenerate supersoft X-ray binary is dominated by the expanded shell-burning primary, a small quasi-sinusoidal modulation is expected from the changing aspect of the irradiated degenerate helium donor star. The stringent upper limit on the ultraviolet variability, however, implies a low orbital inclination (even in the case of a double-degenerate supersoft X-ray binary), or a rather ineffective heating of the degenerate companion, or no companion at all, i.e. a single pre-white dwarf.<sup>1</sup>

## 5. The absence of long-term X-ray variability

In Fig. 3 we have plotted the count rate of RX J0439 from our ROSAT HRI monitoring of RX J0439. The 25 pointings cover a period of almost 3 years. The count rate is not significantly variable, and the data exclude a temperature change (at constant bolometric luminosity) larger than  $\pm 1\,000\text{ K yr}^{-1}$ .

Comparison of the temperature and luminosity of RX J0439 (Sect. 5) with calculations of evolutionary tracks of post-AGB stars (e.g. Blöcker 1995) shows that if RX J0439 is a pre-white dwarf on the horizontal shell-burning track, its mass must be

<sup>1</sup> A substantial UV modulation as the result of reprocessing on the secondary is expected and observed in double-degenerates containing a neutron star and a brown dwarf (e.g. Arons & King (1993); Anderson et al. 1997). In these LMXBs, however, the neutron star contributes only little to the observed UV flux, while in RX J0439 the shell-burning white dwarf is the dominant source of UV radiation.

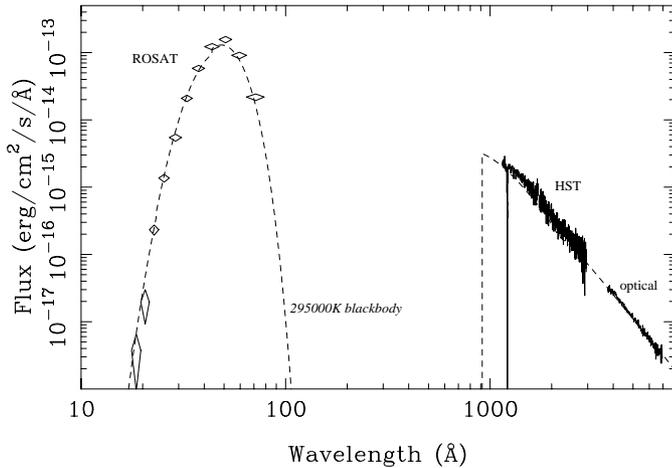


**Fig. 4.** RX J0439 in the Hertzsprung-Russell diagram. Indicated are the results for  $(L, T)$  from three different fits to the overall spectrum, using a pure CO NLTE model spectrum, a blackbody, and a 0.5 solar abundance LTE model spectrum. Plotted as solid lines are evolutionary tracks for  $0.696 M_{\odot}$  ( $M_{\text{ZAMS}} = 4 M_{\odot}$ ) and  $0.940 M_{\odot}$  ( $M_{\text{ZAMS}} = 7 M_{\odot}$ ) white dwarfs from (Blöcker, 1995). Evolutionary times are given in years. The dashed line is the theoretical carbon main sequence (Kippenhahn & Weigert, 1994).

$\gtrsim 0.9M_{\odot}$  (Fig. 4). However, these massive white dwarfs evolve so fast near the turn-over to the white dwarf cooling track that even in the short history of ROSAT observations of RX J0439 we should have seen a significant increase in the HRI count rate (note that on the horizontal shell-burning track the effective temperature increases at nearly constant bolometric luminosity). A lower mass white dwarf [e.g. the  $(M_{\text{ZAMS}}, M_{\text{H}}) = (5 M_{\odot}, 0.836 M_{\odot})$  track of Blöcker 1995] evolves slow enough to be consistent with the available X-ray data, but has a luminosity of  $\lesssim 5 \times 10^{37}\text{ erg s}^{-1}$  at the appropriate temperatures, which is significantly lower than that of RX J0439. This implies either that the shell-burning in RX J0439 is powered by accretion or that RX J0439 is able to stay at its position in the Hertzsprung-Russell diagram by nuclear burning with a much longer lifetime than predicted by the evolutionary tracks. With respect to the last possibility it should be noted that RX J0439 is rather close to the theoretical carbon-burning main sequence.

## 6. The combined X-ray, ultraviolet and optical spectrum

Our ultraviolet spectrum of RX J0439 perfectly agrees both in flux and in slope with the observed optical spectrum presented by van Teeseling et al. (1996). The combined spectrum has a very blue slope consistent with the Rayleigh-Jeans tail of a very hot object, and it is possible to model the entire observed spectrum from X-rays to optical with a single optically thick component. This does not imply, however, that we can exclude additional flux in the ultraviolet and optical, provided that the additional flux has a very blue spectrum as well. Such additional flux is required if the supersoft X-ray component has a higher temperature (and consequentially a smaller inferred radius and bolometric luminosity) than derived with the assumption that



**Fig. 5.** Observed optical, ultraviolet and *deconvolved* X-ray spectrum of RX J0439. The dashed line is an absorbed 295 000 K blackbody spectrum

the ultraviolet flux is the Rayleigh-Jeans tail of this X-ray component.

It is striking how well the overall spectrum of RX J0439, including the absence of any detectable spectral features, matches a single absorbed blackbody with a temperature of 295 000 K (Fig. 5). If we assume a distance of 50 kpc, this blackbody gives a radius  $R = 5 \times 10^9$  cm and a bolometric luminosity  $L = 1.6 \times 10^{38}$  erg s $^{-1}$ . Because the lack of spectral features, in particular in the ROSAT X-ray spectrum, may be the result of the rather limited spectral resolution and signal-to-noise ratio, we follow van Teeseling et al. (1996) and have fitted  $\log g = 7$  white dwarf model atmospheres to the combined X-ray, ultraviolet and optical spectrum (in fact a  $\chi^2$  fit to the ROSAT spectrum with the demand that the Rayleigh-Jeans tail matches the observed ultraviolet and optical flux). In addition to LTE spectra (van Teeseling et al., 1994), we have now also used NLTE white dwarf spectra (Rauch, 1997) in order to investigate which ultraviolet lines might be expected to be present.

Van Teeseling et al. (1996) already argued that the atmosphere must contain a significant amount of metals. If not, there would be either an excess of soft X-ray flux or an excess of ultraviolet and optical flux. Even models with 10% solar metal abundance suffer this problem. With metal abundances within a factor of 2 of solar, both the LTE and the NLTE models give an acceptable fit to the overall spectrum with  $T_{\text{eff}} \approx 300\,000$  K and  $L \approx 1 \times 10^{38}$  erg s $^{-1}$ . Because all models are scaled to the same optical flux, the resulting fit parameters of the LTE and NLTE models do not differ significantly. The near-solar models predict strong Ne VIII absorption edges at 0.22 keV and 0.24 keV. For a cosmic helium abundance, the ultraviolet spectra predict a non-negligible He II  $\lambda$  1640 absorption line which is, however, not detected at the present signal-to-noise ratio. This implies either that the assumption of a single spectral component is incorrect, or that the absorption is filled in with emission (without extra continuum flux), or that the white dwarf atmosphere is helium-poor. Note that also in the optical no He II  $\lambda$  4686 could

be detected and that it appears unlikely that absorption is filled in without the appearance of emission lines

Metal rich and helium poor is reminiscent of the exotic and extremely hot ( $\sim 200\,000$  K) PG 1159 star H1504+65, which is the only known pre-white dwarf whose surface is free from both hydrogen and helium (Werner, 1991; Werner & Wolff, 1999). Indeed, the overall spectrum of RX J0439 can be fitted very well (i.e. best  $\chi^2$  of all used models) with a single  $\log g = 7$  spectrum with a pure CO composition. The inferred effective temperature is  $\sim 310\,000$  K, the radius at 50 kpc is  $\sim 6 \times 10^9$  cm, and the corresponding luminosity is  $\sim 3 \times 10^{38}$  erg s $^{-1}$ . At this point, we can only speculate about further common properties of the two stars. In contrast to the featureless optical continuum of RX J0439, the optical spectrum of H1504+65 contains numerous high excitation C and O lines. VLT and Chandra observations of RX J0439 are scheduled to probe for emission/absorption features which will allow a more detailed spectral modelling.

## 7. Conclusions

Our single orbit of HST/STIS ultraviolet data of RX J0439 have confirmed the previous findings: RX J0439 is a very extreme object, whether as a single post-AGB star or as an accreting (double-degenerate) supersoft X-ray binary. It seems that the flux at all wavelengths is dominated by a very luminous shell-burning white dwarf which is able to maintain its position in the Hertzsprung-Russell diagram near the turnover into the white dwarf cooling track for  $> 8$  years. The combined X-ray, ultraviolet and optical spectrum is consistent with a single spectral component with  $T \sim 300\,000$  K and  $L \sim 10^{38}$  erg s $^{-1}$ , and suggests a high metallicity. Interestingly, both the very good fit with a pure CO model, the absence of long-term variability, and the proximity of RX J0439 to the theoretical carbon-burning main sequence, raises the speculative (but spectacular) possibility that RX J0439 represents a completely new type of star.

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