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Letter to the Editor

The spectra and luminosity of super-soft X-ray sources

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Abstract. We compare the predicted ROSAT PSPC count rates and spectra for H-rich and He-rich white-dwarf LTE atmospheres with those for blackbodies. We show that a model-atmosphere fit to ROSAT PSPC data of the super-soft X-ray source 1E0056.8-7154 tends to give a higher effective temperature, smaller radius, and a much lower bolometric luminosity than a blackbody fit. This super-soft X-ray source has been identified with a planetary nebula in the Small Magellanic Cloud. For white-dwarf atmosphere models, the inferred bolometric luminosity is below the Eddington limit, and the derived radii are in better agreement with those expected for white dwarfs. Both H-burning and He-burning accreting white dwarfs in a binary are consistent with the ROSAT spectrum of 1E0056.8-7154. However, the spectrum, luminosity and radius are also consistent with an exceptionally hot single central star of a planetary nebula.

Key words: accretion - white dwarfs - X-rays: stars

1. Introduction

Super-soft X-ray sources were first detected in the Magellanic Clouds with EINSTEIN (Long et al. 1981) and later with EXOSAT (Pakull et al. 1985). The detection of an orbital period established the close-binary nature of these sources (Smale et al. 1988). The real proof of their super-soft nature was given by observations with ROSAT (Trümper et al. 1991; Greiner et al. 1991), which showed that super-soft X-ray sources do not emit detectable X-ray radiation above ~ 0.5 keV. Typical blackbody parameters of super-soft X-ray sources are a temperature of $3\text{–}5\times10^5$ K and a radius of $1\text{–}3\times10^9$ cm. This suggests that the emitting object has the size of a white dwarf and radiates at or above the Eddington limit of a solar mass object ($\sim 10^{38}\,\mathrm{erg\,s^{-1}}$).

The first thoughts about the nature of the super-soft X-ray sources included accretion onto black holes (Cowley et al. 1990; Smale et al. 1988) and neutron stars accreting above the Eddington rate (Greiner et al. 1991). Van den Heuvel et al. (1992) proposed as a possible explanation that the super-soft X-ray emission is the result of steady nuclear burning of hydrogen accreted onto massive white dwarfs. Such a close binary system would be a strong source of soft X-rays.

Instead of a hydrogen burning white dwarf, Iben & Tutukov (1993) proposed helium burning on a CO degenerate dwarf, which accretes helium from a companion that is burning helium in a shell above a CO core. However, the detection of the Hα line in emission in Cal 83 and Cal 87 (see e.g. Pakull et al. 1988) supports the scenario in which the mass-donor star in these systems is hydrogen rich.

The super-soft X-ray source 1E0056.8-7154 in the Small Magellanic Cloud has been identified with the planetary nebula N67 (Wang 1991), which confirms the (pre)-white-dwarf nature of at least some of the super-soft X-ray sources. Wang (1991) suggested that 1E0056.8-7154 is the single hot nucleus of the planetary nebula N67. Because some of the super-soft X-ray sources are transient sources (Schaeidt et al. 1993; Kahabka et al. 1994) this would imply that there are at least two classes of super-soft X-ray sources: accreting compact stars and hot nuclei of young planetary nebulae.

For all white-dwarf models for super-soft X-ray sources, both single and in a binary, the luminosity must be below the Eddington limit. Otherwise, the white-dwarf atmosphere is blown away by the generated luminosity. In this letter we compare blackbody spectra with white-dwarf model-atmosphere spectra. In particular, we consider the luminosities inferred from both models in relation to the Eddington luminosity. The differences are illustrated by fitting both spectra to ROSAT PSPC observations of 1E0056.8-7154 in the Small Magellanic Cloud (Kahabka et al. 1994). Because this source is identified with a planetary nebula it is an ideal test source for the comparison of white-dwarf model atmospheres with blackbodies.

2. Blackbody spectra and white-dwarf atmosphere spectra

Nuclear burning takes place deep in the white-dwarf atmosphere where the temperature is sufficiently large ($T \gtrsim 10^7$ K), at

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large optical depth below the photosphere. Photo-absorption by highly ionized metals in a white-dwarf atmosphere produces absorption edges in the X-ray spectrum. Therefore, the X-ray spectrum of a white dwarf deviates from a blackbody, also when nuclear burning occurs.

We have calculated high-temperature LTE model-atmosphere spectra for a gravity of $\log g = 8$ appropriate for white dwarfs with masses $\gtrsim 0.5 M_{\odot}$. The models are calculated for $T_{\rm eff} \leq 6 \times 10^5$ K and assuming radiative and hydrostatic equilibrium. LTE atmospheres give a better approximation for the emergent spectrum than blackbodies. However, a final analysis awaits the availability of very hot non-LTE spectra (compare Motch et al. 1993; Werner et al. 1991). The calculated spectrum is not very sensitive to the assumed gravity. The opacities include free-free absorption and bound-free absorption of the 15 most abundant elements. Ionization stages are included up to 3 keV. The procedure to solve the transfer equation is described by Van Teeseling et al. (1994).

We have calculated atmospheres with a He number-abundance of 0.085 (H-rich atmospheres) and with a He number-abundance of 0.999 (He-rich atmospheres). The He-rich atmospheres are appropriate for He-burning white dwarfs which were proposed by Iben & Tutukov (1993). For the comparison with the super-soft X-ray source 1E0056.8-7154 in the Small Magellanic Cloud we have used metal abundances of 0.15 times solar. In spite of the large uncertainty about the metallicity of intermediate-age stars in the Magellanic Clouds (see e.g. Haynes & Milne 1991) a deficiency of a factor of 7 is an acceptable value for an accreting white-dwarf atmosphere.

In Fig. 1 we compare spectra of H-rich atmospheres and blackbody spectra with the same temperatures and emitted by the same area. A model-atmosphere spectrum is much flatter than a blackbody spectrum and shows a high-energy cut off due to several absorption edges. For a temperature of $\sim 4 \times 10^5$ K the strongest edges are the C V K edge at 0.4 keV and the C VI K edge at 0.5 keV. A model-atmosphere spectrum differs significantly from a blackbody spectrum in energy bands where the opacity is a rapidly changing function of the frequency. For soft X-ray energies this is indeed the case in the relevant range of effective temperature and gravity in which most elements are highly ionized.

The deviation of a model-atmosphere spectrum from a blackbody shape depends on the element abundances. For a pure-hydrogen atmosphere the photo-ionization opacity scales with frequency ν as $\sim \nu^{-3}$ and decreases from the Lyman edge to soft X-ray energies. With increasing metal abundances several ion absorption edges cause the opacity to jump with frequency. With temperatures of the order of $2\text{–}5 \times 10^5$ K the effect is an increase in opacity at X-ray energies $\gtrsim 0.4$ keV. With these temperatures the opacity has a minimum at energies $\lesssim 0.4$ keV at which ROSAT observes the super-soft X-ray sources. Therefore, unit optical depth at these energies is reached at deeper and hotter layers of the photosphere than unit optical depth at lower and higher energies.

Consequently, a white-dwarf atmosphere with an effective temperature of the order of 4×10^5 K radiates a relatively larger fraction of its luminosity in the soft-X-ray band than a blackbody with the same effective temperature (Fig. 1). Therefore, a hot white dwarf gives a higher count rate in the ROSAT PSPC than a blackbody with the same radius and temperature.

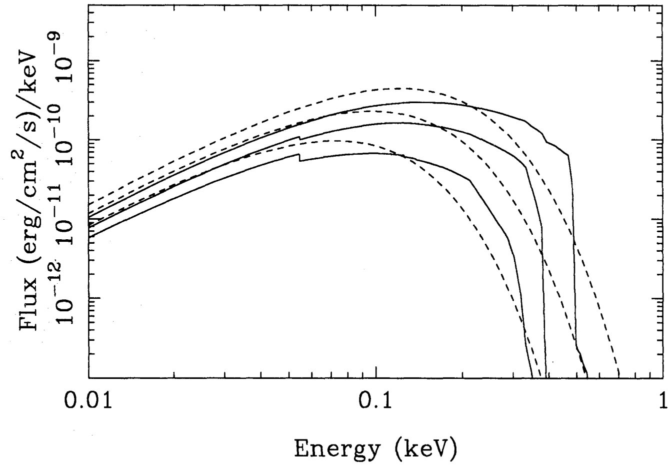

Fig. 1. The solid lines are the spectra radiated by H-rich white dwarfs with effective temperatures of 3×10^5 K, 4×10^5 K, and 5×10^5 K and a metal abundance of 0.15 times solar. The dashes lines are blackbody spectra with the same temperatures and emitted by the same area

3. The luminosity of 1E0056.8-7154

To illustrate the difference between blackbody spectra and model-atmosphere spectra when used to model the spectrum of a super-soft X-ray source, we have fitted these spectra to the ROSAT PSPC spectrum of 1E0056.8-7154. Analysing the spectra of other super-soft X-ray sources with white-dwarf model atmospheres is in progress (Van Teeseling et al. 1995). We interpolated in a grid consisting of models increasing in temperature with steps of 10^4 K. Best fit parameters of the models are given in Table 1.

In Fig. 2 we have plotted the best-fit blackbody spectrum and the best-fit spectrum from a H-rich model atmosphere. The two model spectra give the same observed ROSAT PSPC spectrum and count rate, because the PSPC is only sensitive to X-rays with energies above ~ 0.1 keV and also because the strong absorption hides the low-energy part of the spectrum. However, the bolometric luminosity of the blackbody is more than a factor of 10 higher than the bolometric luminosity of the model atmosphere.

Confidence levels in the absorption column–temperature plane are shown in Fig. 3 for H-rich atmospheres. We did not calculate temperatures below 3×10^5 K. Because the temperature in the white dwarf atmosphere is very high, H and He are almost completely ionized, and it does not make much difference whether the atmosphere consists mainly of H or He.

To calculate the luminosity we have used a distance of 65 kpc to the Small Magellanic Cloud. Figure 4 shows the 1,2 and 3–σ confidence levels in the luminosity–temperature plane

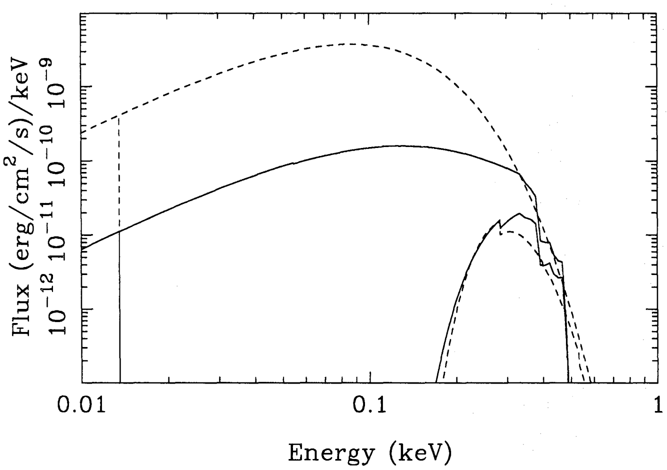

Fig. 2. The best-fit blackbody spectrum (dashed line) and the best-fit white-dwarf model-atmosphere spectrum (solid line) of the super-soft source 1E0056.8-7154. The upper two lines are the spectra as emitted by the source, the lower two with the Lyman edge at 13.6 eV the absorbed spectra incident on the X-ray detector

Table 1. Best-fit parameters of a blackbody spectrum, a H-rich-atmosphere spectrum and a He-rich-atmosphere spectrum to the ROSAT PSPC spectrum of 1E0056.8-7154. We have assumed a distance of 65 kpc to calculate the radius R and the bolometric luminosity L

	blackbody	H-rich atm.	He-rich atm.
$\chi^2/11$	0.82	0.69	0.70
$n_{\rm H}$ (10^{20}cm^{-2})	8	5	5
T (10^5 K)	3.6	4.5	4.3
R (cm)	5×10^9	8×10^8	9×10^8
L (erg s^{-1})	3×10^{38}	2×10^{37}	2×10^{37}

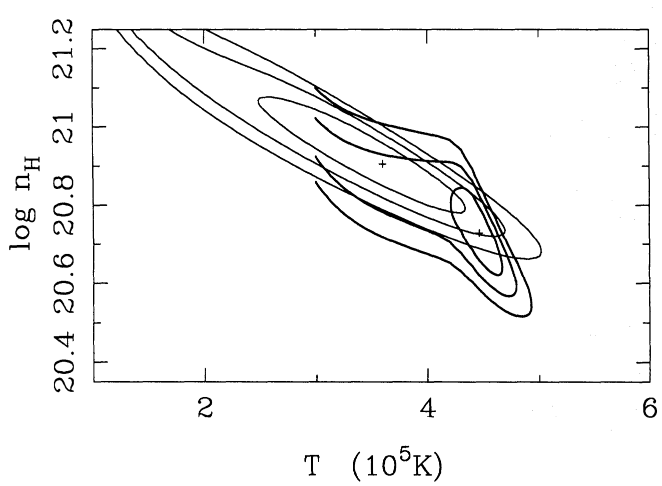

Fig. 3. 1,2 and 3–σ confidence levels of 1E0056.8-7154 for a blackbody spectrum (thin contours) and for a H-rich-atmosphere spectrum (thick contours)

for a H-rich atmosphere. We have also plotted the Eddington luminosity for a $1 M_\odot$ white dwarf.

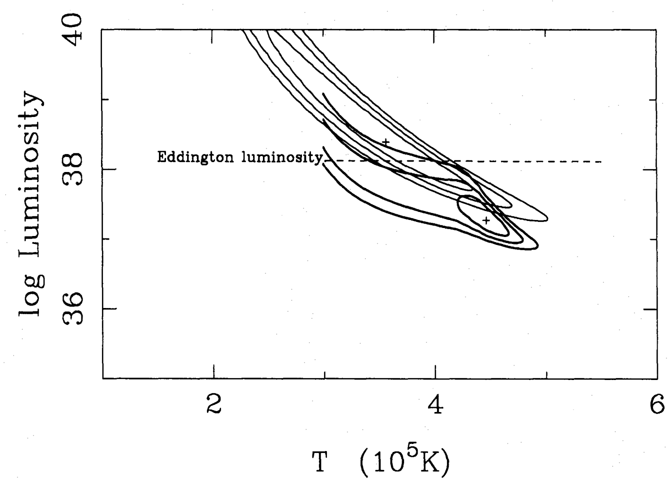

Fig. 4. 1,2 and 3–σ confidence levels of 1E0056.8-7154 for a blackbody spectrum (thin contours) and for a H-rich-atmosphere spectrum (thick contours). The horizontal dashed line is the approximate Eddington luminosity for a $1 M_\odot$ star (1.3×10^{38} erg s^{-1})

Blackbody fits give luminosities in excess of the Eddington limit, and radii rather large for white dwarfs, especially for the relatively massive ($M_{\rm wd} > 0.7 M_\odot$) and hence smaller white dwarfs which are necessary to have stable hydrogen burning in a binary (Van den Heuvel et al. 1992). Model-atmosphere fits give luminosities a factor of 10 smaller than the Eddington luminosity. The interstellar absorption column is smaller than with blackbody spectra. The higher effective temperature inferred from fitting model atmospheres is low enough to be well below the Eddington limit (per cm^2) for a white dwarf atmosphere with $\log g = 8$. The smaller radius inferred from model-atmosphere fits is in better agreement with expectation for a white dwarf. We conclude that the luminosity and soft X-ray spectrum of 1E0056.8-7154 are consistent with a H-burning or He-burning accreting white dwarf in a binary.

The inferred radius decreases with increasing metal abundances. Pure-H and pure-He atmospheres are not acceptable, because then the inferred radius implies the size of a main-sequence star ($R \gtrsim R_\odot$) and the luminosity would be highly super-Eddington. For metal abundances > 0.01 times solar, the best-fit radius is $< 1.5\, 10^9$ cm and $\log g \sim 8$. Therefore, for realistic metal abundances, the X-ray source 1E0056.8-7154 has the dimensions of a white dwarf. This is also consistent with an exceptionally hot single central star of the planetary nebula N67 at the end of the horizontal double-shell burning track or at the start of the white-dwarf cooling track.

Aller et al. (1987) used IUE observations of N67 to show that the nebular emission lines are consistent with an effective temperature of 115 000 K and $\log g = 5.15$, assuming a single central star. Kaler & Jacoby (1990) used the He IIλ4686/Hβ ratio to estimate an effective temperature of 205 000 K for the central star. However, Stasińska & Tylenda (1986) argue that these temperature estimates are probably lower limits.

4. Transient super-soft X-ray sources

Some of the super-soft X-ray sources show a transient behavior. X-ray turn-ons with a time scale of a few days have been observed with ROSAT for RX J0513.9–6951 in the Large Magellanic Cloud (Schaeidt et al. 1993) and for RX J0058.6–7146 in the Small Magellanic Cloud (Kahabka et al. 1994). The change in X-ray count rate is however non-linear with respect to the bolometric flux, because the X-ray count rate also depends on the spectrum.

We have calculated the PSPC count rate as a function of the effective temperature T of the radiation for a blackbody spectrum and a model-atmosphere spectrum. We have assumed that during a turn-on or turn-off the size of the emission area and the absorption column remain constant, which is probably true if the X-rays originate from a hydrogen-burning white dwarf. The results are shown in Fig. 5, where we have used the best-fit values from the χ^2 fitting for the area and the absorption column (Table 1). Figure 5 shows that the count rate increases more rapidly with increasing effective temperature than the bolometric luminosity, which increases as T^4. For a blackbody spectrum the PSPC count rate increases as $T^{\sim 13}$ at $T \sim 2 \times 10^5$ K and as $T^{\sim 6-7}$ at $T \sim 5 \times 10^5$ K. For a model-atmosphere spectrum the PSPC count rate increases as $T^{\sim 16}$ at $T \sim 2 \times 10^5$ K and as $T^{\sim 5}$ at $T \sim 5 \times 10^5$ K.

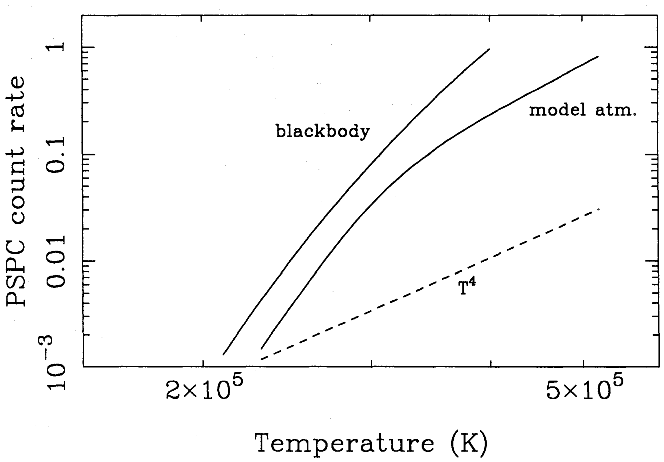

Fig. 5. ROSAT PSPC count rate as a function of the effective temperature of the radiation for blackbody spectra and model-atmosphere spectra. The radius of the source and the absorption column are fixed at the values of Table 1

5. Conclusions

A white-dwarf model atmosphere radiates a larger fraction of its luminosity in the soft X-ray part of the spectrum than a blackbody. Therefore, fitting white-dwarf model atmospheres yields a much smaller luminosity than blackbody spectra. Consequently, if super-soft X-ray sources are white dwarfs the total luminosity of these sources is below the Eddington luminosity.

Fitting the spectra of both hydrogen-burning and helium-burning accreting white dwarfs with the observed X-ray spectrum of 1E0056.8-7154 gives parameters that are consistent with a white dwarf.

If the metal abundances are not too high or too low in the radiating atmosphere it seems also possible that 1E0056.8-7154 is an exceptionally hot single central star of the planetary nebula N67 as suggested by Wang (1991).

For a nuclear-burning white dwarf in the Magellanic Clouds the ROSAT PSPC count rate is proportional to T^{5-16} for $2 \times 10^5 < T < 5 \times 10^5$ K, and thus changes faster than the bolometric luminosity with variations in temperature.

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