Non-LTE model atmosphere analysis of the supersoft X-ray source RX J0122.9−7521

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Abstract: The supersoft X-ray source RX J0122.9−7521 was discovered in the ROSAT all-sky survey and suspected to be a member of the Small Magellanic Cloud (Kahabka et al. 1994). More recently the source has been optically identified with an extremely hot PG 1159 star (Cowley et al. 1995).

Here we present a NLTE model atmosphere analysis of a pointed ROSAT observation combined with medium resolution optical spectroscopy. RX J0122.9 −7521 appears to be the hottest known PG 1159 star. It is compact and relatively massive ($T_{\rm eff}$=180 000 K, $\log g$ =7.5, M = 0.7 $M_\odot$). In contrast to other stars of this group, the carbon and oxygen abundances in the helium-dominated atmosphere of RX J0122.9−7521 are unusually low. Our results allow a distance determination which clearly rules out SMC membership of RX J0122.9−7521.

1 Introduction

A distinct group of supersoft X-ray sources, the PG 1159 stars, comprises very hot hydrogen-deficient post-AGB stars. These stars represent an evolutionary transition phase between the central stars of planetary nebulae and the white dwarfs (WDs). Their masses are low ($M/M_\odot$=0.5–0.9), and their effective temperatures and luminosities (and hence surface gravities) cover a fairly extended region in the HR diagram (see Fig. 6). Seven out of 27 known PG 1159 stars (including the object under discussion here) were detected with the ROSAT PSPC (see e.g. Werner 1996) and two of these appear in the ROSAT all-sky survey. All ROSAT detected PG 1159 stars have temperatures $T_{\rm eff} \geq$140 000 K, and the X-rays are of thermal origin in the hot photospheres. It could be shown that the non-detection of "cooler" PG 1159 stars is the consequence of a very strong O VI edge near 100Å. The strength of this edge arises from the high oxygen abundance (of the order 10% by mass) in these carbon/helium dominated stars. Further details on these interesting objects may be found in recent reviews by Dreizler et al. (1995) and Werner et al. (1996a).

The first PG 1159 star discovered from its X-ray properties was H 1504+65 (Nousek et al. 1986). The first ROSAT selected PG 1159 star is RX J 2117.1 +3412, which was analyzed with NLTE model atmospheres using PSPC data as well as optical spectra (Motch et al. 1993). The second ROSAT discovery is

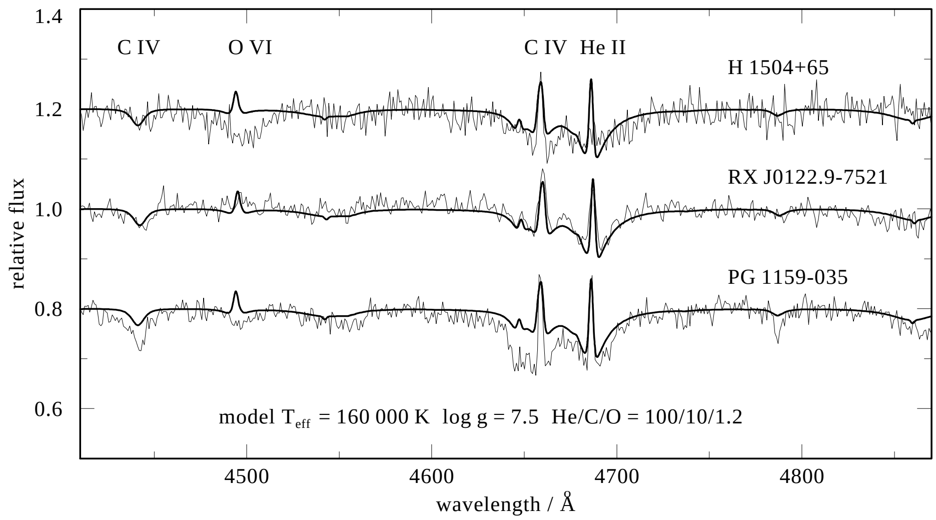

Fig. 1. Optical spectrum of RX J0122.9−7521 (middle) around the characteristic C IV/He II absorption trough region in comparison with spectra from H 1504+65 (top) and the prototype PG 1159−035 (bottom). To facilitate the comparison, overplotted on all three observations is the synthetic spectrum of a model with parameters as given in the panel. The weaker C IV 4660Å and absent O VI 4500Å absorptions in RX J0122.9−7521 are indicative of lower C and O abundances.

RX J0122.9 −7521 (Cowley et al. 1995), and we present a similar analysis in this paper. Although RX J0122.9−7521 lies somewhat far from the main body of the Small Magellanic Cloud it was suspected to be a SMC member (Kahabka et al. 1994). Its identification as a PG 1159 star by Cowley et al. made its SMC membership rather unlikely and we will show that it is in fact a Galactic foreground object. A comparison of visual and X-ray fluxes of both ROSAT discovered stars reveals an unusually high X-ray luminosity for the new PG 1159 star. Although visually fainter by almost 2 magnitudes, the PSPC count rate of RX J0122.9−7521 is more than twice as high as compared to RX J 2117.1+3412 (see Table 1). Our analysis aims at clarifying this behavior.

2 Model atmospheres and Observations

Synthetic optical and X-ray spectra are computed with a NLTE model atmosphere code developed at Kiel/Bamberg/Potsdam institutes (for numerical details see Dreizler & Werner 1993). The models are plane-parallel and assume hydrostatic and radiative equilibrium. Model atmospheres which are particularly tailored for the analysis of optical and X-ray spectra of PG 1159 stars are described in Werner et al. (1991) and Motch et al. (1993).

A hint as to the extraordinarily high X-ray luminosity of RX J0122.9−7521

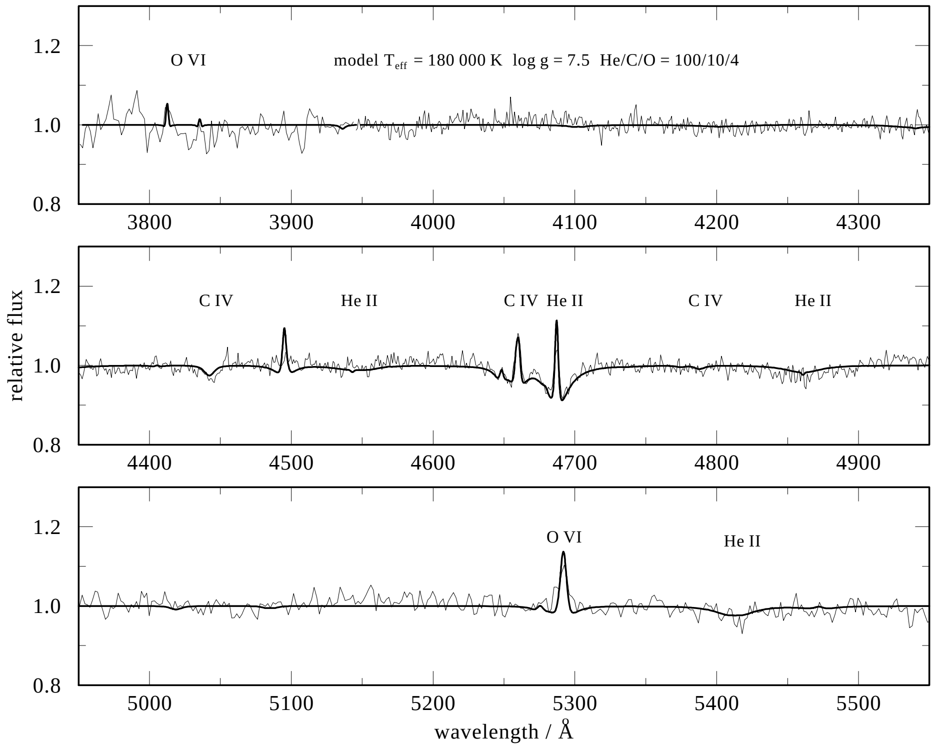

Fig. 2. The complete optical spectrum of RX J0122.9−7521 taken from Cowley et al. (1995). Besides the lines already identified in the close-up in the preceding figure, there is only one additional prominent feature, an emission from O VI 5290Å. Overplotted is the spectrum of the model with the finally adopted parameters.

is immediately evident in Fig. 1 from a comparison of its optical spectrum with those of the prototype star PG 1159−035 and of the above mentioned H 1504+65. It is obvious that the photospheric content of carbon and oxygen in RX J0122.9−7521 is lower than in the comparison stars. Both other stars show a shallow O VI absorption at 4500Å while RX J0122.9−7521 does not, and the depth of the C IV 4660Å absorption complex in RX J0122.9−7521 is much weaker when compared to PG 1159−035. Generally, the appearance of central emission reversals in the C IV 4660Å and He II 4686Å lines indicates that RX J0122.9−7521 is among the hottest members of the PG 1159 group. In fact, a detailed fit to the optical lines (Fig. 2) gives $T_{\rm eff}$=180 000 ± 20 000 K, $\log g$ =7.5±0.5, and an O/He number abundance ratio well below 10% (note that the model predicts an excessively strong O VI 4500Å emission [n=8→10 transitions], which is probably the consequence of a too small model atom). A higher oxygen abundance can be excluded, because otherwise the O VI emission

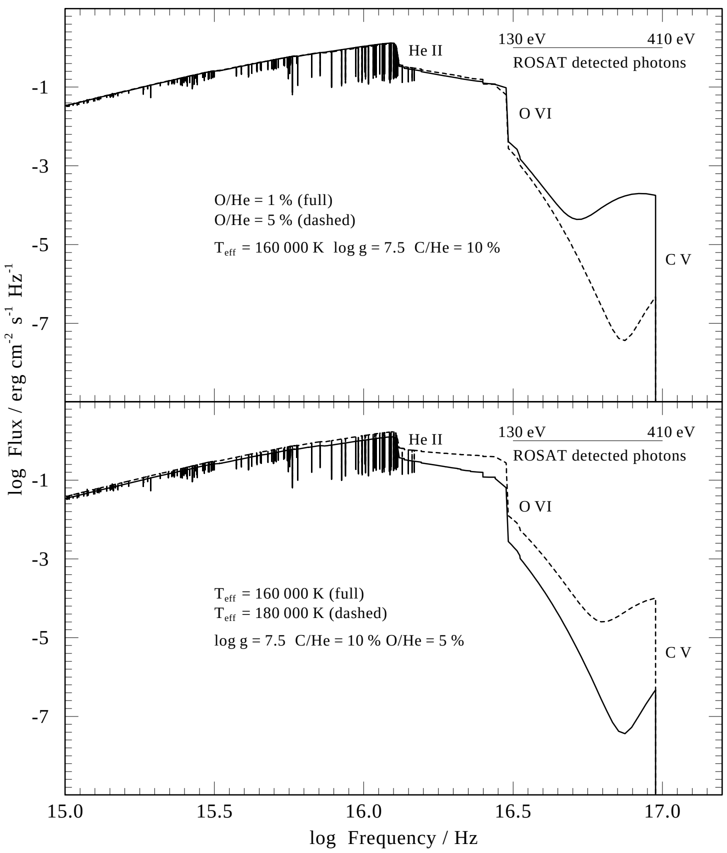

Fig. 3. Top: Flux distribution of two NLTE models with different oxygen abundance. Enhancing the O abundance strengthens the O VI 2p absorption edge at 130 eV and strongly suppresses the secondary flux maximum before the C V ground state edge. The C V edge blocks virtually all photons with energies above 410 eV. Bottom: The influence of the temperature on the soft X-ray flux is extremely strong. Near the C V edge an increase of T_{eff} by 20 000 K produces more than two orders of magnitude more photons.

line at 5290Å would be accompanied by shallow absorption wings, as is the case in the prototype (cf. Werner et al. 1991). The relatively low oxygen abundance is in accordance with the results of our fit to the X-ray spectrum, which will be described below. But in order to understand the basic photospheric features which dominate the X-ray flux let us have a closer look at some models.

In Fig. 3 we compare the fluxes of models which differ in effective temperature and oxygen abundance, demonstrating the effects of these parameters on the emergent spectrum. The figures show the flux distribution from the UV to the soft X-ray region and a horizontal bar indicates the energy range at which

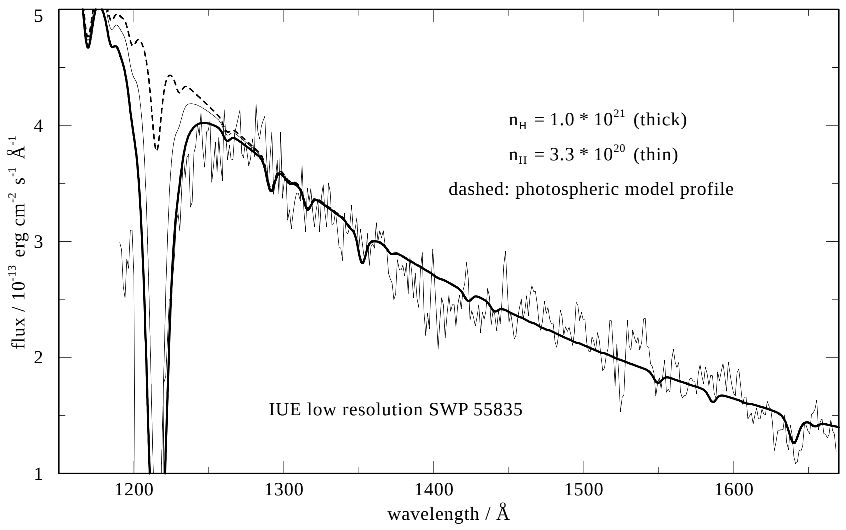

Fig. 4. An attempt to constrain the interstellar hydrogen column density towards RX J0122.9−7521 by a fit to the Ly α red wing fails. See discussion in the text. Due to the high noise, no line features except from interstellar species can be identified.

photons are detected by the ROSAT PSPC. Two prominent features determine the shape of the soft X-ray flux. The first is a strong O VI edge at 130 eV and the second is the even stronger C V ground state edge at 410 eV which virtually blocks all the higher energy photons in every model relevant to the present analysis (for a discussion of NLTE models with much higher temperatures, see contributions by Rauch and Hartmann, this volume). Hence, the only feature which remarkably changes the soft X-ray flux is the O VI edge. From Fig. 3 we learn that $T_{\rm eff}$ as well as the O abundance are the two key parameters which determine the strength of the edge. It follows that the analysis of the X-ray data alone gives no useful results, but that the optical spectra have to be used for a sensible interpretation. It should be noted that a change in the surface gravity, within the limits from the optical analysis, leaves the X-ray flux almost unaffected. The same holds for the C/He abundance ratio which is – like $\log g$ – fixed from the optical line profiles.

Interstellar absorption is another unknown parameter which enters the X-ray analysis so it would be most useful to get an independent estimate of the H column density ($N_{\rm H}$) towards RX J0122.9−7521. We have obtained a IUE low resolution spectrum hoping to constrain $N_{\rm H}$ by fitting the Ly α wing. In Fig. 4 we show the IUE spectrum together with the photospheric model flux and the same flux attenuated by two different values for $N_{\rm H}$ (in $\rm cm^{-2}$). The lower value ($N_{\rm H} = 3.3 \cdot 10^{20}$) represents the Galactic column density towards the SMC (Bessell 1991) and hence should be an upper limit for RX J0122.9−7521.

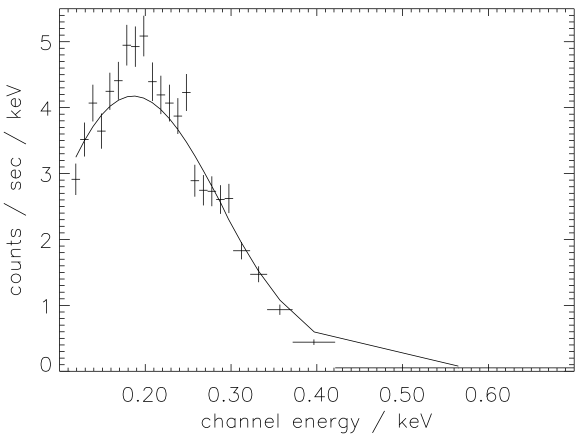

Fig. 5. Best model fit to the observed PSPC pulse height distribution. Model parameters are equal to those for the optical line fit shown in Fig. 2. The resulting interstellar column density amounts to $N_H = 2.6 \cdot 10^{20}$. The pointed observation was performed in Sept./Oct. 1993 and retrieved from the ROSAT archive.

It seems that this value is too low to fit to the observed profile and that a value three times higher fits better. This is, of course, unreasonably high and analysis of the X-ray spectra (see below) gives a value of $2.6 \cdot 10^{20}$. We can only speculate about reasons for the failure to get an acceptable fit to Ly α, e.g. the IUE spectrum is rather noisy and it is difficult to define the continuum. As a consequence, the interstellar column towards RX J0122.9−7521 must be treated as an unknown parameter. Fig. 5 shows our best fit model to the observed pulse height distribution. The model ($T_{\rm eff}$=180 000 K) was selected from a grid which covers $T_{\rm eff}$=150 000–200 000 K and O/He=0.5–10 (% number ratio). The fit is not perfect but represents a compromise. The model flux is too low by about 20% at the observed peak height (near 0.2 keV), but somewhat too high at the highest observed energies. Increasing $T_{\rm eff}$ improves the low energy fit but at the hard end the flux excess becomes too strong. The opposite holds for decreasing $T_{\rm eff}$. Although the shape of the flux distribution can be fitted with the adopted oxygen abundance, it could be slightly improved with a higher O/He value (along with a slight increase of $T_{\rm eff}$ in order to compensate for the stronger O VI edge). But then the optical O VI 5290Å emission line develops absorption wings which are not observed.

3 Summary

RX J0122.9−7521 is the hottest known PG 1159 star (see Fig. 6), closely followed by RX J 2117.1+3412 (see Motch et al. 1993 and a refined analysis with HST

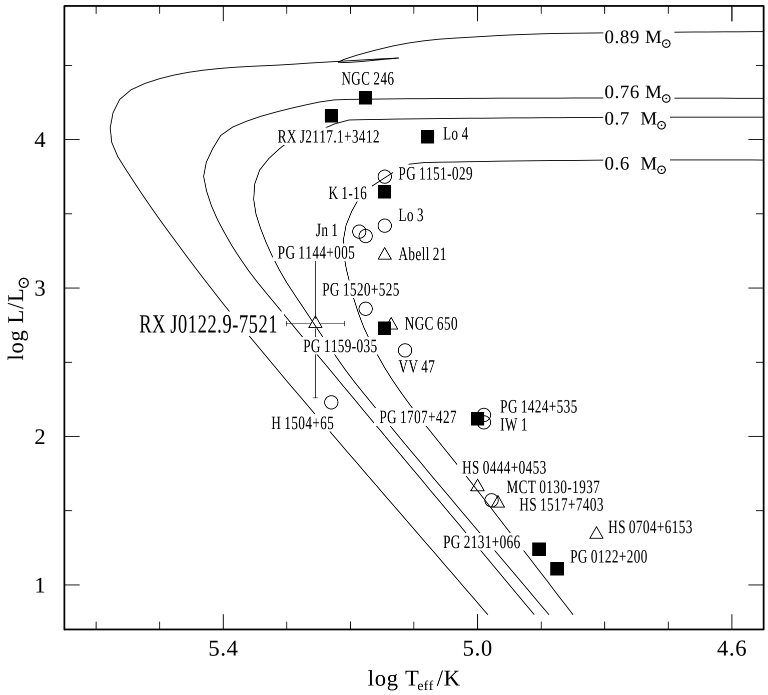

Fig. 6. Position of RX J0122.9−7521 (with error bars) in the HR diagram. It lies on a 0.7 $M_\odot$ post-AGB evolutionary track and represents a descendant of the much more luminous RX J 2117.1+3412. Also shown are positions of previously analyzed PG 1159 stars (different symbols for pulsators □, non-pulsators ○, and unknown photometric behavior △) as taken from Werner et al. (1996a). Evolutionary tracks are from Wood & Faulkner (1986).

spectra by Werner et al. 1996b). Table 1 summarizes the results of the present analysis and compares the properties of both ROSAT discovered objects. The higher X-ray luminosity of RX J0122.9−7521 is a consequence of both its slightly higher effective temperature and its relatively low oxygen abundance. In addition, the interstellar hydrogen column density is lower, but there remains a discrepancy with the IUE Ly α profile. Comparing the position of both stars in the $T_{\rm eff}$–$\log g$ diagram reveals very similar masses. However, the deduced total luminosity of RX J0122.9−7521 shows that it is more evolved than RX J 2117.1+3412 (roughly 10^4 years higher post-AGB age). Comparing the measured V magnitude with the model flux clearly rules out SMC membership of RX J0122.9−7521. It yields a distance determination of 700^{+550}_{-310} pc.

We remark that RX J0122.9−7521 has no associated planetary nebula while about 50% of the PG 1159 members are central stars. In addition, it is located outside of the GW Vir instability strip (Werner et al. 1996c), hence we do not

Table 1. Comparison of results from NLTE analyses of RX J 2117.1+3412 (Motch et al. 1993, Werner et al. 1996b) and of RX J0122.9−7521 (this work)

	RX J 2117.1+3412	RX J0122.9−7521
V-magnitude	13.2	15.4
PSPC ct/s	0.33	0.81
$T_{\rm eff}$/1000 K	170	180
log g (cgs)	6.0	7.5
He/C/O mass fractions (%)	33/50/17	68/21/11
N_H/cm^{-2}	$3.2 \cdot 10^{20}$	$2.6 \cdot 10^{20}$
$\log(L/L_\odot)$	4.16	2.76
$\log(R/R_\odot)$	-0.89	-1.6
$M/M_\odot$	0.70	0.70
distance/pc	1400	700

expect that RX J0122.9−7521 exhibits photometric variability. In fact, no obvious variability was detected by Cowley et al. (1995) and Bond (1996). Other questions not addressed here concern the possible detection of line profile variations as well as weak N V emission lines in some spectra. These findings deserve further attention.

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References

Bessell M.S., 1991, A&A 242, L17
Bond H.E., 1996, private communication
Cowley A.P., Schmidtke P.C., Hutchings J.B., Crampton D., 1995, PASP 107, 927
Dreizler S., Werner K., 1993, A&A 278, 199
Dreizler S., Werner K., Heber U., 1995, in White Dwarfs, eds. D. Koester and K. Werner, Lecture Notes in Physics 443, Springer, Berlin, p. 160
Kahabka P., Pietsch W., Hasinger G., 1994, A&A 288, 538
Motch C., Werner K., Pakull M.W., 1993, A&A 268, 561
Nousek J.A., Shipman H.L., Holberg J.B., et al. , 1986, ApJ 309, 230
Werner K., 1996, in Röntgenstrahlung from the Universe, eds. H.U. Zimmermann, J.E. Trümper, H. Yorke, MPE Report 263, p. 205
Werner K., Heber U., Hunger K., 1991, A&A 244, 437
Werner K., Dreizler S., Heber U., Rauch T., 1996a, in Hydrogen-Deficient Stars, eds. U. Heber and C.S. Jeffery, The ASP Conference Series, p. 267
Werner K., Dreizler S., Heber U., Rauch T., Fleming T.A., Sion E.M., Vauclair G., 1996b, A&A 307, 860
Werner K., Dreizler S., Heber U., Rauch T., 1996c, in Astrophysics in the Extreme Ultraviolet, IAU Colloquium 152, eds. S. Bowyer and R.F. Malina, Kluwer, p. 229
Wood P.R., Faulkner D.J., 1986, ApJ 307, 659