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A BeppoSAX LECS observation of the super-soft X-ray source CAL 83

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Abstract. We report on a BeppoSAX Low-Energy Concentrator Spectrometer (LECS) observation of the super-soft source (SSS) CAL 83. The X-ray emission in SSS is believed to arise from nuclear burning of accreted material on the surface of a white dwarf (WD). The LECS spectrum of CAL 83 can be well fit by both absorbed blackbody and WD atmosphere models. If the absorption is constrained to be equal to the value derived from *Hubble Space Telescope* measurements, then the best-fit blackbody temperature is 46.4 ± 1.4 eV while a Non Local Thermal Equilibrium (NLTE) WD atmosphere model gives a lower temperature of 32.6 ± 0.7 eV. In contrast to CAL 87, there are no strong absorption edges visible in the X-ray spectrum with a 68% confidence upper limit of 2.3 to the optical depth of a C VI edge at 0.49 keV predicted by WD atmosphere models. The luminosity and radius derived from the NLTE fit are consistent with the values predicted for stable nuclear burning on the surface of a $\sim 0.9\text{--}1.0 M_{\odot}$ WD.

Key words: accretion, accretion disks – binaries: close – stars: individual: CAL 83 – white dwarfs – X-rays: stars

1. Introduction

The Einstein observatory performed a survey of the Large Magellanic Cloud (LMC) in which two sources with unusually soft spectra, CAL 83 and CAL 87 were detected (Long et al. 1981). These sources emit little or no radiation at energies $\gtrsim 1$ keV and became known as “super-soft” sources (SSS). Subsequent ROSAT and ASCA observations have revealed approximately 30 similar sources located in the Galaxy, the Magellanic Clouds, a globular cluster and M31 (see Kahabka & Trümper 1996; van Teeseling 1997 for recent reviews). CAL 83 is often regarded as the prototypical SSS. It is identified with a $m_v = 17$ variable blue stellar object which shows strong H_{β} and He II $\lambda 4686$ emission

and an orbital period of 1.04 days (Cowley et al. 1984; Pakull et al. 1985; Smale et al. 1988; Crampton et al. 1987). CAL 83 is surrounded by a weak photoionized nebula (Pakull & Angebault 1986). A blackbody fit to the ROSAT Position Sensitive Proportional Counter (PSPC) spectrum indicates a temperature of < 40 eV, an absorbing column compatible with the LMC value, and a luminosity of $> 10^{39}$ erg s^{-1} (Greiner et al. 1991). A *Hubble Space Telescope* (HST) spectrum of CAL 83 reveals numerous interstellar lines as well as emission features due to O. The depth of a broad Ly α profile corresponds to a neutral hydrogen column of $(6.5 \pm 1.0) \times 10^{20}$ atoms cm^{-2} (Gänsicke et al. 1997).

Van den Heuvel et al. (1992) proposed that SSS are systems undergoing steady nuclear burning of hydrogen accreted onto the surface of a white dwarf (WD) with masses in the range $0.7\text{--}1.2 M_{\odot}$. The mass transfer from a main-sequence or sub-giant companions is unstable on a thermal time scale and for a narrow range of accretion rates, steady nuclear burning can take place. Evolutionary scenarios for such systems are discussed in Rappaport et al. (1994). It is unlikely that SSS compose a homogeneous class and one way of probing the nature of individual sources is by searching for the characteristic spectral signatures of nuclear burning on a WD. This burning takes place deep within the WD atmosphere at a large energy dependent optical depth. Photoelectric absorption by highly ionized metals in the atmosphere can produce edges in the X-ray spectrum. BeppoSAX observations of CAL 87 have revealed the presence of a deep O VIII edge at an energy of 0.871 keV (Parmar et al. 1997a). Such edges are a common feature of WD atmosphere models that assume Local Thermodynamic Equilibrium (LTE) such as that of Heise et al. (1994) and also of non-LTE (NLTE) models such as that of Hartmann & Heise (1997a). The CAL 87 spectral fits support the view that the X-ray emission from at least one SSS results from nuclear burning in the atmosphere of a WD. As part of a systematic study of SSS spectra undertaken with BeppoSAX, we report results from an observation of CAL 83.

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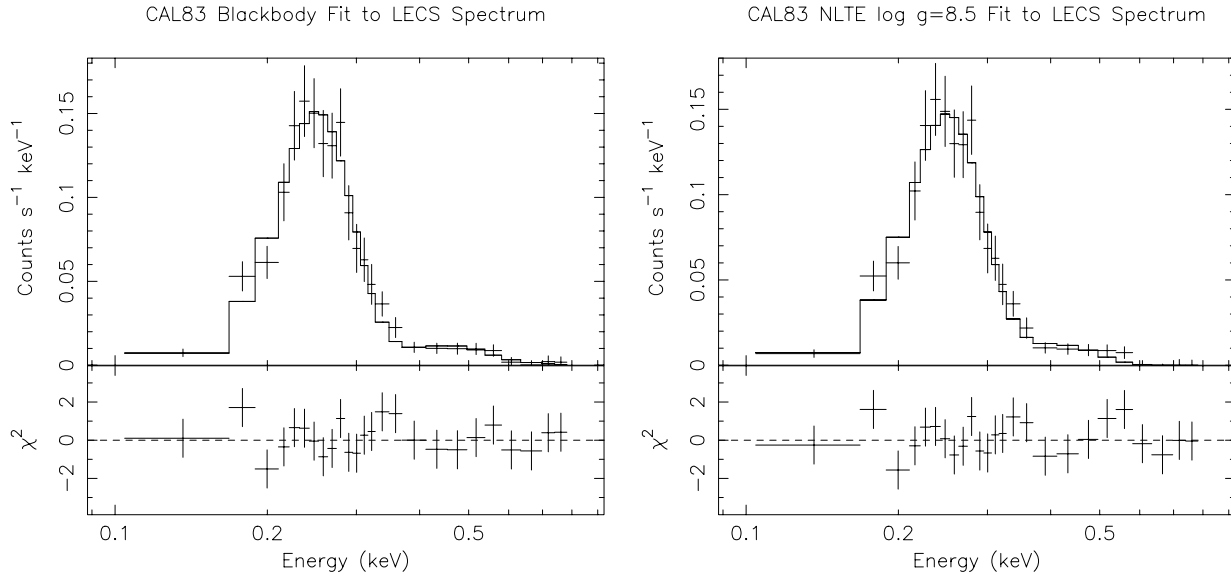


Fig. 1. Best-fit absorbed blackbody (left-panel) and NLTE (right panel) model fits to the LECS CAL 83 spectrum

2. Observations

The scientific payload of the BeppoSAX X-ray Astronomy Satellite (Boella et al. 1997) comprises four coaligned Narrow Field Instruments, or NFI, including the LECS. This is an imaging gas scintillation proportional counter sensitive in the energy range 0.1–10.0 keV with a circular field of view of $37'$ diameter (Parmar et al. 1997b). The usual background counting rate is $9.7 \times 10^{-5} \text{ arcmin}^{-2} \text{ s}^{-1}$ in the energy range 0.1–10.0 keV. The LECS energy resolution is a factor ~ 2.4 better than that of the ROSAT PSPC, while the effective area is between a factor ~ 6 and 2 lower at 0.28 and 1.5 keV, respectively. CAL 83 was observed by the LECS between 1997 March 07 04:04 and March 08 15:58 UTC. Good data were selected from intervals when the minimum elevation angle above the Earth's limb was $>4^\circ$ and when the instrument parameters were nominal using the SAXLEDAS 1.7.0 data analysis package. Since the LECS was only operated during satellite night-time, this gave a total on-source exposure of 36 ks.

Examination of the LECS image shows a source at a position consistent with ($16''$ distant) that of CAL 83. A spectrum was extracted centered on the source centroid using a radius of $8'$. This radius was chosen to include 95% of the 0.28 keV photons. The spectrum was rebinned to have >20 counts in each bin to allow the use of the χ^2 statistic. The XSPEC 9.01 package (Arnaud 1996) was used for spectral analysis together with the response matrix from the 1997 September release. During the observation the particle induced background was a factor of ~ 2 higher than usually encountered. For this reason the background spectrum was extracted from the image itself using an annulus centered on CAL 83 with inner and outer radii of $9'$ and $20'$, respectively. A small correction for telescope vignetting was applied. The CAL 83 count rate above background is $0.01965 \pm 0.00084 \text{ s}^{-1}$. Examination of the extracted spectrum shows that

the source is only detected in a narrow energy range (see Fig. 1) and only the 25 rebinned channels corresponding to energies between 0.1 and 0.8 keV were used for spectral fitting.

2.1. Blackbody spectral fits

In order to compare the LECS spectrum with those obtained from previous observations, an absorbed blackbody spectral model was first fit to the data (Fig. 1). The photoelectric absorption coefficients of Morisson & McCammon (1983) together with the solar abundances of Anders & Grevesse (1989) were used. An acceptable fit is obtained with χ^2_{ν} of 0.71 for 22 degrees of freedom (dof). The best-fit parameters are given in Table 1 and the uncertainty contours are displayed in Fig. 2. A distance of 50 kpc is assumed in order to derive the WD radius, R , and luminosity, L , and all uncertainties are quoted at 68% confidence corresponding to $\chi^2_{\text{min}} + 1.0$.

The uncertainties on the temperature, luminosity and radius can be further constrained if the absorption, N_{H} , is fixed at the best-fit value derived from the HST measurements by Gänsicke et al. (1997) of $6.5 \times 10^{20} \text{ atoms cm}^{-2}$. The best-fit temperature is now somewhat higher ($46.4 \pm 1.4 \text{ eV}$ compared to $41 \pm 6 \text{ eV}$) and much more tightly constrained leading to improved estimates of the emission region radius, luminosity and temperature of $(8.26 \pm 0.30) \times 10^8 \text{ cm}$, $(2.49 \pm 0.19) \times 10^{37} \text{ erg s}^{-1}$ and $46.4 \pm 1.4 \text{ eV}$, respectively. The slightly higher best-fit N_{H} value may indicate the presence of absorption local to the X-ray source.

2.2. WD model atmosphere spectral fits

Parmar et al. (1997a) demonstrate that the X-ray spectrum of CAL 87 is better described by hot WD atmosphere models undergoing hydrogen burning than with a simple blackbody. In

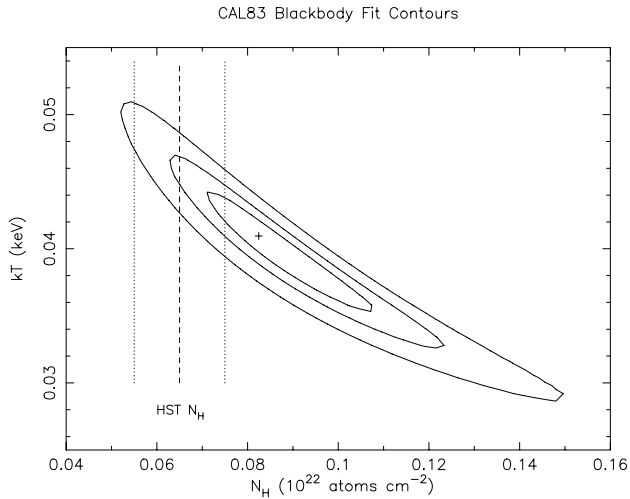


Fig. 2. χ^2 contours of blackbody fits to the LECS CAL 83 spectrum. The contours correspond to 68%, 90%, and 99% confidence levels. The best-fit is indicated with a cross. The value of N_{H} derived from HST measurements by Gänsicke et al. (1997) is indicated along with the $\pm 1\sigma$ uncertainties as dotted lines

Table 1. CAL 83 blackbody spectral fit parameters

Model	Blackbody	
T (eV)	41 ± 6	46.4 ± 1.4
N_{H} (10^{20} cm^{-2})	$8.2^{+1.9}_{-1.1}$	6.5^a
R (10^9 cm)	$1.33^{+1.41}_{-0.36}$	0.826 ± 0.030
L ($10^{37} \text{ erg s}^{-1}$)	$6.4^{+2.1}_{-3.0}$	2.49 ± 0.19
χ^2_{ν}	0.71	0.76
dof	22	23

^aFixed at HST value of Gänsicke et al. (1997)

order to see if this is true for CAL 83, LTE and NLTE WD atmosphere models were fit to the LECS spectrum. In both the LTE and NLTE models plane parallel geometry and hydrostatic equilibrium are assumed and model spectra are calculated for different surface gravities, elemental abundances and temperatures. Bound-free opacities for the ground states of H, He, C, N, O, Ne, Na, Mg, Si, S, Ar, Ca and Fe have been included (Hartmann & Heise 1997b). The effects of line opacities and line-blanketing are not included. This will change the derived atmospheric temperature structure and shift the ionization balance (Hubeny & Lanz 1995a,b). As a result the depths of the edges will be altered with respect to the unblanketed spectra and consequently, due to the constraint of radiative equilibrium, the overall shape of the continuum will change. Details of line-blanketing effects in hot high gravity NLTE white dwarf model atmospheres will be reported in Hartmann & Heise (1998). A surface gravity, g , of 10^9 cm s^{-2} , appropriate to a $\sim 1.0 M_{\odot}$ WD is assumed and the results are given in Table 2. Initial NLTE fits were performed using models cf. Hartmann & Heise (1997b) for surface gravities of $\log g = 8.0, 8.5$ and 9.0 , assuming an LMC abundance of 0.25 times the solar value and allowing N_{H} to vary. The fit

Table 2. CAL 83 LTE (Heise et al. 1994) spectral fit parameters

Model	LTE ($\log g = 9.0$)
T (eV)	$44.0^{+6.3}_{-0.6}$
N_{H} (10^{20} cm^{-2})	$9.5^{+0.3}_{-5.2}$
R (10^9 cm)	$1.05^{+0.08}_{-0.76}$
L ($10^{37} \text{ erg s}^{-1}$)	$5.4^{+0.6}_{-4.7}$
χ^2_{ν}	1.02
dof	22

results are insensitive to abundance (see Sect. 3) and adopting solar abundance gives almost identical values. Examination of Tables 2 and 3 reveals that none of the WD atmosphere models give as good a fit as a simple blackbody. In addition, as g increases the best-fit values of T, N_{H} , R and L derived from the NLTE fits all increase. If N_{H} is constrained to have the HST value of Gänsicke et al. (1997) of $6.5 \times 10^{20} \text{ atoms cm}^{-2}$, then the best fit is obtained with $\log g = 8.45$. This gives best-fit values for T, R, and L of $32.6 \pm 0.7 \text{ eV}$, $(1.25^{+0.08}_{-0.05}) \times 10^9 \text{ cm}$, and $(2.30^{+0.10}_{-0.05}) \times 10^{37} \text{ erg s}^{-1}$, respectively.

In order to set limits on the luminosity of any additional spectral component, a thermal bremsstrahlung model was added to the NLTE WD atmosphere model. The value of N_{H} was constrained as before. The χ^2_{ν} did not improve significantly and the 68% confidence upper-limit to the best-fit 0.4 keV bremsstrahlung component is $5.3 \times 10^{35} \text{ erg s}^{-1}$.

3. Discussion

The LECS spectrum of CAL 83 is well fit by all three types of trial model and a considerably longer exposure is required in order to meaningfully discriminate between these models based on fit quality alone. There are however significant differences in the best-fit parameters derived using the different models (see Tables 1, 2, and 3) with the best-fit blackbody and LTE temperatures higher than with the NLTE fits, and correspondingly smaller emission region radii. If N_{H} is constrained to be equal to the HST value, then both the blackbody and NLTE fits give similar sub-Eddington luminosities of $\sim 2.5 \times 10^{37} \text{ erg s}^{-1}$, but the NLTE fit gives a significantly lower temperature of $32.6 \pm 0.7 \text{ eV}$, compared to $46.4 \pm 1.4 \text{ eV}$ for the blackbody fit.

The good fits to all three types of spectral model is in contrast to the LECS spectrum of CAL 87, which is better fit by both LTE and NLTE WD atmosphere models than a blackbody. This is mainly due to the presence of a deep (a best-fit optical depth > 13) O VIII absorption edge at an energy of 0.871 keV (Parmar et al. 1997a). The CAL 87 results supports the view that the X-ray emission from SSS arises from nuclear burning on the surface of a WD, and the same result would be expected from CAL 83. However, at the temperatures and gravities appropriate to the CAL 83 spectral fits, all the abundant ions that have absorption edges in the energy range 0.2–0.6 keV are completely ionized, with the exception of C VI at 0.49 keV. This depth of this edge is not predicted to be as deep as that of the O VIII edge seen from CAL 87. The 68% confidence upper limit op-

Table 3. CAL 83 NLTE (Hartmann & Heise 1997b) spectral fit parameters

Model	NLTE ($\log g = 8.0$)	NLTE ($\log g = 8.45$)
T (eV)	$31.7^{+0.5}_{-3.8}$	32.6 ± 0.7
N_{H} (10^{20} cm^{-2})	$5.4^{+4.0}_{-2.2}$	6.5^a
R (10^9 cm)	$1.1^{+3.2}_{-0.7}$	$1.25^{+0.08}_{-0.05}$
L ($10^{37} \text{ erg s}^{-1}$)	$1.6^{+7.9}_{-1.0}$	$2.30^{+0.10}_{-0.05}$
χ^2_{ν}	0.92	0.76
dof	22	23
Model	NLTE ($\log g = 8.5$)	NLTE ($\log g = 9.0$)
T (eV)	32.4 ± 1.2	$34.15^{+2.8}_{-0.35}$
N_{H} (10^{20} cm^{-2})	$6.8^{+1.4}_{-1.0}$	$7.8^{+0.5}_{-2.3}$
R (10^9 cm)	$1.35^{+0.6}_{-0.3}$	$1.4^{+2.7}_{-0.7}$
L ($10^{37} \text{ erg s}^{-1}$)	$2.6^{+2.0}_{-0.8}$	$3.4^{+0.7}_{-2.1}$
χ^2_{ν}	0.79	0.81
dof	22	22

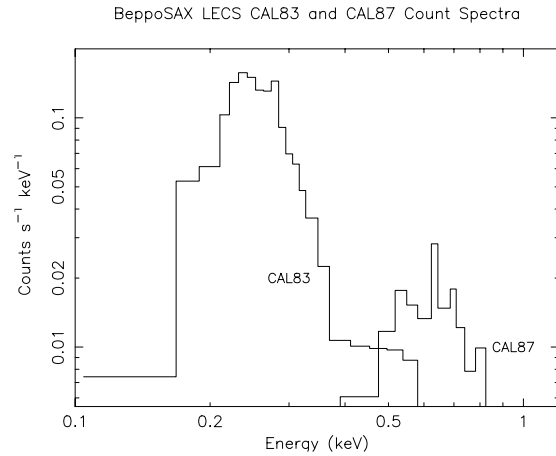
^aFixed at HST value of Gänsicke et al. (1997)

tical depth to an edge at an energy of 0.49 keV is 2.3. This probably explains why smooth functions such as blackbodies provide good fits to the CAL 83 spectrum.

Comparison of the two panels in Fig. 1 reveals that most of the additional contribution to χ^2 for the NLTE models is at energies $\gtrsim 0.4$ keV where the blackbody provides a better fit. One possibility is that the model atmosphere data are less appropriate at the temperatures used for modeling CAL 83 (30–50 eV), rather than CAL 87 (55–75 eV). Some idea of the very different LECS count spectra for these two sources can be seen in Fig. 3, although much of the difference is due to the ~ 10 times lower absorption to CAL 83 compared to CAL 87 ($\sim 10^{21}$ and $\sim 10^{22}$ atoms cm^{-2} , respectively). Alternatively, we cannot exclude the possibility of a hard component from CAL 83 with a luminosity of $\lesssim 5 \times 10^{35} \text{ erg s}^{-1}$ (see Sect. 2.2), which may affect the fits in the $\gtrsim 0.4$ keV energy range.

The WD mass can be constrained assuming that CAL 83 is on the stability line for steady nuclear burning (see Iben 1982, Fig. 2). The best-fit NLTE temperature, when N_{H} is constrained to be equal to the HST value, of 32.6 ± 0.7 eV corresponds to a WD of mass $\sim 0.9\text{--}1.0M_{\odot}$ with a luminosity of $\sim 3 \times 10^{37} \text{ erg s}^{-1}$ (see also Iben & Tutukov 1996). This is very similar to the measured luminosity of $(2.55 \pm 0.35) \times 10^{37} \text{ erg s}^{-1}$. This good agreement is in contrast to CAL 87 where the luminosity derived from the stability line is at least a factor 8 higher than that observed (Parmar et al. 1997a). This implies that in the case of CAL 83, the line of sight to the emitting region is not significantly obscured by e.g., an accretion disk. In addition, the emission region radius of $(1.35 \pm 0.32) \times 10^9 \text{ cm}$ is somewhat larger than the expected WD radius ($6.4 \times 10^8 \text{ cm}$ for a $0.9M_{\odot}$ WD; Bergeron et al. 1992).

In 1996 April CAL 83 underwent a temporary X-ray off-state (Kahabka 1997). This has been modeled by either the cessation of steady nuclear burning in the surface layers of a mas-

**Fig. 3.** Observed LECS count spectra for CAL 87 (taken from Parmar et al. (1997a) and CAL 83

sive ($\gtrsim 1.3M_{\odot}$) WD (Alcock et al. 1997) or by the expansion of the WD atmosphere following an episode of increased mass accretion rate on a massive ($> 1.2 M_{\odot}$) WD (Kahabka 1997). Both these models support the view that the X-ray emission from CAL 83 originates from steady nuclear burning in the surface layers of a WD and it is interesting to note that the WD mass derived above, assuming that the system is on the stability line of Iben (1982), is lower than both the above estimates. The best-fit blackbody spectral parameters derived here, approximately one year after the temporary off-state, are consistent with those derived by Kahabka (1997) using the ROSAT PSPC prior to the off-state. This indicates that CAL 83 has returned to its pre off-state behavior.

In summary, the LECS spectrum of CAL 83 is consistent with the assumption of a hot WD atmosphere heated by nuclear burning, but formally does not prove such an assumption.

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