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Letter to the Editor

A *BeppoSAX* observation of the super-soft source CAL 87

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Abstract. We report on a *BeppoSAX* Concentrator Spectrometer observation of the super-soft source (SSS) CAL 87. The X-ray emission in SSS is believed to arise from nuclear burning of accreted material on the surface of a white dwarf (WD). An absorbed blackbody spectral model gives a χ^2_ν of 1.18 and a temperature of $42\pm^{13}_{11}$ eV. However, the derived luminosity and radius are greater than the Eddington limit and radius of a WD. Including an O VIII edge at 0.871 keV gives a significantly better fit (at >95% confidence) and results in more realistic values of the source luminosity and radius. We also fit WD atmosphere models to the CAL 87 spectrum. These also give reasonable bolometric luminosities and radii in the ranges $2.7–4.8\times10^{36}$ erg s^{-1} and $8–20\times10^{7}$ cm, respectively. These results support the view that the X-ray emission from CAL 87 results from nuclear burning in the atmosphere of a WD.

Key words: X-rays: stars – accretion – binaries:close – stars:individual (CAL 87) – white dwarfs

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 observations have revealed approximately 30 similar sources located in the Galaxy, the Magellanic Clouds, a globular cluster and M31 (see Kahabka 1995; Kahabka & Trümper 1996 for recent reviews). SSS are hard to detect in the galactic plane due to the effects of interstellar absorption. Absorbed blackbody spectral models give typical temperatures of ∼40 eV and bolometric luminosities of $\sim10^{38}$ erg s^{-1}.

SSS were originally interpreted as due to scattering from an accretion disk corona (e.g., Smale et al. 1988), or accreting neutron stars radiating near or above the Eddington limit (Greiner et al. 1991; Kylafis & Xilouris 1993). Van den Heuvel et al. (1992) proposed that these are systems undergoing steady nuclear burning of hydrogen accreted onto the surface of a white dwarf (WD) with masses in the range 0.7–1.2 $M_\odot$. 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. These effects have been modeled assuming Local Thermodynamic Equilibrium (LTE) by Heise et al. (1994) and more recently extended to the non-LTE (NLTE) case by Hartmann & Heise (1997).

CAL 87 exhibits both X-ray and optical eclipses with a period of 10.6 hrs (Callanan et al. 1989; Cowley et al. 1990; Schmidtke et al. 1993; Kahabka et al. 1994), indicating an orbital inclination of >70°. The optical lightcurve shows a deep asymmetric primary minimum with a shallow, variable, secondary minimum while the X-ray eclipse is narrower and shallow. The optical modulation may be due to obscuration by a structured accretion disk (Schandl et al. 1997). Fitting an absorbed blackbody model to a 37 ksec exposure ROSAT Position Sensitive Proportional Counter (PSPC; 0.1–2.5 keV; Trümper 1983) CAL 87 spectrum gives a best-fit temperature, T, of 35 eV and an equiv-

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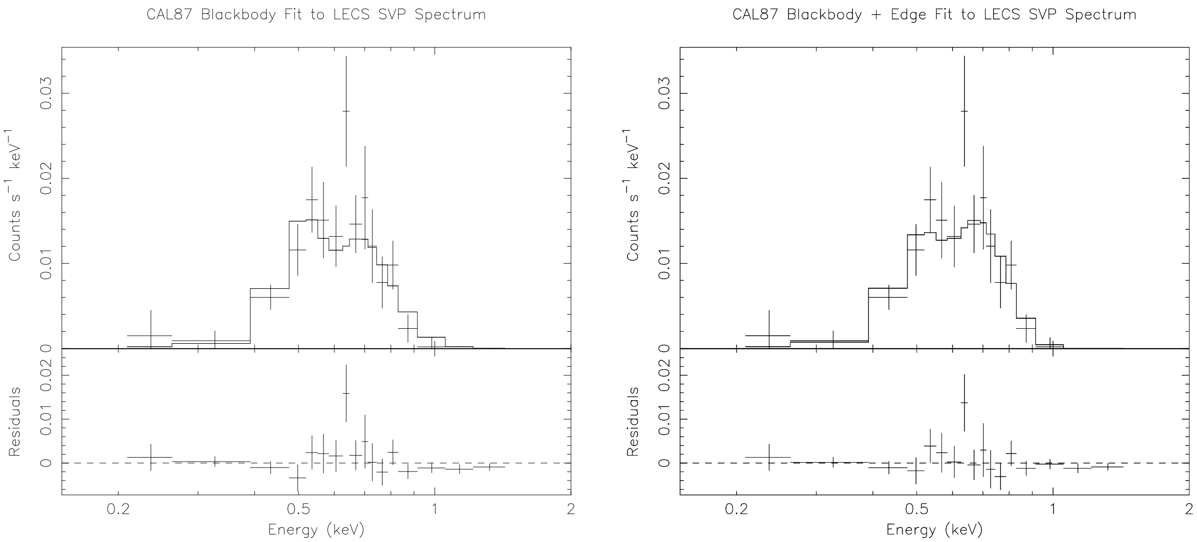

Fig. 1. Absorbed blackbody (left panel) and blackbody with a 0.871 keV absorption edge (right panel) model fits to the LECS CAL 87 spectrum

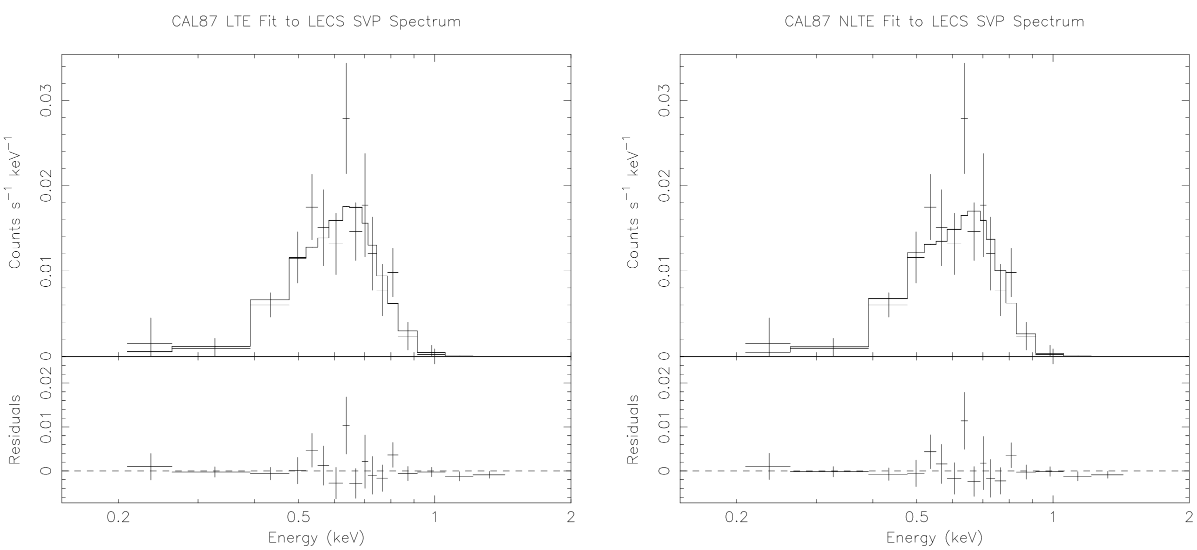

Fig. 2. Absorbed LTE (left panel) and NLTE (right panel) model fits to the LECS CAL 87 spectrum

alent hydrogen column density, N_H, of 1×10^{22} H atoms cm^{-2} (Hartmann & Heise 1997). CAL 87 has been a persistent X-ray source since its discovery in 1980.

2. Observations

The scientific payload of the *BeppoSAX* X-ray Astronomy Satellite (Boella et al. 1997a) comprises four coaligned Narrow Field Instruments, or NFI, including the Low Energy and Medium Energy Concentrator Spectrometers (LECS and MECS). The LECS 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. 1997). The background counting rate is 9.7×10^{-5} arcmin^{-2} 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 87 was observed by the LECS as part of the Science Verification Phase between 1996 October 27 02:14 to October 28 23:42 UTC. Due to the failure of a ground segment link and an instrument anomaly, data between October 28 04:54 and 10:55 UTC were lost. Good data were selected from intervals when the minimum elevation angle above the Earth's limb was $>4°$ and when the instrument's settings were nominal using the SAXLEDAS 1.4.0 data analysis package. Since the LECS was only operated during satellite night-time, this gave a total on-source exposure of 39 ksec. The MECS is sensitive in the energy range 1.5–10 keV, with energy and angular resolutions similar to the LECS (Boella et al. 1997b). The MECS observed

CAL 87 for a total exposure of 120 ksec, but did not detect the source.

Examination of the LECS image shows a source at a position consistent with (32″ distant) that of CAL 87. 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 1996 December 31 release. Background subtraction was performed using a standard blank field with a 46 ksec exposure. The CAL 87 count rate above background was 0.0076 ± 0.0011 s^{-1}. Examination of the extracted spectrum shows that the source was only detected in a narrow energy range (see Figs. 1 and 2) and only the 17 rebinned channels corresponding to energies between 0.2 and 1.5 keV were used for spectral fitting.

2.1. Spectral fits

In order to compare the LECS spectrum with those obtained from previous observations, we first fit an absorbed blackbody spectral model 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 1.18 for 14 degrees of freedom (dof). The best-fit parameters are given in Table 1. 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. The spectrum shows evidence for an abrupt cutoff $\gtrsim$0.8 keV and so an O VIII edge with absorption depth τ at a fixed energy of 0.871 keV, was added to the model. This edge is the dominant spectral feature at energies $\gtrsim$0.8 keV in many WD model atmosphere calculations (e.g. Heise et al. 1994; White et al. 1995). Including the edge gives a higher best-fit temperature and improves the fit quality, resulting in a χ^2_ν of 0.93 (Table 1). The value of the F statistic of 4.76 indicates that the addition of the edge is significant at >95% confidence. If the edge energy is allowed to vary, then the best-fit value of 0.84 ± 0.04 keV is consistent with an O VIII edge.

Heise et al. (1994) show that optically thick plasmas in the temperature range $10^5 - 10^6$ k are more efficient soft X-ray (0.1–1 keV) emitters than blackbodies, assuming plane parallel hydrostatic model atmospheres in which LTE determines the degree of ionization. This conclusion has been extended to the NLTE case by Hartmann & Heise (1997) for both solar and LMC abundances. These models include free-bound opacity sources for all relevant ions, but are still only first order approximations since line blanketing has not been taken into account. In addition, close to the Eddington limit the assumptions of hydrostatic equilibrium and plane parallel atmospheres are no longer valid.

The above LTE and NLTE models were fit to the LECS CAL 87 spectrum. For the LTE case, we assume an LMC abundance of 0.25 times the solar value and a local gravity of $\log(g) = 9$, appropriate to WDs with mass $\geq 0.6 M_\odot$. The fit results are however insensitive to abundance and adopting solar abundance gives almost identical results. Models with $\log(g) \leq 8.5$ cannot be made hot enough in hydrostatic equilibrium (due to the Eddington limit) to fit the spectrum. We note that models with $\log(g) >> 9$ cannot be excluded since they can fit the spectrum at higher effective temperatures and lower source radii.

Table 1. CAL 87 blackbody, LTE (Heise et al. 1994) and NLTE (Hartmann & Heise 1997) WD model atmosphere spectral fit parameters

	Blackbody	Blackbody with 0.871 keV Edge
T (eV)	42^{+13}_{-11}	59^{+27}_{-17}
N_H (10^{22} cm^{-2})	$1.00^{+0.05}_{-0.11}$	$0.53^{+0.58}_{-0.02}$
τ	...	>13
R (cm)	2×10^9 - 7×10^{12}	7×10^7 - 6×10^{10}
L (10^{36} erg s^{-1})	400 - 6×10^8	4 - 1.5×10^5
χ^2_ν	1.18	0.93
dof	14	13
	LTE	**NLTE**
T (eV)	74.4 ± 1.7	$57.3^{+1.9}_{-2.4}$
N_H (10^{22} cm^{-2})	$0.18^{+0.12}_{-0.06}$	$0.19^{+0.17}_{-0.07}$
R (cm)	$(9.1 \pm 1.2) \times 10^7$	$(1.67^{+0.35}_{-0.25}) \times 10^8$
L (10^{36} erg s^{-1})	3.30 ± 0.54	$3.89^{+0.89}_{-0.69}$
χ^2_ν	0.76	0.76
dof	14	14

Assuming a power-law spectrum with a photon index of 2.09 (i.e. similar to that of the Crab Nebula) and a distance of 50 kpc, the 99% confidence upper-limit to any 2.0–10.0 keV emission from CAL 87 obtained using MECS data is 1.3×10^{34} erg s^{-1}.

3. Discussion

The LECS spectrum of CAL 87 can be represented by all four types of trial models and it is clear that a LECS spectrum with significantly greater exposure is required to meaningfully discriminate between these models based on fit quality alone. There are differences in the best-fit values of T determined using the different models (see Table 1), with the blackbody fit giving the lowest T (and hence the largest source radius and luminosity) and the LTE fit the highest. The relatively large uncertainties in the best-fit parameters means that the luminosity and size of the X-ray emitting region are poorly constrained. The values of χ^2_ν favor the interpretation of the spectrum in terms of a model atmosphere fit with the LTE and NLTE fits both giving χ^2_ν values of 0.76. This should be compared with the blackbody fit which gives a χ^2_ν of 1.18. Both WD model atmosphere fits imply similar values of N_H, while the temperature derived from the NLTE fit is significantly cooler ($57.3^{+1.9}_{-2.4}$ eV) than that derived assuming LTE (74.4 ± 1.7 eV). The best-fit blackbody T derived here of 42^{+13}_{-11} eV is slightly higher, but consistent with, those derived using the ROSAT PSPC of 31^{+11}_{-10} eV and 34^{+8}_{-10} eV (Kahabka et al. 1994).

The bolometric luminosity implied by the blackbody interpretation of $>4 \times 10^{38}$ erg s^{-1} is higher than the Eddington luminosity for a $1 M_\odot$ object of 1.3×10^{38} erg s^{-1}. In addition, the required blackbody radius of $>2 \times 10^9$ cm is significantly larger than the expected WD radius (8.7×10^8 cm for a $0.6 M_\odot$ WD; Nauenberg 1972). In contrast, the fits using WD atmosphere models imply a lower luminosity, radius and temperature of 2.7–4.8$\times 10^{36}$ erg s^{-1}, 8–20$\times 10^7$ cm and 55–76 eV, respectively. The WD mass can be constrained assuming that CAL 87 is on the stability line (see Iben 1992, Fig. 2). The above temperature range corresponds to a WD of mass $\sim 1.2 M_\odot$ which has a luminosity of 4–8$\times 10^{37}$ erg s^{-1} while undergoing steady nuclear burning (see also Iben & Tutukov 1996). This is at least a factor 8 greater than the luminosity derived above. Since CAL 87 has an orbital inclination of $>70°$, it is possible that part of the emitting region is obscured, perhaps by the accretion disk. The LECS spectrum of CAL 87 is therefore 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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References

Anders E., Grevesse N., 1989, Geochimica et Cosmochimica Acta 53, 197
Arnaud K.A., 1996, In: Jacoby G., Barnes J. (eds.) Astronomical Data Analysis Software Systems V. ASP Conf. Series, 101, p17
Boella G., Butler R.C., Perola G.C., et al., 1997a, A&AS 122, 299
Boella G., Chiappetti L., Conti G., et al, 1997b, A&AS 122, 327
Callanan P.J., Machin G., Naylor T., et al., 1989, MNRAS 241, 37p
Cowley A., Schmidtke P.C., Crampton D.A., et al., 1990, ApJ 350, 288
Greiner J., Hasinger G., Kahabka P., 1991, A&A 246, L17
Hartmann H.W., Heise J., 1997, A&A, in press
Heise J., van Teesling A., Kahabka P., 1994, A&A 288, L45
Hellier C., Mason K.O., 1989, MNRAS 239, 715
Iben I., 1982, ApJ 259, 244
Iben I., Tutukov A.V., 1996, ApJS 105, 145
Kahabka P., 1995, Supersoft X-ray sources in the LMC and SMC. In: Bianchini A., et al., (eds.) Cataclysmic Variables. Proc. of the Abano Terme Conf., Kluwar, p. 435
Kahabka P., Trümper J., 1996, Supersoft ROSAT Sources in the Galaxies. In: van Paradijs J., van den Heuvel E.P.J. Kuulkers E. (eds.) IAU Symp. 165, Compact Stars in Binaries. p. 425
Kahabka P., Pietsch W., Hasinger G., 1994, A&A 288, 538
Kylafis N.D., Xilouris E.M., 1993, A&A 278, L43
Long K.S., Helfand D.J., Grabelsky D.A., 1981, ApJ 248, 925
Morisson D., McCammon D., 1983, ApJ 270, 119
Nauenberg M., 1972, ApJ 175, 417
Parmar A.N., Martin D.D.E., Bavdaz M., et al., 1997, A&AS 122, 309
Rappaport S.A., di Stefano R., Smith J.D., 1994, ApJ 426, 692
Schandl S., Meyer-Hofmeister E., Meyer F., 1997, A&A 318, 73 472, p. 53
Schmidtke P.C., McGrath T.K., Cowley A.P., Frattare L.M., 1993, PASP 105, 863
Smale A.P., Corbet R.H.D., Charles P.A., et al., 1988, MNRAS 233, 51
Trümper J., 1983, Adv. Space Res. 2, 241
van den Heuvel E.P.J., Bhattacharya D., Nomoto K., Rappaport S.A., 1992, A&A 262, 97
White N.E., Giommi P., Heise J., Angelini L., Fantasia S., 1995, ApJ 445, L125

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