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BeppoSAX observation of Cen X-4 in quiescence

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Abstract. We report on a 61 ks BeppoSAX observation of the soft X-ray transient Cen X-4 during quiescence which allowed to study the source X-ray spectrum from ~ 0.3 keV to ~ 8 keV. A two-component spectral model was required, consisting of a black body with temperature of ~ 0.1 keV and a power law with photon index ~ 2 . These values are compatible with earlier ASCA results indicating that Cen X-4 may be stable, within a factor of a few, over a 5 year baseline.

Key words: stars: neutron — stars: individual (Cen X-4) — pulsars: general — X-ray: stars

1. Introduction

Cen X-4 is one of the best studied sources of the Soft X-Ray Transient (SXRT) class (for a review see Campana et al. 1998a). X-ray outbursts have been detected in 1969 and 1979. During the 1979 outburst Cen X-4 reached a peak flux of ~ 5 Crab, corresponding to $L_X \sim 4 \times 10^{37}$ ergs $^{-1}$ for a distance of $d \sim 1.2$ kpc (Kaluzienski, Holt & Swank 1980). Type I bursts were observed, testifying to the presence of an accreting neutron star.

During the 1979 outburst the optical counterpart could be identified, as it brightened by $\gtrsim 6$ magnitudes (Canizares, McClintock & Grindlay 1979). Extensive spectroscopic and photometric measurements of the optical counterpart in quiescence ($V=18.7$ mag) led to the determination of the orbital period (15.1 hr; Chevalier et al. 1989; McClintock & Remillard 1990) and mass function ($\sim 0.2 M_\odot$, converting to a neutron star mass between $0.5 - 2.1 M_\odot$). The optical spectrum shows the characteristics of a K5-7 main sequence star, contaminated by lines (e.g. H α , H β and H γ) and continuum emission probably resulting from an accretion disk (Shahbaz, Naylor & Charles 1993). The latter was estimated to contribute $\sim 80\%$, $\sim 30\%$, $\sim 25\%$ and $\sim 10\%$ of the quiescent optical flux in the B, V, R and I bands, respectively.

ASCA observed twice Cen X-4 in its quiescent state in Feb. 1994 (28 ks) and Feb. 1997 (39 ks). In the first observation Cen X-4 was detected at a luminosity of $L_X \sim 2_{-1}^{+2} \times 10^{32}$ ergs $^{-1}$ (0.5–10 keV, Asai et al. 1996, 1998). The X-ray spectrum was well fit by a black body component ($kT_{\text{bb}} = 0.16_{-0.02}^{+0.03}$ keV) plus an additional power-law component with photon index $\Gamma = 1.9 \pm 0.3$. The 0.5–10 keV flux from the two spectral components was comparable. The column density was constrained to be $N_H \lesssim 2 \times 10^{21}$ cm $^{-2}$. The equivalent radius of the black body component was determined to be ~ 1.8 km, substantially smaller than the radius of a neutron star. A search for X-ray pulsations gave negative results, providing an upper limit to the pulsed fraction of $\sim 50\%$ for periods between 8 ms and 8200 s (Asai et al. 1996). The second ASCA observation provided similar results: $L_X \sim 3_{-2}^{+3} \times 10^{32}$ ergs $^{-1}$, $kT_{\text{bb}} = 0.13 \pm 0.02$ keV, $\Gamma = 2.5 \pm 0.5$ and $N_H = (3 \pm 1) \times 10^{21}$ cm $^{-2}$ (Asai et al. 1998).

During quiescence Cen X-4 was also observed with the Einstein IPC (in 1980, ~ 440 d after the 1979 outburst; Petro et al. 1981), EXOSAT CMA (in 1986; van Paradijs et al. 1987) and ROSAT HRI (in 1995; Campana et al. 1997). Campana et al. (1997) showed that, taking into account the relative uncertainties, these measurements are consistent with the same luminosity level of the ASCA observations. Yet, during the ROSAT HRI pointing a factor of ~ 3 flux variation was observed on a timescale of a few days (Campana et al. 1997).

Here we report on a BeppoSAX observation of Cen X-4 in its quiescent state. We describe the spectral and timing analysis of the BeppoSAX data as well as a reanalysis of the ASCA data in Section 2. In Section 3 we discuss our results.

2. BeppoSAX observation

A BeppoSAX (Boella et al. 1997a) observation of Cen X-4 took place on 9–11 Feb. 1999 for a total elapsed time of 135 ks. The source was detected only by the Low Energy Concentrator Spectrometer (LECS; 0.1–10 keV, Parmar et al. 1997) and the Medium Energy Concentrator Spec-

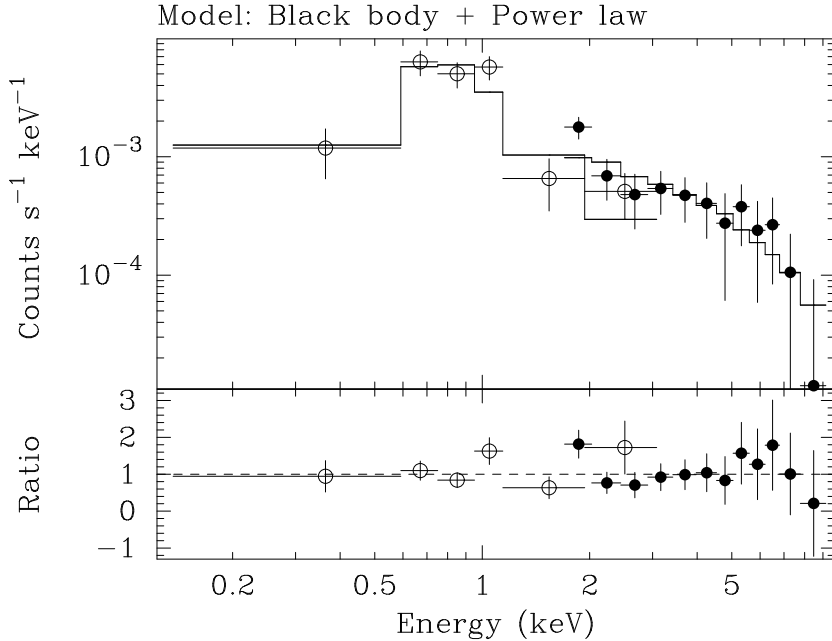


Fig. 1. LECS (circles) and MECS (dots) X-ray spectrum of Cen X-4 in quiescence. The spectrum is fit with a black body plus a power law model. In the lower panel the ratio between the data and the model is presented.

trometer (MECS; 1.3–10 keV, Boella et al. 1997b). Due to the South Atlantic Anomaly and Earth occultations the net exposure was 61 ks with the MECS and 21 ks with the LECS. The latter instrument could be operated only during the satellite night-time.

2.1. Spectral analysis

The LECS and MECS events were extracted within a radius of $4'$ centered on the source position. We collected 233 photons from the LECS and 632 from the MECS in the full energy range. Background subtraction was applied using the standard BeppoSAX files. The source background subtracted count rates were $(4.7 \pm 0.6) \times 10^{-3}$ (0.1–3.1 keV) and $(2.6 \pm 0.4) \times 10^{-3}$ ct s $^{-1}$ (1.7–9.0 keV) in the LECS and MECS instruments, respectively. The LECS and MECS spectral data were rebinned in order to have at least 40 photons per channel. The spectral analysis was carried out in the energy range relative to the count rates. A variable normalization factor was included to account for the mismatch in the absolute flux calibration of the BeppoSAX instruments. This factor is usually in the 0.7–1 range and has a value of ~ 0.7 in the best fit discussed below.

We fit the spectral data with the XSPEC (version 10.00) package. All-single component models provided a

poor fit to the data ($\chi_{\text{red}}^2 \gtrsim 2$). Therefore we applied the conventional model for quiescent neutron star SXRTs, i.e. a soft black body component plus a hard power-law tail (Asai et al. 1996, 1998; Campana et al. 1998a,b). The fit was good ($\chi_{\text{red}}^2 = 1.1$; cf. Figure 1). The corresponding black body temperature was $kT_{\text{bb}} = 103_{-32}^{+53}$ eV and the power law photon index $\Gamma = 2.01_{-0.68}^{+0.65}$ (uncertainties are 90% confidence for a single parameter, $\Delta\chi^2 = 2.71$). The equivalent black body radius was $R_{\text{bb}} = 10.0_{-2.2}^{+420}$ km. Note that this radius, though highly uncertain, is consistent with the neutron star radius. A 3σ lower limit of $R_{\text{bb}} \gtrsim 6.2$ km on the emitting region was derived. The column density was $N_H = 2.6_{-2.3}^{+5.2} \times 10^{21}$ cm $^{-2}$. The absorbed X-ray flux was 7.3×10^{-13} and 2.0×10^{-13} erg s $^{-1}$ cm $^{-2}$ in the 0.1–2 and 2–10 keV energy bands, respectively. The corresponding unabsorbed flux was 8.5×10^{-12} and 2.0×10^{-13} erg s $^{-1}$ cm $^{-2}$, respectively, providing (unabsorbed) luminosities of 1.5×10^{33} erg s $^{-1}$ (0.1–10 keV) and 4.5×10^{32} erg s $^{-1}$ (0.5–10 keV).

2.2. Timing analysis

The relatively small number of counts did not permit to carry out a sensitive search for periodicity and short term variability. The MECS and LECS light curves were consistent with a constant flux. A variation by a factor of ~ 3 on

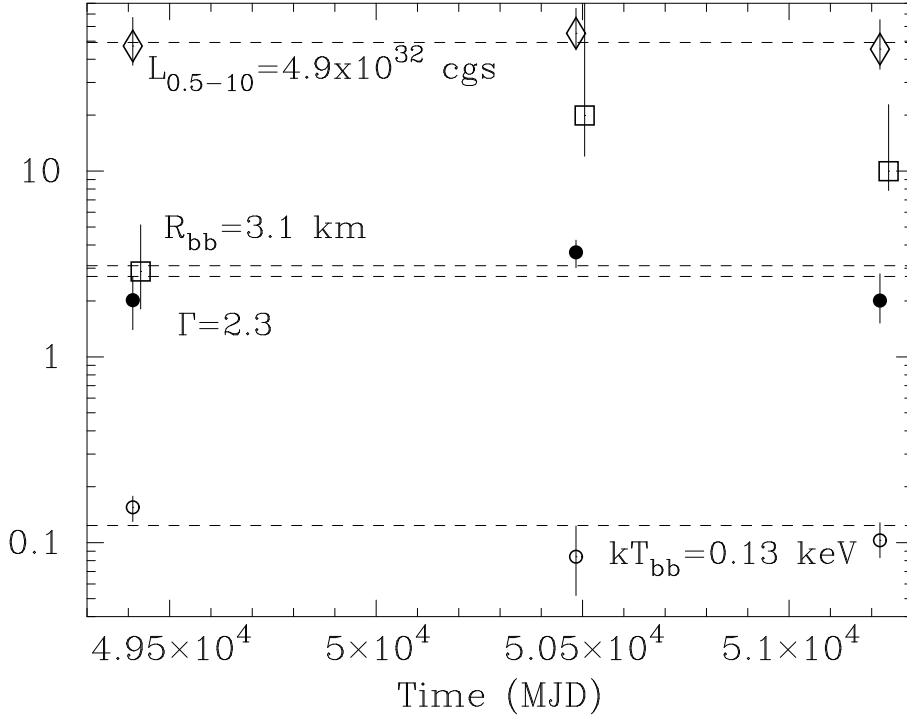


Fig. 2. Long term behaviour of the overall 0.5–10 keV unabsorbed luminosity in units of $10^{31} \text{ erg s}^{-1}$ (diamonds), of the power law photon index (filled circles), of the equivalent black body radius in km (squares, slightly offset in time) and of the equivalent black body temperature in keV (open circles), taken with ASCA and BeppoSAX imaging instruments. Errors are at the 68% confidence level for three parameters of interest ($\Delta\chi^2 = 3.5$). These uncertainties have been adopted to derive the mean in Table 1. The errors on luminosity has been taken from Asai et al. (1996, 1998). In the case of the BeppoSAX observation we assume a 50% error. Luminosities are unabsorbed and in the energy range 0.5–10 keV.

a timescale comparable to the observation duration (i.e. similar to that observed with the ROSAT HRI, see Campana et al. 1997) would have been easily detected in the BeppoSAX light curves.

2.3. Reanalysis of ASCA data

The large equivalent black body radius derived from BeppoSAX data ($R_{\text{bb}} \gtrsim 6.2 \text{ km}$) is larger than that reported by Asai et al. (1996, 1998) using ASCA data. Since these authors do not report the uncertainties on the equivalent black body radius, we reanalysed the ASCA data. We consider only GIS data since Cen X-4 falls across two CCDs in the SIS. The best fit values for the black body plus power law model are given in Table 1. In the first observation the best fit value of the column density is consistent with zero and the other spectral parameters are consistently different from the values derived from the second ASCA and BeppoSAX observations. In the second ASCA observation, the count rates of all the ASCA instruments are systematically lower than those in the first observation, despite the similar source position on the detectors, with a lack of photons at soft energies. For this observation, we

derive an (unabsorbed) X-ray luminosity which is a factor of ~ 3 higher than the value quoted by Asai et al. (1998).

The large uncertainties in the parameters are signs of poor statistics. Due to these uncertainties, we also repeated the spectral analysis keeping the column density value fixed to the BeppoSAX value ($2.6 \times 10^{21} \text{ cm}^{-2}$). These fit provide only a marginally worse description of the data and result in a much more homogeneous spectral parameter values across the different observations.

3. Discussion

There is growing evidence that the quiescent spectrum of SXRTs is made of two components: a soft component, usually modeled with a $k T_{\text{bb}} \sim 0.1 - 0.3 \text{ keV}$ black body, and a hard power law component with photon index $\sim 1.5 - 2$ (Campana et al. 1998a,b; Asai et al. 1996, 1998; Guainazzi et al. 1999). The soft component is usually attributed to the radiative cooling of the neutron star warm interior heated up during the accretion episodes giving rise to the outbursts (Campana et al. 1998a; Brown, Bildsten & Rutledge 1998). Modeling this soft component with a black body, the derived emitting area is usually smaller than

Table 1. Summary of Cen X-4 spectral fit. For the ASCA data we consider only the GIS detectors. Free column densities are considered in the upper part of the table. Column densities fixed to the best fit BeppoSAX value are reported in the lower part. Uncertainties are for one parameter of interest and at the 90% confidence level ($\Delta\chi^2 = 2.71$)

Date (dd/mm/yy)	Column density (10^{21} cm^{-2})	Photon index	Temperature (keV)	Radius (km)	Luminosity ($10^{32} \text{ erg s}^{-1}$)	Red. χ^2
27/02/94	$0.2^{+5.3}_{-0.2}$	$1.7^{+0.9}_{-0.6}$	$0.19^{+0.03}_{-0.07}$	$1.1^{+8.0}_{-0.3}$	2.6	1.0
04/02/97	$3.5^{+4.8}_{-3.5}$	$3.7^{+0.8}_{-0.9}$	$0.08^{+0.14}_{-0.02}$	$29.4^{+287}_{-29.4}$	8.6	1.1
09/02/99	$2.6^{+5.2}_{-2.3}$	$2.0^{+0.7}_{-0.7}$	$0.10^{+0.05}_{-0.03}$	$10.0^{+420}_{-2.2}$	4.5	1.1
27/02/94	2.6 (fixed)	$2.0^{+0.6}_{-0.5}$	$0.15^{+0.02}_{-0.02}$	$2.9^{+1.9}_{-1.0}$	4.7	1.0
04/02/97	2.6 (fixed)	$3.6^{+0.5}_{-0.5}$	$0.08^{+0.03}_{-0.03}$	$18.9^{+145}_{-6.3}$	5.5	1.1
09/02/99	2.6 (fixed)	$2.0^{+0.7}_{-0.5}$	$0.10^{+0.02}_{-0.02}$	$10.0^{+10.8}_{-1.8}$	4.5	1.1
MEAN [‡]	–	2.7 ± 0.7 (1.4%)	0.12 ± 0.03 (2.7%)	$3.1^{+3.7}_{-3.1}$ (74%)	4.9 ± 1.9 (84%)	

[‡] Mean of the three observations in the case of fixed column density. In parenthesis are also reported the null hypothesis probabilities relative to the fit with a constant function for one degree of freedom. The mean has been computed using larger uncertainties than the ones reported in the Table (cf. Fig. 2).

the neutron star surface, with $R_{\text{bb}} \sim 1 - 2$ km (Verbunt et al. 1994; Campana et al. 1998a,b; Asai et al. 1996, 1998). Neutron star atmosphere models have been used to fit the available data. These models provide a good fit to the soft component and substantially a larger effective temperatures and radii with respect to a pure black body model (Rutledge et al. 1999). The radii inferred in this way are consistent with emission from the entire neutron star surface. The hard component has been interpreted as due to the interaction of a relativistic radio pulsar wind with matter outflowing from the companion (shock emission), since when the SXRTs set down to quiescence the neutron star may resume its activity as a radio pulsar (Stella et al. 1994; Campana et al. 1998a). Heating of the polar caps by high energy particles responsible for the radio pulsar emission may also contribute to the soft component (e.g. Becker & Trümper 1999; Campana & Stella 2000). Recently, a UV spectrum of Cen X-4 has been obtained with HST/STIS (McClintock & Remillard 1999). The main result is that in the ν versus νF_ν plot the unabsorbed flux decreases by only a factor of 2 from X-rays to optical (subtracted from the contribution of the companion star). Such a nearly νF_ν flat spectrum is clearly reminiscent of the extended power law spectra that are characteristics of shock emission.

An alternative explanation attributes the soft component to matter accretion onto the neutron star surface in the propeller regime. In this case a small fraction of the mass inflow rate would penetrate the magnetosphere at high neutron star latitudes. The hard component instead would be produced in an advection-dominated accretion flow (ADAF, Zhang et al. 1998; Menou et al. 1999). At the moment this is just a suggestion, lacking self-consistent ADAF models able to fit the multi-wavelength spectra of SXRTs in quiescence.

In principle, an accurate monitoring of the variability on different time scales could help in discriminating between these two possibilities. In fact, while in general accreting binaries show flux variations, in the case of cool-

ing plus shock emission model we expect a more steady luminosity.

The BeppoSAX observation presented here allowed us to further study the quiescent state of Cen X-4. A comparison in the 0.5–10 keV energy range (i.e. including the hard spectral component) can be carried out only with the two ASCA observations. In the upper part of Table 1 we report the fit with free column densities. We obtain large variations in the spectral parameters. On the other hand if we fix the column density to the BeppoSAX value, we obtain similarly good fits and spectral parameters in much more agreement (lower part of Table 1). We are unable to decide which of the two options is correct based on pure statistics. Given the low number of counts, we should prefer the fit with constant column density, since the goodness of the fit is not particularly affected. We remark however that a count rate percentual variation in the soft part of the spectrum by $\sim 30\%$ is observed in the two ASCA observations.

Together with the nearly constant behaviour of the source flux (within a factor of a few in the 0.5–10 keV energy band) on timescales of years variations by a factor $\gtrsim 3$ in a few days in the soft (0.1–2.4 keV) energy band (Campana et al. 1997) and variations by up to ~ 1 mag in the optical (Chevalier et al. 1989; Cowley et al. 1988) have been observed. The interpretation of these variations is not simple based on current models. In principle, mechanisms based on accretion can more readily explain variations in the X-ray luminosity (especially in the ADAF regime where the efficiency is proportional to \dot{M}^2). Variations in the cooling component are not expected whereas the efficiency of the shock emission component should be almost constant at least in the soft X-ray band. In this scenario more promising mechanisms should involve a variation in the enshrouding geometry in proximity of the source and therefore of the absorbing column density.

A different interpretation relies on the coronal activity of the companion star. This mechanism provides too low a quiescent luminosity to power SXRTs in quiescence,

achieving the saturation level of $10^{29} - 10^{30}$ erg s $^{-1}$ for main sequence stars (Eracleous et al. 1991), unless subgiant companions are present ($10^{31} - 10^{32}$ erg s $^{-1}$ for RS CVn systems; Campana & Stella 2000; Bildsten & Rutledge 2000). Even if the basal coronal emission is much lower than the quiescent luminosity observed in SXRTs in quiescence, large flare events may reach peak 0.1–2.4 keV luminosities in excess of a few 10^{32} erg s $^{-1}$ as in the RS CVn stars UX Ari ($\sim 2 \times 10^{32}$ erg s $^{-1}$; Güdel et al. 1999) or Algol ($\sim 2 \times 10^{32}$ erg s $^{-1}$; Ottmann & Schmitt 1996). Given the short orbital period of Cen X-4 (15.1 hr) compared with RS CVn binaries (1–20 d) even more energetic flare might be expected.

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