BeppoSAX Observation of the Black Hole Candidate Cyg X-1

T. Di Salvo, L. Burderi, N. R. Robba
Dipartimento di Scienze Fisiche ed Astronomiche, Università degli Studi Palermo, via Archirafi 36, 90123 Palermo, Italy

C. Done, P. Życki
Department of Physics, University of Durham, South Road, Durham, UK

ABSTRACT

Cyg X-1 is the brightest of the persistent Black Hole Candidates (BHC) that shows transitions from high to low states. The most accepted models for the low states of the BHCs are those in which a Shakura-Sunyaev disc is present in an external region and an optically thin and geometrically thick corona is present in an internal region. A convenient diagnostic tool to study the morphology of these systems is given by the spectroscopy of the Fe line, usually observed in these systems. The broad band data (0.1-30 keV) from BeppoSAX we analysed reveal evidence of relativistical smearing in the reprocessed component. This suggests the presence of cold matter at radii small as 10 Schwarzschild radii in the low state of Cyg X-1, much smaller than the prediction of the ADAF models.

1. Introduction

Cyg X-1 is the prototype of the persistent Galactic Black Hole Candidates (GBHC). It is a binary system consisting of a BH accreting matter from a supergiant type O star. From the orbital parameters of the system an estimate of the mass of the compact object was derived, $M_X = 8-11\ M_\odot$ (Bolton, 1975), that is well above the upper limit estimated for the mass of a neutron star ($2-3\ M_\odot$; see e.g. Hartle, 1978). The uncertainty in this estimate of the mass is due to the uncertainty on the knowledge of the inclination angle i between the normal to the orbital plane and the line of sight. The lack of X-ray eclipses requires $i < 64°$, while spectrophotometric studies have produced $i > 37°$ (Guinan et al., 1979). The accretion of matter in this system seems to occur both via Roche-Lobe overflow (Bolton, 1975) and via stellar wind (Eardley et al., 1978). An accretion disc is believed to form around the compact object. In this case the disc size should be only $R_D \leq 4\times10^3\ R_g$ (Liang & Nolan, 1984), where $R_g = GM/c^2$ is the gravitational radius.

Cyg X-1 was observed in two different spectral states, namely a high (or soft) state, characterized by a strong soft excess ($KT = 0.5-1$ keV) and a steep power-law ($\alpha > 2-3$), and a low (or hard) state, characterized by a weak soft excess ($KT = 0.1-0.3$ keV) and a hard power-law ($\alpha > 1.4-1.9$). In both states the power-law spectrum shows a cutoff at high energies, of the order of hundred of keV. The standard disc (Shakura & Sunyaev, 1973) is not able to explain a soft or hard power-law in the spectrum of Cyg X-1 and it is believed that the power-law originates from successive Compton scatterings of the soft spectrum from the accretion disc in a hot, optically thin, geometrically thick region (corona). In this scenario the high energy cutoff is due to the electron temperature T_e in the corona and the soft excess is the direct emission from the disc. Moreover the radiation scattered in the corona and emitted in the direction of the disc will be reflected by Compton scattering, rising a bump between 20 and 50 keV. The reflected component should contain the iron K_α line at ~ 6.4 keV and the iron edge at ~ 7 keV. The most probable geometry of the corona-disc system is of a central corona around the black hole (with a spherical or torus geometry) and an outer standard disc.

2. BeppoSAX Observation

Cyg X-1 was observed by BeppoSAX NFIs (Boella et al. 1997) on 1998 May 3 and 4, with a total exposure time of ~ 25 ksec. Characteristics of BeppoSAX NFIs are the broad spectral band (0.1-200 keV) and a good spectral resolution in the whole range. During the BeppoSAX observation Cyg X-1 was in its usual low (hard) state with a total (0.1-200 keV) unabsorbed luminosity of $\sim 4.6 \times 10^{37}$ ergs/s adopting a distance of 2.5 kpc (Liang and Nolan 1983). In figure 1 we report the MECS light curves in three energy bands: 1-4 keV (panel 1), 4-7 keV (panel 2), 7-11 keV (panel 3), and the corresponding hardness ratios (panels 4 and 5). Although the MECS light curve shows an increase of the intensity up to 30% during the observation, the hardness ratio appears to be constant, except for a little hardening at the end of the observing period (between 5.5×10^4 and 6×10^4 s). This hardening is probably due to an absorption dip, which is visible in the soft range and disappears in the hard range.

3. Spectral analysis

The spectrum of Cyg X-1 is complex because several components are present. In fact we tried a fit of the 1.8-30 keV spectrum with a simple absorbed power-law (the obtained χ^2/d.o.f. was 2008/274). In the residuals are clearly visible all the features expected in Cyg X-1 spectrum, namely the soft excess, the iron line and edge, and the hardening due to the reflection at ~ 20 keV. We begin to analyse the soft energy range (0.1-4 keV) to study the shape of the soft excess. In this range we can model the direct component with a simple power-law, but a soft excess is still evident. We tried several models for the soft excess (blackbody, disc multitemperature blackbody and combinations of blackbody and comptonized spectra) and we found that a blackbody plus a comptonized spectrum (*comptt* model - see Titarchuk et al., 1994) gives the best value of the χ^2. The results with three of these models are shown in table 1.

Extending the energy range to 0.1-30 keV we used the blackbody plus *comptt* model for

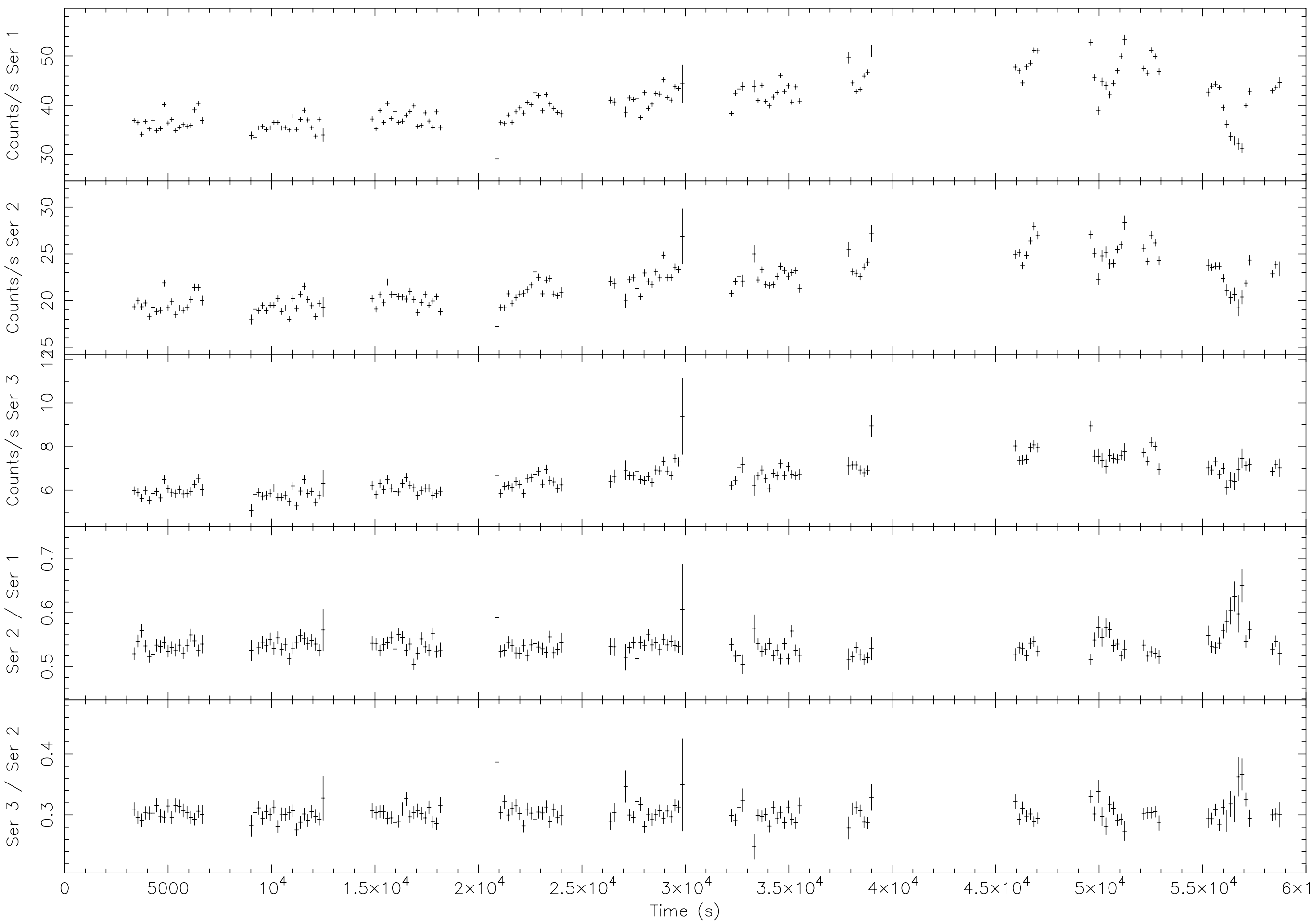

Fig. 1.— Light curves and hardness ratios in the MECS range. Ser 1: 1-4 keV, Ser 2: 4-7 keV, Ser 3: 7-11 keV

Table 1: Results of the fit in the energy range 0.1-4 keV. Uncertainties are at the 90% confidence level for a single parameter. Power-law normalizations are in unit of 10^{-2} ph keV^{-1} cm^{-2} s^{-1} at 1 keV.

Parameter	bbody	disk bbody	bbody+comptt
$N_H \times 10^{22}$ cm^{-2}	0.67 ± 0.04	0.713 ± 0.025	0.77 ± 0.13
Photon Index	1.761 ± 0.026	1.778 ± 0.011	$1.56^{+0.17}_{-0.35}$
Norm	1.51 ± 0.06	1.551 ± 0.018	1.14 ± 0.4
KT (keV)	0.14 ± 0.007	0.1675 ± 0.0024	0.131 ± 0.021
Norm	$(3.8 \pm 1.6) \times 10^{-3}$	$(5.1 \pm 3.3) \times 10^{5}$	$0.09^{+0.13}_{-0.04}$
$KT_{\rm compt}$ (keV)	-	-	$0.4^{+0.5}_{-0.14}$
Norm$_{\rm compt}$	-	-	$2.5^{+2.6}_{-1.0}$
χ^2/d.o.f.	399/311	404/311	381/309

the soft excess, a power-law for the direct spectrum and added the model for the reflection component. To fit the reflection features we used a Compton reflected continuum and the iron K_α line computed self-consistently for that continuum. The reprocessed component can be smeared to take into account the relativistic and kinematic effects of disc emission (see *e.g.* Życki, Done and Smith 1997). In this case we can obtain an estimate of the inner radius of the accretion disc. A relativistically smeared reflection gives a better description of the spectrum than a non-smeared reflection (see Di Salvo et al. 1998). The inferred inner radius of the disc is $\sim 20\ R_g$. Because a narrow reflection component is also expected from reflection by the companion star and/or the stellar wind and/or the outer flared disc (see e.g. Done & Życki, 1998) we added to the previous model another not relativistically smeared and not ionized reflection component, obtaining a χ^2 reduction of $\Delta\chi^2 = 12$. An F-test gives a value of the F function of 9.4, which is significant at more than 99.5% confidence level for one additional parameter. The results of the fit are shown in table 2, where we fixed iron abundance to the solar one and $\cos i = 0.6$, where i is the inclination angle. In figure 2 the unfolded spectrum with the used model and the residuals in unit of σ are shown.

4. Discussion

Recently there has been much excitement about the so called Advection Dominated Accretion Flow (ADAF). This model could naturally explain the presence of hot, optically thin, geometrically thick matter in the inner region of the disk. Using this model, Esin et al. (1997) tried to explain the observed spectral changes in the GBHCs, considering a transition radius between the standard disc and the inner ADAF region in the hard state of $10^4\ R_S$ for the Soft X-ray Transients (SXT) and $> 100\ R_S$ for wind accretion as in Cyg X-1. However these values are much higher than our estimate of the inner radius of the disc. Therefore a revision of these models is required to properly explain the observational results.

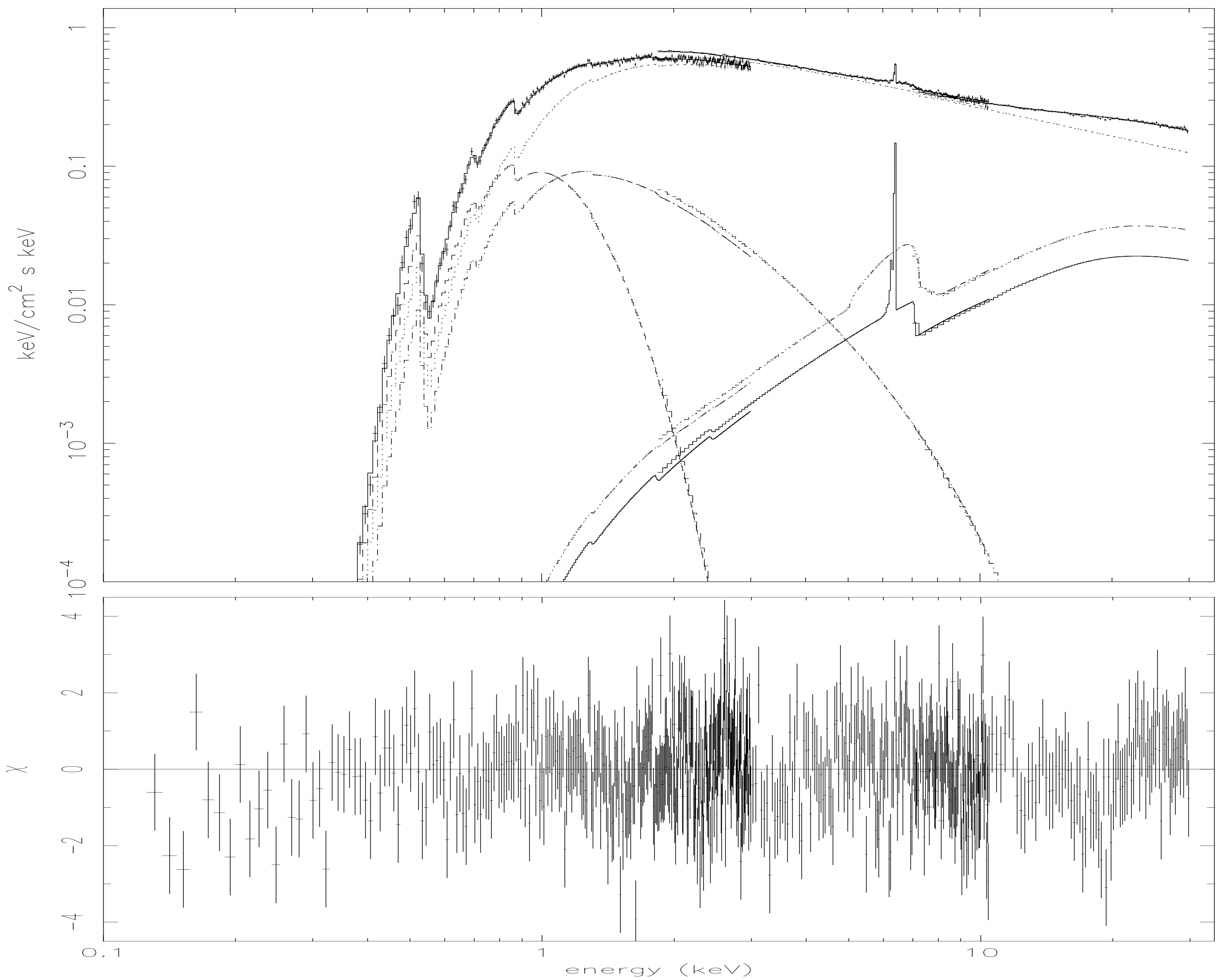

Fig. 2.— Top panel: unfolded spectrum. The several components used for the model are also shown, namely the power-law, the narrow and relativistically smeared reflection and, in the left side, the blackbody and the comptonization model used to fit the soft excess. Bottom panel: residuals in unit of σ respect to the previous model.

Table 2: Results of the fit in the energy range 0.1-30 keV. Uncertainties are at the 90% confidence level for a single parameter. f is the reflection fraction and ξ the ionization parameter.

Parameter	Value
$N_H \times 10^{22}$ cm^{-2}	0.69 ± 0.13
$KT_{\rm BB}$	0.13 ± 0.03
$KT_{\rm comp}$	1.3 ± 0.5
$\tau_{\rm comp}$	10 ± 8
Photon Index	1.69 ± 0.03
Norm	1.33 ± 0.08
$f_{\rm rel}$	0.31 ± 0.08
Fe abund	1.0 (fixed)
$\cos i$	0.6 (fixed)
ξ	< 0.3
$R_{\rm in}/R_g$	20 ± 10
$f_{\rm narrow}$	0.21 ± 0.08
χ^2/d.o.f.	661/535

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