Spectral behaviour of Cygnus X-1 in a broad band 0.1 - 200 keV based on Rosat, TTM and HEXE observations

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ABSTRACT.

We present results of a study of the broad band X-ray spectrum of the black hole candidate Cygnus X-1 made with the *Rosat PSPC*, *TTM* and *HEXE*. The two *TTM* and *HEXE* observations were simultaneous, and the *PSPC* observation was made inbetween these. The X-ray spectrum in the range 0.1 - 200 keV is complex, consisting of a power law, a broad reflection component and the soft excess at energies below 3 keV. The power law has a photon index Γ of $\sim$ 1.7 which did not change between the two *TTM* and *HEXE* observations. The reflection component can be modelled as illumination of an ionized disc by the power law source. The soft excess can be well fitted as a blackbody with temperature $kT_{bb} = 0.13 \pm 0.02$ keV. From the X-ray luminosity of the soft excess, accretion disc temperatures were calculated, in particular the temperature at 7 Schwarzschild radii expected to be highly representative of the total disc emission which was found to be 0.13 keV. The good agreement allows the soft excess to be positively identified for the first time with disc emission.

1. Introduction

Cygnus X-1 is probably the best known black hole candidate. It consists of a O9.7 supergiant and a compact object of mass $\sim 10M_\odot$. The X-ray spectrum is variable and complex, consisting of a number of components. At lower energies, below $\sim$ 3 keV the observed spectrum has a soft X-ray excess which became apparent as the column density N_H obtained from the low energy cut-off was much lower than the galactic $N_H \sim 6 \pm 2 \cdot 10^{21}$ H atom cm^{-2} derived from the reddening towards the companion HDE 226868 (Priedhorsky et al. 1979). Extensive studies of the *Exosat ME* observations by Bałucińska and Hasinger (1991) showed that the inconsistency was removed if the X-ray spectrum was modelled by a blackbody to represent the soft excess with temperature $kT_{bb} \sim$ 0.25 keV, superimposed on a power law to represent Comptonisation in the band 1 - 10 keV. The ME data were not able to constrain the temperature very well, as the peak of the blackbody spectrum was outside the range of the instrument. However the energy range of the *Rosat PSPC* is ideal for study of the soft excess.

At energies below the Comptonisation break, the high energy spectrum was originally modelled by a power law. Typically a power law index Γ of $\sim$ 1.5 - 1.8 was obtained.

In addition, Done et al. (1992) identified the presence of a reflection component in *Exosat GSPC* spectra similar to those seen in AGN. This is a very broad spectral term which contributes to the continuum between $\sim$ 1 and $\sim$ 100 keV. *OSSE* observations (Grabelsky et al. 1992) have shown that the Comptonisation break occurs at $\sim$ 200 keV, so that a power law approximation to the underlying hard component remains good at all energies in the *HEXE* band.

In the present paper we present results of simultaneous observations of Cyg X-1 made with *TTM* and *HEXE* onboard the space station *Mir* which have a combined energy range of 2 - 200 keV allowing studies of the reflection component and of the underlying hard component. In particular, with this spectral coverage, the value of the power law index Γ may be well determined, and was found not to change appreciably between observations made in 1989 April and 1992 April. The *TTM/HEXE* results provide realistic values for the power law index to be used in analysis of the *Rosat PSPC* data, which the *PSPC* is not able to constrain. However the parameters of the soft excess which peaks in the *PSPC* band can be well-determined, and we are able for the first time to identify the soft excess with accretion disc emission.

2. Observations

2.1. *TTM/HEXE*

TTM is a coded mask telescope with a field of view of 7.8° $\times$ 7.8° (FWHM) giving X-ray images with 2' angular resolution in the energy range 2 - 30 keV. *HEXE* contains a phoswich detector operating in the band 20 - 200 keV with a field of view of $\sim$ 1.6° $\times$ 1.6° (FWHM). When the instruments are used simultaneously they provide spectra in the broad energy band 2 - 200 keV.

Cygnus X-1 was observed with *TTM/HEXE* on several occasions. In this paper we present results from two observations: 1989 April 25, and 1992 April 15 - 19. Data from each of these observations were accumulated into a single spectrum equivalent to 4900 s and 6700 s respectively.

2.2. Rosat *PSPC*

The observations were made on 1991 April 18 - 20. We present results for the third part of the observation lasting 1100 s at orbital phase 0.46 calculated using the accurate ephemeris of Gies and Bolton (1982), and so not contaminated by absorption dips. Source data were extracted from a circle of radius 0.21° centred on the source to include photons scattered outwards in the dust halo (Predehl & Schmitt 1995). Background was extracted from an annulus extending from 0.22° to 0.29°, and the data were corrected for deadtime and vignetting. We present results below obtained using the March 1992 response function appropriate to this observation in the early part of the *Rosat* mission. However to assess systematic errors, we also analysed the data using the January 1993 response, and found that parameters derived from spectral fitting changed by only 1.5% to 3%, giving confidence in the results.

The light curve of the third section of data revealed the strong short-term variability well-known in Cygnus X-1. Because of this, it is not possible to accumulate data for a

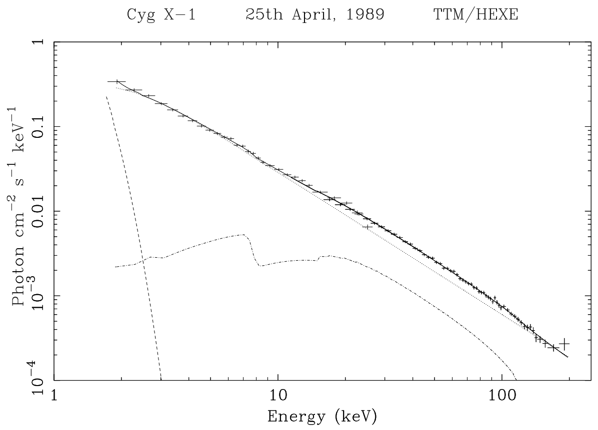

Fig. 1. Results of spectral fitting *TTM/HEXE* data showing the total spectrum together with the soft excess (dashes), power law (dots) and reflection components (dots dashes).

sufficiently long time with the source at a constant intensity level to produce a spectrum of sufficient quality (requiring $\sim$ 100 s of data). Consequently the data were divided into seven intensity bins, each 10 c/s wide covering the ranges from 60 - 70 c/s to 120 - 130 c/s in the band 0.1 - 2.0 keV. These intensity bins were equivalent typically to 130 s of data, so that Poisson errors were sufficiently small for good fitting to be made. For each of these intensity bands, a spectrum was produced, and we added conservatively a systematic error of 2% to each channel.

3. Results

3.1. *TTM/HEXE observation*

The two spectra corresponding to the 1989 and 1992 observations were found to be complex and could not be represented by simple models such as power law or Sunyaev-Titarchuk Comptonisation. It has already been shown with the HEXE data that a reflection component is required (Döbereiner et al. 1995). In order to obtain a satisfactory fit to the combined spectra it was necessary to have a three-component model consisting of a blackbody to represent the soft excess, and a power law and its reflected spectrum resulting from illumination of the ionized disc. The deconvolved spectrum and the best fit to the first observation are shown in Fig. 1, together with the individual components; the characteristic edge at $\sim$ 7 keV can be clearly seen in the reflection component. The power law index could be well-determined in this band and was found to have values of 1.68 ± 0.01 and $\sim$ 1.7 for the two observations, although for the second observation it was not possible to get a formally acceptable fit. However the value of the index depends on the energy at which we assume the underlying power law has the Comptonisation break; we assumed this to be 200 keV, however for a break at 100 keV, Γ would be 1.62, and 1.73 for a break at 300 keV. Thus we can quote our value as $\Gamma = 1.68^{+0.05}_{-0.06}$.

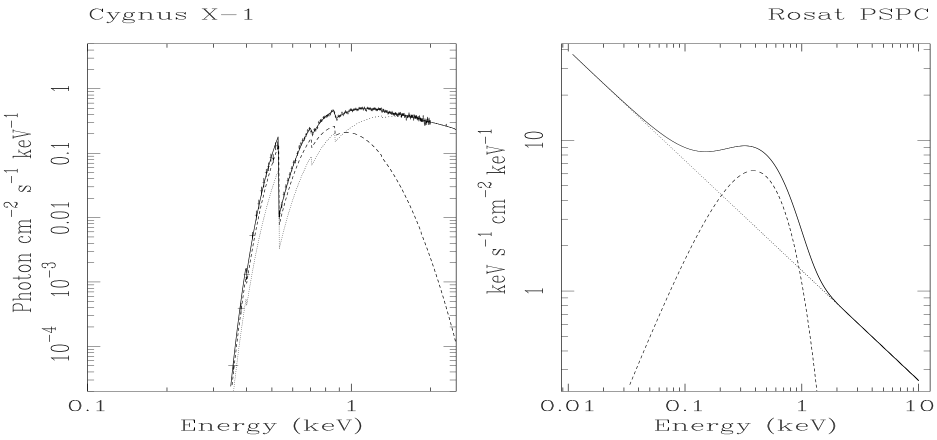

Fig. 2. Typical *Rosat PSPC* spectrum of Cygnus X-1 showing the blackbody component used to model the soft excess (dashes) and the power law component (dots). For clarity, the data are shown in primitive channels.

The spectral fitting showed that the value of the ionization parameter $\xi = L/n_e R^2 = 190 \pm 180$ (90% confidence) which although poorly determined, probably implies a substantially ionized disc.

3.2. *Rosat PSPC* observation

Spectral fits of the spectra in the 7 intensity bins were tried using simple models including an absorbed power law model. In this case, the quality of the fits was unacceptable, with reduced χ^2 typically as large as 1.24 with 21 degrees of freedom. Moreover, the power law photon index Γ averaged over the 7 intensity bands was 2.3 ± 0.2 (1σ), and the individual values of Γ in all 7 bands were significantly higher than the widest range of possible values we obtained in the higher *Exosat ME* energy band, between 1.5 and 1.8 (Bałucińska & Hasinger 1991). This clearly demonstrates the presence of the soft excess. The *Rosat PSPC* is not able to constrain power law index in the presence of a soft component, and therefore data in the band 1 - 10 keV or higher is needed. It is however very well able to determine the parameters of a thermal component peaking within the *PSPC* band, and so the most sensible approach is to use the *PSPC* data in conjunction with the Γ value previously obtained from the *TTM* and *HEXE* analysis, ie 1.7.

Fitting the simple absorbed power law model with Γ fixed at 1.7 gave very poor fits in all 7 intensity bands with $\chi^2_{\rm r}$ typically 1.7. Thus we adopted a physically more realistic two-component model consisting of a power law with Γ fixed at 1.7, plus a blackbody to model the soft excess, with a single absorption term for both components. Good fits were obtained in all 7 intensity bands, with reduced χ^2 significantly improved over simple models. A typical spectral fit showing the soft excess peaking in the centre of the *PSPC* band is given in Fig.2.

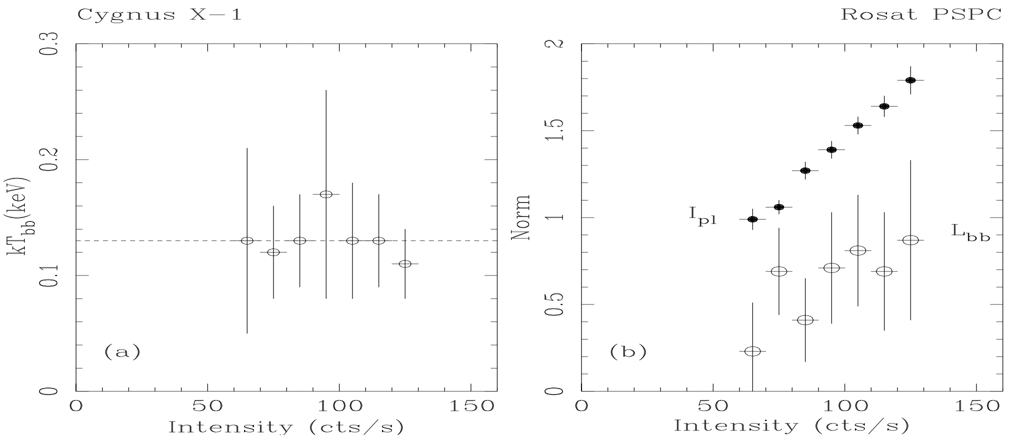

Fig. 3. (a) Blackbody temperature kT_{bb} as a function of X-ray intensity; (b) normalisation for power law and blackbody versus intensity.

In Fig. 3, results for the blackbody temperature kT_{bb} as a function of count rate are shown. It can be seen that there is no variation of kT_{bb} with intensity, showing that the short-term variability apparently takes place without change in the shape of the spectrum. Only the normalisations of the power law and blackbody change, the power law normalisation clearly increasing linearly with intensity.

The mean value of kT_{bb} for all intensity bands was 0.13 ± 0.02 keV, showing that the *PSPC* was able to locate the blackbody peak and so determine the value of kT_{bb} with good accuracy. It was not necessary to specify a separate column density for each component, and the mean value of N_H was $7.5 \pm 1.0 \cdot 10^{21}$ H atom cm^{-2}.

We also fitted the total spectrum formed by adding all intensity bands, using the same two-component model, and fixing Γ at values covering the widest range of acceptable values: 1.5 to 1.8. For these extreme values of Γ, kT_{bb} changed from 0.15 ± 0.02 keV to 0.13 ± 0.02 keV; ie not significantly different from the value we previously obtained in the individual intensity bins.

4. Discussion

Combining results from *TTM/HEXE* and the *Rosat PSPC* has enabled the parameters of the soft excess to be reliably obtained for the first time. These allow us to identify the origin of this thermal emission, comparing the values of kT_{bb} that we obtain with expected values. Firstly we can say that such low values are incompatible with values of kT that have been determined for blackbody emission from the surface or boundary layer of a neutron star where the accretion flow impacts on the star, since values ~ 1 keV or more are typical. The more likely origin is of course thermal emission from the accretion disc around a black hole. Ross and Fabian (1993) discuss how reflection modifies the thermal disc spectrum, and Ross et al. (1992) show that the integrated disc spectrum may be approximated by the blackbody emission at 7 Schwarzschild radii, since at this radius the competition between increasing area of emitting annuli and the decrease in kT_{bb} maximises the emission. In a more detailed discussion (Bałucińska-Church et al. 1995), we calculate $kT_{bb}(7r_S)$ to be 0.13 ± 0.03 keV. This was derived by converting the luminosity of the blackbody into a mass accretion rate, from which the disc temperature as a function of radius follows, assuming the compact object to have mass 10 $M_\odot$. The errors do not include possible errors in distance of the source or mass of the compact object, only errors in the parameters of the soft excess from spectral fitting. The very good agreement of the values of kT_{bb} we have determined from spectral fitting with this calculated value strongly indicates that the emission can be identified with disc emission. It also provides some indirect evidence (independent of that obtained from mass functions) that the mass of the comapact object is $\sim$ 10 $M_\odot$.

5. Conclusions

TTM/HEXE observations spanning a wide energy band have allowed the power law index to be obtained with good confidence, and have clearly confirmed the existence of the reflection component in Cyg X-1.

Rosat PSPC observations have for the first time allowed the temperature of the soft excess to be determined, and the good agreement of kT_{bb} with the characteristic temperature of a multi-temperature accretion disc allows us to identify the soft excess positively with disc emission.

Acknowledgements

TB is supported by NWO under grant PGS 78-277. We thank C. Done for making available her reflection model and for helpful comments.

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