A&A 388, 293–297 (2002)
DOI: 10.1051/0004-6361:20020546

Astronomy & Astrophysics

The broad band X–ray spectrum of the black hole candidate GRS 1758–258

L. Sidoli and S. Mereghetti

Istituto di Astrofisica Spaziale e Fisica Cosmica – Sezione di Milano "G. Occhialini" – CNR
via Bassini 15, 20133 Milano, Italy

Received 11 February 2002 / Accepted 8 April 2002

Abstract. We present the results of a BeppoSAX observation of the black hole candidate GRS 1758–258 carried out in 1997, while the source was in its low/hard state. The X–ray spectrum, simultaneously observed over the broad energy range from 0.1 to 200 keV, can be well described by a Comptonized emission model with electron temperature $kT_{\rm e} = 31.4^{+3.4}_{-2.5}$ keV and optical depth $\tau = 4.0^{+0.2}_{-0.3}$ (spherical geometry), although a cut-off power-law and a reflection model cannot be excluded. Additionally, a broad iron line at 6.4 keV with equivalent width $EW = 67^{+80}_{-40}$ eV has been marginally detected. The 0.1–200 keV luminosity is 1.4×10^{37} erg s^{-1} for an assumed distance of 8 kpc. The soft and hard luminosities are such that the source falls inside the so-called "burster box". No evidence for a soft excess is present.

Key words. accretion, accretion disks – stars: individual: GRS 1758-258 – X-rays: general

1. Introduction

The hard X–ray source GRS 1758–258 was discovered in 1990 (Mandrou 1990; Sunyaev et al. 1991) during the observations of the Galactic Center region performed with the GRANAT satellite. This source and the more famous "microquasar" 1E 1740.7–2942 (e.g. Churazov et al. 1994) were found to be the only persistent sources of hard X-rays ($E > 40$ keV) present within a few degrees from the Galactic Center direction.

Also GRS 1758–258 can be considered a "microquasar" due to its association with a radio source with double-sided relativistic jets (Rodriguez et al. 1992). Recent *Chandra* observations determined the X–ray position of GRS 1758–258 with a sub-arcsecond error radius, confirming the association with the radio point source at the center of the two radio jets (Heindl & Smith 2001).

Monitoring in the X–ray band with the *RossiXTE* satellite revealed a periodicity of 18.45 ± 0.03 days (Smith et al. 2000). Two possible IR candidate counterparts were found by Martí et al. (1998) compatible with the position of the central radio source. However, Eikenberry et al. (2001), based on a different astrometry to link the radio and IR data sets, excluded the objects proposed by Martí et al. (1998) and found that there are no stars brighter than $K_{\rm S} = 20.3$ compatible with the radio position ($K_{\rm S}$ is centered at 2.15 μm). If confirmed, this strong limit on the IR emission implies a low mass companion star that makes unlikely the interpretation of the above periodicity as an orbital period.

Although a dynamical mass measurement is not available, GRS 1758–258 is considered a black hole candidate on the basis of its hard emission extending above 100 keV and its spectral similarities with Cyg X-1. Most of the X–ray observations of GRS 1758–258 determined a power-law spectrum (photon index $\Gamma \sim 1.7$–2) with a cut-off above ∼30 keV (e.g. Churazov et al. 1994; Keck et al. 2001), typical of the so called low/hard state of black hole candidates.

Here we report the results of the first observation of GRS 1758–258 covering simultaneously the broad energy range from 0.1 up to 200 keV. The wide spectral coverage achieved with BeppoSAX is especially important when searching for the presence of a soft excess.

2. Observations and data reduction

GRS 1758–258 was observed with BeppoSAX from 1997 April 10 15:20 to April 11 05:09 UTC. Here we report the results from the Low-Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997), the Medium-Energy Concentrator Spectrometer (MECS; 1.8–10 keV; Boella et al. 1997), and the Phoswich Detection System (PDS; 15–300 keV; Frontera et al. 1997) instruments.

The net exposure times in the LECS, MECS, and PDS instruments were 9.0 ks, 28.3 ks, and 12.7 ks, respectively. For this observation all the three MECS units were

Send offprint requests to: L. Sidoli,
e-mail: sidoli@ifctr.mi.cnr.it

available. The MECS and LECS field of view (see Fig. 1 for the MECS) was contaminated by the stray light contribution from the bright Low Mass X–ray Binary GX 5–1, located about 40′ away from GRS 1758–258. In order to minimize this contamination, the GRS 1758–258 counts for the spectral analysis have been extracted from circular regions with radius (2′ for the MECS and 4′ for the LECS) smaller than that used in standard analysis. We used the appropriate response matrices that take into account the size of the extraction region. To estimate the background for the spectral analysis, we used an ad hoc procedure in order to properly correct for a background as similar as possible to that induced by the stray light: the regular shape and the radial symmetry of the stray light contamination led us to consider the two circular regions with radius 2′ shown in Fig. 1. Both regions have practically the same spectrum that represents well the contribution from the GX 5–1 at the position of GRS 1758–258. We verified that similar results in the fitting parameters (within the 90% confidence range) were found also using a different choice for the LECS and MECS background regions (a standard annular region around the source position). This indicates that the background is not critical for this bright source.

The non-imaging PDS instrument consists of four independent units arranged in pairs, each having a separate collimator. Each collimator was alternatively rocked on- and 210′ off-source every 96 s during the observation. These two off-source fields, free from contaminating sources, were used for the PDS background subtraction. However, the PDS on–source data were affected by the GX 5–1 emission. This effect was relevant only at low energies, due to the very soft spectrum of GX 5–1 (Gilfanov et al. 1993, see their Fig. 6). We therefore neglected the PDS channels from 15 to 40 keV in the spectral analysis. For the same reason, the non–imaging data from the HPGSPC instrument, covering the intermediate energy range between MECS and PDS, could not be used for the spectral analysis and will not be considered here.

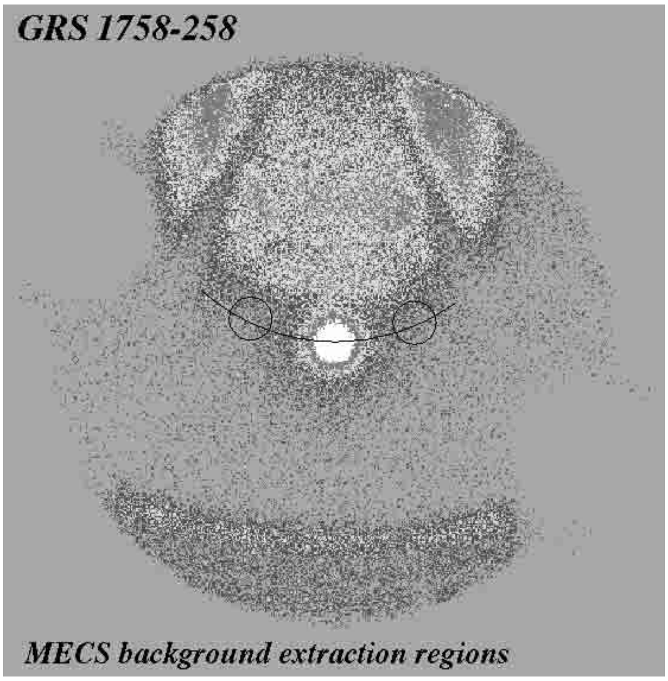

Fig. 1. Image of GRS 1758-258 in the 2–10 keV energy range obtained with the MECS3 unit. A logarithmic scale has been used to better illustrate the faint contamination from the straight light of GX 5–1. The two MECS background extraction regions ($R = 2'$) near to the source are shown (see text).

3. Results

The broad-band spectrum of GRS 1758–258 was investigated by simultaneously fitting data from the LECS, MECS and PDS. The data were selected in the energy ranges 0.1–4.0 keV (LECS), 1.8–10 keV (MECS), and 40–200 keV (PDS) and rebinned using standard procedures. The resulting background-subtracted count rates were 0.74, 3.5, and 3.0 counts s^{-1} for the LECS, MECS, and PDS, respectively. In the spectral fitting, constant factors were included to account for normalization uncertainties between the instruments. These factors were constrained to be within their usual ranges during the fitting. All spectral uncertainties and upper-limits are given at 90% confidence. Spectral analysis has been performed with XSPEC v.11 software package.

Initially, an absorbed power-law model was tried, resulting in photon index $\Gamma = 1.66$ and column density $N_{\rm H} = 1.85 \times 10^{22}$ cm^{-2} ($\chi^2 = 150.3$ for 111 degrees of freedom, d.o.f.). Inspection of the residuals showed that a cut-off in the spectrum is needed above ∼100 keV. The inclusion of a high energy cut-off in the power-law model resulted in a significantly better fit (χ^2/d.o.f. = 123.7/109), with the following parameters: $N_{\rm H} = (1.81^{+0.08}_{-0.05}) \times 10^{22}$ cm^{-2}, $\Gamma = 1.65 \pm 0.02$, cut-off energy $E_{\rm c} = 73 \pm 20$ keV and e-folding energy $E_{\rm fold} = 180^{+120}_{-80}$ keV. The flux in the 0.1–200 keV range, corrected for the absorption, is 1.95×10^{-9} erg cm^{-2} s^{-1}, which corresponds to an X–ray luminosity of 1.4×10^{37} erg s^{-1} (at 8 kpc). About 33% of this unabsorbed flux is emitted in the 0.1–10 keV band. In order to have a more physical picture of the emission spectrum, we also fitted a Comptonization model (COMPST in XSPEC; Sunyaev & Titarchuk 1980), for which we obtained a similar good statistical result (χ^2/d.o.f. = 125.3/110). The resulting parameters are listed in Table 1 and the spectrum is shown in Fig. 2.

Another model often used to fit the low/hard state spectrum of black-hole candidates is the Comptonization of soft photons in a hot plasma which includes relativistic effects (COMPTT model in XSPEC, Titarchuk 1994). The best fit with this model gave a slightly worse χ^2 value than the COMPST model with the parameters reported in Table 1.

The addition of a Gaussian line (centroid energy fixed at 6.4 keV) to the Comptonization best-fit resulted in a line width $\sigma = 700^{+600}_{-440}$ eV and in an equivalent width, $EW = 67^{+80}_{-40}$ eV. The parameters of the continuum

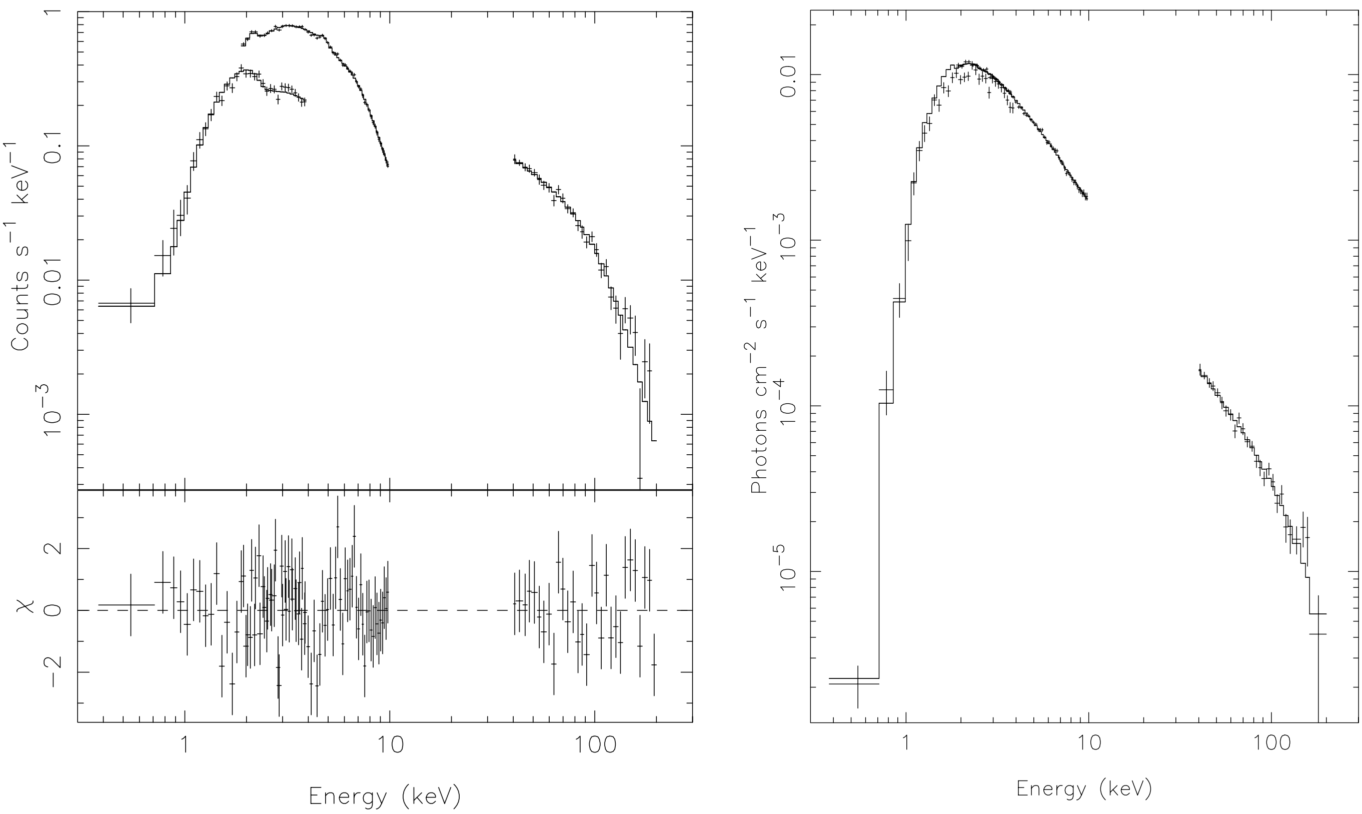

Fig. 2. The 0.1–200 keV BeppoSAX spectrum of GRS 1758–258, fitted with a Comptonization model (see Table 1 for the parameters). The left panels show the best-fit count spectrum and the residuals, in units of standard deviations. The right panel shows the photon spectrum.

Table 1. Best-fit parameters for the broad-band BeppoSAX spectrum of GRS 1758–258 fitted with Comptonization models. Flux is in the 0.1–200 keV energy range. The luminosity (0.1–200) has been corrected for interstellar absorption and is for an assumed distance of 8 kpc.

Parameter	COMPST	COMPTT
$N_{\rm H}$ (10^{22} cm^{-2})	1.83 ± 0.07	$(1.4^{+0.45}_{-0.21})$
$kT_{\rm e}$ (keV)	$31.4^{+3.4}_{-2.5}$	44^{+146}_{-7}
τ	$4.0^{+0.2}_{-0.3}$	$3.6^{+0.4}_{-2.3}$
kT_0 (keV)	–	<0.48
Flux (erg cm^{-2} s^{-1})	2.0×10^{-9}	1.8×10^{-9}
Luminosity (erg s^{-1})	1.4×10^{37}	1.3×10^{37}
χ^2/d.o.f.	125.3/110	128.3/109

remained consistent with those reported in Table 1 and the χ^2 value decreased to 116.2 for 108 d.o.f. An F-test indicates that the probability of such a decrease occurring by chance is 1.7%. Fixing the energy of the line at 6.7 keV resulted in a χ^2 value of 119.0 for 108 d.o.f.

The possible presence of a fluorescent iron line from neutral material is suggestive of X–ray irradiation of cold iron close to the central compact object; however, the exclusion from the spectral fitting of the energy range from 15 to 40 keV due to the nearby contaminating source, prevents us to establish the presence of another important signature of reflection, the "Compton reflection hump".

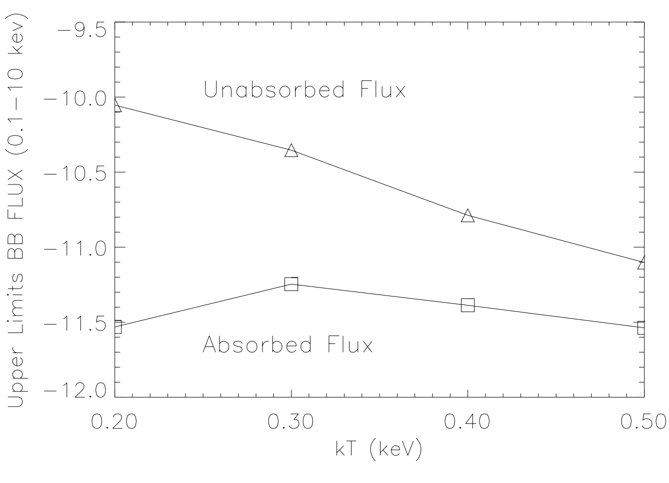

Fig. 3. Upper limits to the presence of a soft component in the BeppoSAX spectrum of GRS 1758–258. Both the absorbed and unabsorbed flux (0.1–10 keV, in logarithmic scale, in units of erg cm^{-2} s^{-1}) are reported for a range of assumed blackbody temperatures. These results have been obtained adopting a broad-band two-component model composed of a blackbody (with fixed temperature) and a power-law ($\Gamma \sim 1.66$, $N_{\rm H} \sim 1.85 \times 10^{22}$ cm^{-2}).

In fact, the fit with an exponentially cut-off power-law spectrum reflected from neutral material (PEXRAV model in XSPEC, Magdziarz & Zdziarski 1995) plus a Gaussian line with energy fixed at 6.4 keV resulted in an

Table 2. Summary of the observations used in Fig. 4.

Instrument	Observation date	Ref.
SIGMA	Fall 1991-Spring 1992	Gilfanov et al. (1993)
SIGMA	Fall 1992	Gilfanov et al. (1993)
ASCA	1995 Mar. 29	Mereghetti et al. (1997)
XTE & OSSE	August 1997	Lin et al. (2000)
Chandra	2001 Mar. 24	Heindl & Smith (2001)
XMM-RGS	2001 Mar. 22	Miller et al. (2002)

unconstrained reflection scaling factor $f_{\rm refl} \lesssim 1.2 (f_{\rm refl} = 1$ for an isotropic source above an infinite flat disk), a power-law with a photon index of ∼1.8 and an iron line with $EW \lesssim 110$ eV.

We searched for the possible presence of a soft excess in the BeppoSAX spectrum, obtaining a negative result: adopting a two-component model composed of a power-law and a blackbody with temperature in the range 0.2–0.5 keV, we can place the upper limits shown in Fig. 3 to the flux contributed by the blackbody.

4. Discussion

The BeppoSAX observation reported here has allowed us to study the black-hole candidate GRS 1758–258 covering simultaneously the broad energy range from 0.1 to 200 keV. Previously, only Mereghetti et al. (1994) and Lin et al. (2000) reported broad band spectral studies of GRS 1758–258 . Both studies were based on *nearly* simultaneous observations with different satellites and, unfortunately, lacked a complete covering of interesting portions of the spectrum. Mereghetti et al. (1994) used ROSAT (<2 keV) and SIGMA (>40 keV) observations, while Lin et al. (2000) analyzed multi-wavelength data from the radio band to ∼500 keV, but lacked the information for the soft X–rays below 2 keV, a particularly interesting region in order to establish the possible presence of a soft spectral component.

This is a particularly interesting point, in view of previous reports of a soft spectral component in GRS 1758–258, possibly coming from the inner regions of the accretion disk. The question is, first, whether such a component is really present in this source and, second, whether it is associated to a particular spectral state, as seen in other black hole candidates.

We have collected from the literature all the observations of GRS 1758–258 and summarized the main spectral results in Fig. 4. It appears that most observations found GRS 1758–258 in a typical state characterized by a hard power-law spectrum extending to ∼100 keV followed by a cut-off. The luminosity in this state is not constant: variability on different timescales is present (see, e.g., Keck et al. 2001 for a long term monitoring with the XTE/ASM and CGRO/BATSE). In Fig. 4 we have reported two broad band spectra that bracket the observed range of values: the XTE/OSSE spectrum (Lin et al. 2000) and our BeppoSAX results.

During this spectral state, at least two reliable observations demonstrate the absence of a soft component: the one obtained with ASCA in March 1995 (Mereghetti et al. 1997) and the BeppoSAX one reported here. Both missions provided a good coverage of the region around ∼1 keV with imaging instruments that minimized the contamination with the nearby source GX 5–1. The possible presence of a soft component suggested by a comparison of ROSAT PSPC ($E < 2$ keV) and SIGMA ($E > 40$ keV) data obtained in 1993 (Mereghetti et al. 1994) is controversial, since it was not confirmed by different analysis of the same data (Grebenev et al. 1997; Keck et al. 2001).

Recently (2001, February 27) GRS 1758–258 entered an "off" state, with a 2–20 keV flux reduced by a factor ten, smaller time variability and a spectrum dominated by a thermal component with blackbody temperature $kT_{\rm bb} \sim 0.4$ keV (Smith et al. 2001). This is the first clear evidence of a different spectral state, although it is possible that GRS 1758–258 was in a similar state in 1992–1992 when only an upper limit could be obtained at energies above 40 keV (Gilfanov et al. (1993); the upper limits obtained with SIGMA are indicated in Fig. 4, no simultaneous observations were available at lower energies).

An observation during this "off" state (March 22, 2001) with the XMM–Newton Reflection Grating Spectrometer (RGS) showed a spectrum dominated by a blackbody component with $kT_{\rm bb} \sim 0.3$ keV and with a steep power-law ($\Gamma \sim 2.9$) contributing to less than 2% of the total flux in the 0.6–2.3 keV band (Miller et al. 2002). Similar results were obtained in an observation performed two days later with Chandra (Heindl & Smith2001). Preliminary results of an observation performed in September 2000 with the EPIC instrument on XMM–Newton seem to indicate that GRS 1758–258 was in an "intermediate" state, in which both a thermal component and a power-law were required to fit the 0.2–10 keV spectrum (Goldwurm et al. 2001). In conclusion, it seems that the soft thermal component has been significantly detected only when GRS 1758–258 is in a low intensity state.

Keck et al. (2001) have interpreted the long-term behavior of GRS 1758–258 in term of an advection-dominated accretion flow model (ADAF), finding that 1990–1993 nearly simultaneous observations support the ADAF predictions. This interpretation is based on a comparison of the soft (1–20 keV) and hard (20–200 keV) luminosities (see Barret et al. 1996). From our BeppoSAX observation we can measure for the first time really simultaneously these quantities, that, assuming as Keck et al. (2001) a distance of 8.5 kpc, are $L_{1-20} = 5.4 \times 10^{36}$ erg s^{-1} and $L_{20-200} = 9.7 \times 10^{36}$ erg s^{-1}. Taking into account the uncertainties of $\lesssim$10%, these luminosity values place GRS 1758–258 well inside the so-called "burster box" in the $L_{1-20}-L_{20-200}$ plane, and are not consistent with the ADAF model for a 10.6 $M_\odot$ black-hole. This confirms that BHCs in low-state are not spectrally distinguishable from neutron stars.

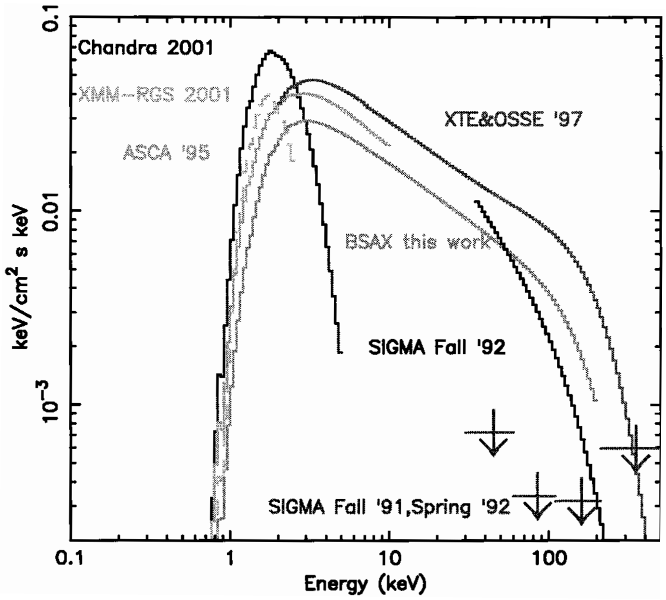

Fig. 4. Comparison of representative spectra of GRS 1758–258. Our BeppoSAX best-fit is also shown. The references used to produce this plot have been reported in Table 2.

5. Conclusions

The BeppoSAX 0.1–200 keV spectrum of GRS 1758–258 is adequately fit with a Comptonized emission model with an electron temperature of ∼30 keV or, alternatively, with a power-law with a high energy cut-off at ∼70 keV. This spectral model is typical of black-hole candidates in their low/hard state. The luminosity in the range 0.1–200 keV is 1.4×10^{37} erg s^{-1}, and the measured column density is almost model-independent in the range $\sim 1.8{-}1.9 \times 10^{22}$ cm^{-2}.

No soft excess is evident from this observation, and we can put stringent upper limits to the flux contributed by a soft component. A blackbody component at a level similar to that reported by Goldwurm et al. (2001), would have been clearly detected in our BeppoSAX observation, being a factor ∼7.5 larger than our upper limits.

We have marginally detected (98.3% confidence level) a broad line from cold iron (6.4 keV). The presence of this line possibly indicates the existence of reflection from the accretion disk of hard X–rays coming from the central source. Another signature of the existence of such a component is a hump in the energy range 20–30 keV (e.g., George & Fabian 1991). Unfortunately, the X–ray data from 15 to 40 keV could not be used in our spectral analysis due to the contamination from a bright off-axis source. Thus, the presence of reflection in GRS 1758–258 deserves further investigations with imaging instruments covering the hard X–ray region, such as those that will be soon available with the INTEGRAL satellite.

References

Barret, D., McClintock, J. E., & Grindlay, J. E. 1996, ApJ, 473, 963
Boella, G., Chiappetti, L., Conti, G., et al. 1997, A&AS, 122, 327
Churazov, E., Gilfanov, M., Sunyaev, R., et al. 1994, ApJS, 92, 381
Frontera, F., Costa, E., Dal Fiume, D., et al. 1997, A&AS, 122, 371
Eikenberry, S. S., Fischer, W. J., Egami, E., & Djorgovski, S. G. 2001, ApJ, 556, 1
George, I. M., & Fabian, A. C. 1991, MNRAS, 249, 352
Gilfanov, M., Churazov, E., Sunyaev, R., et al. 1993, ApJ, 418, 844
Goldwurm, A., Israel, D., Goldoni, P., et al. 2001, Proc. of the Gamma-Ray Astrophysics 2001 Symposium, 4–6 April 2001, Baltimore, Maryland, USA (American Institute of Physics (AIP) Ser.), in press [astro-ph/0106310]
Grebenev, S. A., Pavlinsky, M. N, & Sunyaev, R. A. 1997, in Proc. of the Second Integral Workshop The Transparent Universe, ESA SP-382, 183
Heindl, W. A., & Smith, D. M. 2001, in The High Energy Universe at Sharp Focus: Chandra Science, Proc. of the 113th Meeting of the Astronomical Society of the Pacific, 16–18 July 2001, St. Paul, MN, in press [astro-ph/0107469]
Keck, J. W., Craig, W. W., Hailey, C. J., et al. 2001, ApJ, 563, 301
Lin, D., Smith, I. A., Liang, E. P., et al. 2000, ApJ, 532, 548
Mandrou, P. 1990, IAU Circ., 5032
Martí, J., Mereghetti, S., Chaty, S., et al. 1998, A&A, 338, 95
Magdziarz, P., & Zdziarski, A. A. 1995, MNRAS, 273, 837
Mereghetti, S., Belloni, T., & Goldwurm, A. 1994, A&A, 433, L21
Mereghetti, S., Cremonesi, D. I., Haardt, F., et al. 1997, A&A, 476, 829
Miller, J. M., Wijnands, R., Rodriguez-Pascual, P. M., et al. 2002, ApJ, 565, 1141
Parmar, A. N., Martin, D. D. E., Bavdaz, M., et al. 1997, A&AS, 122, 309
Rodriguez, L. F., Mirabel, F., & Martí, J. 1992, ApJ, 401, L15
Smith, D. M., Heindl, W. A., & Swank, J. H. 2000, AAS, 32, 3114
Smith, D. M., Markwardt, C., Heindl, W. A., & Swank, J. H. 2001, IAUC, 7595
Sunyaev, R. A., Churazov, E., Gilfanov, M., et al. 1991, A&A, 247, L29
Sunyaev, R. A., & Titarchuk, L. G 1980, A&A, 86, 121
Titarchuk, L. 1994, ApJ, 434, 570