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Published in:
Astrophysical Journal

DOI:
10.1086/187538

The Astrophysical Journal, 433:L21–L23, 1994 September 20

EVIDENCE FOR A SOFT X-RAY EXCESS IN THE SPECTRUM OF GRS 1758−258

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Received 1994 May 27; accepted 1994 June 28

ABSTRACT

We report the results of the first simultaneous observation of GRS 1758−258 at soft and hard X-ray energies. The data have been obtained with the *ROSAT* Position Sensitive Proportional Counter (0.1–2.4 keV) and with the SIGMA/*Granat* coded mask telescope at energies greater than 40 keV. The *ROSAT* observation shows the presence of a soft spectral component above the low-energy extrapolation of the flat power law measured at high energies with SIGMA. This soft spectral component was weaker in 1990, when the hard X-ray flux from GRS 1758−58 was in its highest observed state. These characteristics, similar to those observed in black hole candidates such as Cyg X-1 and the ultrasoft X-ray transients, support the interpretation of GRS 1758−258 as an accreting black hole in a binary system.

Subject headings: stars: individual (GRS 1758−258) — X-rays: stars

1. INTRODUCTION

Several sources emitting in the "classical" X-ray range of a few keV are located close to the direction of the Galactic center (see, e.g., Hertz & Grindlay 1984; Skinner et al. 1987). Though only a few of them show the clear presence of an accreting neutron star (i.e., periodic pulsations or X-ray bursts), most of the remaining sources, of which little is known, are probably similar objects. The Galactic center region is also a source of much more energetic photons. In fact, several nonimaging detectors revealed variable emission at energies of a few hundred keV, sometimes extending up to a few MeV (see Lingenfelter & Ramaty 1989, and references therein). Thanks to the imaging capabilities recently obtained at high energies with the coded mask technique, it has become clear that these energetic photons are emitted from a few of the X-ray sources present in this region, and not from the Galactic center itself, as previously assumed.

In particular, many observations carried out from 1990 to 1994 with the SIGMA γ-ray telescope (Paul et al. 1991) have shown that two sources, 1E 1740.7−2942 and GRS 1758−258, are usually the brightest objects at energies greater than 100 keV in this region of sky (Sunyaev et al. 1991). They are probably members of the same class of sources, since they have similar luminosities, hard X-ray spectra, and proposed radio counterparts with double jets (Mirabel et al. 1992; Rodriguez, Mirabel, & Marti 1992). However, mostly owing to the lack of optical/IR identifications, their true nature is still unknown.

On the basis of their similarities to Cyg X-1 at hard X-ray and soft γ-ray energies, 1E 1740.7−2942 and GRS 1758−258 have been proposed as possible black hole candidates (Sunyaev et al. 1991). If their radio identifications are correct (which, at least for 1E 1740.7−2942, seems likely), the lack of bright optical and/or IR counterparts at the accurate radio positions excludes the presence of massive companions similar to that of Cyg X-1 (Mereghetti et al. 1992; Chen, Gehrels, & Leventhal 1994). Thus, though accretion from a low-mass companion cannot be excluded, it has also been proposed that they might be isolated compact objects accreting directly from the interstellar medium (Bally & Leventhal 1991; Mirabel et al. 1991; Campana & Mereghetti 1993).

Here we report the results of a *ROSAT* observation of GRS 1758−258, yielding the first spectral measurement at soft X-ray energies (<2 keV) for this source. The *ROSAT* data were obtained in 1993 March–April, while GRS 1758−258 was also being monitored at higher energies (>40 keV) with the SIGMA telescope. The analysis of these simultaneous observations, and their comparison to all the *ROSAT* and SIGMA data available on GRS 1758−258, show that the similarities with other black hole candidates extend also to the soft X-ray properties of this source.

2. *ROSAT* DATA ANALYSIS

The *ROSAT* observation was carried out using the Position Sensitive Proportional Counter (PSPC) instrument (Pfeffermann et al. 1986) between 1993 March 31 04:16 UT and April 2 11:04 UT. The data consist of five separate time intervals, with durations between ~1000 and 2500 s each, for a total net exposure time of 7860 s. The analysis was performed using EXSAS (Zimmermann et al. 1993). GRS 1758−258 is clearly detected with an average count rate of 1.90 ± 0.02 counts s^{-1}. To measure the source coordinates we applied the standard maximum-likelihood detection technique in the EXSAS system, obtaining R.A. = $18^h01^m12^s.66$, decl. = $-25°44'28''.0$ (J2000). This position, with a 90% error radius of 10″, supersedes that reported by Mereghetti et al. (1992). The best coordinates for the radio counterpart proposed by Rodriguez et al. (1992) are consistent with the *ROSAT* error circle (see Fig. 1 in Mereghetti, Belloni, & Goldwurm 1994).

The source counts were extracted from a circular region of radius 18′ centered on the source. Such a large radius is required to collect all the source photons scattered by the interstellar dust along the light of sight (see Predehl et al. 1991). Three additional very weak sources are present in this circle, contributing for a total of only ~50 net counts compared to

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the over 15,000 net counts from the target, and therefore not significantly affecting the spectral results. The background has been extracted from five circular regions of radius 13′, located in the external region of the detector, away from the possible contamination of the nearby bright source GX 5−1. Significant flux variability is visible across the observation. In particular, the average source flux was fainter during the last time interval (1.61 ± 0.05 counts s^{-1}, compared to 2.05 ± 0.03 counts s^{-1} in the first four intervals). No evidence of spectral variations was found by comparing the source hardness ratios measured during the different intervals. We therefore performed the spectral analysis on the whole observation. An acceptable fit was obtained with a power law of photon index 3.3 ± 0.8 and column density $N_H = (2.1 \pm 0.4) \times 10^{22}$ cm^{-2} (90% confidence intervals). The unabsorbed flux in the 1.0–2.4 keV range corresponding to the best-fit values is 2.8×10^{-10} ergs cm^{-2} s^{-1} (90% confidence interval from 1.9 to 4.5×10^{-10} ergs cm^{-2} s^{-1}).

3. SIGMA DATA ANALYSIS

The SIGMA telescope aboard the *Granat* satellite monitored the Galactic center region during 17 observing sessions of about 20 hours each, between 1993 February 17.7 and April 16.6 (UT), for a total 282 hours of effective exposure time. GRS 1758−258 was always within the partially coded field of view of the instrument and observed between 40% and 100% of the on-axis sensitivity. The source was detected at a level of 9 σ in the averaged 35–150 keV band image (Goldwurm et al. 1994; Churazov et al. 1994; Kuznetsov et al. 1994). Its average flux, ~45 mcrab, was rather high, showing that the steady increase of the hard X-ray emission observed since the end of the low-state period was continuing. No significant intensity or spectral variations were detected during these observations, two of which (starting on March 30 and April 2) were simultaneous to the *ROSAT* pointing.

The average spectrum in the 40–200 keV band can be described by a power law with photon index 1.82 ± 0.31 and flux at 100 keV of $(2.72 \pm 0.39) \times 10^{-5}$ photons cm^{-2} s^{-1} keV^{-1} (errors at 90% confidence level for a single parameter). These values are compatible with previously reported spectral parameters derived from other SIGMA observations of GRS 1758−258, during both its high and low states (Gilfanov et al. 1993).

4. EVIDENCE FOR AN ULTRASOFT COMPONENT

The *ROSAT* and SIGMA measurements of the spring of 1993 are compared in Figure 1, which shows the broadband spectrum of GRS 1758−258 spanning about 3 decades in energy. An extrapolation of the *ROSAT* best-fit falls well below the SIGMA result, indicating that a spectral hardening occurs above a few keV. Unfortunately, the lack of simultaneous coverage in the 2–40 keV range makes it impossible to precisely locate the energy at which the spectrum flattens. Observations in this intermediate range were obtained in 1985 with instruments on *EXOSAT* and Spacelab 2 (Skinner 1991) and in 1990 April with the ART-P telescope on *Granat* (Sunyaev et al. 1991). On both occasions, the 2–20 keV spectrum was a flat power law (photon index ~1.7) and the intensity was consistent with an extrapolation of the 1990 high state SIGMA data. This spectrum, scaled down by a factor of 2 to match the hard X-rays (>40 keV), connects well to the highest energy PSPC points (see dashed line in Fig. 1), suggesting that the spectral steepening might occur around 2–3 keV.

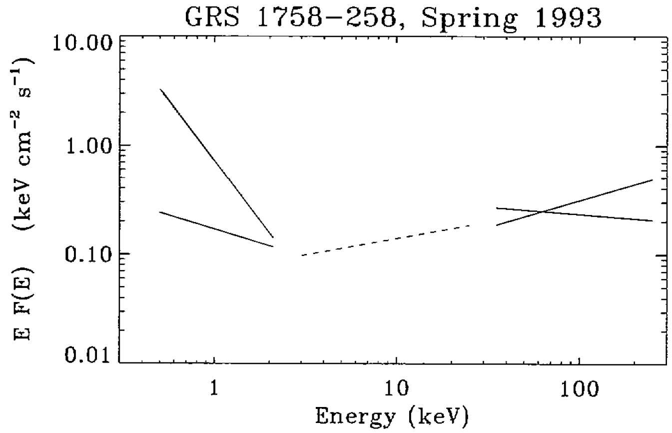

FIG. 1.—Spectrum of GRS 1758−258 (90% confidence intervals) simultaneously measured by *ROSAT* ($E < 2$ keV) and SIGMA ($E > 40$ keV), while the hard X-ray flux was in an "intermediate" state (see Table 1). The dashed line shows the typical spectral slope measured in the 2–20 keV range during the source high state (Skinner 1991; Sunyaev et al. 1991), but scaled down by a factor of 2.

5. ANTICORRELATED SPECTRAL VARIATIONS?

The long-term variations of the high-energy flux from GRS 1758−258 have been monitored with SIGMA since 1990 (Gilfanov et al. 1993). The source was in a high state during all of 1990, with an average flux of 90 mcrab (40–150 keV). It then faded to about 60 mcrab in spring of 1991 and below the SIGMA detection limit in fall of 1991 and spring of 1992. It could be detected again in fall of 1992, but ~3 times fainter than in the 1990 high state, and in spring of 1993. Despite this variability spanning about an order of magnitude (see Table 1 for a summary), no evidence for spectral variations could be derived from the SIGMA data (Gilfanov et al. 1993).

The *ROSAT* PSPC instrument observed GRS 1758−258 also during the All Sky Survey on 1990 September 10–12, while the hard X-ray flux was in its highest state. The count rate measured during the 688 s long exposure from the survey was 0.95 ± 0.04 counts s^{-1}, a factor of about 2 smaller than in 1993. The limited statistics made a spectral fit unfeasible, but the source hardness ratios were compatible with those of the 1993 observation. Thus, the count rate difference is unlikely to be due to a spectral variation, suggesting that the intensities of the soft and hard spectral components are anticorrelated. Between 1990 September and 1993 March both varied by about a factor of 2, but in opposite directions (see Table 1).

However, another *ROSAT* measurement of GRS 1758−258, obtained on 1992 March 13, does not fit in this

TABLE 1

SOFT AND HARD X-RAY FLUXES FROM GRS 1758−258

SIGMA Observation Period	40–150 keV Flux (mcrab)	1.0–2.4 keV Flux (ergs cm^{-2} s^{-1})	*ROSAT* Observation Date
1990 spring	90	...	...
1990 fall	90	1.4×10^{-10}	Sep 10–12
1991 spring	60	...	...
1991 fall	<13	...	...
1992 spring	<13	$\sim 0.8 \times 10^{-10}$ [a]	March 13
1992 fall	30	...	...
1993 spring	45	2.8×10^{-10}	Mar 31–Apr 2

[a] HRI count rate converted to flux assuming the 1993 spectrum.

simple picture of anticorrelated variations. This 2500 s observation was carried out with the High Resolution Instrument (HRI), which provides only very limited spectral information (David et al. 1992). Assuming the same spectrum of the 1993 PSPC data, the HRI count rate of 0.18 ± 0.01 counts s^{-1} corresponds to a flux of 7.6×10^{-11} ergs cm^{-2} s^{-1} in the 1.0–2.4 keV band. Thus, neglecting the possible effects of spectral variations, in spring of 1992 both the hard and soft X-rays were at their lowest level.

6. CONCLUSIONS

The *ROSAT* pointed observation of GRS 1758−258, yielding the first spectral measurement for this source at energies below 2 keV, shows that the overall spectrum cannot be fitted by a single power law with the same slope observed at higher energy. Above 2 keV the spectrum of GRS 1758−258 can be well described by a flat power law (photon index ~ 1.7), followed by a high-energy cutoff above ~ 100 keV. As in the case of the black hole candidate Cyg X-1 and of 1E 1740.7−2942, this spectrum is usually interpreted in the framework of Comptonization models, in which soft primary photons gain energy from collisions with a relativistic population of hot electrons (see Liang & Nolan 1984, and references therein). The steep spectrum observed with *ROSAT* below 2 keV might be the tail of the soft component providing the seed photons, and which could originate, e.g., in the outer and cooler regions of an accretion disk (Shapiro, Lightman, & Eardley 1976). Similar soft (or "ultrasoft") components have been observed also in Cyg X-1 (Priedhorsky et al. 1979; Barr & van der Woerd 1990), in a few X-ray transients for which mass function measurements indicate the presence of accreting black holes (Tanaka & Lewin 1993; Greiner et al. 1994), as well as in the spectra of Seyfert galaxies (Turner & Pounds 1989). For GRS 1758−258, the 0.1–3 keV luminosity of the soft component in spring of 1993 was $\sim 10^{38}$ ergs s^{-1} (for a distance of 8.5 kpc), about 5 times greater than that in the 3–300 keV range (Sunyaev et al. 1991).

The comparison of the two measurements obtained with the PSPC instrument suggests an anticorrelated intensity variation in the soft and hard components, qualitatively in agreement with the predictions of Comptonization models. Since the 1992 data do not confirm this possible evidence, we take it as a simple suggestion to be better assessed by future observations. As noted above, the interpretation of the HRI count rate is strongly dependent on the unknown spectral parameters during that particular observation. For example, the low counting rate in that relatively short observation could be caused by an increased intrinsic absorption similar to the "dips" observed in several low-mass X-ray binaries (Parmar & White 1988), as well as in Cyg X-1 (Kitamoto et al. 1990). Alternatively, the low HRI counting rate might really reflect an intrinsically faint flux, indicating that the soft and hard X-rays are not necessarily always anticorrelated (this is true also for other black hole candidates; see Mereghetti 1993 and references therein). Clearly, other detailed simultaneous observations over a broad X/γ-ray energy range are required to derive better constraints from the intensity and spectral variations of GRS 1758−258. Unfortunately, these will not be easily obtained after the end of the SIGMA/*Granat* mission, since high-energy satellites with good imaging capabilities are required to disentangle GRS 1758−258 from the other sources present in this crowded region of the Galactic bulge.

Chen et al. (1994) discussed how the present optical and IR limits on the possible counterparts of GRS 1758−258 constrain the mass of the potential companion star. Their conclusions are dependent on the value assumed for the unknown optical absorption, which, in the lack of more direct measurements, can be estimated from the column density, N_H, fitted to the soft X-ray spectrum. The value of $N_H = (2.1 \pm 0.4) \times 10^{22}$ cm^{-2} derived from our *ROSAT* data is consistent with the previous, much less accurate estimates obtained with observations at higher energies. This result supports the conclusions that GRS 1758−258 is not accreting from a companion more massive than ~ 2 solar masses and that, contrary to the case of 1E 1740.7−2942, there is no evidence for additional absorption in a dense molecular cloud.

We thank the French-Russian SIGMA/*Granat* Collaboration for the permission of using original unpublished SIGMA data. This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277.

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