THE ASTROPHYSICAL JOURNAL, 423:436–440, 1994 March 1

SIGMA HARD X-RAY OBSERVATIONS OF THE BURST SOURCE MXB 1728−34

A. CLARET, A. GOLDWURM, B. CORDIER, AND J. PAUL
Service d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette Cedex, France

J.-P. ROQUES, L. BOUCHET, M.-C. SCHMITZ-FRAYSSE, AND P. MANDROU
Centre d'Etude Spatiale des Rayonnements, 9 Av du Colonel Roche, BP 4346, 31029 Toulouse Cedex, France

AND

E. CHURAZOV, M. GILFANOV, R. SUNYAEV, N. KHAVENSON, A. DIACHKOV,
B. NOVIKOV, R. KREMNEV, AND V. KOVTUNENKO
Space Research Institute, Profsouznaya, 84/32, Moscow 117296, Russia
Received 1993 April 4; accepted 1993 September 13

ABSTRACT

We report the first detection by the SIGMA telescope of hard X-ray emission from the burst source 4U/MXB 1728−34 (also called GX 354−0). This source has been monitored during the 1992 February–April survey of the Galactic center region for a total of ≈240 useful hr. It underwent two high-energy flares of about 10 days duration each. However, the MXB 1728−34 spectrum does not vary significantly as a function of the source intensity. The average spectrum is well described by a thermal bremsstrahlung model with a temperature of ≈38 keV and a flux of ≈7×10^{-10} ergs cm^{-2} s^{-1} in the 30–200 keV band. The high-quality data of these observations provide the best known hard X-ray spectrum of a bursting low-mass X-ray binary.

Subject headings: binaries: close — gamma rays: observations — stars: individual (MXB 1728−34) — X-rays: bursts

1. INTRODUCTION

In the standard X-ray domain, MXB 1728−34 is a well-known persistent source (this source is referred in the fourth *Uhuru* catalogue; Forman et al. 1978). X-ray bursts from MXB 1728−34 were discovered by *SAS 3* in 1976 (Lewin 1976; Hoffman et al. 1976), and later studied by Basinska et al. (1984). This source has not been optically identified because of the high optical extinction in the Galactic center (CG) direction and the presumably large distance. On the basis of *Einstein* HRI and infrared data, Grindlay & Hertz (1981) claimed the association of MXB 1728−34 with a heavily reddened globular cluster. However, the existence of this cluster was not confirmed by later infrared observations (van Paradijs & Isaacman 1989). MXB 1728−34 appears therefore as a typical low-mass X-ray binary (LMXB) and could be considered as a low-luminosity bursting source, which very likely contains a neutron star.

In the hard X-ray band, the first detection of MXB 1728−34 occurred in 1988, during an 8 hr balloon flight observation performed by the GRIP experiment (Cook et al. 1991). In the spring of 1992, the SIGMA soft γ-ray telescope, on board the *GRANAT* satellite, was performing its fifth survey of the GC region. During this survey, MXB 1728−34 appeared to flare twice (Claret et al. 1993; Goldwurm et al. 1993). An increase of the high-energy flux from the GC region was also observed by nonimaging instruments. In the absence of accurate spatial information, it was attributed to 1E 1740.7−2942 (Harmon et al. 1992). Thanks to its imaging capabilities, SIGMA revealed that this hard X-ray emission was actually due to the flares of MXB 1728−34.

2. OBSERVATIONS, DATA ANALYSIS, AND RESULTS

Fifteen observations of the GC region were performed by SIGMA between 1992 February and April, spanning a total period of 7 weeks. The list of observations is reported in Table 1. Three sources were then unambiguously detected (Cordier et al. 1993a; Churazov et al. 1993; Gilfanov et al. 1992): 1E 1740.7−2942, which dominates the hard X-ray emission of this region when it is in its normal state; the X-ray source in Terzan 2 globular cluster already observed by SIGMA (Barret et al. 1991); and also MXB 1728−34. The last-named source was always in the partially coded field of view of the telescope, for which only part of the mask pattern is projected onto the detector plane (Paul et al. 1991). It was thus observed with a sensitivity varying between 62% and 95% of the on-axis sensitivity (see Table 1).

SIGMA images of fully coded sources are first corrected for the γ-camera and background nonuniformities. They are then deconvolved by standard technique (Fenimore & Cannon 1980; Cordier et al. 1993a). For partially coded sources, the satellite drifts (Paul et al. 1991) are taken into account in the deconvolution process. Several other corrections (effective area, mask element thickness, etc.) are also applied in order to convert the measured count rate into a "fully coded count rate." Finally, the measured pulse height spectrum is compared to various spectral models using the instrumental energy response matrix of the telescope and the standard least-squares method.

Figure 1 is a contour map of the sum of all observations for which the source was detected at more than 3 σ over the background level (see Table 1). The resulting total exposure is about 585,000 s (corrected for dead time). Crosses indicate the *Einstein* HRI position of MXB 1728−34 (Grindlay & Hertz 1981), as well as the position of the nearby X-ray source X1730−333, also called the Rapid Burster (Bradt & McClintock 1984). The best-fit position of the 9.2 σ excess is at R.A. = 262°.187, decl. = 33°.810 (1950 equinox), with an error circle of 2'.9 radius (statistical incertitude at 90% confidence level in four parameters, plus satellite attitude errors). The SIGMA position, 1'.4 away from the *Einstein* position of MXB 1728−34, is unambiguously not compatible with that of the Rapid Burster.

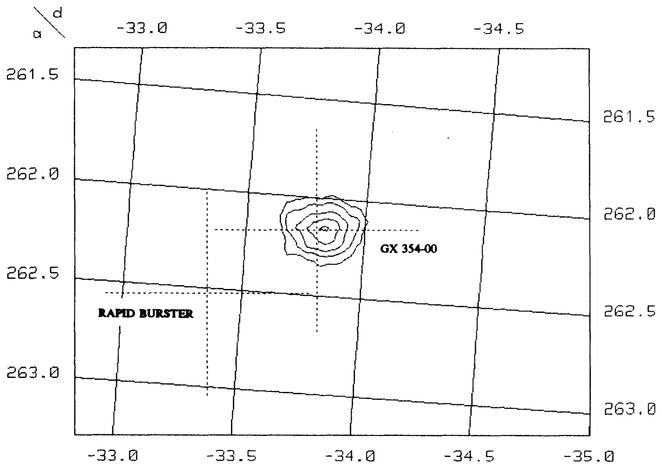

FIG. 1.—Contour plot of the sky region around MXB 1728−34 in the 40–150 keV band. Contour levels are in units of standard deviations (σ) over the background mean, starting from 5 σ and spaced by 1 σ.

The light curve of MXB 1728−34 in the 40–70 keV energy band is displayed in Figure 2, where is given the detected source count rate versus the universal time. Though the data available are rather sparse, it appears that MXB 1728−34 underwent two flares. The source flux increased at least by a factor of 10 on a timescale of 10 days, then decreased in 2 weeks, and displayed a similar but weaker behavior about 10 days later.

Spectral variability from one observation to another was searched by inspecting the hardness ratio. The ratio of detected counts in the 60–100 keV and the 40–60 keV bands does not show significant variation with time. The average spectra of the source are also similar during the two flares. All the spectra recorded when the source was visible at more than 1 σ in the 40–70 keV band (see Table 1) were thus summed in order to improve the statistics. The resulting average spectrum is displayed in Figure 3. Table 2 summarizes the parameters of different spectral models obtained from the fit of the data points between 30 and 200 keV. The best fit ($\chi^2_\nu = 1.04$ for $\nu = 36$ d.o.f.) corresponds to a broken power law with photon indexes of −1.4 and −4.6, respectively, below and above an energy break at ≈58 keV. The integrated photon flux in the 40–70 keV band (see Table 1) was derived for each observation using the best-fit broken power-law parameters. A thermal bremsstrahlung model requires an electron temperature of ≈38 keV and corresponds to a confidence probability similar to that of the best fit. A comptonized disk model (Sunyaev & Titartchuk 1980) yields an electron temperature of ≈12 keV and a Thompson scattering disk half-thickness lower limit $\tau \geq 3.8$. The disk half-thickness cannot be determined accurately from the SIGMA data. Only a few data points are indeed available to derive the power-law slope in the 30–60 keV range (see Table 1). The best-fit comptonized disk model approaches thus a Wien spectrum with a very high value of the optical depth.

TABLE 1

1992 SIGMA OBSERVATIONS OF MXB 1728−34

Starting Date (1992, UT)	Ending Date (UT)	$Flux_{40-70\ keV}$[a] (10^{-10} ergs cm^{-2} s^{-1})	Exposure (s)	Coding Factor
Feb 17.52	Feb 18.51	<1.53[b]	62404	94.8%
Feb 18.64	Feb 19.59	<1.38[b]	60577	69.0
Feb 21.51	Feb 22.51	3.72 ± 0.66	63221	72.5
Feb 22.63	Feb 23.53	3.31 ± 0.69	57539	67.4
Feb 29.71	Mar 1.60	6.16 ± 0.69	55959	67.3
Mar 1.71	Mar 2.59	6.57 ± 0.70	56008	72.5
Mar 2.73	Mar 3.64	6.33 ± 0.69	57828	71.8
Mar 4.82	Mar 5.63	4.27 ± 0.72	51504	70.4
Mar 17.45	Mar 18.52	1.01 ± 0.64	67081	62.4
Apr 2.49	Apr 3.51	2.65 ± 0.65	63081	77.3
Apr 3.63	Apr 4.55	2.89 ± 0.67	57541	76.6
Apr 4.67	Apr 5.62	2.75 ± 0.67	60123	72.5
Apr 6.59	Apr 7.59	2.37 ± 0.66	62400	73.9
Apr 7.71	Apr 8.16	1.94 ± 0.91	28439	73.4
Apr 8.71	Apr 9.71	1.20 ± 0.67	63110	66.5

[a] 1 σ error bar.
[b] 2 σ upper limit.

TABLE 2

PARAMETERS OF SPECTRAL MODELS FOR MXB 1728−34

Spectral Model	$Flux_{100\ keV}$[a] (10^{-5} photons cm^{-2} s^{-1} keV^{-1})	Parameters[a]	χ^2_ν (ν)
Single power-law	1.93 ± 0.20	$\alpha = -2.97 \pm 0.14$	1.59 ($\nu = 38$)
Thermal bremsstrahlung	1.66 ± 0.23	kT (keV) = 38 ± 4	1.31 ($\nu = 38$)
Comptonized disk	1.06 ± 0.25	kT (keV) = $12^{+1.5}_{-0.5}$	1.16 ($\nu = 37$)
		$\tau \geq 3.8$	
Broken power-law	1.13 ± 0.35	$\alpha_1 = -1.40 \pm 0.70$	1.04 ($\nu = 36$)
		$\alpha_2 = -4.64 \pm 0.65$	
		E_0 (keV) = 57.6 ± 3.55	

[a] 68% confidence level in a single parameter.

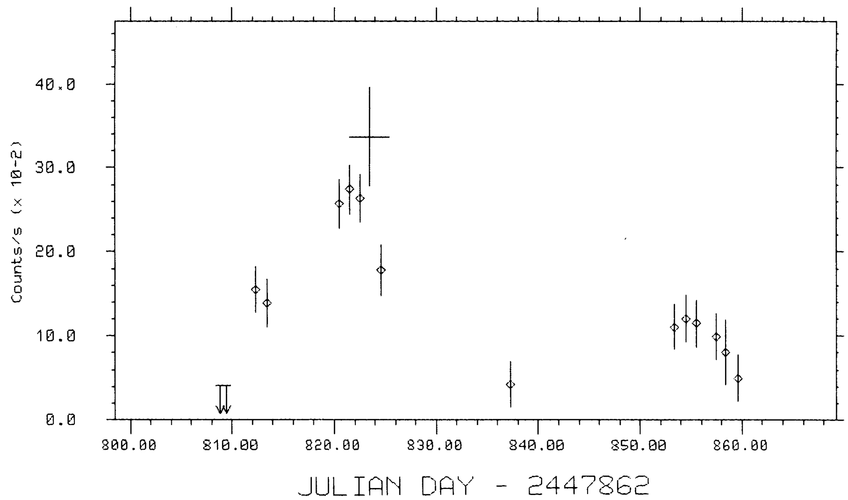

FIG. 2.—Light curve of MXB 1728−34 in the 40–70 keV band measured by SIGMA between 1992 February 17 and April 8: detected count rate at the source position plotted vs. the universal time (*circles*) and mean count rate value (*dotted line*). Error bars, as well as upper limits, are at 1 σ level. The cross is an estimation in SIGMA count rate units of the MXB 1728−34 contribution to the total 40–70 keV flux detected by BATSE from the GC region on March 2–5.

By use of Earth occultation technique, the BATSE experiment, on board the *Compton Gamma-Ray Observatory*, detected an increase of the γ-ray emission from the GC region on 1992 February 28. The intensity of this emission was maximum on March 3. In the absence of precise directional information, the emission was tentatively attributed to 1E 1740.7−2942 (Harmon et al. 1992). However, the SIGMA data revealed that MXB 1728−34 was nearly 3 times brighter than 1E 1740.7−2942 in the 40–70 keV band on 1992 March 2–4 (Cordier et al. 1993a). Considering the flux and the spectral shape reported by Harmon et al. (1992), the contribution of MXB 1728−34 to the total flux detected by BATSE on March 2–5 was derived by subtracting the SIGMA flux of 1E 1740.7−2942. The resulting MXB 1728−34 flux is 2.2×10^{-5} photons cm^{-2} s^{-1} keV^{-1} in the 40–70 keV band. The corresponding count rate is reported in Figure 2. In spite of being roughly derived, the obtained value is consistent with the SIGMA measurements.

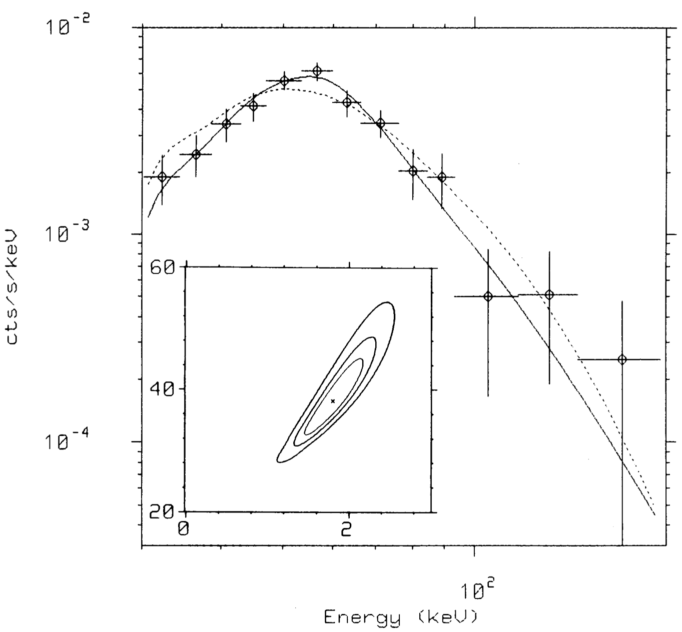

FIG. 3.—Average count spectrum of MXB 1728−34: solid and dashed lines indicate, respectively, the broken power-law and the bremsstrahlung models best fits (see Table 2). Contour map of χ^2 variations for the temperature kT (keV) vs. flux at 100 keV (10^{-5} photons cm^{-2} s^{-1} keV^{-1}) parameters of the bremsstrahlung model: contour levels correspond to 68%, 90%, and 99% confidence probability.

Finally, a 2 σ upper limit for the 40–70 keV flux of the Rapid Burster can be set to 3.7×10^{-11} ergs cm^{-2} s^{-1} from 1992 winter and spring SIGMA data. The same spectral parameters as those of the MXB 1728−34 best-fit broken power law (see Table 1) were considered in order to derive this upper limit.

3. DISCUSSION

SIGMA detected two flares of MXB 1728−34. The source was always in the telescope field of view during each of the six surveys so far performed on the GC region since 1990 March (Cordier et al. 1993b). MXB 1728−34 was thus found active during at least 12 of 46 observing periods for a total of about 960 hr. Hard X-rays (above 30 keV) from MXB 1728−34 were previously detected by the GRIP instrument (Cook et al. 1991). This source is also listed in the *HEAO 1* A-4 catalog, where positive flux above 25 keV is reported for one scan period of three (Levine et al. 1984). Although these measurements might have been contaminated by the nearby source the Rapid Burster, SIGMA results lead us to consider all previous detections of hard X-rays from this direction as due to MXB 1728−34. Hence, the hard X-ray flaring activity of MXB 1728−34 appears to be a rare, but not exceptional, behavior of the source.

The distance of MXB 1728−34 is not known. Assuming that it varies between 4 and 10 kpc (as in Basinska et al. 1984), the 30–200 keV average luminosity ranges between 1.3 and 8.5×10^{36} ergs s^{-1}. The maximum luminosity observed on March 1–2 is nearly twice as high. The detection of MXB 1728−34 by SIGMA enlarges the collection of hard X-ray sources associated with neutron star, able to produce emission up to 100 keV as Terzan 2 (Barret et al. 1991) or KS 1731−260 (Barret et al. 1992). However, all the nonpulsating LMXB already detected by SIGMA do not belong to the luminous LMXB class, but rather to the low-luminosity class of the bursting sources. It is also worth noting that such sources display hard X-ray spectra systematically softer, at least above 60 keV, than those of the black hole candidates (Fig. 4).

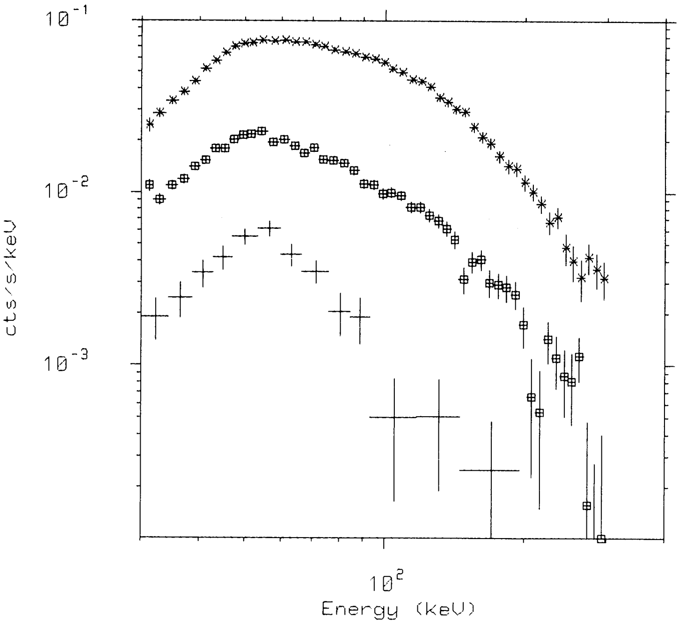

FIG. 4.—Average count spectrum of MXB 1728−34 (*crosses*) compared to that of the black hole candidates Cygnus X-1 (*stars*) and Nova Muscae (*squares*).

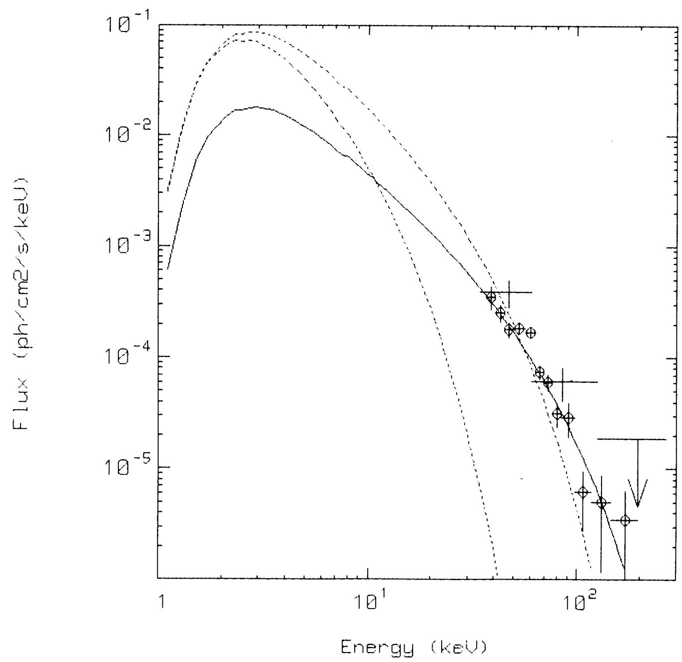

FIG. 5.—MXB 1728−34 average photon spectrum measured by SIGMA (*circles*) and GRIP (*crosses*). Solid and dashed lines correspond, respectively, to the SIGMA and X-ray detectors' best-fit thermal bremsstrahlung model (the *Einstein* spectrum with $kT = 17.7$ keV and $\text{flux}_{1-20\,\text{keV}} = 4.8 \times 10^{-9}$ ergs $\text{cm}^{-2}\ \text{s}^{-1}$, as well as the coldest *SAS 3* spectrum with $kT = 5$ keV and $\text{flux}_{1-20\,\text{keV}} = 2 \times 10^{-9}$ ergs $\text{cm}^{-2}\ \text{s}^{-1}$).

Variations up to a factor of 5 of the MXB 1728−34 persistent flux in the 2–6 keV band were previously observed by *Uhuru* (Forman et al. 1978). Basinska et al. (1984) reported variations of the 1–20 keV flux detected by *SAS 3* between 2 and 4.5×10^{-9} ergs $\text{cm}^{-2}\ \text{s}^{-1}$. They were clearly correlated to variations of the temperature between 4 and 11 keV. The *Einstein* MPC measured the hottest spectrum observed by a low-energy X-ray telescope (Grindlay & Hertz 1981). This spectrum was best fitted by a thermal bremsstrahlung model characterized by the temperature $kT = 17.7$ keV, column density $N_H = 3.6 \times 10^{22}\ \text{cm}^{-2}$, and flux of 4.8×10^{-9} ergs $\text{cm}^{-2}\ \text{s}^{-1}$ in the 1–20 keV band. At higher energy, the GRIP spectrum reported by Cook et al. (1991) was consistent with a thermal bremsstrahlung model with $kT \approx 31$ keV. However, due to the large error bars, the authors concluded that it was consistent with the *Einstein* spectrum.

The average photon spectrum of MXB 1728−34 measured by SIGMA is displayed in Figure 5, together with the GRIP data points. It appears that the SIGMA spectrum is compatible with the GRIP datapoints. The SIGMA thermal bremsstrahlung best fit has been extrapolated at lower energies in order to compare it to the coldest and hottest thermal bremsstrahlung spectra measured by the low-energy detectors mentioned above. Analysis of the confidence levels for the spectral parameters of the thermal bremsstrahlung model shows that SIGMA results are not consistent with the extrapolation of the *Einstein* spectrum (Fig. 3). SIGMA observations yield indeed a much higher temperature. Considering that the whole spectra is described by a thermal bremsstrahlung model with a single component, it appears then that SIGMA has detected the hottest state of the source together with the lowest 1–20 keV flux. This contradicts the correlation observed by Basinska et al. (1984). However, for burst sources, X-ray variability should rather be characterized by anticorrelation between low-energy flux and temperature (White et al. 1988). The blackbody component of the boundary layer is indeed negligible, and the disk-generated thermal component has important contribution by unsaturated up-Comptonization. Such anticorrelation is effectively observed in X 1608−52 (Mitsuda et al. 1989; Tanaka et al. 1989) or EXO 0748−676 (White et al. 1988), for example.

The flares observed by SIGMA are likely to be connected to the variability reported at low energy (recurrence and timescales are compatible). Hence, we can speculate that the whole 1–200 keV spectrum is not described by a single thermal component. In order to explain both SIGMA and previous results, we could assume the existence of two thermal components (at $kT \approx 5$ keV and $kT \approx 30$ keV), the flaring activity being related to the hard one only. The low-energy contribution of the variable hot component would be responsible for the correlation between flux and temperature observed by low-energy detectors in the 1–20 keV band. Within the frame of the standard view of burst sources, the variability of the disk-generated component is not expected to display a flux-temperature correlation (White et al. 1988). Though its origin remains unexplained, the existence of the hard variable component would then reconcile the behavior of MXB 1728−34 at low energy with the standard view of bursting sources. However, only simultaneous soft and hard X-ray observations of the source during the flaring activity would clarify this important issue.

We acknowledge the outstanding contribution of the SIGMA Project Group of CNES Toulouse Space Center for the overall success of the SIGMA mission. We also thank the staffs of the Baikonour Space Center, the Lavotchkine Space Company, the Babakin Space Center, and the Evpatoria Ground Station for their unfailing support.

REFERENCES

Basinska, E. M., et al. 1984, ApJ, 281, 337
Bradt, H. V. D., & McClintock, J. E. 1983, ARA&A 21, 13
Barret, D., et al. 1991, ApJ, 379, L21
Barret, D., et al. 1992, ApJ, 394, 615
Churazov, E., et al. 1993, A&AS, 97, 173
Claret, A., et al. 1993, Adv. Space Res., in press
Cook, W. R., et al. 1991, ApJ, 372, L75
Cordier, B., et al. 1993a, A&A, 272, 277
Cordier, B., et al. 1993b, A&A, in press
Fenimore, E. E., & Cannon, T. M. 1981, Appl. Opt., 20 (10), 1858
Forman, W., et al. 1978, ApJS, 38, 357
Gilfanov, M., et al. 1992, IAU Circ., No 5474
Goldwurm, A., et al. 1993, in Proc. of the Arthur Holly Compton Centennial Symposium on Gamma-Ray Astronomy, Results from the Gamma-Ray Observatory (New York: AIP), 366
Grindlay, J. E., & Hertz, P. 1981, ApJ, 247, L17
Harmon, B. A., et al. 1992, IAU Circ., No. 5475
Hoffman, J. A., et al. 1976, ApJ, 210, L13
Levine, A. M., et al. 1984, ApJS, 54, 581
Lewin, W. H. G. 1976, IAU Circ., No. 2922
Mitsuda, K., et al. 1989, PASJ, 41, 97
Paul, J., et al. 1991, Adv. Space Res., 11 (8), 289
Sunyaev, R. A., & Titartchuk, L. G. 1980, A&A, 86, 121
Tanaka, Y., et al. 1989, in Proc. 23d ESLAB Symp. on Two Topics in X-Ray Astronomy, ed. J. Hunt & B. Battrick (ESA SP-296), 1, 3
van Paradijs, J., & Isaacman, R. 1989, A&A, 222, 129
White, N. E., et al. 1988, ApJ, 324, 363