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SIGMA DETECTION OF HARD X-RAY EMISSION FROM THE TERZAN 1 GLOBULAR CLUSTER

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ABSTRACT

During the survey of the Galactic center region performed by the hard X-ray telescope SIGMA aboard the *Granat* space observatory, a persistent source coincident with the Terzan 1 globular cluster has been observed. This source may be associated with the persistent X-ray source X1732−304 studied by *EXOSAT*, *ROSAT*, and ART-P and with the X-ray burster source detected by *Hakucho* in Terzan 1. The source appears at the 5.5 σ level in the SIGMA images in the 40–75 keV energy range. There is no evidence for time variability, and the photon spectrum is reproduced by a thermal bremsstrahlung law with a temperature equal to 33^{+32}_{-12} keV as well as by a power law with spectral index equal to -3.2 ± 0.7. The luminosity in the 40–75 keV energy range is equal to $4.0 \pm 0.8 \times 10^{35}$ ergs s^{-1}, assuming a distance of 10 kpc. This hard X-ray emission may come from a low-mass X-ray binary with a neutron star as the compact member.

Subject headings: gamma rays: observations — globular clusters: individual (Terzan 1)

1. INTRODUCTION

X-ray emitters have been detected in several globular clusters during the sky surveys performed by the *Einstein* (Hertz & Grindlay 1983), *HEAO 1* (Hertz & Wood 1985), *EXOSAT* (Warwick et al. 1988), and *ROSAT* (Johnston, Verbunt, & Hasinger 1995) satellites, and X-ray burst observations in globular clusters have been reported by several experiments as, for example, the *Astronomical Netherlands Satellite* (*ANS*; Grindlay et al. 1976) and *Hakucho* (Makishima et al. 1981; Inoue et al. 1981). Some steady X-ray–emitting sources have then been found to coincide with burster sources in globular clusters. Tentative classifications have been built to account for the different characteristic features of the observed sources (Hertz & Grindlay 1983):

1. The bright persistent globular cluster X-ray sources with luminosities greater than 10^{36} ergs s^{-1} in the energy range 1–30 keV are frequently associated with bursters and may consist of low-mass close binary systems containing a neutron star and a low-mass companion star.
2. The dim globular cluster X-ray sources exhibit luminosities lower than $10^{34.5}$ ergs s^{-1} and generally do not correspond to an X-ray burster; they may be close binary systems including a white dwarf as the compact member. This structure accounts for the 10^3 factor in luminosity separating the two classes of X-ray sources.

Because globular clusters are regions of high stellar density, different formation processes are plausible for those close binary systems such as capture of a nuclear-burning companion star by a neutron star during a close encounter (Fabian, Pringle, & Rees 1975) or even exchange of a star between a primordial low-mass binary system and a neutron star (Hut & Verbunt 1983).

The SIGMA imaging telescope, which provides images of the sky in the hard X-ray energy domain (35 keV–1.3 MeV), has made a thorough and repeated scanning of the Galactic center region (Paul et al. 1996). We report here on the detection of a persistent hard X-ray emission from a source located in the Terzan 1 globular cluster, and we discuss the temporal and spectral characteristics of this source observed over 5 yr in the 35–200 keV range.

2. SIGMA OBSERVATIONS

The SIGMA telescope is a hard X-ray instrument which provides high resolution images of the sky. A tungsten coded mask associated with a NaI scintillator position-sensitive detector of 797 cm^2 active area leads to an angular resolution of about 15′ over the total field of view (Paul et al. 1991). During all the observations considered in the present paper, the SIGMA telescope was operating in the "spectral imaging mode," and two sets of images were recorded simultaneously by the instrument: "finely sampled images" in four broad energy bands with a pixel size equal to 1′.6 (248 × 232 pixels) and "spectral images" in 95 energy channels with a pixel size of 3′.2 (124 × 116 pixels). The region of the Galactic center has been observed twice a year from 1990 to 1994. The Terzan 1 source is located in the totally coded SIGMA field of view (4°.7 × 4°.3) during 103 observation sessions. The total cumulated observation time is equal to 6.9×10^6 s, and the total effective exposure time (after corrections for dead time) is equal to 5.9×10^6 s.

A soft gamma-ray source is detected on the SIGMA "finely sampled images" at the position R.A. (1950) = 17^{h}32^{m}34^s, decl. (1950) = −30°27′48″ with an

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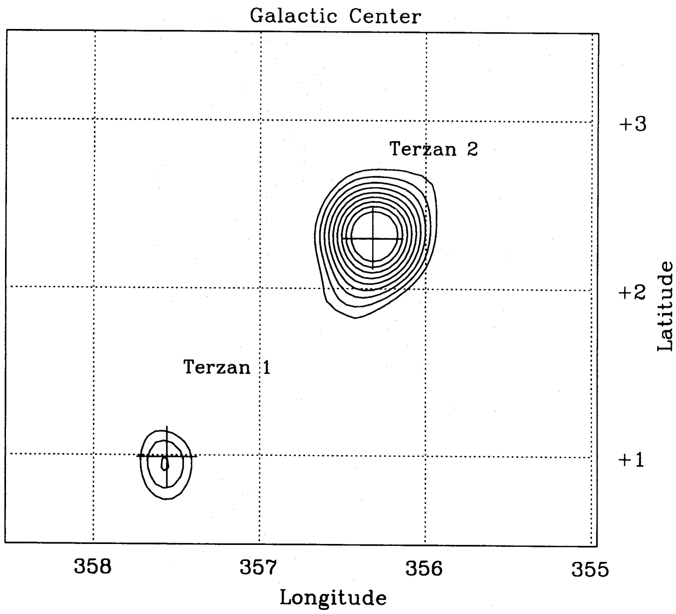

FIG. 1.—Image of the Terzan 1 region obtained by the SIGMA telescope in the 40–70 keV energy range.

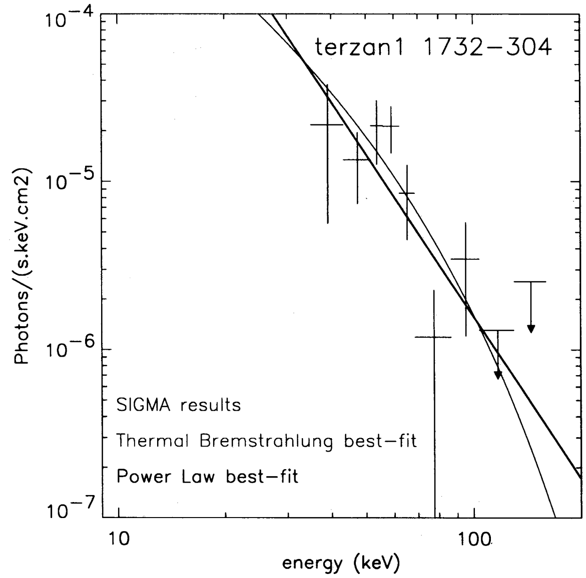

FIG. 3.—Averaged photon spectrum measured by SIGMA. For the points with energies above 100 keV, the 2 σ upper limit is shown. The other error bars are at 1 σ. The two curves represent the best fits obtained for power-law and thermal bremsstrahlung law models, in the 40–170 keV range.

error circle of 4′ radius for 90% confidence as shown on Figure 1 (Godwurm et al. 1994a). This error box is fully compatible with the Terzan 1 position (Terzan 1966). The spectral images are corrected for spatial nonuniformity defects (Schmitz-Fraysse, Stephen, & Ballet 1996) and then deconvolved with standard methods. The source-to-noise ratio, calculated as the ratio of the source number of counts over the statistical error (equal to the square root of the total number of counts in the image before deconvolution) is equal to 5.5 σ for the 40–75 keV energy range.

The light curve gathering all the observations of the source is displayed on Figure 2. Because of the size of the error bars on the flux measured during each observation, it does not seem possible to reach a conclusion on the time variability of this source, as has been possible for the Terzan 2 source (Goldwurm et al. 1994b). It should be noted that the source does not exhibit any flare of intensity higher than

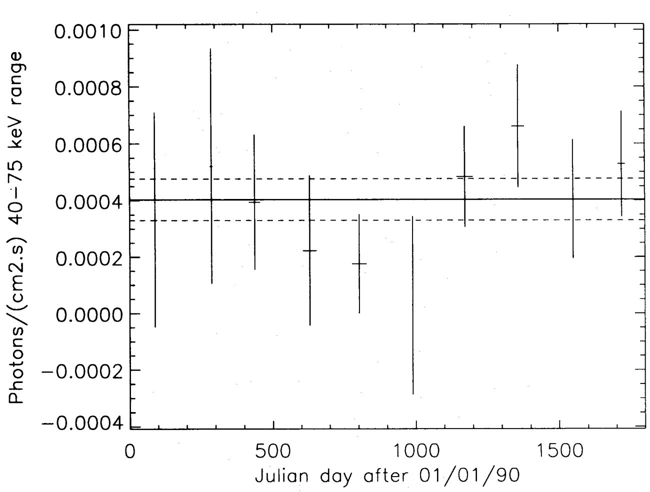

FIG. 2.—Light curve recorded in the 40–75 keV energy band. The solid line represents the mean flux over 5 years, and the dashed lines give the ± 1 σ values.

7 σ, which would have been detected by the SIGMA telescope. The mean flux extracted from the sum of all the observations with the best-fit power law (see below), in the energy range 40–75 keV, is equal to $(3.5 \pm 0.7) \times 10^{-11}$ ergs $cm^{-2}\ s^{-1}$, and the luminosity, calculated under the assumption of a 10 kpc distance, is equal to $(4. \pm 0.8) \times 10^{35}$ ergs s^{-1}.

The measured count spectrum is obtained in each of the 95 deconvolved "spectral images" as the count rate in the sky pixel containing the source. The incident spectrum is then calculated through a deconvolution process based on the maximum entropy method (Skilling & Gull 1985) using the energy matrix of the SIGMA telescope (Bouchet 1992, 1995). The photon spectrum (average of all observation sessions) is given on Figure 3, displayed over 10 energy channels. The source is clearly emitting up to 100 keV; 2 σ upper limits are obtained for higher energies. The best fit of the SIGMA results presented on Figure 3 is obtained with a power law in the 40–170 keV range. The spectral index and the 60 keV flux are equal to $\alpha = -3.2 \pm 0.7$ and $8.1 \times 10^{-6} \pm 3.1 \times 10^{-6}$ photons (keV $cm^2\ s^{-1}$), respectively, with a reduced χ^2 of 1.02 (for 10 degrees of freedom). The thermal bremsstrahlung model leads to a temperature equal to 33.0^{+32}_{-12} keV, a flux at 60 keV equal to $9.1 \times 10^{-6} \pm 3.0 \times 10^{-6}$ photons (keV cm^2 s$)^{-1}$, and the reduced χ^2 value is 0.98 for 10 degrees of freedom. The errors are given at a 68% level of confidence for variation of one parameter: normalization factor, temperature, or spectral index.

3. DISCUSSION

Two X-ray bursts were recorded by the *Hakucho* satellite in 1980 July (Makishima et al. 1981; Inoue et al. 1981) from a source in the Terzan 1 globular cluster region with peak fluxes in the 1–22 keV energy range equal to 7×10^{-8} ergs $s^{-1}\ cm^{-2}$ and total duration of the bursts of about 10 s, but no persistent emission was observed above the level of 1/50

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TABLE 1

SUCCESSIVE OBSERVATIONS OF AN X-RAY SOURCE IN THE TERZAN 1 GLOBULAR CLUSTER

Instrument	Source Position R.A., Decl. (1950) and accuracy	Energy Band (keV)	Flux (ergs s^{-1} cm^{-2})	Power-Law Index	Notes
Hakucho	$17^h32^m05^s \pm 50^s$, $-30.4° \pm 0.3°$	1–22	7×10^{-8}	...	Bursts
		...	<1/50 Crab	...	Persistent
HEAO 1	...	0.5–20	$<1.05 \times 10^{-10}$	...	Persistent
SL2-XRT	$17^h32^m39^s$, $-30°25'41''$	3–30	1.84×10^{-10}	...	Persistent
...	1.6' (90%)	...	...	...	...
EXOSAT	$17^h32^m34.8^s$, $-30°27'2.6''$	1–10	2.5×10^{-10}	2.12	Persistent
...	8'' (90%)	...	...	...	...
ROSAT	$17^h35^m47.2^s$, $-30°28'54''$	0.5–2.5	3.2×10^{-10}	2.1	Time-variable
(J2000)	10''	...	0.5×10^{-10}	...	Persistent
ART-P	$17^h32^m34^s$, $-30°29'26''$	3–30	4.7×10^{-10}	...	Time-variable
...	120'' (90%)	...	1.3×10^{-10}	...	Persistent
...	...	...	3.9×10^{-8}	...	Burst
SIGMA	$17^h32^m34^s$, $-30°27'48''$	40–75	0.35×10^{-10}	3.2	Persistent
...	4' (90%)	...	...	...	...

crab in the 1–22 keV energy range. The burst activity appeared to be sporadic: further observations performed by the *Hakucho* satellite in 1979 and 1980 remained unsuccessful.

There has been no detection during the *Einstein* survey, and the *HEAO 1* experiment has set an upper limit of 1.05×10^{-10} ergs s^{-1} cm^{-2} to the persistent flux emitted by the Terzan 1 X-ray source in the 0.5–20 keV range (Hertz & Wood 1985).

Later on, the coded mask telescope SL2-XRT (Skinner et al. 1987) provided hard X-ray images of the Galactic center, and the total flux observed in the 3–30 keV energy range was equal to 1.84×10^{-10} ergs s^{-1} cm^{-2}.

EXOSAT observed the Terzan 1 X-ray source and searched for orbital modulations of the X-ray light curve without any positive detection, as for Terzan 2 and several other globular cluster X-ray sources, and this led to a power-law fit of the energy spectrum with an index equal to 2.12 ± 0.04 for the 1–10 keV energy range (Parmar, Stella, & Giommi 1989). The persistent flux was measured equal to 2.5×10^{-10} ergs s^{-1} cm^{-2}.

The *ROSAT* high-resolution imager has detected a source in Terzan 1 with a flux varying from 3.2×10^{-10} ergs s^{-1} cm^{-2} to 0.5×10^{-10} ergs s^{-1} cm^{-2} between 1994 March and September (Johnston et al. 1995). The spectrum is reproduced in the 0.5–2.5 keV band by a power law with index $\alpha = 2.1$, and the equivalent hydrogen column density is estimated to be equal to 1.8×10^{22} cm^{-2}.

The ART-P/*Granat* observations, performed in 1990 September and October showed a strong change of the flux of the source in the 3–30 keV energy range on the timescale of 1 month from 4.7×10^{-10} ergs s^{-1} cm^{-2} to 1.3×10^{-10} ergs s^{-1} cm^{-2}, as well as the occurrence of one short X-ray burst with a luminosity of 5×10^{38} ergs s^{-1} (Pavlinsky et al. 1995) (the Terzan 1 distance is assumed to be 10.6 kpc).

A persistent hard X-ray source is observed with the SIGMA telescope at a position which is quite compatible with the Terzan 1 globular cluster position, the extension of the cluster being of 1' radius (Terzan 1966). The successive observations of a X-ray source in the Terzan 1 globular cluster are gathered in Table 1. The SIGMA error circle and the error circles measured for the X-ray sources detected by the SL2-XRT experiment, the *EXOSAT* experiment, and the *ROSAT* observations show a large overlap. The results will then be discussed, assuming that the same object is responsible for these X-ray and hard X-ray emissions.

The two *ROSAT* observations in 1994 March and September show an important variation of the flux emitted by X1732−304 in the 0.5–2.5 keV energy band. SIGMA was in operation on 1994 March 16 and September 16 but the statistics obtained in 1 day is too poor to examine a possible flux variation. On the SIGMA data obtained in about 150 hr around 1991 March, in 200 hr around 1994 March 16, and in 270 hr around 1994 September 16, the source shows up in the 40–75 keV energy range to the 1.7, 1.9, and 2.8 σ level, respectively. The flux values presented in Table 2 and the corresponding significances lead to the conclusion that no significant variation occurred for the source in the SIGMA energy range.

The SIGMA energy spectrum corresponding to the sum of all the observations performed over 5 years (1990–1994) is displayed on Figure 4 together with the ART-P data. The ART-P results obtained in 1990 September and October show the source in a high-state and in a low state, respectively (Pavlinsky et al. 1995). The SIGMA telescope was not working during the ART-P observations of Terzan 1. For this reason, no attempt to derive a common fit has been done. The SIGMA power-law and thermal-law best fits (see also Fig. 3) are extrapolated to lower energies with corrections for absorption by a hydrogen column density $n_H = 10^{22}$ cm^{-2}. The extrapolated power law reproduces fairly well the ART-P high-state data, suggesting the possibility of

TABLE 2

EVOLUTION OF THE FLUX DETECTED IN THE 0.5–2.5 keV (*ROSAT*) AND 40–75 keV (SIGMA) BANDS

Date	Flux (ergs s^{-1} cm^{-2})
ROSAT	
1991 Mar 19–23	3.2×10^{-10}
1994 Mar 16	2.98×10^{-10}
1994 Sep 16	0.52×10^{-10}
SIGMA	
1991 Feb 24–Apr 1	0.33×10^{-10}
1994 Mar 8–Apr 18	0.34×10^{-10}
1994 Sep 1–28	0.44×10^{-10}

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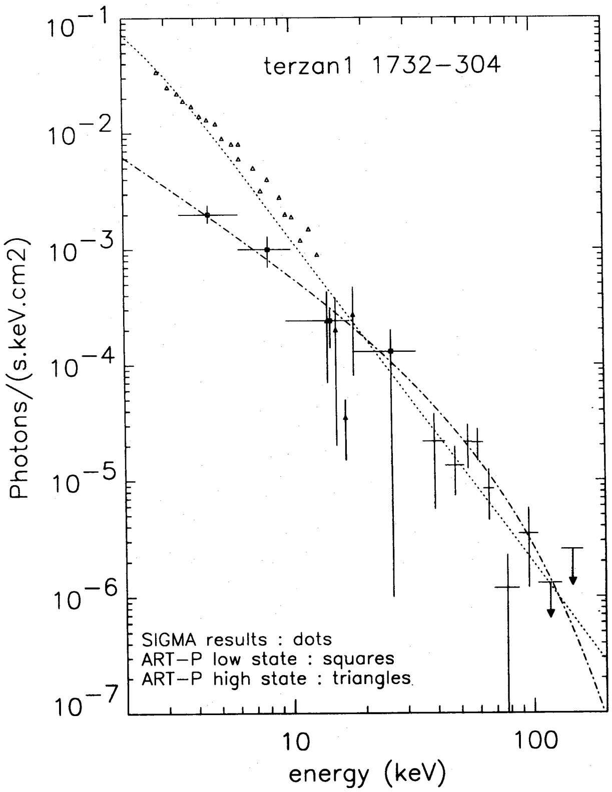

FIG. 4.—The ART-P low-state and high-state spectra are presented as squares and triangles, respectively. The SIGMA power-law best fit is extrapolated to lower energies with $N_H = 10^{22}$ cm^{-2} (*dotted line*). The dot-dashed line represents a thermal bremsstrahlung fit common to the ART-P low-state and SIGMA data (Pavlinsky et al. 1995).

a single mechanism for the photon emission from 3 keV up to 100 keV, which could be a Comptonization process. But a thermal bremsstrahlung model with $kT = 40$ keV links the ART-P low state and the SIGMA data (Gilfanov et al. 1996). Complementary observations of this source in this hard X-ray energy range are required before a decisive conclusion can be drawn on the time variability of the luminosity and its possible correlation with changes in the energy spectrum shape.

4. CONCLUSION

A persistent hard X-ray emission has been observed in the Terzan 1 globular cluster which may be associated with the X1732−304 X-ray source previously observed by SL2-XRT, *EXOSAT*, and *ROSAT* experiments and also measured with the ART-P *Granat* X-ray detector. There is no evidence for such a strong time variability as observed in the X-ray band, and the photon spectrum measured in the 35–100 keV energy range is reproduced by a thermal bremsstrahlung law with a temperature equal to 33 keV as well as by a power law with an index equal to −3.2. Additional experimental studies are required to identify the mechanisms responsible for those X-ray and hard X-ray emissions.

X1732−304 in Terzan 1 is the second persistent hard X-ray source detected by the SIGMA instrument in a globular cluster in the Galactic center region; the previous one was the burster X1724−308 in Terzan 2 (Goldwurm et al. 1994b). The conclusion that this source exhibiting a persistent X-ray emission with a tail extending in the hard X-ray region and also luminous X-ray bursts consists of a low-mass binary with a neutron star as the compact member can be proposed but is not yet completely established.

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