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DISCOVERY WITH THE SIGMA TELESCOPE OF HARD X-RAYS FROM THE GLOBULAR CLUSTER TERZAN 2

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ABSTRACT

During the survey of the Galactic center performed with the Sigma hard X-ray/soft gamma-ray telescope, a new source has been discovered in the 35–200 keV energy range. The location of the source is consistent with the position of the globular cluster Terzan 2. Although we also discuss other possibilities, it is likely that the hard X-rays emission originates in X1724−308 (4U 1724−30), a source of X-ray bursts located in the globular cluster. Under this assumption, it would be the first detection of a low-mass X-ray binary in this energy range.

Subject headings: clusters: globular — stars: individual (X1724−308) — X-rays: binaries — X-rays: sources

1. INTRODUCTION

X-rays with energy greater than ≈100 keV have been detected from several Galactic objects of different classes (see, for example, the *HEAO 1* high-energy sky survey of Levine et al. 1984). Such detections include the Crab Nebula and Pulsar, a few X-ray pulsars and transients, and black hole candidates like Cyg X-1 (see the reviews by Liang & Nolan 1984; Frontera & Dal Fiume 1989; Tanaka 1989). None of these hard X-ray sources is located in a globular cluster. This contrasts with the situation in the "classical" X-ray energy band ($E < 10$ keV), where a number of bright X-ray sources, consisting of accreting compact stars in binary systems, are found inside globular clusters (see, e.g., Lewin & Joss 1983; Charles 1989). In fact, it was soon realized that the high stellar density in globular cluster cores is extremely favorable for the formation of X-ray binary sources (Clark 1975; Fabian, Pringle, & Rees 1975).

Here we report the discovery of a new, variable hard X-ray source (35–200 keV) whose position is compatible with that of the globular cluster Terzan 2. The observations were obtained with the French Sigma experiment on board the *GRANAT* satellite. Sigma is a hard X-ray/soft gamma-ray imaging telescope based on the coded-mask aperture technique. Thanks to its wide field of view and its high angular resolution (≈15′), Sigma is well adapted to study the high-energy emission from the central parts of the Galaxy. Since the soft X-ray sources detected in the Galactic bulge number several tens, all the nonimaging, collimated hard X-ray detectors previously flown have been subject to confusion problems.

If, as likely, the observed source is indeed associated to Terzan 2, this represents the first detection of a globular cluster in the hard X-ray energy range. Terzan 2 also contains the luminous X-ray source X1724−308, a well-studied X-ray burster (Swank et al. 1977; Grindlay et al. 1980). This source is thought to be an accreting neutron star in a low-mass binary system. Although we also consider other possibilities, it is likely that X1724−308 is the source of the observed high-energy emission.

2. OBSERVATIONS AND RESULTS

The Sigma telescope, operating in the 35–1300 keV energy range, has been successfully launched on board the *GRANAT* space observatory from the Baïkonour space center (USSR) on 1989 December 1. It has been designed to provide for the first time in this energy range, arcminute resolution images, over a field of view of 4°7 × 4°3. This field of view is surrounded by a wider field of decreasing sensitivity (the half-sensitivity boundary is a 11°5 × 11° rectangle). The telescope features basically a NaI position-sensitive detector based on the Anger camera principle, associated with a tungsten coded mask, whose basic pattern is a Uniformly Redundant Array (URA; Fenimore & Cannon 1978). During a 1 day long observation, the telescope records simultaneously six series of four high-resolution images (232 × 248 pixels of 1′6 in size) in four adjacent intervals of energy, and three series of 95 low-resolution "spectral images" (116 × 124 pixels of 3′2 in size) in 95 fixed energy channels, taken between 35 and 1300 keV. For further information concerning the instrument and its in-flight performances, the reader is referred to Paul et al. (1990) and Mandrou et al. (1990). A source located in the full sensitivity field of view casts on the detector a shadow of the complete basic pattern of the mask. Its flux is totally modulated by the mask before being recorded by the detector. On the other hand, when the source is in the partially coded field of view, the detector is shadowed by an incomplete basic mask pattern. However it is still possible to reconstruct the position of the source with the nominal angular resolution of 15′ (2′, positioning accuracy), but the sensitivity is decreased according to the fraction of the basic mask pattern projected on the detector.

During the observations of the Galactic center region, centered on the hard X-ray source 1E 1740.7−2942, the globular cluster Terzan 2 was always in the partially coded field of view

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of the telescope. To take into account the partial modulation of the flux, we compute an average sensitivity factor during the session. Only the data corresponding to a flux modulation greater than 60% have then been used. The recorded images have been "flat-fielded" to remove spatial nonuniformities intrinsic to the detector or due to the background as described in Laudet & Roques (1988) and then deconvolved by standard techniques.

During three consecutive sessions of observations performed in 1990 March and April, a source was detected above 3 σ in the high-resolution images at a position R.A. = $17^h24^m14^s$, decl. = $-30°44'14''$. The error box for the source position, in the 40–160 keV energy range, has a 90% confidence level radius of about 4′.

The analysis of the "spectral images" reveals that the source is detected up to 200 keV. Table 1A shows the results for the three consecutive observations. The effective exposure time for a session is computed by multiplying the total exposure time (corrected for the instrumental dead time) by the sensitivity factor. The signal-to-noise ratio is computed as the ratio between the source counts and the statistical error, defined as the square root of the total counts in the image before the deconvolution procedure. In addition to the level of significance in the 38–200 keV energy range, the counting rate and the associated 1 σ error, are shown. The average counting rate 0.305 ± 0.045 counts s^{-1}, corresponds to a flux of about 50 mCrab.

The 95 channel count spectrum is obtained by deconvolving the 95 spectral images and taking the counts in the pixel corresponding to the sky source position. In order to recover the incident photon spectrum, the calibration matrix has been built with Monte Carlo simulations including a very detailed geometrical model of the Sigma telescope (Barret & Laurent 1991). The photon spectrum is then obtained with a process based on the maximum entropy method (Gull 1985). The energy response matrix has been successfully tested on a classical astrophysical site, the Crab Nebula.

We have computed the hardness ratio, in two adjacent energy bands, for each session. No changes in the spectral shape have been detected. This allows us to sum the three observations, to derive the source spectrum. However, the photon statistics are too poor to fit the spectrum with a model more complicated than a simple power law. The best-fit power law spectrum is

$$\Phi(E) = 10^{-5}(1.75^{\pm 0.5})\left(\frac{E}{140\ \mathrm{keV}}\right)^{-(1.65_{-0.6}^{+0.4})}\ \text{photons cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}$$

with a reduced $\chi^2 = 0.35$ for 5 degrees of freedom. The errors given are at a 68% confidence level for joint variation of the two parameters. Figure 1 shows both the incident photon spectrum and the model. In the same figure, for comparison, we have plotted the 1985 April spectrum of X1724−308 in the globular cluster Terzan 2 (Parmar, Stella, & Giommi 1989) as derived from the *EXOSAT* data base.

The results from the spectral analysis indicate that the source has a very hard spectrum; for comparison it is worth noting that the photon spectrum of the Crab Nebula has a spectral index of about 2.

After the 1990 April 8 session, no hard X-ray emission in the direction of this source has been detected above 3 σ, both in the single observations and in their total sum. Using all the observations of the Galactic center region, for which the source was also in the partially coded field of view, we have computed the 2 σ upper limits on its time-averaged flux for three sets of sessions, in the 38–200 keV energy range (see Table 1B). It appears clearly that the hard X-ray emission coming from this source has decreased after the March–April observations.

TABLE 1

SIGMA OBSERVATIONS OF THE GLOBULAR CLUSTER TERZAN 2

A. DETECTION OF TERZAN 2 IN THE 38–200 keV ENERGY RANGE

Observation Date (1990)	Exposure Time (s)	Signal-to-Noise Ratio	Counts s^{-1}	Photons ($cm^{-2}\ s^{-1}$)
Mar 24	50,076	4.5 σ	0.336 ± 0.075	$\approx 6.4 \times 10^{-3}$
Apr 4	47,608	4.5 σ	0.365 ± 0.081	$\approx 6.9 \times 10^{-3}$
Apr 8	58,381	3.0 σ	0.230 ± 0.076	$\approx 4.3 \times 10^{-3}$
Total	156,065	6.8 σ	0.305 ± 0.045	5.8×10^{-3}

B. 2 σ UPPER LIMITS IN THE 38–200 keV ENERGY RANGE

Observation Period	Exposure Time (s)	Counts s^{-1}	Photons ($cm^{-2}\ s^{-1}$)
1990 Aug–Sep	100,100	<0.12	$<2.3 \times 10^{-3}$
1990 Oct	132,492	<0.09	$<1.7 \times 10^{-3}$
1991 Feb	161,800	<0.08	$<1.6 \times 10^{-3}$

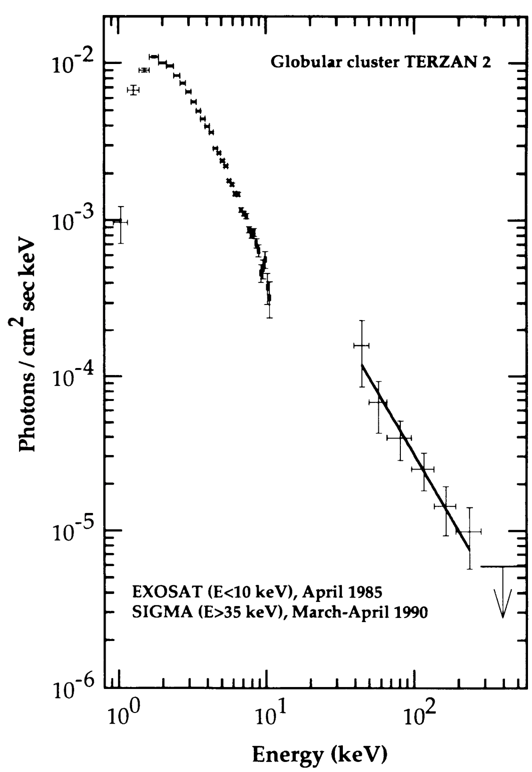

FIG. 1.—Above 40 keV, the average incident photon spectrum of Terzan 2 measured by Sigma during the 1990 March–April observations. The solid line represents the best-fit power-law model (photon index of ≈1.65). The upper limit is at the 95% confidence level. Also shown for comparison, below 10 keV, the 1985 April *EXOSAT* spectrum of X1724−308 in Terzan 2 (Parmar et al. 1989).

3. DISCUSSION

The error box of this hard X-ray source contains the globular cluster Terzan 2 whose position is R.A. = $17^h24^m20^s \pm 1^s$, decl. = $-30°45'37'' \pm 1''$ (Hertz & Grindlay 1983). Clark et al. (1975) have derived an empirical formula which gives the surface density of known globular clusters as a function of the angular distance from the Galactic center. Using this relation, we have estimated as $< 1.5 \times 10^{-3}$ the probability of finding by chance a globular cluster in the ≈ 0.014 deg^2 error box of our hard X-ray source. Therefore, in the following discussion, we will assume that the source is located in Terzan 2. An estimate of the distance of Terzan 2 has been given by Malkan, Kleinman, & Apt (1980), who derive values in the 14–24 kpc range, depending on the assumed metallicity of the cluster. For $d = 14$ kpc, we derive a 38–200 keV average luminosity of $\approx 1.8 \times 10^{37}$ ergs s^{-1} during the March–April observations.

The high luminosity, the time variability, and the hard spectrum extending up to 200 keV immediately suggest that a compact object is responsible for the observed emission. In fact, all the known Galactic sources capable of producing a persistent or variable flux in the hundreds of keV region involve neutron stars (powered by the loss of rotational energy, or by accretion from a companion), or black holes (e.g., Cyg X-1).

3.1. *A Rotation-powered Neutron Star?*

Let us first consider the case of a fast-rotating neutron star emitting in the hard X-ray band via some nonthermal mechanism. Models involving young neutron stars, such as the Crab or Vela pulsars, run into difficulties. First, the X-ray flux from Crab-like pulsars is remarkably constant, in contrast to our results. Second, and more important, such objects are not expected to be found now in globular clusters, simply on the basis of evolutionary considerations. Models of this kind could be retained only if the hard X-ray source were not associated with Terzan 2, a hypothesis which we consider as unlikely.

Another possibility is that the hard X-ray emission is related to an old neutron star which has undergone a phase of mass and angular momentum accretion in a close binary system (van den Heuvel 1988, and references therein). A large number of such "recycled" pulsars is expected in globular clusters (Kulkarni, Narayan, & Romani 1990), and two examples have recently even been discovered in low-density globular clusters (Kulkarni et al. 1991). Of particular relevance is the discovery of the two eclipsing, millisecond pulsars, PSR 1957+20 (Fruchter, Taylor, & Stinebring 1988) and PSR 1744−24A (Lyne et al. 1990). The latter is in the globular cluster Terzan 5. Both objects are in binary systems, and there is strong evidence that their companion stars are being "evaporated" by the beam of relativistic particles and high-energy photons emitted by the pulsars (Nice et al. 1990). This evidence has stimulated several theoretical models predicting that PSR 1957+20 and PSR 1744−24A should be sources of X- and gamma-rays (Phinney et al. 1988; Kluzniak et al. 1988a). A rotational power similar to that of these two pulsars (10^{35}–10^{36} ergs s^{-1}) would, however, be insufficient to account for the observed hard X-ray luminosity. Even for the fastest pulsar (P = 1–2 ms) a very high efficiency to produce X-rays would be required, given the great distance of Terzan 2.

3.2. *An Accretion-powered Neutron Star?*

In the context of binary models, it seems natural to associate the observed hard X-rays to the source X1724−308 (Grindlay et al. 1980), located well within the $\approx 7''$ core radius of Terzan 2. A direct evidence for the binary nature of this source, e.g., orbital modulation, eclipses, or an optical counterpart, has not been found (Parmar et al. 1989). However, X1724−308 shows the typical characteristics of the luminous bursting sources ($L_x > 10^{36}$ ergs s^{-1}) located in globular clusters, which, as a class, are well interpreted in terms of neutron stars in low-mass X-ray binaries (LMXRBs) (see, e.g., Lewin & Joss 1983). Several LMXRBs and, in particular, the bursting sources, show X-ray spectra which include power-law components without evidence of a cut-off up to energies of a few tens of keV, and are generally interpreted in the framework of Comptonization models (White, Stella, & Parmar 1988; Miyamoto, Kitamoto, & Kimura 1989). The quiescent emission from X1724−308 has been equally well fitted with bremsstrahlung spectra ($kT \approx 7$ keV, Hertz & Grindlay 1983; $kT \approx 6$ keV, Parmar et al. 1989) and power law (photon index ≈ 2.3; Parmar et al. 1989). As can be seen in Figure 1, if we extrapolate the *EXOSAT* power-law fit of the latter authors, the expected flux in the 38–200 keV range falls about a factor of 10 below that measured with Sigma. This would indicate a substantial variability possibly correlated with a spectral hardening.

A model which predicts nonthermal hard X-ray/soft gamma-ray emission from LMXRBS has been proposed by Kluzniak et al. (1988b). The energy source of this radiation would be a particle accelerator resulting from the magnetic coupling between the neutron star dipolar field and the differentially rotating accretion disk. The relativistic particles accelerated in the magnetosphere would then radiate by synchrotron emission and inverse Compton scattering on the copious soft X-ray flux resulting from accretion. Electron/positron pair production is also expected to be important. The effect of these processes would be to redistribute below the MeV region the power available from the accelerator.

3.3. *An Accreting Black Hole?*

X-rays in the hundreds of keV region have been observed from Cyg X-1, one of the more convincing black hole candidates (see the review by Liang & Nolan 1984) and from the two hard X-ray sources 1E 1740−2942 and GRS 1758−258 detected by the *GRANAT* satellite (Sunyaev et al. 1991). In addition, power-law tails extending to ≈ 200 keV were detected in a few ultrasoft transients like A0620−00 (Coe, Engel, & Quenby 1976) and GS 2000+25 (Sunyaev et al. 1988), which are generally thought to contain black holes. All of these sources have, in the 30–200 keV range, spectra with a power-law slope similar to that reported here, thus suggesting that also the hard X-ray source we have observed might originate in a black hole system.

In the hypothesis of a persistent source, some level of X-ray emission at lower energy should have been already detected well in the center of the cluster's core. The source X1724−308 is only $\approx 3''$ from the cluster center and, within the one sigma uncertainties, compatible with the position of the latter (Grindlay et al. 1984). We note that the X-ray bursts, indicating the presence of a neutron star, have been positioned and associated with the persistent source X1724−308 on the basis of an observation made with the *Einstein Observatory* HRI instrument, whose angular resolution is $\approx 4''$ (Grindlay et al. 1980). Thus the presence of more than one X-ray source within the $6''.5$ core radius of Terzan 2 cannot be completely ruled out.

4. CONCLUSION

We have detected a hard X-ray source which is very likely located in the globular cluster Terzan 2. The observed radiation can be explained in the easiest way by assuming that it originates in the source X1724−308, although other possibilities cannot be excluded by the present data. If sporadic emission in the hard X-ray energy range is a common characteristic of LMXRBs, as proposed, for example, in the model by Kluzniak et al. (1988b), we expect to detect other LMXRBs, in and out of globular clusters, at high energy. Further hard X-ray imaging observations of the Galactic bulge region will provide important informations. For example, the lack of detection of other well-established LMXRBs would suggest reconsidering the interpretation of the X-ray source(s) in Terzan 2.

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