Astron. Astrophys. 332, L45–L48 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

The radio counterparts of GX 354−0 and Terzan 1

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Received 20 February 1998 / Accepted 24 February 1998

Abstract. We report the discovery of weak radio counterparts for the hard X-ray sources GX 354−0 and Terzan 1. Based on the arcsec accurate radio position, an infrared counterpart with magnitude $K = 15.1 \pm 0.2$ is proposed for GX 354−0. For Terzan 1, its crowded field prevents us from a similar unambiguous identification, and at least four different stellar objects may be consistent with the radio counterpart.

Key words: X-rays: stars – Radio continuum: stars – stars: GX 354−0 – (Galaxy:) globular clusters: Terzan 1

1. Introduction

Both GX 354−0 and Terzan 1 are X-ray bursting sources well known since many years ago. They are tentatively catalogued as low mass X-ray binaries (LMXRBs) in the Galactic Bulge (van Paradijs 1995). A firm classification of these sources as LMXRBs would require a knowledge of its photometric or spectroscopic properties, not yet available since no optical/infrared counterpart has been identified for these X-ray sources.

GX 354−0 (l^{II}=354.°30, $b^{II} = -0.°15$), also designated as MXB 1728−34, was discovered in the seventies with the SAS-3 and the Ariel V satellites (Lewin 1976; Hoffman et al. 1976). The absence of optical counterpart is due to the high optical extinction towards it. A possible association with a heavily reddened globular cluster was proposed by Grindlay & Hertz (1981), but additional infrared observations did not confirm this suggestion (van Paradijs & Isaacman 1989). Observations with the SIGMA telescope on board of the satellite GRANAT detected GX 354−0 up to 100 keV (Claret et al. 1994). The source was also reported to display hard X-ray flares without significant spectral changes as a function of intensity.

The globular cluster Terzan 1 (l^{II}=357.°56, $b^{II} = +0.°99$) was first detected in X-rays as the bursting source XB 1733−30, by Makishima et al. (1981) and Inoue et al. (1981) with the Hakucho satellite. Recent photometric studies by Ortolani et al. (1993) yield a probable distance of 4-5 kpc from the Sun. These authors also point out that the cluster is heavily contaminated by field population in the optical. The lack of an identified optical counterpart in this case is mostly due to the crowded field at the X-ray source position. Persistent hard X-ray emission from the direction of Terzan 1 has been observed with both the SIGMA and ART-P telescopes (Borrel et al. 1996; Pavlinsky et al. 1995). It is currently assumed that this hard emission comes from the same persistent source of softer X-rays X 1732−304 detected by both EXOSAT (Parmar et al. 1989) and ROSAT (Johnston et al. 1995).

In the recent years, we have been carrying out an extensive search for radio counterparts of SIGMA/GRANAT sources in the Galactic Center and Bulge. Our main goal in this project was the search for new microquasar systems in the Galaxy. In this paper we report the discovery of new radio counterparts for GX 354−0 and Terzan 1, the two of them being included in the Goldwurm et al. (1994) list of SIGMA/GRANAT Bulge sources. Although a possible microquasar behavior is not evident from the current radio data, the existence of radio counterparts for GX 354−0 and Terzan 1 represents a significant advance towards the understanding of their nature. In particular, the availability of arcsec accurate radio positions makes feasible the search for optical or infrared counterparts with much higher chances of success than previously.

2. Observations

Radio observations were carried out with the Very Large Array (VLA) interferometer of NRAO[1]. Several different VLA configurations from A to D were used including some hybrid ones. Each source was observed only at 6 cm, with two circular polarizations, and effective bandwidth of 100 MHz. The data have been edited and reduced using the AIPS package of NRAO. The sources 3C286 and 1748−253 were always observed as amplitude and phase calibrator, respectively. The flux densities measured for 1748−253 appear to be fairly stable at the ~ 0.5 Jy level. In addition, we also carried out deep searches for optical and near infrared counterparts using different telescopes from the European Southern Observatory[2] (ESO) in service mode. All ESO frames were reduced using standard procedures based on the IRAF image processing system.

3. Discovery of the GX 354−0 radio counterpart

We observed GX 354−0 in the radio on several epochs in 1995 and 1997. As a result of this effort, a successful detection of a variable radio candidate was finally achieved on 1997 June 25. This discovery is well illustrated in Fig. 1, where a new radio source has clearly

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[1] The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation of the USA.

[2] Based on observations collected at the European Southern Observatory, La Silla, Chile.

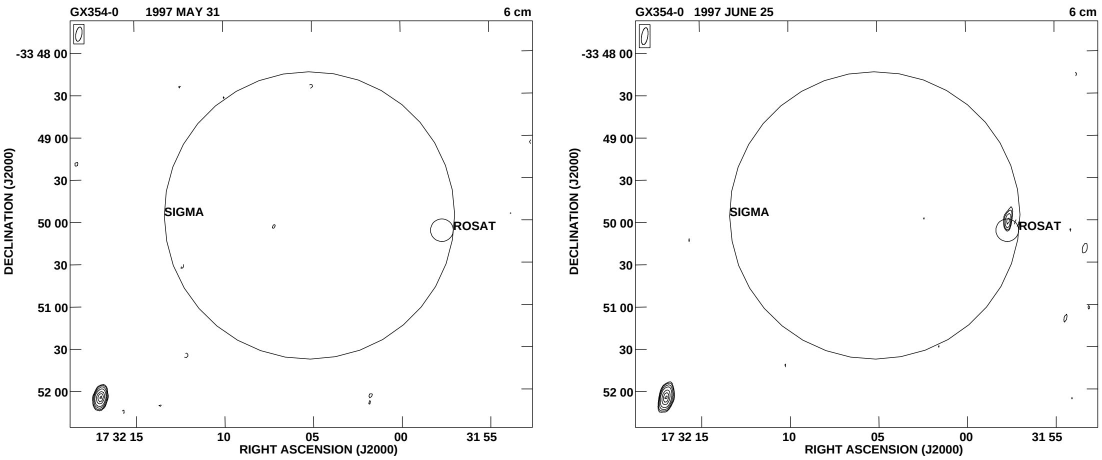

Fig. 1. VLA maps of the GX 354−0 field obtained at 6 cm on 1997 May 31 and June 25. In the second epoch, a clearly variable radio counterpart is detected inside the 90% confidence level radius of the SIGMA and ROSAT positions. This object was not present in the previous epoch above the 4σ upper limit of 0.2 mJy. Contours in both frames are -3, 3, 4, 6, 9, 15, 20 and 24 times 0.05 mJy beam^{-1}, the rms noise. The synthesized beam, shown at the top left corner, is practically identical in both epochs and corresponds to $11'' \times 4''$, with position angle -10°.

Table 1. Flux density history of GX 354−0.

Date	Julian Day -2400000	VLA Configuration	S_{6cm} (mJy)
1995 Jun 19	49887.8	AD	< 0.14
1995 Sep 05	49965.51	AB	< 0.22
1995 Sep 07	49967.67	AB	< 0.32
1997 May 31	50599.76	C	< 0.18
1997 Jun 25	50624.73	C	0.49 ± 0.05
1997 Aug 11	50671.70	C	0.62 ± 0.10
1997 Sep 02	50693.61	C	0.36 ± 0.09
1997 Sep 17	50708.61	C	0.31 ± 0.05
1997 Sep 23	50715.48	C	< 0.32
1997 Dec 14	50797.33	D	< 0.20

emerged in the field, thus suggesting that GX 354−0 was in outburst. This region of the sky is very confused in the radio, mainly because of extended emission from the Galactic Plane. In order to avoid this problem, the maps in Fig. 1 have been computed using natural weight with visibilities corresponding to projected baselines longer than 10 kλ. The flaring radio source was confirmed later in three independent occasions, being always well inside the 90% confidence error circles of both SIGMA (Goldwurm et al. 1994) and the ROSAT All-Sky survey (Voges et al. 1998). The source is also very close to the edge of the 90% confidence circle from the EINSTEIN High Resolution Imager (HRI) (Hertz & Grindlay 1984). The estimated probability that we are dealing with a background unrelated source is rather low in this case (e.g. about 0.5% for the $\pm 8''$ ROSAT position). Given such a positionally good coincidence and specially the clear evidence for variability, we conclude that the identification of the GX 354−0 radio counterpart is highly probable to be correct.

The 6 cm flux density behavior of GX 354−0 is listed in Table 1. The positive detections are, at most, at the half mJy level, implying a monochromatic luminosity of $L_\nu \sim 4 \times 10^{19} [D/8.5 \text{ kpc}]^2$ erg s^{-1} Hz^{-1}, where D is the distance to the source in kpc. The upper limits given in Table 1 are also consistent with previous non-detections ($<$ 0.32 mJy) at the same wavelength by Grindlay & Seaquist (1986). Paredes & Ribó (1998) point out that the radio emission is likely to be systematically correlated with flaring episodes in the 2-10 keV band, as detected by the RXTE All-Sky Monitor.

In order to obtain an accurate radio position, we concatenated the uv data from all epochs with positive detection. The resulting map is presented in the left panel of Fig. 2. Here, GX 354−0 appears unresolved and detected with a signal-to-noise of almost 10. The measured coordinates are $\alpha_{J2000} = 17^h 31^m 57\overset{s}{.}73 \pm 0\overset{s}{.}02$ and $\delta_{J2000} = -33^\circ 50' 02\overset{''}{.}5 \pm 1\overset{''}{.}1$ (1σ errors). Additional improvement of the radio position will be possible by a future detection of the source in the most extended VLA-A configuration.

4. Search for the GX 354−0 optical and infrared counterpart

Previous searches of this type in the past (Liller 1977; Grindlay & Hertz 1981; van Paradijs & Isaacman 1989) did not provide any precise identification with a particular optical or infrared point source. Based on the arcsec accurate radio position given above, a new optical/infrared counterpart search was undertaken in 1997 July 8, i.e, soon after the June 25 radio outburst. Wide field CCD images were acquired with the NTT using the red arm of the ESO Multi Mode Instrument (EMMI). The Johnson R and I-band filters were selected to minimize interstellar absorption. Imaging infrared observations in the J and K-bands were similarly carried out on 1997 July 13, with the IRAC2b camera mounted at the F/35 photometer adapter of the 2.2 m telescope. The results of the ESO observations are presented in the center and right panels of Fig. 2.

An astrometric solution was first established using six nearby stars present in the plates from the Palomar Observatory Sky Survey (POSS). These reference stars were selected because their $\sim 0\overset{''}{.}1$ accurate positions are available from the recent ESA (1997) Tycho Catalogue. We used this primary astrometry to measure the coordinates of stars present both in the POSS and the NTT/IRAC2 images, thus providing a secondary astrometric link in order to locate the radio position in the optical/infrared frames. The overall astrometric error of this process is estimated to be $\sim 0\overset{''}{.}4$.

No optical source is detected at the radio position, with upper limits of $R > 23.0$ and $I > 22.6$. On the contrary, there is a J and K-band infrared source within one arcsec of the VLA source that could well be

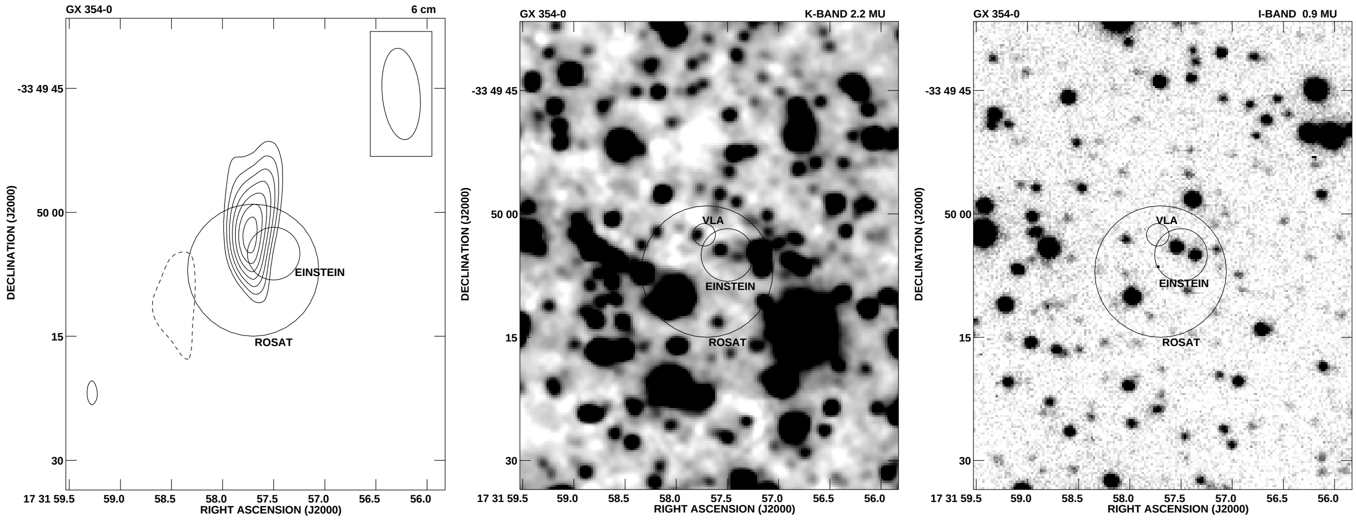

Fig. 2. (Left) Natural weight VLA map of the GX 354−0 field at the 6 cm wavelength. This image was made by concatenating four different epochs when the source was active in the radio, thus improving the signal-to-noise ratio. Contours are −3, 3, 4, 5, 6, 7, 8 and 9 times 0.037 mJy beam^{-1}, the rms noise in the map. The synthesized beam is 11.″1×4.″6, with position angle of 5.°4. The two circles represent the 90% confidence positions obtained from the ROSAT All-Sky Survey and the EINSTEIN High Resolution Imager. The presence of a clear radio counterpart candidate is obvious. **(Center)** K-band image of the same field from the ESO 2.2 m telescope. The additional smallest circle corresponds to the approximate 90% confidence position of the VLA source, taking into account the combined radio and astrometric uncertainties. Only one infrared source is consistent with the radio counterpart. This stellar-like object also lies well inside the ROSAT circle and it is only slightly offset from EINSTEIN's circle. **(Right)** The same field as seen in I-band with the ESO NTT. No counterpart is detected at optical wavelengths.

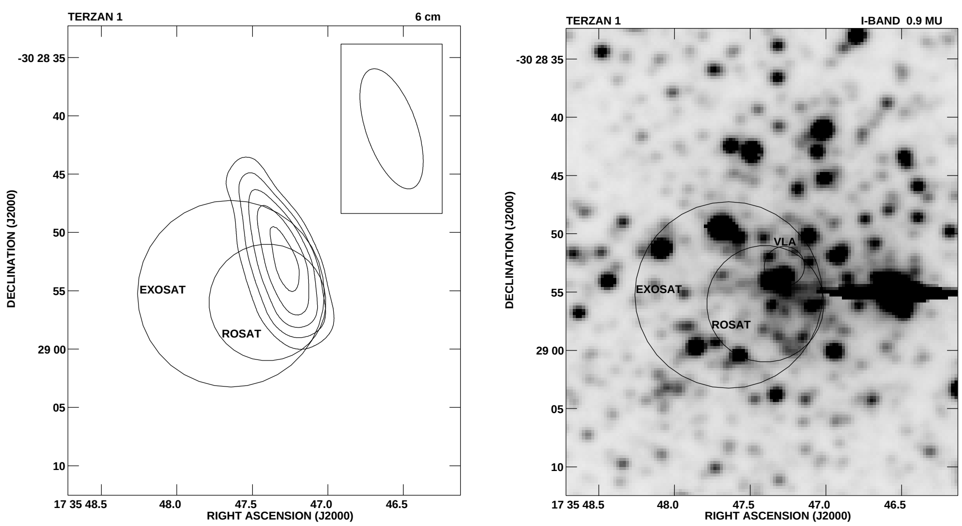

Fig. 3. (Left) Natural weight map at 6 cm of the Terzan 1 field. This map was made from concatenated uv data of different epochs. The radio counterpart of the Terzan 1 X-ray source is clearly detected inside both the EXOSAT and ROSAT 90% confidence circles. Contours are −3, 3, 4, 5, 6 and 7 times 0.021 mJy beam^{-1}, the rms noise. The synthesized beam is 10.″8×4.″3, with position angle of 19.°1. **(Right)** The same region as seen in the optical. This image was acquired with the ESO NTT in the I-band filter. The ROSAT, EXOSAT and VLA 90% confidence error circles are also plotted. At least four different stellar objects are present within the VLA circle.

the infrared counterpart of GX 354−0. The association of this infrared source with GX 354−0 is not firmly established by now. Although it seems quite likely, additional confirmation is still required. For instance, the detection of K-band variability correlated with either the variable X-ray/radio emission, or a much more improved astrometrical coincidence, will certainly warrant that X-ray, radio and infrared emissions arise in the same object.

In the following, we will consider that the infrared source is indeed associated to GX 354−0 in order to explore what consequences this would imply. An 8.5 kpc distance is adopted as this sounds reasonable for a Galactic Bulge source. We also need an estimate of the absorption towards GX 354−0. This can be obtained from: a) the total hydrogen column density of $N_H = 2.5 \times 10^{22}$ cm^{-2}, as recently derived by Strohmayer et al. (1997); b) the N_H vs A_V relationship by Predehl & Schmitt (1995); and c) the Rieke & Lebofsky (1985) interstellar extinction law. Under such assumptions, the optical upper limits and the observed infrared detections $J = 19.6 \pm 0.4$ and $K = 15.1 \pm 0.2$ translate into the following absolute magnitudes: $M_R > -2.3$, $M_I > +1.1$, $M_J = +0.9 \pm 0.7$ and $M_K = -1.1 \pm 0.3$.

These values immediately rule out as a companion any young massive OB star, supergiant or bright giant star (luminosity classes I and II). However, they do are consistent with a F-K giant (class III) or a middle B/early A star of the main sequence (class V). For X-ray binaries, the optical/infrared luminosity may have an important contribution from the accretion disk in addition to that of the companion star. This is specially true for LMXRBs, where the accretion disk often dominates the optical output of the system. Therefore, the stellar types proposed above should be regarded as “upper limits”. This is to say, the true GX

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Table 2. Flux density history of Terzan 1.

Date	Julian Day −2400000	VLA Configuration	S_{6cm} (mJy)
1995 Sep 05	49965.53	AB	< 0.28
1995 Sep 07	49967.66	AB	< 0.40
1997 May 31	50599.85	C	0.19 ± 0.06
1997 Jun 25	50624.84	C	0.20 ± 0.03
1997 Aug 14	50674.67	C	< 0.29
1997 Sep 17	50708.59	C	0.21 ± 0.04
1997 Sep 23	50715.49	C	< 0.24

354−0 companion is constrained to be less luminous and less massive than a middle B/early A V star or a F-K III star. Given that LMXRBs with giant companions are very rare in the Galaxy (e.g. Cyg X-2), we conclude that the most likely interpretation of our photometric data is a main sequence companion with spectral type later than middle B/early A.

5. The radio counterpart of Terzan 1

We observed the Terzan 1 field at 6 cm with the VLA on several epochs in 1995 and 1997. In the three occasions when good sensitivity maps could be obtained, a weak unresolved radio source was detected inside the 90% confidence circle of EXOSAT (Parmar et al. 1989). This object is also consistent with the more accurate ROSAT position by Johnston et al. (1995). All these coincidences are illustrated on the left panel of Fig. 3. The radio image in this Figure is made from the concatenation of the three detection epochs. The VLA source is present here at the 0.2 mJy level, corresponding to a 6 cm monochromatic luminosity of $L_{\nu} \sim 4 \times 10^{18} [D/4 \text{ kpc}]^2$ erg s^{-1} Hz^{-1}. The details of the light curve are presented in Table 2. The object seems to be a weak but steady radio emitter, with no clear evidence for variability. In spite of this, the probability of having an unrelated 0.2 mJy radio source inside the $\sim 5''$ accurate ROSAT position is relatively low, e.g., about 0.4%

From all these considerations, we believe we have certainly detected the radio counterpart of the X-ray source in Terzan 1. This increases to four the examples of radio emitting X-ray binaries in globular clusters, with the other three being NGC 6624 (Grindlay & Seaquist 1986), NGC 6712 and NGC 7078 (Lehto et al. 1990; Machin et al. 1990). From our combined radio map, the measured coordinates of the Terzan 1 radio counterpart are: $\alpha_{J2000} = 17^h 35^m 47\overset{s}{.}27 \pm 0\overset{s}{.}04$ and $\delta_{J2000} = -30^{\circ} 28' 52\overset{''}{.}8 \pm 1\overset{''}{.}4$ (1σ errors).

Unfortunately, this improved position, with respect to those obtained in the X-rays, is not yet good enough to discriminate among optical candidates. This can be seen in the right panel of Fig. 3, showing the crowded field of the Terzan 1 globular cluster in a NTT image. This frame was obtained also on 1997 July 8 using EMMI and the Johnson I-band filter. In order to locate the VLA coordinates on it, we followed a two-step astrometric procedure similar as in GX 354−0. The 90% confidence position provided by the VLA can be approximated here by a circle with $1\overset{''}{.}7$ radius. This includes the combined effect of both the astrometric and radio uncertainties. When plotted on the CCD frame, the circle contains a minimum of four individual stellar objects. Their I-band magnitudes are in the range 15 to 19. While the faintest of them may be consistent with LMXRBs, the two brightest objects may well belong to the field population. Further observations are currently being planned with the hope of obtaining an unambiguous identification, as well as more information on the radio emission mechanism of Terzan 1 and GX 354−0.

Acknowledgements. J.M. acknowledges financial support from a postdoctoral fellowship of the Spanish Ministerio de Educación y Ciencia at the beginning of this work. LFR acknowledges support from DGAPA, UNAM and CONACyT, Mexico.

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