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Radio Emission from Globular Clusters

Xiao-Hui Sun[1,2,3] ⋆, Jin-Lin Han [1,2,3] and Guo-Jun Qiao[1,3]

[1] Department of Astronomy, Peking University, Beijing 100871
[2] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012
[3] Beijing Astrophysical Center, CAS-PKU, Beijing 100871

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Abstract Radio emission of globular clusters is studied by analyzing the VLA radio survey data of the NVSS and FIRST. We find that 13 clusters have radio sources within their half-mass radii of clusters. Sources detected previously in NGC 7078 and NGC 6440 are identified. Pulsars in NGC 6121, NGC 6440 and NGC 7078 cannot be detected because of the insufficient survey sensitivity and resolution. There may be a pulsar in the core of Terzan 1. The nature of the extended radio source near the core of NGC 6440 remains unclear. In the core of a globular cluster, there may be many neutron stars or an intermediate mass black hole, but this cannot be clarified with the current radio observations.

Key words: globular clusters: general — pulsars: general — radio continuum: general

1 INTRODUCTION

Many radio observations have been conducted on globular clusters in the past years, stimulated by the detection of pulsars and X-ray sources in them. Globular clusters are good places for hunting pulsars (Lyne et al. 2000). Until now, about 50 pulsars have been detected in 17 globular clusters (Lyne et al. 1995; Biggs & Lyne 1996; D'Amico et al. 2001; Lyne et al. 2000; Camilo et al. 2000). Except for four long period pulsars, all of these pulsars are millisecond pulsars (MSPs), and some of them are in binary systems. Strikingly, 22 pulsars have been found in 47 Tuc (Camilo et al. 2000), and eight in M15 (Wolszczan et al. 1989; Anderson et al. 1990). It is believed that the pulsars currently detected are only "tip of an iceberg", and there are many more potential pulsars to be detected (Lyne 1995).

Quite a few of X-ray sources in clusters have been found (Grindlay 1995; Mereghetti et al. 1996; Borrel et al. 1996; Martí et al. 1998). The bright ones ($L_{\rm X} \geq 10^{35.5}\,{\rm erg\,s^{-1}}$) are believed to be low mass X-ray binaries (LMXBs), and the nature of dim ones ($L_{\rm X} \leq 10^{35.5}\,{\rm erg\,s^{-1}}$) is still unclear (Johnston et al. 1996). To shed light on the nature of these X-ray sources, their radio counterparts were searched (Gopal-Krishna & Steppe 1980; Grindlay & Seaquist 1986;

⋆ E-mail: xhsun@ns.bao.ac.cn

Mereghetti et al. 1995). With the aid of the radio observations, the precise positions of some of these X-ray sources can be determined. The sources with radio counterparts are probably LMXBs. Other radio sources detected in clusters are mainly pulsars and planetary nebulae (Melean et al. 1983; Biggs et al. 1994; Johnston & Kulkarni 1993). The characteristic spectral indices (assuming flux density $f(\nu) \propto \nu^{-\alpha}$) are about 2.0 for pulsars in globular clusters, and 0.7 for background extragalactic sources (Erickson et al. 1987; Kulkarni et al. 1990a). The spectra of planetary nebulae are thermal and their spectral indices are negative. SNRs are important nonthermal sources. However, in globular clusters pulsars are from LMXBs and they are very old, so SNRs have been diffused already.

Another intriguing question is whether a black hole exists in the core of a globular cluster. Analogous to the elliptical galaxies, the velocity dispersions of globular clusters suggest that the black hole, if exists, should have a mass of about $10^3 M_\odot$ (Zheng 2001). Gebhardt et al. (2000) presented some velocity dispersion measurements of M15. If black holes exist in the cores of clusters, their radio emission may be detectable.

In this paper, we investigate the detailed radio emission of some globular clusters using the radio data of the NVSS[1] and FIRST[2]. We identify some new radio sources and compare them with previous observations. In Section 2, we examine the radio sources in clusters. In Section 3, we discuss briefly the existence of pulsars and black holes in globular clusters.

2 DATA EXTRACTION AND RESULTS

We obtained the catalog containing 147 globular clusters (Harris 1996) from the web site[3]. The radio sources were searched within the tidal radius of each cluster from the NVSS and FIRST catalogs. There are about 100 clusters north of DEC = $-40°$ in the sky region of the NVSS, and only 14 clusters north of DEC = $-10°$ in the sky region of the FIRST. In fact, many sources are extragalactic background sources. We estimated the probability of chance superposition, and found that only eight clusters have sources probably physically associated with them. For these clusters, we got their R-band images from the second generation of DSS[4], and listed their parameters in Table 1. The first three columns are the name and position, column 4 the distance from the sun in kpc, column 5 the absolute V-magnitude. The next three columns list the core radius, the half-mass radius, and the tidal radius, all in arcmin. The last column lists the radio flux density at 1.5 GHz in mJy, which was estimated according to the sources detected within the half-mass radius.

We overlay the contours of the radio images over the R-band images using the software package Karma (Gooch 1995), see Fig. 1 to Fig. 8. The known pulsars in NGC 6121, NGC 6440 and NGC 7078 are marked with "+". Table 2 lists the data on sources that are probably physically associated with the clusters. We now discuss these sources one by one.

2.1 NGC 2298

The point source A is within the core radius (Fig. 1). The probability of chance coincidence is about 0.5%, so it may be considered as associated with the cluster.

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[1] NRAO VLA Sky Survey, conducted at 20 cm, has a resolution of 45″, sensitivity of 2.5 mJy (rms of Stokes I is 0.45 mJy/beam). The data are available at: **http://www.cv.nrao.edu/NVSS/postage.html**

[2] Faint Image of Radio Sky at Twenty centimetres, conducted at 20 cm with VLA, has a resolution of 5″, sensitivity of 0.5 mJy (rms of Stokes I is 0.15 mJy/beam). The data are available at: **http://sundog.stsci.edu**

[3] **http://physun.physics.mcmaster.ca/Globular.html**

[4] Digital Sky Survey conducted with Palomar and UK telescopes by STScI. The data are available at: **http://archive.stsci.edu/cgi-bin/dss_form**

2.2 NGC 5634

Similar to NGC 2298, source A is within the half-mass radius of the cluster (Fig. 2), with a chance coincidence probability about 1.1%.

Table 1 Data of Eight Clusters

Name	RA (2000) (h m s)	DEC(2000) (° ′ ″)	Dist (kpc)	M_V (mag)	r_c (′)	r_h (′)	r_t (′)	$S_{1.5\,GHz}$ (mJy)
NGC 2298	06 48 59.200	−36 00 19	10.7	−6.30	0.34	0.78	6.48	10.55
NGC 5634	14 29 37.300	−05 58 35	25.9	−7.75	0.21	0.54	8.36	4.03
NGC 6121	16 23 35.500	−26 31 31	2.2	−7.20	0.83	3.65	32.49	≤2.5
NGC 6341	17 17 07.300	+43 08 11	8.2	−8.20	0.23	1.09	15.17	2.82
Terzan 1	17 35 47.800	−30 28 11	6.2	−3.30	0.04	3.82	11.07	≤2.5
NGC 6440	17 48 52.600	−20 21 34	8.4	−8.75	0.13	0.58	6.31	3.07
NGC 6681	18 43 12.700	−32 17 31	9.0	−7.11	0.03	0.93	7.91	7.91
NGC 7078	21 29 58.300	+12 10 01	10.3	−9.17	0.07	1.06	21.50	5.29

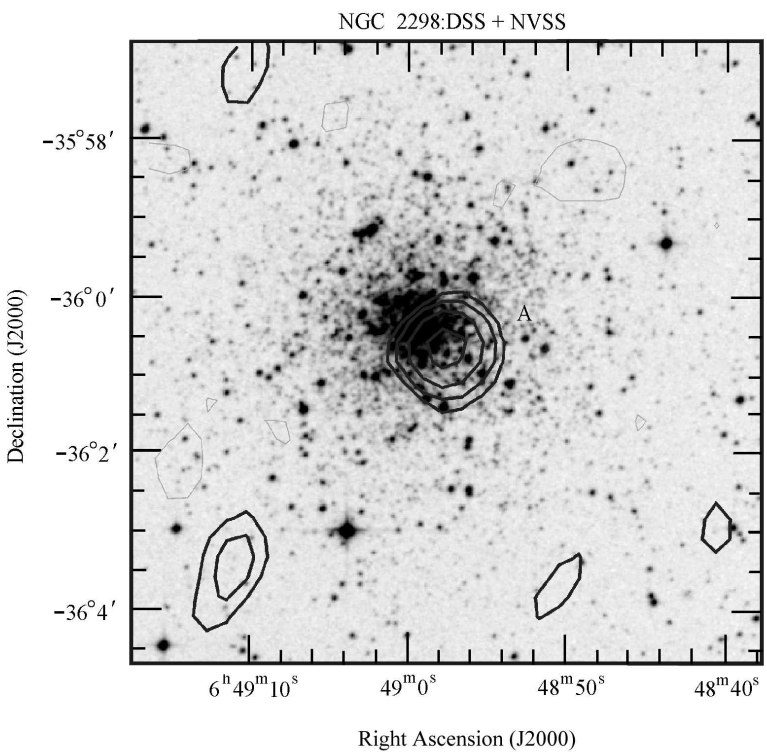

Fig. 1 20 cm radio contours from the NVSS are shown superposed on an *R*-band image (grey) of cluster NGC 2298. The contour levels are $\pm 1 \times 2^n$ mJy beam^{-1}. The radio source is marked with A.

2.3 NGC 6121

Source A is probably an extragalactic source because the probability of chance superposition is about 46.2% (Fig. 3). Lyne et al. (1988) found a pulsar PSR B1620–26 at α_{J2000} =

$16^{\rm h}23^{\rm m}38.203^{\rm s}$, $\delta_{\rm J2000} = -26°31'53.292''$. The period of the pulsar is 11 ms, and its flux density at 408 MHz is about 15 mJy. If the spectral index of this pulsar is about 1.5, then the flux density at 20 cm will be about 2.1 mJy, which is about the survey sensitivity of NVSS. We can marginally see the pulsar in the right direction.

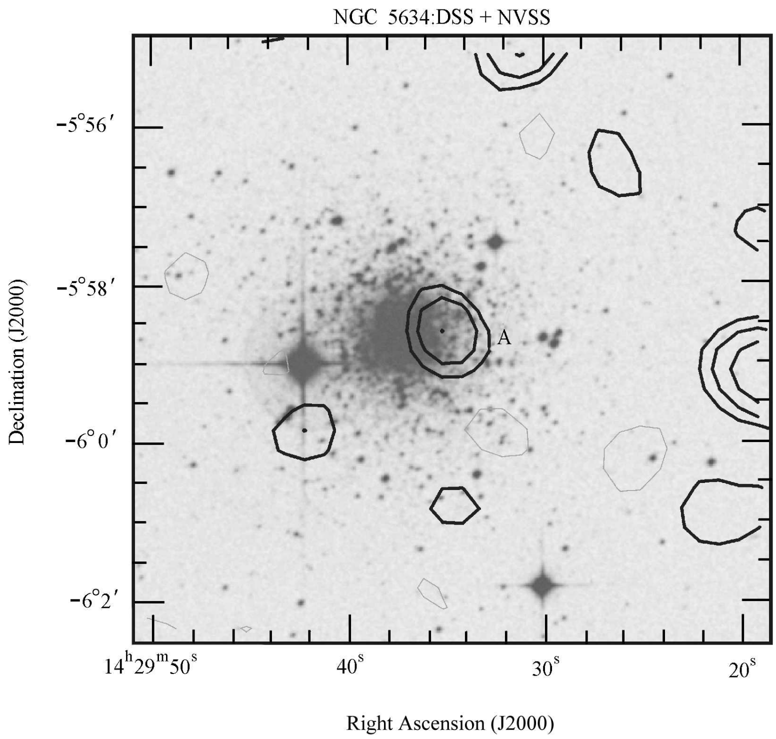

Fig. 2 Same as Fig. 1 but for the cluster NGC 5634.

2.4 NGC 6341

We acquired both the NVSS image and the FIRST image of this cluster (Fig. 4 (a) and Fig. 4 (b)). The probability of source A being a background source is about 2.2%. However, as can be seen from Fig. 4 (b), it is an extended source, so it is either a planetary nebula in the cluster or a background radio galaxy. The probability of chance coincidence for source B or source B′ is about 43%, indicating that it is probably a background source. The other point sources seen from the FIRST survey (Fig. 4 (b)) are also probably background sources.

2.5 Terzan 1

There are no point sources that can be identified in our image (Fig. 5). Johnston et al. (1995) reported the X-ray source XB1733-30 at $\alpha_{\rm J2000} = 17^{\rm h}35^{\rm m}47.4^{\rm s}$, $\delta_{J2000} = -30°28'58''$, and its luminosity: $L_{\rm X} = 1.3 \times 10^{36}$ erg s^{-1}. They also detected a long-term luminosity variability of the source. Martí et al. (1998) found the radio counterpart of this X-ray source at $\alpha_{\rm J2000} = 17^{\rm h}35^{\rm m}47.27^{\rm s} \pm 0.04^{\rm s}$, $\delta_{\rm J2000} = -30°28'52.8'' \pm 1.4''$ with flux density of 0.2 mJy at wave band 6 cm. Borrel et al. (1996) found a persistent X-ray source at the position:

$\alpha_{\rm J2000} = 17^{\rm h}35^{\rm m}47^{\rm s}$, $\delta_{\rm J2000} = -30°29'40''$. Considering the positional uncertainties, they are probably the same source (see Fig. 5). It could be an LMXB containing an MSP. However, in our image we cannot identify any sources at the above positions due to poor sensitivity. If its flux density at 1.5 GHz is weaker than 2.5 mJy, we can derive that the approximate value of its spectral index is about 2. It could really be an undetected pulsar.

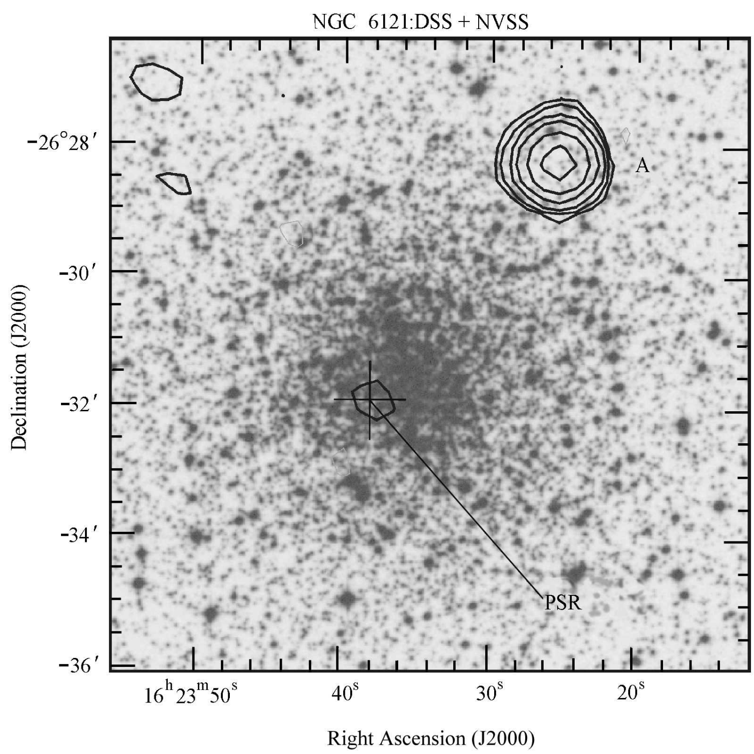

Fig. 3 Same as Fig. 1, but for the cluster NGC 6121. The known pulsar PSR B1620-26 is marked with "+".

2.6 NGC 6440

Source A is near the core and source B and source C are the two peaks of a same extended source (Fig. 6). The probability of chance superposition for source A is about 0.06%, so it is probably the source of the cluster. It is very likely that source A emerges from many weak radio sources like MSPs. In fact, a 280ms pulsar PSR B1745-20 was reported at the position: $\alpha_{\rm J2000} = 17^{\rm h}48^{\rm m}52.66^{\rm s} \pm 0.02^{\rm s}$, $\delta_{\rm J2000} = -20°21'39.3'' \pm 0.1''$ (Fruchter & Goss 2000; Manchester et al. 1989). Fruchter and Goss (1990) estimated that there are at least 60 pulsars in this cluster. Johnston et al. (1995) also found a transient X-ray source MX 1746-20 at $\alpha_{\rm J2000} = 17^{\rm h}48^{\rm m}53.4^{\rm s}$, $\delta_{\rm J2000} = -20°21'43''$. The structure of A is very complicated and further high resolution observations are expected. Johnston (1976) reported a radio source at $\alpha_{\rm J2000} = 17^{\rm h}48^{\rm m}53.14^{\rm s}$, $\delta_{\rm J2000} = -20°22'3.10''$, with flux density about 7.0 mJy at 2.7 GHz, but it cannot be identified in our image at 1.5 GHz.

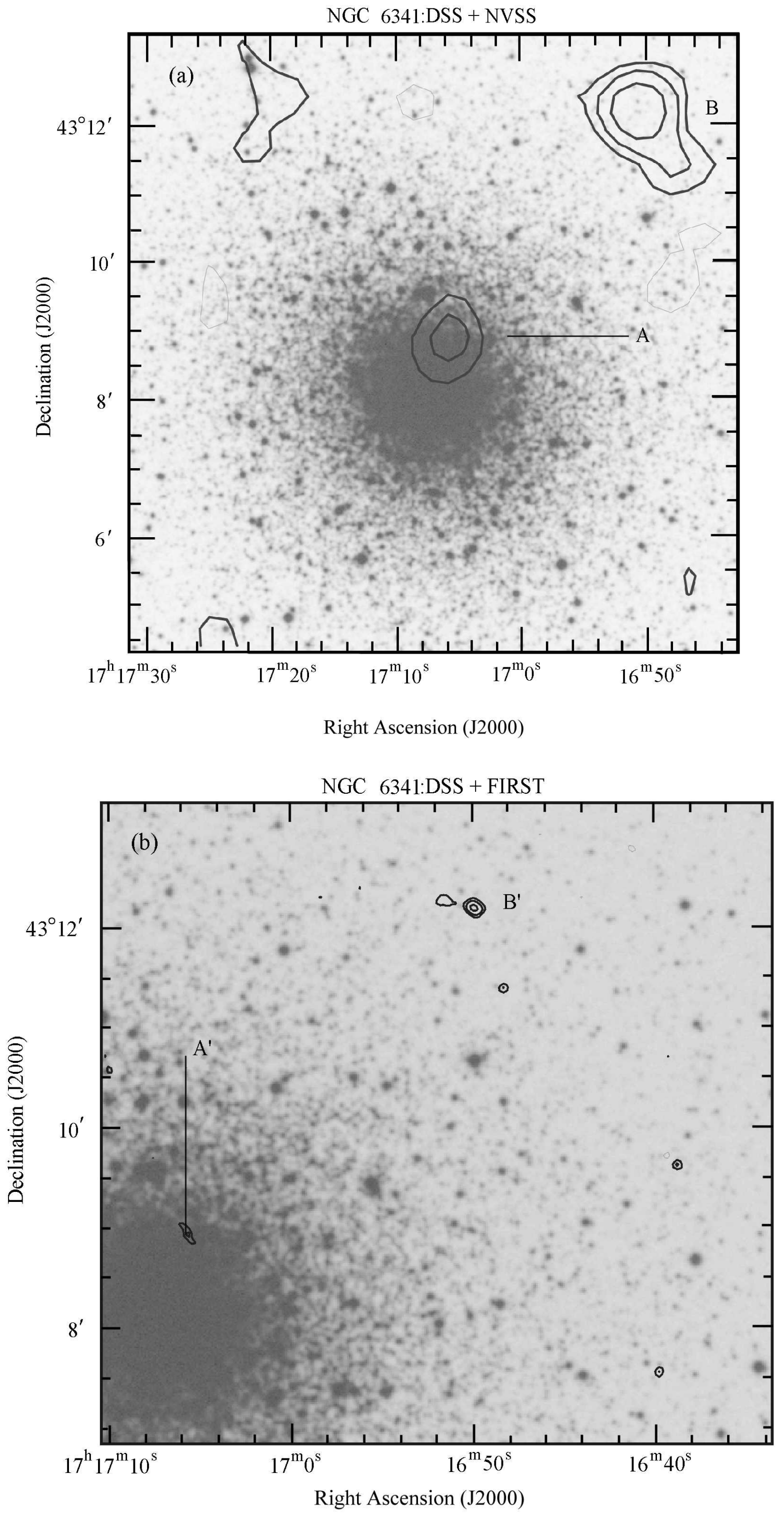

Fig. 4 (a) Same as Fig. 1 but for the cluster NGC 6341. (b) The FIRST 20 cm radio contours are shown superposed on an R-band image (grey) of cluster NGC 6341. Contour levels at $\pm 0.5\times 2^n$ mJy beam^{-1}. The radio sources are marked with "A" and "B".

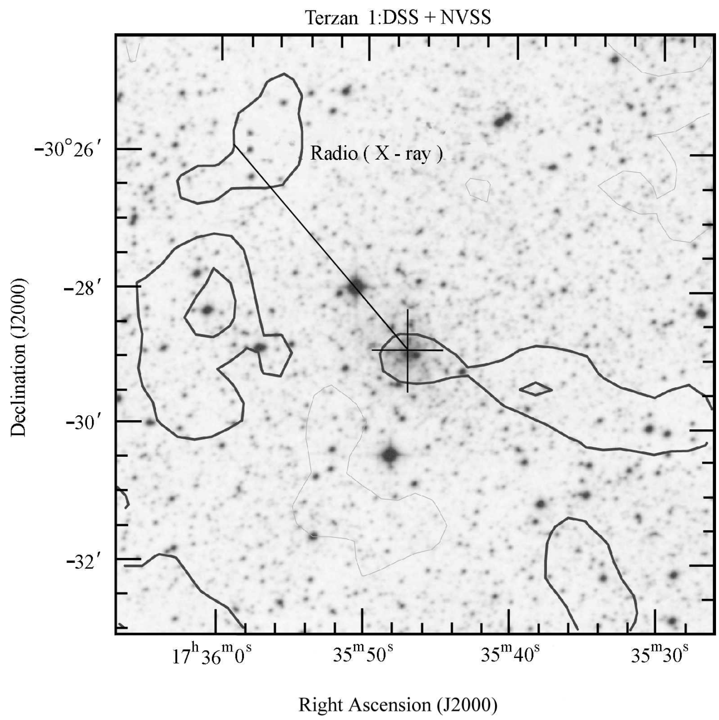

Fig. 5 Same as Fig. 1 but for the cluster Terzan 1. The X-ray source with radio counterpart is marked with "+".

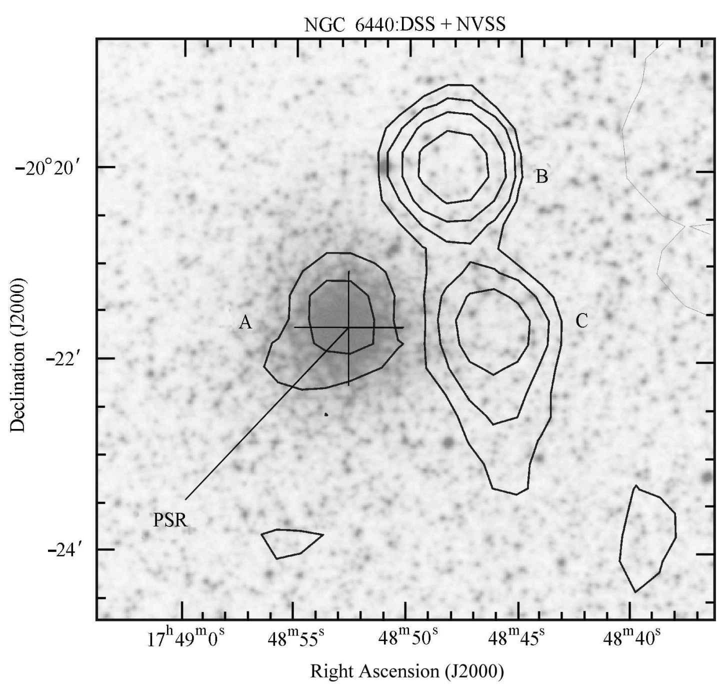

Fig. 6 Same as Fig. 1 but for the cluster NGC 6440. The known pulsar is marked with "+".

The probability of chance coincidence for source B is about 13.3%. The radio source with a flux density of 6.0 mJy at 2.7 GHz reported by Johnston (1976) at $\alpha_{\rm J2000} = 17^{\rm h}48^{\rm m}47.99^{\rm s}$, $\delta_{\rm J2000} = -20°20^{'}01.47''$ coincides well with source B. We found that its spectral index is about 1.4, but its location indicates that it may not be a pulsar. Source C has a probability of chance coincidence about 8.4%, with similar characters to source B.

2.7 NGC 6681

Source A is very close to the core and is elongated to the north (Fig. 7). The probability of chance superposition for source A is about 1.2%. It may be the source of the cluster. Source B is probably a background source with its high probability of chance coincidence of 33%.

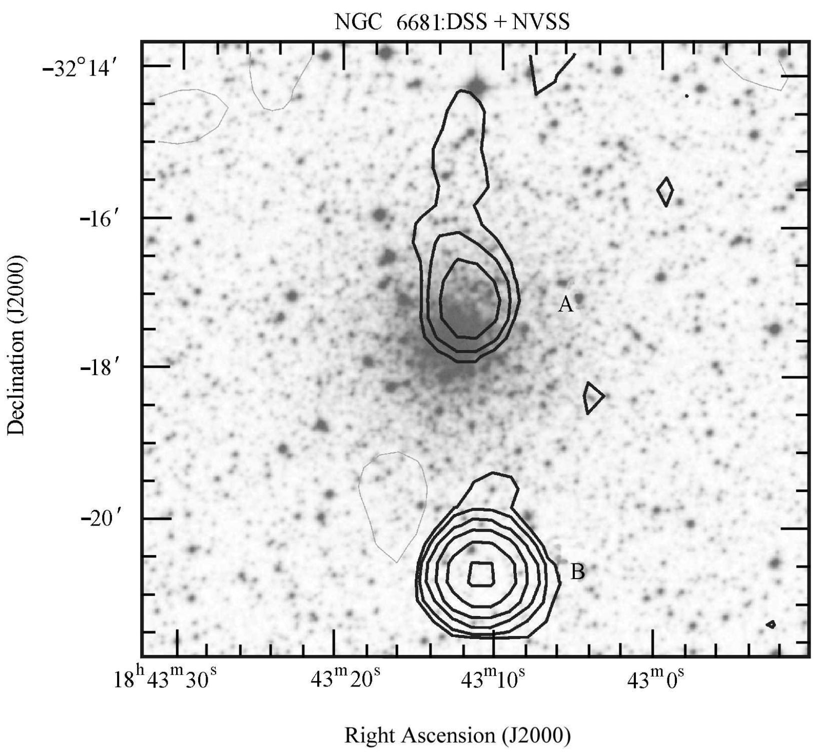

Fig. 7 Same as Fig. 1 but for the cluster NGC 6681.

2.8 NGC 7078

The probability of chance superposition is about 0.02% for source A (Fig. 8). Within 15 arcseconds of source A, there are some known objects reported previously. Johnston (1976) found two sources, one at $\alpha_{\rm J2000} = 21^{\rm h}29^{\rm m}59.623^{\rm s}$, $\delta_{\rm J2000} = 12°10^{'}24.85^{''}$ with flux density 4.4 mJy at 2.7 GHz, the other at $\alpha_{\rm J2000} = 21^{\rm h}29^{\rm m}59.422^{\rm s}$, $\delta_{\rm J2000} = 12°10^{'}25.84^{''}$ with flux density 3.3 mJy at 8.1 GHz, and both of them are coincident with the planetary nebula K648 at $\alpha_{\rm J2000} = 21^{\rm h}29^{\rm m}59.383^{\rm s}$, $\delta_{\rm J2000} = 12°10^{'}26.44^{''}$. The radio counterpart of the bright X-ray source 4U2127+11 was detected at $\alpha_{\rm J2000} = 21^{\rm h}29^{\rm m}58.307^{\rm s}$, $\delta_{\rm J2000} = 12°10^{'}2.69^{''}$ (Machin

1990). In this cluster, eight pulsars have been found (Taylor et al. 1993), and all of them are MSPs. All the foregoing sources are unresolved near source A.

The probability of chance coincidence for source B is about 11.2%. Source B coincides well with the radio source M15B at $\alpha_{J2000} = 21^h29^m51.898^s$, $\delta_{J2000} = 12°10'17.21''$, and has with a flux density of 5.978 mJy at 5 GHz (Machin 1990). The spectral index is about -0.3, the thermal character of this source indicates that it is a planetary nebula. Source C is coincident with the extragalactic source M15A at $\alpha_{J2000} = 21^h30^m00.096^s$, $\delta_{J2000} = 12°06'09.87''$ (Machin 1990), with a spectral index of about 1.1.

Table 2 Parameters of Cluster Radio Sources

Cluster		RA(2000) (h m s)	DEC(2000) (∘ ′ ″)	$S_{1.5\,\mathrm{GHz}}$ (mJy)	Chance Probability(%)
NGC 2298	A	06 48 57.964	−36 00 34.00	10.55	0.5
NGC 5634	A	14 29 35.289	−05 58 35.00	4.03	1.1
NGC 6440	A	17 48 52.600	−20 21 34.00	3.07	0.06
NGC 6341	A	17 17 05.929	+43 08 56.00	2.82	2.2
	A′	17 17 05.819	+43 08 55.60	0.89	2.2
NGC 6681	A	18 43 11.517	−32 17 01.00	7.91	1.2
NGC 7078	A	21 29 59.323	+12 10 16.00	5.29	0.02

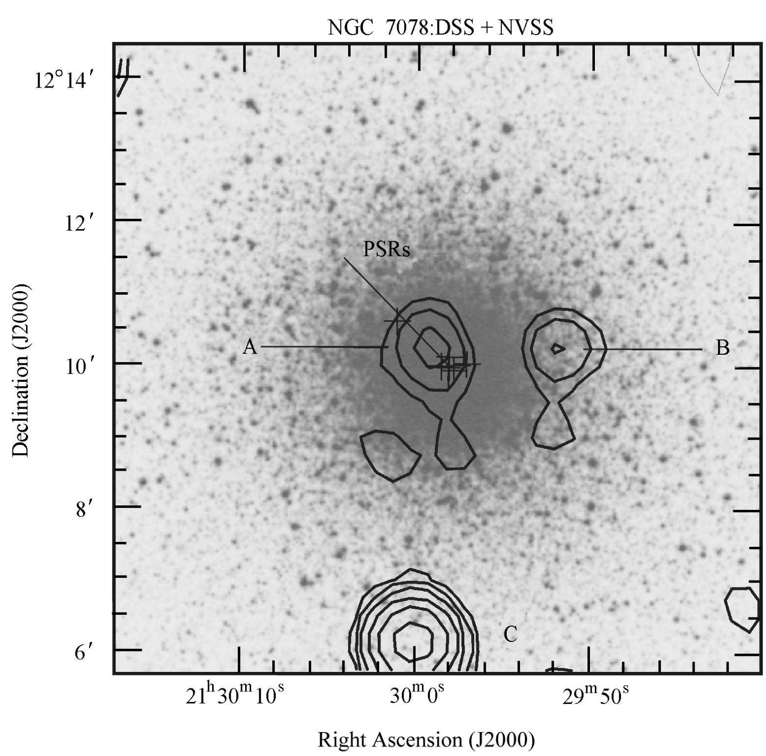

Fig. 8 Same as Fig. 1 but for the cluster NGC 7078. The pulsars are marked with “+”.

3 DISCUSSION

3.1 Pulsars in Globular Clusters

The standard model of the formation of MSP is that an old neutron star is captured by a main sequence star ($M \geq 2\ M_\odot$) or a giant star to form an LMXB. When matter from the companion overflows the Roche lobe, the neutron star accretes the matter, spins up, and emits X-ray (van den Heuvel 1986; Chen et al. 1993). An MSP can also form through three-body exchange interaction (Fabian et al. 1975; Hut & Verbunt 1983), or from white dwarf through accretion induced collapse (Bhattacharya & van den Heuvel 1991). Because the stellar densities in the cores of clusters are very high, globular clusters are favorable environments for the formation of LMXBs and for three-body interactions. So the cores of globular clusters could host substantial numbers of pulsars. Although the radio flux density of an MSP is very weak ($\sim$ mJy), the total flux of many MSPs could be strong enough to be detected. This means that the strong radio sources in the cores of clusters may be the reflection of many potential MSPs.

The number of pulsars in globular clusters has been estimated by dynamical simulations (Johnston et al. 1991; Bailyn & Grindlay 1990), or through the number of LMXBs (Wijers & Paradijs 1991; Verbunt et al. 1989). An approximate total number of pulsars in clusters is about 10^4 (Kulkarni et al. 1990a, 1990b). We estimate the number using the formula given by Fruchter and Goss (1990): $N_{\rm pulsar} = \frac{L_{\rm tot}}{L_{\rm min}\ln(L_{\rm tot}/L_{\rm min})}$, where $L_{\rm tot}$, $L_{\rm min}$ stand for the total radio luminosity of a cluster and the minimal luminosity of an MSP ($\sim$0.2 mJy kpc^2), respectively. Using the values of flux densities and distances in Table 1, we find that Terzan 1 could have about 63 MSPs, NGC 6440 about 150, and NGC 7078 approximately 300. The pulsar number estimated by Fruchter and Goss (1990) in NGC 6440 is less than our estimate, because Fruchter and Goss (1990) underestimated the total radio luminosity based on the pulsars detected in the cluster. In fact, the pulsar numbers we estimated include only the MSPs within the half-mass radius or core radius, and there are also pulsars outside the core regions (Grindlay 1995, figure 2). So we think that the true pulsar numbers should even be larger than our estimates.

In our images, only NGC 6440, NGC 6121 and NGC 7078 have about ten known pulsars each. The total number of pulsars currently detected in globular clusters is only about 50. The difficulties for pulsar detection are the Doppler smearing in binary systems and the insufficient observational sensitivity.

3.2 Black Holes in Globular Clusters

It is widely accepted that there are supermassive black holes in the centers of nearby galaxies (Kormendy & Richstone 1995). Globular clusters are very similar to nearby elliptical galaxies, they are both self-gravitation bounded systems. The difference is mainly a matter of mass and scale. So the natural conclusion is that there is an intermediate mass black hole in the core of a cluster (Zheng 2001). The measurements of the velocity dispersion in M 15 (Gebhardt 2000) seem to be consistent with the suggestion that the core harbors a $2.5 \times 10^3\ M_\odot$ black hole. Using the relation between the black hole mass and velocity dispersion for nearby galaxies, Zheng (2001) estimated the masses of black holes in clusters are all about $10^2\,M_\odot \sim 10^3\,M_\odot$. Miller and Hamilton (2002) proposed a scenario, in which initial 50 $M_\odot$ black holes in clusters could evolve slowly to $10^3\ M_\odot$ black holes through accretion.

If an intermediate mass black hole does exist in the core, can we detect it in X-ray or radio bands? A direct proof would be strong X-ray radiation. The X-ray luminosity $L_{\rm X}$ should be

$L_X \geq 10^{40}$ erg s^{-1}, and the time scale of variability should be very small, which is very different from the X-ray emission from the LMXBs. However, Miller and Hamilton (2002) pointed out that the black hole of clusters in the core accretes matter in a special form, swallowing a whole star like neutron star or white dwarf, so the black hole may not emit X-ray at all.

A black hole in the core might affect the observational characters of a pulsar through its strong gravitational field. De Paolis et al. (1996) ruled out the existence of a black hole in globular clusters through an analysis on two pulsars 0.05 pc from the center of M 15.

Radio emission may provide a clue as to whether such a black hole exists or not. Franceschini et al. (1998) found a tight relationship between the radio luminosity L_R (at 5 GHz) and black hole mass M_{BH}: $L_R \propto M_{BH}^{\alpha}$, where $\alpha \approx 2 \sim 3$, based on the data of 13 nearby galaxies (Fig. 9). If the black holes in globular clusters emit radio emission with the same mechanism (though this is not yet known), the radio luminosity of a black hole of $M_B \sim 10^3 M_\odot$ in clusters should be approximately between 10^{25} erg s^{-1} and 10^{28} erg s^{-1} at 5 GHz, or larger at 1.5 GHz by a factor of 2.5 for a power-law spectrum index of 0.75.

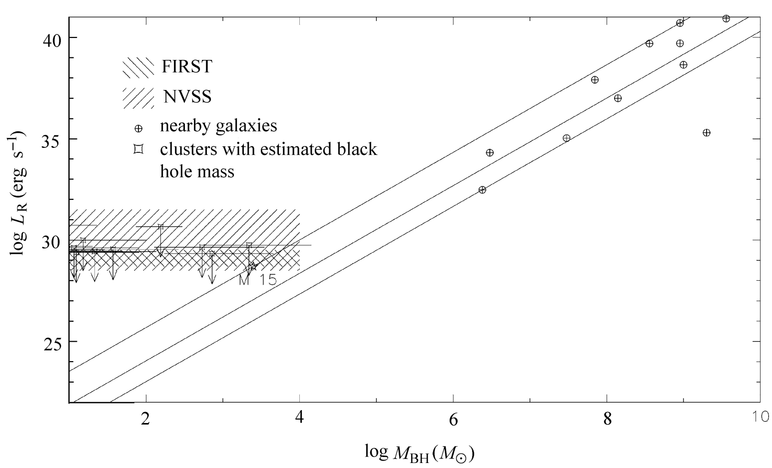

Fig. 9 Relation between the black hole mass and radio luminosity.

For those clusters with detected sources, we consider the flux densities of the sources as the total flux densities, and for the other clusters we need to take the NVSS sensitivity of 2.5 mJy as the upper limits of their flux densities. Using the flux data of the NVSS and the distances from the catalog, we estimate the total L_R (or the upper limits) of the clusters. The values are in the range between about $10^{28.5}$ erg s^{-1} and $10^{31.5}$ erg s^{-1}. Using the FIRST survey upper limits (0.5 mJy) for the cluster centers, the L_R of the clusters should be at a level of $10^{28.7}$ erg s^{-1} and $10^{29.5}$ erg s^{-1}. They are both greater than the expected luminosities of black holes (Fig. 9). This shows that we cannot detect the radio emission for the black holes by current radio observations if they really exist and hence regrettably the radio observations current available cannot help to determine whether the black holes exist or not. Machine et al. (1990) made a very deep observation on M 15 with sensitivity about 0.09 mJy, even with this, the obtained L_R was about $10^{28.7}$ erg s^{-1}, and the radio emission from the black hole should be marginally detected (Fig. 9), but they did not detect any of the radio emission from the core.

If many MSPs are hosted by the core of the globular cluster, we can make a crude estimate of the radio luminosity of the cluster. Supposing that the characteristic radio power of an MSP at 1.5 GHz is about several mJy kpc^2, and the number of MSPs is about 100, the total radio power at 1.5 GHz of the cluster should be about 100 mJy kpc^2, or 10^{19} erg s^{-1} Hz^{-1}, and the total radio luminosity from MSPs about 10^{28} erg s^{-1}. This also cannot be detected by current radio observations. If we can detect in future, the radio emission from so many pulsars would appear as an extended source, while a black hole would be a jet-like source, then we will be able to distinguish them by radio morphology.

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