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TIMING OF MILLISECOND PULSARS IN NGC 6752: EVIDENCE FOR A HIGH MASS-TO-LIGHT RATIO IN THE CLUSTER CORE

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ABSTRACT

Using pulse timing observations, we have obtained precise parameters, including positions with ∼20 mas accuracy, of five millisecond pulsars in NGC 6752. Three of them, located relatively close to the cluster center, have line-of-sight accelerations larger than the maximum value predicted by the central mass density derived from optical observation, providing dynamical evidence for a central mass-to-light ratio $\gtrsim 10$, much higher than for any other globular cluster. It is likely that the other two millisecond pulsars have been ejected out of the core to their present locations at 1.4 and 3.3 half-mass radii, respectively, suggesting unusual nonthermal dynamics in the cluster core.

Subject headings: globular clusters: individual (NGC 6752) — pulsars: individual (PSR J1910−5959B, PSR J1910−5959D, PSR J1910−5959E, PSR J1911−5958A, PSR J1911−6000C)

1. INTRODUCTION

During a deep search of the globular cluster (GC) system for millisecond pulsars (MSPs), carried out using the Parkes radio telescope, we discovered (D'Amico et al. 2001a) a binary MSP (hereafter PSR A) associated with NGC 6752, a core-collapsed cluster showing evidence of mass segregation (Ferraro et al. 1997). The resulting knowledge of the dispersion measure (DM) for this cluster has facilitated the discovery of four additional MSPs (hereafter PSRs B, C, D, and E) in the same cluster (D'Amico et al. 2001b). We have made frequent observations using the Parkes telescope to obtain coherent timing solutions for these pulsars. These results can be used to estimate a variety of physical properties of the pulsars and of the host cluster. In particular, if the measured period derivatives are dominated by the dynamical effects of the cluster gravitational field, they can be used to constrain the mass-density distribution of the cluster, giving information on the GC's dynamical status and on the population of optically unseen cluster members. In this Letter, we report on the first 15 months of pulse timing observations, providing rotational and positional parameters for the five MSPs known in NGC 6752, and we use the pulsar positions and inferred accelerations to probe the dynamical status of the cluster.

2. OBSERVATIONS AND RESULTS

Regular pulsar timing observations of NGC 6752 have been carried out since 2000 September with the Parkes 64 m radio telescope, using the center beam of the multibeam receiver at 1400 MHz. The hardware system is the same as that used in the discovery observations (D'Amico et al. 2001a). The effects of interstellar dispersion are minimized by using a filter bank having 512 × 0.5 MHz frequency channels for each polarization. After detection, the signals from individual channels are added in polarization pairs, integrated, 1 bit–digitized every 125 μs, and recorded to magnetic tape for off-line analysis. Observation times are typically 1–2 hr. Pulse times of arrival (TOAs) are determined by fitting a standard high signal-to-noise ratio pulse profile to the observed mean pulse profiles and analyzed using the program TEMPO[8] and the DE 200 solar system ephemeris (Standish 1982).

Table 1 lists the timing parameters obtained for the five pulsars, including precise positions. Because these pulsars have relatively low DMs, ∼33 cm^{-3} pc, interstellar scintillation strongly affects their detectability. In particular, PSR B was detected on only 27 of 140 observations of the cluster. The mean flux densities at 1400 MHz (S_{1400}) in Table 1 are averaged values, derived from the observed signal-to-noise ratios. Nondetections were accounted for by assuming values of S_{1400} corresponding to half the detection limits. As can be seen from Table 1, all but PSR A are isolated MSPs. PSRs B, D, and E are located close to the cluster center. PSR D has the third largest period derivative, $\dot{P} = 9.6 \times 10^{-19}$, among known MSPs, after PSR B1820−30A in NGC 6624 and PSR B1821−24 in M28, suggesting that $\dot{P}$ is dominated by the line-of-sight acceleration in the cluster gravitational field. This interpretation is supported by the large negative $\dot{P}$-values observed for PSR B and PSR E, which are also located close to the cluster center.

PSR C is located 2′.7 from the cluster center, equivalent to about 1.4 half-mass radii or 24 core radii, assuming a core radius $\theta_c = 6''.7$ (Lugger, Cohn, & Grindlay 1995), a half-mass radius $\theta_{hm} = 115''$ (Djorgovski 1993), and an optical center for the cluster of (J2000) R.A. = $19^h10^m51^s.8$, decl. = −59°58′55″ (Harris 1996). Previously, the largest offset of an associated pulsar from a GC center was for PSR B2127+11C (Prince et al. 1991), a member of a double–neutron star eccentric binary in M15, located at ∼0.8 half-mass radii. Given the large offset of PSR C from the GC center, its period derivative is not significantly affected by the GC potential well, allowing the measurement of the characteristic age ($\tau_c = P/2\dot{P} = 3.8 \times 10^{10}$ yr, the largest among known pulsars), the surface magnetic field [$B_{surf} = 3.2 \times 10^{19}(P\dot{P})^{1/2} = 1.1 \times 10^8$ G], and the rotational energy loss ($\dot{E} = 3.95 \times 10^{46}\dot{P}/P^3 = 5.9 \times 10^{32}$ ergs s^{-1}).

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[8] See http://www.atnf.csiro.au/research/pulsar/timing/tempo.

TABLE 1
Measured and Derived Parameters for Five Millisecond Pulsars in NGC 6752

Parameter	PSR A	PSR B	PSR C	PSR D	PSR E
Name	J1911−5958A	J1910−5959B	J1911−6000C	J1910−5959D	J1910−5959E
R.A. (J2000)	19 11 42.7562(2)	19 10 52.050(4)	19 11 05.5561(7)	19 10 52.417(2)	19 10 52.155(2)
Decl. (J2000)	−59 58 26.900(2)	−59 59 00.83(3)	−60 00 59.680(7)	−59 59 05.45(2)	−59 59 02.09(2)
P (ms)	3.2661865707911(5)	8.35779850080(3)	5.277326932317(4)	9.03528524779(2)	4.571765939765(7)
$\dot{P}$	$3.07(10) \times 10^{-21}$	$-7.99(5) \times 10^{-19}$	$2.2(7) \times 10^{-21}$	$9.63(3) \times 10^{-19}$	$-4.37(1) \times 10^{-19}$
Epoch (MJD)	51920.0	52000.0	51910.0	51910.0	51910.0
DM (cm $^{-3}$pc)	33.68(1)	33.28(4)	33.21(4)	33.32(5)	33.29(5)
P_{orb} (days)	0.837113476(1)	…	…	…	…
$a_p \sin i/c$ (s)	1.206045(2)	…	…	…	…
T_{asc} (MJD)	51919.2064780(3)	…	…	…	…
Eccentricity	$<10^{-5}$	…	…	…	…
M_c ($M_\odot$)	>0.19	…	…	…	…
MJD Range	51710–52200	51745–52202	51710–52201	51744–52197	51744–52201
Number of TOAs	74	27	94	38	38
Residual (μs)	10	83	55	55	60
S_{1400} (mJy)	0.22	0.06	0.30	0.07	0.09
Offset[a] (arcmin)	6.39	0.10	2.70	0.19	0.13

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Angular separation in the plane of the sky between the MSP and the center of NGC 6752 (Harris 1996).

PSR A, the first pulsar discovered in this cluster, is located even farther from the center, at 6′.4, equivalent to 3.3 half-mass radii or ∼57 core radii. Given this large radial offset, one could question the association of the pulsar with the cluster. Based on the 19 MSPs with $S_{436} \gtrsim 2$ mJy detected by the Parkes Southern Pulsar Survey (Lyne et al. 1998) and assuming a typical spectral index ~ -1.9 (Toscano et al. 1998) for MSPs, the probability of chance superposition of a Galactic field MSP with $S_{1400} \gtrsim 0.2$ mJy within 6′.4 of the center of NGC 6752 is at most 10^{-5}. This probability is further reduced by noting that all five pulsars have very similar DM values. Also in this case the observed period derivative can be used to measure the pulsar parameters $\tau_c = 1.7 \times 10^{10}$ yr, $B_{surf} = 1.0 \times 10^{8}$ G, and $\dot{E} = 5.9 \times 10^{32}$ ergs s^{-1}.

Accurate DMs were obtained for each pulsar by splitting the 256 MHz bandwidth into two adjacent subbands and computing the differential delays. The maximum deviation (∼0.3 cm^{-3} pc) of the DM values derived for each pulsar from the average (33.36 cm^{-3} pc) is similar to that observed in other GCs hosting several MSPs like 47 Tucanae (Freire et al. 2001) and M15 (Anderson et al. 1990). Given the wide angular offsets of some of the pulsars, the scatter in some of the DMs could arise from gradients in the Galactic column density across different lines of sight toward the cluster (Armstrong, Rickett, & Spangler 1995). It could also arise from an enhanced electron density within the cluster (see Freire et al. 2001). Excluding the peripheral PSR A, a rough estimate of the density of such gas is given by $n_e \sim \langle(\Delta \mathrm{DM})^2\rangle^{1/2}/(D\langle\theta_\perp^2\rangle^{1/2}) = 0.025 \pm 0.005$ cm^{-3}, where $\langle(\Delta \mathrm{DM})^2\rangle^{1/2}$ is the rms deviation in the DMs and $\langle\theta_\perp^2\rangle^{1/2}$ is the one-dimensional dispersion of the angular offsets in radians with respect to the GC center in the plane of the sky for the four inner MSPs; $D = 4.1 \pm 0.1$ kpc (Renzini et al. 1996) is the cluster distance (the errors are reported at the 1 σ level, as everywhere in this Letter and in Table 1). This n_e-value is about a factor of 10 smaller than that inferred from the four MSPs (with $P < 10$ ms) in the core-collapsed cluster M15 and ∼40% of that derived using a more refined modeling of the plasma content in 47 Tuc (Freire et al. 2001).

NGC 6752 was observed recently for ∼28,700 s with the Advanced CCD Imaging Spectrometer S array (ACIS-S) detector aboard the *Chandra X-Ray Observatory* by Pooley et al. (2002). The position of PSR D is consistent with that of the *Chandra* source labeled CX 11 by Pooley et al. All the MSPs but PSR A are located in the *Chandra* field of view, but PSR C is outside the half-mass radius region searched for X-ray sources by Pooley et al. Thus, we have processed the full ACIS-S3 image in the 0.5–6.0 keV band using the CIAO v.2.2 software,[9] resulting in the detection of two additional probable X-ray counterparts to the MSPs. Using the WAVEDETECT tool, we have found a weak soft source whose error circle encloses PSR C, having a hardness ratio (as defined by Grindlay et al. 2001a) greater than 5.5. Assuming isotropic X-ray emission and a hydrogen column density $N_H = 2.2 \times 10^{20}$ cm^{-2}, we obtain (see footnote 9) for three different spectral models (a power law of photon index −2.5, a blackbody with $kT = 0.3$ keV, or a thermal bremsstrahlung with $kT = 1$ keV) similar values of the X-ray luminosity in the 0.5–2.5 keV band, $L_X = 2.2 \times 10^{30}$ ergs s^{-1}, corresponding to a conversion efficiency $L_X/\dot{E} \sim 0.004$. This is somewhat higher than that predicted on the basis of both the sample of MSPs observed in 47 Tuc and the sample of MSPs in the Galactic field (Grindlay et al. 2002). Using the CELLDETECT tool, we have also found marginal evidence for a slightly harder source compatible with the position of PSR B, having a hardness ratio ∼4 and $L_X = 1.1 \times 10^{30}$ ergs s^{-1}. This source is surrounded by many other sources, and the nominal CELLDETECT signal-to-noise ratio, ∼1.5, is low. No X-ray source is associated with PSR E, with an upper limit to the X-ray luminosity in the 0.5–2.5 keV band of 10^{30} ergs s^{-1}. Based on the three probable positional coincidences, we have used the MSP positions obtained via radio timing to derive a corrected *Chandra* astrometric solution, requiring a shift of the *Chandra* positions by −0″.05 in right ascension and −0″.03 in declination, with a final rms (of the differences between *Chandra* and radio positions) of 0″.28 in right ascension and 0″.39 in declination, consistent with the expected positional uncertainties of ∼0″.3 (Pooley et al. 2002).

Figure 1 shows an optical image of the cluster, the positions of the five MSPs, and the contour levels of the *Chandra* image. Pooley et al. (2002) pointed out that the X-ray sources in the central 1′.6 × 1′.6 region lie in the southeast quadrant. While they ascribe this to chance, we note that most of the X-ray sources within the half-mass radius region are roughly distributed along a stretched S-shaped pattern, whose elongated ends are oriented in the east-west direction.

[9] See http://asc.harvard.edu/ciao.

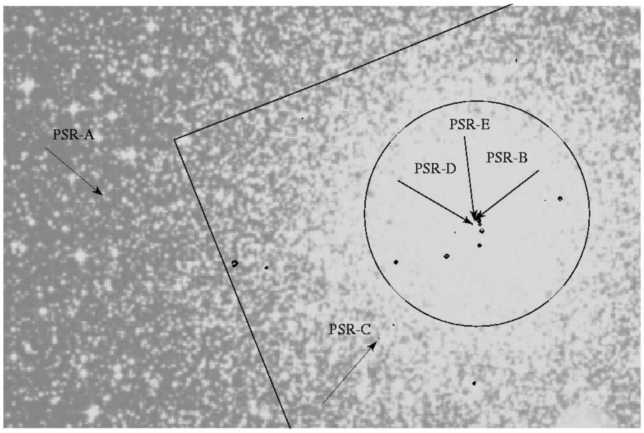

FIG. 1.—Positions of the five millisecond pulsars (*arrows*) and of the X-ray sources (*black contours*) in NGC 6752, superposed on an optical image retrieved from the Digital Sky Survey. The circle indicates the half-mass radius region ($\theta_{hm} = 115''$). The box indicates the *Chandra* ACIS-S3 field of view. North is to the top, and east is to the left.

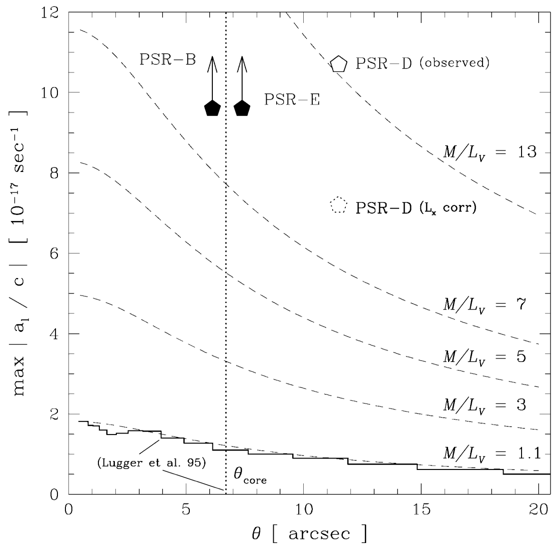

FIG. 2.— Maximum line-of-sight acceleration $|a_{l_{max}}/c| = |\dot{P}/P|$ vs. displacement θ with respect to the center of NGC 6752. The histogram represents the prediction based on the available optical observations. The dashed lines are analytical fits to the optical observations, labeled according to the adopted mass-to-light ratio. The filled pentagons represent lower limits to the line-of-sight acceleration based on the observation of PSRs B and E. The open pentagon shows the value of $\dot{P}/P$ for PSR D assuming a negligible intrinsic $\dot{P}$. If various observed scalings (Becker & Trümper 1997; Possenti et al. 2002; Grindlay et al. 2002) between X-ray luminosity and spin-down power for the MSPs are used to estimate the intrinsic $\dot{P}$, $\dot{P}/P$ for PSR D assumes values in the interval between the open and the dotted pentagon (see § 3).

3. CENTRAL MASS-TO-LIGHT RATIO

The large negative $\dot{P}$-values observed in PSRs B and E can be used to derive lower limits to the line-of-sight accelerations, $a_l/c = \dot{P}/P = (-9.6 \pm 0.1) \times 10^{-17}$ s^{-1}, for both pulsars, which are the largest known after those of PSRs B2127+11A and D in the core of M15 (Anderson et al. 1990). Contributions from centrifugal acceleration (Shklovskii 1970), differential Galactic rotation (Damour & Taylor 1991), and vertical acceleration in the Galactic potential (Kuijken & Gilmore 1989) are all negligible. Finally, according to Figures 3 and 4 of Phinney (1993), the probability that the accelerations of both PSRs B and E are dominated by a nearby star in the cluster is $\lesssim 10^{-4}$. Thus, we can conclude that the inferred high values of $|a_l/c|$ are due to the potential well of NGC 6752.

A lower limit to the mass-to-light ratio in the inner regions of NGC 6752 can be derived from the following rule, which holds to within ~10% in all plausible cluster models (Phinney 1992):

$$\left|\frac{\dot{P}}{P}(\theta_\perp)\right| < \left|\frac{a_{l,\max}(\theta_\perp)}{c}\right| \simeq 1.1\,\frac{G}{c}\frac{M_{\rm cyl}(<\theta_\perp)}{\pi D^2\theta_\perp^2}$$

$$= 5.1 \times 10^{-18}\,\frac{\mathcal{M}}{L_V}\left[\frac{\Sigma_V(<\theta_\perp)}{10^4\ L_{V,\odot}\ {\rm pc}^{-2}}\right]\ {\rm s}^{-1}. \quad (1)$$

Here $\Sigma_V(<\theta_\perp)$ is the mean surface brightness within a line of sight subtended by an angle $\theta_\perp$ with respect to the cluster center, $M_{\rm cyl}(<\theta_\perp)$ is the mass enclosed in the cylindrical volume of radius $R_\perp = D\theta_\perp$, and $\mathcal{M}/L_V$ is the mean *projected* mass-to-light ratio in the *V* band. We use the most recent published brightness profile for this cluster (Lugger et al. 1995), normalized to the central surface brightness in the *V* band reported by Djorgovski (1993), in order to plot the curves of maximum $|a_l/c|$ for different values of $\mathcal{M}/L_V$. In Figure 2, the histogram represents the data for $\mathcal{M}/L_V = 1.1$, as suggested by Pryor & Meylan (1993). This greatly underestimates the observed values of $\dot{P}/P$. The dashed lines are analytical fits (with reduced $\chi^2 \sim 1$) to the observed data, scaled according to increasing values of $\mathcal{M}/L_V$. Only $\mathcal{M}/L_V \gtrsim 9$ can account for the observed $|\dot{P}/P|$ of PSRs B and E. An even larger $\mathcal{M}/L_V \gtrsim 13$ is required if PSR D has a negligible intrinsic $\dot{P}/P$, as might be expected given the close projected positions and the similar absolute values of $\dot{P}/P$ for PSRs B, D, and E. A reasonable interpretation is that PSR D is at about the same distance from the GC center as the PSRs B and E, but in the closer half of the cluster, whereas PSRs B and E reside in the further half. In this case, for these three MSPs the intrinsic $\dot{P}/P \sim 5 \times 10^{-18}$ can be estimated as the average of those of PSRs B (or E) and D. Values of $\mathcal{M}/L_V$ in the interval 9–13 result if the observed scalings between X-ray luminosity and spin-down power for MSPs are used to estimate the magnetic dipole braking contribution to $\dot{P}/P$ for PSR D (see Fig. 2 caption). We finally note that these estimates of the projected $\mathcal{M}/L_V$ are independent of distance, excepting the effects of extinction, which are very small for NGC 6752, with $E(B-V) = 0.04$ (Harris 1996), and of modeling of the cluster potential.

These results imply (see eq. [1]) that there must be $M_{\rm cyl}(<\theta_{\perp,E}) \gtrsim 1.3 \times 10^4\ M_\odot$ of matter in the form of low-luminosity stellar objects within the projected radius of PSR E, 0.15 pc. Adopting the prescription of Djorgovski (1993) and a core radius $\theta_c = 6''.7$ (Lugger et al. 1995), this in turn corresponds to a central mass density $\gtrsim 7 \times 10^5\ M_\odot$ pc^{-3}, at least 5 times larger than that derived from measurements in the optical band (Pryor & Meylan 1993). The stars whose initial mass was in the interval 0.6–0.8 $M_\odot$ (bracketing the current turn-off point of the cluster) now dominate the total integrated *V*-band luminosity of NGC 6752, $1.2 \times 10^5\ L_{V,\odot}$ (Djorgovski 1993). Assuming a typical mass-to-light ratio for these stars of ~0.25 (Phinney 1993), the number of 0.6–0.8 $M_\odot$ stars is $N_{\rm to} \sim 4 \times 10^4$. Assuming a Salpeter initial mass function (IMF) $\propto m^{-\alpha}$ with $\alpha = 2.35$, the evolution of stars having initial mass $\gtrsim 8\ M_\odot$ should have left at most $N_{\rm dr} \sim 4 \times 10^3$ dark remnants. If they sank toward the cluster center and are responsible for the high value of the mass-to-light ratio in the core, their average mass would be $\langle m_{\rm dr}\rangle = M_{\rm cyl}(<\theta_{\perp,E})/N_{\rm dr} \gtrsim 3.2\ M_\odot$, suggesting that at least some of them must be black holes. The same conclusions apply to any power-law IMF steeper than Salpeter's.

Conversely, if we assume that the low-luminosity objects within the central 0.15 pc are all 1.4 $M_\odot$ neutron stars, this would imply $\alpha_{NS} < 2.1$ for the slope of the IMF. Given the very low upper limit on the density of any ionized gas, $\gtrsim 10^4$ neutron stars could reside in the inner region of NGC 6752 without producing an accretion luminosity detectable in the deep *Chandra* exposure of Pooley et al. (2002). Alternatively, if the population of the central region is dominated by massive white dwarfs (descendents of stars of initial mass $\gtrsim 2.5$ $M_\odot$), we obtain a nominal limit $\alpha_{WD} < 2.5$. However, these ∼1 $M_\odot$ remnants (less massive than the population of MSPs) should distribute out to larger distances from the cluster center than PSR E. A conservative 60% increase in their estimated number implies an IMF flatter than Salpeter's in this case as well.

We note that both the uncertainties in the average mass-to-light ratio of the 0.6–0.8 $M_\odot$ stars and the unknown number of these stars that have been tidally stripped or evaporated from the cluster since its formation could affect N_{to} and thus our results. However, simulations of strongly concentrated clusters (e.g., Joshi, Nave, & Rasio 2001) indicate that the relative depletion of 0.6–0.8 $M_\odot$ stars should be smaller than that of neutron stars, which escape the cluster potential well owing to supernova kicks at birth (Rappaport et al. 2001). Such an effect would further increase the average mass $\langle m_{dr} \rangle$ of dark remnant stars and/or make the IMF even flatter.

4. DISCUSSION

Our results provide the first direct dynamical evidence for a high density of unseen remnants in the core of a GC, suggesting a mass-to-light ratio $\gtrsim 10$ in the core region. For comparison, we note that a much smaller value of ∼3 was obtained for the case of M15 (Phinney 1993), a core-collapsed GC long suspected to host a central black hole (see, e.g., van der Marel & Roeland 1999). The nature of the remnants in the core of NGC 6752 is not clear, as it strongly depends on assumptions about the IMF. However, the possibility that they are black holes, or that many stellar remnants have collapsed into a single massive black hole, is intriguing.

In addition, the large offsets of PSRs A and C from the cluster center indicate the occurrence of highly effective nonthermal dynamics in the cluster core. No other GC shows an MSP ejected beyond its half-mass radius (which requires a finely tuned impulse to avoid prompt expulsion of the neutron star from the GC), while NGC 6752 has two of them. They could result from exchange encounters in the core (Phinney & Sigurdsson 1991), but the large offset of PSR A suggests also the occurrence of more powerful scattering events (Colpi, Possenti, & Gualandris 2002). The scattering target must have treated this binary system as a point mass, ejecting it without inducing appreciable eccentricity. Assuming a value of 1.4 $M_\odot$ for the pulsar, the total mass of the binary system containing PSR A is at least 1.6 $M_\odot$. Simple dynamical considerations favor a scattering target significantly more massive than the scattered binary, supporting the conclusion that it could be of many solar masses. A black hole binary system would be a natural candidate. The *Chandra* X-ray observations do not place severe limits on its maximum mass. The arguments of Grindlay et al. (2001a) applied to an electron gas density $\lesssim 0.025$ cm^{-3} and a detection threshold of $\sim 10^{30}$ ergs s^{-1} allow for up to a few hundred solar masses in the form of black hole(s) present in the central region of NGC 6752.

Finally, the pattern of X-ray sources, roughly oriented midway between the probable projected ejection directions of PSRs A and C suggests a preferential geometry for ejection, similar to that discussed by Grindlay et al. (2001b) for NGC 6397. Its physical connection with the inferred high density of unseen matter in the core is not clear, but it could be a further signature of significant nonthermal activity in the core region.

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