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

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Accepted by ApJ Letter

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 > 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 non-thermal dynamics in the cluster core.

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

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, 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 paper 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 s, and recorded to magnetic tape for off-line analysis. Observation times are typically 1–2 hours. 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 TEMPO1 and the DE200 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−3pc, 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 (SS1400) in Table 1 are averaged values, derived from the observed signal-to-noise ratios. Non-detections were accounted for by assuming SS1400 values 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, E = 9.6 × 10−19; among known MSPs, after PSR B1820−30A in NGC 6624 and PSR B1821−24 in M28, suggesting that the E is dominated by the line-of-sight acceleration in the cluster gravitational field. This interpretation is supported by the large negative E values observed for PSR B and E, which are also located close to the cluster center.

PSR-C is located 2° from the cluster center, equivalent to about 1.4 half-mass radii or 24 core-radii, assuming a core radius = 6.27 (Lugger, Cohn & Grindlay 1995), a half-mass radius = 115° (Djorgovski 1993), and an optical center for the cluster of (J2000) R.A.=19° 10′ 51′′ 8 and Dec.=−59° 58′ 55″ (Harris 1996). Previously, the largest offset of an associated pulse from a GC center was for PSR B2127+11C (Prince et al. 1991), a member of a double-neutron-star eccentric binary

1See http://www.atnf.csiro.au/research/pulsar/timing/tempo.
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 \( \dot{P} = 2.5 \times 10^{-10} \) yr, the largest among known pulsars), the surface magnetic field \( B_{\text{surf}} = 3 \times 10^{12} \) G, and the rotational energy loss \( \dot{E} = 3.95 \times 10^{36} \text{erg s}^{-1} = 5.9 \times 10^{32} \text{erg s}^{-1} \).

PSR-A, the first pulsar discovered in this cluster, is located even farther from the center, at 6\( \sigma \), 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 \( S_{\text{500}} > 2 \) 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 \( S_{\text{500}} > 0.2 \) mJy within 6\( \sigma \) 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 \( \dot{P} = 3 \times 10^{-10} \) yr, \( B_{\text{surf}} = 1 \times 10^{9} \) Gauss, and \( \dot{E} = 5.9 \times 10^{32} \text{erg s}^{-1} \).

Accurate DMs were obtained for each pulsar by dividing the 256-MHz bandwidth into two adjacent sub-bands and computing the differential delays. The maximum deviation \( (0.3 \text{ cm}^{-3} \) pc) of the DM values derived for each pulsar from the average \( (33.36 \text{ cm}^{-3} \) 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 \( n_e \sim ( \text{DM})^{2} \times (Dh)^{-1} \times (1 + z)^{-1} \sim 0.025 \times 0.005 \text{ cm}^{-3} \), where \( ( \text{DM})^{2} \times (Dh)^{-1} \times (1 + z)^{-1} \) 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 4 inner MSPs. \( D = 4 \text{ d} \) 0.3 kpc (Renzini et al. 1996) is the cluster distance (the errors are reported at the 1 -level, as everywhere in this paper and in Table 1). This \( n_e \) value is about a factor of ten smaller than that inferred from the four MSPs (with \( P < 10 \text{ ms} \)) 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 28700 s with the 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 CX11 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 2.2 software\(^2\), resulting in the detection of two additional probable X-ray counterparts to the MSPs. Using the wavdetect 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) > 5.5. Assuming isotropic X-ray emission and a hydrogen column density \( N_H = 2.2 \times 10^{20} \text{cm}^{-2} \), we obtain\(^3\) 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, \( L_X = 2.2 \times 10^{30} \text{ erg s}^{-1} \), corresponding to a conversion efficiency \( L_X = 0.004 \). 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 celdetect 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 \( L_X = 1.1 \times 10^{30} \text{ erg s}^{-1} \). This source is surrounded by many other sources and the nominal celdetect 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 \( 10^{30} \text{ erg s}^{-1} \). 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 \(-0.005 \) in RA and \(-0.003 \) in Dec, with a final rms (of the differences between Chandra and radio positions) of \( 0.028 \) in RA and \( 0.039 \) in Dec, 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 \( 3 \) of the \( 3 \) region lie in the south-east 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.

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, \( \dot{V}_l = \dot{P} = -9 \times 10^{-17} \text{ m s}^{-1} \), 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 \(< 10^{-4} \). Thus we can conclude that the inferred high values of \( \dot{V}_l = \dot{P} \) 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):

\[
\frac{P}{L^*_{\nu}} (\gamma) < \frac{a_{\text{rms}}(\gamma)}{c} \times \frac{1}{\sqrt{1 + \frac{M_{\nu}(\gamma)}{M_{\nu}}} \times \frac{M_{\nu}(\gamma)}{L_{\nu}}} \times \frac{\gamma}{L_{\nu} (\gamma)} \times \frac{1}{\nu^2} \times \frac{1}{c^2} \times \text{s}^{-1}.
\]

Here \( L_{\nu}(\gamma) \) is the mean surface brightness within a line of sight subtended by an angle \( \gamma \) with respect to the cluster center. \( M_{\nu}(\gamma) \) is the mass enclosed in the cylindrical volume of radius \( R_{\gamma} = D \gamma \) and \( M = L_{\nu} \) is the mean projected mass-to-light ratio in the V-band.

\(^2\)See http://asc.harvard.edu/ciao
\(^3\)See http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html
We use the most recent published brightness profile for this cluster (Lugger, Cohn & Grindlay 1995), normalized to the central surface brightness in the V-band reported by Djorgovski (1993), in order to plot the curves of maximum $\dot{P}/P\times10^{-17}$ for different values of $M_{\text{cyl}}=L_V$. In Figure 2 the histogram represents the data for $M_{\text{cyl}}=1.1$, as suggested by Pryor & Meylan (1993). This greatly underestimates the observed values of $E(L_P)$. The dashed lines are analytical fits (with reduced $^{\text{2}}_{\text{1}}$) to the observed data, scaled according to increasing values of $M_{\text{cyl}}$. Only $M_{\text{cyl}}=9$ cm can account for the observed $E(L_P)$ of PSRs B and E. An even larger $M_{\text{cyl}}=13$ is required if PSR-D has a negligible intrinsic $E(L_P)$; as might be expected given the close projected positions and the similar absolute values of $E(L_P)$ 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 3 MSPs the intrinsic $E(L_P)=5\times10^{-18}$ can be estimated as the average of those of PSRs B (or E) and D. Values of $M_{\text{cyl}}=L_V$ 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 $E(L_P)$ for PSR-D (see caption of Fig. 2). We finally note that these estimates of the projected $M_{\text{cyl}}=L_V$ are independent of distance, excepting the effects of extinction, which are very small for NGC 6752, with $E(B-V)=0.004$ (Harris 1996), and of modeling of the cluster potential.

These results imply (see eq. 11) that there must be $\dot{M}_{\text{ej}}(<\gamma,\xi)>1.3\times10^4\ M_\odot$ 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 $c=6^{\prime\prime}$ (Lugger, Cohn & Grindlay 1995) this in turn corresponds to a central mass density $>\gamma\times10^7\ M_\odot$ pc$^{-3}$, at least five 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 $\times10^7\ L_\odot$ (Djorgovski 1993).
light ratio of the 0.6–0.8 M
depletion of 0.6–0.8 M
to smaller than that of neutron
escape the cluster potential well due to supernova
further increase the average mass
kicks at birth (Rappaport et al. 2001). Such an effect would
increase the relative abundance 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 globular cluster,
suggesting a mass-to-light ratio \( \gtrsim 10 \) in the core region. For
comparison, we note that a much smaller value \( \gtrsim 10 \) 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 assump-
tions 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 non-
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 NS from the GC),
while NGC 6752 has two of them. They could result from ex-
change 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 syst-
em as a point mass, ejecting it without inducing appreciable
eccentricity. Assuming a value of 1.4 M
do the pulsar, the
total mass of the binary system containing PSR-A is at least 1.6
M. 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 \( n_e < 0.025 \, \text{cm}^{-3} \) and a detection threshold of
10\(^{30} \) erg 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 mid-
way 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 non-thermal activity in the core region.

We acknowledge stimulating discussions with Luca Ciotti and Monica
Colpi, and Piero Ranalli, Marcella Brusa and Paolo Montegriffo for
assistance with reduction of the X-ray data and astrometry. N.D.A. and
A.P. received financial support from the Italian Space Agency (ASI)
and the Italian Minister of Research (MIUR). F.C. acknowledges sup-
port from NASA grants NAG5-9095 and NAG5-9950. The Parkes
radio telescope is part of the Australia Telescope which is funded by
the Commonwealth of Australia for operation as a National Facility
managed by CSIRO. The Chandra Data Archive is operated for NASA
by the SAO.

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Table 1
MEASURED AND DERIVED PARAMETERS FOR FIVE MILISECOND PULSARS IN NGC 6752

| Pulsar | 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\(^{h}\) 11\(^{m}\) 42\(^{s}\) 7562(2) | 19\(^{h}\) 10\(^{m}\) 52\(^{s}\) 050(4) | 19\(^{h}\) 11\(^{m}\) 05\(^{s}\) 5561(7) | 19\(^{h}\) 10\(^{m}\) 52\(^{s}\) 417(2) | 19\(^{h}\) 10\(^{m}\) 52\(^{s}\) 155(2) |
| Dec (J2000)  | -59 58\(^{s}\) 26\(^{s}\) 900(2) | -59 59\(^{s}\) 00\(^{s}\) 83(3) | -60 00\(^{s}\) 59\(^{s}\) 680(7) | -59 59\(^{s}\) 05\(^{s}\) 245(2) | -59 59\(^{s}\) 02\(^{s}\) 09(2) |
| \(P\) (ms)    | 3.2661865707911(5) | 8.3577859080(3) | 5.27732693231(4) | 9.03528524779(2) | 4.571765939765(7) |
| \(P_\text{orb}\) (d) | 0.837113476(1) | 1.206045(2) | 51920.0 | 52000.0 | 51910.0 |
| DM (cm\(^{-3}\)pc) | 33.68(1) | 33.28(4) | 33.21(4) | 33.32(5) | 33.29(5) |
| Eccentricity | < 10\(^{-5}\) | 1-0.19 | 0.19 |
| MJD Range | 51710–52200 | 51745–52202 | 51710–52201 | 51744–52197 | 51744–52201 |
| No. TOAs | 74 | 27 | 94 | 38 | 38 |
| residual (s) | 10 | 83 | 55 | 55 | 60 |
| \(S_{1400}\) (mJy) | 0.22 | 0.06 | 0.30 | 0.07 | 0.09 |
| Offset (\(\circ\)) | 6\(\circ\)39 | 0\(\circ\)10 | 2\(\circ\)70 | 0\(\circ\)19 | 0\(\circ\)23 |

\(^{a}\)Angular separation in the plane of the sky between the MSP and the center of NGC 6752 (Harris 1996).