THE ASTROPHYSICAL JOURNAL, 599:475–484, 2003 December 10

THREE BINARY MILLISECOND PULSARS IN NGC 6266

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Received 2003 April 24; accepted 2003 August 20

ABSTRACT

We present rotational and astrometric parameters of three millisecond pulsars located near the center of the globular cluster NGC 6266 (M62), resulting from timing observations with the Parkes radio telescope. Their accelerations toward the cluster center yield values of the cluster central density and mass-to-light ratio consistent with those derived from optical data. The three pulsars are in binary systems. One (spin period $P = 5.24$ ms) is in a 3.5 day orbit around a companion of minimum mass 0.2 $M_\odot$. The other two millisecond pulsars ($P = 3.59$ and 3.81 ms) have shorter orbital periods (3.4 and 5.0 hr) and lighter companions (minimum masses of 0.12 and 0.07 $M_\odot$, respectively). The pulsar in the closest system is the fifth member of an emerging class of millisecond pulsars displaying irregular radio eclipses and having a relatively massive companion. This system is a good candidate for optical identification of the companion star. The lack of known isolated pulsars in NGC 6266 is also discussed.

Subject headings: globular clusters: individual (NGC 6266) — pulsars: individual (PSR J1701−3006A, PSR J1701−3006B, PSR J1701−3006C) — radio continuum: stars — stars: neutron

1. INTRODUCTION

Recycled pulsars are old neutron stars revived through transfer of matter and angular momentum from a mass-donor companion in a binary system (e.g., Alpar et al. 1982; Smarr & Blandford 1976; Bhattacharya & van den Heuvel 1991). They are pointlike objects and can be considered as test masses for probing gravitational effects. Most of them are also extremely stable clocks, allowing for accurate measurements of their rotational parameters, position, and apparent motion in the sky. Because of these characteristics, recycled pulsars found in globular clusters (GCs) have proved to be valuable tools for studying the GC potential well (e.g., Phinney 1992; Camilo et al. 2000; D'Amico et al. 2002), the dynamical interactions in GC cores (e.g., Phinney & Sigurdsson 1991; Colpi, Possenti, & Gualandris 2002), and neutron star retention in GCs (e.g., Rappaport et al. 2001). In the case of 47 Tucanae, they also allowed the first detection of gas in a GC (Freire et al. 2001).

GCs are a fertile environment for the formation of recycled pulsars: besides evolution from a primordial system, exchange interactions in the ultradense core of the cluster favor the formation of various types of binary systems suitable for spinning up the neutron stars they host (Davies & Hansen 1998). Because of this, about 60% of all known millisecond pulsars (MSPs) are in GCs. Unfortunately, pulsars in GCs are elusive sources, since they are often distant and in close binary systems. Their large distances make their flux density typically very small and their signals strongly distorted by propagation through the dispersive interstellar medium. In addition, they frequently are members of close binary systems, causing large changes in the apparent spin period and sometimes periodic eclipsing of the radio signal.

The Parkes Globular Cluster (PKSGC) survey is a search for pulsars in the system of southern GCs using the Parkes 64 m radio telescope that commenced in 2000. It exploits the high sensitivity of the central beam of the Parkes multibeam receiver (Staveley-Smith et al. 1996), the efficiency of a modern data acquisition system (e.g., Manchester et al. 2001; D'Amico et al. 2001a), and the high resolution of a new filter bank designed and assembled at Jodrell Bank and Bologna, with the aim of improving the capability for probing distant clusters. Time series data are analyzed with a modern algorithm for the incoherent search of periodicities over a range of dispersion measures (DMs) and accelerations resulting from orbital motion.

This project has already resulted in the discovery of 12 MSPs in six GCs that had no previously associated pulsars (D'Amico et al. 2001a, 2001b, 2002; Possenti et al. 2001). These detections reversed the declining trend in discoveries of additional clusters hosting these objects; in the 7 years from 1987 (when the first pulsar in a GC, B1821−24 in M28, was discovered at Jodrell Bank by Lyne et al. 1987) to 1994 (B1820−30A and B1820−30B in NGC 6624: Biggs et al. 1994), 13 GCs were shown to contain at least one pulsar, whereas no new cluster joined the list in the following 6 years. More recently, pulsars have been detected in a further three GCs (Ransom et al. 2003; Ransom 2003;[8] Jacoby 2003[9]), bringing the current total to 73 pulsars in 22 clusters.[10]

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[8] Ransom (2003) is available at http://online.itp.ucsb.edu/online/clusters_c03/ransom.

[9] Jacoby (2003) is available at http://online.itp.ucsb.edu/online/clusters_c03/jacoby.

[10] The association of the long-period pulsar B1718−19 with the cluster NGC 6342, questioned by some, is included in this list.

This paper discusses results from the PKSGC survey of NGC 6266 (M62). The discovery of the first pulsar in this cluster, PSR J1701−3006A, was presented by D'Amico et al. (2001a). A preliminary announcement of the discovery of two more MSPs was also made by D'Amico et al. (2001b), while three further MSPs were later detected at the Green Bank Telescope (Jacoby et al. 2002). Here we report details of the discovery of the second and third pulsars, PSRs J1701−3006B and J1701−3006C, both members of short-period binary systems, and discuss timing results obtained over a 3 yr interval for all three MSPs discovered at Parkes. On the basis of these results, we investigate the properties of the pulsars and the host cluster. We particularly discuss the MSP in the tightest of the three systems, which belongs to the rare class of eclipsing radio pulsars.

2. DATA COLLECTION AND PROCESSING

The PKSGC survey uses the dual-polarization central beam of the 20 cm multibeam receiver of the Parkes radio telescope. The two channels have a system temperature of $\sim$22 K and a central frequency of 1390 MHz. A high-resolution filter-bank system consisting of 512×0.5 MHz adjacent channels per polarization is used to minimize dispersion smearing, preserving significant sensitivity to a 3 ms pulsar with a DM up to 300 $\mathrm{cm^{-3}}$ pc. In this case, the limiting sensitivity is $\sim$0.15 mJy for a signal-to-noise ratio (S/N) of 8 and a standard 2 hr observation (assuming a typical duty cycle of $\sim$20% and negligible scattering). After adding the outputs in polarization pairs, the resulting 512 data streams are each high-pass–filtered, integrated, and 1 bit–digitized every 125 μs. Each observation typically produces 2–4 Gbytes of data; a cluster of 10 Alpha 500 MHz CPUs at the Astronomical Observatory of Bologna has been used for off-line processing.

The processing pipeline first splits each data stream into nonoverlapping segments of 1050, 2100, 4200, or 8400 s, which are processed separately. When no pulsar is known in a GC (and the DM is therefore unknown), the data are dedispersed over a wide range of $\sim$500–1000 trial DMs, spanning the interval $(1.0 \pm 0.4)\mathrm{DM_{exp}}$, where $\mathrm{DM_{exp}}$ is the DM expected for the cluster according to a model for the Galactic distribution of the ionized gas (Taylor & Cordes 1993). Each dedispersed series is then transformed using a fast Fourier transform, and the resulting spectra are searched for significant peaks. The process is repeated for spectra obtained from summing 2, 4, 8, and 16 harmonics. This produces a large number of candidate periods above a threshold. The time domain data are then folded in subintegrations at each of these periods in turn and searched for both a linear and a parabolic shift in pulse phase. A linear shift corresponds to a correction in the candidate period, whereas a parabolic correction is a signature of acceleration of the pulsar due to its orbital motion. Parameters for final pulse profiles with significant S/Ns are displayed for visual inspection. This processing scheme led to the discovery of the first pulsar in NGC 6266 (D'Amico et al. 2001a).

For an MSP in a very close orbit and with relatively high minimum companion mass, the acceleration may undergo significant variations during an observation. As a consequence, weak sources can be missed at the confirmation stage if a constant acceleration term is applied to the data. Hence, a code has been developed at Bologna for searching both the acceleration and the derivative of the acceleration in the subintegration arrays of interesting candidates. Spanning a cubic space, the code also searches for the period in a small interval of values around the nominal candidate period. Using this code, we were able to confirm two more binary MSPs in NGC 6266.

Once a pulsar is detected and confirmed in a cluster, the data are reprocessed, with dedispersion at the DM value of the newly discovered pulsar. The resulting time series is then subjected to a fully coherent search for Doppler-distorted signals over a large range of acceleration values. Applying this extremely CPU-intensive procedure to NGC 6266, exploring accelerations in the interval $|a| < 35$ m $\mathrm{s^{-2}}$ for 35 minute–long segments (and $|a| < 17.5$ m $\mathrm{s^{-2}}$ for 70 minute–long segments), resulted in no further discoveries.

Regular pulsar timing observations at the Parkes 64 m radio telescope began shortly after the discovery of these pulsars, using the same observing system as the search observations. Timing observations, typically of 30–60 minutes' duration, are dedispersed and synchronously folded at the predicted topocentric pulsar spin period in an off-line process, forming pulse profiles every few minutes of integration. Topocentric pulse times of arrival (TOAs) are determined by convolving a standard high-S/N pulse template with the observed pulse profiles and then analyzed using the program TEMPO.[11] TEMPO converts the topocentric TOAs to solar system barycentric TOAs at infinite frequency (using the DE200 solar system ephemeris; Standish 1982) and then performs a multiparameter fit to determine the pulsar parameters.

Table 1 lists the timing parameters obtained for the three pulsars, including precise positions. Values of the DM were obtained for each pulsar by splitting the total bandwidth into four adjacent 64 MHz wide subbands and computing the differential delays. The available data do not yet allow a constraining fit for the orbital eccentricity e for any of the three pulsars (see the footnotes to Table 1 for details of the fitting procedure). The mean flux densities at 1400 MHz (S_{1400}) in Table 1 are average values, derived from the system sensitivity estimate and the observed S/N. In the case of PSR J1701−3006B, the quoted flux density refers only to epochs away from the eclipse (see below). As expected from the relatively high DMs, interstellar scintillation does not significantly affect the detectability of these sources; observed variations are within 30% of the nominal flux density reported in Table 1.

The inferred radio luminosities of the three MSPs ($\sim$10–20 mJy $\mathrm{kpc^2}$ at 1400 MHz, corresponding to a luminosity at 400 MHz of $L_{400} \gtrsim 100$ mJy $\mathrm{kpc^2}$ for a typical spectral index of -1.7; see Table 1) place all these sources in the bright tail of the luminosity function of MSPs in the Galactic disk (Lyne et al. 1998) and in 47 Tuc (Camilo et al. 2000). If we assume a luminosity distribution $dN \propto L^{-1}\, d\log L$ (Lorimer 2001[12]), NGC 6266 would contain a few hundred pulsars with $L_{400} \gtrsim 1$ mJy $\mathrm{kpc^2}$, the approximate limiting luminosity observed for Galactic disk pulsars. Unfortunately, the cluster distance and the lack of any strong signal enhancement due to scintillation will make difficult detecting the fainter pulsar population, probably preventing a direct investigation of the shape of the pulsar luminosity function in this cluster.

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

[12] Lorimer (2001) is available at http://relativity.livingreviews.org/articles/lrr-2001-5/index.html.

TABLE 1

Observed and Derived Parameters for Three Pulsars in NGC 6266

Parameter	PSR J1701−3006A	PSR J1701−3006B	PSR J1701−3006C
Observed Parameters			
R. A. (J2000.0)	17 01 12.5127 (3)	17 01 12.6704 (4)	17 01 12.8671 (4)
Decl. (J2000.0)	−30 06 30.13 (3)	−30 06 49.04 (4)	−30 06 59.44 (4)
Period, P (ms)	5.2415662378289(16)	3.5938522173305(14)	3.8064243637728(18)
Period derivative, $\dot{P}$	$-1.3196(9) \times 10^{-19}$	$-3.4978(7) \times 10^{-19}$	$-3.189(11) \times 10^{-20}$
Epoch (MJD)	52,050.0	52,050.0	52,050.0
DM ($\mathrm{cm^{-3}}$ pc)	115.03 (4)	113.44 (4)	114.56 (7)
Orbital period, P_b (days)	3.805948407 (16)	0.1445454304 (3)	0.2150000713 (15)
Projected semimajor axis, x (lt-s)	3.483724 (8)	0.252775 (13)	0.192880 (12)
Eccentricity[a], e	$<4 \times 10^{-6}$	$<7 \times 10^{-5}$	$<6 \times 10^{-5}$
Time of ascending node, T_{asc} (MJD)	52,048.5627980 (15)	52,047.2581994 (9)	52,049.855654 (2)
Span of timing data (MJD)	51,714–52,773	51,714–52,773	51,714–52,773
Number of TOAs	80	74	73
rms timing residual (μs)	21	26	32
Flux density at 1400 MHz, S_{1400} (mJy)	0.4 (1)	0.3 (1)	0.3 (1)
Derived Parameters[b]			
Galactic longitude, l (deg)	353.577	353.573	353.572
Galactic latitude, b (deg)	7.322	7.319	7.316
Mass function, f_p ($M_\odot$)	0.00313392 (2)	0.00082999 (13)	0.00016667 (3)
Companion mass, M_c ($M_\odot$)	>0.20	>0.12	>0.07
Radio luminosity, L_{1400} (mJy $\mathrm{kpc^2}$)	19 (7)	14 (6)	14 (6)
Offset, $\Theta_\perp$ (arcsec)	19.2	1.7	10.5

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Values in parentheses are twice the nominal TEMPO uncertainties in the least significant digits quoted.

[a] The 2 σ upper limits on the orbital eccentricities were obtained using the TEMPO ELL1 model, where T_{asc} and ($e\cos\omega$, $e\sin\omega$) are fitted (Lange et al. 2001). The value given for PSR J1701−3006B is tentative, as not all of the orbit is sampled. All the other parameters are derived using the standard (BT) binary model with $e = 0$.

[b] The following formulae are used to derive parameters in the table: $f_p = x^3(2\pi/P_b)^2 T_\odot^{-1} = (M_c \sin i)^3/(M_p + M_c)^2$, where $T_\odot \equiv GM_\odot/c^3 = 4.925\ \mu$s, M_p and M_c are the pulsar and companion masses, respectively, and i is the orbital inclination angle. M_c is obtained from the mass function, with $M_p = 1.40\ M_\odot$ (Thorsett & Chakrabarty 1999) and $i < 90°$. The assumed distance is that of the GC, $d = 6.9$ kpc, and $L_{1400} \equiv S_{1400} d^2$. $\Theta_\perp$ is the angular separation in the plane of the sky between the MSP and the center of NGC 6266 (Harris 1996; the 2003 catalog revision is available at http://physun.physics.mcmaster.ca/~harris/mwgc.dat).

The pulsar PSR J1701−3006A has the largest flux density and the longest orbital period among the three and was first detected in an observation during 1999 December (D'Amico et al. 2001a). PSR J1701−3006B and J1701−3006C are weaker pulsars in closer binary systems and were confirmed in 2000 November. Once the orbits were determined, signals from these two pulsars were recovered in all the observations performed prior to their confirmation. Therefore, the timing solutions reported in Table 1 (and whose residuals are displayed in Fig. 1) cover the same time span for all three MSPs, from 2000 June to 2003 May. Inspection of Figure 2 shows that all the orbits have been uniformly sampled (except that of PSR J1701−3006B, for which we have excluded TOAs in the region of the eclipse; see below) and that there are no systematic trends in the residuals as a function of binary phase.

3. CONSTRAINTS ON PULSARS AND CLUSTER PARAMETERS

NGC 6266 is listed in the Webbink (1985) catalog as a moderately reddened, $E(B-V) = 0.48$, medium-low metallicity GC, with $[\mathrm{Fe/H}] = -1.38 \pm 0.15$, located $\sim 6.9 \pm 1.0$ kpc from the Sun (Brocato et al. 1996) and probably having a collapsed core (Harris 1996).

The three MSPs discussed here are all located close to the center of mass of the cluster, at least in projection, with projected distances $\lesssim 1.8\Theta_c$, where $\Theta_c = 10\farcs8$ is the core radius of NGC 6266 (Harris 1996). This is consistent with the hypothesis that the cluster has reached thermal equilibrium, in which energy equipartition gives less velocity to the most massive species, constraining them to reside deep in the cluster potential well.

The spin period derivatives $\dot{P}$ are all negative, implying that the line-of-sight acceleration a_l imparted to the pulsars is directed toward the observer and that it overcomes the (positive) $\dot{P}_i$ because of intrinsic spin-down (see, e.g., Phinney 1993). The probability that a nearby passing star in the crowded cluster core is significantly accelerating at least one of the three MSPs is less than 1% (Phinney 1993). Moreover, given the position and the kinematics of the GC NGC 6266, the centrifugal acceleration of the system (Shklovskii 1970) and the vertical acceleration in the Galactic potential (Kuijken & Gilmore 1989) produce only negligible effects on the measured $a_l = |c\dot{P}/P|$. The differential Galactic rotation (Damour & Taylor 1991) can contribute at most a positive $\sim$10%, $\sim$2%, and $\sim$25% to the observed $\dot{P}/P$ of PSRs J1701−3006A, J1701−3006B, and J1701−3006C, respectively; hence, we conclude that the sign of the line-of-sight accelerations is dominated by the radially symmetric mean

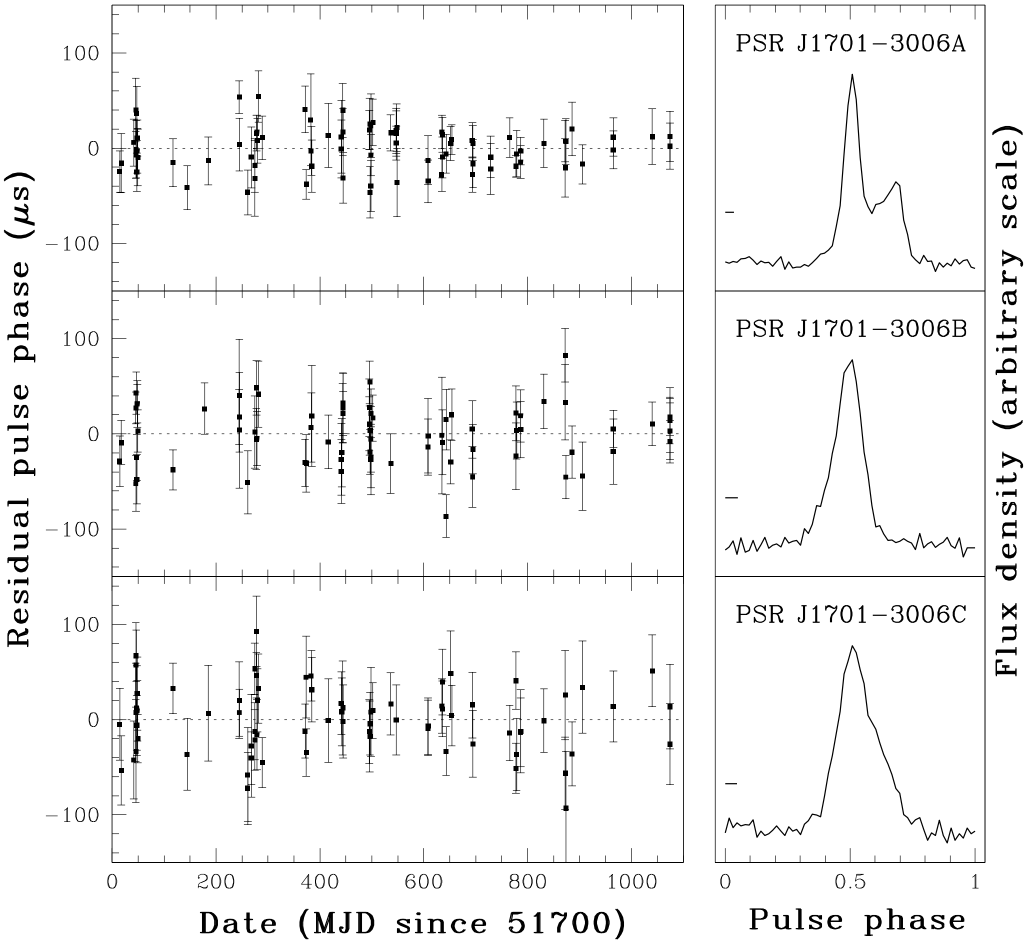

FIG. 1.—Postfit timing residuals as a function of the MJD of observation (*left*) and integrated pulse profiles at a central frequency of 1390 MHz (*right*) for the three MSPs in NGC 6266 discussed in this paper. The short horizontal line on the left side of each pulse profile represents the time resolution of the integrated profile including DM smearing.

gravitational field of the GC and that the three MSPs are located behind the plane of the sky through the cluster center.

The maximum possible a_l due to the mean gravitational field in NGC 6266 is given by the following relation (accurate at the 10% level for $\Theta_\perp \lesssim 2\Theta_c$; Phinney 1992):

$$a_{l,\max} = \frac{3}{2}\frac{\sigma_l^2}{D(\Theta_c^2 + \Theta_\perp^2)^{1/2}} , \qquad (1)$$

where $\sigma_l = 14.3 \pm 0.4$ km s^{-1} is the line-of-sight velocity dispersion (Dubath, Meylan, & Mayor 1997) and $D = 6.9 \pm 1.0$ kpc is the distance (Brocato et al. 1996). Θ_c and $\Theta_\perp$ are, respectively, the angular core radius and the angular displacement with respect to the GC center, located at R.A. $17^{\rm h}01^{\rm m}12\overset{\rm s}{.}8$, decl. $-30°06'49''$ (J2000.0; Harris 1996[13]). In particular, for a pulsar with negative $\dot{P}$ the following inequality must hold:

$$\left|\frac{\dot{P}}{P}(\Theta_\perp)\right| = \left|\frac{a_l}{c}(\Theta_\perp)\right| - \frac{\dot{P}_i}{P} < \frac{a_{l,\max}(\Theta_\perp)}{c} , \qquad (2)$$

where c is the speed of light.

The observed lower limit on the magnitude of the line-of-sight acceleration of PSR J1701−3006B, $a_l = 2.9 \times 10^{-6}$ cm s^{-2}, is the third-largest after those of PSRs B2127+11A and B2127+11D in M15 (Anderson et al. 1990) and is almost identical to those of the two MSPs with negative $\dot{P}$ recently discovered in the central regions of NGC 6752 (D'Amico et al. 2002). For NGC 6752, the high values of $\dot{P}$ imply a central mass-to-light ratio larger than that from optical estimates (D'Amico et al. 2002). For NGC 6266 on the other hand, the top panel in Figure 3 shows that the parameters derived from optical observations can entirely account for the large $\dot{P}/P$ of PSR J1701−3006B (the vertical size of the points in Fig. 3 represents the contribution to a_l/c due to the differential Galactic rotation). In particular, applying equation (1) of D'Amico et al. (2002), we derive a lower limit on the central mass-to-light ratio (expressed in solar units) for NGC 6266, $\mathcal{M}/\mathcal{L} = 1.6$, which is compatible with the optical value reported in the literature, 2.0 (Pryor & Meylan 1993). Similarly, from the observed $\dot{P}/P$ of J1701−3006A (corrected for the Galactic contribution) and equation (7) of Camilo et al. (2000), the inferred lower limit $\rho_0 = 2.1 \times 10^5\ M_\odot$ pc^{-3} of the central mass density of NGC 6266 is within the limits obtained from optical data (Pryor & Meylan 1993). These results suggest that, even though all three clusters display a compact core and very high line-of-sight accelerations for the embedded pulsars,

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[13] For the 2003 revision of the Harris catalog, see http://physun.physics.mcmaster.ca/~harris/mwgc.dat.

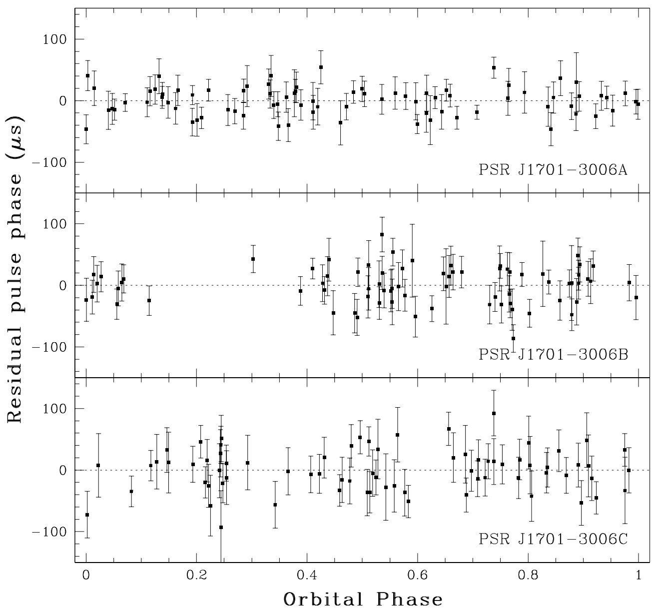

FIG. 2.—Postfit timing residuals as a function of orbital phase for the three MSPs in NGC 6266 discussed in this paper. All the orbits have been uniformly sampled except that of PSR J1701−3006B, for which we have excluded from the fit the TOAs in the region of the eclipse.

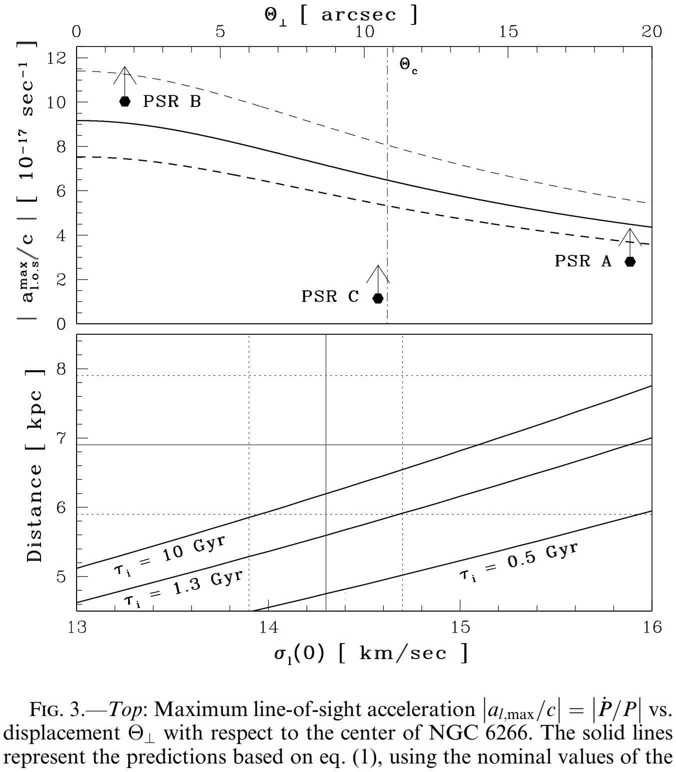

FIG. 3.—*Top*: Maximum line-of-sight acceleration $|a_{l,\max}/c| = |\dot{P}/P|$ vs. displacement $\Theta_\perp$ with respect to the center of NGC 6266. The solid lines represent the predictions based on eq. (1), using the nominal values of the distance and line-of-sight dispersion velocity, and the dashed lines their 1 σ uncertainties, obtained from the available optical observations (see text). The dot-dashed vertical line marks the assumed angular core radius $\Theta_c = 10''.8$ (Harris 1996). The points represent lower limits to the line-of-sight accelerations based on the timing solutions for the three MSPs. The vertical size of the points corresponds to the contribution to $|\dot{P}/P|$ due to the Galactic potential. *Bottom:* Constraints on the age of PSR J1701−3006B obtained from eqs. (1) and (2). The thin solid lines and the dotted lines represent the values of the parameters reported in literature and their 1 σ uncertainties, respectively. An intrinsic characteristic age of PSR J1701−3006B larger than about 1 Gyr is compatible with the available observations.

the dynamics in the inner region of NGC 6266 is probably more similar to that of M15, for which $2 < \mathcal{M}/\mathcal{L} < 3$ was inferred by Phinney (1993).

The satisfactory match between the dynamical parameters of NGC 6266 constrained from pulsar timing observations and those derived from optical data allows use of the latter for deriving reliable constraints on the age and surface magnetic field of the MSPs. For instance, the bottom panel in Figure 3 shows that the intrinsic characteristic age of PSR J1701−3006B should be greater than ∼1.3 Gyr, to be consistent with the cluster's distance and velocity dispersion (including their 1 σ uncertainties). This, in turn, implies an upper limit on the surface magnetic field of $B_s = 3.2 \times 10^{19} \left(P\dot{P}\right)^{1/2} = 4.0 \times 10^8$ G. Less stringent limits can be similarly derived for PSR J1701−3006A ($\tau_i \gtrsim 0.15$ Gyr and $B_s \lesssim 17 \times 10^8$ G) and PSR J1701−3006C ($\tau_i \gtrsim 25$ Myr and $B_s \lesssim 31 \times 10^8$ G). These values are typical for MSPs, in both GCs and the Galactic disk.

4. RANGE OF DISPERSION MEASURES

The MSPs in NGC 6266 show the second-largest range in DM (a maximum deviation $\Delta \mathrm{DM} = 0.9$ cm^{-3} pc with respect to the average, $\mathrm{DM}_{\rm ave} = 114.34$ cm^{-3} pc) after PSR B1744−24A and PSR J1748−2446C in Terzan 5 (Lyne at al. 2000). This large range is probably due to a significant gradient in the Galactic electron column density across different lines of sight toward the cluster, an interpretation supported by the strong variations in reddening observed across this cluster: $\delta E = \Delta E(B-V)/E(B-V) = 0.19/0.48$ for an angular displacement of $\Delta\theta_E \sim 7'$ (as derived from Fig. 3 of Minniti, Coyne, & Claria 1992). Alternately, the variations may have a local origin, as in the case of 47 Tuc, where pulsar timing observations show that they are due to a plasma permeating the cluster (Freire et al. 2001). The same explanation has been proposed in the cases of M15 (Freire et al. 2001) and NGC 6752 (D'Amico et al. 2002). For NGC 6266, the electron number density of a uniform, fully ionized gas would be surprisingly high, $n_e = 1.6 \pm 0.4$ cm^{-3}, at least an order of magnitude larger than that estimated for the other clusters. The determination of positions, accelerations, and precise DMs of the additional MSPs discovered in this cluster (Jacoby et al. 2002) will help in determining the origin of the scatter in DM.

5. THE ABSENCE OF ISOLATED PULSARS IN NGC 6266

In contrast to other GCs in which at least five pulsars have been discovered (in order of decreasing number of pulsars: 47 Tuc, M15, and NGC 6752), all the MSPs known in NGC 6266 are in binary systems (including the three detected by Jacoby et al. 2002). The absence of known isolated pulsars in NGC 6266 cannot simply be ascribed to a selection effect, since for a given spin period and flux density, an isolated MSP is easier to detect than a binary MSP. Unfortunately, the observational biases affecting the fraction $\mathscr{F}_{\rm is}$ of isolated pulsars discovered in a given cluster (with respect to the total observed MSP population) are difficult to quantify precisely. Considering all the other clusters, $\mathscr{F}_{\rm is} \gtrsim \frac{2}{5}$. If this ratio applies to NGC 6266, the probability of having the first six detected pulsars be all binary is $\lesssim 5\%$.

TABLE 2

Encounter and Disruption Rates for Binaries in Four Globular Clusters

Cluster	Isolated PSRs	Binary PSRs	$\mathscr{R}_{\rm form}$	$\mathscr{R}_{\rm disr}$	$\mathscr{R}_{\rm form}/\mathscr{R}_{\rm disr}$
NGC 6266.......	0	6	1.4	2.5	0.57
NGC 6752.......	4	1	0.19	3.4	0.056
M 15	7	1	1.0	5.5	0.19
47 Tuc	7	15	1.0	1.0	1.00

Notes.—$\mathscr{R}_{\rm form}$ is estimated as $\propto \rho_0^{1.5} r_c^2$, whereas $\mathscr{R}_{\rm disr} \propto \rho_0^{0.5} r_c^{-1}$ (see text for details). All the values are normalized to the parameters of 47 Tuc. Central luminosity density ρ_0 and core radius r_c are obtained from the catalog of Harris 1996; the 2003 catalog revision is available at http://physun.physics.mcmaster.ca/~harris/mwgc.dat.

If this absence of isolated pulsars in NGC 6266 is not a statistical fluctuation, it must relate to the mechanisms of formation of these objects and their interplay with the dynamical state of the cluster. The few isolated MSPs observed in the Galactic disk (where $\mathscr{F}_{\rm is} \sim \frac{1}{3}$) are thought to be endpoints of a rare process of ablation and eventually evaporation of the companion star by the energetic flux of particles and electromagnetic waves emitted by the pulsar (e.g., Ruderman, Shaham, & Tavani 1989). Besides this formation channel, the isolated MSPs seen in GCs can also result from close stellar encounters disrupting a binary system that had previously been through the recycling process (e.g., Sigurdsson & Phinney 1993).

This suggests that NGC 6266 is now in a dynamical state in which the rate $\mathscr{R}_{\rm form}$ of formation (and hardening) of binary systems containing a neutron star (and suitable for producing new MSPs) is much larger than the rate of disruption $\mathscr{R}_{\rm disr}$ of such systems. This idea is supported by comparison of the relevant rates with those of other clusters. Table 2 summarizes the values of $\mathscr{R}_{\rm form}$ and $\mathscr{R}_{\rm disr}$ for the four clusters containing at least five known pulsars. $\mathscr{R}_{\rm form}$ scales as the rate of close encounters in the cluster, in turn proportional to $\rho_0^{1.5} r_c^2$, where ρ_0 is the central luminosity density and r_c the core radius of the cluster (Verbunt 2003). Inspection of Table 2 shows that the expected frequency of close encounters in the core of NGC 6266[14] is 40% larger than that of M15 and 7 times that of NGC 6752. Although the numbers of known pulsars in these clusters are similar, the comparison of their radio luminosities (see discussion in § 2) indicates that NGC 6266 hosts many more pulsars than NGC 6752, in accordance with the trend suggested by the values of $\mathscr{R}_{\rm form}$.

On the other hand, the probability that a binary, once formed, will experience a further encounter, which may change or split it (sometimes creating an isolated MSP), scales as $\mathscr{R}_{\rm disr} \propto \rho_0^{0.5} r_c^{-1}$ (Verbunt 2003). Hence, large values of the ratio $\mathscr{R}_{\rm form}/\mathscr{R}_{\rm disr} \propto \rho_0 r_c^3$ should indicate that more neutron stars are in binary systems than are isolated. As Table 2 shows, this prediction roughly conforms with the numbers for the three GCs having collapsed cores: NGC 6266 (six binary pulsars) has a ratio $\mathscr{R}_{\rm form}/\mathscr{R}_{\rm disr}$ a few times larger than M15 (one binary and seven single pulsars) and NGC 6752 (one binary and four single pulsars).

Despite these encouraging agreements, the scaling relations may miss many factors that could strongly differentiate the pulsar population in the clusters, e.g., the mass-to-light ratio, the mass function in the core, the neutron star retention fraction, the period distribution of the binary systems, and the effects of the collapse of the core. The last point could be especially relevant, as the only non-collapsed cluster containing more than five known pulsars, 47 Tuc, fits with the predictions based on $\mathscr{R}_{\rm form}$ but does not satisfy those related to $\mathscr{R}_{\rm disr}$ (see Table 2)—its binary disruption rate should be less than half that of NGC 6266, but it hosts several isolated MSPs, with a value of $\mathscr{F}_{\rm is}$ similar to that seen in the Galactic field, where dynamical encounters are unimportant in the formation of isolated MSPs.

Detailed numerical simulations are required to investigate if trapping of almost all the neutron stars in close binary systems can really occur, for instance, during the phase immediately preceding the core collapse or its reversal.

6. THE ECLIPSES IN PSR J1701−3006B

PSR J1701−3006B displays partial or total eclipses of the radio signal at 1.4 GHz near the superior conjunction, i.e., at orbital phase 0.25 (see Fig. 4), clearly due to gas streaming off the companion. A typical event starts at orbital phases in the range 0.15–0.20 and ends at orbital phase ~0.35, hence sometimes displaying a slight asymmetry with respect to the expected nominal center of the eclipse at phase 0.25. At both eclipse ingress and egress, the pulses usually exhibit excess propagation delays (see Figs. 4 and 5). The eclipse region covers up to 20% of the entire orbit, but as illustrated in Figure 4, unpredictable irregularities affect both the duration and the appearance of the eclipses. Sometimes the pulsation remains barely visible (see, e.g., Fig. 4*a*), while on other occasions the pulse is totally eclipsed for a large portion of the event (e.g., Fig. 4*e*). In a favorable case (Fig. 4*b*), it has been possible to measure a slight reduction of the S/N of the pulse (although at the 1 σ level only; see caption of Fig. 5) as the pulsar signal crosses the region of interaction with the matter released by the companion.

Pulse broadening and reduction of the S/N prevent investigation of the frequency-dependent behavior of the delays in our 256 MHz bandwidth. However, assuming that they are completely due to dispersion in an ionized gas (as shown for other eclipsing pulsars; e.g., Fruchter et al. 1990; D'Amico et al. 2001c), the corresponding electron column density variations ΔN_e may represent a first viable explanation of the eclipse phenomenology. With $\Delta N_e \sim 1.5 \times 10^{18} \Delta t_{-3}$ cm^{-2}, where Δt_{-3} is the delay at 1.4 GHz in milliseconds, whenever $\Delta t_{-3} \lesssim 2$ (which could be the case for the entire events in Figs. 4*a* and 4*b*), the implied pulse broadening over the receiver bandwidth $\Delta P_{-3} = 0.36 \Delta t_{-3}$ ms is at most 80% of the intrinsic pulse width (~$0.50P$ at 10% of the peak). Hence, the pulse may be only largely broadened (with an implied reduction of S/N) but not disappear completely. On other occasions, the delays may increase much more rapidly, possibly growing well beyond $\Delta t_{-3} = 2$. In this case, the DM variations alone could completely smear the signal, causing a total disappearance of the pulsations.

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[14] The absence of pulsars in long-period orbital systems (easily destroyed in dynamical interactions) suggests that close encounters have been occurring at a significant rate in the central region of NGC 6266 since a time at least comparable to the cluster relaxation time, ~1.5 Gyr at the half-mass radius (Harris 1996).

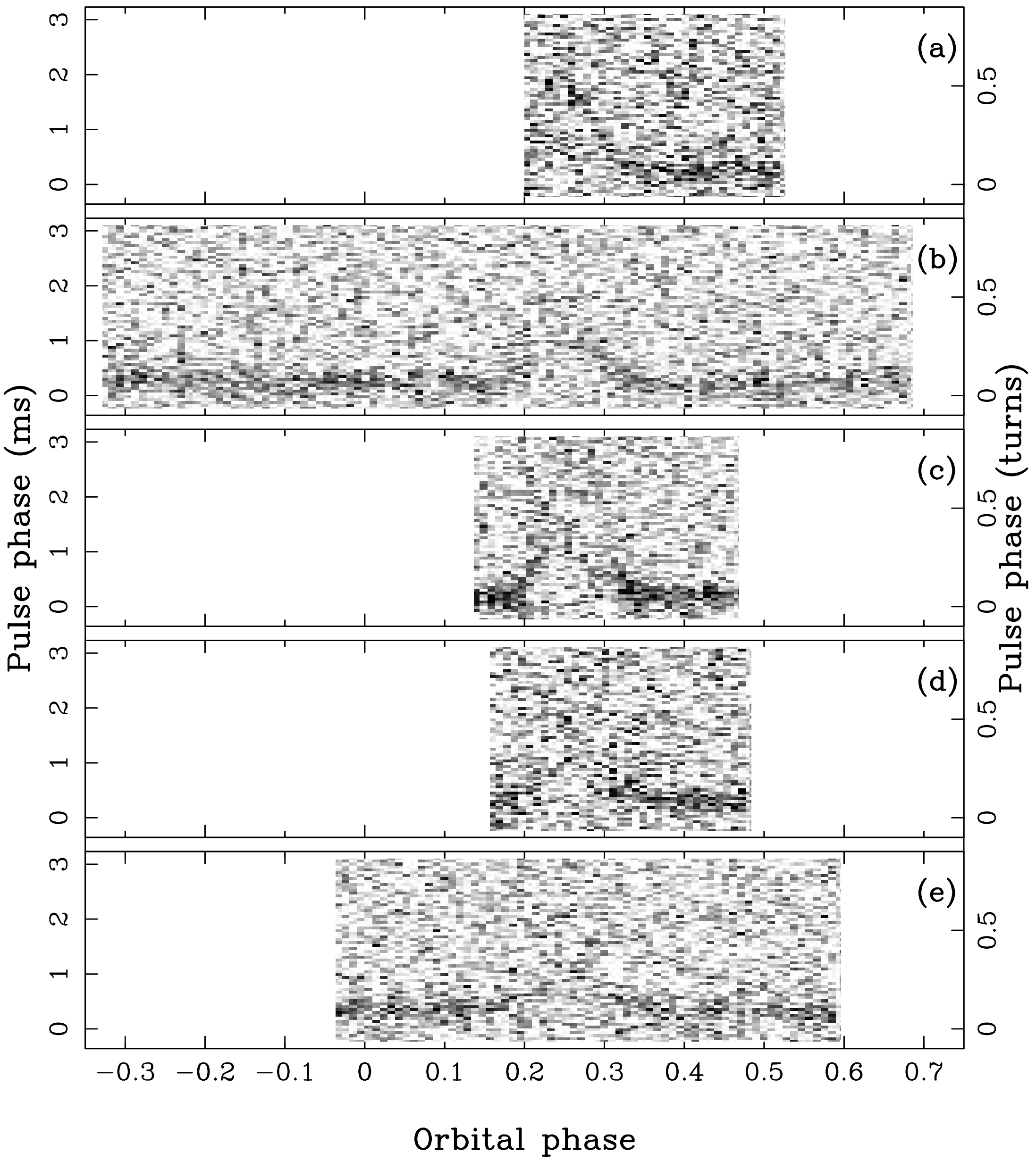

FIG. 4.—Observed signal intensity as a function of orbital phase and pulsar phase for five observations of PSR J1701−3006B centered at 1390 MHz with a bandwidth of 256 MHz. Eclipses are expected to occur around the superior conjunction (phase 0.25). The data are processed in contiguous integrations of 120 s duration. (*a*) A ∼68 minute observation starting on 2002 November 27 at 05:41 UT. (*b*) A ∼210 minute observation starting on 2003 January 26 at 00:01 UT. (*c*) A ∼69 minute observation starting on 2000 July 21 at 07:54 UT. (*d*) A ∼68 minute observation starting on 2002 July 10 at 07:12 UT. (*e*) A ∼131 minute observation starting on 2002 April 29 at 13:52 UT.

Alternatively, free-free absorption of the radio waves in an ionized envelope of matter released from the companion and expanding adiabatically can explain both the weakening and the total disappearance of the radio signal. The optical depth for this process can be written (see Spitzer 1978; Rasio, Shapiro, & Teukolsky 1989) as

$$\tau_{\rm ff} = 0.74\left(\frac{a}{1.32\ R_\odot}\right)\left(\frac{0.8\ R_\odot}{R_E}\right)^2\left(\frac{10^4\ {\rm K}}{T}\right)^{3/2}\Delta t_{-3}^2\ , \quad (3)$$

where the orbital separation a and the radius of the eclipse R_E, defined to be the chord at radius a subtended by the angle between the orbital phase of eclipse ingress and orbital phase 0.25, are scaled for PSR J1701−3006B (assuming an orbital inclination of 60°; see below), T is the temperature of the fully ionized gas, and Δt_{-3} is the observed delay in milliseconds at the border of the event. Relatively small delays ($\Delta t_{-3} \lesssim 0.4$) imply only a small reduction in the observed flux density [$\tau_{\rm ff}(\Delta t_{-3}) \lesssim 0.1$], whereas $\Delta t_{-3} \gtrsim 1$ would be accompanied by significant or complete absorption of the signal. Interferometric observations of the unpulsed continuum and observations at other wavelengths will help to clarify the nature of the eclipses.

The occurrence of eclipses suggests that the orbital inclination i is not small. For $i = 60°$, the median of all possible inclination angles, and an assumed pulsar mass of 1.40 $M_\odot$, $M_{c,60} = 0.14\ M_\odot$. For $i \gtrsim 30°$, the companion mass spans the interval 0.12–0.26 $M_\odot$, corresponding to a Roche lobe

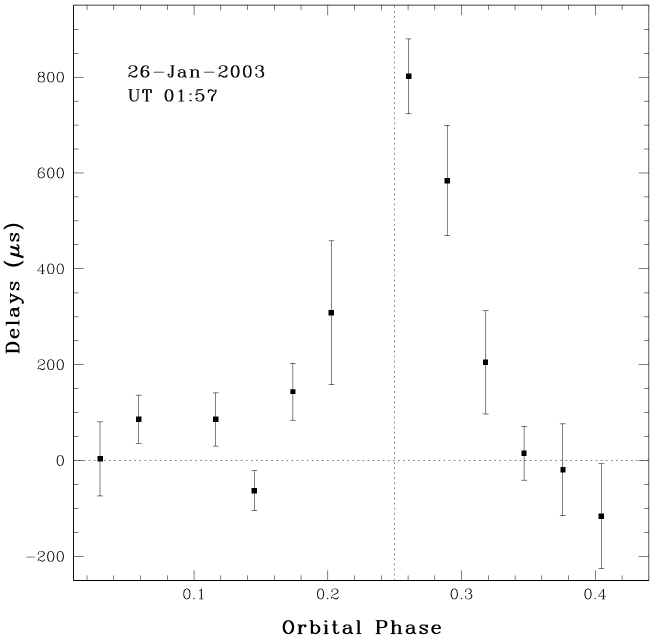

Fig. 5.—Excess group delays of the signal of PSR J1701−3006B, measured on 2003 January 26 (UT time refers to orbital phase 0.25). The observation was centered at 1390 MHz, with a bandwidth of 256 MHz, and the data are processed in contiguous 360 s integrations. The error bars are twice the formal uncertainty in the pulse arrival times. The average value of the S/N within the eclipse region is 4.6 ± 0.6, whereas it is 5.7 ± 0.5 (1 σ uncertainty) outside.

radius in the range $R_L = 0.26$–$0.34\ R_\odot$. Hence, independent of the eclipse mechanism, the extension of the eclipsing cloud, $\gtrsim 0.8\ R_\odot$, is larger than R_L, and the cloud must be continuously refilled with matter released from the companion. The plasma density in the eclipse region is $\rho_E \sim 1.6 \times 10^{-17} \Delta t_{-3}$ g cm^{-3}, and assuming isotropic emission, mass continuity implies that the donor star loses gas at a rate $\dot{M}_c = 4\pi R_E^2 \rho_E v_f \sim 1.0 \times 10^{-12} \Delta t_{-3} v_{f,8}\ M_\odot$ yr^{-1}, where $v_{f,8}$ is the wind velocity at R_E in units of 10^8 cm s^{-1} (the order of magnitude of the escape velocity from the surface of the companion).

If the companion is a helium white dwarf (whose maximum radius is $R_{\rm wd} = 0.04\ R_\odot$ for masses greater than 0.12 $M_\odot$ and $T \lesssim 10^4$ K; Driebe et al. 1998), and assuming isotropic emission of the pulsar flux, a significant fraction $f = (0.04$–$0.2) \times \left(3.7 \times 10^{34} \text{ ergs s}^{-1}/\dot{E}\right)$ of the energy deposited onto the companion surface is necessary for releasing the observed $\dot{M}_c$ (where $\dot{E}$ is the spin-down power of the pulsar and 3.7×10^{34} ergs s^{-1} its upper limit derived using the arguments of § 3). However, the energy requirements are more easily satisfied for a nondegenerate, bloated companion (as appears to be the case in most eclipsing binary pulsars; Applegate & Shaham 1994). For example, $f = (0.0004 - 0.002) \times \left(3.7 \times 10^{34} \text{ ergs s}^{-1}/\dot{E}\right)$ for a donor with the radius of a main-sequence star of the same mass, that is, 3–10 times larger than that of a white dwarf. Mass loss from the donor star can be sustained by ablation of its loosely bound surface layers by the relativistic wind emitted by the pulsar. This model has been successfully applied to explain the radio eclipses in close orbital systems having very light companions, e.g., PSRs B1957+20 (Fruchter et al. 1990) and J2051−0827 (Stappers et al. 2001). As with these other systems, the apparent mass-loss rate from the companion to PSR J1701−3006B is very small; the ablation timescale $\tau_{\rm abl} = \chi M_{c,60}/\dot{M}_c = \chi 140$ Gyr, where χ is the ionized fraction, is longer than the upper limit on the pulsar age (i.e., the cluster age), unless $\chi < 0.09$.

Following an alternate interpretation, the PSR J1701−3006B system may resemble that of PSR J1740−5340, where the effects of the pulsar irradiation are negligible in triggering the eclipsing wind from the secondary star (D'Amico et al. 2001c), and the eclipses (or the excess propagation delays, sometimes seen far from the nominal phases of eclipse) are caused by matter overflowing the Roche lobe of the donor star because of the nuclear evolution of the companion (Ferraro et al. 2001). In that system, accretion of matter onto the neutron star is inhibited by the sweeping effect of the pulsar energetic wind, according to the so-called radio-ejection mechanism (Burderi, D'Antona, & Burgay 2002). We note that J1701−3006B shares with PSR J1740−5340 (1) a companion significantly more massive than those of PSRs B1957+20 and J2051−0827, (2) the occurrence of excess propagation delays at 1.4 GHz that are much larger (up to ~1 ms vs. a few tens of μs) than those observed in any of the systems having very low mass companions,[15] and (3) the presence of irregularities in the eclipses.

A new class of eclipsing recycled pulsars having relatively massive companions ($M_{c,60} = 0.10$–$0.22\ M_\odot$) is emerging from the GC searches. Besides PSR J1701−3006B in NGC 6266 and PSR J1740−5340 in NGC 6397, there are PSR B1744−24A in Terzan 5 (Lyne et al. 1990), PSR J0024−7204W in 47 Tuc (Camilo et al. 2000), and PSR J2140−2310A in M30 (Ransom et al. 2003), whereas no similar system has been detected in the Galactic field to date. A simple explanation for the overabundance of evaporating "black widow" pulsars in GCs with respect to the Galactic disk has been recently proposed by King, Davies, & Beer (2003): namely, the current companion of most of the eclipsing pulsars in globulars would be the swelled descendent of a turnoff star, which replaced the original white dwarf companion of the pulsar in an exchange interaction in the cluster core. This scenario posits that the radio-ejection mechanism (Burderi et al. 2001) is now operating in all the eclipsing MSPs and provides an evolutionary basis for separating the systems with very low mass companions from those having more massive donor stars; in the former, the mass loss would be driven by angular momentum loss through gravitational radiation, whereas in the latter the mass-loss rate would be determined by the nuclear evolution of the companion.

The relatively massive systems in GCs are good candidates for the optical detection of the donor star[16] and follow-up observations. Unlike the Galactic eclipsing systems, their age, metallicity, extinction, distance, and hence intrinsic luminosity and radius can be estimated from the parent cluster parameters (see, e.g., Edmonds et al. 2001a, 2002; Ferraro et al. 2001). In the case of J1740−5340 in NGC 6397, the companion is a red variable star of magnitude $V \sim 16.5$ (Ferraro et al. 2001), and stringent constraints have been set

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[15] A possible exception is the pulsar C in the GC M5 (S. M. Ransom 2003, private communication).

[16] In fact, the optical identification of the secondary star has been recently reported for two noneclipsing MSPs having companions with $M_{c,60} \sim 0.2\ M_\odot$: PSR J0024−7204T in 47 Tuc (Edmonds et al. 2003) and PSR 1911−5958A in NGC 6752 (Ferraro et al. 2003; Bassa et al. 2003).

on the effectiveness of the irradiation of the companion (Orosz & van Kerkwijk 2003), on the occurrence of the radio-ejection mechanism (Sabbi et al. 2003), and on the evolutionary path of the system (e.g., Burderi et al. 2002; Grindlay et al. 2002; Ergma & Sarna 2003).

More recently, the companion of the MSP J0024−7204W in 47 Tuc has been optically identified with a blue variable star of mean magnitude $V \sim 22.3$, probably a heated main-sequence star close to the center of the cluster (Edmonds et al. 2002). Unfortunately, the pulsar is weak and only occasionally detectable, which makes the system difficult to characterize (Camilo et al. 2000). In the case of PSR B1744−24A in Terzan 5, the strong obscuration toward the Galactic center ($\gtrsim 7$ mag in V) prevents detection of the optical counterpart, even with deep *Hubble Space Telescope* observations (Edmonds et al. 2001b).

Consequently, PSR J1701−3006B is likely to be a primary candidate for improving the modeling of eclipsing MSPs with relatively massive companions. Indeed, PSR J1701−3006B seems to be a twin of PSR J0024−7204W in 47 Tuc, with similar orbital parameters and hence minimum companion mass (Camilo et al. 2000). Also, the pulsar periods are comparable, 3.6 versus 2.4 ms. Moreover, unlike PSRs J1740−5340 and B1744−24A, both PSRs J1701−3006B and J0024−7204W reside well within one core radius of the parent cluster center and hence are in more similar environments. Assuming that the companion to PSR J1701−3006B has the same luminosity and colors as the companion to PSR J0024−7204W, its photometry would be feasible with deep exposures reaching V-magnitude 24.5. Photometry would of course be much easier if the companion fills its Roche lobe, as is believed to be the case in PSR J1740−5340.

The X-ray counterparts of two of the five eclipsing MSPs with relatively massive companions (namely, PSRs J1740−5340 and J0024−7204W) have been identified using *Chandra* observations (Grindlay et al. 2001a, 2001b). Their spectra appear significantly harder than those of most other known X-ray counterparts to MSPs in GCs. That suggests (Edmonds et al. 2002) that a nonthermal contribution to the X-ray emission, perhaps arising from shock interactions at the interface between the companion and pulsar winds, dominates over the thermal component seen in the other MSPs, which probably originates from heated magnetic polar caps on the neutron star. The identification of the X-ray counterpart of PSR J1701−3006B and a comparison of its X-ray hardness ratio with that of the other MSPs in NGC 6266 would test the above picture. Interestingly, a long *Chandra* pointing toward NGC 6266 shows that it hosts the largest number of X-ray sources (with luminosity greater than 4×10^{30} ergs s^{-1} in the 0.5–6.0 keV range) observed so far in a GC (Pooley et al. 2003). Possibly among the 51 detected sources is a significant population of neutron stars, of which the six pulsars discovered so far are a manifestation.

7. CONCLUSION

We have presented rotational and astrometric parameters of three binary millisecond pulsars located within 1.8 core radii of the center of the globular cluster NGC 6266. One of these systems, PSR J1701−3006B, displays eclipses for ∼20% of the orbit. In summary, we note the following:

1. The derived lower limits on the central mass density (2.1×10^5 $M_\odot$ pc^{-3}) and the central mass–to-light ratio ($\mathscr{M}/\mathscr{L} > 1.6$ in solar units) of NGC 6266 are consistent with optical estimates.
2. The large spread in the dispersion measures of the three MSPs is probably due to a significant gradient in the Galactic electron column density across different lines of sight toward the cluster.
3. Even though the nature of the eclipses cannot yet be fully constrained, the relatively low mass-loss rate from the secondary star makes it unlikely that PSR J1701−3006B will evaporate its companion.
4. The lack of known isolated pulsars in NGC 6266 is unlikely to be due to chance or observational bias and suggests that the cluster is in a dynamical phase favoring formation over disruption of binary systems containing a neutron star.

We thank the referee, Scott Ransom, for very helpful criticisms of the original manuscript. N. D'A. and A. P. received financial support from the Italian Space Agency (ASI) and the Italian Minister of Research (MIUR) under the Cofin 2001 national program. F. C. acknowledges support from NSF grant AST 02-05853. 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.

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