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PSR B1745−20 AND YOUNG PULSARS IN GLOBULAR CLUSTERS

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ABSTRACT

Recent searches for radio pulsars in globular clusters have targeted the millisecond pulsars (MSPs) that are expected to result from the spin-up of old neutron stars in low-mass X-ray binary systems. These surveys have been very successful, discovering 34 pulsars, most of which are old and probably recycled by accretion-powered spin-up in a binary system. However, three objects have properties that are more like those of the normal population of Galactic pulsars. Timing measurements of one such pulsar, PSR B1745−20, show that it is clearly associated with the cluster NGC 6440 and that it is solitary and young, with a large magnetic field. This pulsar, together with PSR B1820−30B in NGC 6624, establishes long-period pulsars associated with globular clusters as a distinct group that seems to have a completely different genesis to the MSP population in globular clusters. Produced at a comparable rate to the MSPs, the origin of such apparently young objects in very old stellar systems is not understood.

Subject headings: globular clusters: general — pulsars: general — pulsars: individual (PSR B1745−20)

1. INTRODUCTION

The radio pulsar PSR B1745−20 (PSR J1748−2021) was discovered in NGC 6440 in a survey of globular clusters with the 64 m Parkes radio telescope at 640 MHz. NGC 6440 is a particularly massive and dense cluster, and VLA observations have shown it to have a high radio flux density (Fruchter & Goss 1990), attributable either to radio pulsars or to X-ray binary systems. The pulsar was first detected in 1989 and confirmed soon after (Manchester et al. 1989) to be a solitary pulsar with a period of 289 ms, which is very long for a pulsar in a globular cluster. The pulse is weak and broad, occupying ~25% of the period.

Subsequent measurements were carried out using the 76 m Lovell telescope at Jodrell Bank at frequencies between 408 and 1660 MHz to determine the position and spin-down parameters. A total of 127 observations, each typically of 18 minutes duration, were made between 1989 December and 1994 November. For each observation, a mean pulse profile was formed by on-line folding of the data at the nominal topocentric period. Arrival times were obtained by convolving these profiles with an appropriate template and then correcting for Earth's motion using the JPL DE200 barycentric ephemeris (Standish 1982). A simple model for the pulsar's period, period derivative, and position was fitted to the barycentric arrival times (Manchester & Taylor 1977), yielding the results presented in Table 1; the positions of the radio source detected with the VLA (Fruchter & Goss 1990) and the cluster's core (Shawl & White 1986) are also listed. The broad, weak pulse and small ecliptic latitude of the pulsar result in a rather large timing-declination error. However, the position and pulsed flux density are consistent with those of the VLA source (1.45 ± 0.10 mJy) within the combined errors, and PSR B1745−20 is clearly the dominant (if not sole) contributor to the VLA source.

The pulsar lies at a distance of 6″ ± 3″ from the center of the target cluster, near the edge of the core, which has a radius of 7″ (Webbink 1985). The probability of a random field pulsar lying so close to the center of the target cluster in a primary telescope beam of 0°.5 diameter is less than 10^{-4}. The dispersion measure of 219 cm^{-3} pc indicates a distance of 5.3 ± 1.7 kpc, according to the distance model of Taylor & Cordes (1993). At a Galactic latitude of $b = +3°.8$, its distance above the Galactic plane is ~0.4 kpc, well within the 1 kpc layer of ionized gas that causes dispersion, so this distance estimate should be reliable. The cluster is believed to be 5.8 kpc away (Martins, Harvel, & Miller 1980), which is in good agreement with the distance of the pulsar. There can be little doubt that the pulsar is associated with NGC 6440.

The measured period derivative of PSR B1745−20 indicates that it is a relatively young pulsar, with a characteristic age of ~12 Myr and a surface magnetic flux density of 4×10^{11} G, a value more typical of pulsars in the Galactic plane than the $\lesssim 10^9$ G typical of other globular cluster pulsars. We note that the maximum line-of-sight acceleration, a_l, of the pulsar in the cluster's gravitational field is $\sim 2 \times 10^{-8}$ m s^{-2} (Phinney 1992), which implies a possible contribution to the period derivative of up to $\dot{P} = Pa_l/c \sim 0.02 \times 10^{-15}$ s s^{-1}, or only ~5% of the observed value.

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TABLE 1

MEASURED AND DERIVED PARAMETERS OF PSR B1745−20

Parameter	Value[a]
Epoch	MJD 49,215
Period, P	0.28860262639(4) s
Period derivative, $\dot{P}$	$0.400(1) \times 10^{-15}$ s s^{-1}
Dispersion measure, DM	220(1) cm^{-3} pc
Timing R.A., decl. (B1950.0)	$17^h45^m54^s.1(1)$, $-20°21'05''(30)$
Timing R.A., decl. (J2000.0)	$17^h48^m52^s.6(1)$, $-20°22'01''(30)$
VLA R.A., decl. (J2000.0)	$17^h48^m52^s.7(2)$, $-20°21'40''(3)$
Cluster R.A., decl. (J2000.0)	$17^h48^m52^s.65(5)$, $-20°21'34''.5(7)$
rms timing residual	13 ms
Mean flux density at 400 MHz	10(4) mJy
Mean flux density at 1660 MHz	1.5(5) mJy
Pulse width (FWHM)	70 ms
Characteristic age, $\tau_c = P/(2\dot{P})$	12×10^6 yr
Surface magnetic flux, B	0.4×10^{12} G
Pulsar distance, d	5.8 kpc
Luminosity, $L_{400} = S_{400}d^2$	340 mJy kpc^2

[a] Numbers in parentheses following the measured parameters represent the estimated uncertainty in the last quoted digit.

2. YOUNG PULSARS IN GLOBULAR CLUSTERS

Altogether, four pulsars with periods in excess of a few tenths of a second have been found in globular cluster searches. In addition to PSR B1745−20, in NGC 6440, PSR B1820−30B is clearly associated with the globular cluster NGC 6624 because it has the same dispersion measure as the millisecond pulsar (MSP) PSR B1820−30A, which lies in the core of the cluster (Biggs et al. 1994). Of the other two pulsars, PSR B1718−19 is very probably associated with the cluster NGC 6342 (Lyne et al. 1993) because of the close positional coincidence in a region of modest Galactic pulsar surface density ($b = +10°$), while the position of PSR B1744−24B and its association with the cluster Terzan 5 have not been established and we consider it no further.

There are thus at least two, and probably three, pulsars associated with globular clusters with periods P, characteristic ages $\tau_c = P/2\dot{P}$, and magnetic fields B similar to those of the general pulsar population in the Galactic plane (Table 2). Their unlikely properties are demonstrated in Figure 1, which shows the P-B diagram for all known pulsars. Most of the pulsars in globular clusters lie in the region occupied by low magnetic field, short-period objects, which are thought to be old neutron stars that have been spun up by accretion in binary systems. The three pulsars discussed above, however, lie in the main body of the normal pulsar population. Moreover, two of the three are solitary pulsars, unlike many of the MSPs in globular clusters. It is a great surprise to find these young pulsars in globular clusters, mainly because of the apparent implication of neutron star formation only $\sim 10^7$ yr ago. Neutron stars are commonly believed to have formed in the supernovas of massive, young Population I stars, not from the old, low-mass, Population II stars that now inhabit the clusters. Consequently, the likely neutron star progenitors all lived and died within the first 10^8 yr or so of the 10^{10} yr lifetimes of the clusters.

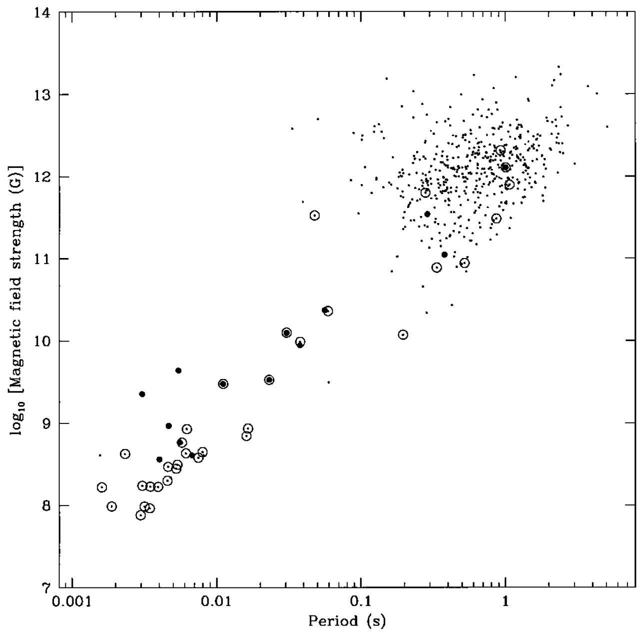

FIG. 1.—P-B diagram for all known pulsars with measured positive period derivatives. Pulsars thought to be associated with globular clusters are represented by large filled circles; the presence of a binary companion is indicated by open circles. Three globular cluster pulsars lie in the region occupied by the majority of normal Galactic pulsars.

A simple calculation indicates that, although these pulsars represent only $\sim$10% of the 34 pulsars discovered in globular cluster searches, their characteristic ages are 10% or less of those typical of the cluster MSPs (Phinney 1992; Robinson et al. 1995), so whatever process forms them occurs at least as frequently as the process that forms MSPs (Michel 1993). A somewhat better estimate of the relative birthrates can be obtained by comparing the values of $\Sigma(1/\tau_c)$ for the two groups, since they were discovered in the same surveys. Unfortunately, the period derivatives of many of the pulsars in globular clusters are contaminated by the effects of acceleration in the cluster gravitational field, and only upper limits to the values are available (Phinney 1992). Only nine of the MSPs have measured period derivatives that are reliable or only marginally affected by acceleration effects. The birthrate for these is $\lesssim 40$ Gyr^{-1}, which suggests a birthrate of $\lesssim 120$ Gyr^{-1} for the whole of the observed globular cluster MSP population, somewhat less than the ~ 180 Gyr^{-1} for the long-period group. Surveys have greater sensitivity to longer period pulsars, but this is likely to be offset by smaller beaming factors for these pulsars (Lyne & Manchester 1988).

It is worth noting that MSPs are typically associated with clusters of modest mass and central density while the long-

TABLE 2

LONG-PERIOD PULSARS IN GLOBULAR CLUSTERS

PSR	Cluster	P (ms)	$\dot{P}$ (10^{-15} s s^{-1})	τ_c (Myr)	B (10^{12} G)	d (kpc)	S_{400} (mJy)	L_{400} (mJy kpc^2)
B1718−19	NGC 6342	1004	1.6	10	1.5	11.6	3	400
B1745−20	NGC 6440	289	0.4	12	0.4	5.8	10	340
B1820−30B	NGC 6624	379	0.03	200	0.11	6.4	3	120

period pulsars seem to have formed in the massive, high-density, metal-rich clusters of the Galactic bulge. Table 2 shows that, despite their small flux densities, the observed long-period pulsars are very luminous and probably represent a much larger population of weaker objects. If these pulsars have the same luminosity function as the normal Galactic population, then the globular cluster system may contain as many as 10^3 active long-period pulsars with luminosities greater than 1 mJy kpc^2.

3. DISCUSSION

There seem to be two main possibilities for the origin of these apparently young, long-period pulsars. The first is that the neutron stars were formed recently, in the accretion-induced collapse (AIC) of a massive white dwarf (Grindlay & Bailyn 1988). While it is not clear that this process occurs sufficiently often (Narayan & Popham 1989), it might provide a relatively quiet collapse to a neutron star, with a small enough kick to keep it bound to the cluster. The point here is that the birth velocities of normal pulsars in the Galaxy have been shown to have a mean value of 400–500 km s^{-1} (Lyne & Lorimer 1994), and only a small fraction have sufficiently small velocities that they would remain bound to a cluster. These velocities probably arise from asymmetry in the supernova collapse of the cores of the progenitor stars. It is conceivable that the formation kicks in AICs would be much smaller than in the supernovas that produce normal pulsars (Helfand, Ruderman, & Shaham 1983). Those formed with larger kicks may be ejected from the parent cluster; this may explain the observations of young pulsars at large distances from the Galactic plane but moving toward it (Harrison, Lyne, & Anderson 1993).

The second possibility is that the neutron stars were formed shortly after cluster formation in the supernovas of massive stars, remained bound to the cluster, and lived their normal pulsar lives of 10^7–10^8 yr. They will have spun down to very long periods and sunk into the cluster core until they were caught up in collision and tidal capture with noncompact stars (Fabian, Pringle, & Rees 1975; Di Stefano & Rappaport 1992), which subsequently caused mild spin-up, so "rejuvenating" them.

The main problem with these two formation mechanisms is finding some process to remove the companion star within the last 10^7 yr, a very short time for a further collision to disrupt the system or for ablation by pulsar radiation to evaporate the companion. While PSRs B1745−20 and B1820−30B are both single, PSR B1718−19 still has its companion.

A rather more attractive variant is that the collision was a recent direct hit of a neutron star with a noncompact star, followed by a brief common-envelope phase and tidal disruption of the companion star (Krolik, Meiksin, & Joss 1984; Becker & Helfand 1987). The neutron star would experience a mild spin-up from the resulting accretion disk, possibly accompanied by a mild accretion-induced reduction of the magnetic field (Phinney & Kulkarni 1994). This requires that the $\sim 10^{12}$ G birth magnetic fields of neutron stars do not decay substantially over their 10^{10} yr lifetimes and that such neutron stars exist in large numbers in the cores of globular clusters. It may be that some intermediate-period, solitary pulsars, such as PSRs B2127+11A and B in M15, were spun up in a similar manner. We note that the required collisions will be more frequent in massive clusters like those in which these long-period pulsars are indeed found. These clusters are also more likely to have retained a significant fraction of the neutron stars formed within them in their early years.

The unexpected youth of these objects in old globular clusters is akin to the surprising presence of blue stragglers, which are hot luminous stars, more massive ($\lesssim 1.6\ M_\odot$), and hence younger than stars at the current turnoff (Stryker 1993; Bailyn 1995). While they are not generally thought to be massive enough to be the progenitors of pulsars, it has been suggested that low-metallicity stars with masses as small as this might be capable of forming neutron stars (Jura 1986). On the other hand, it may just be that both owe their apparent youth to stellar collisions in the cores of their parent clusters.

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