Millisecond Radio Pulsars in 47 Tucanae

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Abstract. We review the properties of the 22 millisecond radio pulsars currently known in the globular cluster 47 Tucanae, and their implications for the mass and gas content of the cluster. Further details can be found in the publications from this project to date (Camilo et al. 2000; Freire 2000; Freire et al. 2001a,b; Freire et al. 2003). Throughout the review, we look ahead to the future results anticipated from this fascinating cluster.

1. Parkes Observations of 47 Tucanae: 1990–Present

The globular cluster 47 Tucanae (hereafter 47 Tuc) contains the highest number of radio pulsars currently known in any cluster, and about a third of the total number of known cluster pulsars. Early searches at 50 and 70-cm wavelengths using the Parkes telescope discovered the first 11 millisecond pulsars in 47 Tuc by the mid 1990s (Manchester et al. 1990; Manchester et al. 1991; Robinson et al. 1995). Four of the pulsars had binary companions with a median orbital period of 30 hr. Significant modulation of the pulsar signals by interstellar scintillation meant that most pulsars were not detected regularly at these wavelengths; consequently, timing solutions were only possible for two pulsars.

Interest in 47 Tuc was renewed in the late 1990s following the installation of the sensitive 20-cm Parkes multibeam receiver. Using the central beam of this system, a further nine pulsars (all members of binary systems) were discovered by Camilo et al. (2000). The high incidence of binary systems was largely a result of the use of acceleration search techniques in this survey which permitted the detection of short orbital period systems. In addition to better sensitivity, regular observations with the 20-cm system provided more frequent detections of the pulsars. This allowed timing solutions for 16 pulsars to date (Freire et al. 2001a; 2003). Since 1999, data have been acquired using a high-resolution (512 \times 0.5 MHz) filterbank which has resulted in a threefold increase in time resolution (Freire et al. 2003). Searches of these data are on-going, with recent (so far unpublished) discoveries of 4.771 and 2.196 ms binary pulsars. Currently the total number of millisecond pulsars known in 47 Tuc stands at 22.
2. Profiles, Luminosities and Spin Periods

The current sample of 22 millisecond pulsars in 47 Tuc display similar emission properties to their counterparts in the Galactic disk. In their compilation of pulse profiles, Camilo et al. (2000) noticed a similar number of components and incidence of interpulses to the sample of disk millisecond pulsars studied by Kramer et al. (1998). A large sample of pulsars at a common distance means that the flux density distribution is a direct measure of the luminosity distribution. Freire (2000) found that the form of the 1400-MHz luminosity function over the interval 1–10 mJy kpc$^{-2}$ is a power law with a slope of $-1$, similar to that found for the pulsars in M15 (Anderson 1992), and the population of normal and millisecond pulsars in the Galactic disk (e.g. Lyne et al. 1998). Assuming a spectral index of $-2$, the observed 1400-MHz luminosities scale roughly to a 400-MHz luminosity interval of 10–100 mJy kpc$^{-2}$. Based on the detection of $\sim 20$ pulsars in 47 Tuc, the population of objects with 400-MHz luminosities above 1 mJy kpc$^{-2}$ beamed towards us is of order 200 (Camilo et al. 2000).

![Figure 1](image)

Figure 1. (a): Spin period distribution for the 22 currently known 47 Tuc pulsars. The thick line shows the sensitivity curve for the Camilo et al. search (linear scale). (b): Dispersion measure relative to cluster center ($\Delta DM$) versus $\dot{P}/P$ for the 16 pulsars with timing solutions. (c): $\Delta DM$ versus derived radial position in the cluster. The dashed line is the best fit assuming a constant electron density.

The spin periods of all 22 pulsars lie in the range 2–8 ms (Fig. 1a). The absence of long-period pulsars is a real effect. Particularly striking is the dearth of pulsars in the 1–2 ms bin compared to 19 objects currently known between 2 and 5 ms. Whether this dropoff at 500 Hz is a real effect (Bildsten, these proceedings) or due to observational selection is currently a matter for debate. The theoretical period sensitivity curve shown in Fig. 1a suggests that the 1–2 ms pulsars should be almost as easy to detect as the 2–8 ms pulsars. We are currently searching the high-resolution data to place much more stringent limits on the pulsar population with periods below 2 ms than the Camilo et al. search.

3. Binary Pulsars

The current population of binary pulsars in 47 Tuc bifurcates into two main groups: those with orbital periods of order 0.4–2.3 days and companion masses $\sim 0.2 M_\odot$ and the so-called very low-mass binary systems which are characterized
by shorter orbital periods (1.5–5.5 hr) and lighter companions (∼ 0.02 M⊙). Five binaries (J, O, R, V and W) are eclipsed for some portion of the orbit by their companion stars. Of these, J, O and R belong to the very-low-mass group.

The acceleration searches employed by Camilo et al. revealed a much higher incidence of binary systems in 47 Tuc than the earlier searches. Currently, 15 of the 22 pulsars (68%) are in binary systems and the median orbital period is 5 hours. The shortest orbital period found so far is the 95-min binary pulsar 47 Tuc R. This is the shortest orbital period currently known for any radio pulsar binary. Could this system and the 11-min orbit of the X-ray source in NGC 6624 (Stella, Friedhorsky & White 1987) be the tip of the iceberg of a large population of short-period binaries in globular clusters? Population syntheses (Rasio, Pfahl & Rappaport 2000) suggest that this may be the case. Sensitive acceleration searches are currently underway to probe this proposed population.

4. Astrometry

Phase-coherent timing solutions currently exist for 16 of the 22 pulsars (Freire et al. 2003) resulting in milliarcsecond positional determinations (or better in some cases). All 16 pulsars lie within 1.2 arcmin (4 core radii) of the cluster center, in spite of the fact that the radius of the 20-cm Parkes beam is 7 arcmin. This concentration suggests that the pulsars have reached thermal equilibrium (Rasio 2000; Freire et al. 2001a). The accurate positions have enabled CHANDRA and HST follow-up work on some of the pulsars (Heinke et al., these proceedings). The pulsar radial distribution is consistent with that of the soft X-ray sources.

Proper motions have now been measured for 11 of the pulsars and upper limits for 5 others (Freire et al. 2003). Currently the weighted mean of the pulsar proper motions is consistent with the optical proper motion (Odenkirchen et al. 1997) at the 3σ level. Pulsar proper motions are currently dominated by the bulk motion of 47 Tuc. In future, as the time baseline extends, it should be possible to measure pulsar motions with respect to the cluster center.

5. Probing the Mass and Gas in 47 Tuc

Currently, 10 out of the 16 pulsars with phase-coherent timing solutions are observed to have negative period derivatives ($\dot{P}_{\text{obs}} < 0$). Rather than being intrinsic to the pulsars, the most natural explanation for this apparent spin-up is the line-of-sight accelerations as the pulsars move within the gravitational potential of the cluster. Freire et al. (2001a) demonstrated that a simple King model potential was consistent with the observed period derivatives. Neglecting Galactic and proper motion terms we have $(\dot{P}/P)_{\text{obs}} = (a_l/c) + (\dot{P}/P)_{\text{int}}$, where $a_l$ is the line-of-sight acceleration. It follows that all pulsars with $\dot{P}_{\text{obs}} < 0$ are on the “far side” of the cluster. Assuming the intrinsic period derivative $\dot{P}_{\text{int}} > 0$ implies $a_l/c > (\dot{P}/P)_{\text{obs}}$. A lower bound on $a_l$ can be used to place a lower bound on the surface mass density of the matter interior to the pulsar, $\Sigma$ (see e.g. Phinney 1992). The most stringent constraint so far is for 47 Tuc S (Freire et al. 2003) which lies, in projection, about 12′′ from the center of the cluster. For this pulsar $a_l > 1.3 \times 10^{-6}$ cm s$^{-2}$ implies $\Sigma > 8.4 \times 10^4$ M⊙ pc$^{-2}$. 
Perhaps the most striking result from the radio pulsars in 47 Tuc to date is the combination of the above $\dot{P}$ data with high-precision measurements of the pulsar dispersion measures which has permitted the detection of ionized gas within the cluster (Freire et al. 2001b). This is shown in Fig. 1b where those pulsars with higher dispersion measure are all on the far side of the cluster ($\dot{P}_{\text{obs}} < 0$). Under the assumption of a King model potential, and an intrinsic $\dot{P}/P$ for each pulsar similar to those known in the Galactic disk, Freire et al. (2001b) calculated the radial distance along the line of sight for each pulsar and, as shown in Fig. 1c, showed that this strongly correlates with dispersion measure, implying a mean free electron density of $0.067 \pm 0.015 \text{ cm}^{-3}$. Within the central region of 47 Tuc occupied by these pulsars, this corresponds to a total gas content of $\sim 0.1 \, M_\odot$. This value is much less than the $\sim 100 \, M_\odot$ expected to accumulate within the cluster core over $10^{7-8}$ yr (Roberts 1996).

So where has all the gas gone? As proposed by Spergel (1991), one mechanism is from the pulsars themselves. For a typical millisecond pulsar spin-down luminosity $\dot{E} = 10^{34} \text{ ergs s}^{-1}$, the energy required to expel the gas can be provided by only 0.5% of $\dot{E}$ for a total population of $\sim 200$ pulsars. Somewhat ironically, the very objects responsible for the detection of gas in 47 Tuc might also be responsible for much of its ejection during the last billion years.

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