

PERIOD DERIVATIVE OF THE MILLISECOND PULSAR IN GLOBULAR CLUSTER M28

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ABSTRACT

We have measured the period derivative of the recently discovered 3 ms pulsar PSR 1821–24 reported by Lyne and colleagues in 1987 located near the center of globular cluster M28. While the observed slow-down rate, $\dot{P} = 1.6 \times 10^{-18} \text{ s s}^{-1}$, is somewhat larger than expected, it is still consistent with models of millisecond pulsar evolution that involve spin-up during mass accretion from an orbiting companion star. It is possible that a substantial fraction of the observed period derivative could be the result of a gravitational encounter with a neighboring star in the cluster core. The probability of observing such an event is rather small, however. Timing residuals have so far placed constraints on the possibility of PSR 1821–24 being in a wide binary system. Continued timing observations should provide, through tests of the constancy of $\dot{P}$ and measurement of the pulsar's proper motion, interesting results concerning gravitational dynamics near the core of M28.

Subject headings: astrometry — clusters: globular — pulsars

I. INTRODUCTION

PSR 1821–24, the first known pulsar in a globular cluster and the second fastest of all known pulsars, holds potentially important clues concerning the formation and evolution of neutron stars, especially those created in globular clusters. Even before its confirmed existence as a radio pulsar, Blandford, Romani, and Applegate (1987) showed that this object might be usable as a sensitive *in situ* probe of the gravitational potential in the core of M28. The proposed technique relies on high-precision timing observations of the pulsar, which should allow measurement of its intrinsic spin-down rate as well as perturbations caused by gravitational encounters in the cluster. In this *Letter* we report the first results of such a program of timing observations, as well as an improved interferometer position measurement obtained to facilitate analysis of the timing data.

II. OBSERVATIONS AND RESULTS

a) Green Bank Timing Measurements

Timing measurements were made with the NRAO 42 m telescope at Green Bank, W.V. at an observing frequency of 1335 MHz. A dual-mode feed provided antenna sensitivity of 0.28 K Jy^{-1} in each sense of circular polarization, and cooled HEMT amplifiers yielded zenith system noise temperatures (including sky background and spillover contributions) of approximately 20 K. Pulse time-of-arrival data were recorded using equipment and procedures similar to those described by Taylor and Weisberg (1982). Briefly, signals from each circular polarization were converted to 30 MHz intermediate frequency and fed to a pair of 32 channel filter-bank spectrometers having bandwidths of 0.25 MHz per channel. The detected outputs from both polarizations were summed and introduced to a digitally clocked delay line to remove the

effects of interstellar dispersion. The dedispersed total power signal was averaged modulo the topocentric pulsar period, using 128 samples per period for PSR 1821–24. For comparison purposes, observations of the 1.5 ms pulsar PSR 1937+21 were also made before and after each set of measurements on PSR 1821–24; for the faster pulsar we sampled at a rate of 64 samples per period and used a total bandwidth of only 4 MHz. Average profiles were recorded every 2 minutes along with time tags from the observatory's hydrogen maser clock. This clock was calibrated against UTC (as kept at the US Naval Observatory) by using LORAN-C transmissions and signals from orbiting satellites in the Global Positioning System.

For PSR 1821–24 the data were further averaged in 30 minute segments to enhance the signal-to-noise ratio. The average profiles were cross-correlated with pulse templates to yield the effective arrival time. A total of 60 half-hour arrival-time estimates were obtained for PSR 1821–24, and 281 2 minute estimates obtained for PSR 1937+21, on 1987 July 1 and 2, September 8, 9, and 13, and October 14.

b) VLA Position Measurement

In order to obtain an accurate position measurement independent of the timing observations, we observed PSR 1821–24 with the Very Large Array at Socorro, N.M. in its A-configuration with angular resolution of $2''.0$ by $1''.0$ and the position angle of the major axis of the elongated beam close to zero. Observations were centered on 1465 and 1515 MHz and lasted for 1 hr on July 30 and 3 hr on August 5. The source 1748–253, assumed to lie at B1950.0 right ascension $17^{\text{h}}48^{\text{m}}45^{\text{s}}.791 \pm 0^{\text{s}}.007$, declination $-25^{\circ}23'17''.58 \pm 0''.15$ (Backer and Sramek 1982; Perley 1982) was used as a phase reference on both nights. There is a small unresolved inconsistency in the declination of 1748–253; the quoted declination error reflects this uncertainty.

TABLE 1
MEASURED PARAMETERS OF PSR 1821–24

Parameter	Value
VLA position measurement (FK4 coordinate system):	
Right ascension (B1950.0)	18 ^h 21 ^m 27 ^s .382 ± 0 ^o 010
Declination (B1950.0)	–24°53′50″95 ± 0″22
Assumed position (PEP740-R coordinate system):	
Right ascension (B1950.0)	18 ^h 21 ^m 27 ^s .407
Declination (B1950.0)	–24°53′50″96
Timing parameters:	
Period (s)	0.0030543144932 ± 6
Period derivative (10 ^{–18} s s ^{–1})	1.55 ± 0.07
Epoch (Julian Ephemeris Date)	2,446,977.61

The positions of PSR 1821–24 obtained on the two nights are consistent with the expected measurement uncertainties, differing by 0^o11 in right ascension and 0^o16 in declination. The average of the two positions is quoted in Table 1, together with an estimated uncertainty of 0^o22 in declination and 0^o14 in right ascension, made up of nearly equal contributions from random noise in the VLA data and from uncertainty in the absolute coordinates of 1748–253. The VLA flux density of the source PSR 1821–24 on August 5 was 2.0 mJy with an rms noise level of 0.08 mJy.

c) The Period Derivative

The topocentric pulse arrival times were transformed to the reference frame of the solar system barycenter and analyzed in the conventional manner (see, for example, Manchester and Taylor 1977; Rawley, Taylor, and Davis 1988). A least-squares fit for the period, period derivative, and initial phase of PSR 1821–24 yielded the parameters listed in Table 1, with a post-fit rms residual of 26 μ s. Because our measurements are rather sparsely sampled and span much less than a year, a robust solution including the celestial coordinates of the pulsar is not yet possible. (A trial solution including right ascension and declination as free parameters yielded results consistent with the VLA position, but with uncertainties $\sim 1'$.) The uncertainties quoted in Table 1 for P and $\dot{P}$ are dominated by an allowance for errors in the VLA position relative to the reference frame of the PEP740-R planetary ephemeris used in the timing analysis (see Becker and Hellings 1986).

The comparison observations of PSR 1937+21 were processed in almost the same manner as for PSR 1821–24. In order to reduce the volume of data and to make the post-fit residuals directly comparable for the two sources, arrival-time estimates for PSR 1937+21 were combined in 30 minute groups to yield 21 equivalent half-hour arrival times. The pulsar period and derivative were then determined as for PSR 1821–24 and found to be consistent with much more accurate values determined in recent observations at Arecibo Observatory (Rawley *et al.* 1987; Rawley, Taylor, and Davis 1988). PSR 1937+21 is nearly an order of magnitude stronger than PSR 1821–24, and in addition its pulse is narrower. For these reasons the post-fit residuals for PSR 1937+21 in the present observations were considerably smaller, approximately 4.9 μ s rms for the half-hour average arrival times.

Although our measured value for the slow-down rate of PSR 1821–24 is 1.6 times larger than the upper limit quoted by Lyne *et al.* (1987), periods extrapolated backward from our parameters are in excellent agreement with the Lyne *et al.* observations in 1987 June as well as the period derived in the

1986 December and 1987 January discovery observations (Middleditch *et al.* 1987). We conclude that the $\dot{P}$ quoted in Table 1 is reliable and that the previously published upper limit was somewhat underestimated.

III. DISCUSSION AND CONCLUSIONS

It is noteworthy that for our observed value of period derivative, the period of PSR 1821–24 is about a factor of 2 less than the equilibrium period P_{eq} estimated by Alpar *et al.* (1982) for a 1.4 $M_{\odot}$ neutron star spun up by accretion at the self-limiting “Eddington” rate in an evolving close binary system. A version of the equilibrium relation given recently by Verbunt *et al.* (1987) is

$$P_{\text{eq}} \approx 1.9 B_9^{6/7} \left(\frac{M}{1.4 M_{\odot}} \right)^{-5/7} \left(\frac{\dot{m}}{\dot{m}_E} \right)^{-3/7} R_6^{18/7} \text{ ms},$$

where B_9 is the strength of the dipole component magnetic field on the neutron star surface in units of 10^9 G, M is the mass of the pulsar, $\dot{m}$ is the accretion rate, $\dot{m}_E$ is the Eddington accretion rate, and R_6 is the pulsar radius in units of 10^6 cm. The leading numerical coefficient is derived from models of disk accretion by magnetized neutron stars which involve a number of simplifying assumptions (e.g., van den Heuvel 1977; Ghosh and Lamb 1979), and it could be uncertain by 50% or more. Conventional arguments imply that $B_9 \approx 3.2 \times 10^{10} (P \dot{I}_{45})^{1/2} R_6^{-3}$, where $I_{45} \approx M/M_{\odot}$ is the moment of inertia in units of 10^{45} g cm² (see, for example, Manchester and Taylor 1977). For our measured value of $\dot{P}$, the equilibrium condition can thus be restated in the form

$$P_{\text{eq}} \approx 5.6 \left(\frac{M}{1.4 M_{\odot}} \right)^{-1/2} \left(\frac{\dot{m}}{\dot{m}_E} \right)^{-3/4} \text{ ms};$$

for the observed period to be consistent with this relation requires some combination of an overestimated numerical coefficient, an unusually massive neutron star, or “super-Eddington” accretion during at least part of an earlier evolutionary phase. The required factor of ~ 1.8 does not seem to press credibility too far, however, and we conclude that most likely PSR 1821–24, like all other known pulsars with $P < 30$ ms, is a recycled pulsar that was spun up by accretion.

Attempts to interpret an appreciable fraction of the observed $\dot{P}$ as the result of dynamical effects within M28 appear improbable but cannot yet be ruled out. The mean stellar mass density near the core of M28 is probably $\sim 5 \times 10^4 M_{\odot} \text{ pc}^{-3}$ (Peterson and King 1975). This value corresponds to a typical separation of ~ 2000 astronomical units between $\sim 0.5 M_{\odot}$ stars, while the gravitational acceleration required to explain $\dot{P}$ on dynamical grounds would require such a star within ~ 140 AU of the pulsar. Although the pulsar will certainly experience such close encounters as it moves about within M28, the fraction of time spent within 140 AU of a neighboring star will be less than 10^{-4} . Thus it seems that the measured $\dot{P}$ is probably a good indicator of the intrinsic magnetic braking of PSR 1821–24.

It is somewhat surprising, nevertheless, that the spin-down age of the pulsar, $P/(2\dot{P}) = 30$ Myr, is so much smaller than both the pulsar “life expectancy” and the age of the cluster. One possible explanation, that has not been completely ruled out, is that the pulsar is in a very weak binary system. Assuming that the orbital radius is around 50 AU with moderate eccentricity, the effects of the binary orbit could be hidden

in the present residuals. Continued timing studies will resolve this question.

It has already been pointed out by Blandford, Romani, and Applegate (1987) that the apparent second period derivative of PSR 1821–24 will probably be dominated by the effects of cluster dynamics. With our present level of timing accuracy, the expected dynamical contribution to $\dot{P}$ should be detectable within 2 or 3 yr. On a similar time scale, continued timing observations should yield the pulsar's proper motion (or useful upper limits), thereby revealing its transverse motion and providing unambiguous information on gravitational interactions in the cluster environment. Contemporaneous long-term

timing of this and other known millisecond pulsars will also help to provide a data base for correlation studies of their timing residuals, from which one can set important constraints on the energy density of low-frequency gravitational radiation in the universe (see Rawley *et al.* 1987, and references therein).

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