1995ApJ...453..419L

THE ASTROPHYSICAL JOURNAL, 453:419–423, 1995 November 1

A MILLISECOND PULSAR IN A 6 HOUR ORBIT: PSR J0751+1807

S. C. LUNDGREN,[1,2,3,4] A. F. ZEPKA,[3,4] AND J. M. CORDES[3,4]

Received 1994 December 30; accepted 1995 May 8

ABSTRACT

A 3.48 ms pulsar in a 6.3 hr binary orbit has been discovered in a systematic survey of error boxes around unidentified gamma-ray sources. The spin-down energy of the pulsar is not sufficient to power the estimated γ-ray emission from the putative γ-ray source. The mass function, small orbit, low eccentricity, and large timing age imply that the companion is most likely a $0.12\ M_\odot < m_c < 0.6\ M_\odot$ white dwarf. Lack of eclipses or propagation delays varying with orbital phase imply that the companion is well contained inside its Roche lobe. Pulsar J0751+1807 fits into a class of small circular orbit (<30 days) objects which have undergone spiral-in. Examining the known population of short orbital period objects, we find a positive correlation between orbital period and magnetic field strength.

Subject headings: binaries: close — gamma rays: observations — pulsars: individual (PSR J0751+1807) — stars: fundamental parameters — white dwarfs

1. INTRODUCTION

Since the launch of the *Compton Gamma Ray Observatory* (*CGRO*) in 1991, pulsar studies have received substantial benefits from sensitive new γ-ray observations. The Energetic Gamma-Ray Experiment Telescope (EGRET) (Kanbach et al. 1989) has detected pulsations from five known young pulsars: B0531+21, B0833−45, Geminga, B1055−52, and B1706−44 (Ulmer et al. 1991; Fierro et al. 1993; Kniffen et al. 1992). Of those, B1055−52 and B1706−44 had not been detected previously in γ-rays.

In 1993 January, the EGRET team announced a list of high-energy γ-ray sources unidentified with any known source (Hartman et al. 1992). We predicted that some of the unidentified γ-ray sources could be the missing young pulsars predicted by pulsar birth models (Narayan & Ostriker 1990). For sources within the declination range of the Arecibo observatory, we conducted a radio pulsar search targeted at the γ-ray error boxes.

In our search we discovered a binary millisecond pulsar (MSP) J0751+1807. Unexpectedly, we found an old recycled pulsar, rather than a young pulsar. If J0751+1807 were associated with the γ-ray source, it would have been the first MSP detected in γ-rays. However, we find that the rotational spin-down energy is not sufficient to power the observed γ-ray emission. Improved analysis of the original EGRET data calls into question the reality of the γ-ray source. The source was not included in the final EGRET source catalog (Fichtel et al. 1993) because of its low significance ($<4\ \sigma$).

Although confirming J0751+1807 as the first γ-ray MSP now appears unlikely, several other properties give it a significant place in the population of MSPs. It has the shortest orbital period of any known pulsar in the Galactic disk. All known pulsars with shorter orbits represent a different population residing in globular clusters, in which the density of stars influences binary pulsar evolution. In two other tightly bound systems, PSR B1957+20 and PSR B1744−24A, the pulsar emission and wind are destroying the companion (Ruderman, Shaham, & Tavani 1989; Fruchter, Stinebring, & Taylor 1988; Shaham & Tavani 1991; Lyne et al. 1990). Studies of the J0751+1807 system, in comparison with similar pulsars, will identify factors which determine the amount of neutron star (NS) spin-up, orbital evolution, and disruption of the companion.

In § 2 we discuss the pulsar search observations made and the properties of the new MSP. Next, in § 3 we argue against association of the pulsar with the γ-ray source. Finally, in § 4 we determine where this system fits in evolutionary scenarios for recycled pulsars and what constraints we can place on such models with current and future observations.

2. OBSERVATIONS

EGRET conducted an all-sky survey from 1991 May through 1992 November of sources emitting high-energy γ-rays in the range 20 MeV to 30 GeV (Fichtel et al. 1993). Prior to publication of the full list of sources, the EGRET team released 12 sources which, so far, are unidentified at other frequencies (Hartman et al. 1992). We observed the seven sources that are in the Arecibo declination range (Table 1).

Identification of the new γ-ray sources as pulsars could not be made using the γ-ray data alone. The photon rate is so low ($\sim 100\ \text{week}^{-1}$) that a search for unknown periodicity is virtually impossible. However, radio emission from these sources, if they are pulsars and the radio beam points toward Earth, would be easily detectable in a few minute integration.

To collect the search data at Arecibo we used the 32 channel filter bank with 180 μs sampling and a 330 μs time constant at 430 MHz with a total bandwidth of 8 MHz. The $\sim 1°$ radius of the error boxes required 100–200 beam positions per source. A total of 680 beam areas were covered by the search.

For each position observed, 32 time series were generated, one for each trial dispersion measure (DM) used to sum the 32 frequency channels. The maximum DM used was 27 pc cm^{-3} for $|b| > 60°$ and 193 pc cm^{-3} for $|b| < 20°$. We used a standard method of pulsar searching by calculating harmonic sums in the Fourier transform of the time series to maximize sensitivity to low duty cycle pulsars. Candidates for reobservation must exceed a threshold set high enough to minimize the number of false detections, typically 9 σ. Full details of the analysis have been published elsewhere (Zepka 1995).

---

[1] Code 7210, Naval Research Laboratory, Washington, DC 20375; lundgren@rira.nrl.navy.mil.

[2] National Research Council Research Associate.

[3] Astronomy Department, Cornell University, Ithaca, NY 14853.

[4] National Astronomy and Ionosphere Center.

TABLE 1

Unidentified EGRET Source Error Boxes

Source Name	b	Error Radius	Number of Beams
GRO J0430+29......	−13	30	44
GRO J0539+25......	−3	45	99
GRO J0614+22......	3	30	44
GRO J0633+05......	−1	60	176
GRO J0749+17......	21	45	44
GRO J1220+16......	77	60	176
GRO J1221+23......	82	45	99

Our 3 minute integrations search a factor of 2.5 fainter than currently ongoing all-sky pulsar surveys at Arecibo (Foster, Wolszczan, & Camilo 1993; Camilo, Nice, & Taylor 1993; Thorsett et al. 1993b). We express our modeled estimate of the sensitivity at the zenith in terms of the data acquisition parameters as $S_{\rm min} = 0.5$ mJy $\eta^{0.5}(T_{\rm sys}/63\ {\rm K})$, where η is the pulse duty cycle and $T_{\rm sys}$ is the system temperature. The sensitivity given is the flux density averaged over the pulse period. For periods shorter than 3 ms, $S_{\rm min}$ increases by the ratio $(3\ {\rm ms}/P)^{1/2}$.

The pulsar was discovered with a signal-to-noise ratio of 20 on 1993 September 20 at a location 30′ from the center of the 48′ error box of CGRO J0749+17. Confirming observations were made on 1993 September 30. Timing observations using the Princeton Mark 3 timing system (Stinebring et al. 1992) have been ongoing since then. At 430 (1400) MHz, the timing data used the 32 channel filter bank across 8 (40) MHz with a 100 (39) μs time constant and 128 (512) phase bins across the pulse.

We calculated arrival times by cross-correlating 2 minute average profiles with high signal-to-noise templates (Fig. 1). The correlations are done in the Fourier domain as discussed by Taylor (1992). The software package TEMPO (Taylor & Weisberg 1989) translates the arrival times to the solar system barycenter using the JPL DE200 ephemeris and fits the pulsar spin-down and orbital parameters. Dispersion measure is estimated from the delay between 430 MHz and 1400 MHz arrival times. Dispersion smearing across a single channel is 0.79 ms at 430 MHz but only 0.1 ms at 1400 MHz. Figure 1 displays the 430 MHz profile at higher frequency resolution to achieve 0.03 ms time resolution. The Taylor & Cordes (1993) model for electron density of the interstellar medium predicts a distance $d = 2.0 \pm 0.4$ kpc. The parameters are displayed in Table 2. Figure 2 plots the residuals of the fit ($\sigma = 22\ \mu$s) and the measured period as a function of orbital phase.

TABLE 2

PSR J0751+1807 Parameters

Parameter	Value	Parameter	Value
α (J2000)	$07^{\rm h}51^{\rm m}09\overset{\rm s}{.}1582(7)$	l	$202\overset{\circ}{.}72962$
δ (J2000)	$18°07'38\overset{''}{.}71(5)$	b	$21\overset{\circ}{.}08588$
P................	3.47877078151(1) ms	$P_{\rm orb}$	6.31546243(1) hr
$\dot{P}$	$8.0(8) \times 10^{-21}$ s s^{-1}	$a_0 \sin i$	0.396615(2) lt-sec
Epoch (MJD)...	49301.0	T_0(MJD)...	49301.0317095(3)
DM.............	30.2471(2) pc cm^{-3}	e............	$<10^{-4}$
d................	2.0 ± 0.4 kpc	Ω...........	$219\overset{\circ}{.}195 \pm 47°$
$\dot{E}$	6.3×10^{33} ergs s^{-1}	$f(m_p, m_c)$ ...	0.00096739(2) $M_\odot$
B................	1.3×10^8 G	S_{430}........	10 mJy
τ_c	8.2×10^9 yr	S_{1400}.......	1 mJy

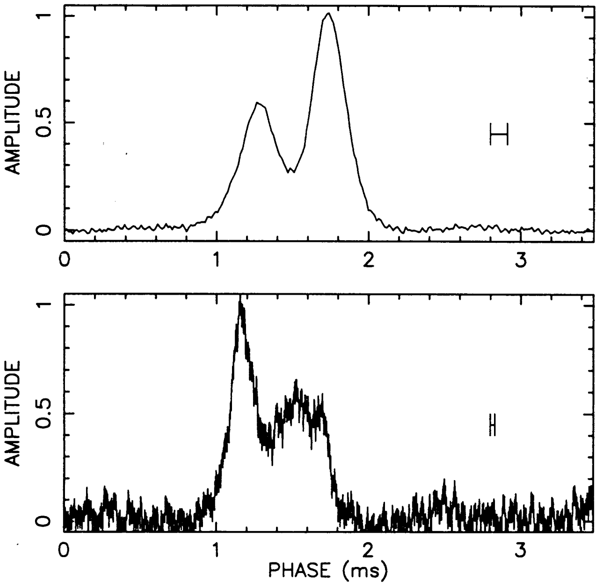

Fig. 1.—PSR J0751+1807 pulse profile at 1400 (*upper*) and 430 (*lower*) MHz. Each profile is an average of ~100 30 s integrations using the Mark 3 pulsar timing system for data acquisition. Bars indicate the amount of dispersion smearing in each profile.

3. SPIN-DOWN ENERGY, MAGNETIC FIELD, γ-RAY EMISSION

The most important question is whether the pulsar is losing enough spin-down energy to power the possible γ-ray emission. From the measured period derivative, $\dot{P} = 8.0 \times 10^{-21}$ s s^{-1}, we estimate the spin-down energy available and the surface magnetic field strength (B). For an NS with a moment of inertia $I = 10^{45}$ g cm^2, the power available from spin-down is $I\omega\dot{\omega} = 7.5 \times 10^{33}$ ergs s^{-1} ($\omega = 2\pi/P$). Assuming the spin-down results from magnetic dipole radiation, we estimate $B = 10^{8.1}$ G, comparable to other MSPs. Unless the transverse velocity (v_t) turns out to be particularly large, the kinematic contribution to $\dot{P}$ (Shklovskii 1970; Camilo, Thorsett, & Kulkarni 1994) does not significantly affect these results ($\dot{P} = 2 \times 10^{-21}$ s s^{-1} v_{100}^2 for $d = 2$ kpc, $v_{100} = v_t/100$ km s^{-1}).

From the γ-ray flux of $10^{-10.0}$ ergs cm^{-2} s^{-1} for the marginal EGRET source near the position of PSR J0751+1807, we

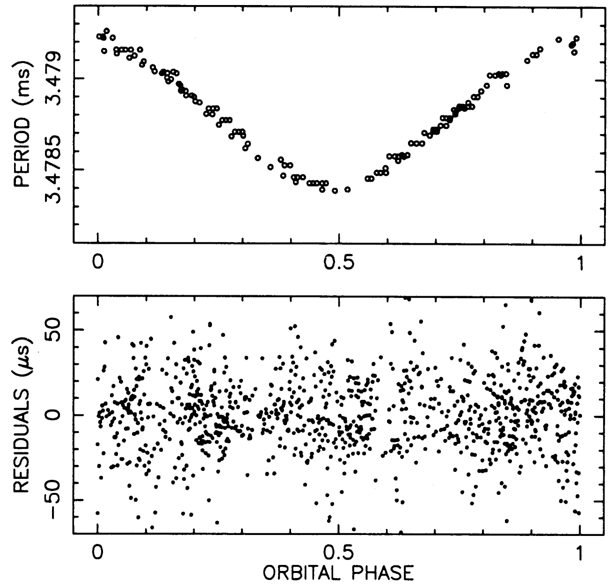

Fig. 2.—PSR J0751+1807 orbital fit. *Top frame*: variation of period over the orbit. *Bottom frame*: timing residuals vs. orbital phase for 1 yr of data.

estimate a γ-ray luminosity of $10^{34.0} f d_{\rm kpc}^2$ ergs s^{-1}, where f is the fraction of a sphere swept out by the beam. If the γ-ray beam size is similar to that observed in radio emission and the magnetic axis is not aligned with the spin axis, $f \sim 0.2$. For a distance of 2 kpc, the energy needed exceeds the spin-down energy available by a factor of 1.4, even with 100% efficiency for converting rotational energy into γ-rays. Efficiencies close to 100% are observed in the magnetospheric emission of some *young* γ-ray pulsars such as B1055−52 and Geminga (Fierro et al. 1993; Bertsch et al. 1992). However, such large efficiencies are not consistent with upper limits on γ-ray emission from *recycled* pulsars similar to PSR J0751+1807 (Fichtel et al. 1993). Sturner & Dermer (1994) summarized much of the work on emission models in which the γ-rays originate close to the polar cap. Efficiencies predicted by the models range from 0.001 to 0.1 (Dermer & Sturner 1994). All these models predict that no γ-rays should be observed from PSR J0751+1807. If PSR J0751+1807 does turn out to be a γ-ray emitter, it will have to be explained by a novel mechanism in order to differentiate it from all the other undetected MSPs.

We estimate the probability of random coincidence of an MSP with an error box in our survey to be $\sim$10%, based on one pulsar per 250 deg^2 found in other high-latitude pulsar searches (Camilo et al. 1993; Thorsett et al. 1993b), 7 deg^2 in our survey, and sensitivity a factor of 2.5 better in our survey than in other surveys. Especially in view of the fact that follow-up γ-ray observations with EGRET did not detect the original unidentified source, we conclude that we have discovered a pulsar that happened to be in the error box of a marginal EGRET source, but is not physically associated.

4. DISCUSSION

The 6 hr orbital period of PSR J0751+1807 is the shortest of any known pulsar outside of globular clusters, perhaps approaching the limiting evolutionary outcome for systems in its class. By examining the current NS and companion properties, we can trace the evolutionary history of the system and relate it to other known binary pulsars.

We predict the expected type of companion by combining our knowledge of the mass function, eccentricity, orbital size, and age into a coherent picture.

The mass function favors a low-mass companion. Figure 3 displays m_p versus m_c for several values of inclination angle i, using

$$f(m_p, m_c) = \frac{(m_c \sin i)^3}{(m_p + m_c)^2} = 4\pi^2 \frac{(a_0 \sin i)^3}{G P_{\rm orb}^2} = 9.7 \times 10^{-4}\, M_\odot\,, \tag{1}$$

where G is the gravitational constant. Although an NS companion ($m_c \sim 1.4\, M_\odot$) is possible for $6° < i < 10°$, a low-mass companion is far more likely. The 10^{-4} upper limit on eccentricity (e) adds to the argument against an NS companion, which would be in an eccentric orbit as a result of the mass loss in any second supernova explosion (Dewey & Cordes 1987; Bhattacharya & van den Heuvel 1991). All known NS-NS binaries are in highly eccentric orbits (Bailes et al. 1993). With 80% probability, the companion mass will fall in the range $0.1\, M_\odot < m_c < 0.6\, M_\odot$, for the expected range of pulsar mass, $1.1\, M_\odot < m_p < 1.8\, M_\odot$ (Finn 1994).

A low-mass companion could be either a white dwarf (WD) like J0437−4715 (Bell, Bailes, & Bessell 1993) or a stripped main-sequence (MS) turnoff star as proposed for PSR B1718−19 (Zwitter 1993). To evaluate these two possibilities, we compare the expected size and history of each type of companion with current observations. Lack of eclipses or extra radio timing delays at any orbital phase implies that the companion is currently fully contained inside its Roche lobe. However, in order for the NS to have been spun up, it must have accreted mass from the companion. The duration of the accretion phase is short compared with the 8 billion year spin-down time for J0751+1807.

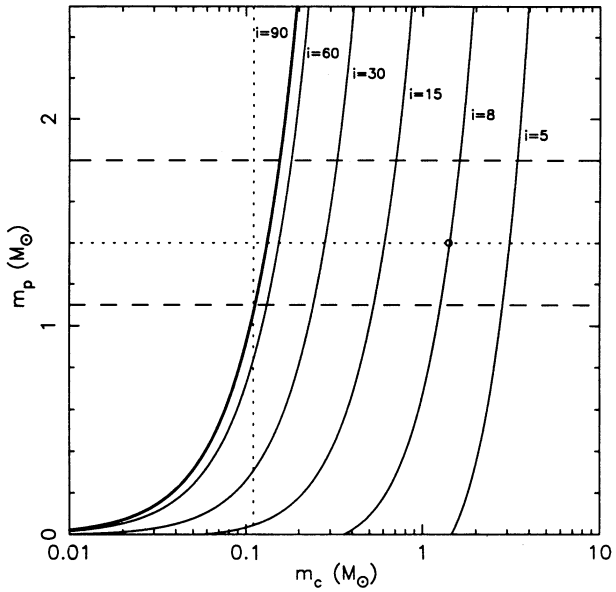

FIG. 3.—PSR J0751+1807 mass function. Solid curves indicate allowed combinations of m_p and m_c for several possible inclinations. Dashed lines delineate the range of reasonable values for m_p. Dotted lines correspond to $m_p = 1.4\, M_\odot$ (the canonical value) and $m_c = 0.11\, M_\odot$ (the Roche lobe–filling helium core mass). The NS-NS binary possibility is marked with an open circle.

Zwitter (1993) showed that an MS star with mass $< 0.5\, M_\odot$ could fit inside its Roche lobe in a 6.3 hr orbit. If the companion lost mass to the NS earlier and is still on the main sequence, it must still fill its Roche lobe. However, recent or current Roche lobe overflow is difficult to reconcile with lack of eclipses or propagation effects in the timing of the NS. In addition, the short duration of the giant to WD stage makes this an unlikely model for the system, particularly given its 8 billion year spin-down age (τ_c). These difficulties lead us to favor the WD model for the companion.

The helium core of the giant star progenitor of a WD companion must have fit inside the Roche lobe of the current orbit, since no significant orbit evolution could have occurred since the end of the accretion phase. Using two similar methods for estimating the upper limit on the mass of helium core fitting inside the Roche lobe of a 6.3 hr orbit (Joss, Rappaport, & Lewis 1987; Savonije 1987), we find $m_c \sim 0.11\, M_\odot$, just below the lower limit of mass allowed by the mass function for a 1.4 $M_\odot$ neutron star.

If the WD mass can be measured, using Shapiro delay or optical measurements, Figure 3 can be used to place upper limits on the NS mass. With current timing data, the Shapiro delay constraint on m_c is no better than the constraint already provided by the mass function with $m_p = 2\, M_\odot$ at any inclination. Even for an edge-on orbit, the limit on Shapiro delay gives $m_c < 0.2\, M_\odot$.

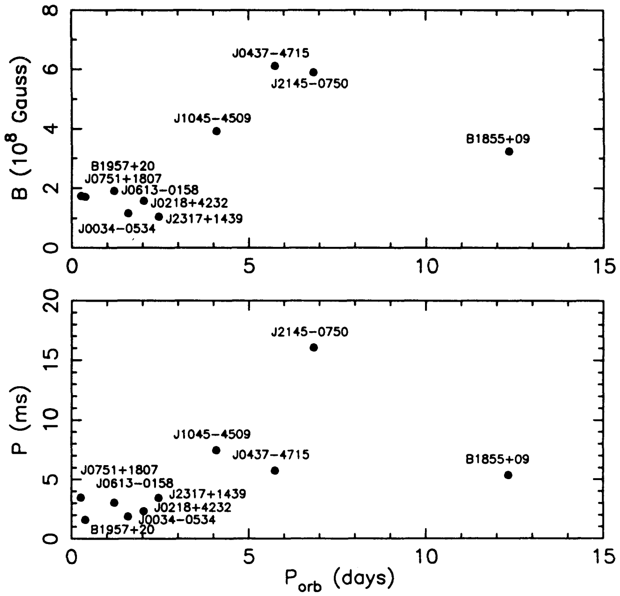

FIG. 4.—The pulsar surface magnetic field and spin period are plotted against orbital period for known pulsars to illustrate the correlations between these parameters for millisecond pulsars in compact circular orbits.

If the WD mass agrees with the prediction from the Roche lobe size (0.11 $M_\odot$), we find $m_p < 1.21$ $M_\odot$. Such a limit has important consequences for theories of NS formation and equations of state for nuclear matter (Thorsett et al. 1993a). These implications emphasize the importance of optical and timing measurements to verify predicted model-dependent constraints on the companion mass.

Finally, we summarize the most likely evolutionary model, based on measurements so far. The short orbital period and small eccentricity suggest that the NS spiraled in toward the companion and the orbit circularized during a low-mass X-ray binary phase. Substantial accretion at that time recycled the pulsar to less than its current 3.48 ms spin period. The mass function, large characteristic age, and lack of eclipses point toward a WD companion which is now fully contained inside its Roche lobe. The 0.11 $M_\odot$ mass of the helium core which filled its Roche lobe for the observed orbital period is an upper limit on the expected mass of the companion.

Looking at the population of known binary MSPs in the field (Camilo 1995, and references therein), several natural subclasses appear, each with a different evolutionary path. In orbital period, we distinguish between wide (>30 day) and small orbits. Those pulsars in wide orbits did not spiral in. The spiral-in of the pulsars in short orbits resulted in Roche lobe overflow of the companion helium core, in some cases substantially reducing the final WD mass. Of the known sources, $\sim\frac{1}{3}$ are in wide and $\sim\frac{2}{3}$ are in small orbits, suggesting a preference for spiral-in. Small-orbit systems are selected against in pulsar surveys, so the fraction with small orbits may be even larger.

Among the short orbital period objects, P_{orb}, P, and B are strongly correlated. The effect can be seen in Figure 4. All known sources with $P_{orb} < 3$ days have $B < 2 \times 10^8$ G and $P < 5$ ms, whereas those with 30 days $> P_{orb} > 3$ days have $B > 3 \times 10^8$ G and $P > 5$ ms. The disappearance of the correlation for small ranges of B or P_{orb} is expected as a result of variations in the parameters before recycling. The correlation indicates either that the magnetic field strength determines the amount of spiral-in and spin-up, or more spiral-in allows more accretion, which reduces the magnetic field by a larger amount. In either scenario, the wide-orbit binaries do not undergo spiral-in; hence, their orbital period is independent of magnetic field. More short-period systems will need to be found to confirm the magnetic field/orbital period connection.

Pulsar B1957+20 has such a strong spin-down power that it heats its companion to the point of evaporation. Some of the isolated MSPs could have met this fate as well, making it difficult to estimate how many pulsars maintain a strong enough magnetic field while approaching close enough to the companion for spin-down energy to evaporate the companion. With comparable pulsar companion separation to B1957+20, but 30 times less spin-down power, PSR J0751+18 emits too little energy to evaporate a companion similar to that of B1957+20. Companion-destroying pulsars provide a third possible explanation for a magnetic field/orbital period connection. Perhaps the higher field objects in the smaller orbits emit enough spin-down energy at the time the accretion stops to destroy their companion, thus converting the high-field, short-orbit systems to isolated MSPs.

We would like to thank F. Camilo for help with Mark 3 pulsar timing. We appreciate the aid of telescope operators A. Vazquez, W. Portalatin, and B. Santiago with Arecibo observing. Additional timing by A. Lyne at Jodrell Bank helped to determine the initial timing model. R. Nemiroff and J. Mattox provided us with the EGRET γ-ray results. We had enlightening discussions with R. Foster and S. Johnston. Basic research in precision pulsar astrophysics at the Naval Research Laboratory is supported by the Office of Naval Research. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under cooperative agreement with the National Science Foundation. This research was funded by NASA grants NAG 5-1452 and NAG 5-2436 and National Science Foundation grant AST 92-18075.

REFERENCES

Bailes, M., et al. 1993, ApJ, 425, L41
Bell, J. F., Bailes, M., & Bessell, M. S. 1993, Nature, 364, 603
Bertsch, D., et al. 1992, Nature, 357, 306
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1, 63
Camilo, F. 1995, Ph.D. thesis, Princeton University
Camilo, F., Nice, D., & Taylor, J. H. 1993, ApJ, 412, 41
Camilo, F., Thorsett, S. E., & Kulkarni, S. R. 1994, ApJ, 421, L15
Dermer, C. D., & Sturner, S. J. 1994, ApJ, 420, L75
Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780
Fichtel, C. E., et al. 1993, A&AS, 94, 13
Fierro, J. M., et al. 1993, ApJ, 413, L27
Finn, L. S. 1994, Phys. Rev. Lett., 73, 1878
Foster, R. S., Wolszczan, A., & Camilo, F. 1993, ApJ, 410, L91
Fruchter, A. S., Stinebring, D. R., & Taylor, J. H. 1988, Nature, 333, 237
Hartman, R. C., et al. 1992, BAAS, 24, 1155
Joss, P. C., Rappaport, S., & Lewis, W. 1987, ApJ, 319, 180
Kanbach, G., et al. 1989, in Proc. Gamma-Ray Observatory Science Workshop, ed. N. Johnson (Greenbelt: NASA), 2-1
Kniffen, D. A., et al. 1992, in AIP Conf. Proc. 280, Compton Gamma-Ray Observatory, ed. M. Friedlander, N. Gehrels, & D. J. Macomb (New York: AIP), 177
Lyne, A. G., et al. 1990, Nature, 347, 650
Narayan, R., & Ostriker, J. P. 1990, ApJ, 352, 222
Ruderman, M., Shaham, J., & Tavani, M. 1989, ApJ, 336, 507
Savonije, G. J. 1987, Nature, 325, 416
Shaham, J., & Tavani, M. 1991, ApJ, 377, 588
Shklovskii, I. S. 1970, Soviet Astron., 13, 562
Stinebring, D. R., Kaspi, V. M., Nice, D. J., Ryba, M. F., & Taylor, J. H. 1992, Rev. Sci. Instrum., 63, 3551
Sturner, S. J., & Dermer, C. D. 1994, A&A, 281, L101

Taylor, J. H. 1992, Philos. Trans. R. Soc. London A, 341, 117
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Taylor, J. H., & Weisberg, J. 1989, ApJ, 345, 434
Thorsett, S. E., Arzoumanian, Z., McKinnon, M. M., & Taylor, J. H. 1993a, ApJ, 405, L29
Thorsett, S., Deich, W., Kulkarni, S. R., Navarro, J., & Vasisht, G. 1993b, ApJ, 416, 182
Ulmer, M. P., et al. 1991, in Proc. Compton Observatory Science Workshop, ed. C. R. Shrader, N. Gehrels, & B. Dennis (Greenbelt: NASA), 253
Zepka, A. F. 1995, Ph.D. thesis, Cornell University
Zwitter, T. 1993, MNRAS, 264, L3