The Astrophysical Journal, 630:L61–L64, 2005 September 1

GETTING ITS KICKS: A VLBA PARALLAX FOR THE HYPERFAST PULSAR B1508+55

S. Chatterjee,[1] W. H. T. Vlemmings,[2,3] W. F. Brisken,[4] T. J. W. Lazio,[5] J. M. Cordes,[3] W. M. Goss,[4]
S. E. Thorsett,[6] E. B. Fomalont,[7] A. G. Lyne,[2] and M. Kramer[2]
Received 2005 June 17; accepted 2005 July 29; published 2005 August 15

ABSTRACT

The highest velocity neutron stars establish stringent constraints on natal kicks, asymmetries in supernova core collapse, and the evolution of close binary systems. Here we present the first results of a long-term pulsar astrometry program using the VLBA. We measure a proper motion and parallax for the pulsar B1508+55, leading to model-independent estimates of its distance ($2.37^{+0.23}_{-0.20}$ kpc) and transverse velocity (1083^{+103}_{-90} km s^{-1}), the highest velocity directly measured for a neutron star. We trace the pulsar back from its present Galactic latitude of $52\overset{\circ}{.}3$ to a birth site in the Galactic plane near the Cyg OB associations, and find that it will inevitably escape the Galaxy. Binary disruption alone is insufficient to impart the required birth velocity, and a natal kick is indicated. A composite scenario including a large kick along with binary disruption can plausibly account for the high velocity.

Subject headings: astrometry — pulsars: individual (B1508+55) — stars: kinematics — stars: neutron

1. INTRODUCTION

The high velocities of young radio pulsars relative to their progenitor stellar populations have been readily apparent, both in their proper motions and through the bow shock nebulae produced in some cases. Models to explain these high neutron star (NS) velocities have invoked the disruption of close binary systems (Blaauw 1961; Gott et al. 1970; Iben & Tutukov 1996), natal kicks from asymmetric supernova (SN) explosions (Shklovskii 1969; Dewey & Cordes 1987), and postnatal acceleration through the electromagnetic rocket effect (Harrison & Tademaru 1975). As the pulsar population velocity distribution has been elucidated (see, e.g., Arzoumanian et al. 2002; Hobbs et al. 2005), binary disruption and the electromagnetic rocket effect have required more extreme assumptions to remain viable, and natal kicks have emerged as the most plausible mechanism for NSs to gain high velocities. In turn, observed pulsar velocities have placed stringent constraints on SN core-collapse mechanisms. In simulations, a natal kick of the correct order of magnitude has been obtained from hydrodynamic and convective instabilities (Burrows & Hayes 1996; Janka & Mueller 1996), and more exotic mechanisms involving asymmetric neutrino emission in the presence of strong magnetic fields ($B \gtrsim 10^{15}$ G) have also been suggested (Arras & Lai 1999).

At this point, two caveats are worth careful attention. First, the current pulsar velocity distribution suffers from severe selection effects. The stellar progenitors of NSs inhabit the Galactic plane, as do we, and thus higher velocity pulsars spend less time within our detection volume than do lower velocity ones. The effect is exacerbated by pulsar searches that focus more heavily on the target-rich environment of the Galactic plane. The extremely successful Parkes Multibeam survey, for example, spans only $|b| < 5°$ (e.g., Manchester et al. 2001). Thus the observed velocity distribution is likely to be biased toward lower velocities.

Second, most pulsar distances (and hence velocities) are inferred from their pulsar dispersion measures ($\mathrm{DM} \equiv \int_0^D n_e\, dl$) and models for the Galactic distribution of electron density (n_e) along the line of sight (Taylor & Cordes 1993, hereafter TC93; Cordes & Lazio 2005, hereafter NE2001), which have substantial uncertainties. For example, the Guitar Nebula pulsar B2224+65 (Cordes et al. 1993) is a showcase example of ultrahigh transverse velocities, $V_\perp \approx 1640(D/1.9\ \mathrm{kpc})$ km s^{-1}, but the distance uncertainty in the NE2001 model implies that $V_\perp \lesssim 1000$ km s^{-1} cannot be ruled out. The highest extant model-independent estimate of a NS velocity is 630 ± 40 km s^{-1} for PSR B1133+16 (Brisken et al. 2002).

Here we present the first hyperfast pulsar ($V > 1000$ km s^{-1}) with a *model-independent* distance and transverse velocity measurement. PSR B1508+55 was part of a recently concluded astrometry program with the NRAO Very Long Baseline Array (VLBA), in which 27 pulsars were observed for eight epochs each, spanning 2 yr. This Letter serves to introduce the project, while comprehensive papers on our astrometric methods and parallax results for ∼20 pulsars are in preparation (W. F. Brisken et al.; S. Chatterjee et al.). Below we report astrometric results for the distance, velocity, and birth site of B1508+55 and discuss the implications of the high observed velocity.

2. OBSERVATIONS AND DATA ANALYSIS

B1508+55 was observed with the VLBA over eight epochs spaced by approximately 3 months between 2002 June and 2004 April. As a trade-off between increasing pulsar flux at lower frequencies and improved resolution as well as reduced ionospheric effects at higher frequencies, the observations were conducted between 1.4 and 1.7 GHz, with four frequency bands of 8 MHz each and dual polarization in each band. In order to retain visibility phase coherence, observations were phase-referenced by nodding between the target and a primary calibrator source (J1510+5702) ∼$1\overset{\circ}{.}5$ away, with a cycle time of 120 s on target and 90 s on the calibrator. Residual calibration errors (primarily from the unmodeled ionosphere over $1\overset{\circ}{.}5$) are much reduced by employing in-beam calibration (Fomalont et

---

[1] Jansky Fellow, National Radio Astronomy Observatory; and Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; schatterjee@cfa.harvard.edu.

[2] Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire SK11 9DL, UK.

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

[4] National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801.

[5] Naval Research Laboratory, Code 7213, Washington, DC 20375.

[6] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064.

[7] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903.

TABLE 1
Parameters for PSR B1508+55

Parameter	Value
Epoch	2003.0 (MJD 52,640)
α_0	$15^h09^m25^s.6211$
δ_0	$55°31'32''.331$
μ_α (mas yr^{-1})	-73.606 ± 0.044
μ_δ (mas yr^{-1})	-62.622 ± 0.088
π (mas)	0.415 ± 0.037
D (kpc)	$2.37^{+0.23}_{-0.20}$
$V_\perp$ (km s^{-1})	1083^{+103}_{-90}
l, b	$91^\circ.325$, $52^\circ.287$
μ_l, μ_b (mas yr^{-1})	-6.39, 96.06
Magnetic field B (G)	1.95×10^{12}
Spin-down age (yr)	2.34×10^{6}
$D_{\rm DM}$ (kpc)	1.9 (TC93), 0.9 (NE2001)

Notes.—All astrometric parameters are in the J2000.0 coordinate system. Absolute positions are referenced to J1510+5702 and have an uncertainty ~1 mas; μ_l, μ_b, and $V_\perp$ are corrected for differential Galactic rotation.

al. 1999; Chatterjee et al. 2001), which reduces the angular throw and eliminates the need for time interpolation. Thus the observations are finally referenced to a faint (~7.1 mJy) extragalactic source (J151148+554156) only 22'.6 away from the pulsar. The signal-to-noise ratio (S/N) for the pulsar was boosted by gating the correlator on at the expected times of arrival of pulses, using current pulse timing solutions obtained for each epoch from ongoing observations at the Jodrell Bank Observatory.

Data reduction was conducted in AIPS using a customized pipeline (W. F. Brisken et al. 2005, in preparation). Briefly, it included amplitude calibration based on system temperatures at each antenna, followed by calibration of the visibility phases, rates, and delays based on the observed visibility phases of the primary calibrator and the in-beam source. Consistency between epochs was ensured by constructing models of the primary and in-beam calibrators based on all eight epochs of data and using these models to iteratively calibrate each individual epoch.

The astrometric positions and position uncertainties were fit for a reference position, proper motion, and parallax using a linear least-squares algorithm. The random position uncertainties were determined by fitting Gaussians to the pulsar images at each epoch and frequency. Systematic errors were estimated by scaling the scatter in astrometric positions at each epoch. The scaling factor of 1.8 was determined such that the final reduced χ^2 for the fit was 1.0, with 59 degrees of freedom. The fit results are summarized in Table 1, and the proper-motion and parallax signatures are plotted in Figure 1. We find a proper motion $\mu_\alpha = -73.606 \pm 0.044$ mas yr^{-1}, $\mu_\delta = -62.622 \pm 0.088$ mas yr^{-1}, and a parallax $\pi = 0.415 \pm 0.037$ mas. We verify the robustness of the parallax estimate by omitting each epoch in turn from the fit and find that the results are consistent (within ~1 σ).

3. DISTANCE, VELOCITY, AND BIRTH SITE

From the measured parallax and proper motion, we calculate the one-dimensional probability distributions for the distance (D) and transverse velocity ($V_\perp$). We infer the most probable values and the most compact 68% confidence intervals as $D = 2.37^{+0.23}_{-0.20}$ kpc and $V_\perp = 1083^{+103}_{-90}$ km s^{-1}, the first measured *model-independent* NS velocity >1000 km s^{-1}.

The pulsar is at a large height above the Galactic plane ($z = D \sin b \approx 2.0$ kpc), where DM-based distance estimates are sensitive to the model Galactic electron density scale height. Based on the pulsar DM of 19.6 pc cm^{-3}, the model distance estimate is $1.9^{+0.3}_{-1.2}$ kpc from TC93, and 1.0 ± 0.2 kpc from NE2001. While TC93 is fortuitously close to the parallax distance, NE2001 produces a significant underestimate, implying a much lower electron density along part of the line of sight. Such a reduction may possibly be due to voids or "chimneys" (Norman & Ikeuchi 1989) associated with the Cygnus super-

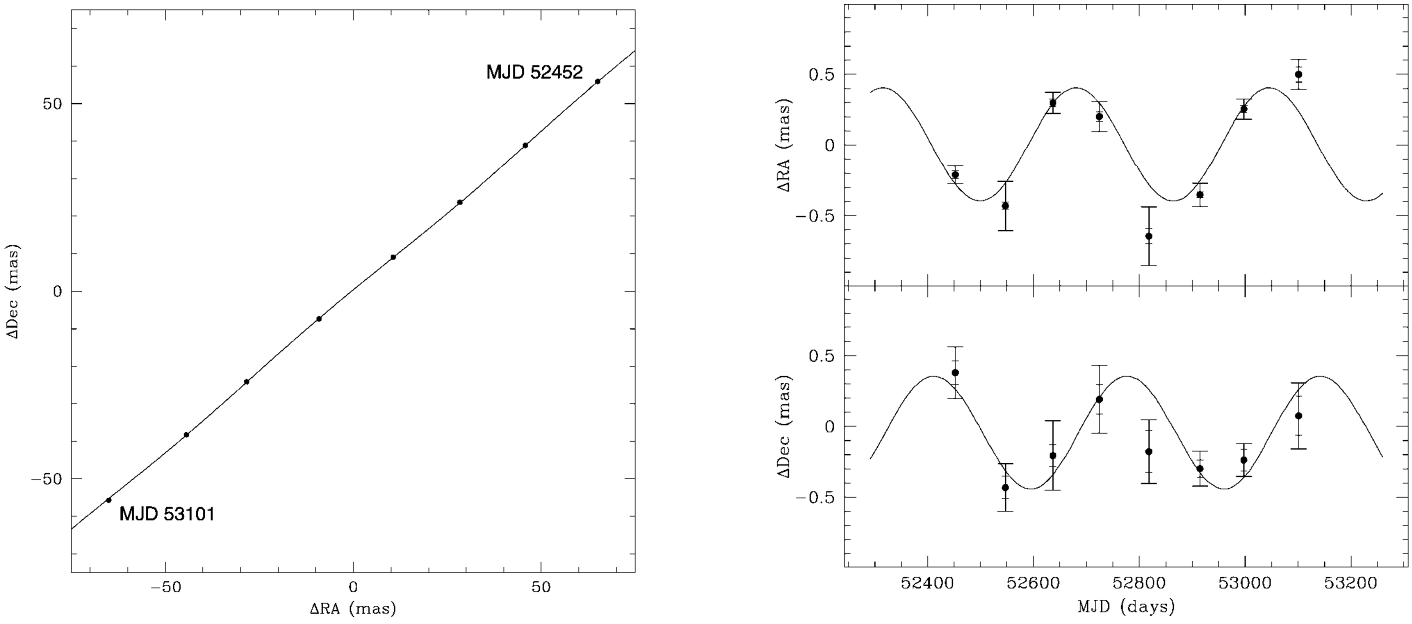

Fig. 1.—*Left*: The motion of PSR B1508+55 in right ascension and declination, with the best-fit proper motion and parallax model overplotted. The error estimates for each data point are smaller than the size of the points. *Right*: The parallax signature of PSR B1508+55 in right ascension and declination, after subtracting the best-fit proper motion from the astrometric positions. Curves corresponding to the best-fit parallax $\pi = 0.415$ mas are overplotted. The inner error bars indicate the random position uncertainties, while the outer error bars indicate the net uncertainties (random and systematic, added in quadrature).

bubble. The electron density must then decay rapidly after ~0.8 kpc along the line of sight.

While B1508+55 is well above the birth scale height for the Galactic pulsar population (Arzoumanian et al. 2002), its proper-motion vector ($\mu_l, \mu_b = -6.39, 96.06$ mas yr^{-1} after correcting for differential Galactic rotation) suggests that it was born in the Galactic plane. Given the pulsar period P and period derivative $\dot{P}$, and assuming that the pulsar was born with a rapid initial spin and has been braking due to a constant torque solely from magnetic dipole radiation[8] (i.e., $\dot{P} \propto P^{2-n}$, braking index $n = 3$), the spin-down age $\tau = P/2\dot{P} = 2.34$ Myr.

Tracing the pulsar back in the Galactic potential, we find that it could have been born 2.34 Myr ago at $|z| < 0.2$ kpc for a range of modest (unknown) radial velocities between 0 and 300 km s^{-1}, and sample orbits are shown in Figure 2. The pulsar appears to have originated in or around the Cyg OB associations, although we cannot identify the exact birth cluster due to the lack of proper motions and accurate distance estimates for the clusters. Spin-down age is known to be an imperfect estimate of the pulsar chronological age (e.g., Narayan & Vivekanand 1981; Cordes & Chernoff 1998). If the true age of the pulsar is significantly larger than the spin-down age, the pulsar birth location would be several kpc beyond the Cyg OB associations in the Galactic plane. However, reasonable values of the pulsar radial velocity and a range of pulsar ages (or equivalently, a range of braking indices or birth periods) produce a birth location in the Galactic plane toward the Cyg OB associations.

We thus establish a self-consistent narrative for B1508+55 that ties together its current location, distance, and velocity vector with its spin-down age and birth site. Born in the Cygnus region, B1508+55 is moving rapidly away from the Galactic plane and on course to irrevocably escape the Galaxy. For $v_r = 200$ km s^{-1}, the implied three-dimensional NS birth velocity $V_{\rm NS} \approx 1120$ km s^{-1}.

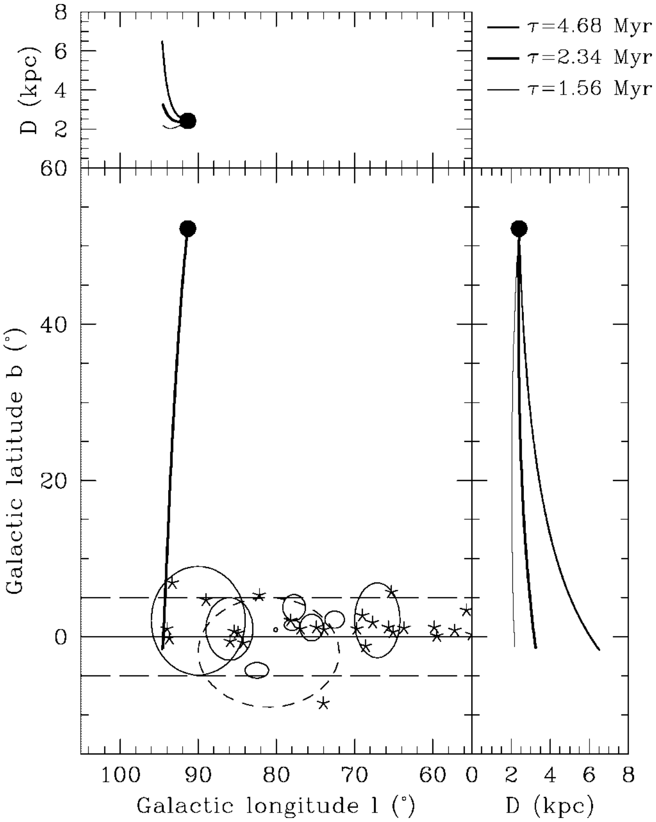

FIG. 2.—Possible orbits for B1508+55, traced back in the Galactic potential. The filled circles denote the current pulsar position, and the thick solid lines denote the path it has followed for an age $\tau = 2.34$ Myr (the spin-down age, with braking index $n = 3$) and a radial velocity $v_r = 200$ km s^{-1}. Other possible orbits are shown (*thinner lines*) for $\tau = 4.69$ Myr (i.e., $n = 2$ for a small initial birth period) with corresponding $v_r = -300$ km s^{-1}, and for $\tau = 1.56$ Myr ($n = 4$) with $v_r = 700$ km s-1. Also indicated are the Cygnus superbubble (2 kpc away, *dashed ellipse*) and the Cyg OB associations (*solid ellipses*) with positions and extents as tabulated by Uyaniker et al. (2001). The star symbols are the Galactic SN remnants identified in this region (Green 2004). The solid horizontal line is the Galactic plane, and the horizontal dashed lines indicate the pulsar birth scale height from Arzoumanian et al. (2002) at the distance of the Cygnus superbubble.

4. DISCUSSION: IMPLICATIONS OF THE HIGH VELOCITY

The high birth velocity of B1508+55 constrains evolutionary scenarios for the pulsar. It could have been born in an isolated system, in which case a large natal kick is required. Alternatively, it could have formed in a binary system that was disrupted by a first or second SN. If so, its companion could have been a longer lived (and thus less massive) star, or a compact object. However, in order to attain the highest possible velocity solely from binary disruption, B1508+55 should have formed in a first SN and remained bound to a massive He star companion in a tight orbit that was subsequently disrupted by the second SN (Iben & Tutukov 1996). The net velocity of the pulsar then derives from either one or two mass-loss events. Given the steeply declining initial mass function for stellar progenitors, He cores are expected to have masses $\lesssim 16\ M_\odot$. The highest velocities are obtained for the smallest possible binary radius, which corresponds to the He core filling its Roche lobe (i.e., a semidetached binary). Such binary systems would be rapidly circularized due to the interaction between the NS and the envelope of the massive companion. (However, B1508+55 has a canonical field strength and thus cannot have accreted much material.) For a circular orbit, $V_{\rm NS} = [GM_c/a(1 + M_{\rm NS}/M_c)]^{1/2}$, where M_c is the companion mass, a is the orbital radius, and $M_{\rm NS}$ is the NS mass (assumed to be 1.4 $M_\odot$). When such a system is disrupted by a symmetric SN explosion of the massive companion, the fraction of the orbital velocity imparted to the NS depends on the mass ratio $M_{\rm NS}/M_c$ (e.g., Boersma 1961). Using estimates for the companion star radius (Paczyński 1971) and the size of the Roche lobe (Verbunt 1993) for companion masses of 4, 8, and 16 $M_\odot$, we find (following Iben & Tutukov 1996) $V_{\rm NS} \approx 40$, 560, and 1000 km s^{-1}, with a possible small contribution from the prior systemic velocity ($\lesssim$100 km s^{-1}). Thus the disruption of a close binary is very unlikely to solely account for the birth velocity of B1508+55, and a natal (or postnatal) kick is indicated.

Natal kicks from asymmetric SN explosions are believed to be ubiquitous (e.g., Fryer & Kalogera 1997; Portegies Zwart & van den Heuvel 1999; Lai et al. 2001), but the driving mechanism remains unclear. Global asymmetric perturbations during SN core collapse may produce hydrodynamically driven kicks (Burrows & Hayes 1996). In recent two-dimensional simulations (Scheck et al. 2004), velocities comparable to that measured for B1508+55 have been obtained. However, the first full three-dimensional simulations of SN core collapse (Fryer 2004) suggest that as the proto-NS moves through the convective region, asymmetric downflows and neutrino emis-

---

[8] While an estimate for $\ddot{P}$ exists for this pulsar (Hobbs et al. 2004), it is affected by timing noise and does not give a physically meaningful value for the braking index.

sion damp out the initial kick velocities, producing final kicks $\lesssim 200$ km s^{-1}. Such kicks are insufficient to account for the observed velocity of B1508+55, but the issue is not yet settled.

If convective instabilities in core-collapse simulations fail to reproduce large kick velocities, this may suggest the existence of neutrino driven kicks and require the presence of extreme magnetic fields ($B > 10^{16}$ G) during core collapse (Janka & Raffelt 1999; Arras & Lai 1999). Such a high B may also allow a postnatal rocket effect to accelerate the pulsar (Lai et al. 2001). However, a kick driven by the NS B field should produce alignment between the spin axis and the velocity vector due to rotation averaging. The spin axis may be inferred from the polarization sweep of the radio pulse for some pulsars (Radhakrishnan & Cooke 1969; however, this is model dependent). For B1508+55, the pulse centroid polarization angle (after correcting for Faraday rotation along the line of sight) is 161° ± 5° (Deshpande et al. 1999), which differs from the proper-motion angle by ~71° (or ~19° for emission in the orthogonal mode). Assuming it survives future scrutiny, the measurement does not support alignment of the spin axis and $V_{\rm NS}$.

We conclude that a kick is required to provide B1508+55 with its high birth velocity, but that a single model is not uniquely preferred based on our current understanding. It is possible that binary disruption and a natal kick act in concert for this object. Such a composite scenario would produce a misalignment between the spin axis and velocity vector, as is (possibly) observed, with the relative weights of the contributions depending on whether the emission is in regular or orthogonal modes. However, such a scenario is not well supported unless the polarization angle is verified and a runaway binary companion is identified in the future (e.g., Vlemmings et al. 2004). Finally, we note that in their seminal paper, Duncan & Thompson (1992) argued that magnetars had high space velocities ~1000 km s^{-1} due to kicks that required intense magnetic fields ($B \gtrsim 10^{15}$ G), and that such strong kicks would not be accessible to ordinary pulsars (like B1508+55, with $B = 2 \times 10^{12}$ G). If this argument is to hold, then B1508+55 had a large birth magnetic field that rapidly decayed. It is more likely that B-driven kicks are not *required* for high velocities and that large natal kicks are not a defining difference between pulsars and magnetars. Rather, the dividing line between them may lie elsewhere in their birth and evolutionary history (e.g., in their progenitor mass; Gaensler et al. 2005).

Ongoing deep pulsar searches, and especially searches at high Galactic latitudes, coupled with long-term VLBA astrometry programs, are likely to discover further high-velocity pulsars and continue to elucidate the velocity distribution and birth circumstances of neutron stars.

We acknowledge the Very Long Baseline Array operations team for their efforts in scheduling and supporting a large VLBA astrometry program. S. C. gratefully acknowledges support from the National Radio Astronomy Observatory (NRAO) through a Jansky Fellowship. NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Basic research in radio astronomy at the Naval Research Laboratory is supported by the Office of Naval Research. This work was supported in part by NSF grants AST 98-19931 and AST 02-06036 at Cornell, and AST 00-98343 at the University of California.

REFERENCES

Arras, P., & Lai, D. 1999, ApJ, 519, 745

Arzoumanian, Z., Chernoff, D. F., & Cordes, J. M. 2002, ApJ, 568, 289

Blaauw, A. 1961, Bull. Astron. Inst. Netherlands, 15, 265

Boersma, J. 1961, Bull. Astron. Inst. Netherlands, 15, 291

Brisken, W. F., Benson, J. M., Goss, W. M., & Thorsett, S. E. 2002, ApJ, 571, 906

Burrows, A., & Hayes, J. 1996, Phys. Rev. Lett., 76, 352

Chatterjee, S., Cordes, J. M., Lazio, T. J. W., Goss, W. M., Fomalont, E. B., & Benson, J. M. 2001, ApJ, 550, 287

Cordes, J. M., & Chernoff, D. F. 1998, ApJ, 505, 315

Cordes, J. M., & Lazio, T. J. W. 2005, ApJ, submitted (astro-ph/0207156) (NE2001)

Cordes, J. M., Romani, R. W., & Lundgren, S. C. 1993, Nature, 362, 133

Deshpande, A. A., Ramachandran, R., & Radhakrishnan, V. 1999, A&A, 351, 195

Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780

Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9

Fomalont, E. B., Goss, W. M., Beasley, A. J., & Chatterjee, S. 1999, AJ, 117, 3025

Fryer, C., & Kalogera, V. 1997, ApJ, 489, 244

Fryer, C. L. 2004, ApJ, 601, L175

Gaensler, B. M., McClure-Griffiths, N. M., Oey, M. S., Haverkorn, M., Dickey, J. M., & Green, A. J. 2005, ApJ, 620, L95

Gott, J. R. I., Gunn, J. E., & Ostriker, J. P. 1970, ApJ, 160, L91

Green, D. A. 2004, Bull. Astron. Soc. India, 32, 335

Harrison, E. R., & Tademaru, E. 1975, ApJ, 201, 447

Hobbs, G., Lorimer, D. R., Lyne, A. G., & Kramer, M. 2005, MNRAS, 360, 974

Hobbs, G., Lyne, A. G., Kramer, M., Martin, C. E., & Jordan, C. 2004, MNRAS, 353, 1311

Iben, I. J., Jr., & Tutukov, A. V. 1996, ApJ, 456, 738

Janka, H.-Th., & Mueller, E. 1996, A&A, 306, 167

Janka, H.-Th., & Raffelt, G. G. 1999, Phys. Rev. D, 59, 023005

Lai, D., Chernoff, D. F., & Cordes, J. M. 2001, ApJ, 549, 1111

Manchester, R. N., et al. 2001, MNRAS, 328, 17

Narayan, R., & Vivekanand, M. 1981, Nature, 290, 571

Norman, C. A., & Ikeuchi, S. 1989, ApJ, 345, 372

Paczyński, B. 1971, Acta Astron., 21, 1

Portegies Zwart, S. F., & van den Heuvel, E. P. J. 1999, NewA, 4, 355

Radhakrishnan, V., & Cooke, D. J. 1969, Astrophys. Lett., 3, 225

Scheck, L., Plewa, T., Janka, H.-Th., Kifonidis, K., & Müller, E. 2004, Phys. Rev. Lett., 92, 011103

Shklovskii, I. S. 1969, AZh, 46, 715

Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674 (TC93)

Uyaniker, B., Fürst, E., Reich, W., Aschenbach, B., & Wielebinski, R. 2001, A&A, 371, 675

Verbunt, F. 1993, ARA&A, 31, 93

Vlemmings, W. H. T., Cordes, J. M., & Chatterjee, S. 2004, ApJ, 610, 402