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Pulsar Distances and Velocities

from VLBA Astrometric Observations

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Summary

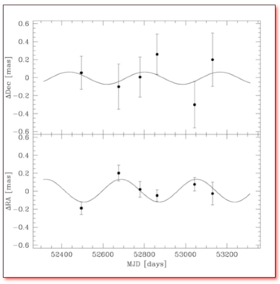
Precision astrometry campaigns with the NRAO Very Long Baseline Array (VLBA) yield model-independent distances and velocities to neutron stars which address fundamental astrophysical questions. These include, for example, determining the birth locations and velocity distribution, modeling the Galactic electron density distribution, establishing reference frame ties, and constraining the astrophysics of supernova explosions. Here we report on new velocities and distances that we have measured in a recent VLBA astrometry campaign. Specifically, we present PSR B1508+55, which has a transverse velocity of ~1100 km/s, the highest velocity directly measured for a neutron star. Binary disruption alone is insufficient to impart the required birth velocity. Not only is a natal kick indicated, but the extreme velocity challenges current simulations of supernova core collapse.

New Pulsar Distances and Velocities

Our recently completed VLBA pulsar astrometry campaign will yield model-independent parallaxes and proper motions of 20 pulsar, **thereby doubling the number of pulsars with astrometric distances and velocities**. While a detailed analysis is still ongoing the table below present the first *preliminary* results for a large number of the observed pulsars. The pulsars were observed at 8 epochs spread over approximately 2 years.

Pulsar Name	Distance [kpc]	Velocity [km/s]
B0031-07	$1.10^{+0.07}_{-0.06}$	81^{+7}_{-5}
B0136+57	$2.62^{+0.23}_{-0.18}$	294^{+26}_{-21}
B0450+55	$1.51^{+0.19}_{-0.15}$	424^{+54}_{-44}
B0609+37	$2.23^{+0.55}_{-0.39}$	51^{+14}_{-9}
B0818-13	$1.96^{+0.09}_{-0.09}$	451^{+22}_{-20}
B1508+55	$2.37^{+0.23}_{-0.20}$	1083^{+103}_{-90}
B1541+09	$7.41^{+1.32}_{-1.10}$	303^{+57}_{-44}
J1713+0747	$1.07^{+0.07}_{-0.06}$	25^{+2}_{-3}
B1933+16	$3.36^{+0.90}_{-0.58}$	214^{+59}_{-37}
B2045-16	$1.14^{+0.07}_{-0.05}$	624^{+34}_{-29}
B2053+36	$2.91^{+0.84}_{-0.48}$	67^{+19}_{-13}
B2154+40	$3.33^{+0.73}_{-0.49}$	348^{+76}_{-52}
B2310+42	$1.05^{+0.05}_{-0.05}$	150^{+8}_{-7}

Preliminary distances and velocities to 13 of the pulsar of our astrometric sample. The errors indicate the most compact 68% confidence interval.



The parallax signature of PSR B1541+09, the most distant pulsar in our sample with a parallax $\pi = 0.13 \pm 0.02$ mas.

References

Brisken, W. et al. 2003, ApJ, 593, L89
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Chatterjee, S. et al. 2005, ApJ, 630, L61
Hoogerwerf, R. et al. 2001, A&A, 365, 49
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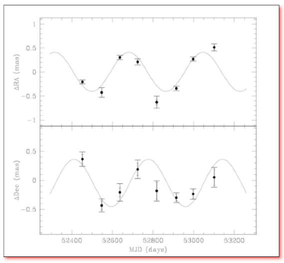
B1508+55



The parallax signature of B1508+55 with the best fitted proper motion subtracted. The solid line indicates the best fitted model and the symbols with error bars are the VLBA observations at 8 different epochs.

The pulsar with the highest directly measured velocity. (Chatterjee et al. 2005)

Proper Motion:

$\mu_\alpha = -73.61 \pm 0.04$ mas/yr

$\mu_\delta = -62.62 \pm 0.09$ mas/yr

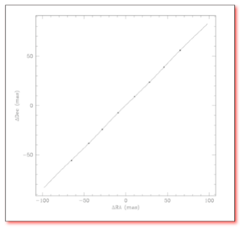
Parallax *(preliminary)*:

$\pi = 0.415 \pm 0.037$ mas

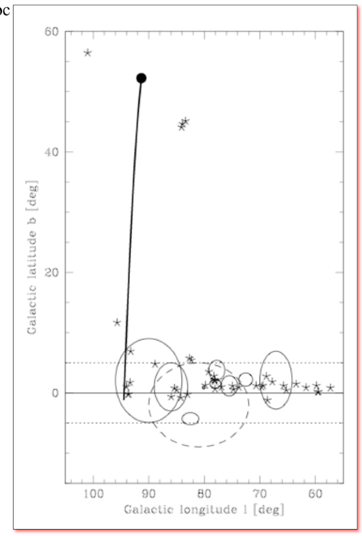
$\Rightarrow D = 2.37^{+0.23}_{-0.20}$ kpc

and

$V_\perp = \mathbf{1083^{+103}_{-90}}$ ***km/s***

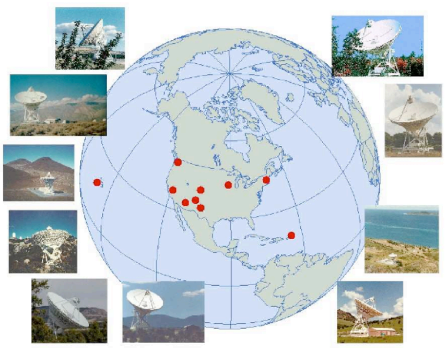


The motion of B1508+55 on the sky. The solid line is the best fitted proper motion and parallax.



The trajectory of B1508+55 traced back in time through the Galactic potential determined using its spin-down age of 2.34 Myr and a radial velocity of 200 km/s. The Galactic plane is indicated with the solid horizontal line and the estimated scale height of the pulsar progenitor distribution is indicated with the dashed horizontal line. The dashed circle indicates the Cygnus Superbubble, and the solid ellipses are the Cygnus OB associations. The starred symbols are the known supernova remnants. A birth in the Galactic plane indicates B1508+55 had a birth velocity of ≈ 1120 km/s.

The Very Long Baseline Array



Pulsar Astrometry: Fundamental Astronomy and Physics

Galactic Electron Density: Most pulsar distances are estimated from their dispersion measures (DM) and a Galactic electron density model (e.g. Taylor & Cordes 1993; Cordes & Lazio 2002). Parallax distances provide essential calibration for the model, particularly for the local medium.

NS Birth Sites and Supernova Remnant Associations: Pulsar proper motions and distances can identify their birth sites (e.g. Vlemmings et al. 2004; Hoogerwerf et al. 2001) and clarify putative pulsar-SNR associations. True ages of both pulsars and their associated SNRs may be estimated from their angular separations and the proper motions.

VLBI and Interstellar Scintillation: The time and bandwidth scales of pulsar scintillation depend upon the *radial* distribution of scattering material. Combining proper motions and parallaxes with scintillation observations constrain this radial distribution. For B0919+06 Chatterjee et al. (2001) find 10-pc turbulent clumps on the edge of the Local Bubble.

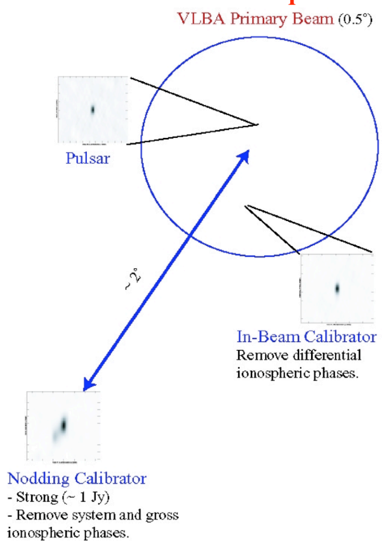
NS Velocities: Parallaxes and proper motions provide model-independent velocities, which constrain the population velocity distribution. Pulsar velocities represent fossil information about the evolution of close binary systems and core collapse supernovae.

Reference Frame Ties: Astrometry on millisecond pulsars (MSPs) verifies solar system-extragalactic reference frame ties and the accuracy of timing parallaxes. The measurements also constrain orbital and relativistic parameters of MSPs in binary systems.

Nuclear Physics: Accurate distance measurements, combined with observed thermal radiation from the NS surface, constrain the size of the NS photosphere, with implications for the nuclear Equation of State (e.g., PSR B0656+14, Brisken et al. 2003).

Other Neutron Star Flavors: Other known classes of neutron stars include anomalous X-ray pulsars (6 known), soft γ-ray repeaters (4 known), and radio-quiet γ-ray pulsars (10 known). Quantifying the kinematics of radio pulsars as well as possible is essential in order to compare and contrast them with other NS sub-classes.

Astrometric Technique



Key requirements are to calibrate phase of the system and to remove ionospheric phase fluctuations:

- **Nodding calibrator:** Strong, compact source used to calibrate system and remove gross ionospheric phase fluctuations.
- **In-Beam calibrator:** Within the same primary beam and observed simultaneously with the pulsar, used to calibrate differential ionospheric phase fluctuations between the nodding calibrator and the pulsar line of sight.