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Pulsar Astrometry at the Microarcsecond Level

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Abstract. Determination of pulsar parallaxes and proper motions addresses fundamental astrophysical questions. We have recently finished a VLBI astrometry project to determine the proper motions and parallaxes of 27 pulsars, thereby doubling the total number of pulsar parallaxes. Here we summarise our astrometric technique and present the discovery of a pulsar moving in excess of 1000 km s^{-1}. As an example of the application of high precision pulsar astrometry we also infer the identification of 2 pulsars originating from a disrupted binary in the Cygnus Superbubble.

Key words. pulsars – astrometry – stars: kinematics

1. Introduction

Parallax and proper motion measurements obtained through high-resolution astrometry or pulse-timing observations provide the only model-independent distances and velocities of pulsars. Highly accurate pulsar distances and velocities are essential for a wide range of problems. These include:

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NS Birth Sites and SNR associations: Accurate proper motions and parallaxes can help clarify putative pulsar–SNR associations, leading to estimates of their true ages. Some pulsars may be traced back to their birth sites in stellar clusters (e.g. Hoogerwerf, de Brujne & de Zeeuw 2001) or, as discussed below, to a common origin in a disrupted binary (Vlemmings et al. 2004).

Galactic n_e: Most pulsar distances are estimated from their dispersion measures (DM), using a model for the Galactic electron density (e.g. Cordes & Lazio 2005). Model-independent distances provide essential calibration points for the electron density model, and in particular, allow much better modeling of the local interstellar medium (e.g. Chatterjee et al. 2001).

VLBI and Interstellar Scintillation: The characteristics of pulsar scintillation, i.e., scintillation time and bandwidth, depend in part upon the distribution of scattering material along the line of sight. Combining proper motion and parallax measurements with interstellar scintillation observations of pulsars allows modeling of the distribution of scattering material, and thus contributes to modeling of the free electron density in the Galaxy. Chatterjee et al. (2001) demonstrate this analysis for B0919+06, from which they find evidence for "clumps" with a probable scale size of 10 pc at the edges of the Local Bubble.

NS Population Velocities: Parallaxes and proper motions provide model-independent transverse velocities for neutron stars (NS), which constrain the shape of 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 MSPs allows the verification of solar system–extragalactic reference frame ties and the accuracy of timing parallaxes. The measurements also constrain model fitting for orbital and relativistic parameters of MSPs in binary systems.

Nuclear physics: An accurate distance, in combination with observed thermal radiation from the NS surface, can be used to constrain the 'size' of the NS photosphere, with important implications for the NS Equation of State.

Here we present a project designed to obtain accurate distances and proper motions to a large number of pulsars to address several of the items listed above. The results and project details are given in Chatterjee et al. (2005) and Brisken et al. (2005).

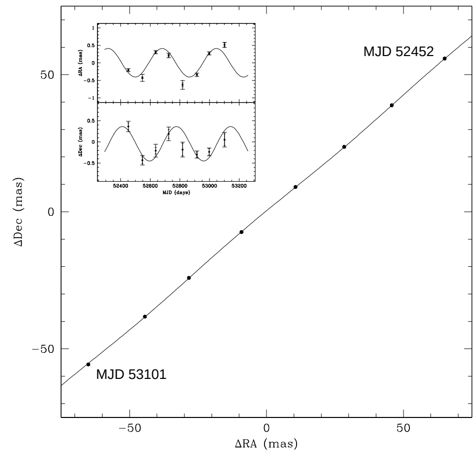

Fig. 1. The motion of PSR B1508+55 in Right Ascension and Declination, with the best fit proper motion and parallax model over-plotted. The error estimates for each data point are smaller than the size of the points. The inlay shows the parallax signature of B1508+55 with the best fit proper motion subtracted.

2. Observational Technique

In this project, 27 pulsars were observed with the NRAO Very Long Baseline Array (VLBA) for 8 epochs each, spanning 2 years and over 500 hours of VLBA observing time. As a trade-off between increasing pulsar flux at lower frequencies and improved resolution as well as reduced ionospheric effects, all VLBA observations were conducted between 1.4 and 1.7 GHz. Observations were phase-referenced by nodding back and forth between the target and a nodding calibrator within 4°. For most pulsars residual calibration errors were reduced further by employing in-beam calibration (Fomalont et al. 1999; Chatterjee et al. 2004), calibration on a faint extra-galactic source within the primary VLBA telescope beam ($\sim$ 30′). For the remaining pulsars we used wide-band ionospheric calibration (Brisken et al. 2000). This allows us to reach an astrometric precision in the pulsar position often better than 100 μarcseconds.

3. A hyper-fast moving pulsar: B1508+55

High pulsar velocities place stringent constraints on supernova core collapse mechanisms. Fig. 1 shows the proper motion and parallax of B1508+55, which was observed as part of our large astrometry project. The proper motion and parallax values ($\mu_\alpha = -73.606 \pm 0.044$ mas yr^{-1}, $\mu_\delta = -62.622 \pm 0.088$ mas yr^{-1} and $\pi = 0.415 \pm 0.037$ mas) imply a pulsar velocity with the most compact 68% probability interval of 1085 ± 97 km s^{-1}($\sim$ 1100 km s^{-1}when corrected for differential galactic rotation), making B1508+55 the first pulsar with such a high measured, model independent, velocity. Constraints due to the high velocity of B1508+55 on its formation scenario are discussed in Chatterjee et al (2005).

4. Separated at birth: B2021+51 and B2020+28

One of the applications of high precision astrometry is the determination of pulsar birth sites (e.g. Hoogerwerf, de Brujne & de Zeeuw 2001). Using the birth location information for example true kinematic ages and initial spin periods can be determined, and pulsar birth (velocity) distributions can be constrained.

In a sample of pulsars previously observed by the VLBA (Brisken et al. 2002), we identified two pulsars that, when their orbits are calculated back through the Galactic potential, appear to originate in a disrupted binary in one of the Cygnus OB associations (Vlemmings et al. 2004). The trajectories of these pulsars are shown in Fig. 2. This discovery implies that the kinematic age of the pulsar formed when the second SN explosion disrupted the binary (most likely B2020+28) is 2.0 Myr (compared to the spindown age of 2.74 Myr), and the initial spin period is $\sim$ 200 ms (assuming a braking index $n = 3$).

Many such applications will be enabled by ongoing projects.

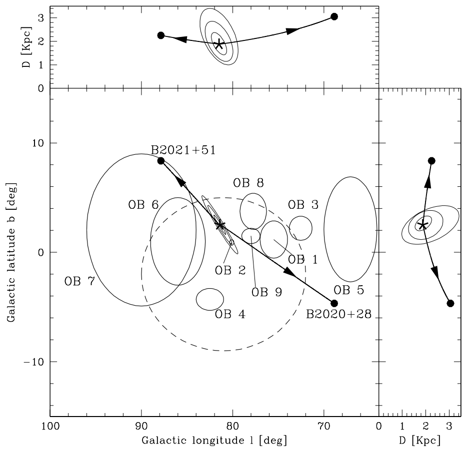

Fig. 2. The 3-dimensional pulsar motion through the Galactic potential for B2020+28 and B2021+51. The dashed circle represents the Cygnus superbubble, while the labelled solid ellipses are the Cygnus OB associations with positions and extents as tabulated by Uyaniker et al. (2001). The extent of OB 2 is unknown and only the centre of the association is indicated. The thick solid lines indicate the pulsar paths, with the origin denoted by the starred symbol and the arrows pointing in the direction of motion. The current positions are indicated by the solid dots. The elliptical contours around the pulsars' origin in these panels indicate the 1, 2 and 3σ levels of the likelihood solution for the birth location.

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