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VLBI astrometry of two millisecond pulsars

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Abstract. We present astrometric results on two millisecond pulsars, PSR B1257+12 and PSR J1022+1001, as carried out through VLBI. For PSR B1257+12, a model-independent distance of 710^{+43}_{-38} pc and proper motion of ($\mu_\alpha = 46.44 \pm 0.08$ mas/yr, $\mu_\delta = -84.87 \pm 0.32$ mas/yr) were obtained from 5 epochs of VLBA and 4 epochs of EVN observations, spanning about 2 years. The two dimensional proper motion of PSR J1022+1001 ($\mu_\alpha \sim -10.13$ mas/yr, $\mu_\delta \sim 16.89$ mas/yr) was also estimated, using 3 epochs of EVN observations. Based on our results, the X-ray efficiency of PSR B1257+12 should be in the same range as other millisecond pulsars, and not as low as previously thought.

Keywords. (stars:) pulsars: general

1. Introduction

The distance and proper motion are fundamental and important pulsar parameters. A model-independent distance and proper motion measurement is especially important for millisecond pulsars (MSPs). Firstly, MSPs are old enough to leave the Galactic disk. Model-independent pulsar distance measurements indicate that the TC93 (Taylor & Cordes 1993) or NE2001 (Cordes & Lazio 2002) Galactic electron density distribution model underestimates the distances for high-latitude pulsars (Chatterjee *et al.* 2009). Secondly, the distance and proper motion of a pulsar are also important parameters in the pulsar timing observation. In the Shklovskii effect, for example, a transverse component of this pulsar velocity gives rise to an appreciable increase in the apparent period even if the pulsar is not slowing down (Shklovskii 1970). For MSPs, $\dot{P}_{\rm Shk}$ is $\sim 10^{-19}$ s/s, comparable to their observed first order period derivative. Furthermore, MSPs have more parameters to fit in timing observations, as most of them have companions. If the distance and proper motion have been obtained independently, it will be helpful for the other parameters fitting.

High precision VLBI astrometry offers a powerful way to directly measure the parallaxes and proper motions of pulsars. With the steady progress of VLBI observation, correlation and data processing techniques, VLBI astrometry of some pulsars has been accomplished successfully (Campbell *et al.* 1996; Fomalont *et al.* 1999; Brisken *et al.* 2002; Chatterjee *et al.* 2009; Deller *et al.* 2009).

Here, we report the progress of our astrometry project on two MSPs, PSR B1257+12 and PSR J1022+1001, with the VLBA and EVN. PSR B1257+12 is the first extra-solar planetary system discovered. It has been confirmed that PSR B1257+12 has three planets in approximately co-planar orbits (Wolszczan *et al.* 2000). PSR J1022+1001 is an intermediate mass binary pulsar accompanied by a 0.9 $M_\odot$ white dwarf. It lies

Table 1. The distance and proper motion of PSR B1257+12 and PSR J1022+1001

Pulsar	Distance (pc)	Proper motion (mas/yr)	Method	Reference
B1257+12	~ 620	–	TC93	Taylor & Cordes (1993)
	800 ± 200	$\mu_\alpha = 46.4 \pm 0.1$ $\mu_\delta = -82.2 \pm 0.2$	Timing	Wolszczan *et al.* (2000)
	~ 450	–	NE2001	Cordes & Lazio (2002)
	–	$\mu_\alpha = 45.5 \pm 0.4$ $\mu_\delta = -84.7 \pm 0.7$	Timing	Konacki & Wolszczan (2003)
	660^{+210}_{-130}	–	Timing	Wolszczan (2008)
	710^{+43}_{-38}	$\mu_\alpha = 46.44 \pm 0.08$ $\mu_\delta = -84.87 \pm 0.32$	**VLBI**	**This work**
J1022+1001	~ 600	–	TC93	Taylor & Cordes (1993)
	–	$\mu_\lambda = -17 \pm 2$	Timing	Kramer *et al.* (1999)
	~ 440	–	NE2001	Cordes & Lazio (2002)
	300^{+100}_{-60}	–	Timing	Hotan *et al.* (2004)
	–	$\mu_\alpha \sim -10.13$ $\mu_\delta \sim 16.89$	**VLBI**	**This work**

near the ecliptic plane, so that only the component of proper motion along the ecliptic longitude can be accurately measured with pulsar timing method (Kramer *et al.* 1999). For these two pulsars, the astrometry results obtained by various methods are by now very different (see Table 1). So, it is meaningful to perform VLBI astrometry on these pulsars and further study their related astrophysics.

2. Observations and data reduction

The flux density of PSR B1257+12 and PSR J1022+1001 is about 2 and 3 mJy at 1400 MHz, respectively. The corresponding observing wavelength of VLBA and EVN is 21 cm and 18 cm, respectively. Including 5 epochs of VLBA observation and 4 epochs of EVN observation, there are 9 epochs of VLBI observations of PSR B1257+12 spanning 2 years. In the VLBA observations of PSR B1257+12, two calibrators, J1300+1206 and J1300+141A, located on opposite sides of PSR B1257+12 in RA direction with the separation of 0.58° and 1.61°, were selected as phase reference sources. In the EVN observations of PSR B1257+12, only J1300+141A was selected as the phase reference source. One phase reference source at 2.96° away was chosen in PSR J1022+1001 observations with the EVN. Only 3 of 5 epochs EVN observations of PSR J1022+1001 were successful. The VLBA and EVN data were correlated with NRAO-DiFX and Bonn-DiFX software correlators under the pulsar binning mode, respectively. The data was processed with AIPS following the normal data reduction steps of phase reference observations.

3. Results and Discussion

Firstly, the astrometric parameters of PSR B1257+12 are fitted with the standard weighted least squares method with 5 degrees of freedom that astrometry measurements usually use. But, there are some systematic offset in the DEC direction between VLBA results and EVN results. To overcome this, one more parameter $\Delta\delta_{(\mathrm{EVN-VLBA})}$ is added to the new data fitting. The reduced χ^2 of the new fitting is 0.67 with a fitted systematic

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offset $\Delta\delta_{(\mathrm{EVN-VLBA})}$ of 1.22 mas. The parallax fitted is 1.41±0.08 mas, which corresponds to a distance 710^{+43}_{-38} pc. The corresponding proper motion in RA and DEC direction is 46.44 ± 0.08 and -84.87 ± 0.32 mas/yr. The covariance between parallax (π) and proper motion (μ_α, μ_δ) is -0.0239 and -0.0897, respectively. For comparison our astrometric measurement results are listed in Table 1.

Some debris left over from the planet formation may cause PSR B1257+12 to be of low apparent X-ray efficiency. It is hard to conclude whether this pulsar is low apparent X-ray efficient or not because of distance uncertainties (Pavlov *et al.* 2007). According to the X-ray measurement results from Pavlov *et al.* (2007) and our new distance result, for the 90% confidence lower boundary of the distance 649 pc, the X-ray efficiency of this pulsar is 9.63×10^{-5}. The best fitted distance 710 pc gives an X-ray efficiency of 1.68×10^{-4}. So, our new VLBI result indicates that the X-ray efficiency of PSR B1257+12 should still be in the same range ($\sim 10^{-4} - 10^{-2.5}$) as other MSPs.

As we only have 3 epochs of successful observations of PSR J1022+1001 with the EVN, it is impossible to fit both the distance and proper motion of this pulsar. Using the distance (∼300 pc) of PSR J1022+1001 obtained with timing method (Hotan *et al.* 2004), the two dimensional proper motions $\mu_\alpha = -10.13$ mas/yr, $\mu_\delta = 16.89$ mas/yr, as estimated with these 3 epochs EVN measurements.

We plan an astrometry project of more MSPs, including PSR J1022+1001, whose model-independent distance has not been obtained in our present work.

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