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SCINTILLATION VELOCITIES OF FIVE MILLISECOND PULSARS

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ABSTRACT

Millisecond pulsars differ from normal pulsars in their mode of origin and their properties. They are thought to be born either through binary interaction or through accretion-induced collapse (AIC) of white dwarf stars. Several theoretical considerations suggest that these different mechanisms for the origin of millisecond pulsars would lead to different distributions of the space velocities of millisecond pulsars. Therefore, it is important to estimate the average space velocity of millisecond pulsars and compare it with that of normal pulsars. Here we present transverse velocity estimates of five millisecond pulsars obtained from interstellar scintillation observations, carried out with the Ooty Radio Telescope (ORT) at 327 MHz. For the pulsars J0437−4715, B1257+12, B1534+12, J1730−2304, and J2145−0750 we obtain velocity estimates of 231, 225, 191, 56, and 113 km s^{-1}, respectively. The average velocity for these is much smaller than that of the normal pulsars and larger than that expected from the AIC process. Present velocity estimates are closer to other recent measurements of millisecond pulsars.

Subject headings: ISM: general — pulsars: general — radio continuum: ISM — stars: neutron

1. INTRODUCTION

It is well accepted that millisecond pulsars differ from normal pulsars in several properties and in the mode of their origin. The ratio of the period-to-period derivative for millisecond pulsars and the estimates of their magnetic fields suggest their ages to be $\sim 10^9$ yr, which is about 3 orders of magnitude larger than that for normal pulsars. While normal pulsars originate in supernova explosions, two different mechanisms have been proposed for the origin of millisecond pulsars. Millisecond pulsars are thought to originate either from the spin-up of old neutron stars by accretion of mass from their binary companions (Bhattacharya & van den Heuvel 1991) or from the accretion-induced collapse (AIC) of white dwarf stars (van den Heuvel 1983). Unlike normal pulsars, a majority of the millisecond pulsars are found in binary systems. These binary systems exhibit a range of eccentricities and masses of the binary companion. The high-mass binary systems tend to have highly eccentric orbits, while the low-mass binaries have smaller eccentricities.

It is believed that millisecond pulsars in high-mass binaries originate from the spin-up of old normal neutron stars via mass transfer. The origin of millisecond pulsars in low-mass binaries could be due to either AIC or supernova explosion. If millisecond pulsars are formed by the AIC process, their average velocity would be much lower than that of normal pulsars (Bailes et al. 1989; Bailes et al. 1994; Tauris & Bailes 1996; Johnston, Nicastro, & Koribalski 1998). These theoretical predictions suggest that a comparison of the velocity distribution of millisecond pulsars and that of normal pulsars would provide useful information on their origin and evolution.

There are three main methods used for estimating the transverse velocities of pulsars. Direct measurement of the proper motion of a pulsar can be obtained with multiple epochs of very long baseline interferometry (VLBI) observations. Combined with the distance estimate, these yield an estimate of the transverse speed of the pulsar (e.g., Bailes et al. 1990; Fomalont et al. 1992; Harrison, Lyne, & Anderson 1993). However, such measurements are realistic only for relatively nearby pulsars that have high flux densities and large transverse velocities. In the second method, pulsar timing observations spanning a few years are used for estimating the transverse velocities of pulsars. This technique works best for pulsars with low timing noise. Recently, proper motion measurements for nine millisecond pulsars have been obtained by this method (Toscano et al. 1999). In the third method, interstellar scintillation observations provide an indirect but simpler technique for estimating the transverse speeds of pulsars (e.g., Lyne & Smith 1982; Cordes 1986; Gupta, Rickett, & Lyne 1994). Interstellar scintillations are produced when the radio signals from a pulsar traverse the electron-density inhomogeneities along the line of sight to the pulsar. As a result, random intensity modulations that have a typical frequency decorrelation scale and a typical spatial decorrelation scale at the observing plane are produced. Because of the net relative velocity between the pulsar and the scintillation pattern, the spatial decorrelation scale is mapped to a temporal scale, and the combination of this scale with the frequency decorrelation scale can be used to infer the net transverse speed between the pulsar and the scintillation pattern (see Gupta et al. 1994). Since the convective velocity of the density perturbations in the interstellar medium is typically much smaller than that of the pulsar, the velocity estimate reflects the transverse speed of the pulsar.

Scintillation velocities have been measured for several normal pulsars (Lyne & Smith 1982; Cordes 1986; Gupta et al. 1994) and a few millisecond pulsars. A recent comparison shows that scintillation velocities of normal pulsars show a good agreement with proper motion velocities and can thus be used as reliable estimators of the transverse speeds of pulsars (Gupta 1995). The first measurements of scintillation velocities of millisecond pulsars (Nicastro & Johnston 1995) suggested that velocities of millisecond pulsars are significantly lower than those of normal pulsars. These estimates of scintillation velocities were subsequently revised using an improved formula (Gupta 1995) for scintillation velocity (Johnston et al. 1998). Nevertheless, the average velocity of millisecond pulsars computed using the

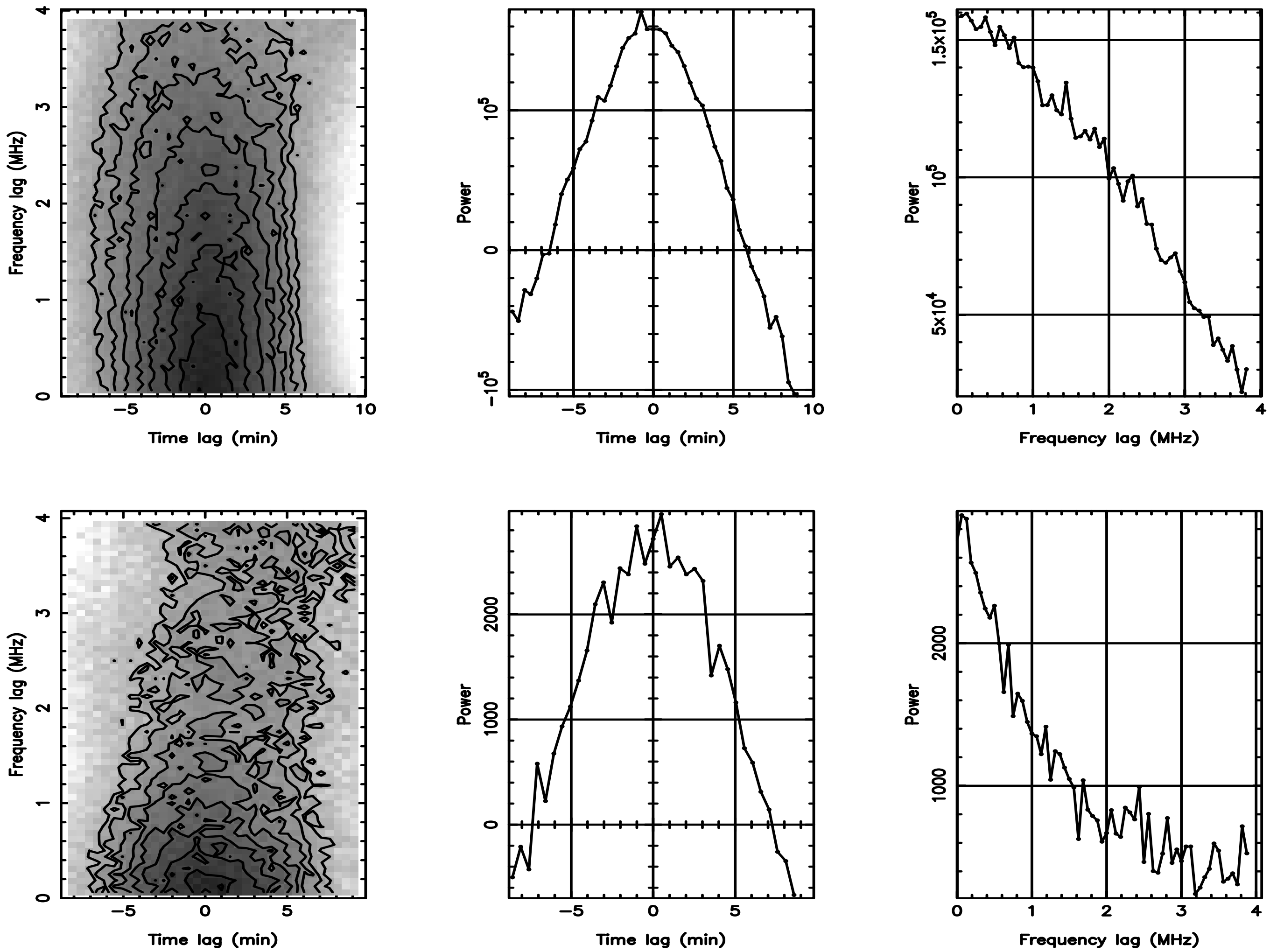

FIG. 1.—Typical cross-correlation functions obtained for J0437−4715 and B1534+12. *Left*: Gray plot of the decorrelation function superposed with contour plots for the two pulsars. *Middle and Right*: Time decorrelation at zero frequency lag and frequency decorrelation at zero time lag.

scintillation technique appears to be about 87 km s^{-1}, which is considerably smaller than the average velocity of normal pulsars. This value is, however, larger than the average velocity expected from the AIC process.

In this paper we present scintillation velocity measurements for the five millisecond pulsars PSR J0437−4715, PSR B1257+12, PSR B1534+12, PSR J1730−2304, and PSR J2145−0750. Section 2 gives details of observations and analysis. Section 3 gives the results and discusses their significance.

2. OBSERVATIONS AND ANALYSIS

Scintillation observations were carried out at 327 MHz using the Ooty Radio Telescope (ORT). ORT is an equatorially mounted parabolic cylinder that is mechanically steered about its north-south axis to provide continuous hour angle coverage for about 9 hr. Declination coverage of $\pm 50^\circ$ along the north-south is provided by selectively phasing the 1056 dipoles along the focus (Swarup et al. 1971). The large effective area of 8000 m^2 and continuous tracking capability makes ORT a suitable instrument to undertake pulsar scintillation measurements.

A sample of 12 pulsars was chosen based on their dispersion measure (DM), period, and flux density. Since the dispersion delay at 327 MHz is about 0.225 ms MHz^{-1} unit DM^{-1}, a pulsar of period 10 ms and maximum DM of 45 pc cm^{-3} could be observed using the above receiver setup. Millisecond pulsars whose flux at 408 MHz was greater than 20 mJy and whose DM was smaller than 40 pc cm^{-3} were chosen. Of these 12 pulsars, signals with sufficient signal-to-noise ratio were detected for pulsars J0437−4715, B1257+12, B1534+12, J1730−2304, and J2145−07, and scintillation velocity estimates were obtained only for these. Each pulsar was observed at several epochs between 1994 and 1997. Observations were separated by a few months so as to minimize the effect of refractive scintillations. At each epoch a pulsar was observed for several sessions of 40 minutes each.

Observations were carried out at 327 MHz with a bandwidth of 8 MHz. The baseband signals from the north and south halves of the telescope were processed separately using the dual-beam pulsar receiver available at the observatory. Each of these signals was sampled at Nyquist rate and Fourier transformed on-line to obtain a 256 point spectral representation of the 8 MHz signal. The power spectra data were then integrated in each channel (by the digital hardware) to the desired sampling rate. These data were then written to tape for off-line analysis. A sampling interval of 0.516 ms was used for most observations, while a faster sampling of 0.258 ms was used for observations of PSR J0437−4715.

In the off-line analysis, the data from the north and south halves of ORT were dedispersed and folded to obtain a stable pulse profile of the pulsar. This profile was used to mark the "on-pulse" and "off-pulse" windows. Each sample of the dynamic spectrum was computed as the difference between on-pulse energy and the mean off-pulse energy. Typically, each session was several times the scintillation timescales, and each point in the dynamic spectrum was obtained by integrating several hundred periods. The dynamic spectrum for the off-pulse was used to flag interference in time and frequency to ensure reliability of the data.

Normally, decorrelation time and decorrelation bandwidth are obtained from the time-frequency autocorrelation of the dynamic spectra. However, we computed the cross-correlation function of the on-pulse dynamic spectra from the north and south halves. Since the receiver noise and gain variations in the data from the north and south halves are expected to be uncorrelated, while the scintillation pattern over the two halves of the telescope was identical, the cross-correlation function eliminates the uncorrelated fluctuations of the power and provides a more reliable correlation function. Figure 1 shows typical cross-correlation functions computed for J0437−4715 and B1534+12. The decorrelation time, τ_d, and decorrelation bandwidth, ν_d, were obtained from the best-fit Gaussians to the cross-correlation function along time and frequency lag axes, respectively. In keeping with the existing definitions in the literature, the $1/e$ width of the correlation function was used for the estimate of τ_d, whereas for ν_d, the half-width of the correlation function was used.

The scintillation velocity, $V_{\rm iss}$, was obtained for each session as follows (Gupta et al. 1994):

$$V_{\rm iss} = 3.85 \times 10^4 \frac{\sqrt{\nu_d({\rm MHz})D({\rm kpc})X}}{f({\rm GHz})\tau_d({\rm s})} \ {\rm km\ s^{-1}} , \quad (1)$$

where f is the radio frequency of observations (in GHz), D is the pulsar distance (in kpc), and X is the ratio of the distances from the effective location of the scattering medium to the observer and the pulsar. For our work, we considered the effective location of the scattering medium to be midway between the pulsar and the observer (i.e., $X = 1$), unless known otherwise. Note that the scintillation velocity would appear smaller than the proper motion measurement if the region of dominant scattering were closer to the observer ($X < 1$) and larger if the screen were closer to the pulsar ($X > 1$). The error on the scintillation velocity can be due to error in the estimation of distance to the pulsar, statistical error arising from the finite number of scintles present in the data, and the signal-to-noise ratio of the cross-correlation. The nominal error on scintillation velocity was found to be about ± 30 km s^{-1} for pulsars J0437−4715, B1534+12, and J1730−2304 and ± 50 km s^{-1} for pulsars B1257+12 and J2145−07.

3. RESULTS AND DISCUSSION

Our results are summarized in Table 1. The first column gives the pulsar name. The second gives the distance to the pulsar, based on the distance model of Taylor & Cordes (1993). Column (3) gives the epochs of observation. The measured values of decorrelation widths in time and frequency are given in columns (4) and (5), respectively, while column (6) gives the computed scintillation velocity. For J2145−07, measurement was possible at only one epoch. B1257+12 showed an exceptionally high velocity of 445 km s^{-1} on 1995 February 25. This measurement was excluded while we considered average properties. The mean velocities for pulsars J0437−4715, B1257+12, B1534+12, J1730−2304, and J2145−07 were found to be 231, 225, 191, 56, and 113 km s^{-1}, respectively. The average velocity for our millisecond pulsar sample turns out to be about 163 km s^{-1}. This value reduces to 135 km s^{-1} when the scintillation velocity for J0437−4715 is corrected for the effect of the local interstellar medium, as discussed below. Our results are fairly close to the recent estimate of 87 km s^{-1}, based on scintillation observations of 13 millisecond pulsars (Johnston et al. 1998).

From a study of pulsar proper motions (Lyne & Lorimer 1994), the average velocity for 99 normal pulsars has been found to be 300 km s^{-1}. Thus, the average velocity of millisecond pulsars, as determined from scintillation experiments, is at least a factor of 2 smaller than for normal pulsars. We note that the highest velocity for a millisecond pulsar is 225 km s^{-1} (obtained for B1257+12 from our data), and none of the millisecond pulsars has a velocity greater than the average velocity of normal pulsars. Our estimates are also comparable to the recent estimates of proper motion velocities for millisecond pulsars (Toscano et al. 1999).

In their study, Lyne & Lorimer (1994) concluded that their observed average velocity of normal pulsars is consistent with a kick velocity of 450 km s^{-1} at the time of birth. Such a kick velocity can result from an asymmetric supernova explosion that creates the pulsar. Thus, the smaller observed velocities for millisecond pulsars tend to rule out the direct supernova explosion as a source of their origin. On the other hand, the asymmetric mass loss during the accretion-induced collapse of a white dwarf is expected to provide kick velocities of about 50 km s^{-1} or less (Tauris & Bailes 1996). Our observed velocities are significantly higher than this, and except for possibly J1730−2304, none of the millisecond pulsars in our sample are consistent with this evolutionary scenario. Spin-up of neutron stars by accreting material from their binary companions is yet another mechanism proposed for the origin of millisecond pulsars (Alpar et al. 1982). Normal pulsars that originated with smaller kick velocities would remain in binaries and hence eventually lead to the formation of millisecond binary pulsars with smaller space velocities (Nice & Taylor 1995; Tauris & Bailes 1996; Dewey & Cordes 1987). Our data appear to be more consistent with this scenario.

Selection effects in a small sample of millisecond pulsars can bias the estimate of average velocity (Thorsett et al. 1993). Millisecond pulsars are in general weaker than normal pulsars and hence difficult to detect at large distances. Their shorter periods also make them difficult to detect through the dispersive interstellar medium at larger interstellar distances. It is thus possible that a sample of millisecond pulsars is biased toward low velocity and relatively nearby millisecond pulsars. However, in the present sample B1257+12 shows large scintillation velocity compared to other millisecond pulsars. It is possible that millisecond pulsars, being older, are undergoing oscillatory motion along the z-direction in the gravitational potential

TABLE 1

DECORRELATION FREQUENCY AND TIMESCALE FOR THE FIVE PULSARS AND RESPECTIVE SCINTILLATION VELOCITIES

Pulsar (1)	Distance (kpc) (2)	Epoch (3)	ν_d (MHz) (4)	τ_d (minutes) (5)	V_{iss} (km s^{-1}) (6)
J0437−4715......	0.18	1997 Mar 16	1.41	3.96	227
	0.18	1997 Mar 16	2.59	5.07	240
	0.18	1997 Mar 16	1.73	3.97	251
	0.18	1997 Mar 16	0.18	1.87	171
	0.18	1997 Mar 17	0.51	3.08	175
	0.18	1997 Mar 17	2.96	4.04	321
Average					231
B1257+12........	0.62	1994 Apr 28	0.19	3.17	193
	0.62	1995 Feb 21	0.73	2.70	445
	0.62	1995 Feb 24	0.71	5.18	229
	0.62	1996 May 1	0.21	2.55	253
Average					225
B1534+12........	0.68	1994 Apr 15	0.83	6.60	203
	0.68	1996 May 6	0.63	6.59	179
Average					191
J1730−2304......	0.50	1995 Feb 24	0.12	7.40	59
	0.50	1996 May 4	0.10	7.50	53
Average					56
J2145−0750......	0.50	1995 Feb 24	0.33	6.41	113
Average					113

of the galaxy. In this case, millisecond pulsars would spend a large fraction of their time with low velocity away from the galactic disc and would appear to be moving at high velocities while crossing the disc. Reliable velocity estimates are needed for a larger sample of millisecond pulsars to understand the effect of the above selection effects and to distinguish between the various proposed mechanisms for the origin of millisecond pulsars.

We now briefly consider the results for individual pulsars.

PSR J0437−4715.—This pulsar, which is one of the strongest and closest millisecond pulsars, was observed for several sessions at two epochs. The mean scintillation velocity is found to be 231 km s^{-1}. This value is comparable to that from observations at 660 MHz, which estimate the scintillation velocity of the pulsar to be 170 km s^{-1} (Johnston et al. 1998). Proper motion measurements for PSR 0437−4715 were taken, and a V_{pm} of 91 ± 3 km s^{-1} was found (Bell et al. 1995). A recent estimate of the proper motion, however, suggests a velocity of 120.5 ± 2 km s^{-1} (Toscano et al. 1999). The scintillation velocity is thus significantly larger than the proper motion estimates. Since this is a local pulsar (at a distance of about 180 pc), we expect the scintillation properties to be significantly affected by the distribution of scattering material in the Local Bubble. Recent modeling of scattering from the Local Bubble (Bhat, Gupta, & Rao 1998) shows that the scattering along the line of sight to this pulsar is dominated by scattering from the shell of the Local Bubble. From a model local interstellar medium (Bhat et al. 1998), we estimate the shell of the Local Bubble to be located at a distance of 120 pc in this direction. If we consider this as an effective thin screen that dominates the interstellar scattering for this pulsar, then we expect the estimated scintillation speed to be higher than the proper motion speed, as is indeed the case. The ratio of the two speeds (see eqs. [1], [2], and [5] of Gupta 1995) should be $(D_o/D_p)^{1/2} = 1.4$. Our measurements give a ratio of 1.9, which is close to the prediction. Thus, the discrepancy between the scintillation and proper motion speeds for this pulsar is due to scattering from the Local Bubble.

PSR B1257+12.—Our measurement of 201 km s^{-1} is the first published estimate for the scintillation velocity of this pulsar. This result is in reasonable agreement with the proper motion speed of the pulsar, estimated to be 279 km s^{-1} (Nice & Taylor 1995) and more recently 284 ± 2 km s^{-1} (Toscano et al. 1999), with the distance to the pulsar taken to be 620 pc.

PSR B1534+12.—Our scintillation velocity estimate of 191 km s^{-1} was obtained by averaging measurements from multiple sessions at two epochs. Our results are consistent with the value of 190 km s^{-1} estimated in a recent study (Johnston et al. 1998).

PSR J1730−2304.—The scintillation velocity of pulsar PSR J1730−2304, observed at two epochs, was found to be 56 km s^{-1}. These measurements are in agreement with the scintillation speed of 62 km s^{-1} obtained at 436 MHz (Johnston et al. 1998). Both these scintillation velocities are consistent with the recent lower limit on the proper motion velocity of 51 ± 1 km s^{-1} (Toscano et al. 1999).

PSR J2145−0750.—The scintillation velocity for PSR 2145−0750 was found to be 113 km s^{-1}. This appears to be a factor of 2 larger than the velocity of 51 km s^{-1} obtained from scintillation measurements at 436 MHz (Johnston et al. 1998) and a factor of 3 larger than the proper motion velocity of 38 ± 4 km s^{-1} (Toscano et al. 1999). Since our estimate is obtained from a single-epoch measurement, it may be biased because of refractive modulations of the measured decorrelation widths and should therefore be treated with some caution.

4. CONCLUSION

The scintillation velocities for five pulsars, PSR J0437−4715, PSR B1257+12, PSR B1534+12, PSR J1730−2304, and PSR J2145−0750, were obtained from the interstellar scintillation observations carried out at 327 MHz using the Ooty Radio Telescope at multiple epochs. Their scintillation velocities were estimated to be 211, 225, 191, 56, and 113 km s^{-1}, respectively. The average scintillation velocity was found to be 158 km s^{-1}. This is considerably smaller than the velocity for normal pulsars and appears to be larger than the velocity expected from an accretion-induced collapse process.

Present measurements are in agreement with independent observations and suggest that the average velocity of millisecond pulsars is a factor of 2 smaller than that of normal pulsars, implying that the process of origin is not supernovae. The average velocity appears to be a factor of 3 larger than the velocity expected from the accretion-induced collapse of white dwarfs. Thus, velocity measurements for a larger and complete sample of millisecond pulsars are desirable in order to identify the process of their origin.

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