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MULTIFREQUENCY TIMING MEASUREMENTS ON THE MILLISECOND PULSAR PSR 1937+214

J. M. CORDES[1] AND DANIEL R. STINEBRING[2]
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ABSTRACT

Measurements at four radio frequencies show to high accuracy that interstellar dispersion and scattering produce the only frequency-dependent time delays in pulse arrival times. The dispersion measure is DM = 71.0440 ± 0.0002 pc cm^{-3}. All frequencies are emitted from the same altitude to within ± 2 km, but the variation of pulse width with frequency proportional to $f^{-1.5}$ at low frequencies implies beaming is strongly frequency dependent. The interpulse to main pulse separation (174°) appears to be independent of frequency. Dual-frequency monitoring should allow intrinsic timing activity or timing variations due to gravity wave backgrounds to be distinguished from changes in dispersion measure.

Subject headings: gravitation — pulsars

I. INTRODUCTION

The millisecond-period pulsar PSR 1937+214 is of great interest because its properties are so extreme. Its narrow pulse allows arrival times to be determined more accurately than for any other pulsar, and it may prove to be more accurate than any terrestrial clock on time scales of years. In this *Letter*, we report multifrequency measurements whose aim is to determine if the extreme nature of the magnetosphere (10^8 gauss magnetic field and 76 km light-cylinder radius) is at all manifest in the pulse shapes and in the times of arrival (TOAs).

II. OBSERVATIONS

Data were obtained in 1983 March–April at the Arecibo Observatory using the 305 m antenna and line feeds at 0.32, 0.43, 0.93, and 1.4 GHz. Narrow-band intermediate-frequency (IF) signals from Butterworth bandpass filters in one or two polarizations (see Table 1) were mixed to base band and sampled (in phase and in quadrature) in bursts of 8, 16, or 32 ms ($\approx$ 5–20 pulse periods) at 4 μs or 8 μs intervals. Dispersion distortion was removed either by processing in real time with ~ 10% ratio of data acquisition time to processing time or otherwise by recording data on tape with subsequent off-line processing.

Dispersion removal was accomplished by applying a filter that compensates the phase shifts imposed on the signal during propagation through the interstellar medium (Hankins and Rickett 1975). Convolution of filter and data was effected in a FPS 120B array processor by multiplying discrete Fourier transforms (DFTs) of raw data and filter. The product was transformed back to the time domain, squared, and folded by the number of samples corresponding to one pulse period (200 or 400 samples). The resultant average pulse shapes were recorded on tape along with timing information accurate to 1 μs. The dispersion measure must be known to reasonable accuracy. Figure 1 shows the signal-to-noise loss for an impulse dispersed by an amount *DM* and then de-dispersed with DM + δDM. For our observations, $\delta\mathrm{DM}/\mathrm{DM} \leq 7 \times 10^{-4}$, so the resultant pulse shapes are essentially dispersionless.

Dispersionless waveforms are shown in Figure 2 at three radio frequencies along with a 0.4 GHz pulse shape with no dispersion removal. The waveforms are aligned with all interstellar propagation delays removed. The separation of main pulse and interpulse is frequency independent, but both pulse components become broader at lower frequencies. Some of the broadening is due to interstellar scattering, but some of it appears to be intrinsic, as we show below.

a) *Interstellar Scattering*

Multipath propagation in the interstellar medium causes intrinsic pulse structure to be convolved with a function of approximate form $h_{\mathrm{ISS}}(t) = \exp\,(-t/\tau_{\mathrm{ISS}})U(t)$, where U is the unit step function. The arrival time analysis discussed below requires removal of the associated time delay, so we determined τ_{ISS} from the "uncertainty" relation $2\pi\Delta f_{\mathrm{ISS}}\tau_{\mathrm{ISS}} = 1$ (Rickett 1977) by computing the decorrelation bandwidth Δf_{ISS} of frequency structure also caused by multipath propagation.

We obtained Δf_{ISS} at 0.43 GHz from the cross-correlation function (CCF) of dynamic spectra for the two circular polarizations. Spectra from 250 2048-sample DFTs of the data were averaged before cross-correlating, and a total of 20 minutes of data were used to form the CCF in Figure 3. The half-width at half-maximum of the CCF, $\Delta f_{\mathrm{ISS}} \approx 6.3 \pm 0.7$ kHz, is in good agreement with a value predicted from $\Delta f_{\mathrm{ISS}} \approx 2$ MHz at 1.4 GHz (Backer *et al.* 1982) after scaling by $\Delta f_{\mathrm{ISS}} \propto f^{+4.4}$ which conforms to the ISS of other pulsars and corresponds to scattering from electron-density irregularities with a Kolmogorov wavenumber spectrum (Rickett 1977; Cordes, Weisberg, and Boriakoff 1983). Using the uncertainty relation, we estimate the ISS smearing time to be $\tau_{\mathrm{ISS}}(f) \approx (620 \pm 70)\, f_{\mathrm{GHz}}^{-4.4}$ ns.

[1]National Astronomy and Ionosphere Center, and Cornell University.
[2]National Radio Astronomy Observatory.

TABLE 1

DATA ACQUISITION PARAMETERS

Frequency (GHz)	Bandwidth (kHz)	Sample Interval (μs)	Dispersion Sweep Time T_s (μs)	Polarization
0.32	125	8	2292	single linear
0.43	125	8	927	dual circular
	250	4	1854	dual circular
0.93	250	4	183	single linear
1.39	250	4	55	dual circular

b) *Pulse Shapes*

The main pulse and interpulse have constant separation, weakly frequency-dependent amplitude ratio (Table 2), and widths that are strongly frequency dependent. After correcting for scattering broadening, we find the pulse width to increase by nearly a factor of 3 between 2.38 and 0.32 GHz. Roughly, widths are approximately $63 f_{\rm GHz}^{-0.37}$ μs over the entire frequency range and are proportional to $f^{-1.5}$ between 0.43 and 0.32 GHz. The frequency dependence at low frequencies is much stronger than for other pulsars which show variations as strong as $f^{\pm 0.5}$ only when two pulse components are blended together and have different amplitude spectra (Sieber, Reinecke, and Wielebinski 1975; Backer 1976). The broadening observed here suggests an actual increase in radiation beam size that is different from other objects. We discuss the implications of this fact below.

III. ARRIVAL TIME ANALYSIS

Topocentric arrival times were determined by recording the local time to an accuracy of 1 μs, as allowed by the slaving of the observatory's rubidium standard to the Loran C time service, and by convolving a template pulse waveform with all

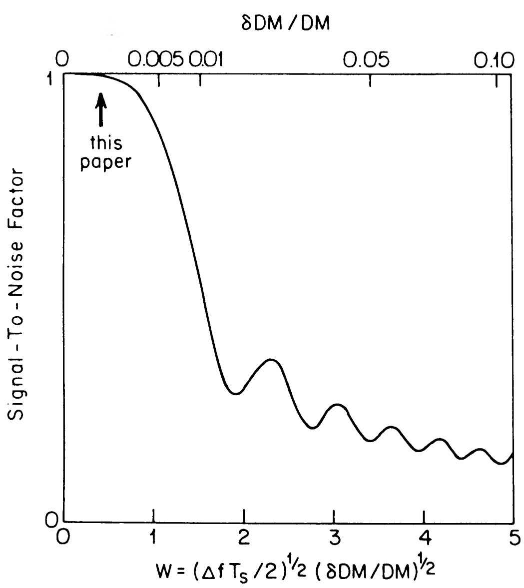

FIG. 1

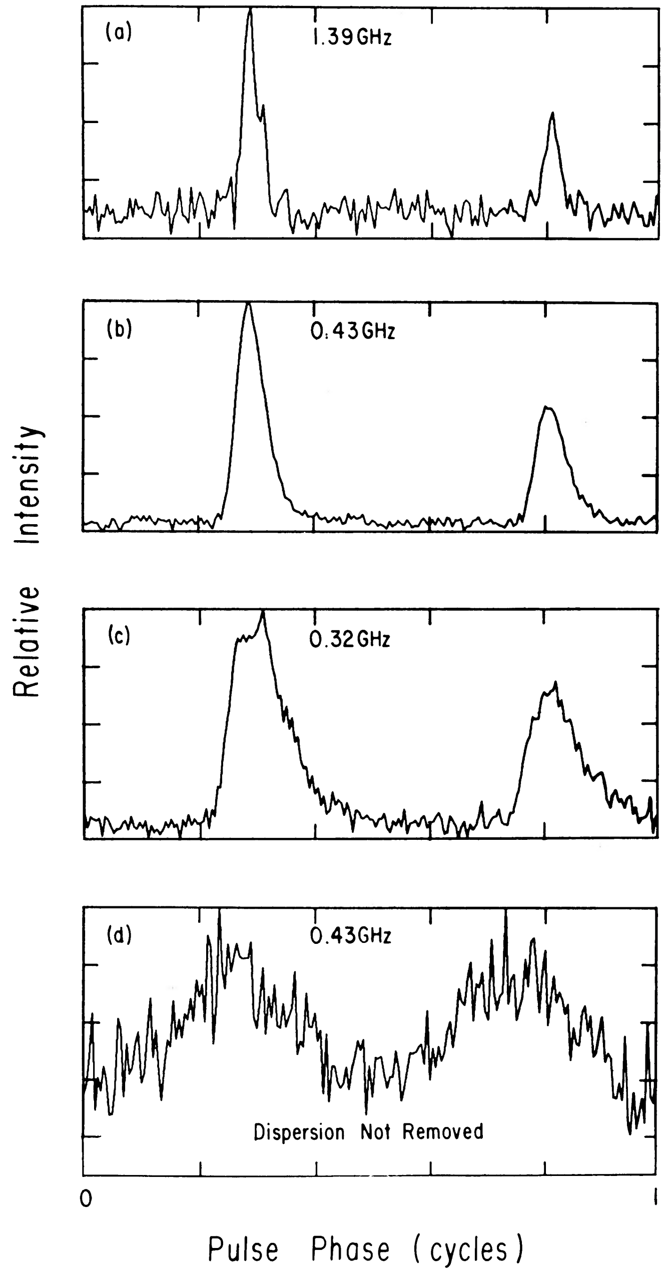

FIG. 2

FIG. 1.—Signal-to-noise loss as a function of error in dispersion measure. The receiver bandwidth is Δf, and T_s is the dispersion sweep time.

FIG. 2.—Waveforms at three frequencies with alignment after removing frequency-dependent time delays due to the interstellar medium: (*a*) 1.39 GHz, 3×10^5 pulses; (*b*) 0.43 GHz, 3×10^5 pulses; (*c*) 0.32 GHz, 10^6 pulses; (*d*) 0.43 GHz without removing dispersion distortion.

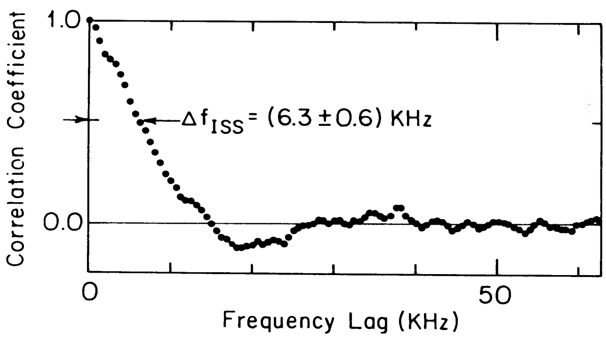

FIG. 3.—Correlation function of scintillation frequency structure

sample average waveforms (e.g., Helfand *et al.* 1980). Barycentric arrival times were determined using the Lincoln Lab solar system ephemeris.

A suitable model for the barycentric pulse phase at frequency f and time t is

$$\phi(f,t) = \phi_{NS}(t) + \phi_{ISD}(f) + \phi_{ISS}(f) + \phi_{NF}(f), \quad (1)$$

where we assume estimation errors to be negligible. The various terms are (i) $\phi_{NS}(t) = \phi_0 + \nu_0 t + \dot{\nu}_0 t^2/2$, the rotational phase of the neutron star with ν_0 = rotational frequency and $\dot{\nu}_0$ its time derivative; (ii) $\phi_{ISD}(f) = \nu \Delta t_{ISD}(f)$, where $\Delta t_{ISD} \propto \mathrm{DM} f^{-2}$ is the interstellar dispersion delay; (iii) $\phi_{ISS}(f) = \nu \Delta t_{ISS}(f)$, where $\Delta t_{ISS} \approx 0.6\ \tau_{ISS}$ is the delay due to interstellar scattering, a relation determined from numerical tests in the regime where τ_{ISS} is comparable to the pulse width and has an accuracy $\lesssim 5\ \mu$s for data discussed here; (iv) $\phi_{NF}(f)$ is a "nonfiducial" phase corresponding to possible frequency dependence in the location of emission regions in the magnetosphere.

We used R.A.(1950)=$19^h37^m28^s\!.75$, δ(1950)=$21°28'01''\!.58$, DM = 71.056 pc cm^{-3}, and the scattering delay to obtain preliminary "infinite frequency" barycentric TOAs. Rotational phase was estimated using P = 1.55780644890 ms and $\dot{P} = 9.109 \times 10^{-20}$ s s^{-1} at the epoch JED 2,445,303.3 (parameters provided by S. Kulkarni, J. H. Taylor, and M. M. Davis except for DM which is consistent with the work of Ashworth, Lyne, and Smith 1983 and Backer, Kulkarni, and Taylor 1983). The phase residuals from this model (Fig. 4*a*) can be adequately modeled as

$$\delta\phi(f,t) = \delta\nu t + \Delta\phi_{ISD}\delta\mathrm{DM}/\mathrm{DM} + \phi_{NF}(f). \quad (2)$$

Small corrections $\delta\nu$ and δDM yield residuals (Fig. 4*b*) which have no systematic time or frequency dependence and DM = 71.0440 ± 0.0002 pc cm^{-3}.

We are faced with two possible interpretations: either nonfiducial contributions to the phase (e.g., aberration and retardation) are negligible or they must scale as f^{-2} or $f^{-4.4}$ to mimic cold plasma dispersion or scattering. We regard this latter possibility as implausible because f^{-2} and $f^{-4.4}$ scalings for ϕ_{NF} do not arise naturally out of pulsar magnetospheres. To first order, retardation and rotational aberration yield $\phi_{NF} \propto \Delta r/c \propto f^{-2X}$, a scaling which associates empirical pulse widths $\propto f^{-X}$ (with $0.1 \lesssim X \lesssim 0.5$) with the opening angle

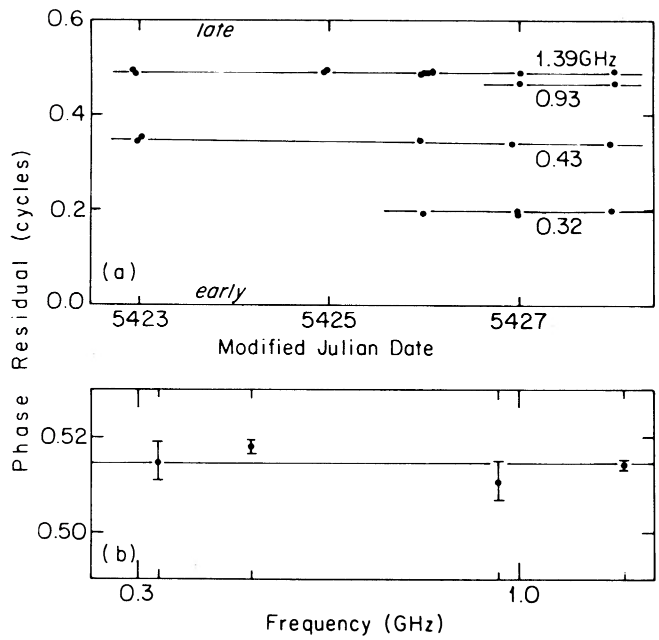

FIG. 4.—(*a*) Residual phase vs. Julian date for four radio frequencies using nominal parameters. (*b*) Residual phase vs. frequency after correcting phases in (*a*) for errors in rotation frequency and dispersion measure.

TABLE 2

PULSE PROPERTIES AS A FUNCTION OF FREQUENCY

Frequency (GHz)	Main Pulse Width (HWHM) (μs)	Interpulse Width (HWHM) (μs)	τ_{ISS} (μs)	MP − IP Separation (deg)	IP/MP Ratio
0.32	160 ± 10 (110 ± 10)[a]	160 ± 10 (110 ± 10)	95	175 ± 1.0	0.52
0.43	90 ± 10 (65 ± 10)	90 ± 10 (68 ± 10)	25	174 ± 0.6	0.55
1.39	65 ± 10	56 ± 10	0.14	174 ± 2	0.52
2.38[b]	43 ± 4	47 ± 4	0.01	173 ± 1	0.36

[a]Values in parentheses are widths after deconvolving a one-sided exponential from the waveform to correct for interstellar scattering.
[b]Results from Stinebring 1983.

proportional to (radius)$^{1/2}$ of field lines near the axis of a magnetic dipole (Cordes 1978). Neither PSR 1937+214 nor any other pulsar shows the required $X = 1$ or $X = 2.2$ to mimic the interstellar propagation effects.

Our conclusion, therefore, is that the only frequency-dependent time delays are due to interstellar dispersion and scattering, within errors of ± 6 μs. All emission from 0.3 to 1.4 GHz arises from the same altitude to within ± 2 km, a conclusion that assumes only relativistic beaming and retardation/aberration time delays proportional to $\Delta r/c$. Delays nonlinear in Δr (i.e., emission radii $\approx$ light cylinder radius) yield a more stringent altitude range.

IV. SUMMARY AND CONCLUSIONS

Our multifrequency timing measurements on the millisecond pulsar PSR 1937+214 have led to the most precise determination of a pulsar DM (3 parts in 10^6), observation of anomalous scaling of pulse width with frequency, and measurement of the simultaneity of emission over a 4:1 frequency range to within ± 6 μs. These results have implications for the study of pulsar magnetospheres, plasma turbulence in the interstellar medium, and the use of pulsars as gravity wave detectors.

The small observed pulse widths ($\sim 15°$–$30°$ of pulse phase) are a puzzle given the magnetic polar cap size $2(R_\star/R_{\rm LC})^{1/2} \approx 41°$, where $R_\star = 10$ km and $R_{\rm LC} \equiv c/\Omega = 76$ km are the neutron star and light-cylinder radii (Goldreich and Julian 1969). Emissions at radii $r \ll R_{\rm LC}$ imply pulse widths proportional to $(\frac{3}{2})$ $41°$ $(r/R_\star)^{1/2}$ for a dipolar field and if the radiation beam is a hollow cone bounded by the polar cap, as appears true for many pulsars. Some objects, however, suggest the presence of an additional pencil beam centered more or less on the dipole axis (Rankin 1983), so PSR 1937+214 may be of this class.

The accuracy of our measurement of DM suggests that sustained observations will be sensitive to DM fluctuations at the level $\delta{\rm DM} \sim 2 \times 10^{-4}$ pc cm^{-3} $= 6 \times 10^{14}$ cm^{-2}, a column density that could be produced by variations in the solar system or interstellar medium, or even by the pulsar's motion through the interstellar medium.

Our measurements also suggest that plans to use PSR 1937+214 as a probe for a stochastic background of gravitational radiation are viable. If it proves to remain rotationally stable, then frequency-independent TOA fluctuations due to such backgrounds can be detected at the microsecond level or less. From the results of Detweiler (1979), dual-frequency measurements over 5 years will be sensitive to a gravity wave energy density (for wavelengths $\approx$ a few light years) of 10^{-7} times the closure density of the universe (Bertotti, Carr, and Rees 1983).

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JAMES M. CORDES: Astronomy Department, Cornell University, Ithaca, NY 14853

DANIEL R. STINEBRING: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901