D.C. Backer and T. Wong

Interstellar Weather—Radio Wave Propagation Through the Turbulent Ionized Interstellar Medium

Abstract

Turbulence, or turbulent-like structures, in the interstellar medium when combined with motions of the medium and the pulsar-earth line of sight lead to observable changes in pulse arrival time via dispersion measure changes and multipath propagation or pulse broadening. In the Vela (PSR B0833−45) and Crab (PSR B0531+21) pulsars the column density variations are dominated by structures within the high density material associated with the surrounding supernova remnants and pre-stellar matter. In the millisecond pulsar B1937+21 the effects are much smaller and are associated with the general intervening interstellar medium. Precision timing in the presence of unstable interstellar weather require multifrequency observations at the highest possible radio frequencies with dense sampling in time.

I Radio wave propagation primer

Useful references on radio wave propagation through the turbulent interstellar medium include: Rickett (1977); Cordes, Pitwerbetsky & Lovelace (1986); Hu et al. (1991); Foster & Cordes (1990).

The index of refraction in a dilute, thermal plasma contains a term dependent on the electron density divided by the radio frequency ($\nu = c/\lambda$) squared. The medium is thus dispersive. A path integral of the inverse of the group velocity at any frequency provides the dispersive delay, $\tau_{\rm DM}$, which depends on the column density of electrons. Radio astronomers call this column density the Dispersion Measure, or DM, and use units of pc cm^{-3},

$$\mathrm{DM}(\mathrm{pc\ cm}^{-3}) = \int n_e \mathrm{d}l$$

$$\tau_{\rm DM} \propto \mathrm{DM}/\nu^2.$$

The interstellar plasma density is not uniform. There are fluctuations on all scales—from kpc down to 10^8 m or less. On scales below one parsec the fluctuations in some regions may be described by a single power law wave number spectrum. Furthermore this spectrum may indicate the operation of a Kolmogorov-like turbulent cascade with injection of density and velocity fluctuations at an outer scale and dissipation of turbulent energy after the cascade at an inner scale. One goal of the pulsar observations described below is better understanding of the location and spectrum of the interstellar plasma fluctuations.

The transverse motion of the pulsar-earth line of sight at $v_\perp$ through turbulent plasma leads to variations in the DM. The structure function of DM(t) is a useful statistical summary:

$$D_{\rm DM}(\tau) \equiv \langle [({\rm DM}(t+\tau) - {\rm DM}(t)]^2 \rangle \propto \tau^\delta.$$

Here δ is 2 for $\tau/v_\perp$ less than the inner scale and 0 when greater than the outer scale. For intermediate length scales the slope is related to the slope of the power spectrum and has been shown to be near 2.

The dispersive delay can be written as radio wave phase by multiplying by the radio frequency. (In a dilute plasma the phase velocity and group velocity are very near c and inversely proportional to each other.) The phase fluctuations are much larger than one radian on transverse length scales equal to the first Fresnel radius for most pulsar observations. Consequently diffraction plays an important role. We can define a transverse coherence length $l_\circ$ from the phase structure function, $D_\phi(l_\circ) \equiv 0$. This coherence length is roughly proportional to radio frequency,

$$l_\circ \propto \nu.$$

The presence of a power law wave number spectrum (3D) of density fluctuations with an index near -4 will change this dependence slightly.

Consider a slab of turbulent plasma along the line of sight as shown in Figure 1. A plane wave incident upon this slab will be scattered by the phase fluctuations into a cone of dimension $\Theta_s = \lambda/l_\circ$. This scattering angle is a property of the slab independent of its location. As an aside the scattering here is by plasma waves and not single electron Thompson scattering. Fig. 1 provides the geometry of scattering for source and observer at finite distances. The apparent size of a point source seen through the slab is

$$\Theta_\circ = x\Theta_s \propto \nu^2.$$

The observable effect of scattering by the slab decreases as it is moved toward the emitter.

The angular scattering results in multipath propagation and a broadening of sharp impulses sent through the slab by a time

$$\tau_s = x(1-x)D\Theta_s^2/2{\rm c} \propto \nu^4.$$

Pulse broadening is maximized when the slab is half way between the pulsar and the observer. A further effect of scattering is that the region of the slab through which

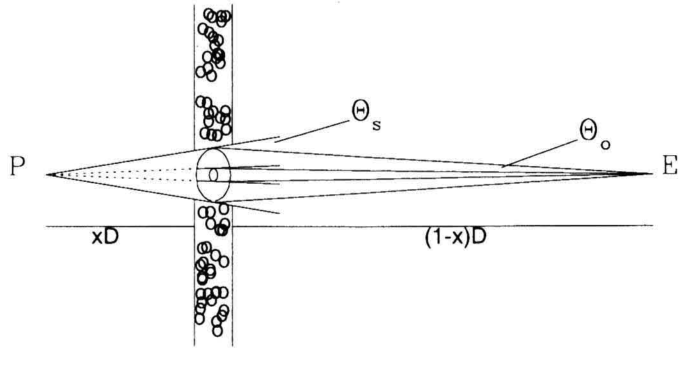

Figure 1. Geometry of interstellar scattering. Inner cone corresponds to scattering at 610 MHz and outer to scattering at 327 MHz.

radiation is received has a transverse scale of

$$l_d = x(1-x)\Theta_s D.$$

The DM that we measure is then an average of the column density over this scale. This averaging smooths the DM(t) that would be observed in the absence of scattering. In the case illustrated in Fig. 1 the smoothing time scale is $l_d/(1-x)v_\perp = x\Theta_s/v_\perp$.

Finally those phase fluctuations on scales larger than a Fresnel radius lead to refraction effects such as small (25%) intensity modulation. The time scale for changes in the refractive effects is the same as that just described for smoothing of DM changes. Refraction also changes the effective scattering angle, and thereby modulates angular (Θ_o) and temporal (τ_s) broadening. The paths of signals through the slab in Fig. 1 will be bent by refraction and the bending will be frequency dependent. For steep power law density irregularity spectra the refraction angles can exceed the scattering cone angle Θ_s while for shallow spectra refraction is small with respect to Θ_s.

II Observations

Most of the observations described below were obtained with the 85 ft pulsar monitoring telescope in Green Bank, WV. Receivers with linearly polarized feeds at 327 and 610 MHz are mounted off axis for continuous use by offset pointing. The bandwidths are 10 and 40 MHz respectively. Average pulse profiles are obtained after 5–10 minutes of integration with the Green Bank-Berkeley Pulsar Processor (e.g., Backer et al. 1997). The multichannel data from this processor are reduced to flux calibrated average pulse profiles. Further reduction includes estimation of flux, pulse broadening in some cases and arrival times.

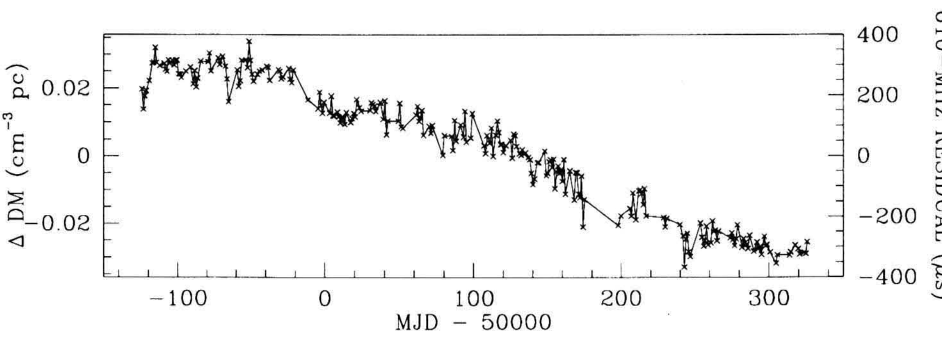

Figure 2. Dispersion measure variations for PSR B0833−45 from Green Bank pulsar monitoring telescope.

PSR B0833−45, the Vela pulsar

Figure 2 shows that the DM of the Vela pulsar continues to decline at the rate of -0.04 pc cm^{-3} y^{-1} first reported by Hamilton et al. (1977). Apparently a large wedge of plasma is exiting the line of sight. Given the pulsar's proper motion of 115 km s^{-1} (Bailes et al. 1989) and assuming a factor x of 0.5, we can infer a typical density in this wedge of 10^3 cm^{-3} and a transverse scale exceeding 10^{16} cm. Gradients of DM are seen in other pulsars (Phillips & Wolszczan 1992; Backer et al. 1993). The gradient for the Vela pulsar is very large by comparison. One can conclude that the DM changes for the Vela pulsar are the result of dense material in the Gum nebula within which the Vela pulsar resides. The gradient will lead to a frequency dependent source position (about 10 mas at 1 m λ) that could be detected by astrometric observations with a global VLBI array.

Small changes in the pulse broadening of the Vela pulsar at 327 MHz are also observed. The amplitude and time scale of these changes suggest an origin in the refractive properties of the intervening medium as discussed in the primer section. A useful followup study to our monitoring of pulse broadening would be contemporaneous angular broadening measurements. The combined measurements should show correlated changes and can determine the location of the scattering slab if the effects are dominated by a single portion of the line of sight (see Gwinn, Bartel, & Cordes 1993).

PSR B0531+21, the Crab pulsar

Rankin & Counselman (1973) reported on changes in the DM and pulse broadening of the Crab pulsar. Their analysis of pulse broadening led to the conclusion that the line of sight was dominated by two scattering slabs and that one was highly variable. The natural conclusion was that the highly variable slab was in or around the Crab nebula.

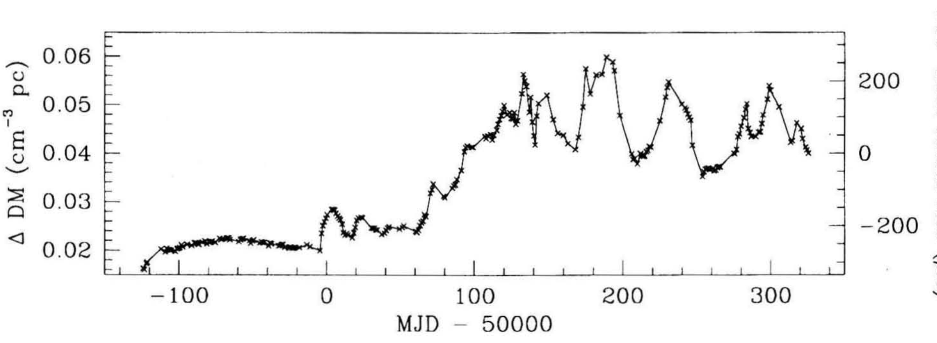

Figure 3. Dispersion measure variations for PSR B0531+21 from Green Bank pulsar monitoring telescope. A large dispersion and scattering event began around MJD 50000, 1995 October 10.

Lyne & Thorne (1975) and Rankin et al. (1988) reported on extreme variations of the scattering during 1974. Again these variations were attributed to Crab nebula plasma.

Figure 3 displays the DM record from our observations over the past 1.5 yr. Extreme variations similar to the event in 1974 are evident in this DM record as well as in the pulse broadening. Conversion of time scales to transverse length scales leads to density estimates around 10^3 cm^{-3} which is comparable to the densities in the web of filaments that surround the optical synchrotron nebula (Lawrence et al. 1995; Hester et al. 1996). We conclude that this is the likely site for the extreme scattering material and that $x = 10^{-3}$. Note that this small value of x means that the apparent size of the pulsar may not have changed very much. In a more complete report (Wong, Backer & Lyne 1997) we present a structure function for the DM variations both from the results in Fig. 3 and from the historic record kept at Jodrell Bank. The structure function has a rather flat index, near +1, that also distinguishes these variations from those in the general interstellar medium.

PSR B1937+21, a millisecond pulsar

In Green Bank we are conducting precision timing of PSR B1937+21 at four radio frequencies: 327, 610, 800 & 1395 MHz. Figure 4 displays the timing residuals from a model fit to the 1395 MHz data. Deviations of the 800 MHz data with microsecond amplitude are expected from DM variations along the line of sight through the general interstellar medium (Backer et al. 1993; Kaspi, Taylor & Ryba 1994). The figure also displays the 610 MHz residuals from the same timing model. These residuals are larger as expected from the radio frequency dependence of the dispersion. The dotted lines in Fig. 4 follow the 800 MHz data with scaling by the ratio of $(1/610^2 - 1/1395^2)/(1/800^2 - 1/1395^2)$ to show what the effects of dispersion would be assuming that the 800 MHz residuals are dispersive. There is good agreement

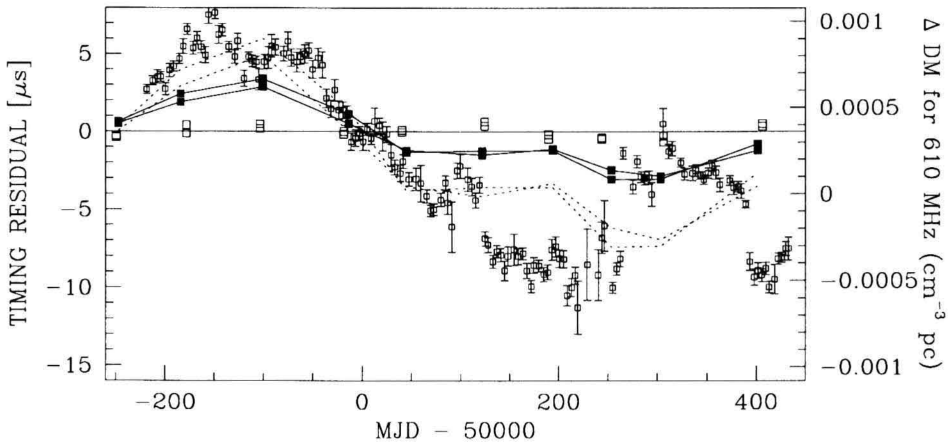

Figure 4. Dispersion measure variations for PSR B1937+21 from Green Bank pulsar monitoring and 140 ft telescopes. Open squares are 1395 MHz data; solid squares are 800 MHz data and densely sampled open squares with error bars are 610 MHz data. A model is fit to the 1395 MHz data to produce near zero residuals. The deviations of the 800 MHz data from zero are interpreted as dispersive and the dashed lines represent how this dispersive delay would scale to 610 MHz. There is an arbitrary zero for the three sets of residuals, and some uncertainty surrounds the continuity of 610 MHz residuals at MJD 50228 owing to equipment changes.

through about MJD 50120 (1996 February 07). After this date there appear to be several swings of the 610 MHz residuals above and below the dispersive extrapolation. Inspection of other data from this telescope show no evidence for equipment problems. In particular the residuals for PSR J0437−4715 in the interval since MJD 50228 are smaller than that shown in Fig. 4. Furthermore there is evidence in the 327 MHz data (not shown here) for events with different temporal behavior associated with the abrupt changes in the 610 MHz residuals shown in Fig. 4. Cognard et al. (1993) report on sudden changes in the propagation effects of B1937+21 which they conclude are the result of crossing a caustic.

There is a good reason for the lack of agreement of the four frequency data with a simple model of variable plasma dispersion. As discussed in the primer the effects of angular scatteringmean that *the* dispersion measure (column density of electrons) is in fact an average over a volume of the intervening path established by the diffractive and refractive properties along the path. In the simplest case this volume is a tube of growing diameter out to the midpath point and then contracting as the observer is approached (see Fig. 1). (In the absence of scattering the tube diameter would be established by the Fresnel radius along the line of sight.) The diameter of this volume is set by the path geometry and the scattering angle. The total volume of this averaging tube is thus dependent approximately on $-nu^{-4}$. As a consequence, *the* dispersion measure is *not* an accurately defineable quantity at any instant—the column density of electrons depends to some extent on frequency. The inaccuracy is most evident on the refractive time scale, the time scale for the averaging volume to displace itself, and this time scale is itself frequency dependent as stated above. At 610 MHz we estimate that the refractive time scale is 40 d.

Precision timing of millisecond pulsars, if limited by dispersive effects, can best be improved both by going to higher observing frequency and with dense sampling in time to average over independent samples. On time scales less than the refractive time scale, the variance of the variations will increase as t^2.

Acknowledgements

We are grateful for the Naval Research Laboratory's support of the Green Bank pulsar monitoring telescope, and assistance from the NRAO operators and David Nice.

References

Backer, D.C. et al. 1997, PASP, 109, 61
Backer, D. . et al. 1993, ApJ, 404, 636
Bailes, M. et al. 1989 ApJ, 343, L53
Cognard, I. et al. 1993, Nature, 366, 320
Cordes, J.M., Pitwerbetsky, A. & Lovelace, R.V.E. 1986, ApJ, 310, 737
Foster, R.S. & Cordes, J.M. 1990, ApJ, 364, 123
Gwinn, C.R., Bartel, N. & Cordes, J.M. 1993, ApJ, 410, 673
Hamilton, P.A. et al. 1977, Nature, 265, 224
Hester, J.J. et al. 1996, ApJ, 456, 225
Hu, W., Romani, R.W. & Stinebring, D.R. 1991, ApJ, 366, L33
Kaspi, V.M., Taylor, J.H. & Ryba, M.F. 1994, ApJ, 428, 713
Lawrence, S.S. et al. 1995, AJ, 109, 2885
Lyne, A.G. & Thorne, D.J. 1975, MNRAS, 172, 97
Phillips, J.A. & Wolszczan, A. 1992, ApJ, 385, 273
Rankin, J.M. & Counselman, C.C. 1973, ApJ, 181, 875
Rankin, J.M. et al. 1988, AA, 202, 166
Rickett, B.J. 1977, ARAA, 15, 479
Wong, T., Backer, D.C. & Lyne, A.G. 1997, in preparation

Authors' Addresses

Astronomy Department, University of California, Berkeley, CA 94720, USA