Part 6
Winds and the ISM

Section C
The Insterstellar Medium

https://doi.org/10.1017/S0252921100042068 Published online by Cambridge University Press

Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

Interstellar Scattering: Observations and Interpretations

Barney Rickett

University of California San Diego, La Jolla, CA 92093-0407

Abstract. The successful theory for radio propagation through the interstellar plasma is reviewed, where the density spectrum follows the Kolmogorov model. However, there are also several observations indicating more refraction than expected. A particular model of enhanced refraction is proposed in which isolated regions of the warm ionized medium support filaments of enhanced density on a scale of 1 AU, which do not couple to a turbulent cascade.

1. Introduction

Interstellar dispersion, scintillation and scattering are intimately tied to all manner of pulsar observations. There now exists a detailed model for the distribution of dispersing electrons in our Galaxy (Taylor & Cordes, 1993 - TC); the model also gives a similarly detailed description of the spatial distribution of the level of turbulence in the interstellar plasma. The turbulence model assumes that the wavenumber spectrum of plasma density follows the Kolmogorov form:

$$P_N(\kappa) = C_N^2 \kappa^{-\beta} \;, \text{ where } \; r_{\text{outer}}^{-1} < \kappa < r_{\text{inner}}^{-1} \tag{1}$$

where κ is wavenumber and $\beta = 11/3$; this has become the *de facto* standard. Armstrong et al (1995) recently summarized the evidence for this model in the solar neighbourhood, concluding that it was valid for $10^{-13}\text{m}^{-1} \leq \kappa \leq 10^{-7}$ m^{-1}. The Kolmogorov spectral model, with a strength parameter C_N^2 varying according to the TC Galactic distribution, now successfully describes very many propagation phenomena familiar to pulsar observers. The model is also important in its own right for the astrophysics of the Galaxy. I will briefly review these propagation phenomena, and then emphasize where the model fails and end by presenting an argument for an additional distribution of (refracting) plasma in the interstellar medium (ISM).

2. Interstellar Propagation Effects

Consider radio propagation between a pulsar P at distance L from an observer O at transverse position $\vec{s}$. Define the straight-line phase by integrating along the line PO.

$$\phi(\vec{s}) = \int_0^L kn(\vec{s}z/L, z)dz \;=\; kL - r_e \lambda DM \tag{2}$$

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The second equality results when the refractive index n is given by the weak plasma dispersion law and $DM = \int_0^L N(\vec{s}z/L, z)dz$ for electron density N. The frequency dependence of this phase causes the well-known dispersive group delay:

$$T_{\rm g} = L/c + DMr_{\rm e}c/2\pi f^2 \tag{3}$$

where $r_{\rm e} = 2.8\ 10^{-15}$m. This law is followed with high precision for all pulsars, with slight differences for left and right circular polarization due to Faraday rotation in the presence of a longitudinal magnetic field. As time goes by the group delay and DM change due to the relative motion $\vec{s} = \vec{V}t$ of the line PO through the inhomogenous plasma. This small change has now been measured for a few pulsars (eg Phillips and Wolszczan, 1991 Kaspi et al 1994).

It is the transverse variations of N that cause most of the scattering and scintillation phenomena. The lateral variations of phase cause a decorrelation over baseline $\vec{s}$. Thus in a VLBI measurement the fringe visibility is reduced:

$$\Gamma_2(\vec{s}) = \langle E(\vec{s'})E^*(\vec{s'} + \vec{s})\rangle = \exp[-0.5D_\phi(\vec{s})] \tag{4}$$

Here the D_ϕ is phase structure function, given by

$$D_\phi(\vec{s}) = \langle[\phi(\vec{s'}) - \phi(\vec{s'} + \vec{s})]^2\rangle = (s/s_o)^{5/3} \tag{5}$$

where the Kolmogorov density spectrum is assumed. Here s_o is the field coherence scale $\propto f^{1.2}L^{-0.6}$. The scattered angular radius (at $e^{-1/2}$) is then $\theta_{\rm d} = 1/(ks_o) \propto f^{-2.2}L^{0.6}$. Related to the angular broadening there is a temporal broadening, caused by the longer paths of the scattered waves. The impulse response has a rapid rise time and a slower (approximately) exponential decay in time $\tau_{\rm d} \approx L\theta_{\rm d}^2/c \propto f^{-4.4}L^{2.2}$. $\tau_{\rm d}$ has been measured for many pulsars, as listed in the Taylor et al (1993) catalog.

In most pulsar observations there are also strong intensity scintillations (ISS), formally when $s_o < r_{\rm F} = \sqrt{L/k}$. In strong ISS there are narrow-band variations of the pulse-intensity, $\Delta I(t, f)$ referred to as diffractive interstellar scintillation (DISS). These are readily observed as a dynamic spectrum, which varies randomly over time scale $\Delta t_{\rm d}$ and frequency scale $\Delta f_{\rm d}$.

$$\Delta t_{\rm d} \approx s_o/V \propto f^{1.2}L^{-0.6} \text{ and } \Delta f_{\rm d} \approx 1/(2\pi\tau_{\rm d}) \propto f^{4.4}L^{-2.2} \tag{6}$$

These quantities are important to an observer, and have been measured for many pulsars by Cordes (1986). A convenient measure u of the strength of scintillation emerges here:

$$u \equiv \sqrt{f/\Delta f_{\rm d}} = r_{\rm F}/s_o \propto f^{-1.7}L^{1.1} \tag{7}$$

Cordes also used the data to compute a scintillation estimate of the transverse velocity $V_{\rm iss} = s_o/\Delta t_{\rm d}$, where s_o is found from $\Delta f_{\rm d}$ and eq (7). It should be noted that this formulation for $V_{\rm iss}$ gives a result about a factor 3 larger than that used by Cordes. The discrepancy concerns the normalizing factors in eq (6) and (7); the present formula (derived by Gupta et al 1994: GRL) has been shown by Gupta (1995) to give reasonable agreement wih proper motion velocities using the revised TC distance scale, without the reduced scale height for the plasma turbulence invoked by Harrison and Lyne (1993).

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There are also random interstellar refractive phenomena, associated with the Kolmogorov spectrum (see Cordes et al 1986, Romani et al 1986, Rickett 1990, for details). The simplest of these is a slow variation in the angle of arrival due to the phase gradient imposed by the medium, averaged over the scattering volume. This volume, through which signals travel from pulsar to observer, is cigar-shaped for a homogeneous distribution of turbulence, or like two cones if the scattering were localized as in a screen. In any case, the diameter of this region can be approximated as $L\theta_d$, often called the scattering disk. The rms amplitude of the changing angle of arrival is approximately $\theta_{r,rms} \approx \theta_d u^{-.33} \propto f^{-1.63} L^{0.23}$ The angle should typically change on the time scale for the scattering volume to be renewed, $\Delta t_r = L\theta_d/2V$, which I call the refractive time scale. The refractive tilt of the wavefront also modulates the diffractive pattern, by displacing it laterally by $(\sim L\theta_{rx}, L\theta_{ry})$. Since the displacement is frequency dependent, it causes sloping features in the diffractive dynamic spectra, with typical slope $dT/df \approx L\theta_r/Vf$. This also causes a narrowing in the apparent decorrelation bandwidth that varies slowly with u (see GRL). These modulations should vary randomly on the refractive time scale.

A further refractive effect is due to curvature of the wavefront across the scattering disk. This can either focus or defocus the scattered waves and so increase or decrease the pulsar flux, as averaged over the refractive time scale. The phenomenon is referred to as refractive interstellar scintillation (RISS); the fractional rms flux variation (scintillation index) is $m_r \sim u^{-0.33} \sim [\Delta f_d/f]^{1/6}$. We can also write the time scale $\Delta t_r \approx 0.5\Delta t_d f/\Delta f_d$; thus the predicted refractive parameters can both be expressed in terms of observed diffractive parameters.

Pulsars have diameters small enough to show both DISS and RISS. The detection of scintillation requires source angular diameter $\leq$ the ratio of scintillation scale over distance. Since the DISS scale is a factor u^2 smaller than the RISS scale, DISS is only visible for source diameters in the microarsec range. Papers in this volume by Smirnova et al, Gupta and Gwinn et al, probe the pulsar structure on this angular scale, by comparing DISS across a pulse profile.

3. Problems for the Kolmogorov Model

Whereas the simple Kolmogorov model for the density spectrum successfully explains a wide variety of interstellar propagation effects, there are some significant discrepancies between observation and theory.

Excess RISS. Most pulsars show an rms level of RISS m_r that agrees with that predicted from its DISS parameters, assuming the Kolmogorov spectrum as described above. However, a number of nearby pulsars show an excess in m_r, relative to this prediction. Gupta et al (1993) found that about a third of the published values lay significantly above the Kolmogorov prediction. However, the most extensive observations by Kaspi and Stinebring (1992) and recently by Stinebring and Smirnova (1996) show a much smaller number of pulsars with an excess m_r. The influence of an inner scale cut-off to the Kolmogorov spectrum has been advanced to explain the excess refraction (Coles et al 1987) and used by Gupta et al (1993) to infer inner scales in the range 10^7 to 10^9m.

VLBI observations. When the baseline is comparable to the coherence scale of the scattered field s_o, the fringe visibility is reduced as eq (4), i.e. the scattering disk is resolved. A variety of objects have now been studied in this fashion, from which fundamental measurements of the scattering medium can be made. Clearly s_o can be estimated, which provides a measure of the scattering strength on that line-of-sight. If multiple baselines are used eq (4) provides an estimate of $D_\phi(\vec{s})$. When ploted versus the baseline length the 5/3 scaling in eq (5) can be checked. Spangler and Gwinn (1990) found that, for VLBI baselines less than about 100km, the visibilty scaled as baseline squared, while longer baselines were consistent with the 5/3 law. They deduced an inner scale of about 10^5m, much smaller than those inferred from RISS observations.

A further important result, from observations where the baselines covered a sufficient range of angles, is that the structure function is not always circularly symmetric. Examples of anisotropic scattering have been reported by Lo et al 1985, Spangler and Cordes, 1988, Desai et al, 1994, Frail et al 1994, Wilkinson et al 1994. The simplest geometry is uniformly distributed turbulence over the entire line-of-sight; in such a model any local anisotropy should be randomized in the image due to superposition from very many independent regions. Conversely if the turbulence is concentrated in a thin layer, a residual anisotropy might well result for the image if the magnetic field, that must control the orientation of the anisotropy in the layer, is not very tangled.

Spatial variation of turbulence. Pulsar measurements of DISS parameters have been used to infer the line of sight integral $\int C_N^2 dz \equiv SM$ on many lines of sight (Rickett 1977, Cordes et al 1985 [CWB], Cordes et al 1991). TC model the results as the superposition of a smooth background turbulence in a disk with a FWHM of 1.5Kpc and various regions of enhanced turbulence. In many cases there are very large changes in line-of-sight average of $C_N^2 = SM/L$, over small angular scales. As found by CWB this implies that the enhanced turbulence is very clumpy, having a mean free path for an intersection of about 1 kpc, on sight-lines through the galactic disk. As a consequence the actual C_N^2 in these enhanced regions can be 3-6 orders of magnitude above the background. On physical grounds we have to wonder if the conditions needed for a Kolmogorov turbulent cascade exist in both the background diffuse plasma and the isolated regions where δN is as much as 1000 times greater.

Refractive phenomena in dynamic spectra. There are a variety of phenomena observed in pulsar dynamic spectra that are not readily understood in the light of the Kolmogorov spectrum model. As discussed in the previous section one expects sloping features whose slopes $\mathrm{d}T/\mathrm{d}f$ should vary randomly on the refractive time scale Δt_r. This expectation has been looked for by GRL and by Stinebring et al (1996). While the latter authors confirm this behaviour for PSR B0329+54, GRL reported that 2 out of 8 pulsars studied, whose refractive time scales were less than two weeks, showed slopes that did not change sign over 14 months. They concluded that the sight-lines to these pulsars pass through regions of plasma much larger than the scattering disk, which give a persistent angle of refraction.

The most dramatic phenomenon in dynamic spectra is the occasional episode of periodic fringes crossing a normal DISS pattern. Examples have been reported as far back as Ewing et al (1970). A notable example was found by Cordes & Wolszczan (1986 - CW) in PSR B0919+06 at 430 MHz, in which multiple fine fringes with periods of about 14 kHz and 72 seconds modulated a DISS pattern where $\Delta f_d \sim 60$ kHz and $\Delta t_d \sim 90$ sec. These authors reported fringe episodes from three pulsars. Wolszczan & Cordes (1987) recorded another fringe episode, from PSRB1237+25 in which they were able to study the phenomenon versus pulse phase. They used the result to estimate the spatial extent of the emitting region at the pulsar itself, achieving an effective angular resolution of about 1 microarcsec. Rickett et al (1996 - RLG) also report very fine fringes for PSRB0834+06. In another unusual phenomenon, discontinuities in the dynamic spectrum were observed from PSR B0823+26 by Clegg et al (1993). They found occasions where a DISS pattern showed nearly discontinuous changes in the frequency structure; in the most obvious example there was also a criss-cross fringe pattern evident, which suggests three interfering rays.

The interpretation of the periodic fringes is agreed to be due to the interference of waves from two directions of arrival; and indeed estimates can be made of the angular separation between the ray-bundles (CW). Whenever there are multiple fringes across a single diffractive peak in the spectrum, the angular separation must be greater or comparable to the angular radius of each scatter-broadened ray bundle. Under the Kolmogorov model with an inner scale, there can be occasions when two discrete ray-bundles happen to dominate the signal and cause fringes (Goodman et al 1987). In the event analyzed by RLG the separation of the raybundles is more than 10 times their diameters, which rules out an inner scale explanation; RLG propose that fringing events have the same origin as "extreme scattering events" (Fiedler et al 1987) and are caused when the sight-line passes through a region of enhanced refraction on a scale larger than the scattering disk. The idea of enhanced refraction is similar to that proposed by Romani et al (1987: RBC) but differs in the details. The key point is that there are regions with substantial modulations of electron density in (possibly anisotropic) structures with a smallest scale ~1 AU. A specific model is proposed below.

4. Model for Enhanced Refracting Layers

The previous section discussed various observations that are at odds with the simple Kolmogorov model. I suggest here that they might all have a common origin in regions of the interstellar medium (ISM) in which there is an enhanced level of power in the density spectrum at very low wavenumbers, corresponding to scales bigger than about 1 AU. Such a possibility has been advanced by various authors (see figure 1b of Coles et al 1987, RBC and CW). In such regions I suggest that the density inhomogeneities do not excite a compressive turbulent cascade, having a local spectral exponent steeper than or near 4.

I suggest that the observer is usually too near for intensity scintillations from these regions to have developed, i.e. the condition for multipath interference is not normally met. There are, however, larger than Kolmogorovian angles of refraction which can explain the persistence of slopes in some dynamic spectra. The regions can contribute only weakly to enhanced levels of RISS. Occasionally the multipath condition is satisfied. Then the number of ray paths jumps from one to two and fringe patterns suddenly appear. In fact when first satisfied, the multipath condition corresponds to a ray and a fold caustic (see Hannay, 1983). As the observer continues to move, the fold splits making a total of three ray paths for a certain time. When the multipath condition fails, the reverse takes place, two of the rays merge making another bright fold which then disappears, leaving a single raypath. The idea of a refracting layer pulls together all of the dynamic spectra effects, assuming that the spectral discontinuities are part of the same process. It also sugests that the large inner scales are not necessary to explain RISS levels above the Kolmogorov prediction.

The following scenario is proposed by RLG to explain a fringing episode from PSR B0834+06 (it is one from a continuum of possible models) ; related ideas have been proposed by Wilkinson et al (1994) in regard to VLBI observations of Sag A* and by RBC in regard to the extreme scattering events. In a layer of warm ionized medium, surrounding a warm HI cloud, there are filaments (or sheets) of plasma about 1AU thick randomly and sparsely distributed. The proposed density is, say, equal to $0.25\ \mathrm{cm}^{-3}$, corresponding to a typical interstellar pressure. The associated density spectrum at wavenumbers above $(1\mathrm{AU})^{-1}$ falls more steeply than a power law of exponent 4, and does not correspond to a turbulent cascade. A line of sight passing through such a layer would typically encounter many such filaments (or sheets); the greatest refracting effect comes when the sight-line is approximately normal to a filament. A filamentary geometry might occur where the magnetic field is strong enough to dominate the plasma dynamics. The net effect is a random phase modulation with an rms angle of refraction that can be much larger than that due to the background Kolmogorov plasma. The layer imposes an angle of arrival deviation that can last for a month or more (the crossing time for 1AU).

It is even possible that the clumps of highly enhanced scattering, could have similar properties to the regions of enhanced refraction. Such regions that are far enough from the observer may routinely satisfy the multipath condition and give rise to a heavily scattered image. Such images should then be of Gaussian form. There may also be occasions where the line of sight encounters a small number number of filaments, leaving an anisotropic image.

5. Propagation Effects on Pulsar Timing

The advent of millisecond pulsars has brought new importance to the randomly changing propagation effects in the ISM. At typical observing frequencies there are modulations at the microsecond level. Foster and Cordes (1990) studied such effects for the first millisecond pulsar PSR B1937+21. The propagation time can be written as:

$$T = T_{\mathrm{g}} + \Delta T_{\mathrm{geo}} + \Delta T_{\mathrm{d}} + \Delta T_{\mathrm{bary}} \tag{8}$$

Here T_{g} is the group delay, calculated for a straight line path given by eq (3), with DM changing due to the motion of the pulsar and the ISM with respect to the Earth. In reality this is the DM averaged over the scattering volume. In the timing measurements of PSR1937+21 reported by Kaspi et al (1994) and Cordes et al (1990), the dispersion delay was estimated by dual-frequency timing observations, from which estimates of $DM(t)$ have been made and show typical changes of a few microseconds over a few years. ΔT_{geo} is the geometric delay due to the longer refracted paths. For an extended turbulence distribution $\Delta T_{\mathrm{geo}} \sim 0.25 L\theta^2_{\mathrm{r,rms}}$, which for the Kolmogorov spectrum should change on

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the refractive scintillation time Δt_r; for an enhanced refracting layer this term may be larger and change more slowly. ΔT_d is the jitter associated with each diffractive "scintle", changing randomly on DISS scales of Δt_d and Δf_d; see figure 5 of Cordes et al (1990). ΔT_{bary} is the error in correcting to the barycenter due to variations in the angle of arrival.

Lestrade et al (1995) found an inverse correlation between arrival time and flux from 1.4 GHz observations of PSR B1937+21 at Nancay. Since the negative correlation is associated with flux variations on a time scale of about 15 days, which are clearly RISS, one concludes that there is also a 15-day interstellar modulation of the arrival times. A negative correlation means that late pulses are typically weaker than early ones. This is the sense expected from the dispersive delay due to an intervening plasma cloud, since it acts as a diverging lens and also increases the group delay. A *positive* cross-correlation is expected between flux and ΔT_{geo} (Romani et al 1986). I have a paper in preparation with Lestrade, that explains the negative correlation as due to short-term variations in DM, not corrected since the DM estimate was smoothed over 50 days. However, when the Kolmogorov model is used to predict this arrival time modulation, it underestimates the effect. Here again is evidence for larger variations in DM than extrapolated from the small scale measures for a pulsar; the associated length scales are about 0.5 AU consistent with the phenomena listed above.

6. Conclusions

The Kolmogorov model for the interstellar plasma density spectrum boldly suggests that the physics of the density inhomogeneities are driven by a turbulent cascade, common throughout the ISM. The TC model provides for large changes in the level C_N^2 in differing parts of the ISM. At first order this model successfully describes a large variety of pulsar propagation phenomena, giving frequency and distance scaling laws that are largely borne out by observation. There are, however, a number of phenomena that suggest an excess of density structure on AU scales, causing enhanced refraction but only a slight increase in scintillation. I have outlined a possible site for such structures, suggesting that they might be filaments whose typical radius is 1 AU which are controlled by the local magnetic field and randomly distributed in layers of the Warm Ionized Medium.

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