INTERSTELLAR SCATTERING +

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INTRODUCTION

Fine scale electron density fluctuations in the interstellar medium (ISM) are manifest as scintillations and temporal broadening of pulsar signals and as angular broadening of galactic and extragalactic sources. Although scattering off the fluctuations is often a nuisance for conventional studies of radio sources, analysis or searches for interstellar scintillations (ISS) can lead to information about the ISM or radio sources that otherwise would not be obtainable. For example, the length scale probed by ISS in the ISM is typically 10^{11} cm and the characteristic angular size for quenching ISS is less than 1 μarc sec.

In this paper we discuss the distribution of scattering material in the Galaxy as probed by ISS observations of a large sample of pulsars. The parameters of a two-component model for scattering material are given and the typical scattering angle is predicted as a function of galactic latitude, path length through the Galaxy, and frequency. The predictions indicate that pulsars sample most, if not all, scattering material in or near the Galaxy because the observed scattering of extragalactic objects conforms to the predictions. The results imply the absence of significant scattering material in intergalactic space. We also discuss how ISS can be used to determine space velocities of a large sample of pulsars, corresponding to proper motions of $\sim$mas/yr.

PULSAR SCATTERING AND SCINTILLATIONS

Temporal broadening of pulsar signals appears as an asymmetric tail on pulse shapes whose time constant τ is related to the scattering angle θ (FWHM) and the pulsar distance L by

$$\tau \sim L\theta^2 / 8c. \qquad (1)$$

Pulsar scintillations appear as intensity variations with characteristic frequency and time scales, Δf and Δt. The so-called decorrelation

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R. Fanti et al. (eds.), VLBI and Compact Radio Sources, 303–307.

https://doi.org/10.1017/S0074180900078335 Published online by Cambridge University Press

bandwidth Δf and the scattering time τ are related by

$$2\pi \Delta f \tau = 1 \tag{2}$$

because both depend on path-length differences. Pulsar ISS is consistent with δn_e having a power-law wavenumber spectrum of the form

$$P_{\delta n_e}(q) = Qq^{-\alpha}, \ \alpha \sim 3.7 \pm 0.3 \tag{3}$$

(Rickett 1977; Armstrong and Rickett 1981; Armstrong, Cordes, and Rickett 1981; Cordes, Weisberg, and Boriakoff 1983). The exponent α is best constrained by the scaling of scintillation bandwidth with observation frequency. If α is assumed to be equal to 11/3, then the coefficient Q can be estimated as

$$Q = L^{-11/6} f^{11/3} \Delta f^{-5/6} \tag{4}$$

with units of $(\text{meters})^{-20/3}$; Q is the same quantity as C_n^2 referred to by Rickett. Rather than showing a constant value, within errors, measurements show large systematic variations of Q with galactic latitude, longitude, and distance as well as random variations from object to object. Errors in the pulsar distance scale can account for only a factor of five range in Q whereas the actual range is four orders of magnitude.

GALACTIC DISTRIBUTION OF SCATTERING MATERIAL

Pulsars with $|b| > 10^\circ$ show values of Q in the range $10^{-3.5\pm0.5}$ while objects with $|b| < 5^\circ$ cover the range $10^{-3.5}$ to 1. As a function of path length, Q begins to systematically increase for L > 2 kpc for pulsars with $|b| < 5^\circ$ in the first quadrant of the Galaxy. Cordes, Weisberg, and Boriakoff (1983) have used these results to deduce that scattering material exists in two components: Component A with scale height $H_A > 0.5$ kpc, $Q \sim 10^{-3.5}$, and volume filling factor ~ 1; Component B wherein Q is large (1-100) only in clumplike regions whose filling factor is very small, $\sim 10^{-4}$, and which have small scale height, $H_B \sim 0.1$ kpc. The pulsar measurements suggest that the component B clumps are more common inside the solar circle, as is consistent with the angular broadening measurements of extragalactic sources by Dennison(1983)

SCATTERING ANGLES

The scattering angle for an extragalactic source is

$$\theta\ (\text{FWHM}) = 0.133\ \{L_{kpc}Q\}_{eff}^{3/5}\ f_{GHz}^{-11/5}\ \text{arc sec} \tag{5}$$

where the bracketed quantity is a path-length integrated value. Because of the evident inhomogeneity of scattering material, θ varies at least as fast as $\theta \propto L^2$ (for $b \sim 0^\circ$ and $-90^\circ < \ell < 90^\circ$) rather than varying as $L^{1/2}$.

https://doi.org/10.1017/S0074180900078335 Published online by Cambridge University Press

We estimate roughly

$$\theta_{FWHM}\, f^{11/5} \sim \begin{cases} 0.53 \text{ arc sec} & |b| < 0^\circ\!.6 \\ 0.035|\sin b|^{-3/5} \text{ arc sec} & 0^\circ\!.6 < |b| < 3^\circ - 5^\circ \\ (0.66 - 1.1)|\sin b|^{-3/5} \text{ mas} & |b| > 3^\circ - 5^\circ \end{cases} \quad (6)$$

for paths in the first quadrant around $\ell \sim 45^\circ$ where most of the pulsar measurements have been made; in this expression we have assumed a maximum path length through scattering material of 10 kpc. The scattering angle is deterministic at high latitudes but is statistical at low latitudes, depending on the probability of encountering a region of large Q. The dropoff of probability with b associated with the scale height of the "B" component causes the apparent discontinuity in θ at $|b| \sim 3^\circ$. Figure 1 shows the scattering angle versus b along with angular diameters of extragalactic sources that show λ^2 dependence. Figure 2 shows the frequency dependence of predicted and measured angles. The hatched region is bounded by inferred scattering angles of two pulsars, PSR1541+09 with b = 46° and 1 kpc distance above the galactic plane and PSR1641-45 with b = $-0^\circ\!.1$ and 4.9 kpc total distance. Also shown are angular sizes for synchrotron-Compton sources with designated maximum brightness temperatures.

The conclusions to be made are that 1) although the galactic center source Sgr A and various maser sources (Sgr B2, W49) show much larger sizes than the most scattered pulsar, the greater distances of these sources suggest that their scattering diameters are in accord with an extrapolation from the pulsar results; 2) The minimum observable angular size for b = 90° is $\sim$1 mas at 1 GHz; and 3) The 0.07 and 0.1 GHz VLBI observations of Resch (1974) are compatible with there being little or no scattering outside the Galaxy along lines of sight to distant QSO's.

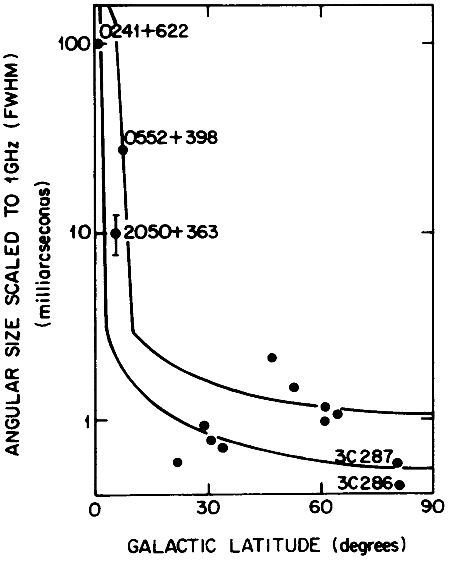

Figure 1 Scattering angles versus galactic latitude. The lines bracket the predicted range of angles. Note that the sources 0241, 0552, and 2050 are at galactic longitudes of 138°, 172°, and 79°. References are given in Cordes and Simonetti (in preparation).

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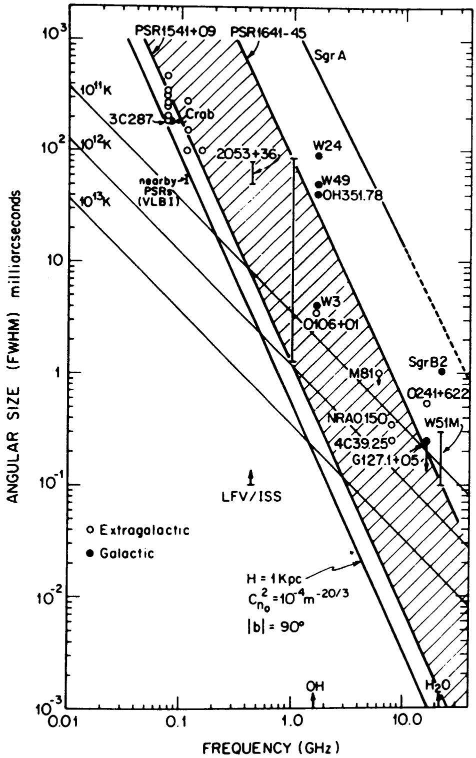

Figure 2. Scattering angles versus frequency. The diagonal line labeled with a scale height H is the predicted minimum angular size of the scattering disk when looking toward b = 90°. This line is uncertain because the scale height is not well constrained from pulsar observations, but the uncertainty is probably no more than a factor of two.

ISS AND PULSAR PROPER MOTIONS

Scintillations have a characteristic time scale Δt related to the speed and spatial scale ($\propto (L\Delta f)^{1/2}$) of a diffraction pattern across a telescope. Lyne and Smith (1982) have shown that the velocity estimate

$$V_{ISS} \propto (L\Delta f)^{1/2} / \Delta t \qquad (7)$$

is 66% correlated with the velocity derived from interferometric proper motion measurements for 20 objects. Turning this around, one can make single epoch ISS observations of a large number of pulsars and determine their transverse speeds to an accuracy limited by the projected Earth velocity, differential galactic rotation, the unknown distribution of scattering material along the line of sight, and by the uncertainty in the pulsar distance scale. Improvements can be made by 1) observing binary pulsars whose known orbital motion will calibrate the proportionality in (7); 2) making multiple epoch estimates of Δt to remove the effects of the Earth's motion and thereby determine the vector pulsar velocity; 3) comparing $V_{ISS} \propto L^{1/2}$ with $V_{PM} \propto L$ from interferometer measurements to check the pulsar distance scale. The achievable accuracy is probably ±10 km/sec.

https://doi.org/10.1017/S0074180900078335 Published online by Cambridge University Press

SUGGESTIONS FOR FURTHER OBSERVATIONS

The previous discussion leads to the following suggestions for new observations: 1) VLBI on distant pulsars to compare measured angular sizes with those predicted from scintillation measurements; disagreement is expected if dominant scattering material is near the pulsar or near the observer; 2) VLBI mapping of a highly scattered maser or pulsar to see if the visibility function is cylindrically symmetric for comparison with Sgr A; asymmetry can occur in media with a preferred direction defined by (e.g.) a velocity flow; 3) interferometric proper motions on more pulsars to calibrate the ISS velocity technique; 4) an undirected search for ISS; any sources found would necessarily have angular structure on the micro-arcsecond level and brightness temperatures well in excess of 10^{15} °K.

This research was supported by the Cal Tech President's Fund and by the National Astronomy and Ionosphere Center which runs Arecibo Observatory under contract with the National Science Foundation.

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