Radioastronomical Remote Sensing of Turbulence in the Interstellar Medium

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These are preliminary lecture notes, intended only for distribution to participants.
Radioastronomical Remote Sensing of Turbulence in the Interstellar Medium

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The Interstellar Medium: Diffuse Plasma Between the Stars
### Phases of the Interstellar Medium

<table>
<thead>
<tr>
<th>Phase</th>
<th>Astro. Name</th>
<th>Density (cm$^{-3}$)</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Molecular Cloud</td>
<td>$\geq 10^4$</td>
<td>$\leq 70$</td>
</tr>
<tr>
<td>Medium - Neutral</td>
<td>CNM</td>
<td>10 - 100</td>
<td>$\sim 100$</td>
</tr>
<tr>
<td>Medium - Ionized</td>
<td>HII envelopes</td>
<td>5 - 10</td>
<td>8000</td>
</tr>
<tr>
<td>Low</td>
<td>DIG and WNM</td>
<td>0.1 - 0.5</td>
<td>8000</td>
</tr>
<tr>
<td>Tenuous</td>
<td>Coronal</td>
<td>$10^{-3}$</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>
How ISS Observations Can Map Out Turbulence in the Disk and Halo

EXTRAGALACTIC SOURCE

Distant Halo

1 kpc

EARTH

pulsar

HALO

DISK

pulsar

measurement of $\int c_n^2 ds$
INTERSTELLAR SCINTILLATION PHENOMENA

ANGULAR BROADENING

INTENSITY SCINTILLATIONS

PULSE BROADENING

SPECTRAL CORRUGATION

--- WITHOUT TURBULENT MEDIUM
--- VIEWED THROUGH MEDIUM

- PULSAR TIME-OF-ARRIVAL FLUCTUATIONS
- ROTATION MEASURE FLUCTUATIONS
- IMAGE DISTORTION AND WANDERING
$s^2 = x^2 + n^2 y^2$

$\eta = 1.83 \pm 0.10$

Figure 2(b)
Scattered Angular Size, $\theta_1$ GHz

Galactic Longitude (deg)

Galactic Latitude (deg)
SCATTERING NEAR CYGNUS OB1 ASSOCIATION

GALACTIC LONGITUDE (DEGREES)

GALACTIC LATITUDE (DEGREES)

1.00 m$^{-2013}$ - kpc

Figure 6
"The Big Power Law in the Sky"

No spectral "features" from $k \sim 10^{-6} \text{ m}^{-1} - 10^{-3} \text{ m}^{-1}$, perhaps $10^{-1} \text{ m}^{-1}$
# TABLE 6

**Observed Turbulent Properties of the Interstellar Medium toward l = 145°, b = −20°**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_0 ) (cm(^{-3}))</td>
<td>0.029</td>
</tr>
<tr>
<td>( B_y ) ((\mu)G)</td>
<td>−0.8</td>
</tr>
<tr>
<td>( L ) (pc)</td>
<td>2900</td>
</tr>
<tr>
<td>( l_0 ) (pc)</td>
<td>3.6 ± 0.2</td>
</tr>
<tr>
<td>( l_0^{2D} ) (pc)</td>
<td>( \leq 70 \leq 3.6 )</td>
</tr>
<tr>
<td>( C_2 ) (m(^{-20/3}))</td>
<td>( 10^{-3.0} )</td>
</tr>
<tr>
<td>( C_3 ) ((\mu)G(^2) m(^{-2/3}))</td>
<td>( 2.2 \pm 0.4 \times 10^{-13} )</td>
</tr>
</tbody>
</table>

# TABLE 1

**Properties of Turbulence in DIG**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle n_e \rangle ) (cm(^{-3}))</td>
<td>0.025</td>
</tr>
<tr>
<td>Filling factor</td>
<td>0.25</td>
</tr>
<tr>
<td>( n_e ) (cm(^{-3}))</td>
<td>0.08</td>
</tr>
<tr>
<td>( B_y ) ((\mu)G)</td>
<td>3</td>
</tr>
<tr>
<td>( C_2 ) (m(^{-20/3}))</td>
<td>( 10^{-3} )</td>
</tr>
<tr>
<td>( C_3 ) ((\mu)G(^2) m(^{-2/3}))</td>
<td>( 2.2 \times 10^{-13} )</td>
</tr>
<tr>
<td>( l_0 ) (pc)</td>
<td>3.6</td>
</tr>
<tr>
<td>( l_0 ) (km)</td>
<td>(∼800)</td>
</tr>
<tr>
<td>( v_s ) (10(^6) cm s(^{-1}))</td>
<td>0.93</td>
</tr>
<tr>
<td>( V_{A} ) (10(^6) cm s(^{-1}))</td>
<td>2.33</td>
</tr>
<tr>
<td>( v_0 (s^{-1})^2 )</td>
<td>8.3 \times 10^{-10}</td>
</tr>
</tbody>
</table>

* The ion-neutral collision frequency depends on the ionization state of the medium. The quantity listed is for 70% ionization of the hydrogen.
Turbulence Generation Mechanisms

(1) Solar Wind:

- "Fossil Turbulence" from chromosphere, convected out
- Nonlinear interactions, decaying turbulence
- Generation and conversion at stream interactions
- Kinetic plasma instabilities at shocks

(2) Interstellar Medium:

- Kinetic Instabilities at SNRs
- Galactic Balbus-Hawley instability (probably not)
- Structuring by massive stars + mode conversion
- "Star Murmuring"

*Further discussions in this Symposium*
Mechanisms for Generation of Turbulence in Shells

- Rayleigh-Taylor Instability
- Secondary Shocks
- Global Shell Instability
- Heat Flux Instability
- Acoustic Wave Instability
- Upstream Waves
- Shock Amplification of Turbulence
- Plasma Wave Generation by Pickup Ions
Figure 3

$B_T = 0.3 \mu G$

- Linear Landau damping
- Ion-neutral collisional damping
- Nonlinear Landau damping
- Wave packet steepening
- Decay instability

Log heating rate (ergs/sec/cm$^3$) vs. log outer scale (cm)
Faraday Rotation and the Interstellar Medium

- How can we learn about the B field in the ISM?
- Large scale B field
- Turbulent B field
- Use of optical emission lines to get electron density
Results and Conclusions

- Faraday rotation allows us to do remote magnetometry of astrophysical plasmas
- The same instrument (VLA) can study the ionosphere, the solar wind, and the ISM
- B field in ISM is 3-4 μG, strong enough to be dynamically important
- We can measure the amplitude and outer scale of ISM magnetic turbulence
- We have a good model for the coronal magnetic field and coronal turbulence
Main Results of Radio Wave ISM Studies

- Turbulence responsible for radio wave scintillations resides in low density ionized phase (DIG) and medium density-ionized (HII region envelopes).

- "The Big Power Law in the Sky"; density irregularities exist with scale sizes from \( \geq 10^{18} \text{ cm} \rightarrow 10^7 \text{ cm} \). Spectral index \( \alpha \) close to, or equal to the Kolmogorov index \( \alpha = 5/3 \). Suggests turbulent cascade in wavenumber through an inertial subrange to the dissipation range.

- Extreme variability in \( C_N^2 \) in the interstellar medium. Regions of very high \( C_N^2 \) "fluctiferous regions" or fluctifers seem associated with HII regions, star formation regions. Turbulent intermittency or ISM geography?

- Irregularities are anisotropic, in sense of being drawn out along a symmetry axis (probably interstellar magnetic field). Axial ratios \( \simeq 1.5 - 2.0 \).

- \( \delta B \) fluctuations detectable, with \( \delta B/B_0 \leq \delta n/n_0 \) (Minter & Spangler, ApJ 485, 182); suggests turbulence highly compressible.
Desiderata and Enigmata

- We must obtain information on \( \vec{V} \) and \( \vec{B} \) to progress to a satisfactory theoretical understanding of interstellar turbulence. \( \vec{B} \) information can be obtained from Faraday rotation (A. Minter, this meeting) \( \vec{V} \) information can be obtained from the timescale of scintillations, extraction of \( V_{\text{eff}} \) (Bondi et al., A & A 287, 290, 1994; Cordes and Rickett, ApJ 507, 846, 1998, Rickett, Coles, and Markkanen, 1999)

- Are the spectra perpendicular and parallel \( \vec{B}_0 \) the same? **Theory:** no, **Observations:** yes

- Where is the evidence for mesoscale \( (\sim 10^{15} - 10^{16} \text{cm}) \) dissipation processes (ion-neutral collisional damping)?

- "Purification of the ISM" of highly dissipative Fast Mode Magnetosonic waves. Even small fraction of interstellar turbulence in Fast Mode waves would overwhelm cooling capacity of the DIG