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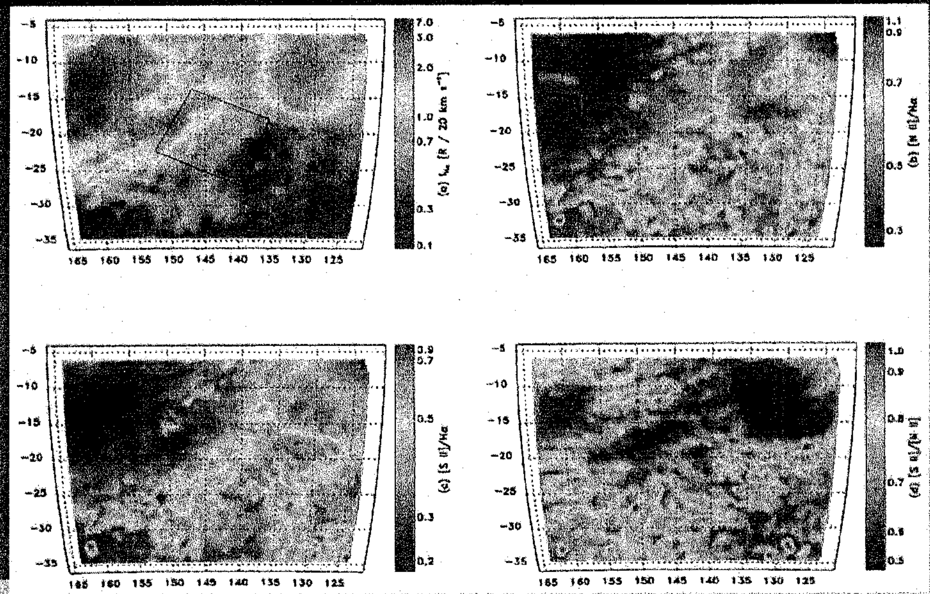
Radioastronomical Remote Sensing of Turbulence in the Interstellar Medium

S.R. Spangler

University of Iowa, Dept. of Physics
U.S.A.

These are preliminary lecture notes, intended only for distribution to participants.

Radioastronomical Remote Sensing of Turbulence in the Interstellar Medium

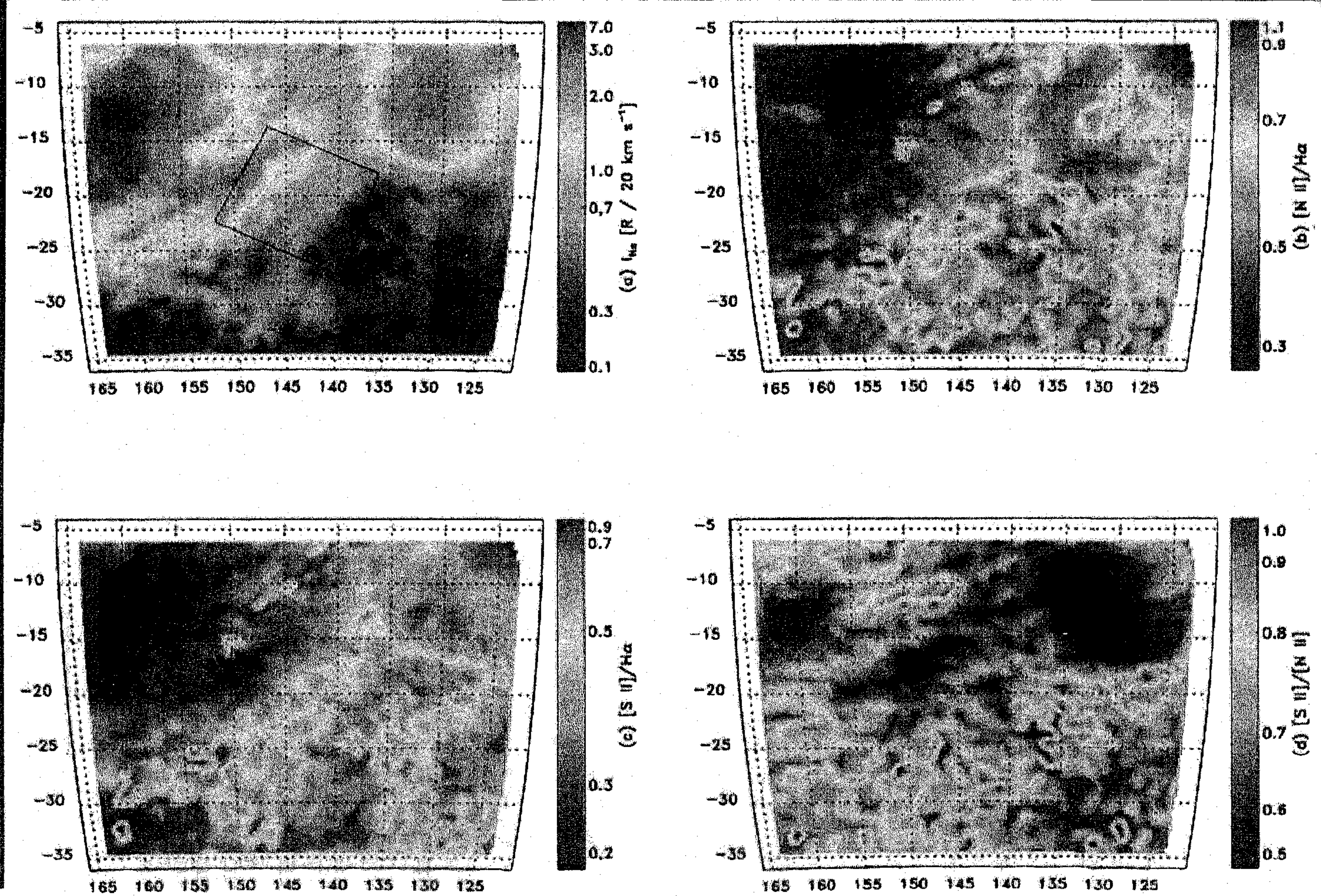


Steven R. Spangler

Department of Physics and Astronomy

University of Iowa, USA

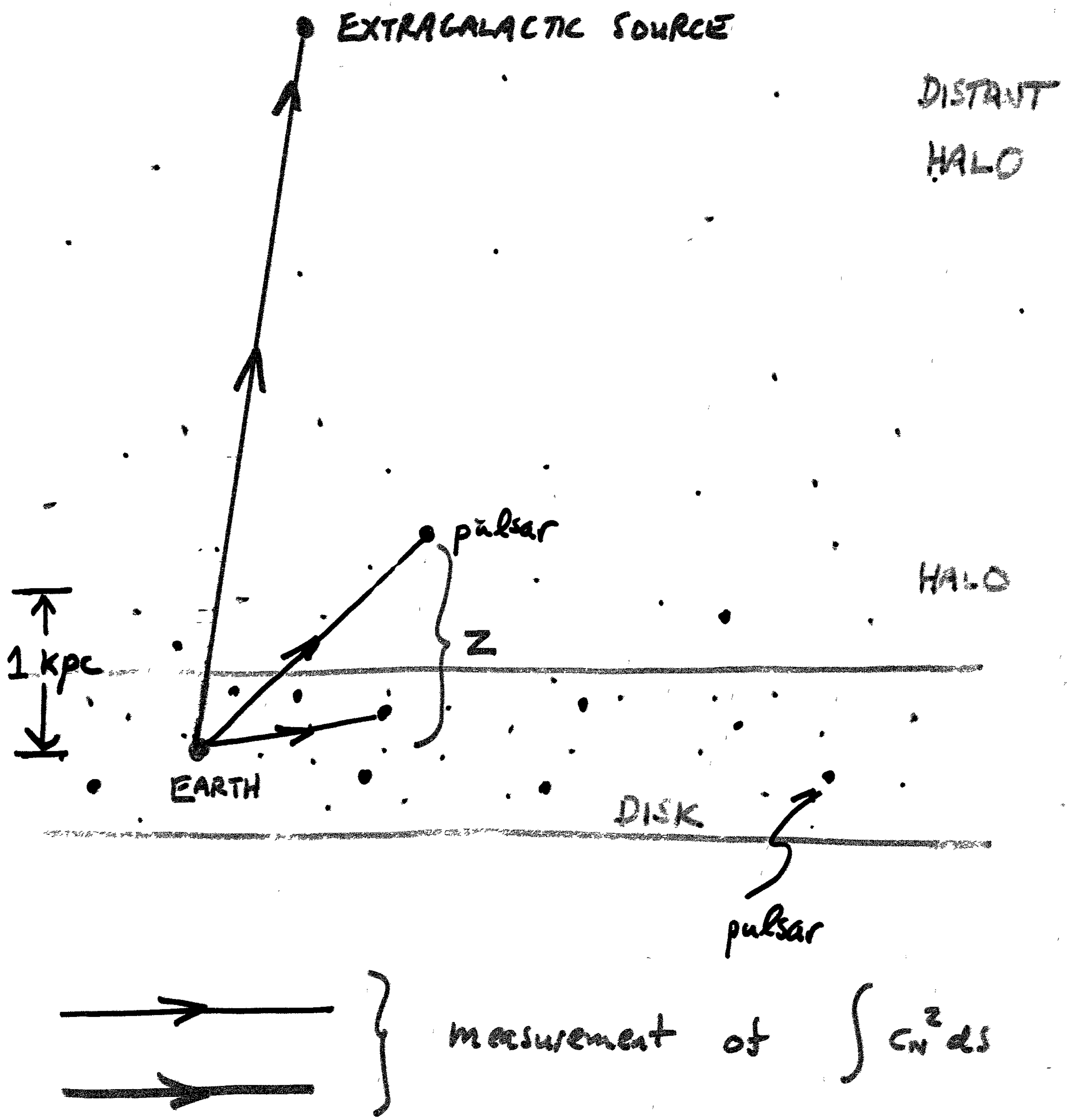
The Interstellar Medium: Diffuse Plasma Between the Stars



Phases of the Interstellar Medium

Phase	Astro. Name	Density (cm^{-3})	Temperature
High	Molecular Cloud	$\geq 10^4$	≤ 70
Medium - Neutral	CNM	10 - 100	~ 100
Medium - Ionized	HII envelopes	5 - 10	8000
Low	DIG and WNM	0.1 - 0.5	8000
Tenuous	Coronal	10^{-3}	10^6

How ISS Observations Can Map Out Turbulence in the Disk and Halo.



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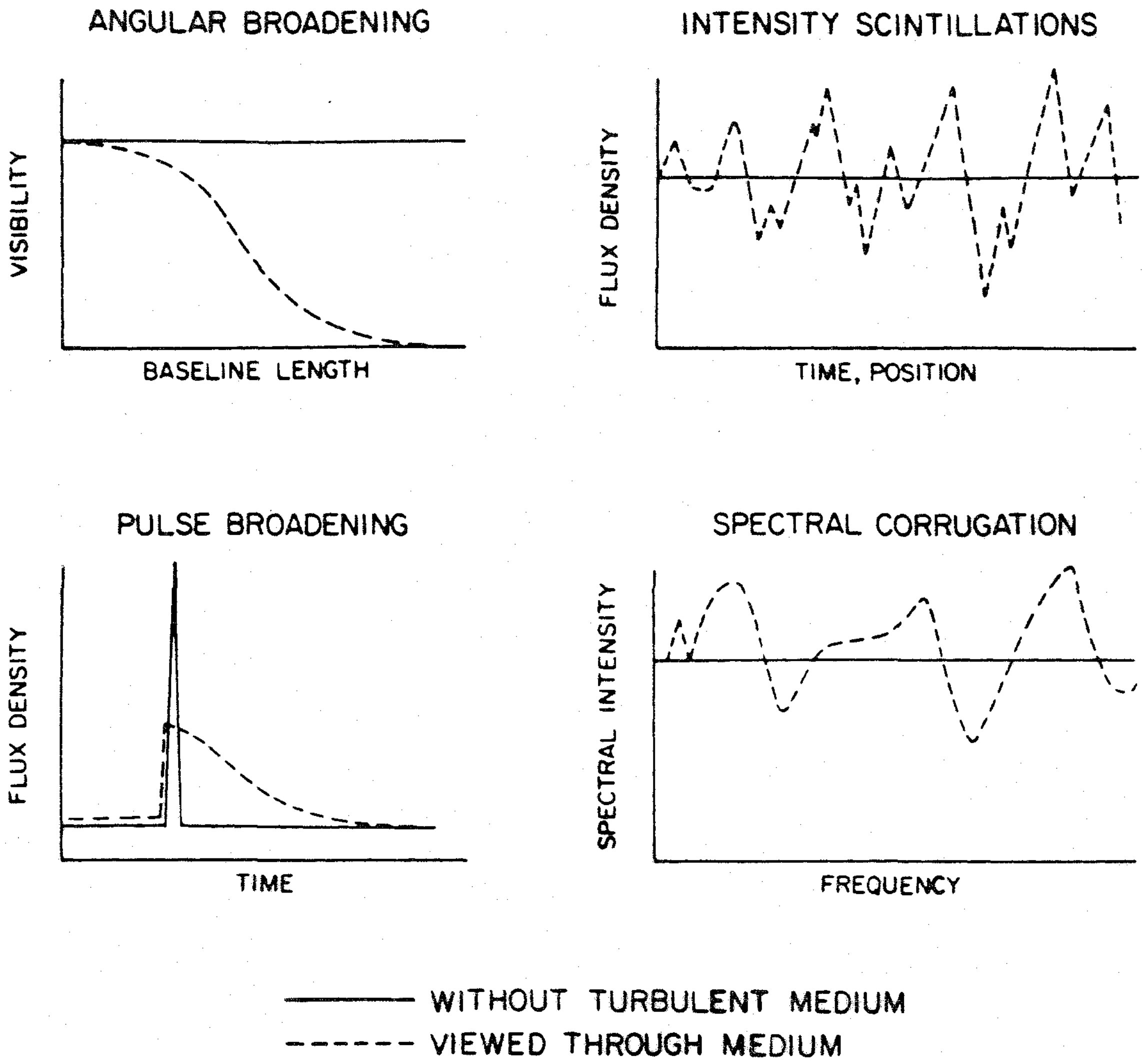
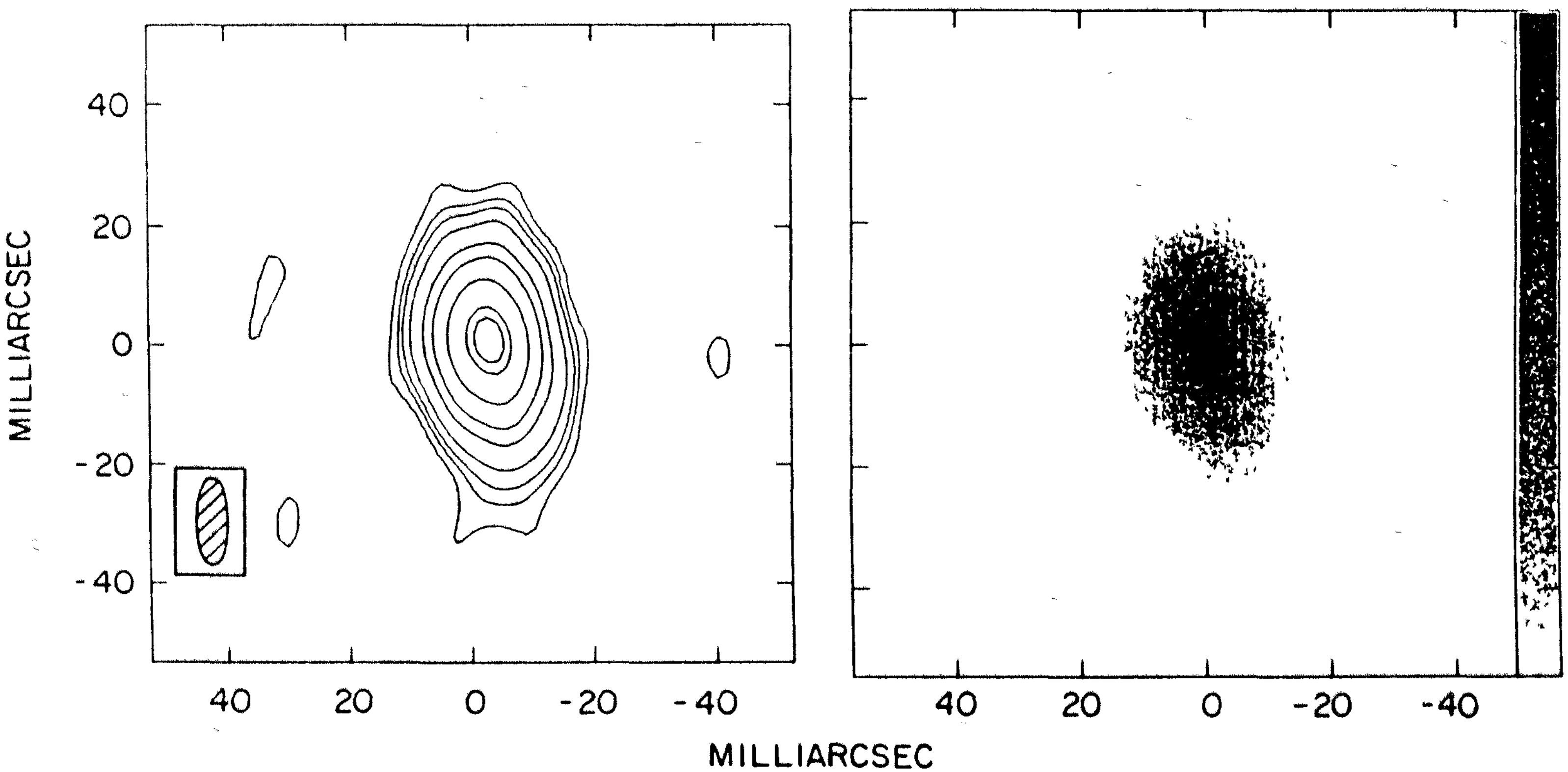
INTERSTELLAR SCINTILLATION PHENOMENA



- PULSAR TIME-OF-ARRIVAL FLUCTUATIONS
- ROTATION MEASURE FLUCTUATIONS
- IMAGE DISTORTION AND WANDERING

B-G87-279

2013 + 370 1663 MHz



Spangler & Cordes, ApJ 1998

A-G97-129

2005+372..1.67 GHz..rotundate baseline

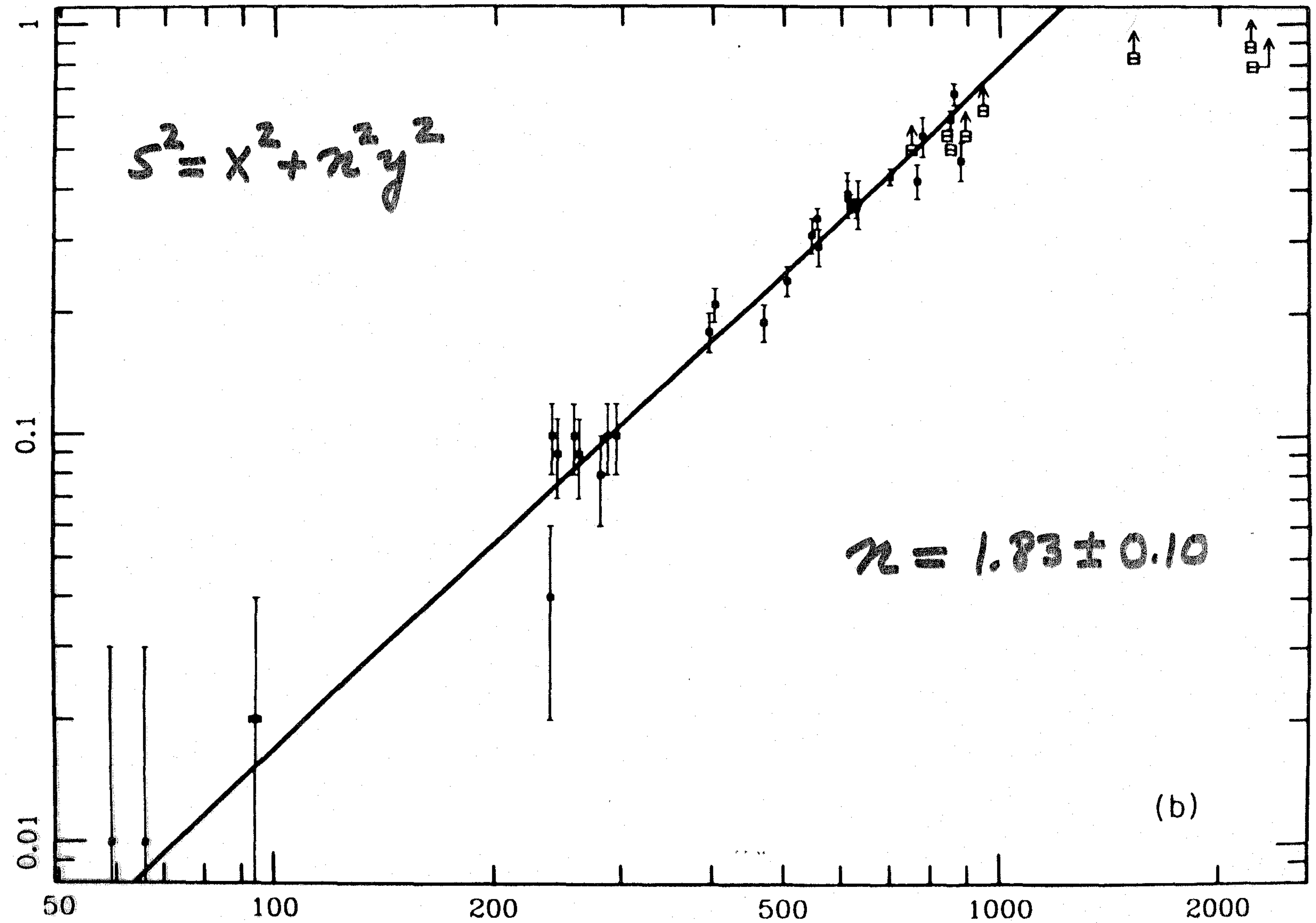
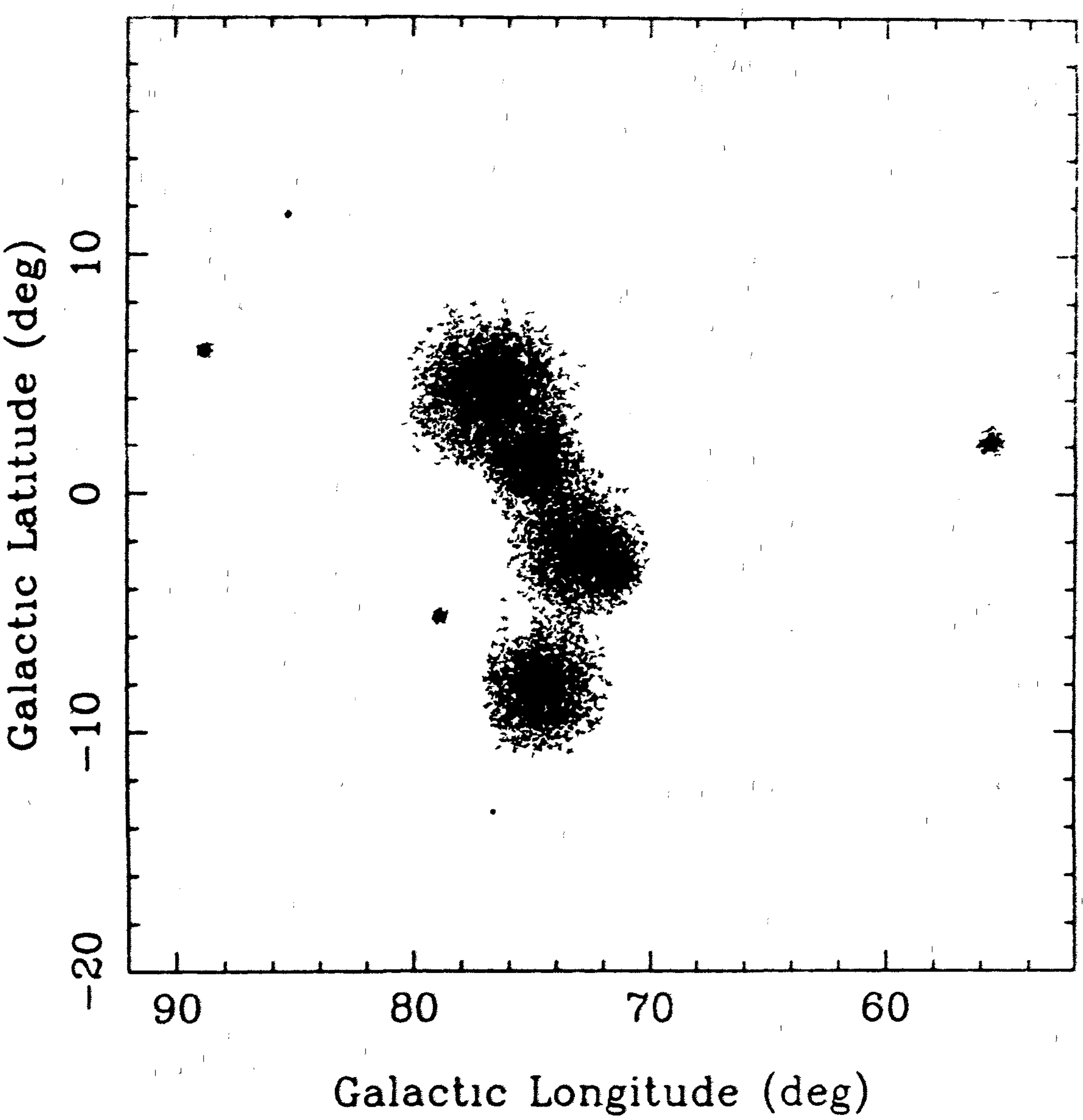


Figure 2(b)

Fey, Spangler, Cordes 1989, Ap.J., 337, 730.

A-988-350

Scattered Angular Size, $\theta_{1\ GHz}$



8-G90-348-1

SCATTERING NEAR CYGNUS OB1 ASSOCIATION

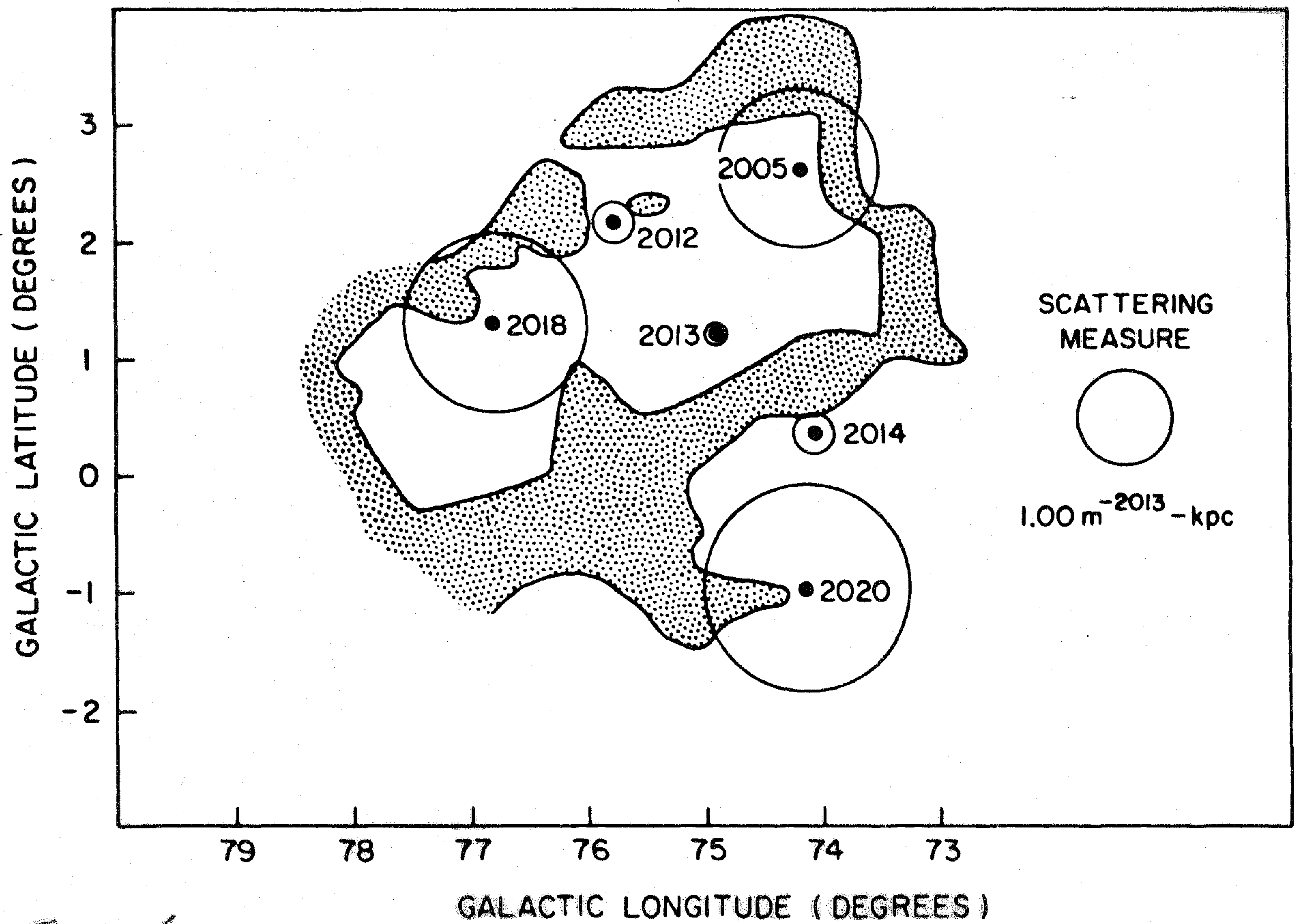
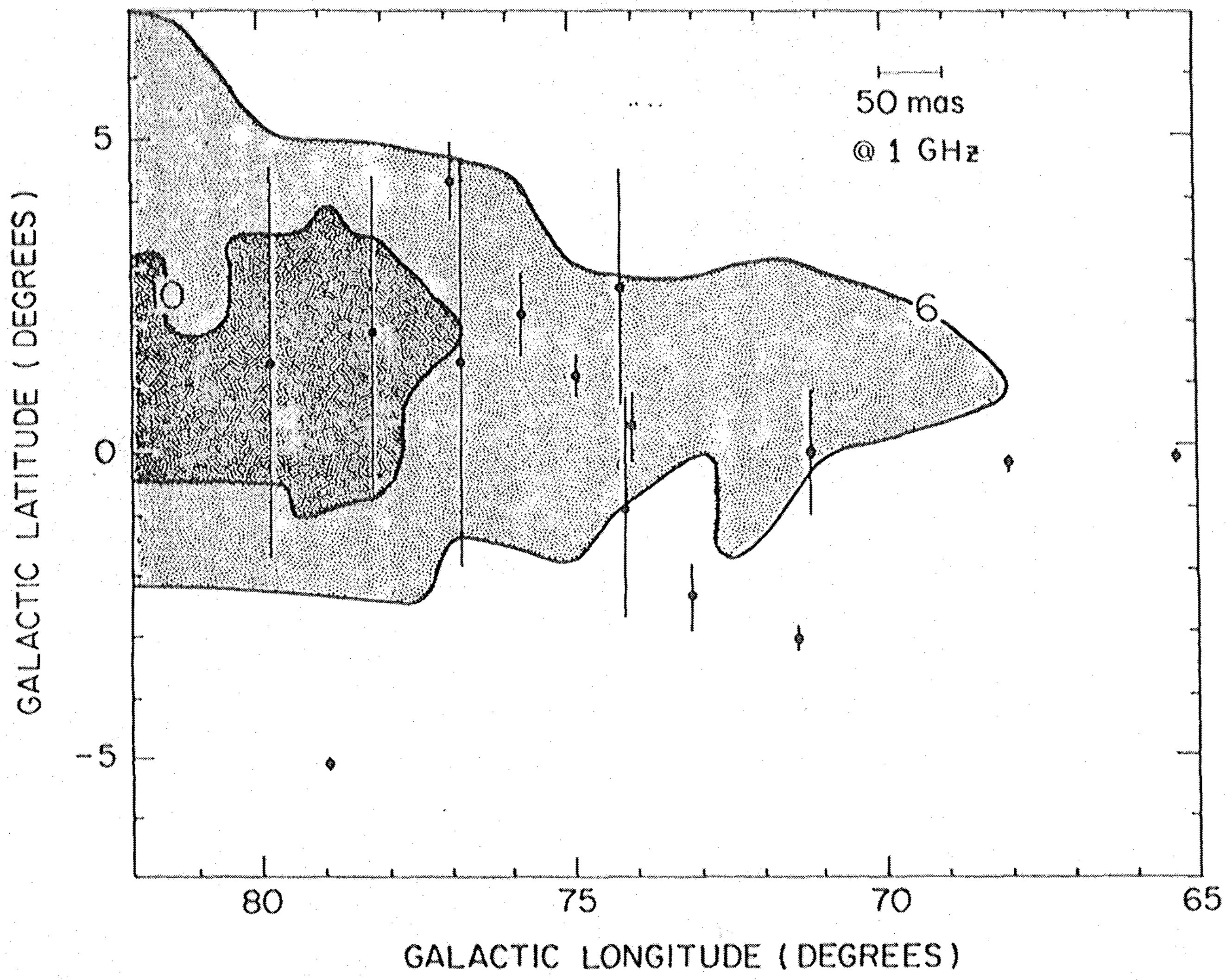


Figure 6

B-G90-347

RADIO WAVE SCATTERING IN CYGNUS

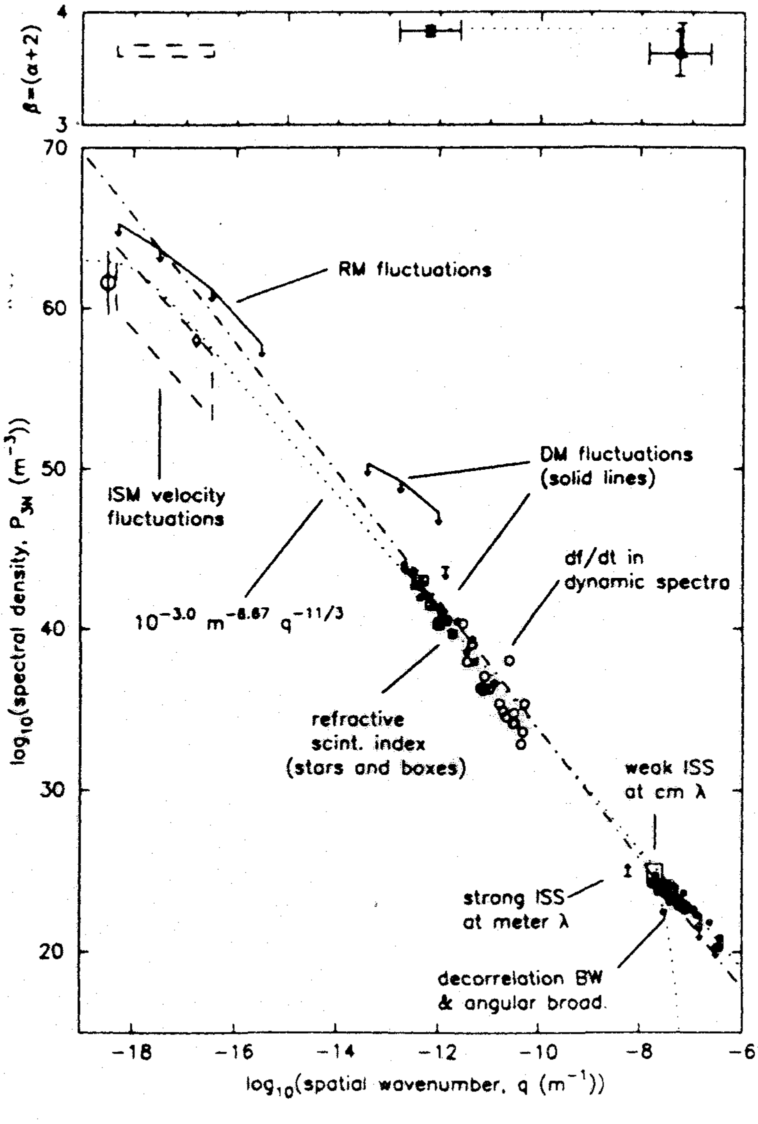


"The Big Power Law in the Sky"

Armstrong, Rickett, Spangler 1995, ApJ 443, 209

No spectral "features" from

$K \sim 10^{-6} m^{-1} — 10^{-13} m^{-1}$, perhaps $10^{-17} m^{-1}$



Minter & Spangler, ApJ 1996, 1997

TABLE 6

Observed Turbulent Properties of the Interstellar Medium toward $l = 145°$, $b = -20°$

Quantity	Value
n_0 (cm^{-3})	0.029
$B_{\parallel}$ (μG)	-0.8
L (pc)	2900
l_0 (pc)	3.6 ± 0.2
l_0^{2D} (pc)................	$70 \leq l_0^{2D} \leq 96$
C_n^2 (m$^{-20/3}$)	$10^{-3.0}$
C_B^2 (μG^2 m$^{-2/3}$)......	$2.2 \pm 0.4 \times 10^{-13}$

TABLE 1

Properties of Turbulence in DIG

Quantity	Value
$\langle n_e \rangle$ (cm^{-3})	0.025
Filling factor	0.25
n_e (cm^{-3})	0.08
B_0 (μG)	3
C_n^2 (m$^{-20/3}$)...........	10^{-3}
$C_{B_i}^2$ (μG^2 m$^{-2/3}$)......	2.2×10^{-13}
l_o (pc)..................	3.6
l_i (km).................	($\sim$800)
v_s (10^6 cm s^{-1}).......	0.93
V_A (10^6 cm s^{-1})	2.33
ν_0 (s^{-1})[a]...............	8.3×10^{-10}

[a] 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:

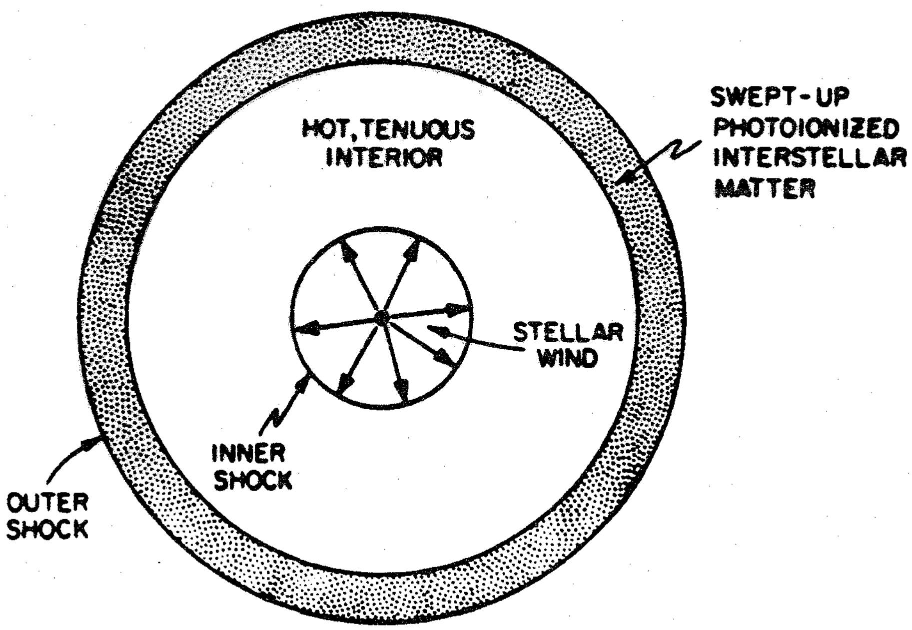
⋮

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

- Further discussions in this Symposium

8-081-434

INTERSTELLAR BUBBLE



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 ⋆

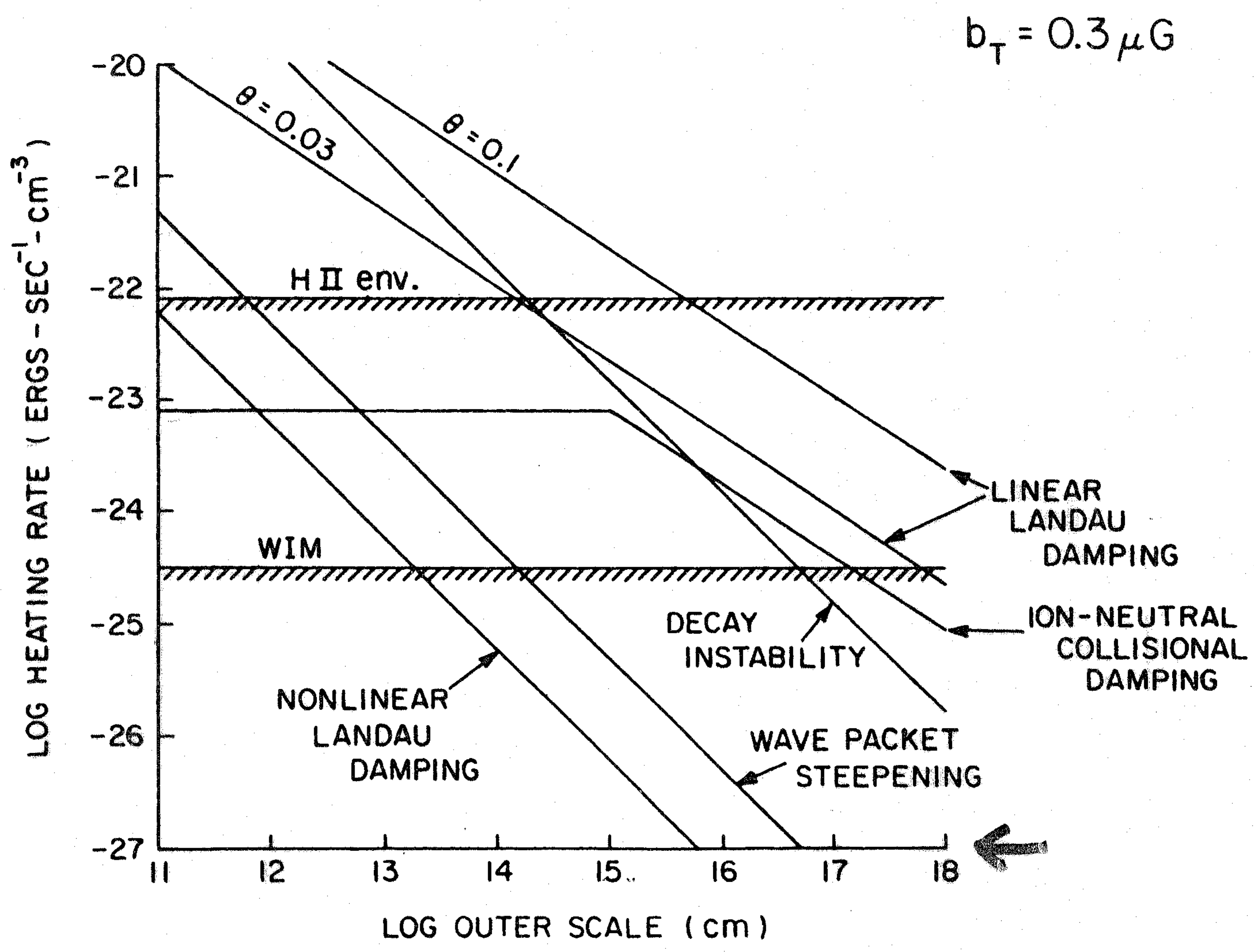

$b_T = 0.3\,\mu G$
LOG HEATING RATE (ERGS - SEC^{-1} - cm^{-3})
-20
-21
-22
-23
-24
-25
-26
-27
$\theta = 0.03$
$\theta = 0.1$
H II env.
WIM
LINEAR LANDAU DAMPING
ION-NEUTRAL COLLISIONAL DAMPING
DECAY INSTABILITY
NONLINEAR LANDAU DAMPING
WAVE PACKET STEEPENING
11
12
13
14
15
16
17
18
LOG OUTER SCALE (cm)

Figure 3

Faraday Rotation and the Interstellar Medum

- 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 $\geq 10^{18}$ cm $\longrightarrow 10^7$ cm. Spectral index α ***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 $\simeq 1.5 - 2.0$.
- δB 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_{eff} (Bondi *et al* A & A 287, 290, 1994; Cordes and Rickett, ApJ 507,846,1998, Rickett, Coles, and Markkanen, 1999)

- Are the spectra $\perp$ and $\|$ $\vec{B}_0$ the same? **Theory:** no, **Observations:** yes

- Where is the evidence for mesoscale ($\sim 10^{15} - 10^{16}$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

- What generates the turbulence? Shear flows, buoyancy-driven turbulence, kinetic plasma instabilities, "star murmuring"? One possibility: gravity and star formation impresses "structure" on the ISM at large (≥ 1 parsec) scales (e g Ballesteros-Paredes, Vazquez-Semadini, and Scalo, ApJ 515, 286, 1999, Ostiker, Gammie, and Stone, ApJ 513, 259, 1999), then MHD nonlinearities cause cascade to smaller scales Does this work? Is it the correct explanation?