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Radioastronomy and the Nature of Turbulence in the Interplanetary Medium

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

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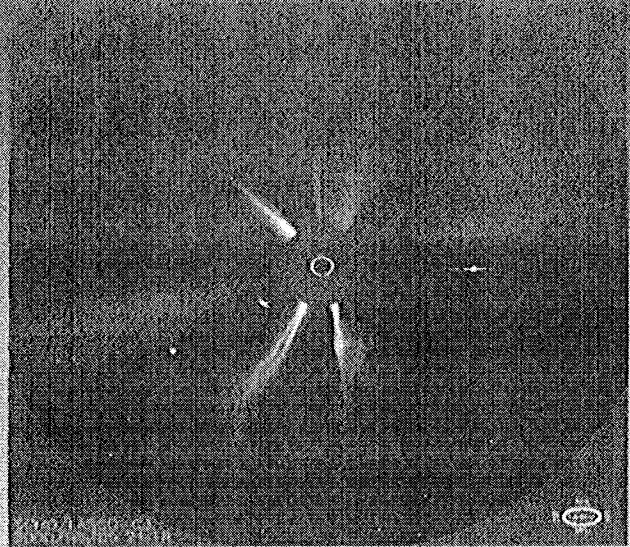
Radioastronomy and the Nature of Turbulence in the Interplanetary Medium



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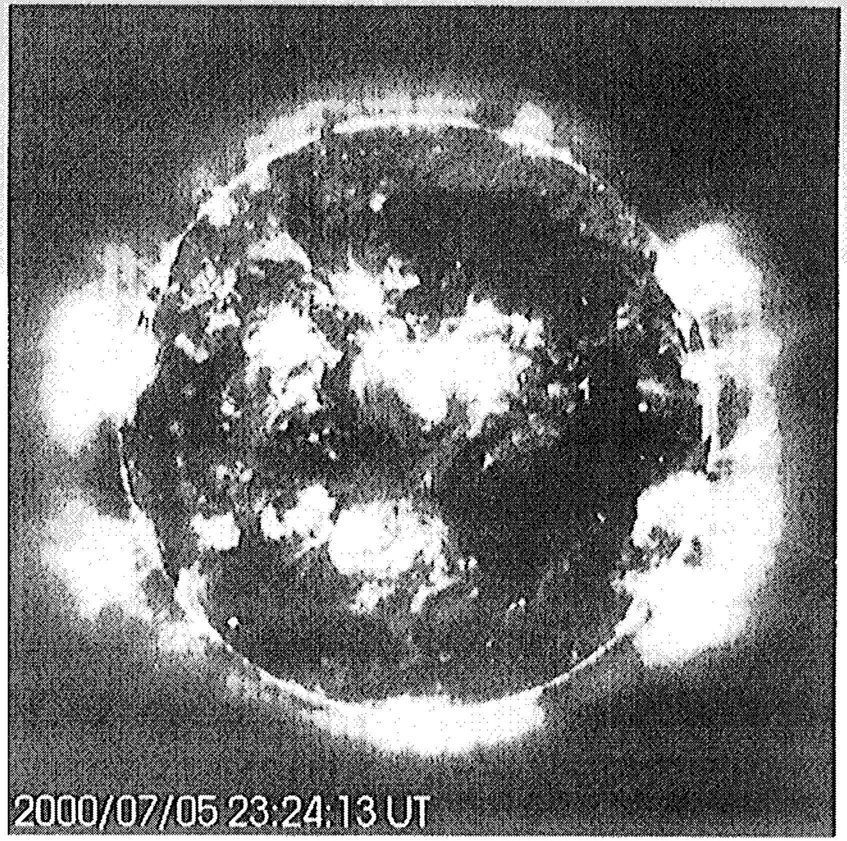
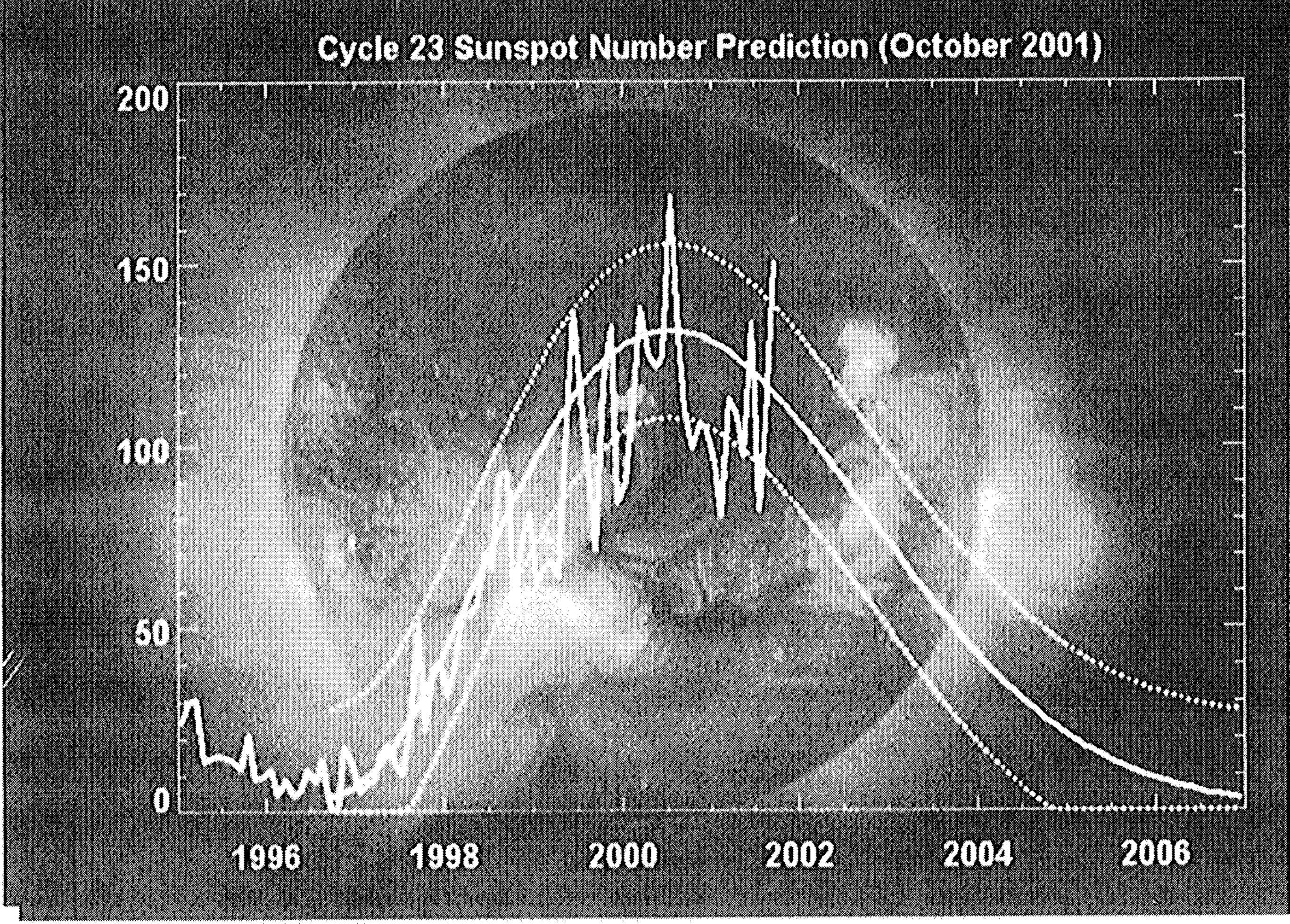
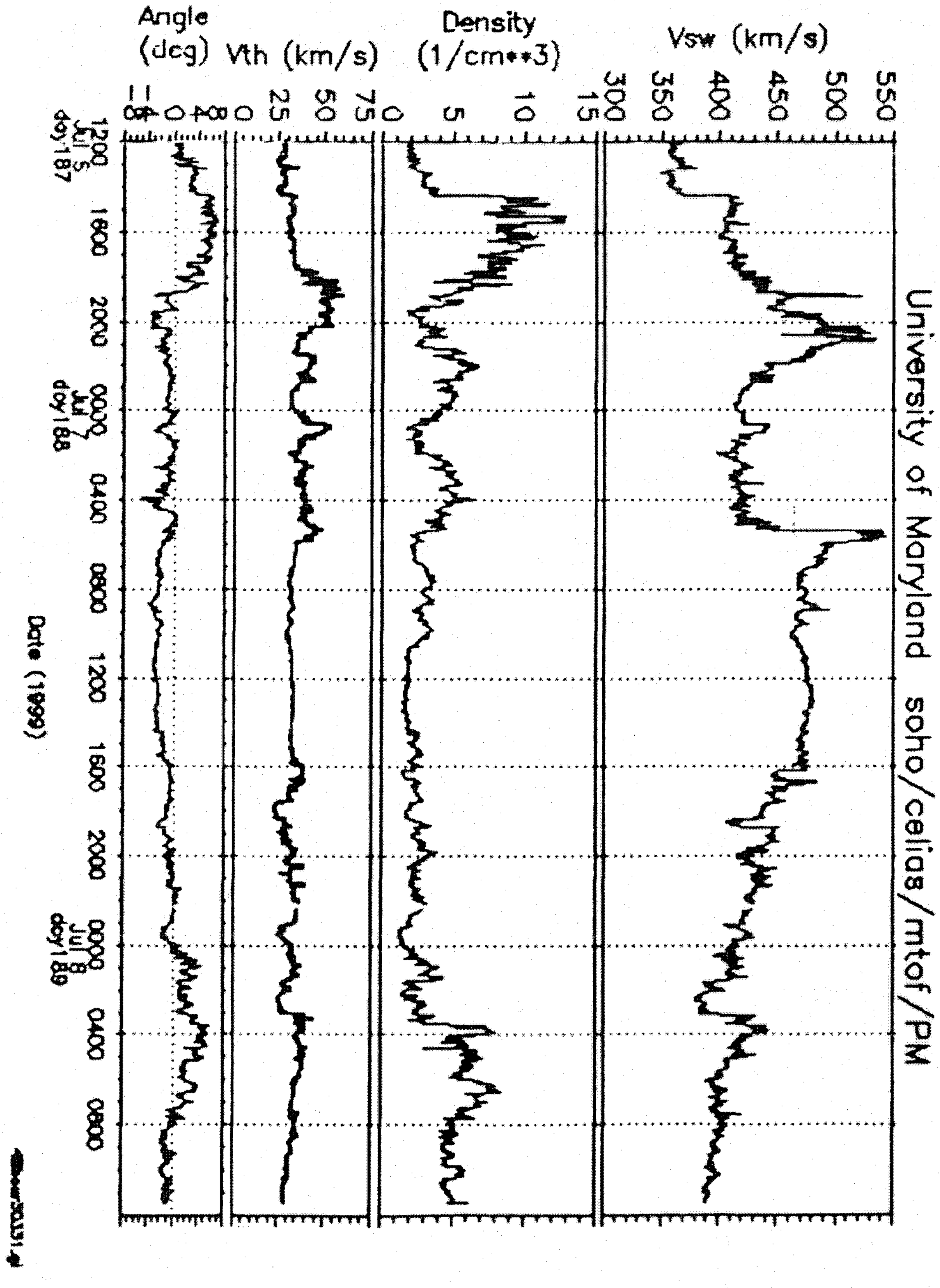
Magnetism and the Solar Corona

- Loops show hot gas confined by Sun's magnetic field



The Solar Atmosphere and the Sunspot Cycle




University of Maryland soho/celias/mtof/PM
Vsw (km/s)
300 350 400 450 500 550
Density (1/cm**3)
0 5 10 15
Vth (km/s)
0 25 50 75
Angle (deg)
-8 -4 0 4 8
1200 Jul 5 doy 187
1600
2000
0000 Jul 7 doy 188
0400
0800
1200
1600
2000
0000 Jul 8 doy 189
0400
0800
Date (1999)

A Comparison of the Solar Wind and ISM

Parameter	Diffuse Ionized Phase of ISM	Solar Wind at 1a.u.
$B_0(\mu G)$	5	50
$n_e(cm^{-3})$	0.080	5
T_e (K)	8000	1.5×10^5
T_i (K)	≤ 15000	5×10^4
V_A (km/sec)	23	50
$\nu_{ION-NEUT}(sec^{-1})$	8.3×10^{-10}	0
"Turbulent Age"[1]	4×10^6 years	4 days

Notes

(1) Rough estimate of time from generation of turbulence to arrival at point of observation.

Eine Kleine Nachtphysik ...

The equations of hydro/magnetohydrodynamics

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

With "steady state" spherical symmetry $\longrightarrow$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 \rho v_r\right) = 0 \tag{2}$$

$$v_r \frac{dv_r}{dr} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{GM_\odot}{r^2} - \boxed{\frac{1}{\rho}\frac{d}{dr}\left(\frac{\delta B^2}{8\pi}\right)} \tag{3}$$

If far from the Sun, the right hand side $\longrightarrow 0.$ $\Rightarrow$

$$\frac{1}{2}\frac{dv_r^2}{dr} = 0 \tag{4}$$

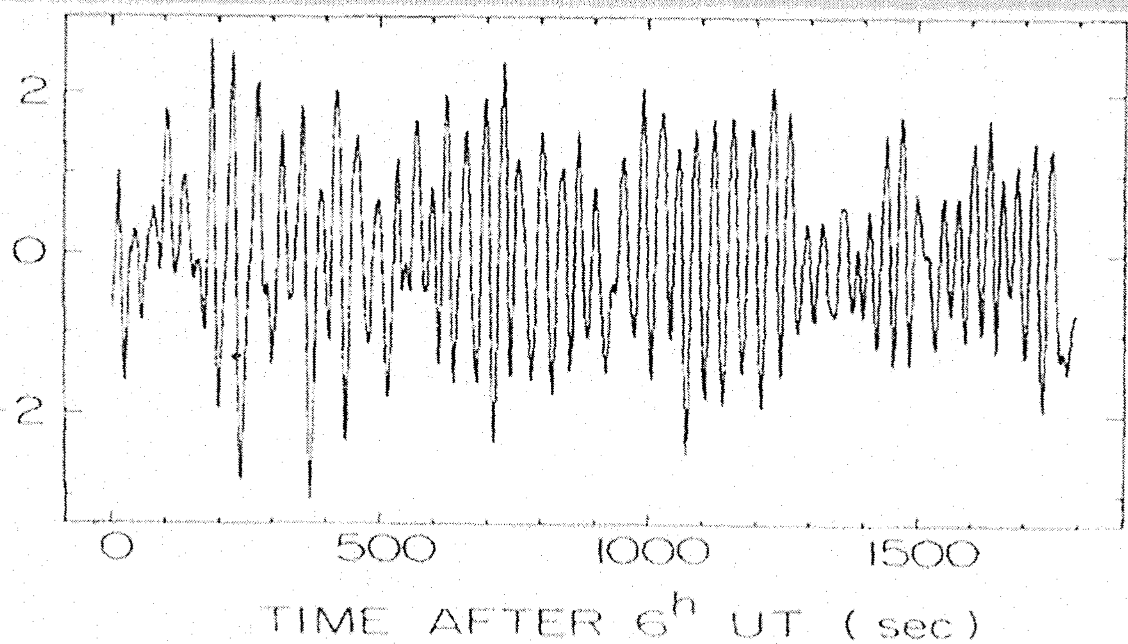
Therefore $v_r^2 = C$

$$\frac{de}{dt} + \vec{v} \cdot \nabla e = e \nabla \cdot \vec{v} - \boxed{\frac{1}{\tau}\left(\frac{\delta B^2}{4\pi}\right)} \tag{5}$$

Therefore "*Distant Wind*" has $v = C$, $\rho \propto r^{-2}$.

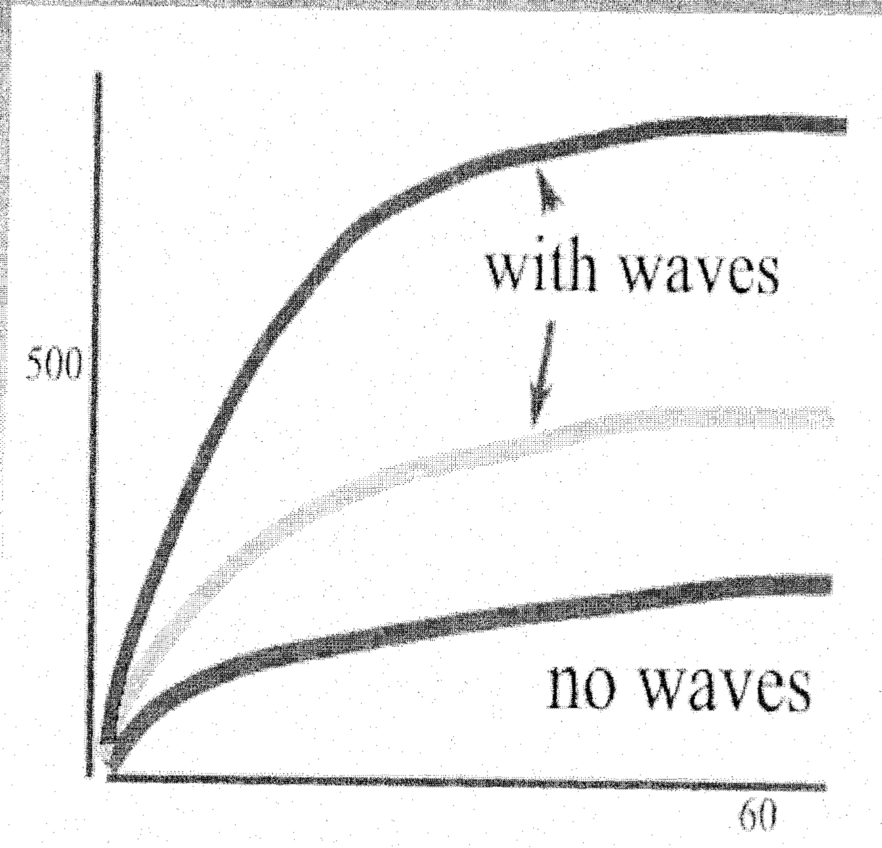
Coronal Magnetohydrodynamic Waves

- They have temporally and spatially varying magnetic fields
- Associated phenomenon of Faraday rotation



Why is Near-Sun Turbulence of Interest?

- Observed wind is faster and hotter than models
- Damping of turbulence provides heat and momentum
- Phenomenon similar to flow in middle atmosphere



Velocity versus Heliocentric Distance

The Wave Driven Solar Wind

For wave-driven models to be viable (1) the must be a sufficient wave flux (turbulent energy density) $\simeq (2-5)\times 10^5$ ergs/sec/cm^2, and (2) the waves should damp sufficiently rapidly ($\leq 10 - 20R_\odot$).

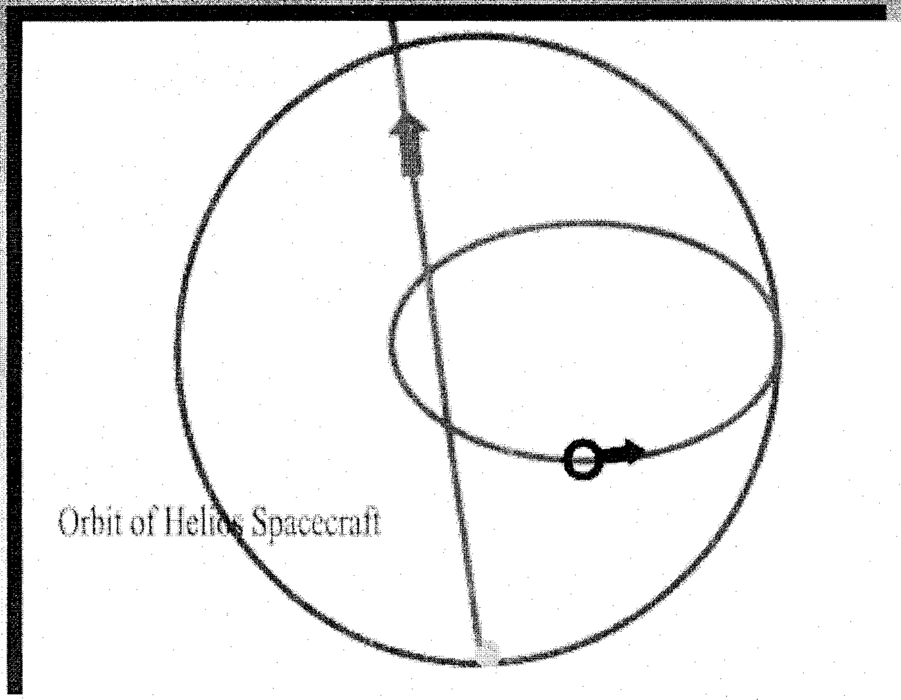
Two Models for Turbulence

(1) Low Frequency Waves (periods of tens of minutes to couple of hours)
(2) High Frequency Waves (plasma frame frequencies of 1 - 1000 Hertz).

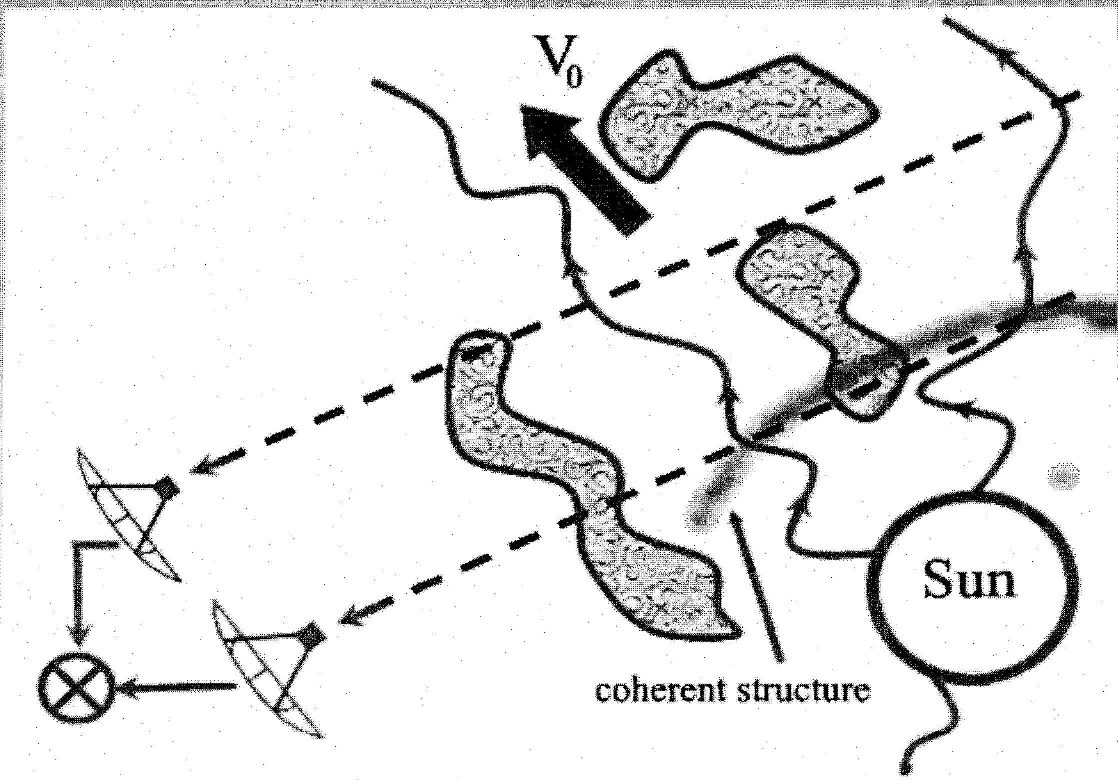
The Sector of Space for Remote Sensing

Remote Sensing of Plasmas and Plasma Turbulence

- Why bother?
- Information important where in-situ data not available
- Helios spacecraft found solar wind fully accelerated at 0.28 au

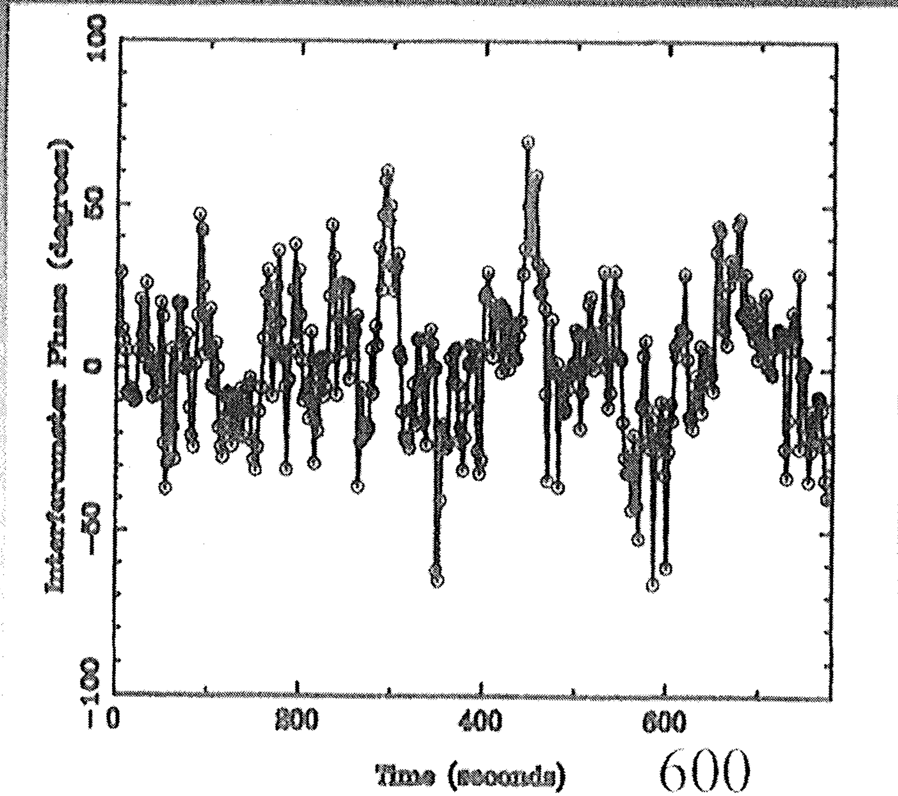


The Physical Basis of Phase Scintillations



Measured VLBI Phase Scintillations

- Characteristics of observations
  - Frequency 8.4 GHz
  - Source elongation 22.6 solar radii
  - Baseline Medicina-Noto (500 – 800 km)



600

Time (seconds)

Expression for Phase Power Spectrum

R. L. Mutel, 1975

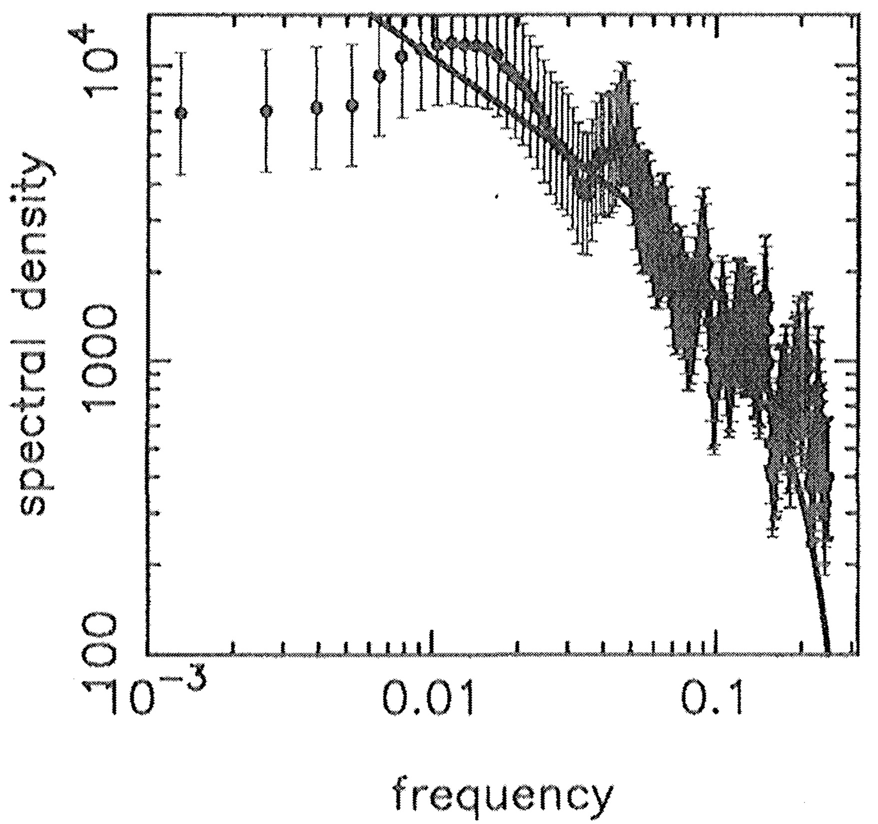
Physical Variables in Phase Power Spectrum

- Density power spectrum, $P_{\delta n}(q) = C_N^2 q^{-\alpha}$. $C_N^2(r)$ expression given by Spangler *et al* 1996, *Solar Wind 8*.
- Solar Wind flow speed V_0.
- Effective thickness of solar wind plasma screen, L.
- Outer scale l_0

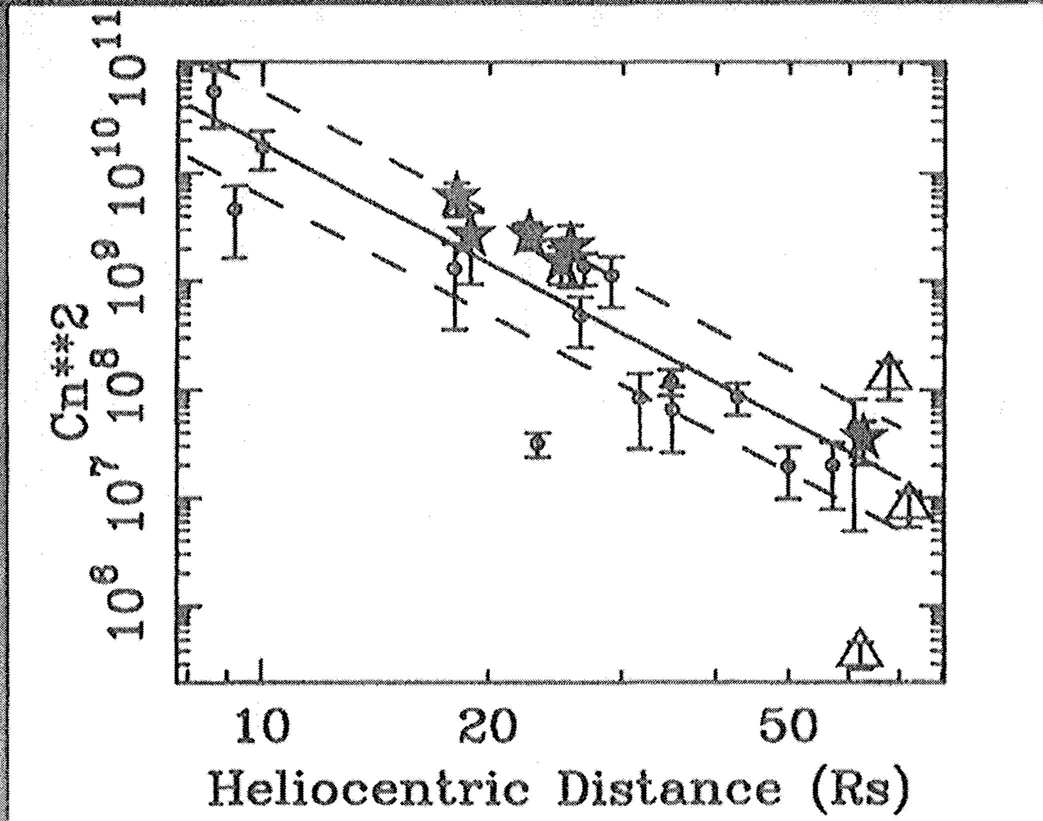
Then ...

$$P_{\delta\phi}(f;\alpha, C_N^2, L, V_0) = \frac{32\pi^2 r_e^2 \lambda^2}{V_0} C_N^2 L l_0^\alpha \int_0^\infty dq_\perp \frac{1}{\left(1 + l_0^2[q_\perp^2 + q_{||}^2]\right)^{\alpha/2}} \sin^2\left[\frac{\pi f \rho_{||}}{V_0} + \frac{q_\perp \rho_\perp}{2}\right] \tag{1}$$

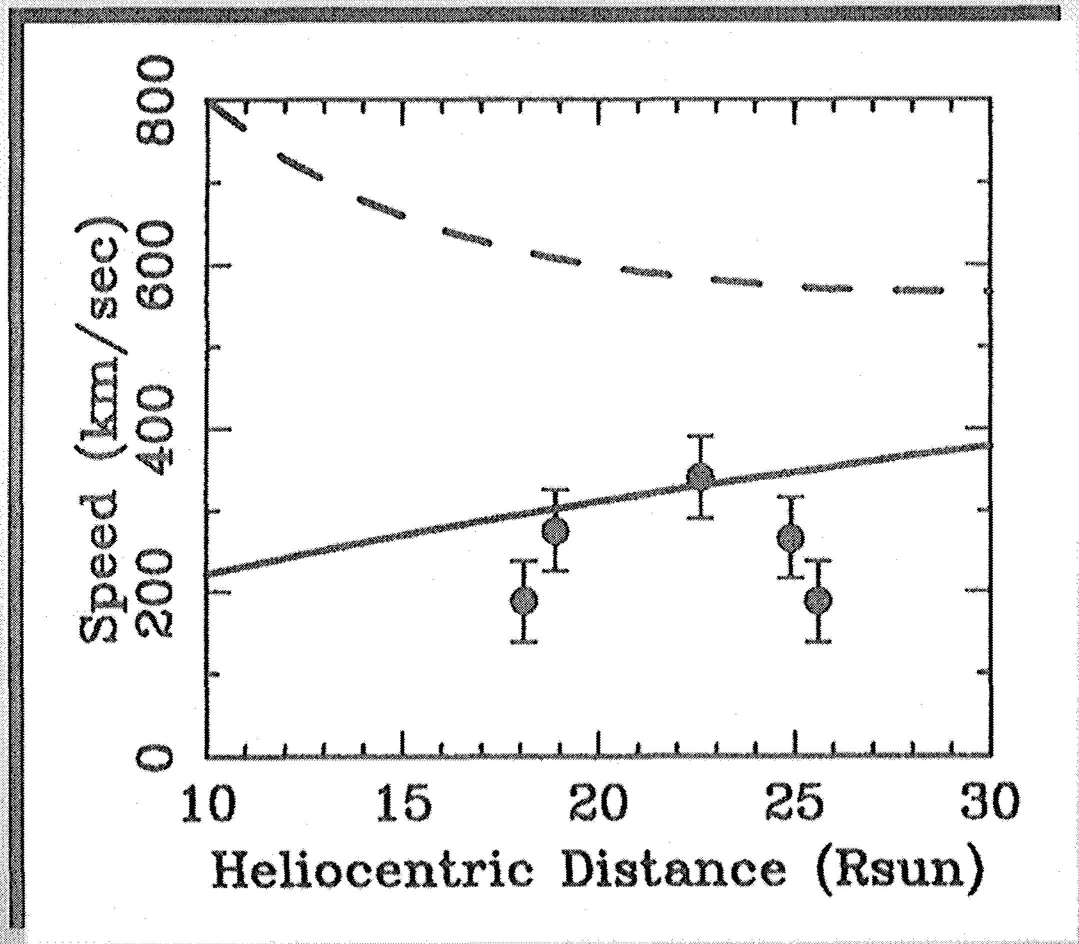
Measuring Solar Wind Parameters: Fits to Phase Power Spectra



Evolution of C_N^2 with Heliocentric Distance



Remote Measurement of the Speed of the Solar Wind

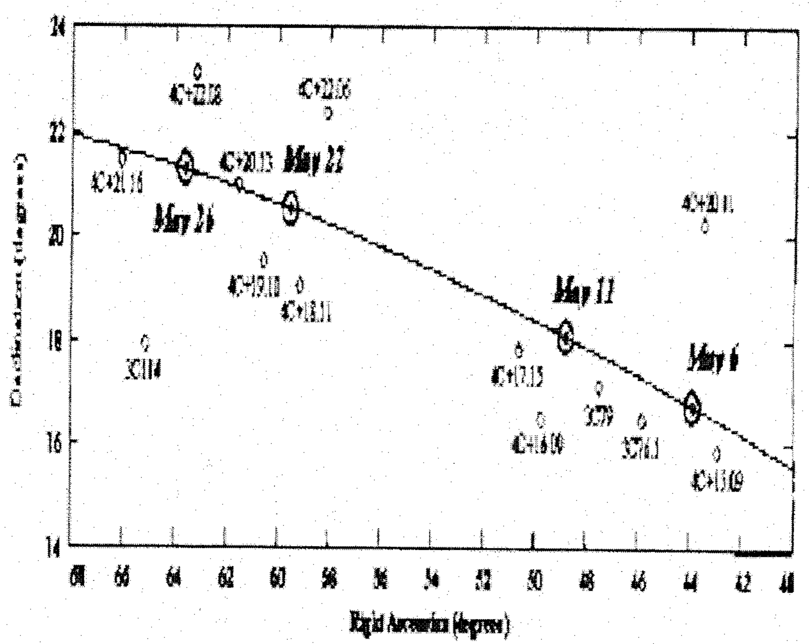


What can one do with coronal Faraday rotation observations?

- RM fluctuations $\longrightarrow$ coronal Alfvén waves
- $\bar{RM}$ $\longrightarrow$ magnetohydrodynamic structure of corona
- *Depolarization* $\longrightarrow$ small scale Alfvén waves

Tomography of the Corona

- Mancuso & Spangler, ApJ 525,195,1999; also M&S submitted
- RM along 13 lines of sight
- Goal: determine B and Ne models



A Model for the Plasma Structure of the Solar Corona

- Density distribution

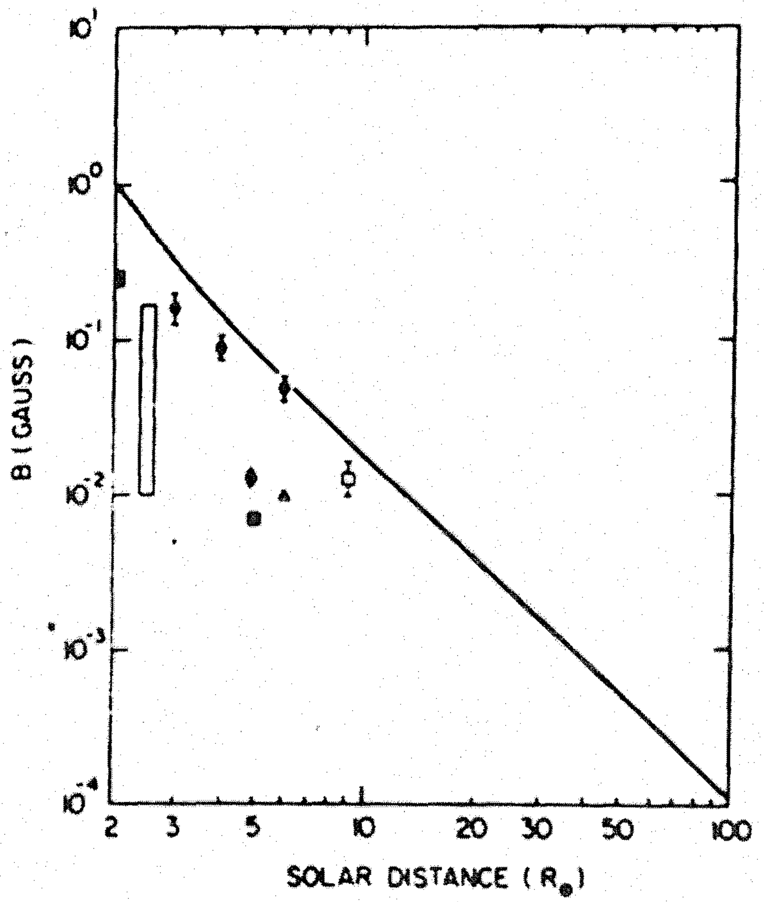
$$n(r,\theta,\phi) = n_{CH}(r) + (n_{CS}(r) - n_{CH}(r)) \exp\left[-(\theta/w(\phi)^2\right] \quad (8)$$

n_{CH} and n_{CS} compound power laws in r.

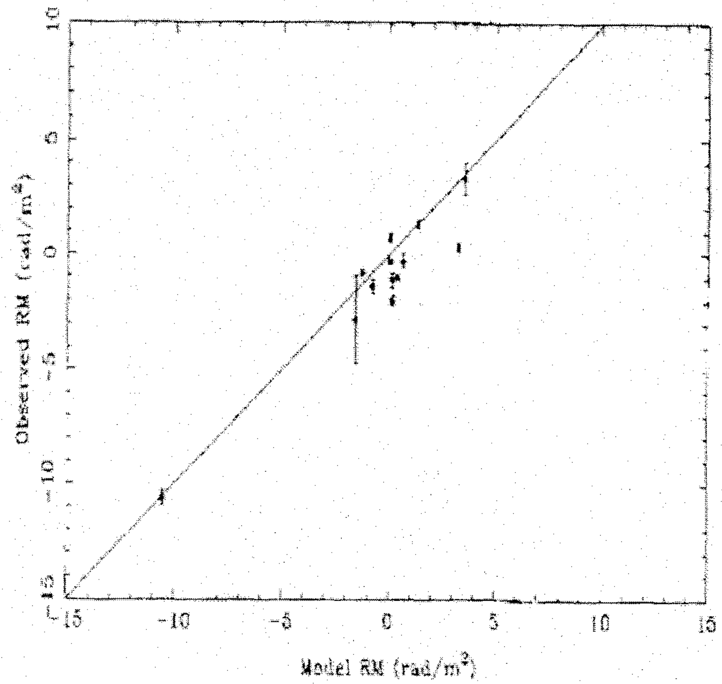
- Magnetic Field model

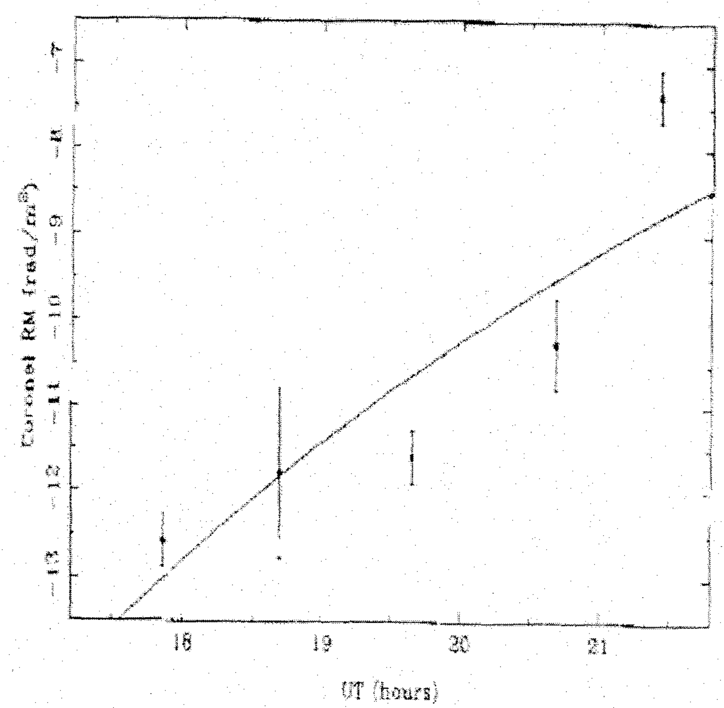
$$B(r) = 0.06(r/R_{\oplus})^{-3} + 3.1(r/R_{\oplus})^{-2} \text{ nT} \quad (9)$$

with $R_{\oplus} = 1$ astronomical unit (Pätzold, 1987).



Agreement of Model Corona with Observations





How Observables Relate to the Theory

(1) RMS Rotation Measure Fluctuation

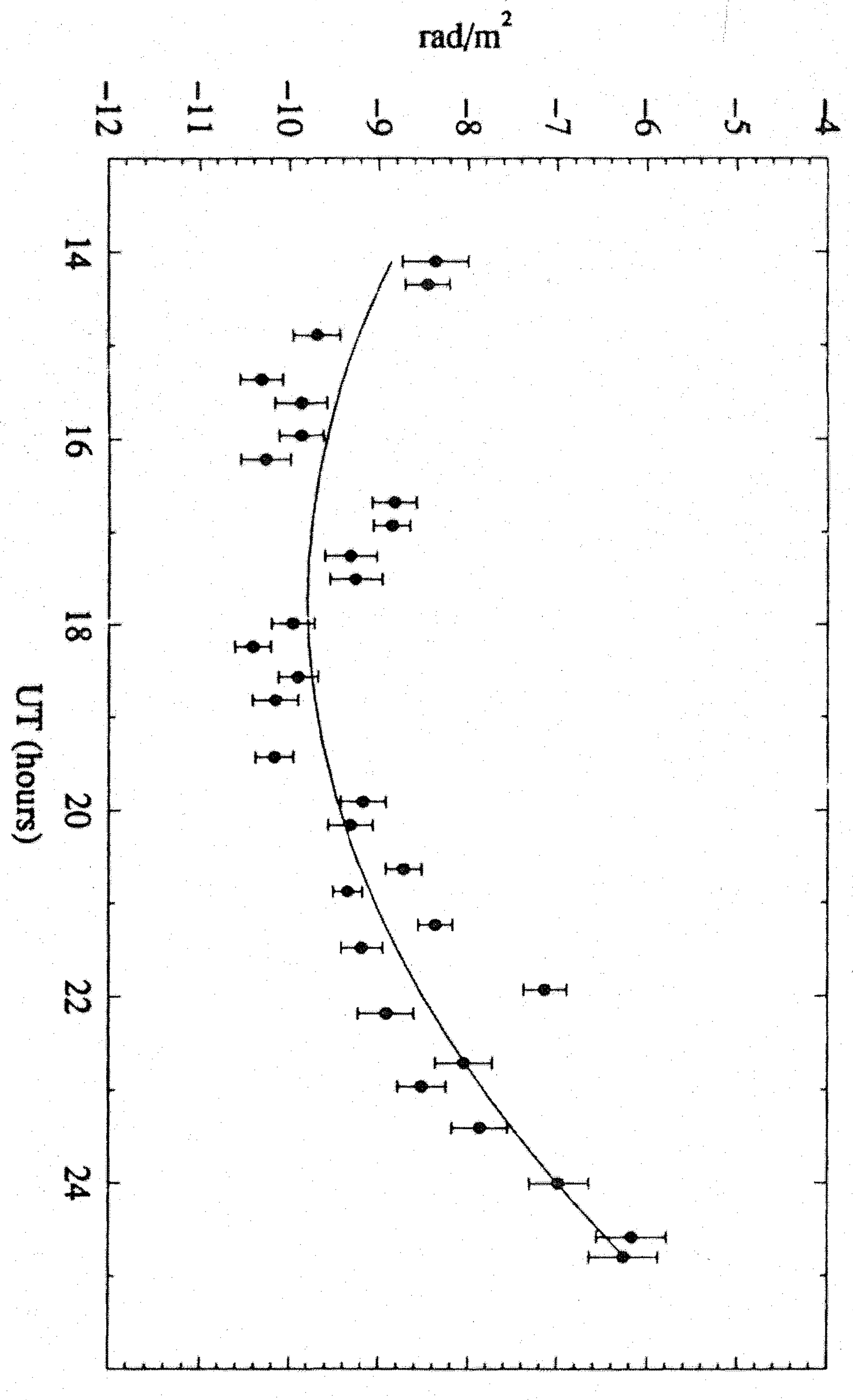
$$< (\delta RM)^2 >= \left(\frac{e^3}{2\pi m_e^2 c^4}\right)^2 \int_0^\infty n_e^2 < (\delta B_z)^2 > Lds \qquad (1)$$

(2) Relating δB_z to wave flux

$$F_A = \frac{< \delta B^2 >}{8\pi}(3U + 2V_A) \qquad (2)$$

(3) Relating flux to coronal base

$$F_{A0} = \frac{< \delta B^2 >}{4\pi V_A}(U + V_A)^2 \left[\frac{A}{A_0}\right] \qquad (3)$$



rad/m^2
−12
−11
−10
−9
−8
−7
−6
−5
−4
14
16
18
20
22
24
UT (hours)

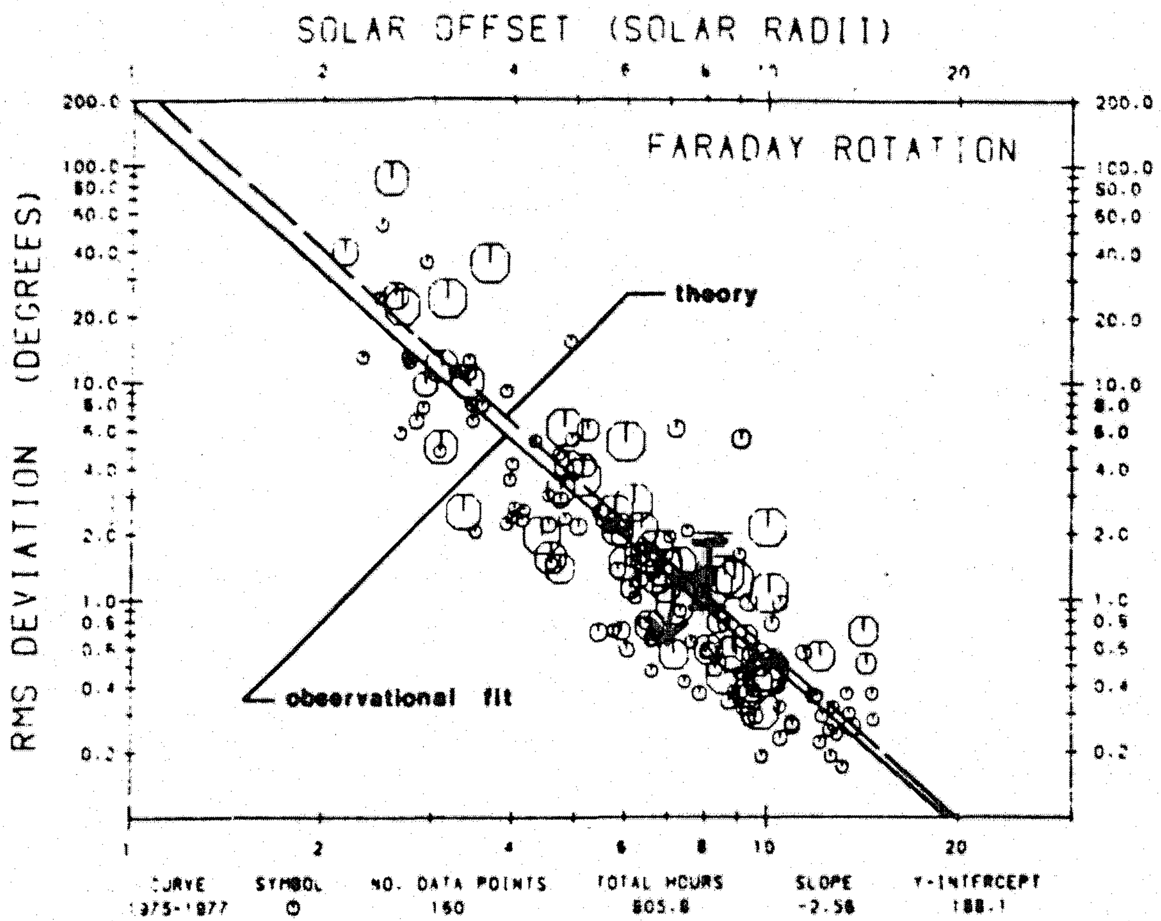


Fig. 6. Standard deviation of the Faraday rotation from the mean linear trend over each observation pass versus solar offset; all data from 1975 through 1977. The solid line is a power law fit to the observations. The dashed line is the theoretical expression (25), which is based on the assumption that most of the Faraday rotation variance is caused by fluctuations of the coronal magnetic field and not the electron concentration.

Summary: Radio Remote Sensing of the Corona and Solar Wind

- Magnitude of scintillations are consistent with small amplitude, passive, dynamically unimportant fluctuations
- Observations consistent with non-propagating fluctuations
- Faraday rotation "tomography" consistent with independent measures of coronal plasma state
- Observations consistent with "smooth" corona, without large waves or turbulence