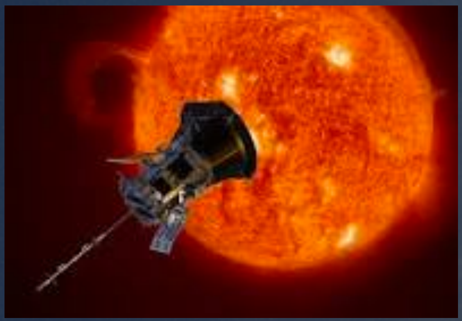
Angular Broadening Measurements as a Probe of the Corona and Solar Wind



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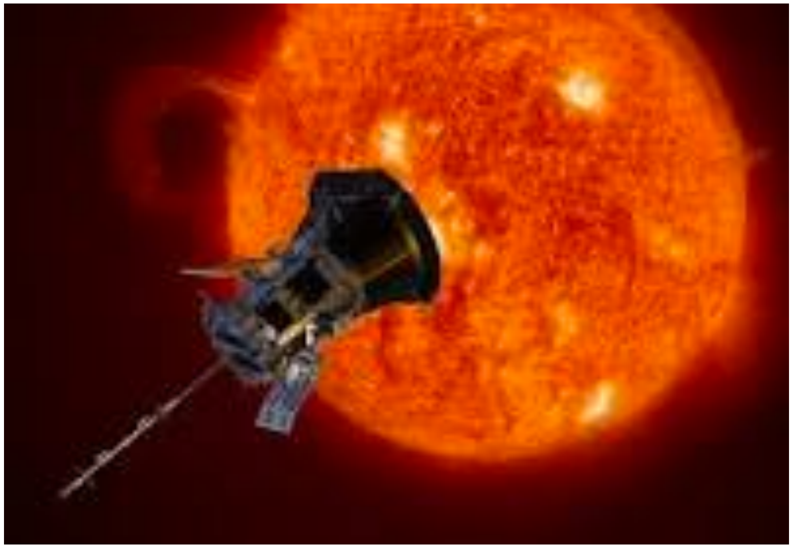
Parker Solar Probe

- Trace the flow of energy that heats and accelerates the solar corona and solar wind.
- Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.
- Explore mechanisms that accelerate and transport energetic particles.



Instrumentation suite:

FIELDS – E and B fields, radio, dust (PI Bale)
SWEAP – electrons, protons, alphas (PI Kasper)
WISPR – wide field WL imager (PI Howard)
ISIS – mass spectroscopy (PI McComas)

Launched on 12 Aug 2018, the first perihelion passage of PSP in Nov 2018 already came within ~35 $R_\odot$ of the photosphere.

PSP perihelia will eventually pass within 10 $R_\odot$ the photosphere! Compare with Helios 1 & 2: perihelia of ~0.3 AU, or 65 $R_\odot$

Supporting Observations

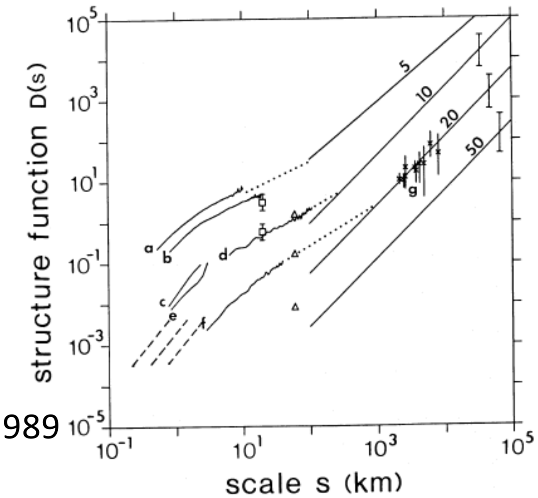
- The PSP offers an unprecedented opportunity to characterize the solar wind, solar wind turbulence, and SEPs near their origin
- Comprehensive and complementary observations of the Sun and corona are needed to provide global perspective and a broader framework within which to interpret PSP data
- Ground-based radio observations are a part of this effort using a variety of direct and indirect observations
    - Jansky Very Large Array (JVLA)
    - Low Frequency Array (LOFAR)
    - Institute for Space-Earth Environment (ISEE)
    - Arecibo Observatory (AO)

Solar Wind Spectrum

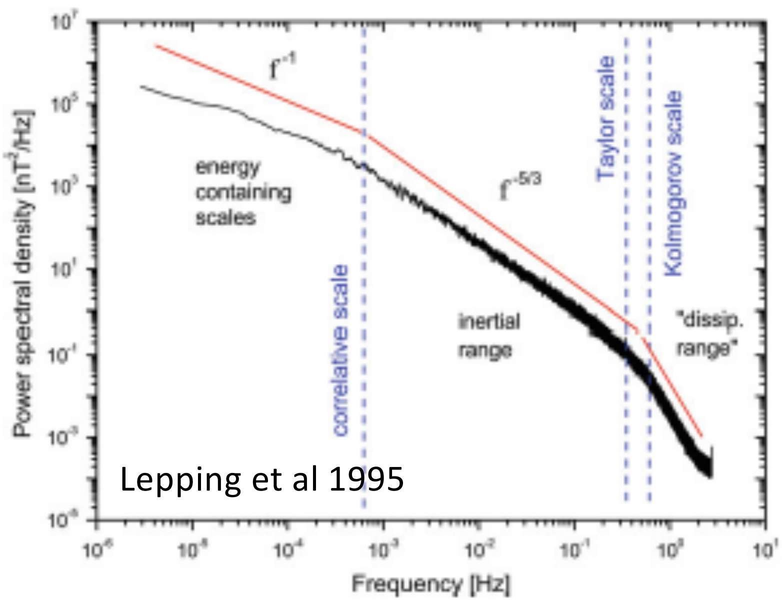
The spectra of B variations in the solar wind show a turbulence spectrum characterized by a Kolmogorov-like inertial range.

The spatial spectrum of electron density fluctuations is more complex, Kolmogorov-like on large spatial scales but flatter (power excess) on smaller spatial scales.

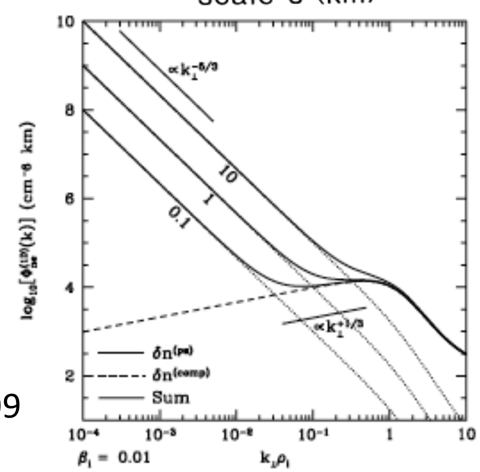
As determined by density fluctuations …



Coles & Harmon 1989



Lepping et al 1995



Chandran et al 2009

Remote Sensing at Radio Wavelengths

	Observation/Technique	Plasma Property
	Group delay	Mean electron number density n_e
	Refraction	Electron density gradient ∇n_e
JVLA	Angular broadening	Index α of Φ_n on scales of km to 100s of km Inner scale l_o, degree of anisotropy, B orientation
	Spectral broadening	Index α of Φ_n on scales of km to 100s of km Inner scale l_{in}
	Phase scintillations	Index α of Φ_n on scales of 100s to 1000s of km Outer scale l_{out}
	Doppler (freq) scintillations	Index α of Φ_n on scales of km to 100s of km Solar wind velocity v_{sw}
LOFAR, ISEE, AO	Intensity scintillations (diffractive & refractive)	Index α of Φ_n on scales of km to 100s of km IPS: Solar wind velocity v_{sw}, δv, l_o
	Faraday rotation	$B_{\parallel}$, n_e
	Faraday fluctuations	Magnetic field fluctuations δB

Reminders

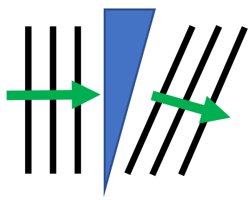
Fully ionized plasma: $\mu_\nu^2 = \epsilon_\nu = \frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega^2}$ $\qquad \omega_{pe}^2 = 4\pi n_e e^2/m_e$

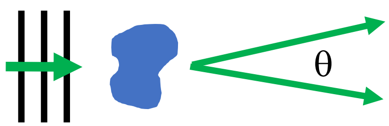
Taking $n_e = n_\circ + \delta n_e$ we have $\delta\mu = \frac{1}{2\mu_\circ}\frac{\omega_{pe}^2}{\omega^2}\frac{\delta n_e}{n_e} = \frac{1}{2\pi}\frac{\lambda^2 r_e}{\mu_\circ}\delta n_e$

For radiation incident on a uniform slab of plasma of thickness Δz:

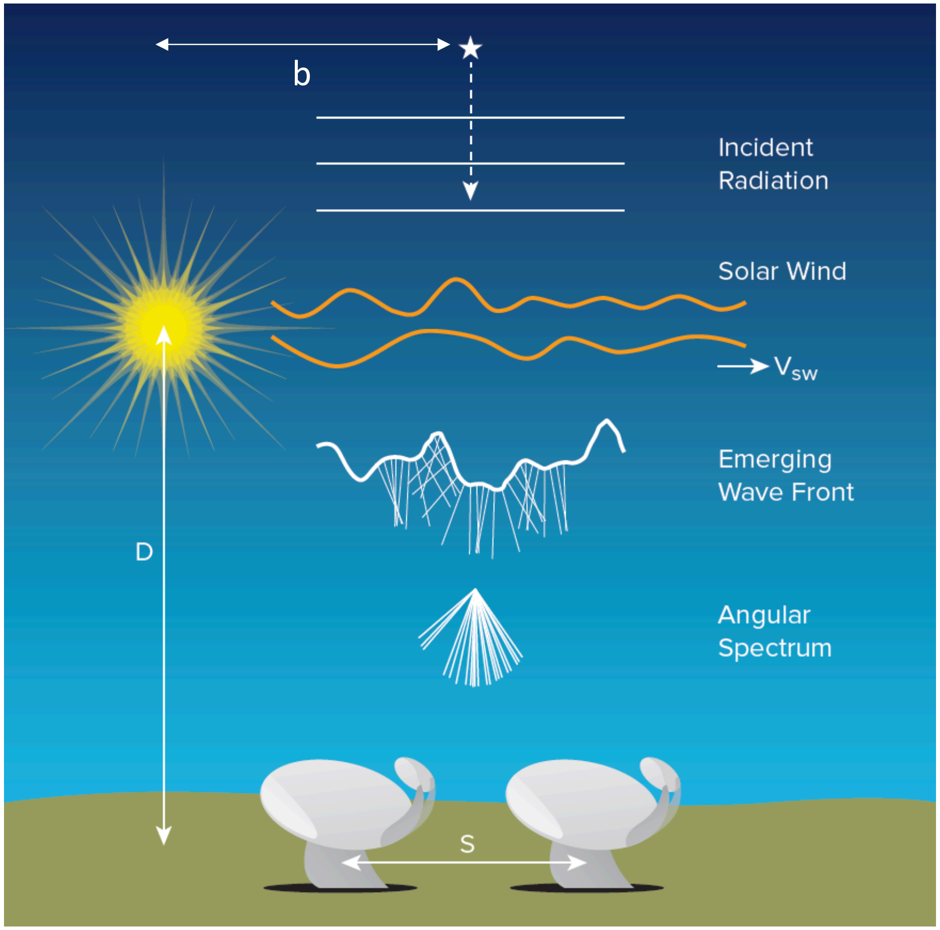
$$\delta\phi = 2\pi\left(\frac{\Delta z}{\lambda} - \frac{\Delta z \mu_\nu}{\lambda}\right) = k\Delta z \delta\mu_\nu = \lambda r_e \Delta z \delta n_e$$

A density gradient yields a phase gradient. Since the direction of the incident radiation is given by the phase normal, this results in **refraction**.





For an inhomogeneity of transverse scale d, incident radiation is also forward scattered into a cone $\theta \sim \lambda/d$, a result of **diffraction**.



Angular Broadening

It is useful to treat the plasma medium as a thin, non-absorbing, phase-changing screen ($\Delta z \sim b << D$)

The medium perturbs the phase front from a point source in the transverse dimension. The emergent wave front can be decomposed into an angular spectrum of planes waves: angular broadening.

A useful statistic is the wave structure function:

$$D(s) = \langle |\phi(\mathbf{r}) - \phi(\mathbf{r}+\mathbf{s})|^2 \rangle = 2[B_\phi(0) - B_\phi(s)]$$

The electric field covariance is related to D(s) as

$$\Gamma(s) = \langle E(\mathbf{r}) E^*(\mathbf{r}+\mathbf{s}) \rangle / \langle |\mathbf{E^2}| \rangle = \exp[-\mathbf{D(s)/2}]$$

The coherence scale is the transverse scale on which $D(r_o) = 1$ and the angular width is then $\theta = 1/kr_o$.

We also have $t \sim \Delta\theta^2/2c$ (temporal broadening) and $\Delta\nu/\nu \sim v_{sw}\theta/c$ (spectral broadening).

Radio Interferometers are Machines for Measuring D(s)

The JVLA is a Fourier synthesis telescope; i.e., it measures the Fourier transform of the radio brightness distribution on the sky, referred to as the visibility function.

For a point source, suitably normalized, it is simply measuring the electric field covariance:

$$\Gamma(s) = \langle E(\mathrm{s})E^*(\mathbf{r}+\mathrm{s})\rangle / \langle |\mathbf{E^2}| \rangle = \exp[-\mathbf{D}(\mathrm{s})/\mathbf{2}]$$

It can be therefore be used as a useful probe of the solar wind.

Angular Broadening

Use angular broadening to constrain the spatial spectrum of electron density inhomogeneities in a turbulent plasma:

The wave structure function is related to the spatial spectrum of density inhomogeneities $\Phi_{ne}(q)$ through:

$$D(s) = \langle|\phi(\mathbf{r}) - \phi(\mathbf{r}+\mathbf{s})|^2\rangle = 8\pi^2\lambda^2 r_e^2 \Delta z \int_0^\infty [1 - J_\circ(qs)]\Phi_{n_e}(q) q\,dq$$

If $\Phi_{ne}(q)$ is described, say, by a power law with in inner scale l_o:

$$\Phi_{n_e}(q,z) = C_{n_e}^2(z) q^{\alpha-2} e^{-(ql_\circ/2)^2}$$

The relation has the following asymptotic dependencies when $0 < \alpha < 2$:

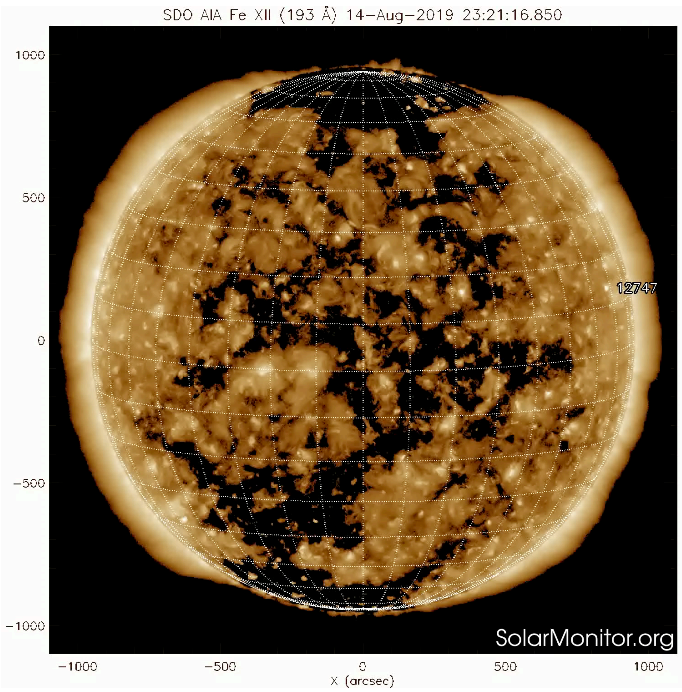
$$D_\phi(s) \sim C_{n_e}^2 \Delta z \lambda^2 s^\alpha \qquad s > l_\circ$$

$$D_\phi(s) \sim C_{n_e}^2 \Delta z \lambda^2 l_\circ^{\alpha-2} s^2 \qquad s < l_\circ$$

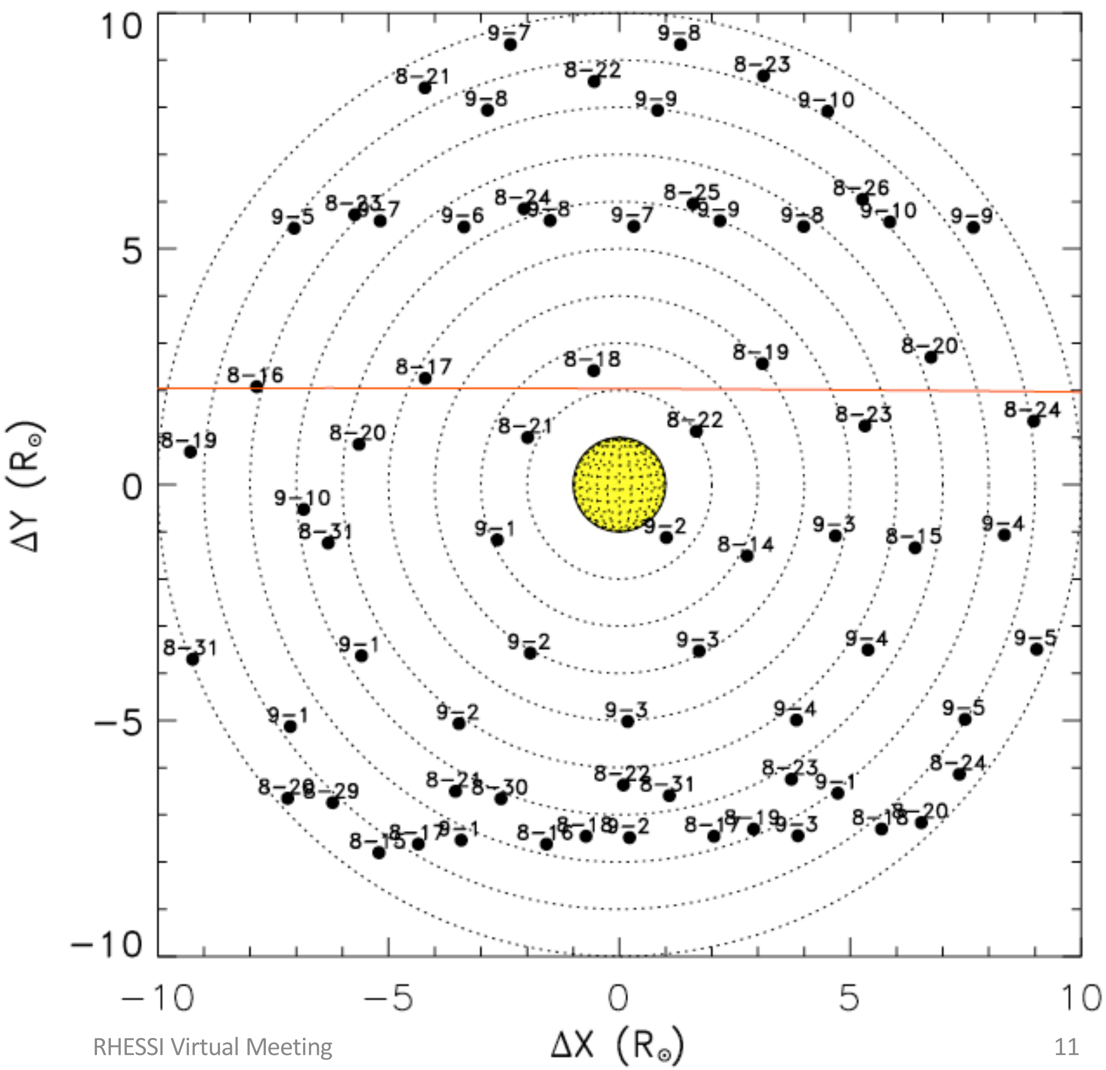
Notice proportionality to λ^2 in either case.

PSP Perihelion 3

A near-minimum corona

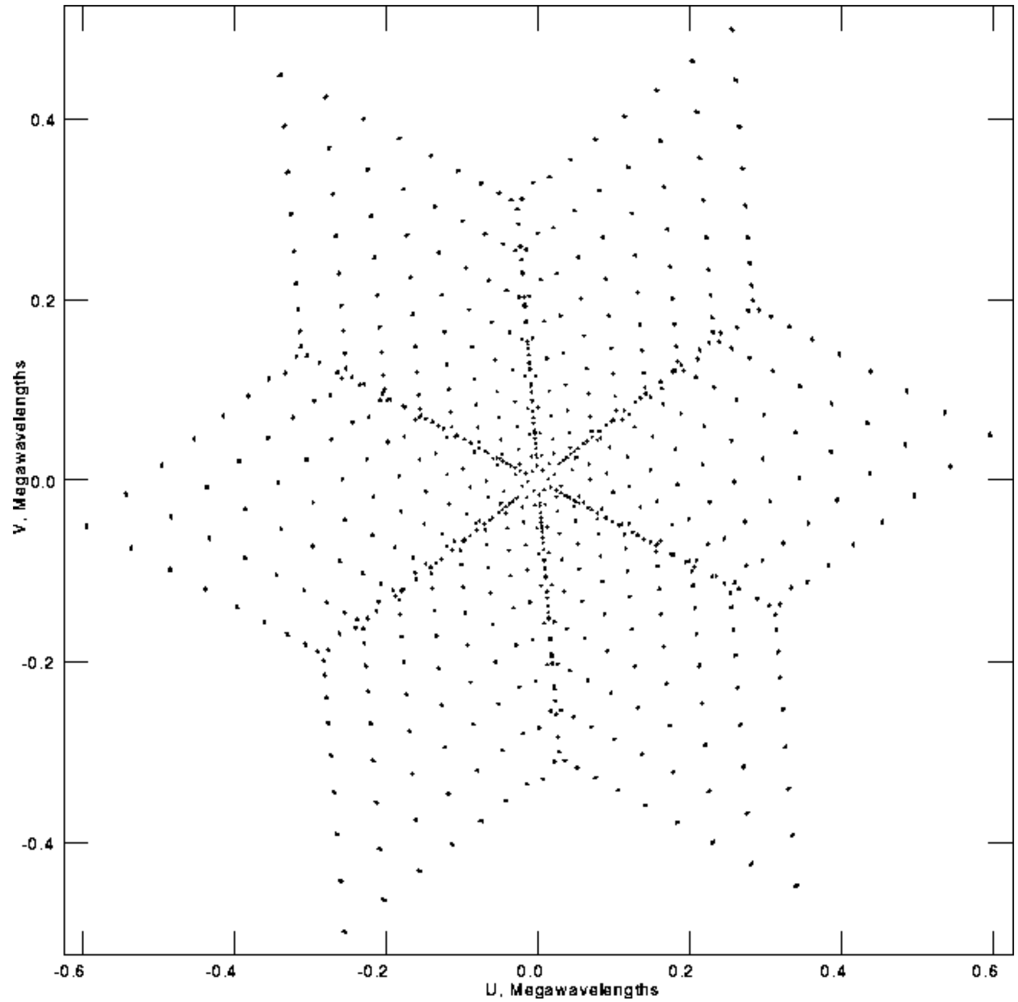


Observations were conducted over a solar rotation, from Aug 14– Sep 10



VLA A Configuration

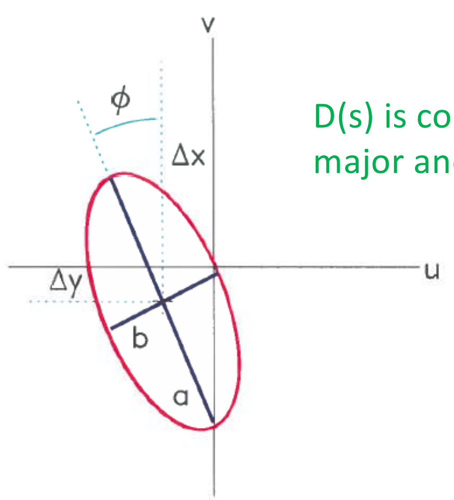
- Angular resolution is $\theta \approx 1.5''/\nu_{GHz}$
- Frequency bands 1-18 GHz, or $\lambda =$ 1.7-30 cm, were used



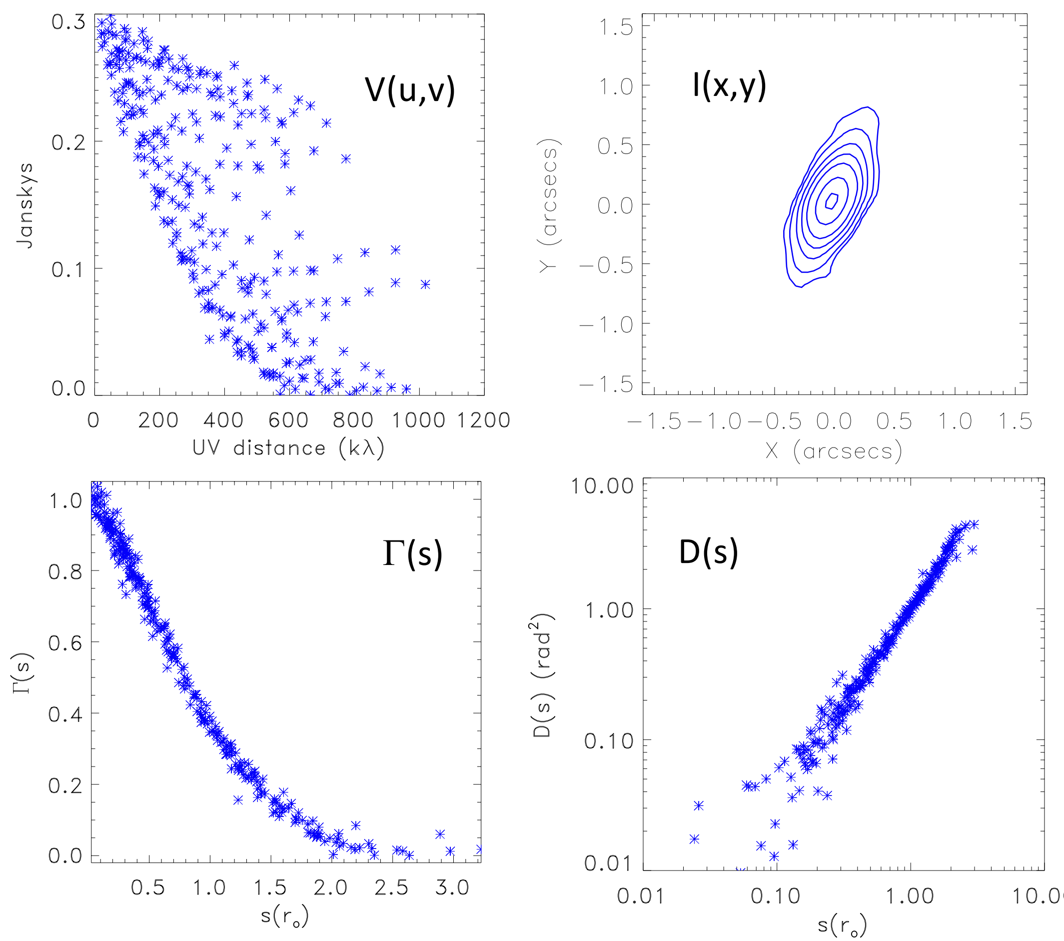
Analysis

$$V(u,v) = V(0)\overbrace{e^{-(u_t^2/a^2+v_t^2/b^2)^{\alpha/2}}}^{\text{D(s)}\propto s^{\alpha}}\overbrace{e^{2\pi i(u\Delta x+v\Delta y)}}^{\text{ref offset}}$$

$$u_t = u\cos\psi + v\sin\psi \qquad -u\sin\psi + v\cos\psi$$



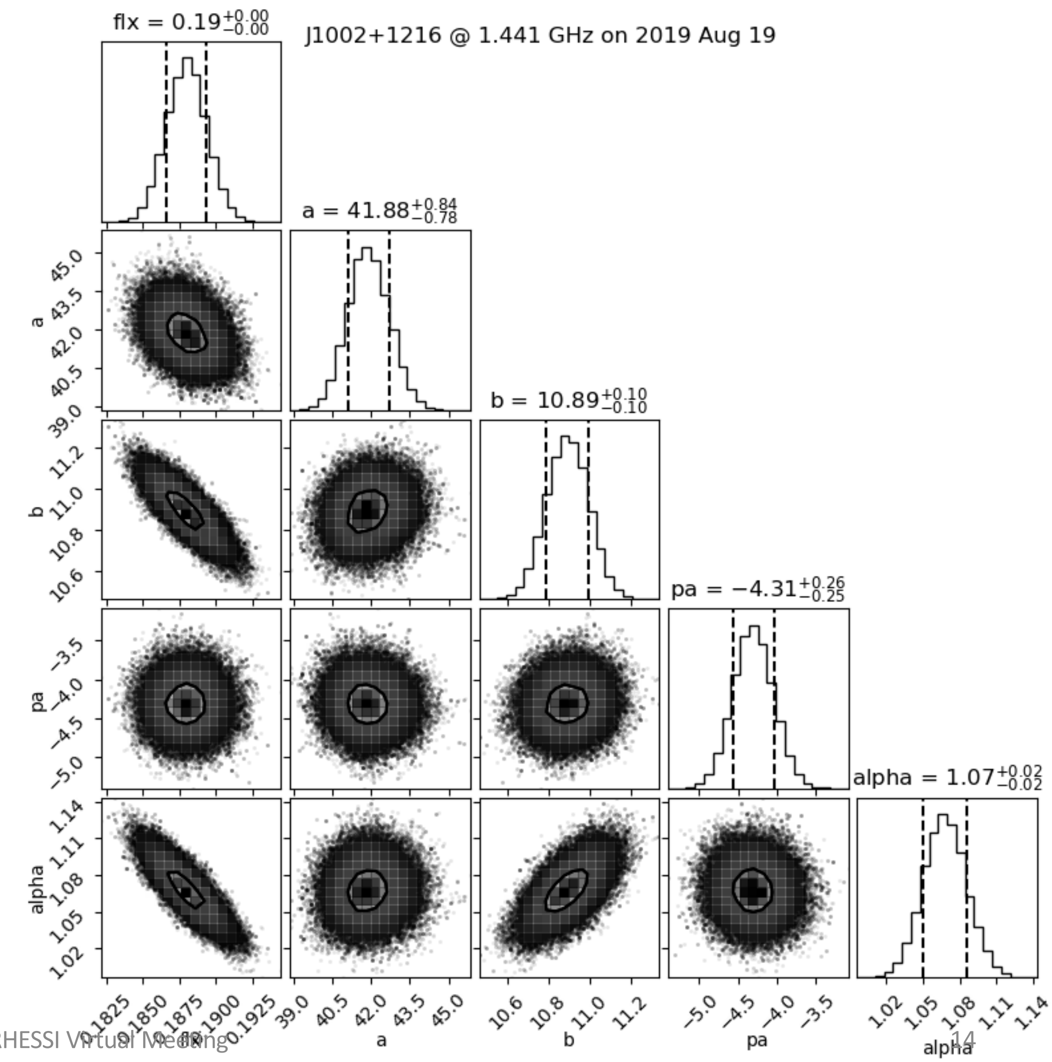
D(s) is constant on an ellipse with major and minor axes a and b.

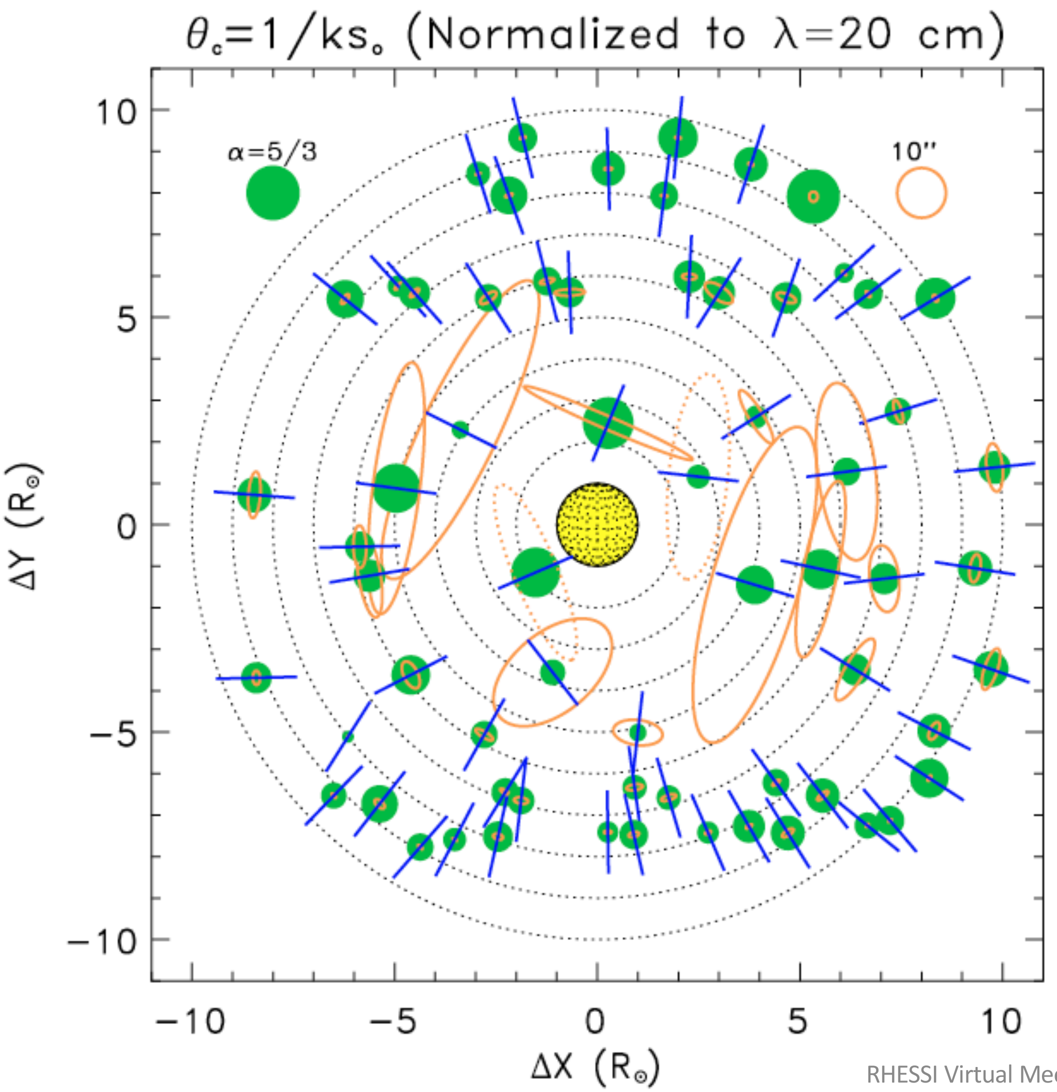


Analysis

Fits performed using a Markov Chain Monte Carlo procedure (emcee package – Foreman-Mackey et al 2012)

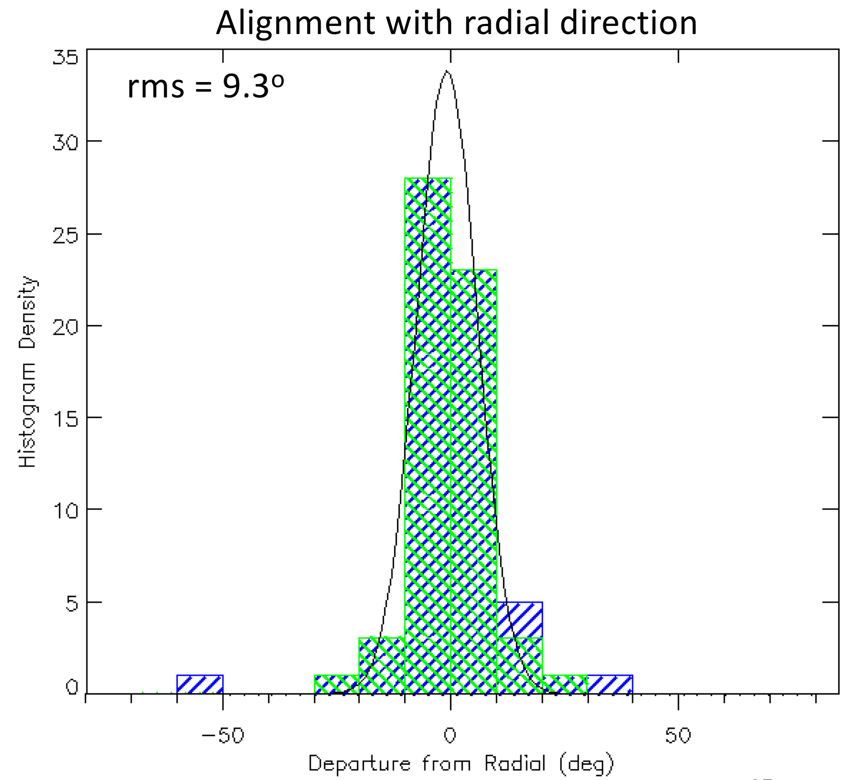
The data were first "self-calibrated" to center the source; i.e., correct for the refractive offset. This eliminated two fitting parameters Δx and Δy, leaving the total source flux V(0), the coherence scales a & b, the position angle of the source, and the spectral index α to be determined along with their uncertainties.

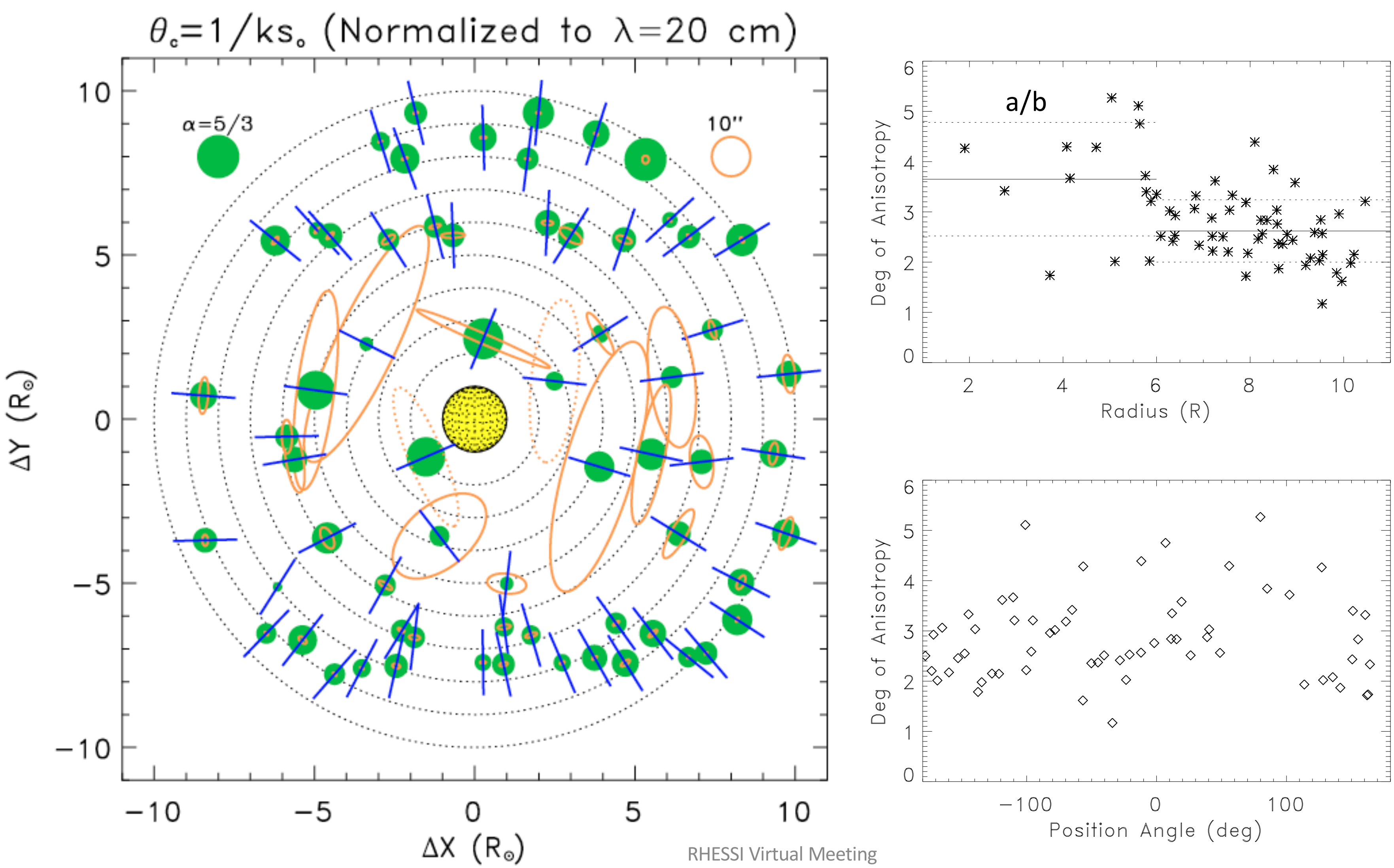




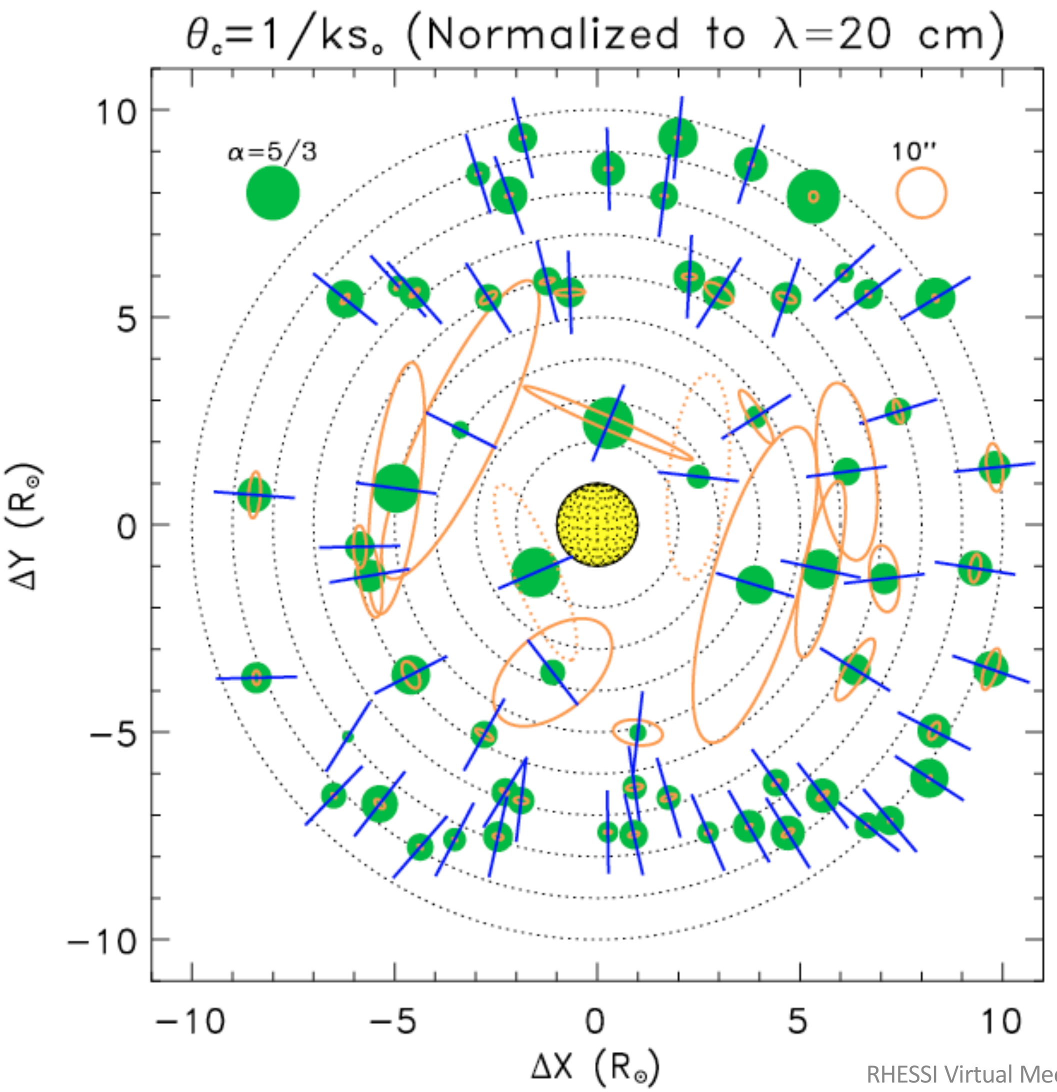
Results

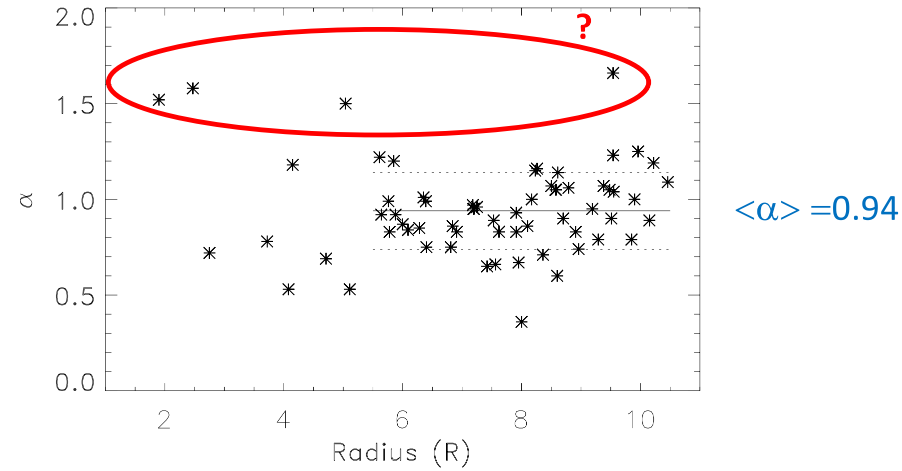
Anisotropy determined by magnetic field – source anisotropy provides POS direction of B!

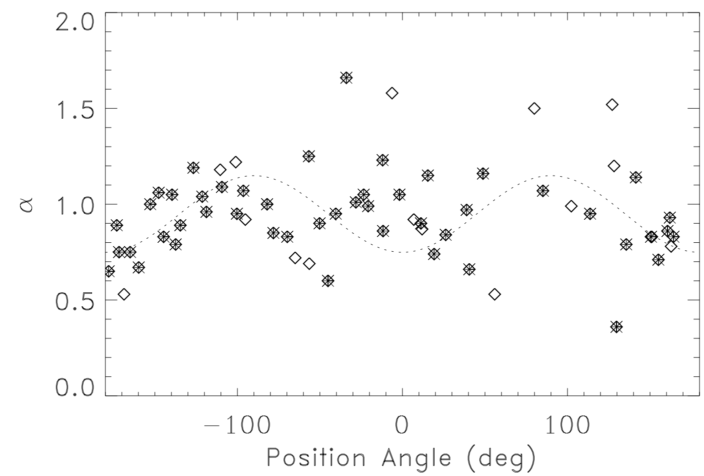




PA is measured E from N.


θ_c=1/ks$_o$ (Normalized to λ=20 cm)
α=5/3
10″
ΔY (R$_\odot$)
ΔX (R$_\odot$)


?
α
Radius (R)
<α> =0.94


α
Position Angle (deg)

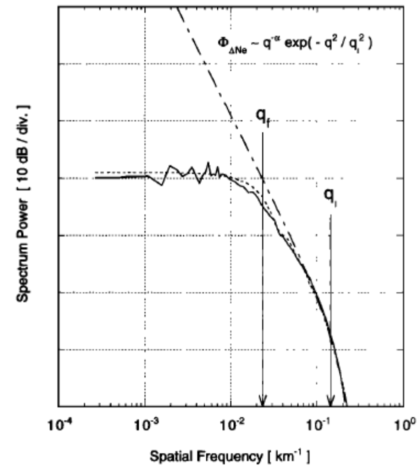
Summary

These results are largely consistent with previous observations of small numbers of sources:

- All sources (except one) show a significant degree of anisotropy
  - the anisotropy is such that the scattering inhomogeneities are close to radial in orientation
  - The degree of anisotropy – the ratio of the coherence scales - appears to be larger and more variable for $r < 5\text{-}6\ R_{\odot}$
  - there does not appear to be a clear dependence of anisotropy on position angle
- The spectral index α is significantly flatter than 5/3 in most cases (0.94)
  - Values of α are more variable for $r < 5\text{-}6\ R_{\odot}$ (but are more sparsely sampled)
  - Possible modulation of α with position angle ?
- Evaluation of spectra displaying breaks is underway
- Ditto for analysis of refractive scintillations (not to be confused with IPS)

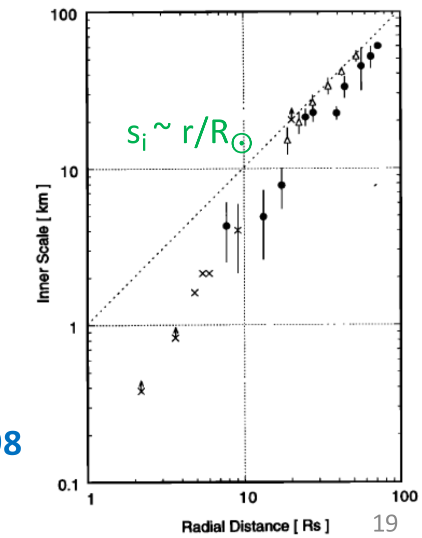
Inner/dissipation scale

- Previous work based on angular broadening measurements (e.g., Anantharamaiah et al 1994) did not find evidence for a dissipation scale in the structure function between 2-16 $R_\odot$
- On the other hand IPS observations report a roll-off in the spectrum that is interpreted as the presence of an inner scale at a frequency scale consistent with the proton cyclotron frequency



1994

Fundamental inconsistency?



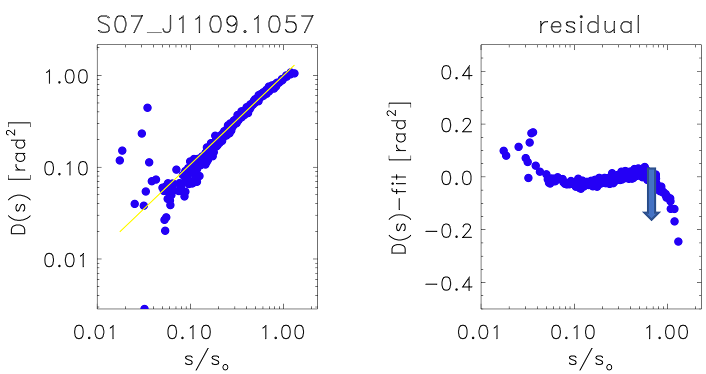
For PSP3, 8 LOS show clear signs of spectral breaks. Several other LOS show spectral that are Kolmogorov-like; i.e, with indices ~5/3 (or 3/2?).

Yamauchi et al 1998

Dissipation scale

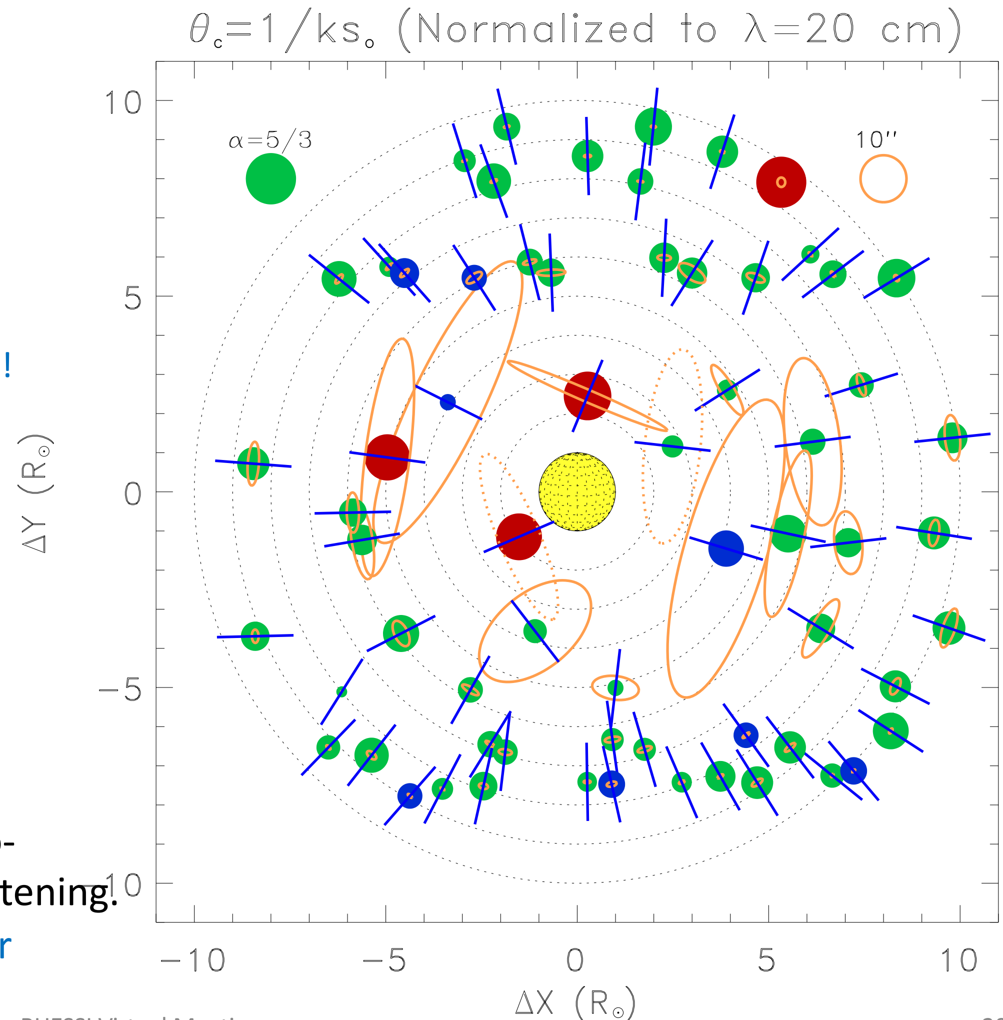
At least 8 LOS show spectral breaks? Do they correspond to a dissipation scale?

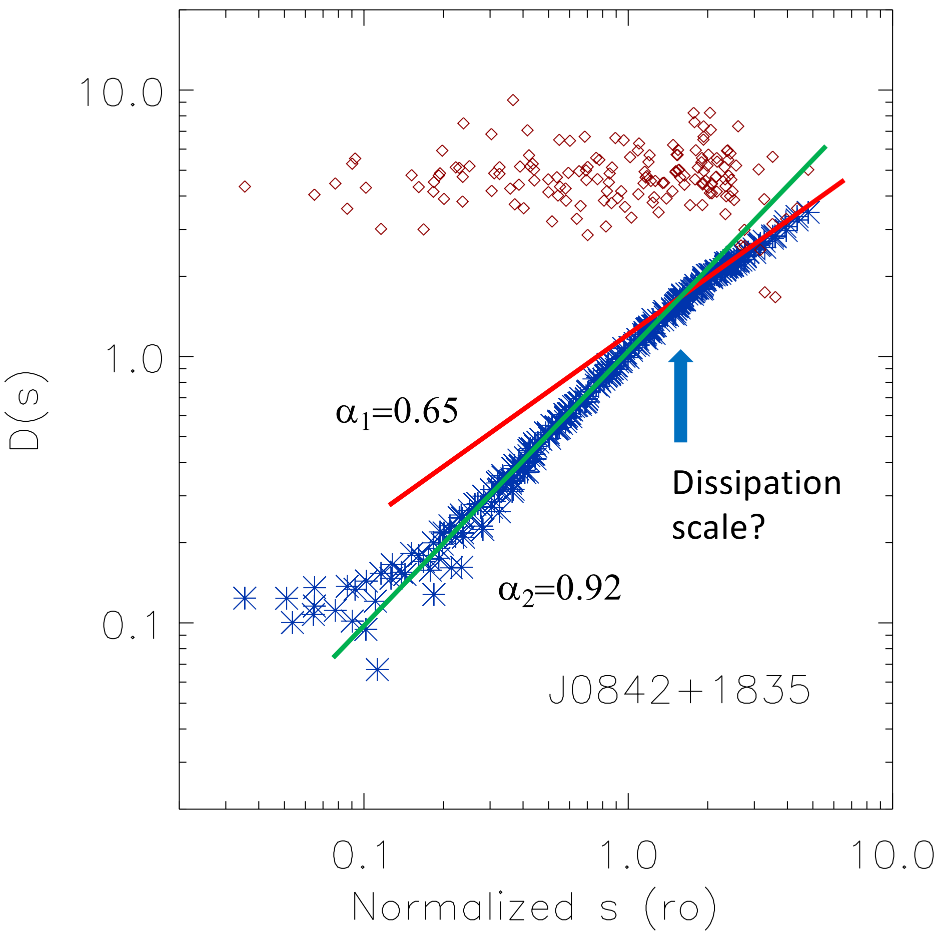
The breaks are clear, but the index below the break is by no means as steep as a = 2!

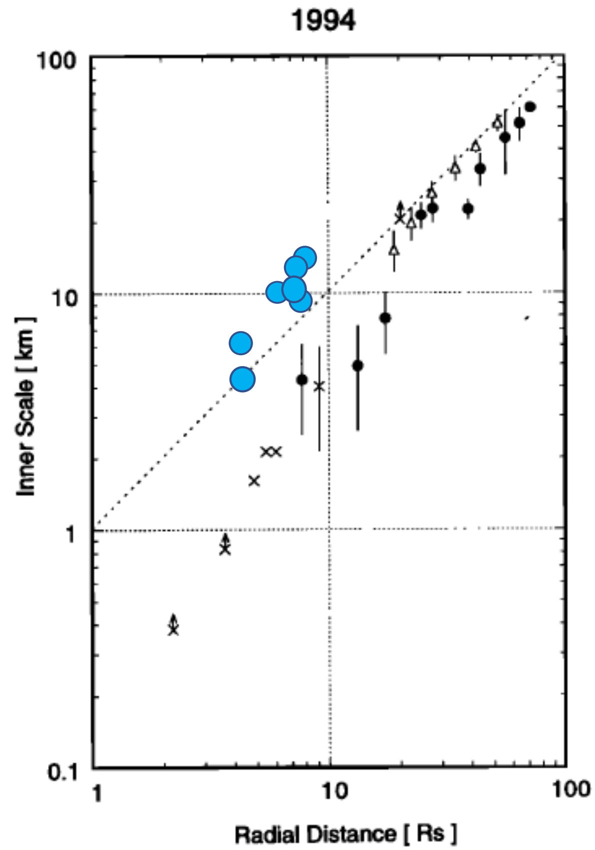


In addition, several LOS show steep Kolmogorov-like spectral – i.e., no significant flattening.

Spectrum dominated by passive scalar component? Below inner scale?







Yamauchi et al 1998
See Harmon & Coles 2005

Concluding Comments

- The Parker P3 results validate past earlier results using the VLA
- Unlike the VLA, the JVLA allows broadband observations of background sources to be made with much greater sensitivity - to 10s of mJy - than previously possible (~1 Jy)
- This enables many more sources to be observed over relatively short times to probe the foreground corona and inner heliosphere
- In contrast to previous work, ~15% sources show signs of spectral features that **may** be consistent with an inner scale.
  - If so, puzzling that so few breaks are seen, because JVLA baseline coverage is well-suited for detecting spectral breaks for elongations ~2-15 solar radii
  - Also striking that several LOS show no significant excess power

Concluding Comments

- Joint angular broadening and IPS observations of selected sources are needed.
- Also of great interest:
  - Angular broadening observations to greater elongations using lower frequency observations
  - Faraday rotation measurements using MSPs
  - Angular broadening and FR measurements of transients (CMEs)
  - Very long baseline (VLBA) observations are needed to probe larger spatial scales to determine inflection scale to flatter-than-Kolmogorov spectrum and its evolution