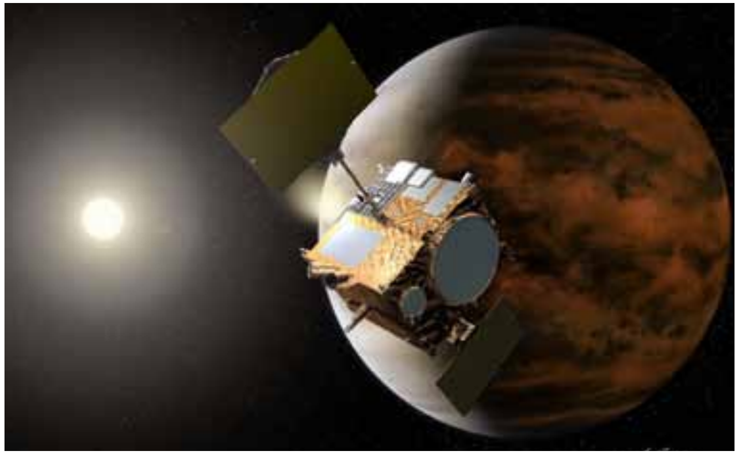


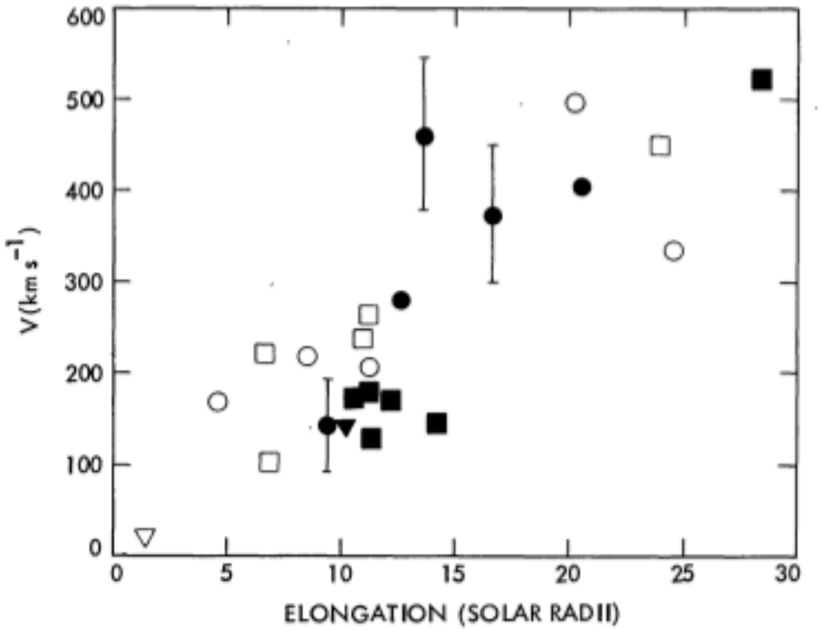
Outflow speed structure of the low corona revealed by spacecraft radio scintillation observations in strong scattering

Takeshi Imamura[1], Munetoshi Tokumaru[2], Hiroki Ando[1], Hiroaki Isobe[3], Ayumi Asai[3], Daikou Shiota[5], Kentaro Yaji[6], Mayu Miyamoto[4], Tomoaki Toda[1], Alexander Nabatov[7]

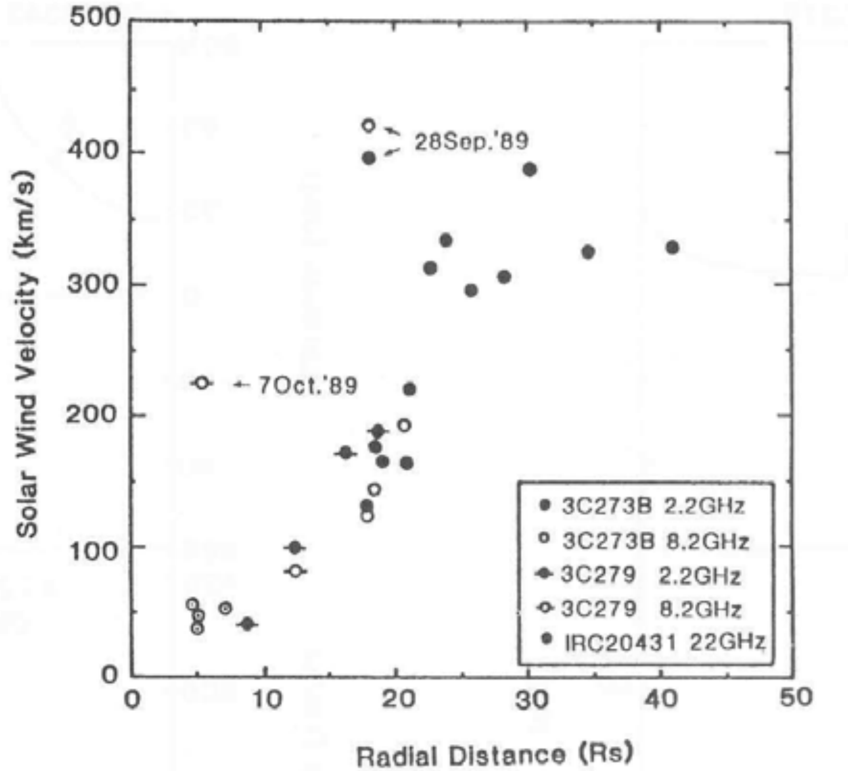
1. Aerospace Exploration Agency, Japan. 2. Solar-Terrestrial Environment Laboratory, Nagoya University. *3. Kyoto University, Japan.* *4. The University of Tokyo, Japan, 5. RIKEN, Japan. 6. Rikkyo University, Japan. 7. Ukrainian Academy of Science, Ukraine.*

Flow speed measurements by radio scintillation method

Summary of previous results
(Armstrong & Woo, 1981)



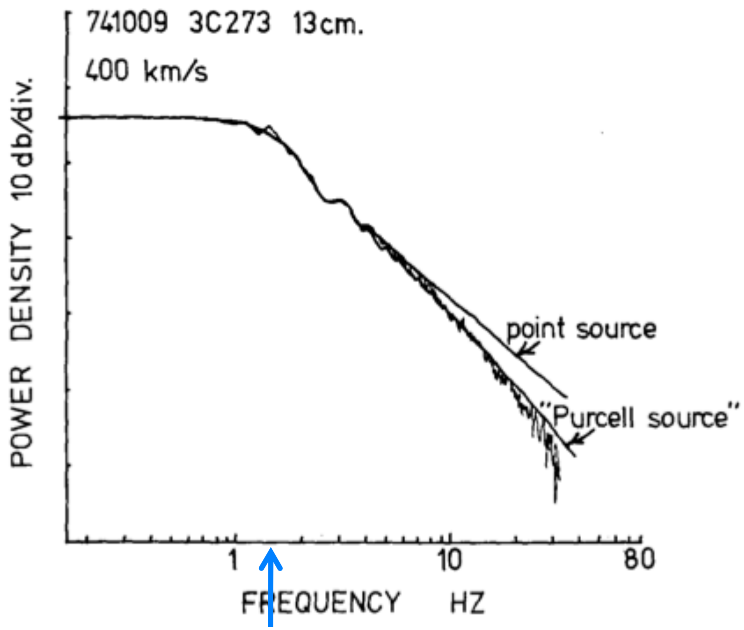
IPS measurements
(Tokumaru et al., 1991)



Measurements are scarce in the low corona (below ~5 Rs) where strong scattering prevents reliable measurements.

Scintillation spectrum

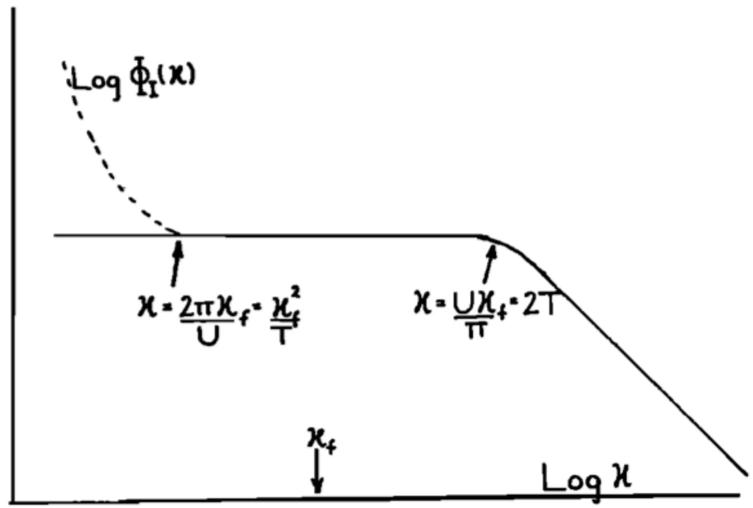
Weak scattering



Fresnel Frequency

Coles (1977)

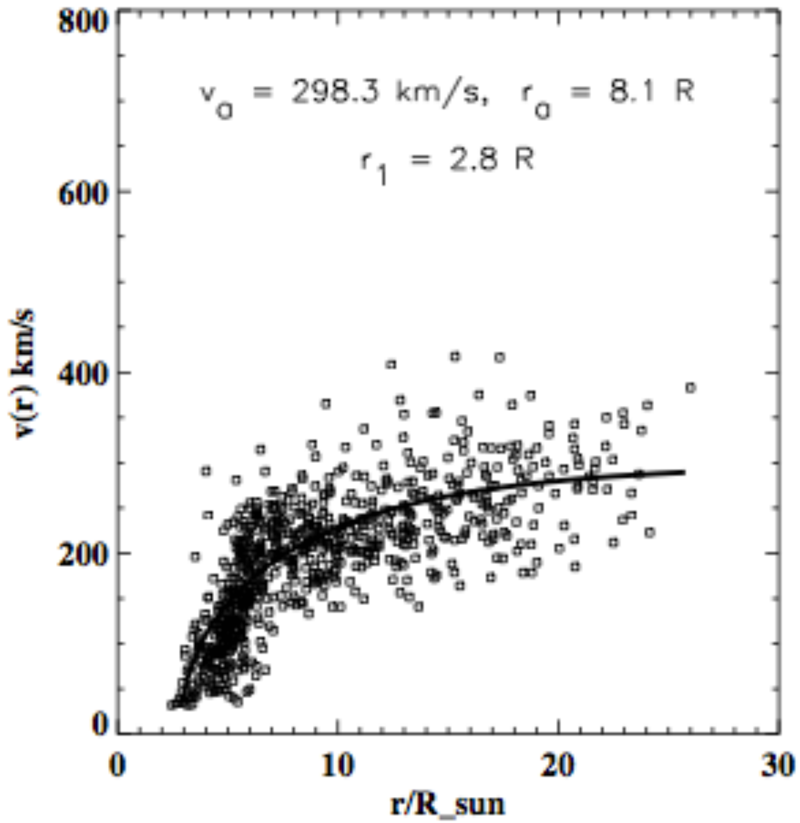
Strong scattering



Fresnel Frequency

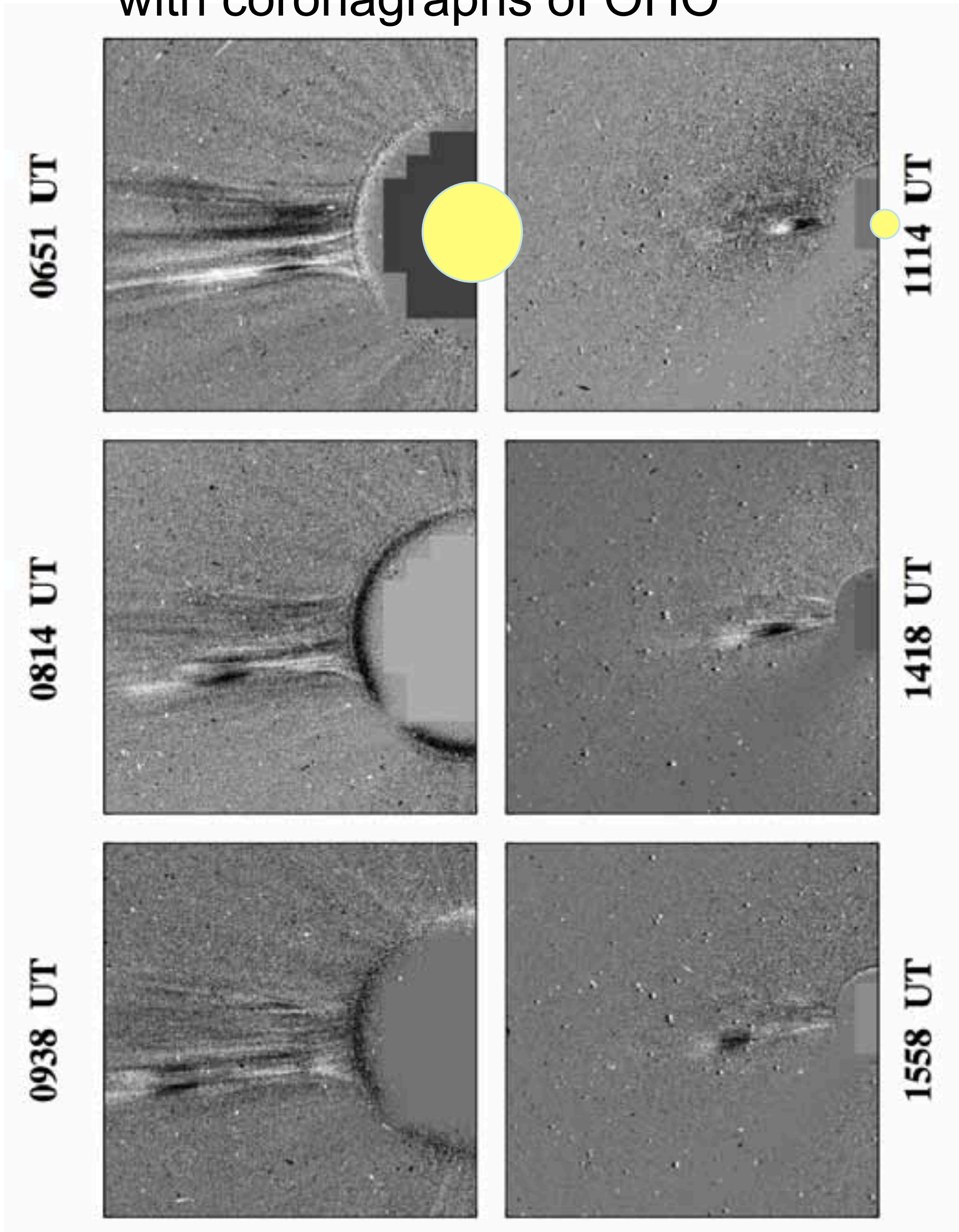
Rumsey (1975)

Flow measurements by tracking moving coronal features

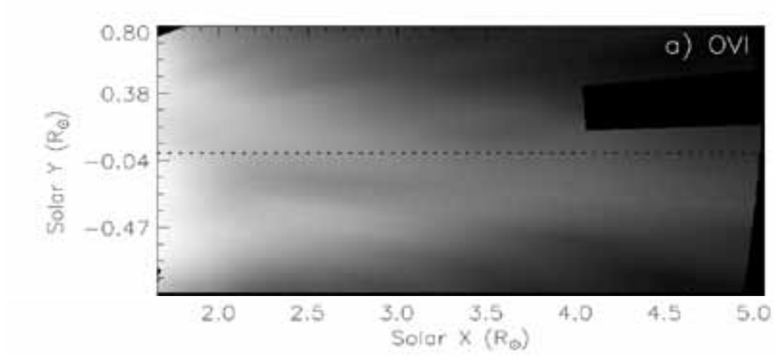


Measurements in streamer belts (Sheeley et al., 1997)

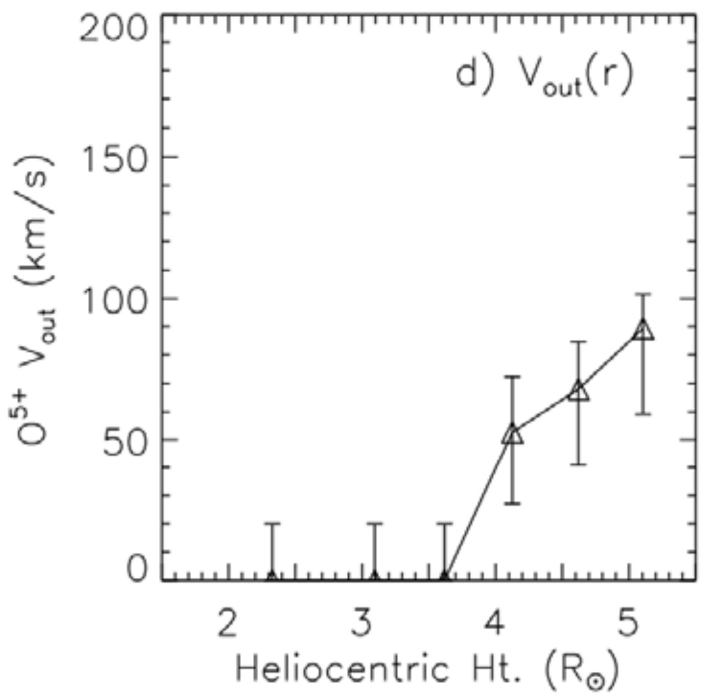
Running difference images obtained with coronagraphs of OHO



O^{5+} velocity retrieval from Doppler dimming effect

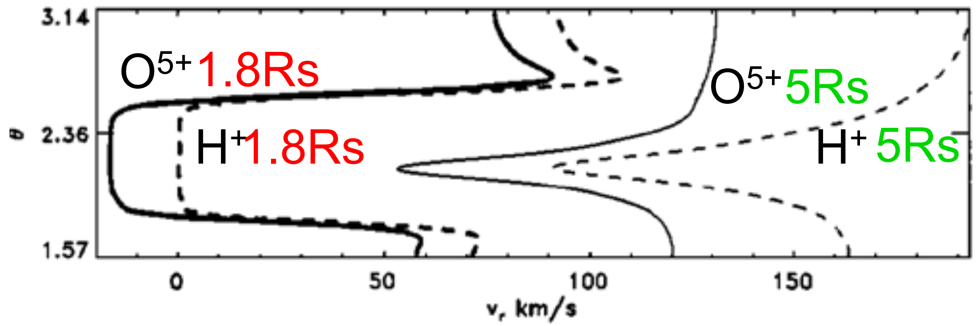


Velocities in the equatorial streamer belt (Strachan et al., 2002)

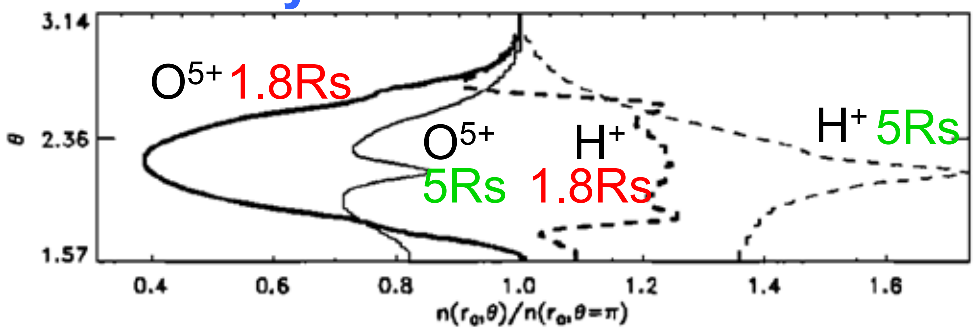


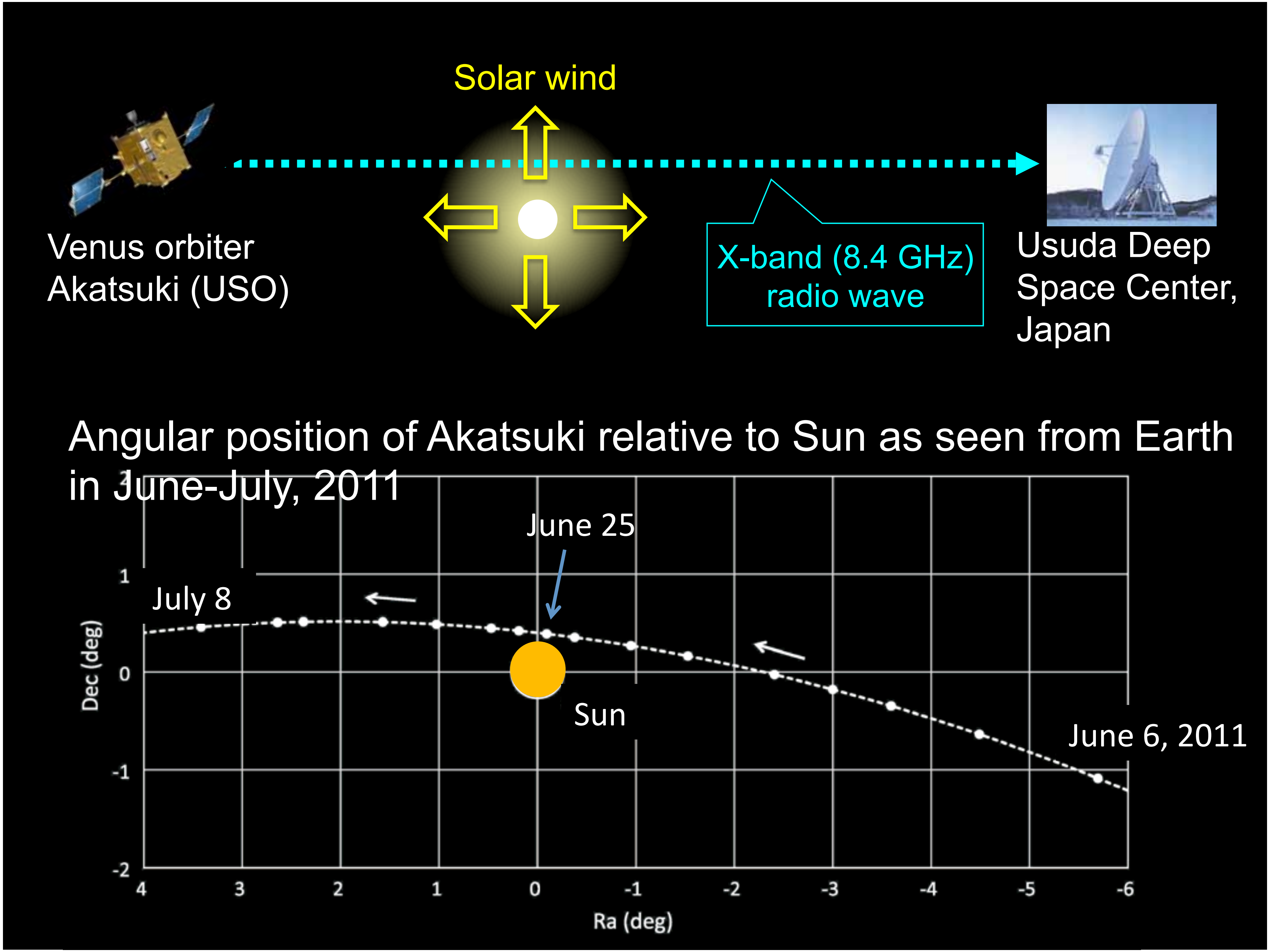
Three-fluid MHD model of a streamer (Ofman, 2000)

Velocity



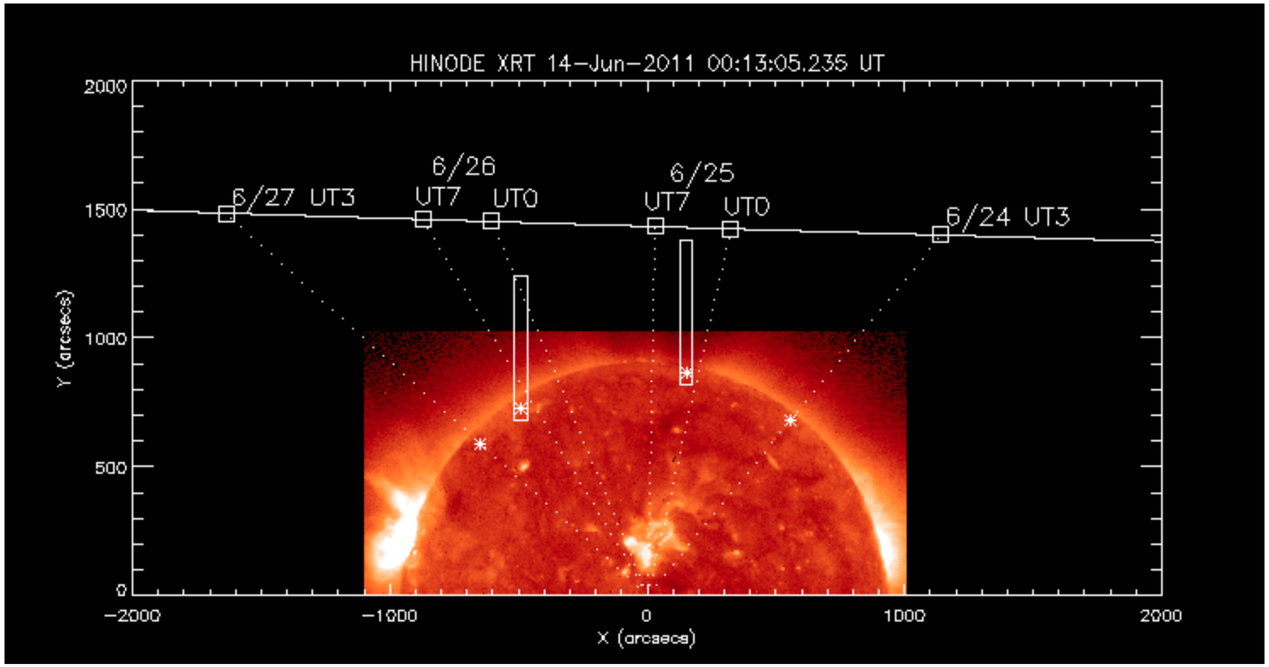
Density



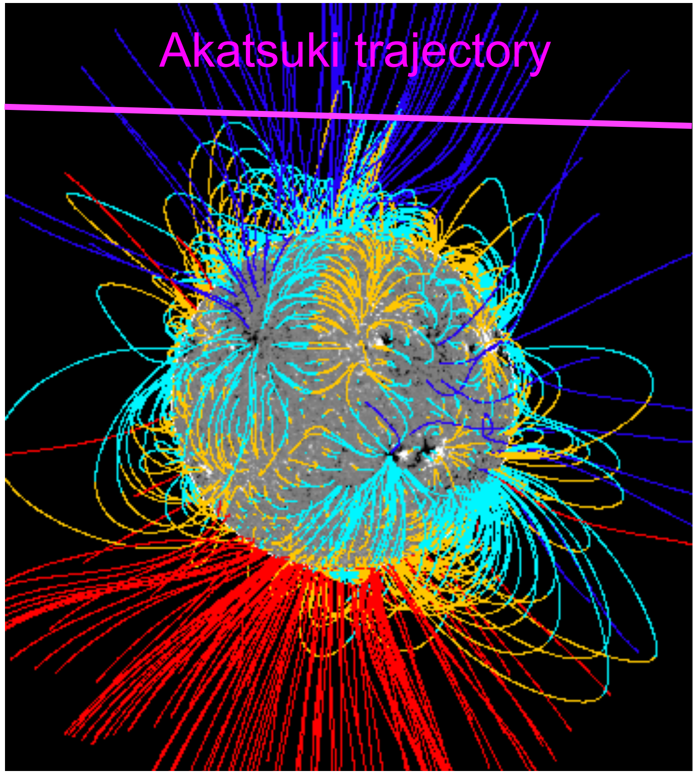

Solar wind
Venus orbiter
Akatsuki (USO)
X-band (8.4 GHz)
radio wave
Usuda Deep
Space Center,
Japan
Angular position of Akatsuki relative to Sun as seen from Earth in June-July, 2011
June 25
July 8
Sun
June 6, 2011
Dec (deg)
1
0
-1
-2
4
3
2
1
0
-1
-2
-3
-4
-5
-6
Ra (deg)

Observations

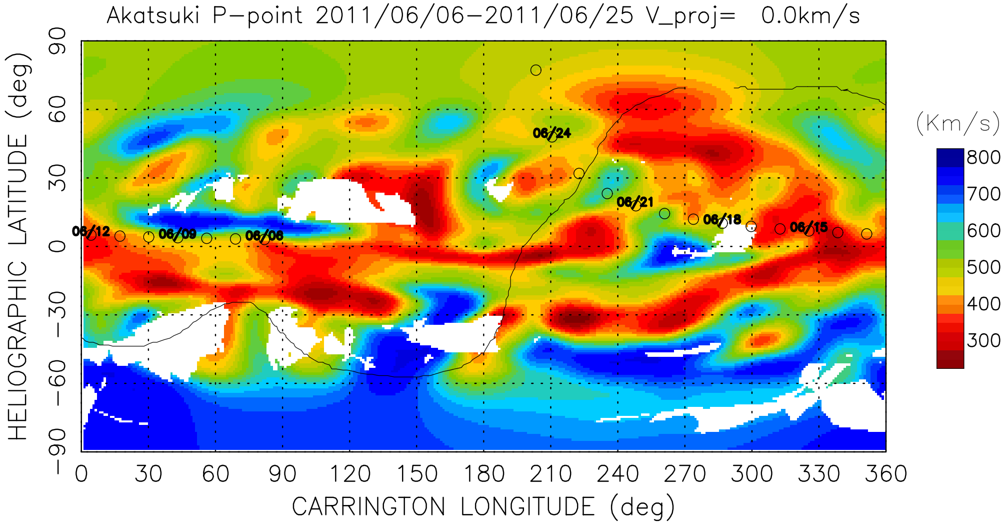
- 17 experiments at heliocentric distances of 1.5-20 Rs
- X-band, open-loop recording (500 kHz sampling)
- Recording length is 6-7 hours in each measurement
- Simultaneous observations with a space solar telescope HINODE were conducted on June 24, 25, 26, 27

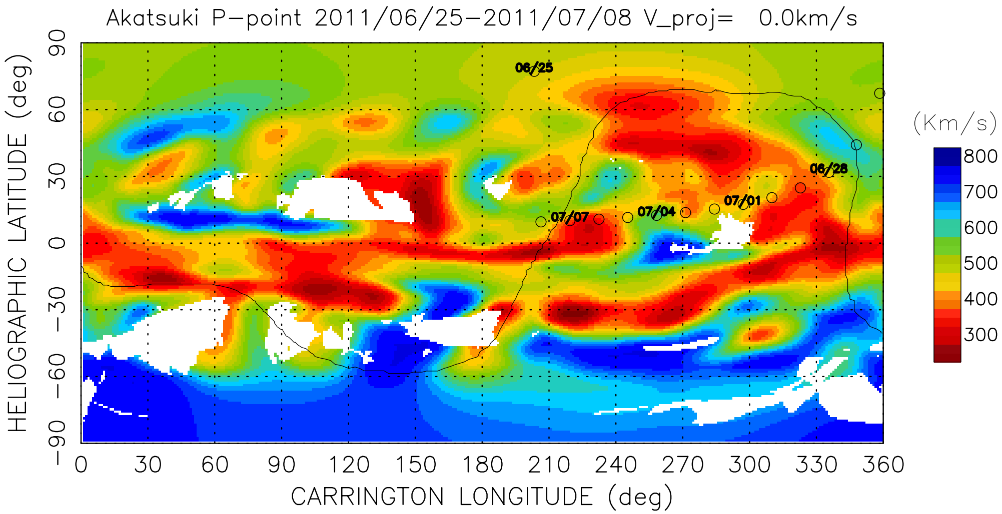


Potential magnetic field seen from the Earth on June 25, 2011 calculated from a synoptic magnetic field map provided by Global Oscillation Network Group



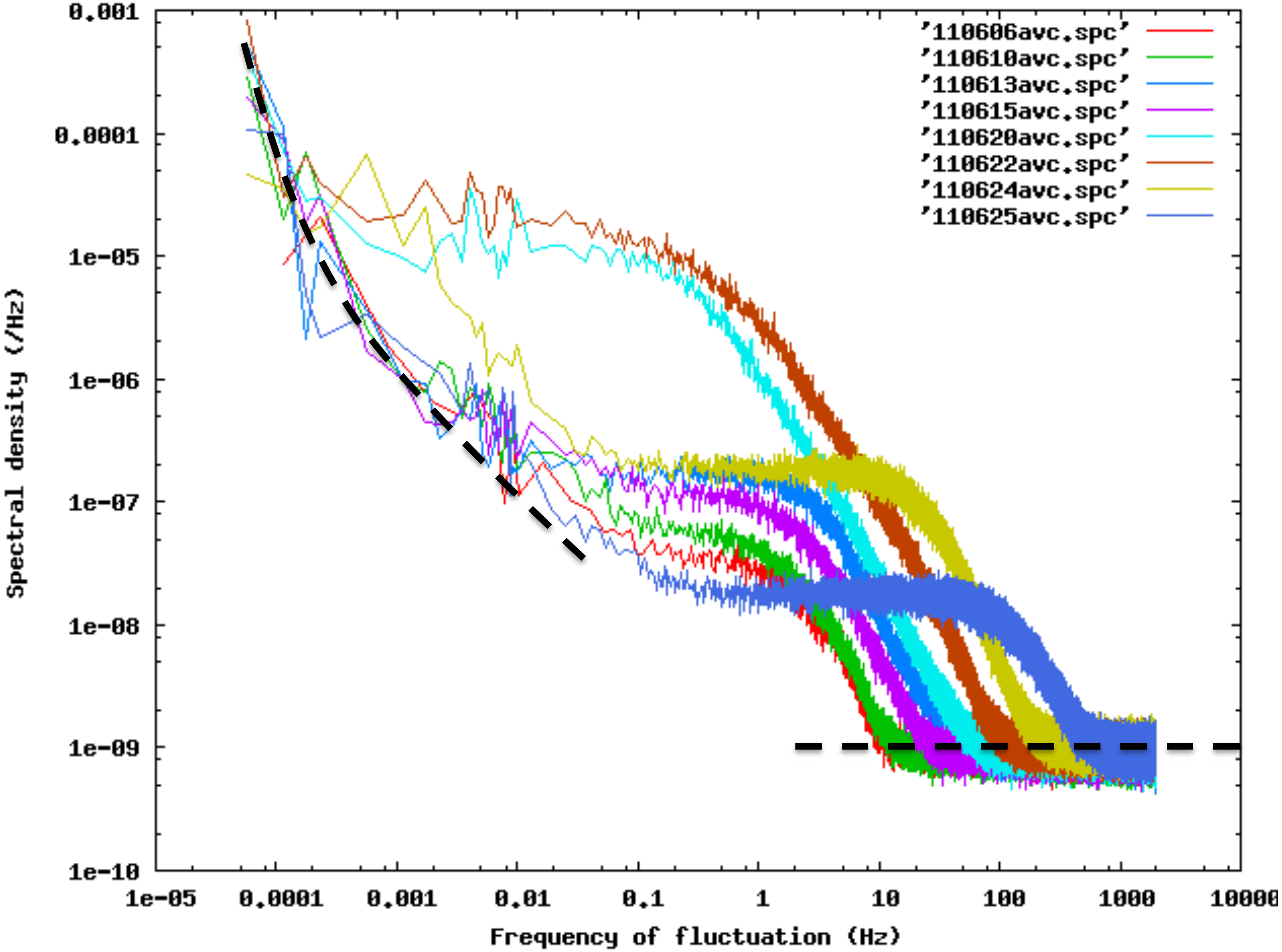
Synoptic velocity map generated with IPS measurements by STEL

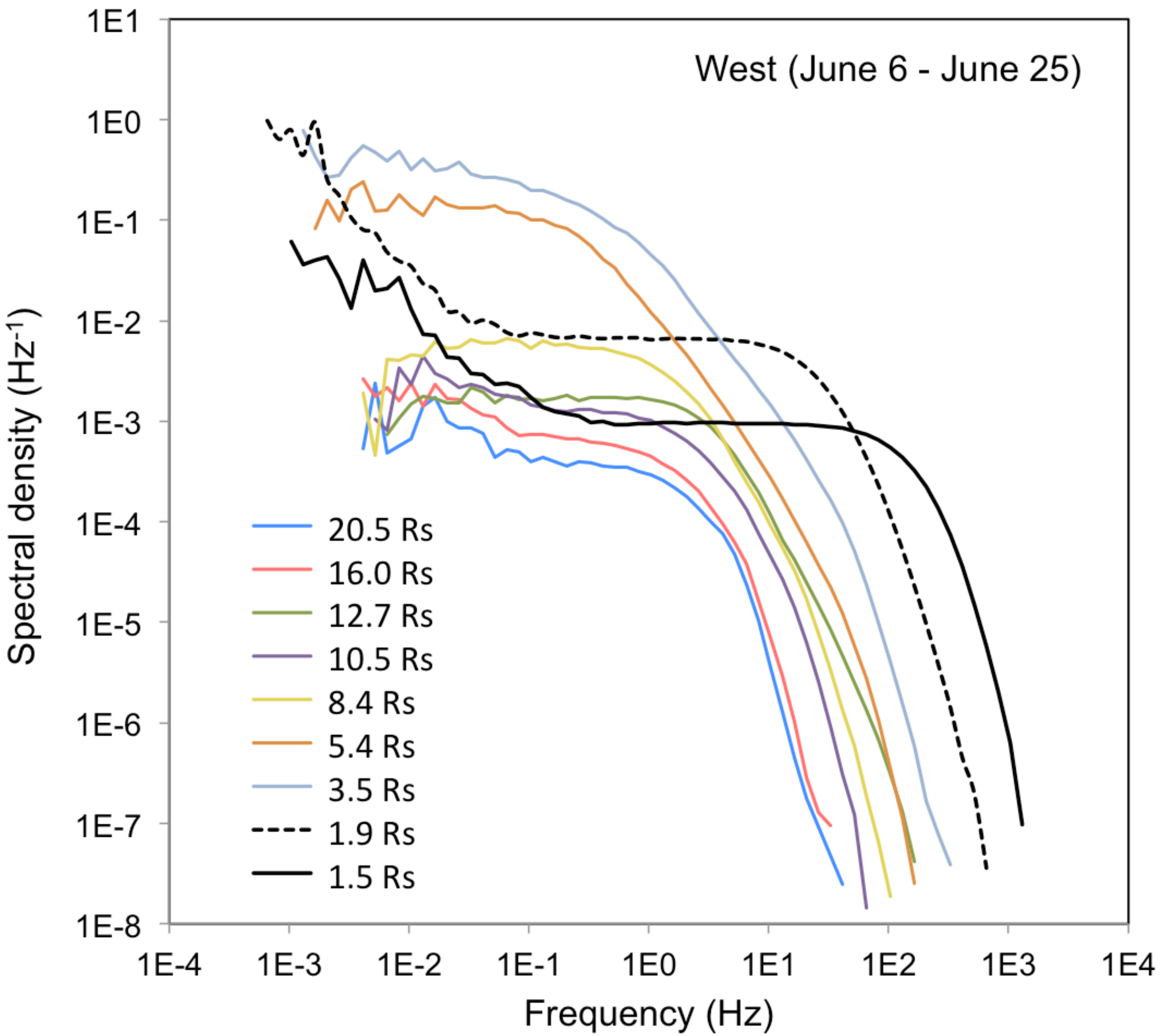


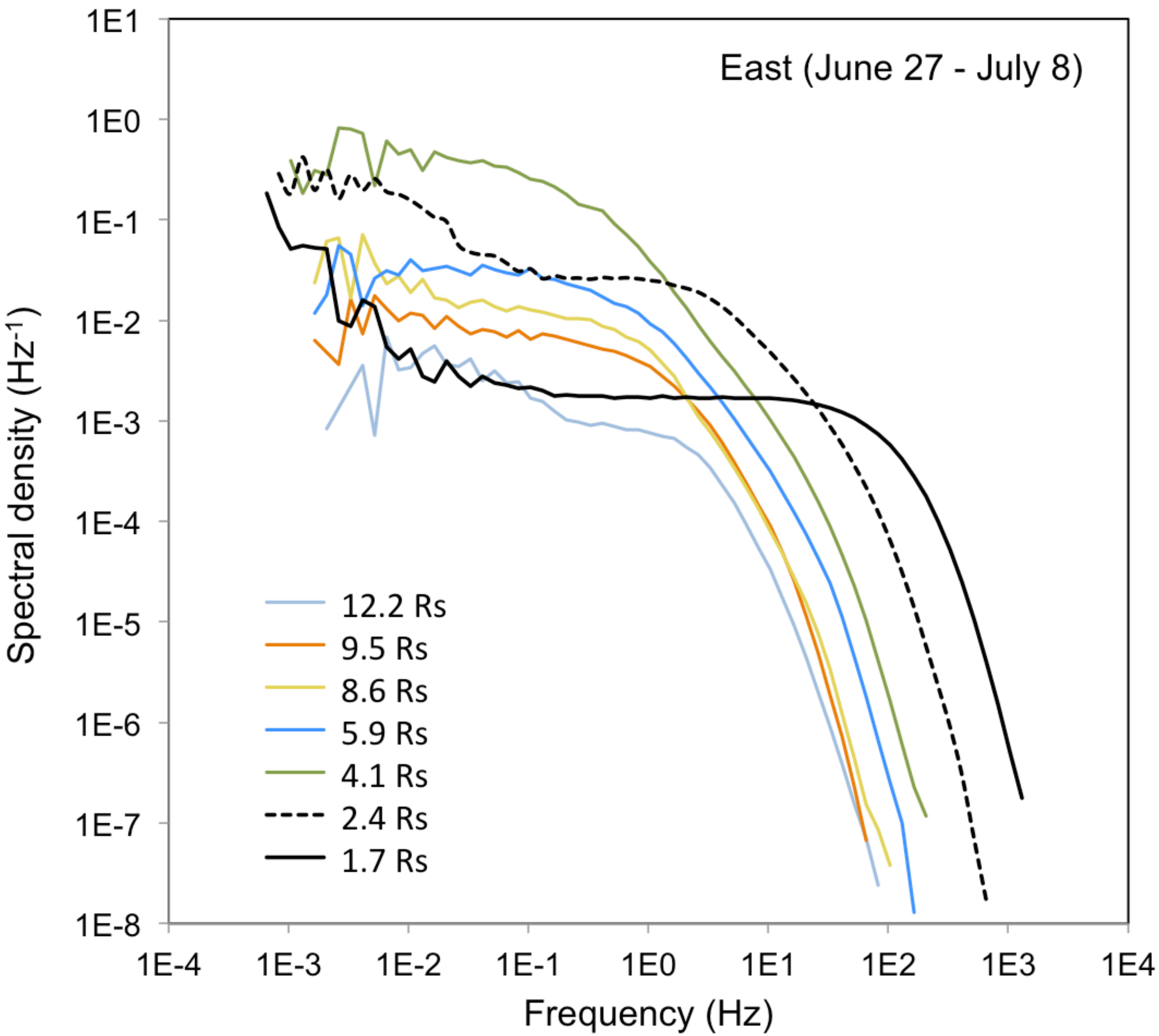


- Mostly quiet-Sun, slow-wind regions were observed.
- Observations near the North pole may be influenced by coronal holes.

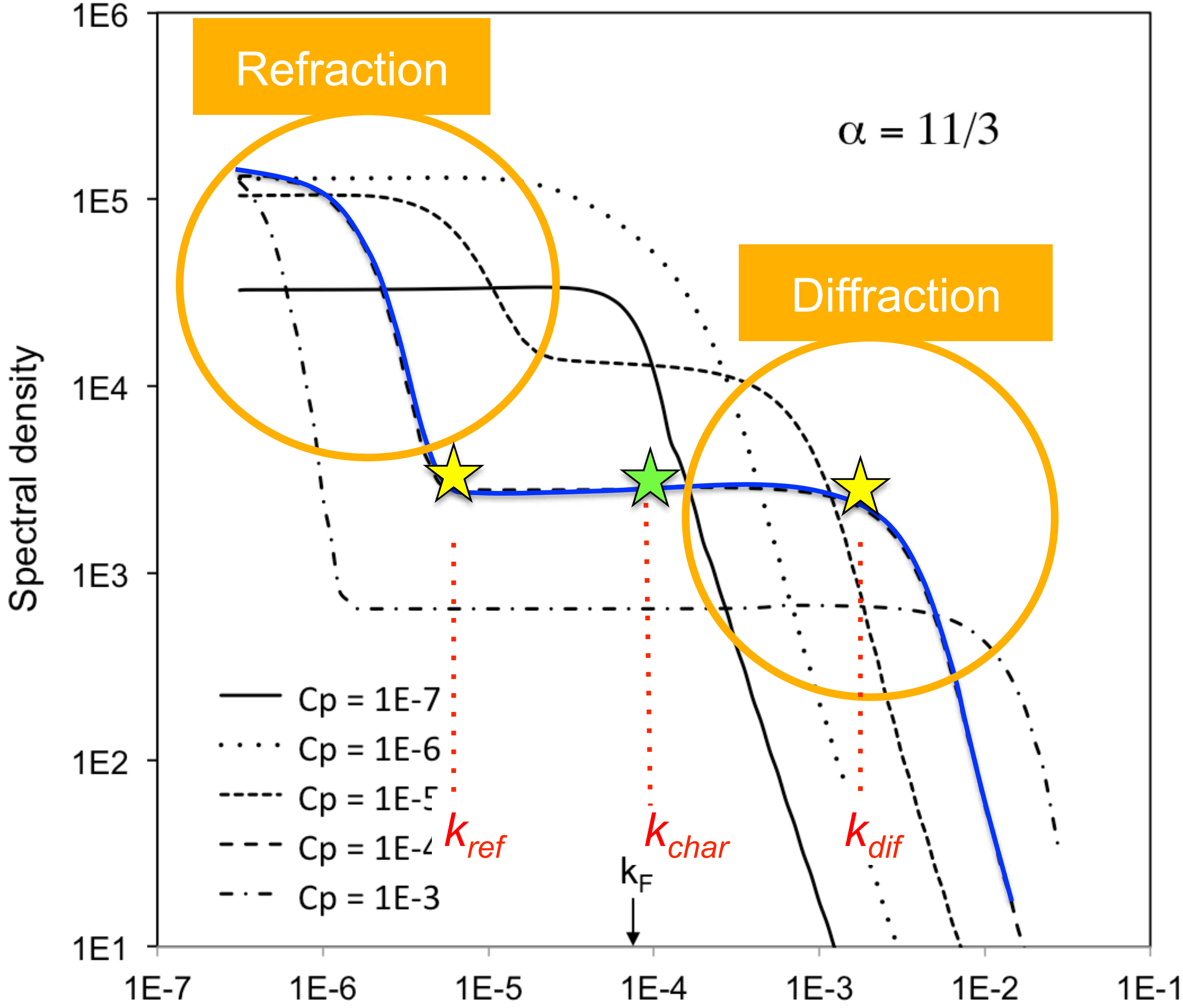
Amplitude spectra before subtracting background noise (West)



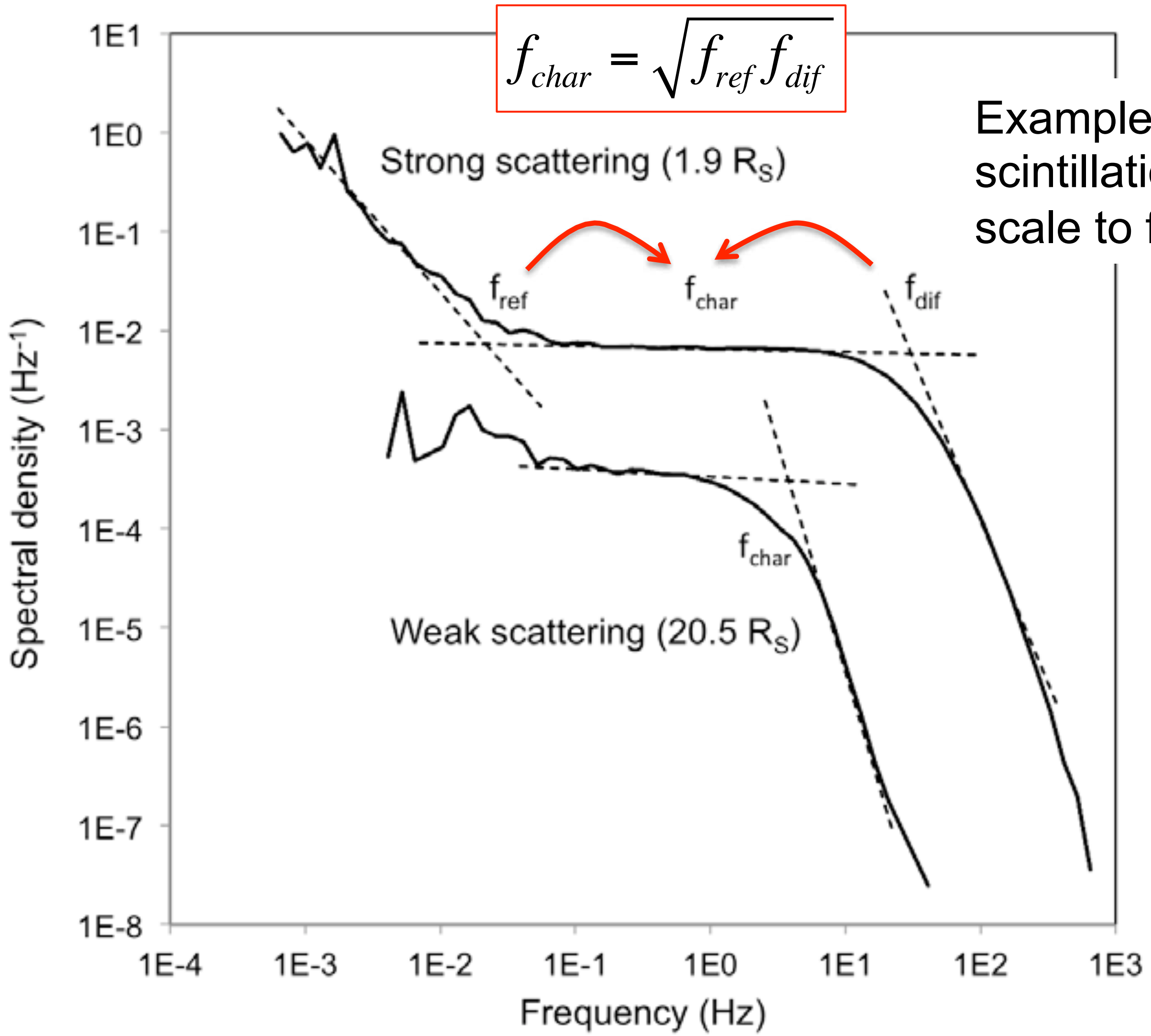

West (June 6 - June 25)
Spectral density (Hz^{-1})
Frequency (Hz)
1E1
1E0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-4
1E-3
1E-2
1E-1
1E0
1E1
1E2
1E3
1E4
20.5 Rs
16.0 Rs
12.7 Rs
10.5 Rs
8.4 Rs
5.4 Rs
3.5 Rs
1.9 Rs
1.5 Rs


East (June 27 - July 8)
Spectral density (Hz^{-1})
Frequency (Hz)
1E1
1E0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-4
1E-3
1E-2
1E-1
1E0
1E1
1E2
1E3
1E4
12.2 Rs
9.5 Rs
8.6 Rs
5.9 Rs
4.1 Rs
2.4 Rs
1.7 Rs

Theoretical spectrum using the formula by Rino (1979)



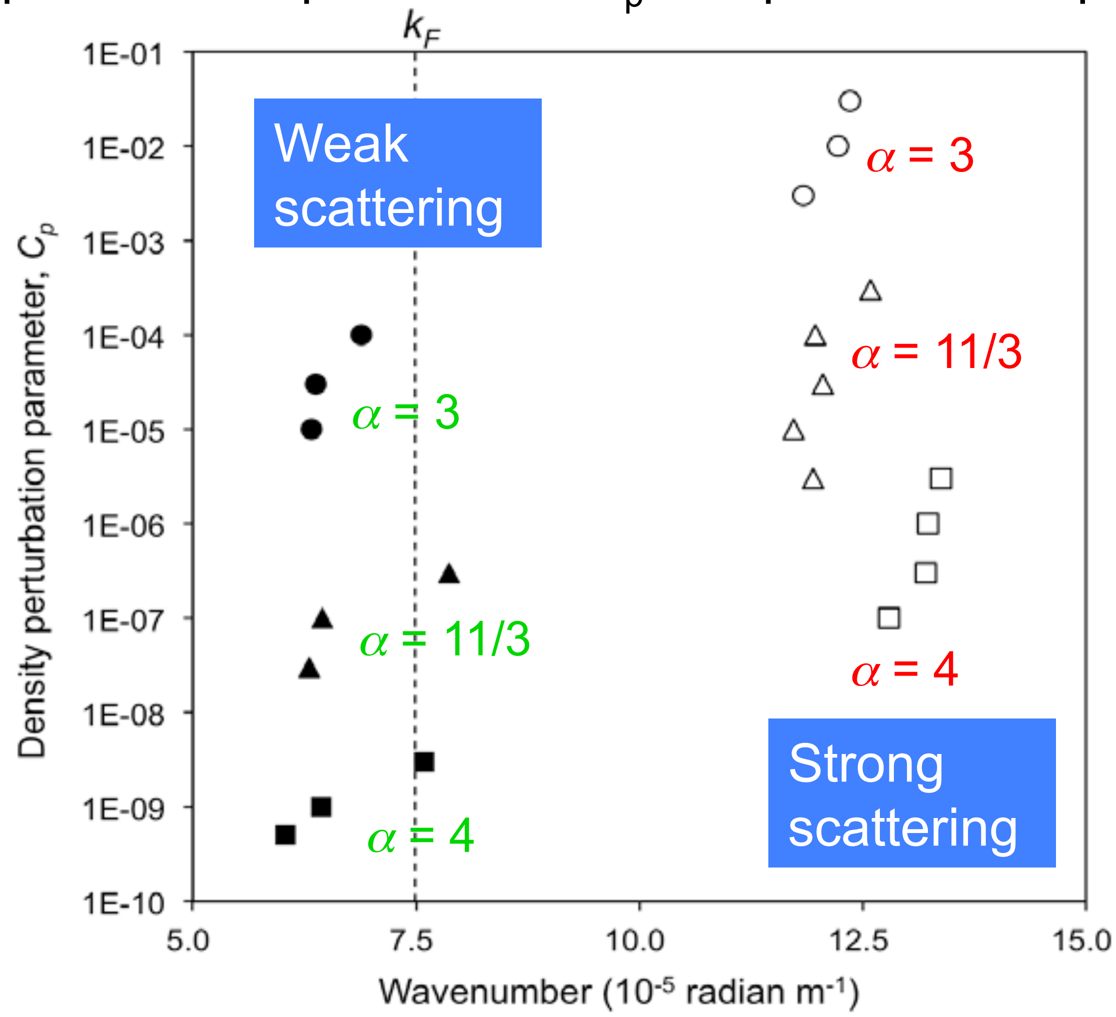
$$k_{char} = \sqrt{k_{ref} k_{dif}}$$



Examples of fitting linear functions to scintillation spectra in logarithmic scale to find characteristic frequencies

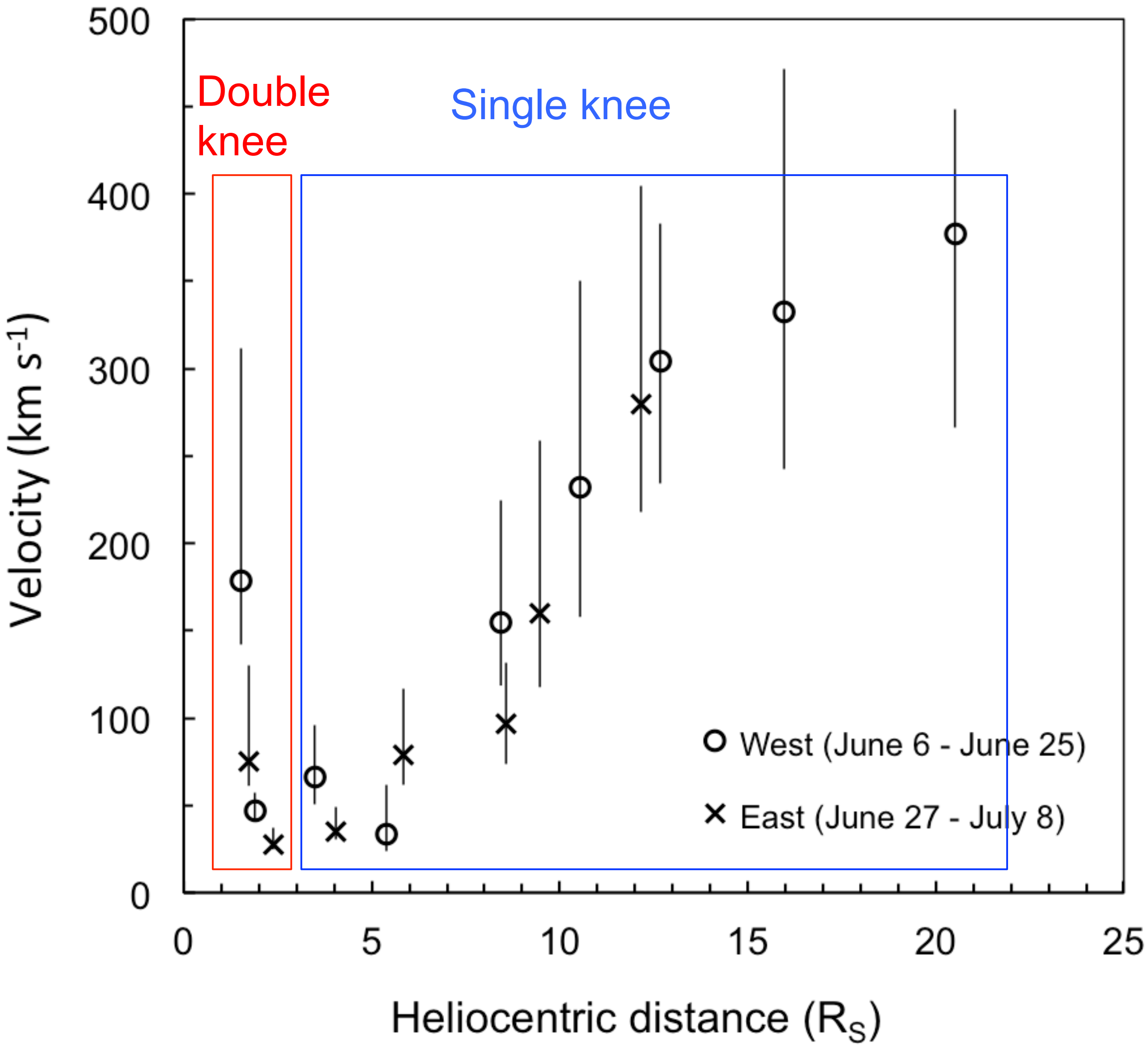
Characteristic wavenumber from scintillation model : k_{char}
Characteristic frequency from observation : f_{char}
→Solar wind velocity $V_{sw} = 2\pi f_{char}/k_{char}$

Characteristic wavenumbers k_{char} for different density perturbation parameters C_p and power-law exponents

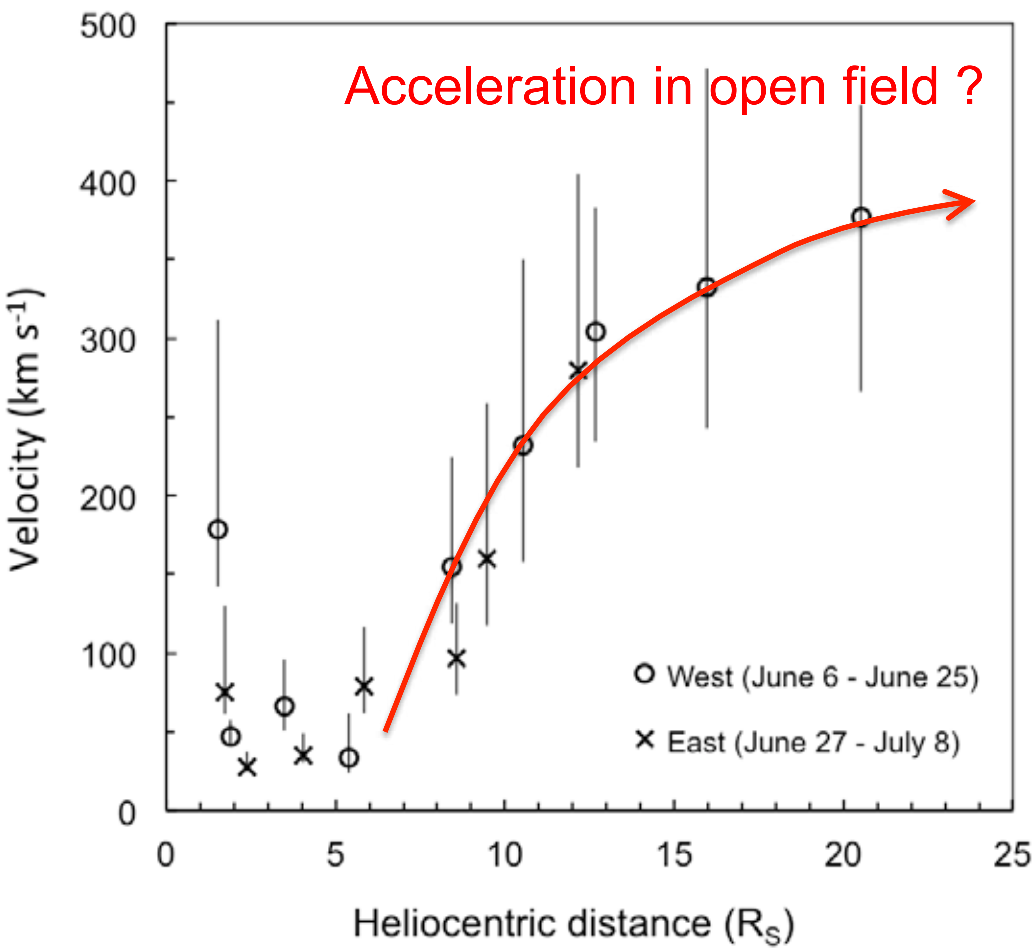


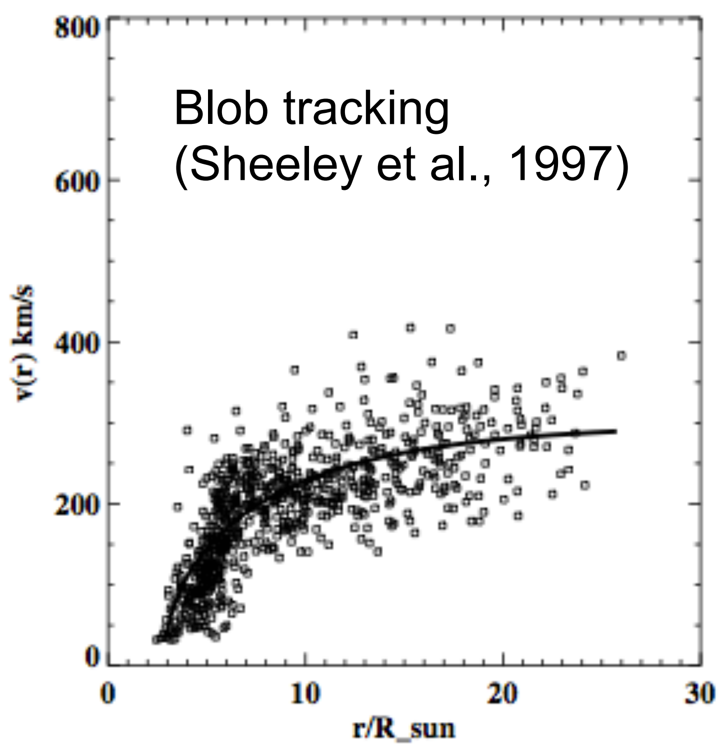
- k_{char} is roughly constant for each of the weak scattering regime and the strong scattering regime.
- The variability of k_{char} is included in the error estimation.

Derived solar wind speeds

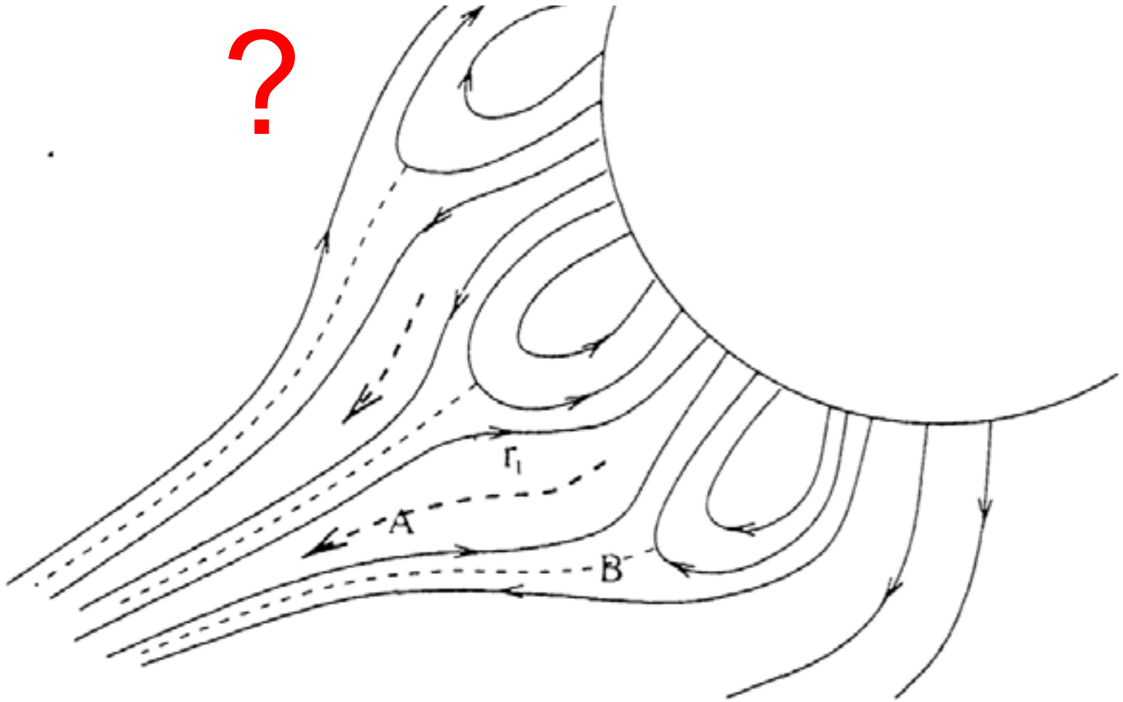


Derived solar wind speeds





Supply of plasma to the solar wind in closed-field regions

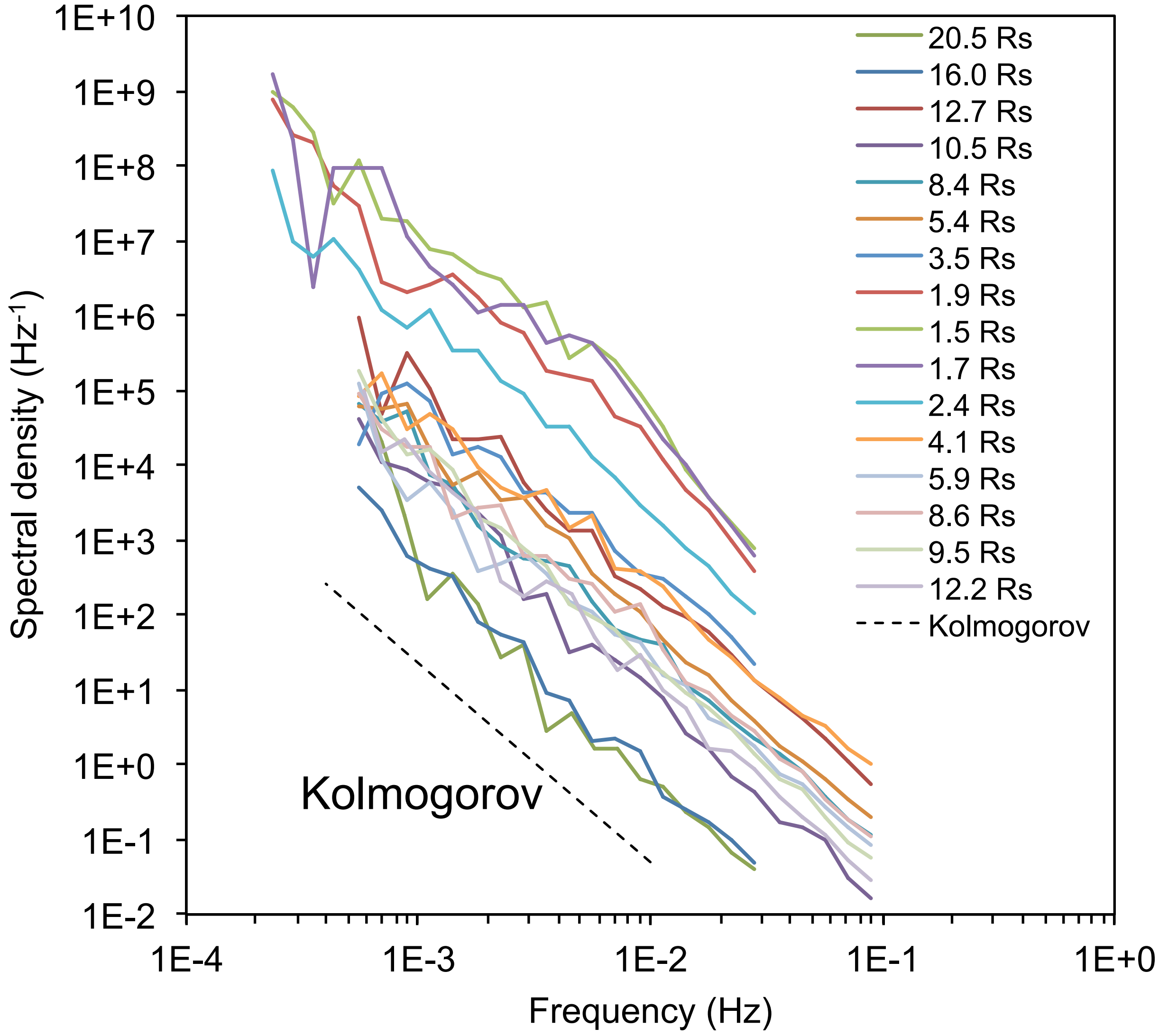


Noci et al. (1997)

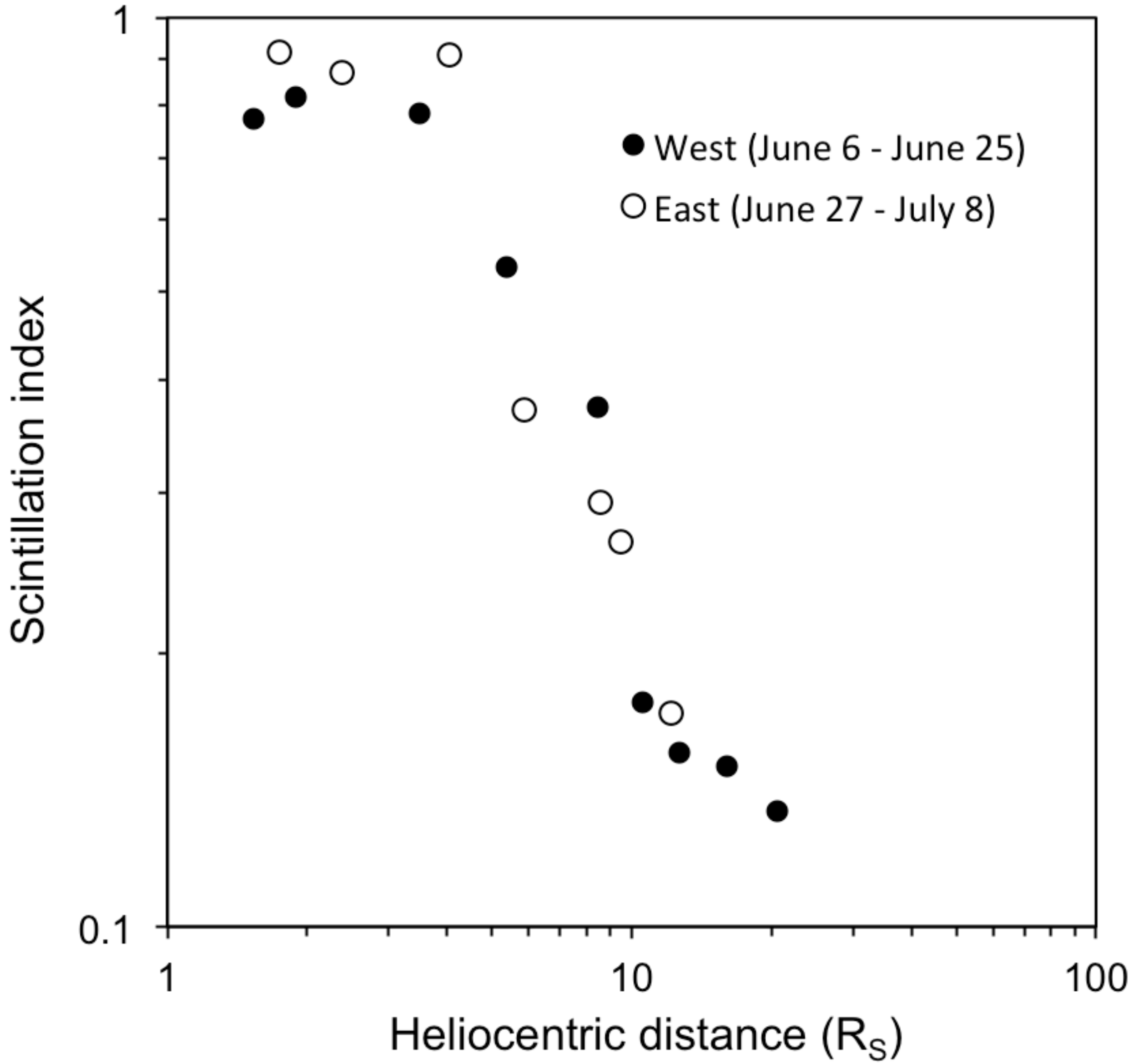
Summary

- Bulk outflow speeds of the low corona were obtained by spacecraft radio scintillation observations including the strong scattering regime.
- The speed profile shows slow motions (< 100 km s^{-1}) at 1.5-6 R_S, rapid acceleration at 7-13 R_S, and weaker acceleration at > 15 R_S to reach ~400 km s^{-1} at 20.5 R_S. Such a speed profile is typical of the low corona in the quiet Sun region: closed fields near the Sun suppress radial acceleration, while rapid acceleration occurs at high altitudes in open field lines.
- Localized fast flows were also observed at 1.5 R_S and 1.7 R_S near the North pole probably due to the influence of open fields originated from coronal holes.
- The ubiquitous outflow of several tens of km s^{-1} in the quiet-Sun low corona region suggests that the supply of plasma to the slow solar wind occurs continuously over an extended area.

Phase scintillation spectra



Scintillation index



Constant acceleration model

Sheeley et al., 1997

$$r = r_0 + v_0 t + \frac{1}{2}at^2$$

$$v^2 = 2a(r - r_1)$$

$$r_1 = r_0 - v_0^2/(2a)$$

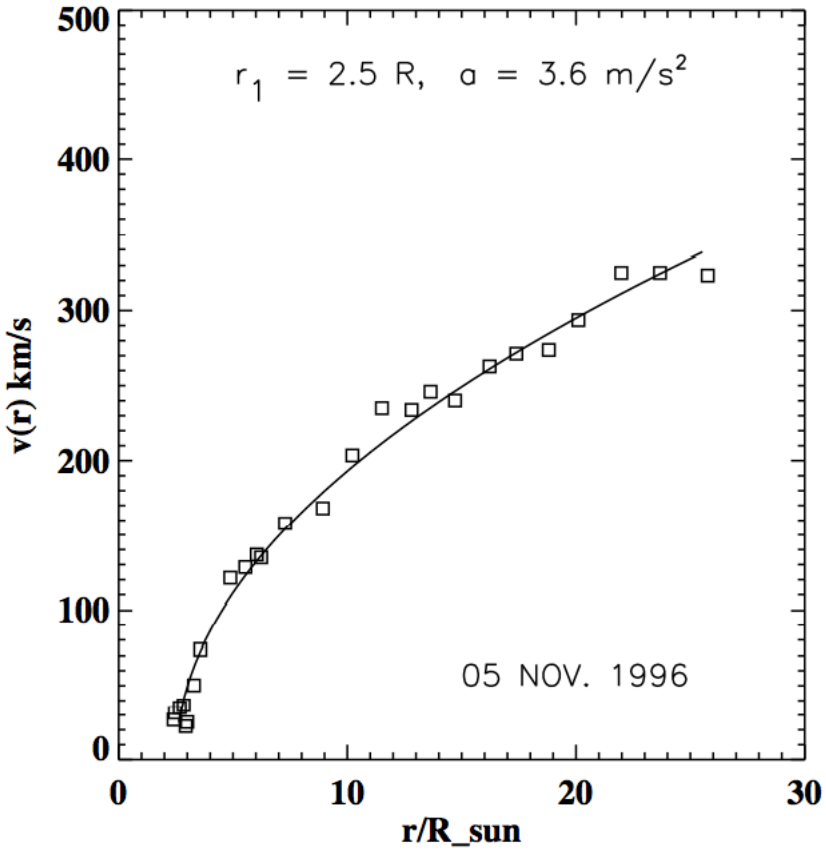


FIG. 8.—Tracking measurements for the central core of the 1996 November 5 CME of Fig. 7, showing some nonradial motion initially and a parabolic speed profile similar to those of Figs. 3–6.

Parker's solar wind model

$$\rho v \frac{\partial v}{\partial r} = -\frac{\partial p}{\partial r} - \frac{GM\rho}{r^2}$$

Momentum eq.

$$\rho v r^2 = \text{const}$$

Mass conservation

$$p = 2nkT \qquad n = \rho/m_p$$

Eq. of state

$$v_s^2 = \partial p/\partial \rho = 2kT/m_p$$

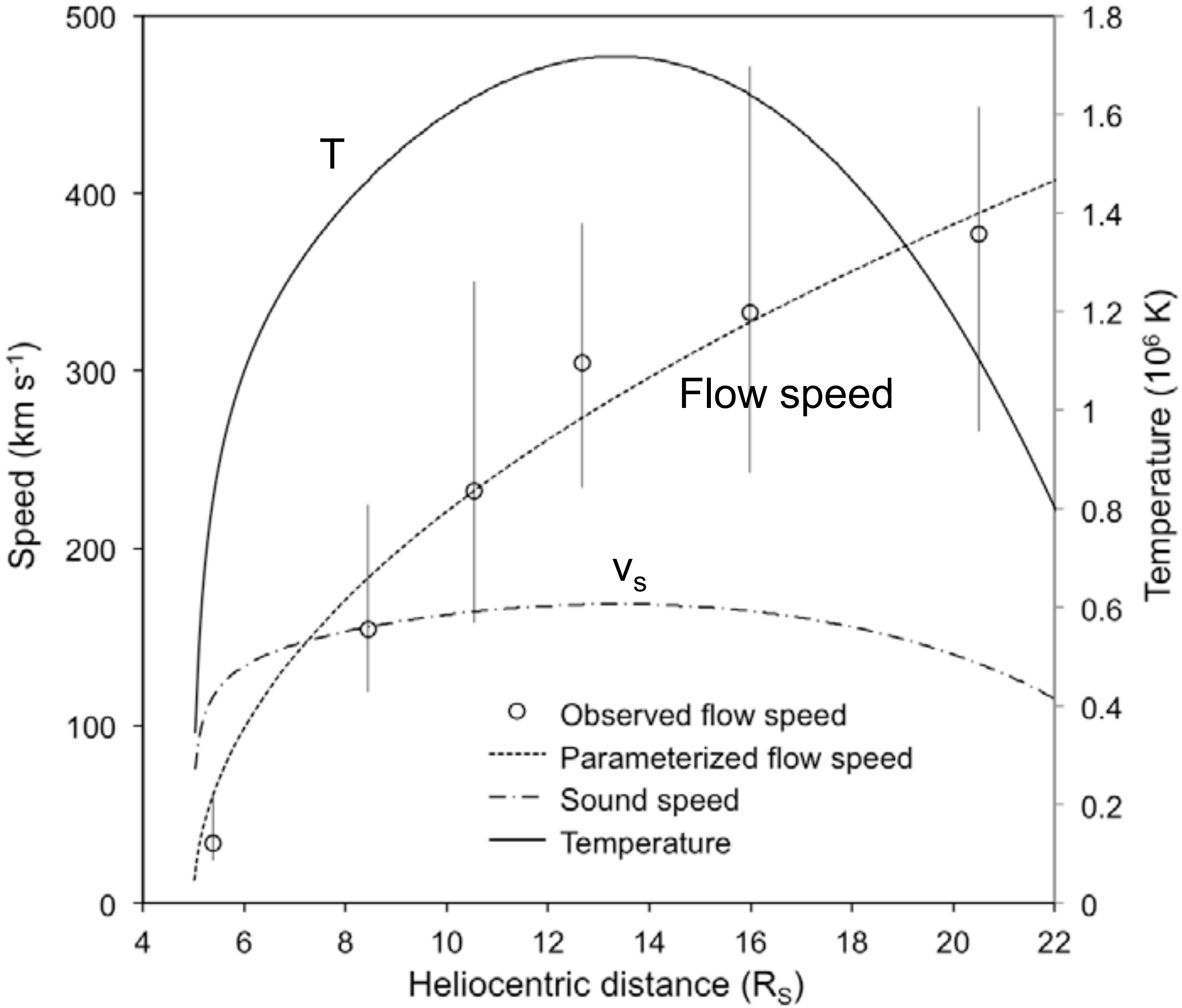
v_s : sound speed

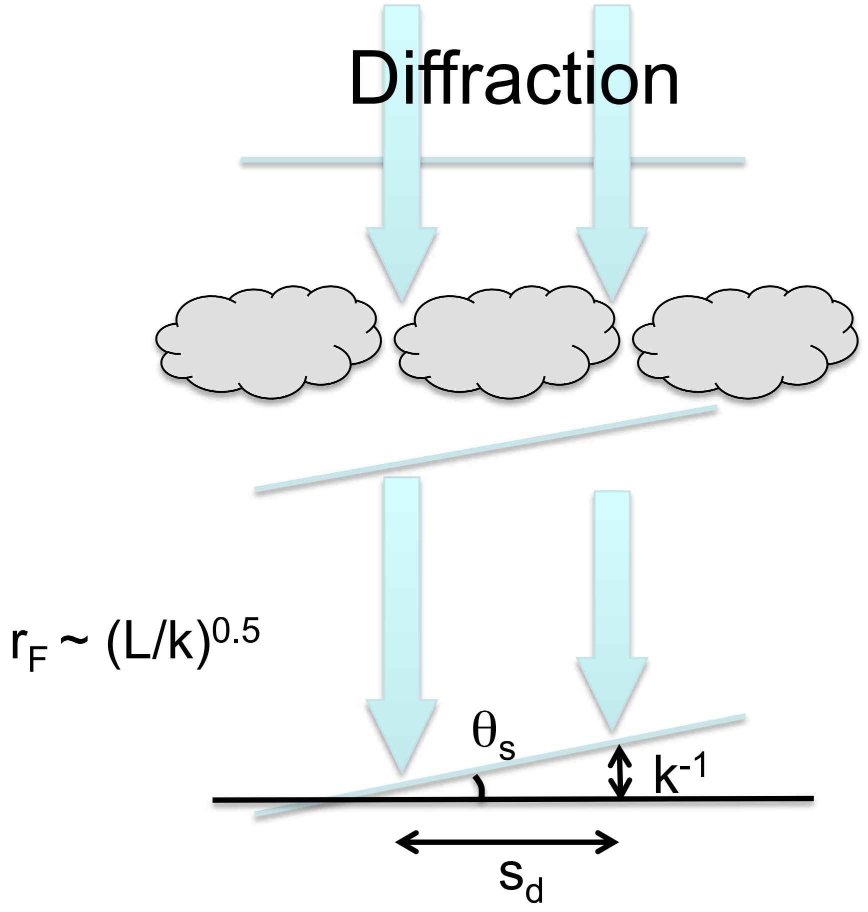
Combining these, we have (Sheeley et al., 1997)

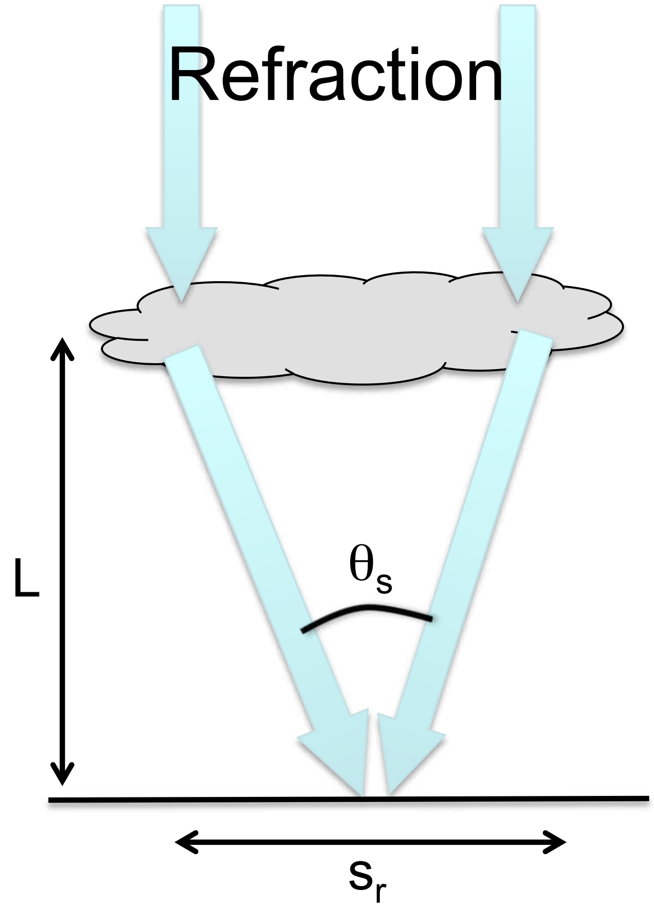
$$\frac{\partial}{\partial r}\left(\frac{v_s^2}{vr^2}\right) = -\left(\frac{1}{vr^2}\right)\left(v\frac{\partial v}{\partial r} + \frac{GM}{r^2}\right)$$

$$\frac{v_s^2(r)}{v(r)r^2} - \frac{v_s^2(r_{\max})}{v(r_{\max})r_{\max}^2} = \int_r^{r_{\max}} \left(\frac{1}{vr^2}\right)\left(v\frac{\partial v}{\partial r} + \frac{GM}{r^2}\right)dr$$

- Fitting to 'West' data taken at > 6 Rs







$\theta_s = 1/(k\ s_d)$

$U = r_F / s_d$

$s_d = r_F / U$

$s_r = L\ \theta_s$

$= r_F^2\ k\ \theta_s = r_F^2 / s_d$

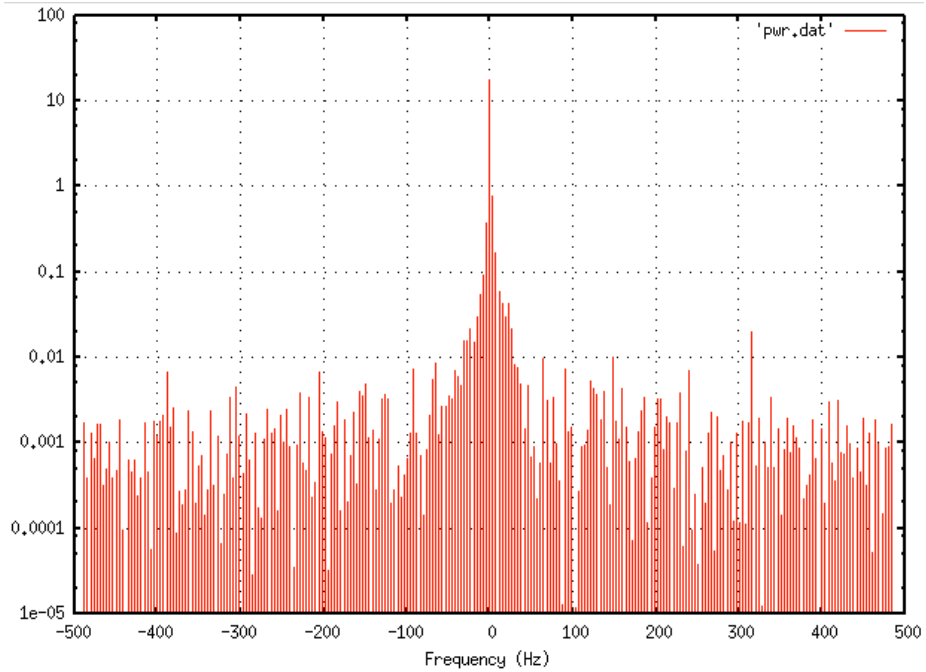
$= U\ r_F$

U > 1 ($r_F > s_d$) Strong scattering

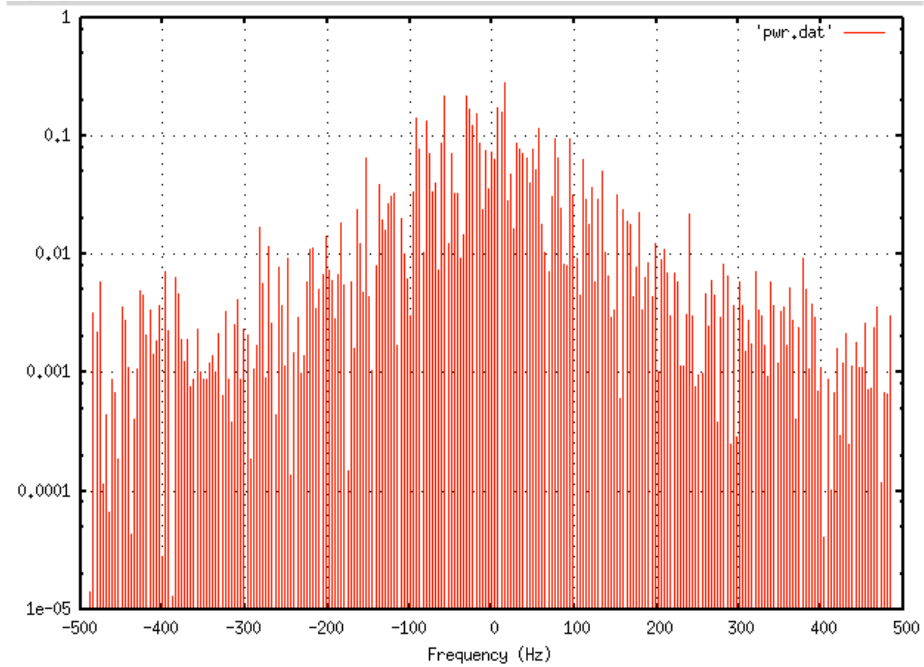
U < 1 ($r_F < s_d$) Weak scattering

$\rightarrow s_d\ s_r \sim r_F^2$

(Rickett, 1990)



6/6 (20.7 Rs)



6/26 (1.7 Rs)