Solar Wind Physics

Marty Lee

University of New Hampshire

USA

University of Chicago 1966

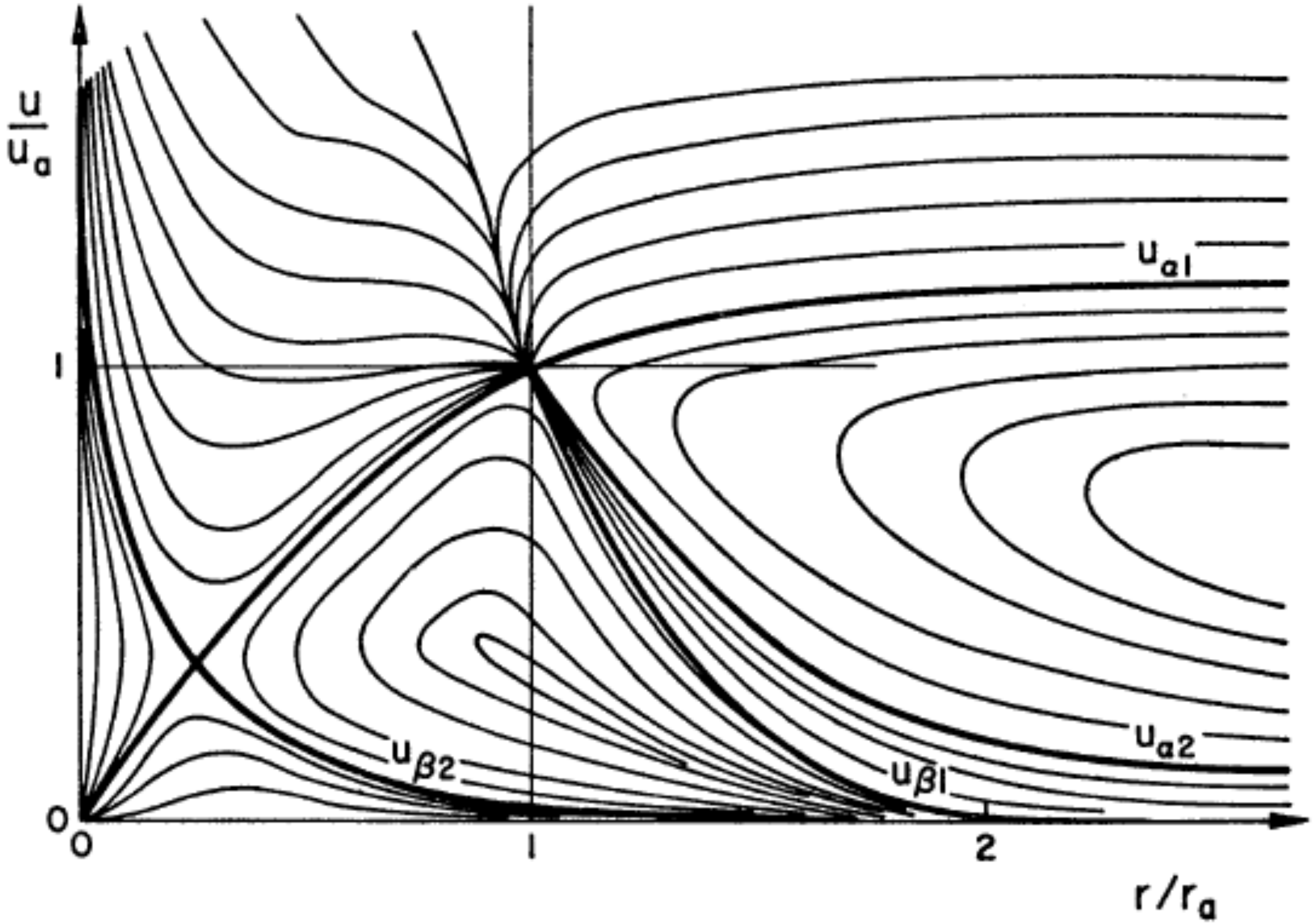
- Gene Parker's solar wind was a story of mythical proportions: it changed and defined "Heliophysics"
- Most rejected the concept of a wind replacing a static atmosphere
- The Solar Breeze was an alternative
- Treating the "solar corpuscular radiation" as a fluid was challenging
- Gene taught my E&M course: tough!
- Parker Solar Probe

Gene Parker

Some Other Issues

- The concept of the “critical point”
- Bondi accretion
- Magnetic Field and Angular Momentum
- Solar Wind Heating: The weak dependence of T(r)
- Complexities of fluid equations – particularly for early space physicists (trained in physics)!

Magnetic Field



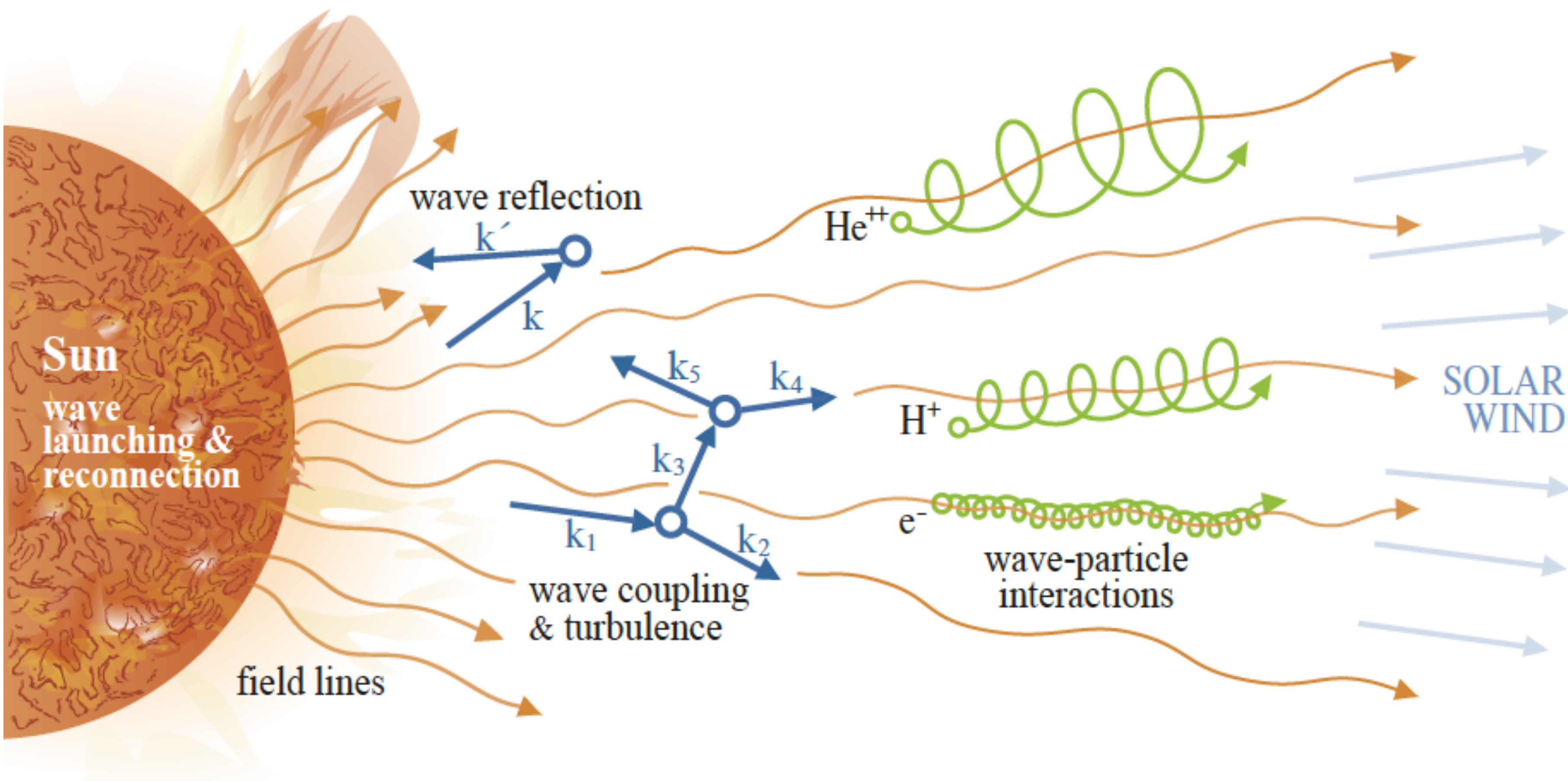
Weber&Davis, 1967

Loss of Angular Momentum

$$L = \Omega r_A^2$$

per unit mass

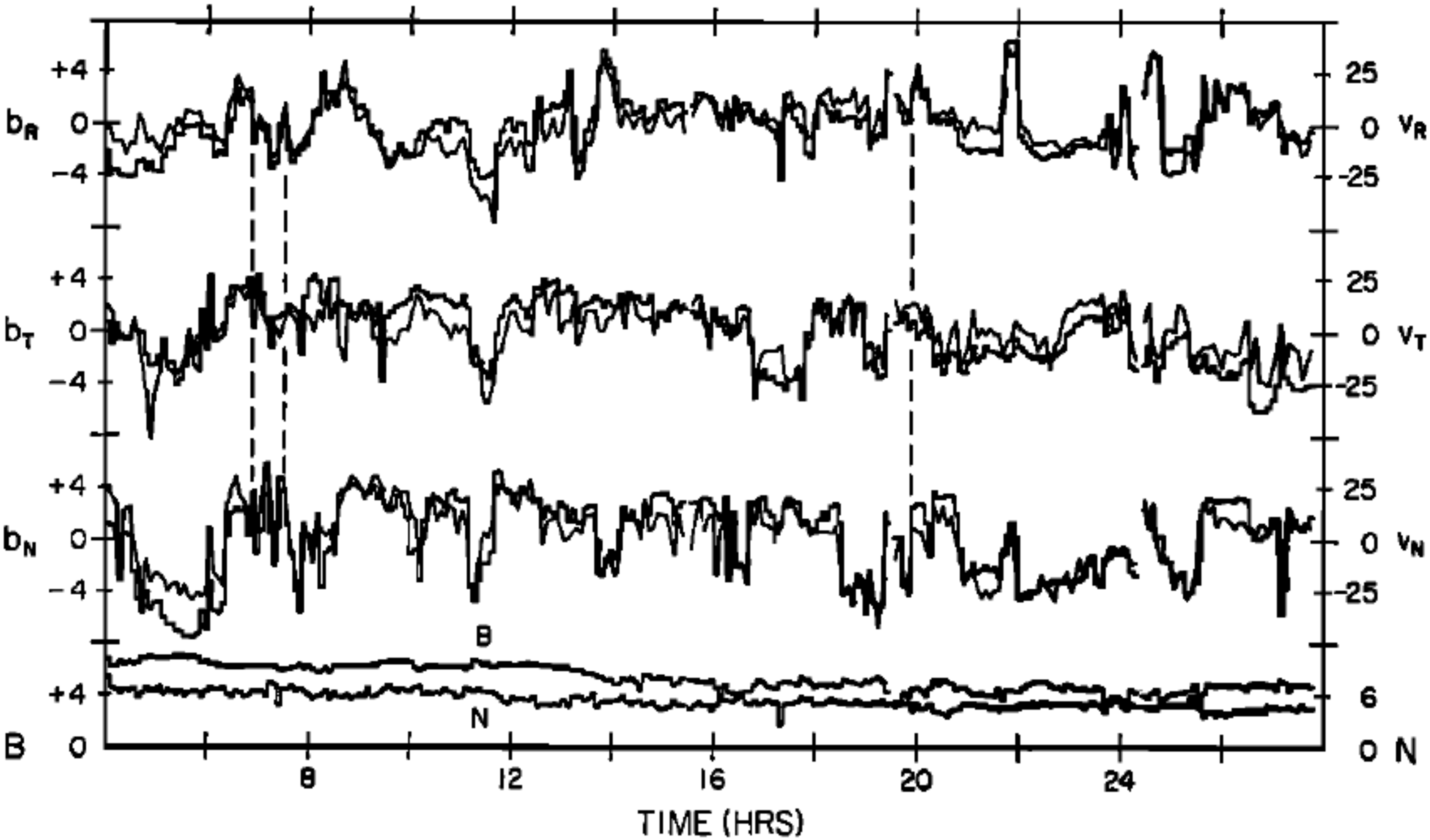
Extended Heating of the Solar Wind



Heating/Acceleration processes in SW

- Turbulent perpendicular heating of ions
- Outward mirroring of ions
- Turbulent wave interactions
- Wave dissipation at higher frequencies
- Electron heat flux (charge separation)
- Magnetic reconnection
- Complex structure of ion distributions
- Spatial structures?

ALFVÉN WAVES IN SOLAR WIND



Belcher and Davis, 1971

Electron Strahl

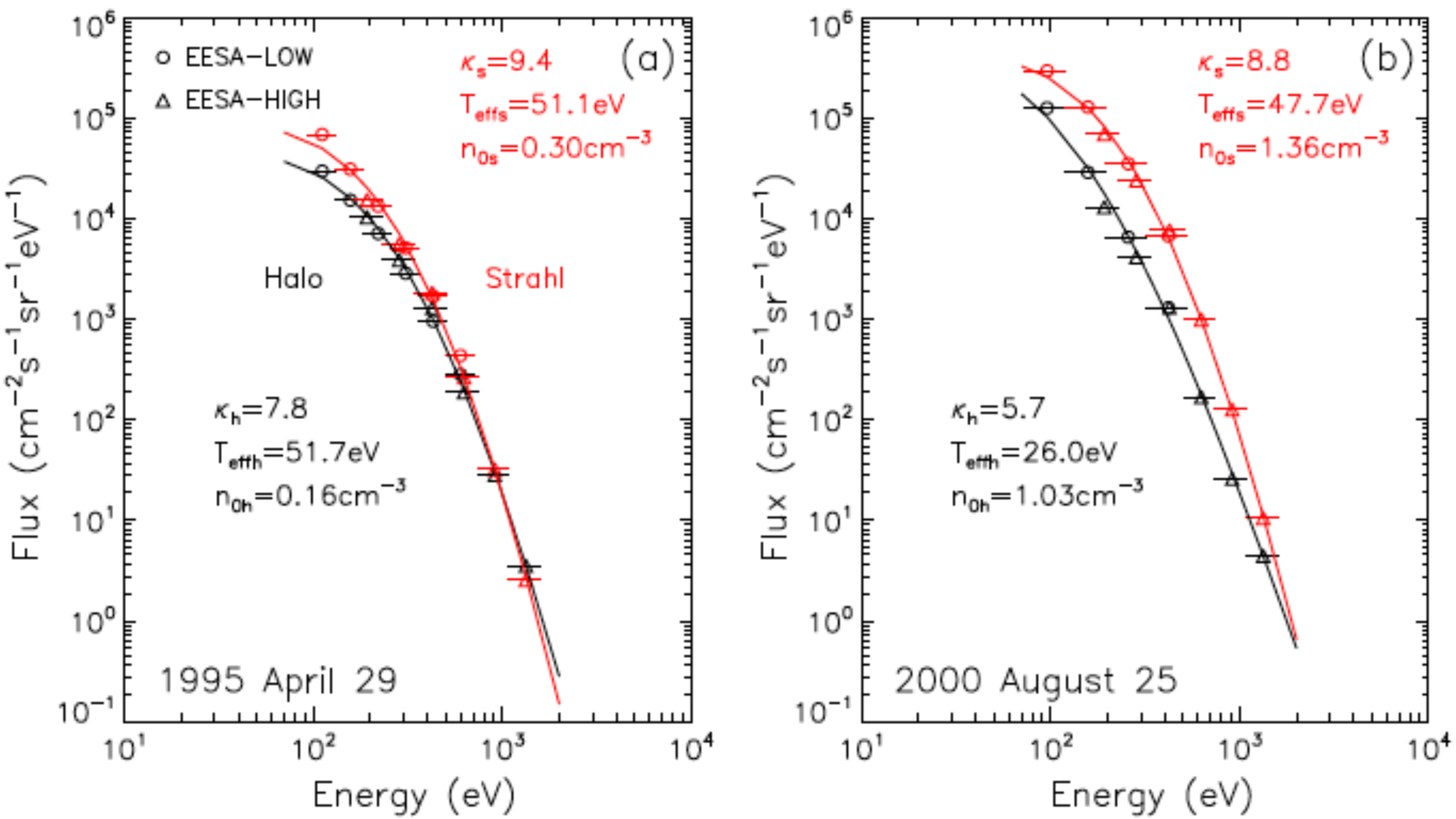
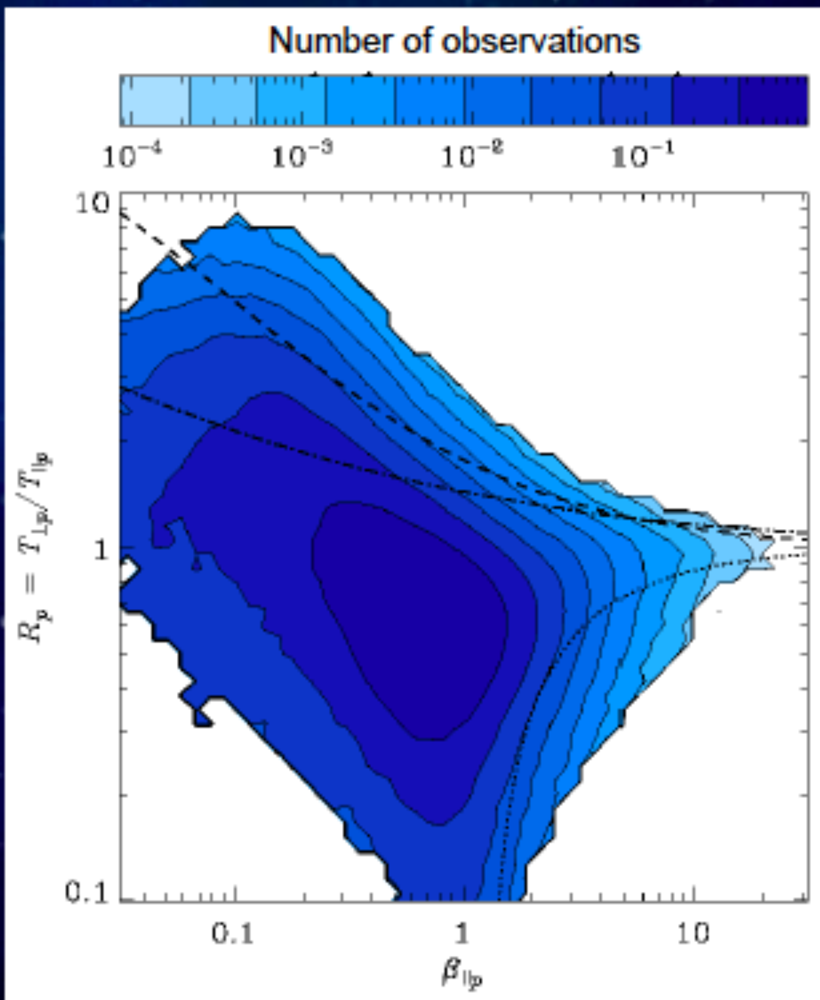


Figure 2. Examples of the energy spectrum of the 0.1–1.5 keV strahl (red) and halo (black) electrons observed by EESA-L (circles) and -H (triangles) on 1995 April 29 (left) and 2000 August 25 (right).

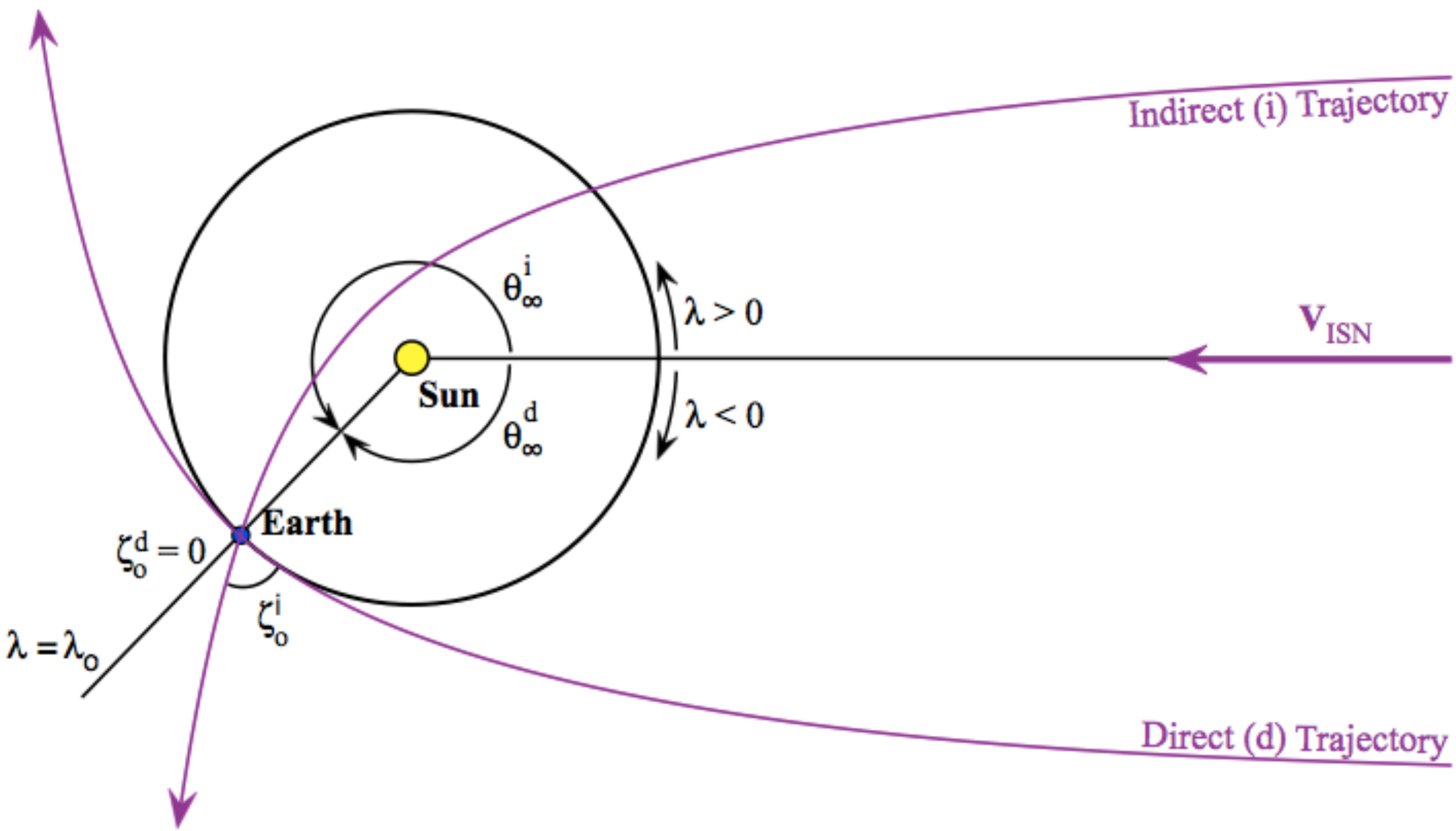
Temperature anisotropy



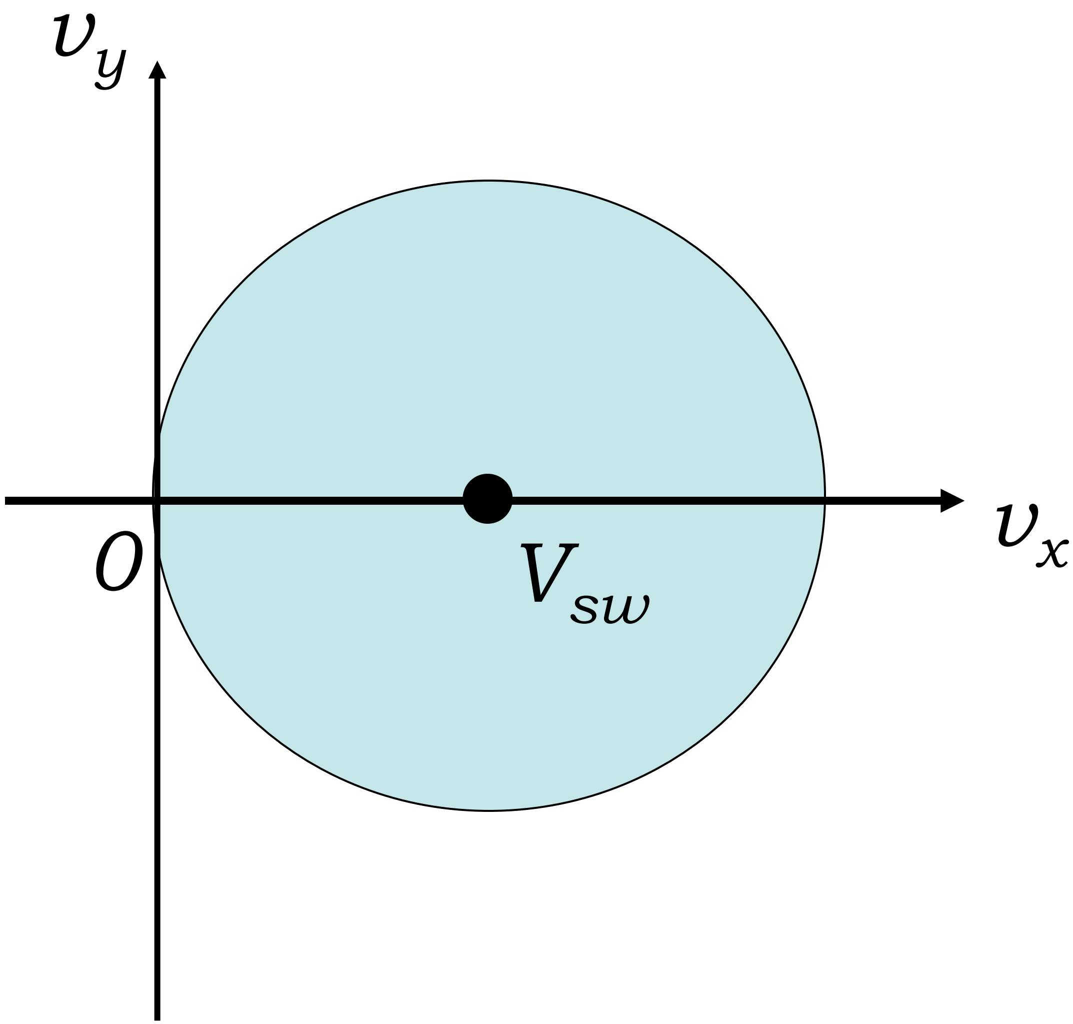
- In the heliosphere
  - Large in the corona
  - Limited by instabilities
- Significance
  - Generates EM fluctuations
  - Modifies particle accel., transport
  - Limits anisotropic heating
- Applied in astrophysics
  - Accretion disks
  - Heat diffusion in galaxy clusters
- Laboratory exp
  - Drives improvements to numerical simulations

Pickup Ions

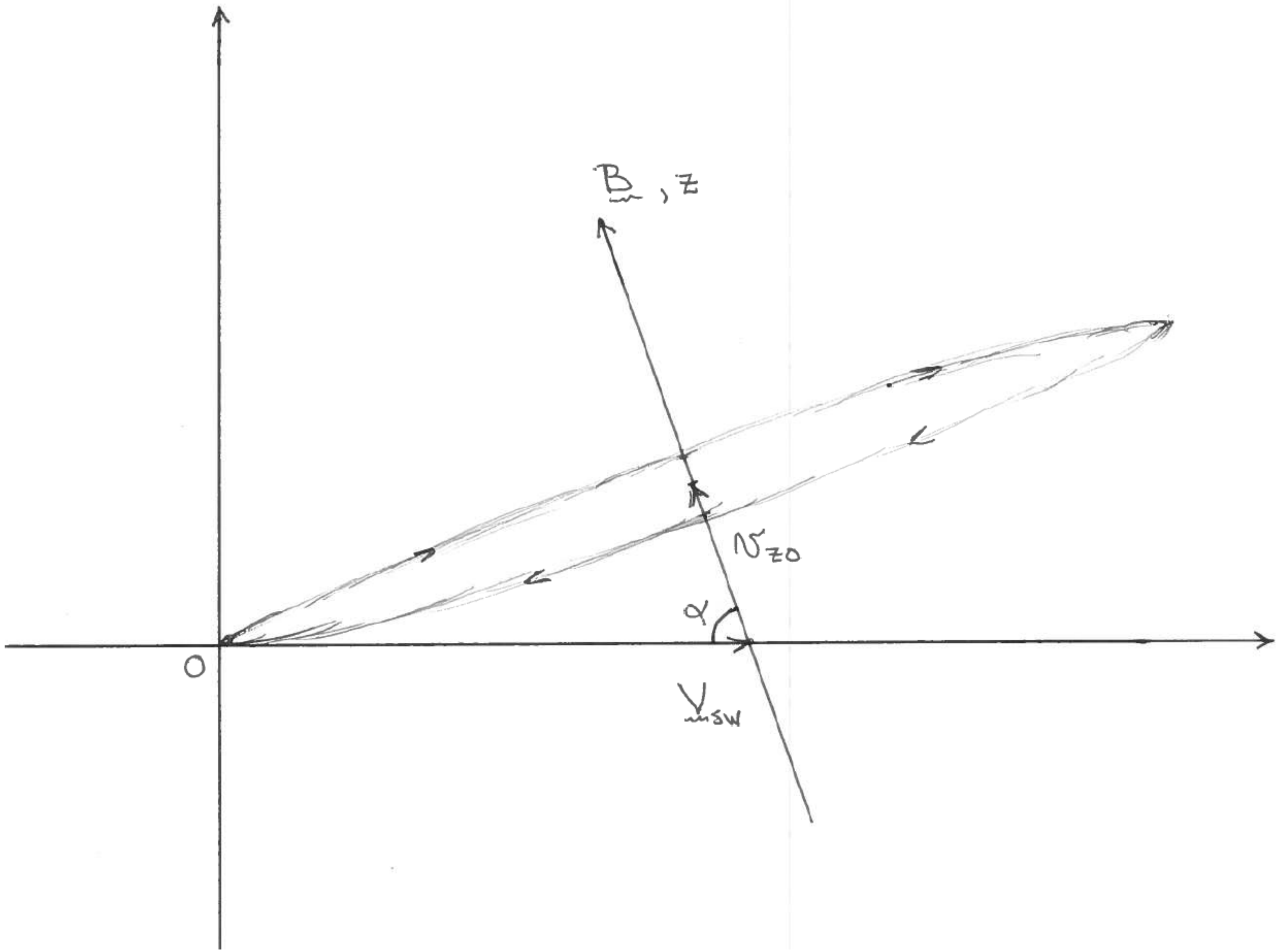
Direct and Indirect Trajectories



Pickup Ion Distribution in SW



Pickup Ion Ring-beam Configuration



Pickup Ion Loading of the Solar Wind I

$$\frac{1}{r^2}\frac{d}{dr}(r^2\rho V) = m_p\left(\frac{r_0}{r}\right)^2(\nu_H^0\ n_{H,\infty} + 4\nu_{He}^0\ n_{He,\infty})$$

$$\frac{1}{r^2}\frac{d}{dr}(r^2\rho V^2) = -\frac{dP}{dr} - \sigma n_{H,\infty}\rho V^2$$

$$\frac{1}{r^2}\frac{d}{dr}\left[r^2 V\left(\frac{1}{2}\rho V^2 + \frac{\gamma}{\gamma - 1}P\right)\right] = -\sigma n_{H,\infty}\frac{1}{2}\rho V^3$$

Lee, 1997

Pickup Ion Loading of the Solar Wind II

$$P = \frac{1}{2}\frac{\gamma - 1}{2\gamma - 1}\frac{r_0^2}{r}\rho_0 V_0 \alpha$$

$$\alpha \equiv \sigma\, n_{H,\infty} V_0 + m_p \rho_0^{-1} \left(\nu_H^0\, n_{H,\infty} + 4\nu_{He}^0\, n_{He,\infty}\right)$$

$$C_S^2 = \frac{1}{2}\gamma\frac{\gamma - 1}{2\gamma - 1} V_0 \alpha r$$

$$V = V_0 - \left[1 - \frac{1}{2}\frac{\gamma - 1}{2\gamma - 1}\right]\alpha r$$

Lee, 1997

Interstellar Pickup Ion Transport

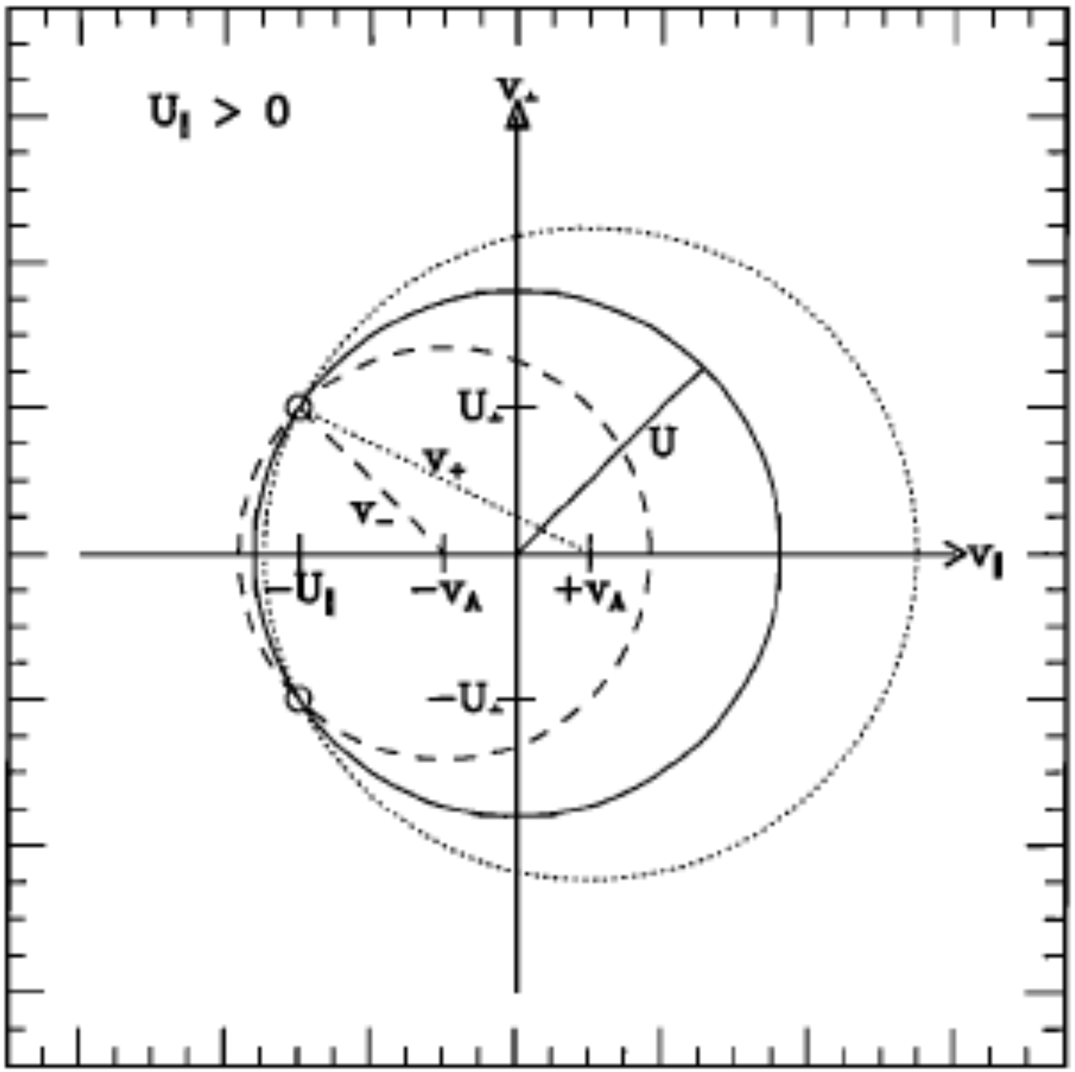
$$\mathbf{V}_D \cong 0, \ \mathbf{K} \cong 0, \ \mathbf{V} = \mathbf{e}_r V, \ \partial / \partial t = 0$$

$$\frac{\partial f}{\partial t} + \mathbf{V} \cdot \nabla f - \frac{1}{3} \nabla \cdot \mathbf{V} v \frac{\partial f}{\partial v} = \beta_0 \left(\frac{r_0}{r} \right)^2 n_g(\mathbf{x}) \frac{\delta(v - V)}{4\pi v^2}$$

$$f(r, v < V) = \frac{3\beta_0 r_0^2}{8\pi V^{5/2}} \frac{1}{r v^{3/2}} n_g \left[r(v/V)^{3/2}, \theta, \phi \right]$$

Exercise 4 in Heliospheric Problems (M. Lee)

Why are waves excited?



Williams & Zank, 1994

Quasilinear Theory

$V_A / v << 1$

$$\frac{\partial F}{\partial t} = \frac{\partial}{\partial \mu}\left\{A(\mu)\left[I_+\left(\frac{\Omega}{v\mu}\right) + I_-\left(\frac{\Omega}{v\mu}\right)\right]\frac{\partial F}{\partial \mu}\right\}$$

$$A(\mu) = \frac{\pi}{2}\left(\frac{q}{mc}\right)^2\left(1-\mu^2\right)\frac{1}{v_0\,|\,\mu\,|}$$

$$\frac{\partial I_\pm}{\partial t} = \pm I_\pm B(|\,k\,|)\int dv\,d\mu (v/v_0)^2\left(1-\mu^2\right)\delta\left(\mu - \frac{\Omega}{kv}\right)$$

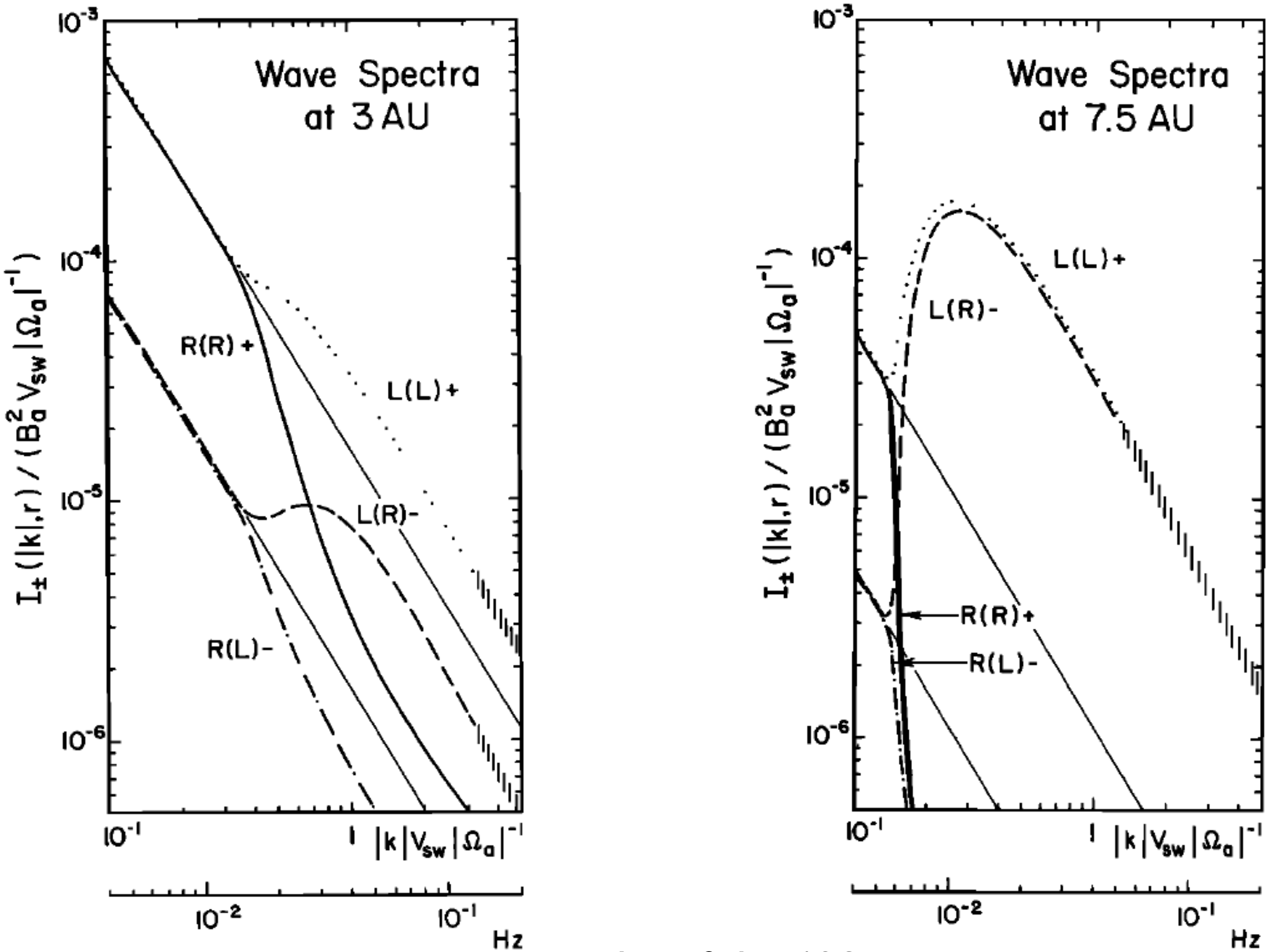
$$B(|\,k\,|) = \frac{4\pi^3 V_A q^2 v_0^2}{|\,k\,|\,c^2 m}$$

$$\Rightarrow I_\pm(k,\infty) = (1/2)\left\{\left[C(k)\right]^2 + 4I_+(k,0)I_-(k,0)\right\}^{1/2} \pm (1/2)C(k)$$

$$C(k) = I_+(k,0) - I_-(k,0) + 2\pi N V_A \frac{|\,\Omega\,|}{k^2}\left[\frac{\Omega}{kv_0} - \frac{\Omega k^{-1}v_0^{-1} - \mu_0}{|\,\Omega k^{-1}v_0^{-1} - \mu_0\,|}\right]$$

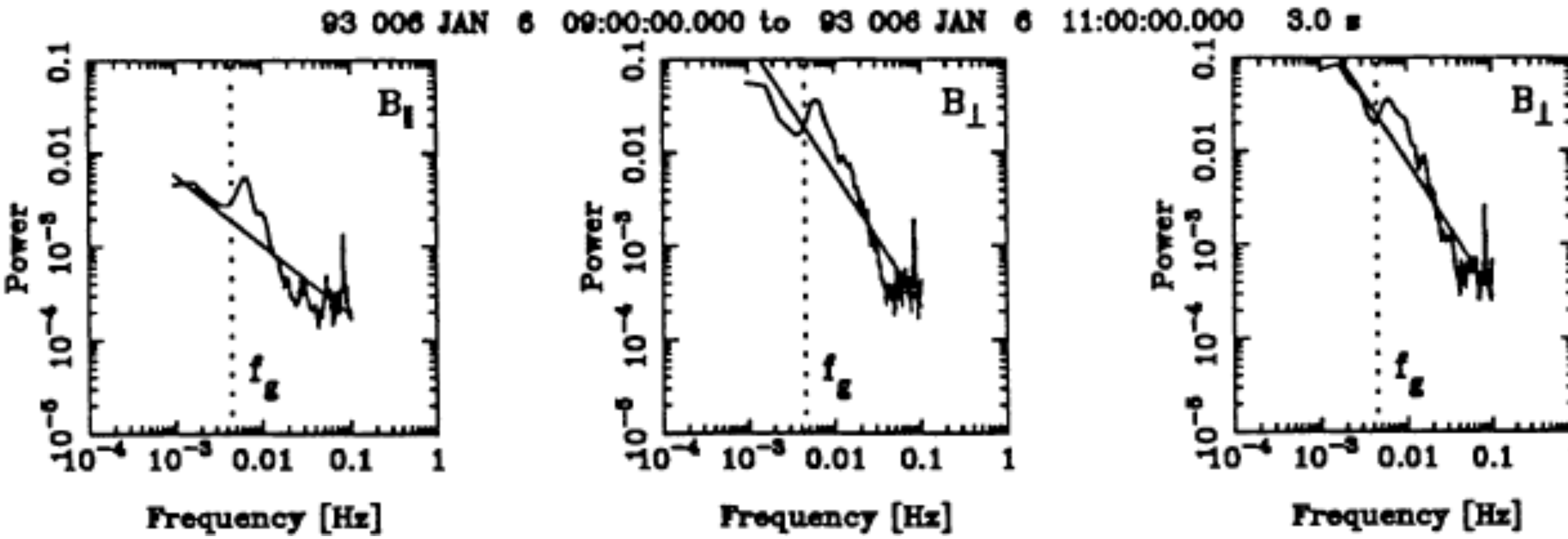
Lee&Ip, 1987

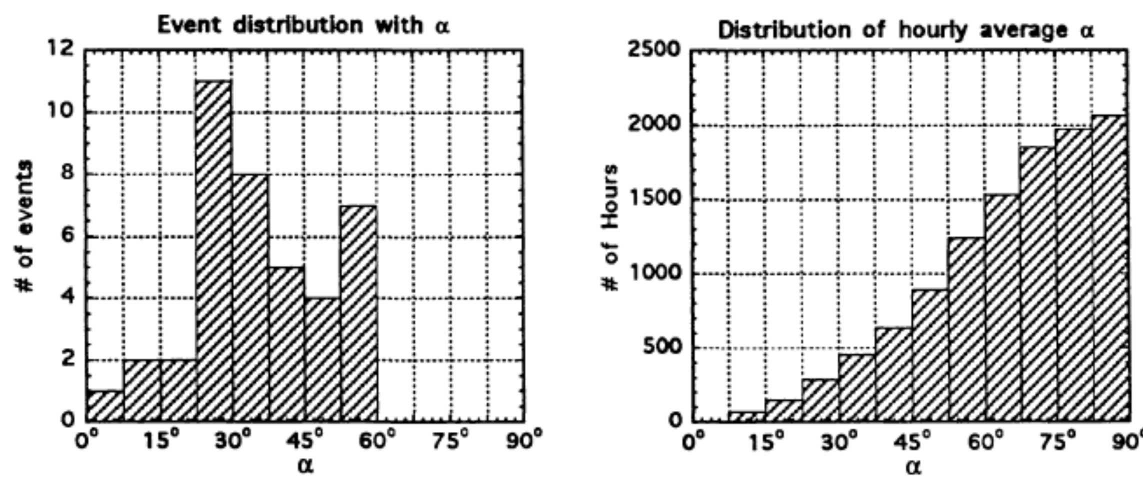
PUI Excited Waves With WKB Evolution



Lee & Ip, 1987

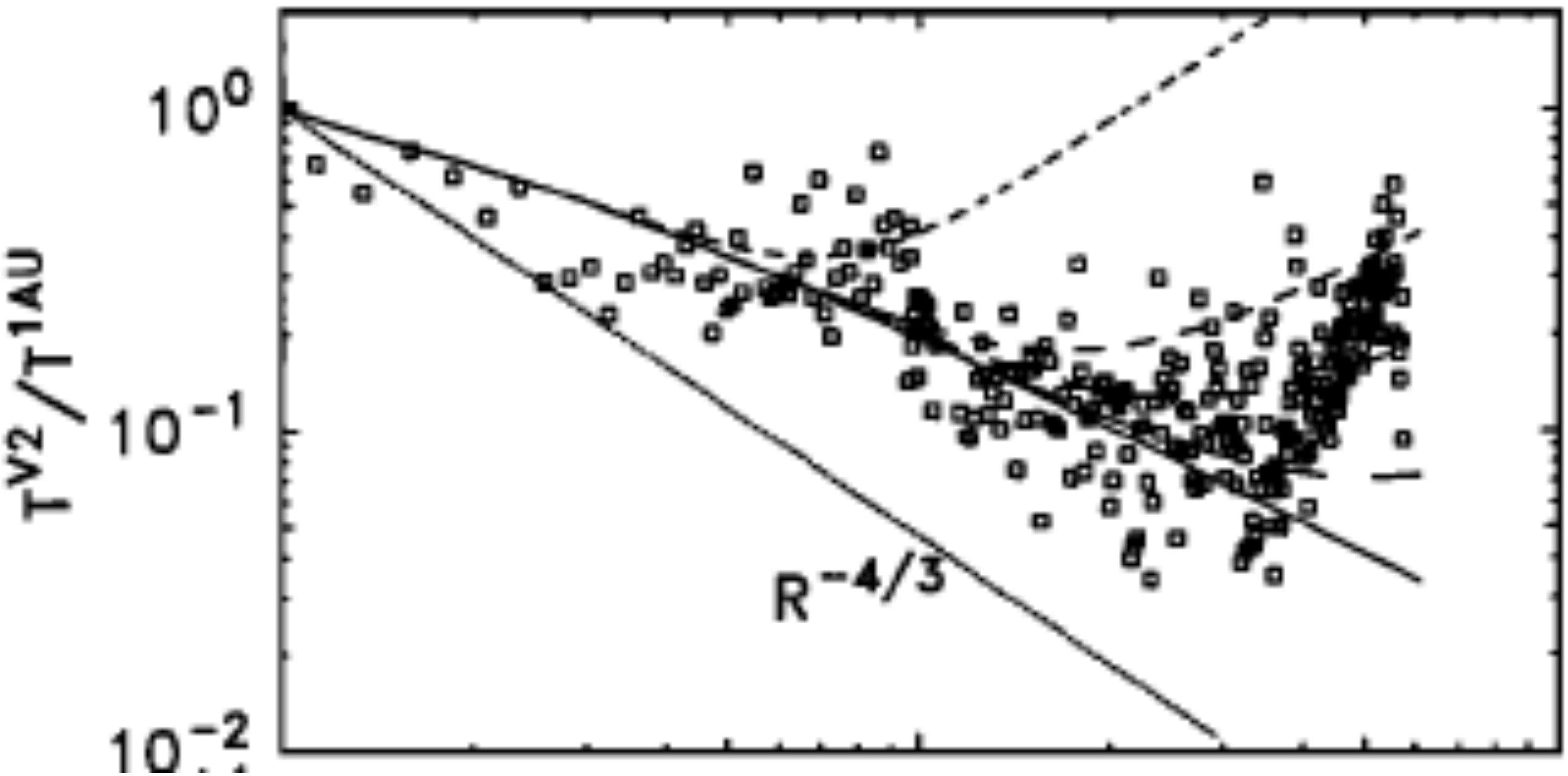
31 Ulysses PU-Proton Events Finally Detected!





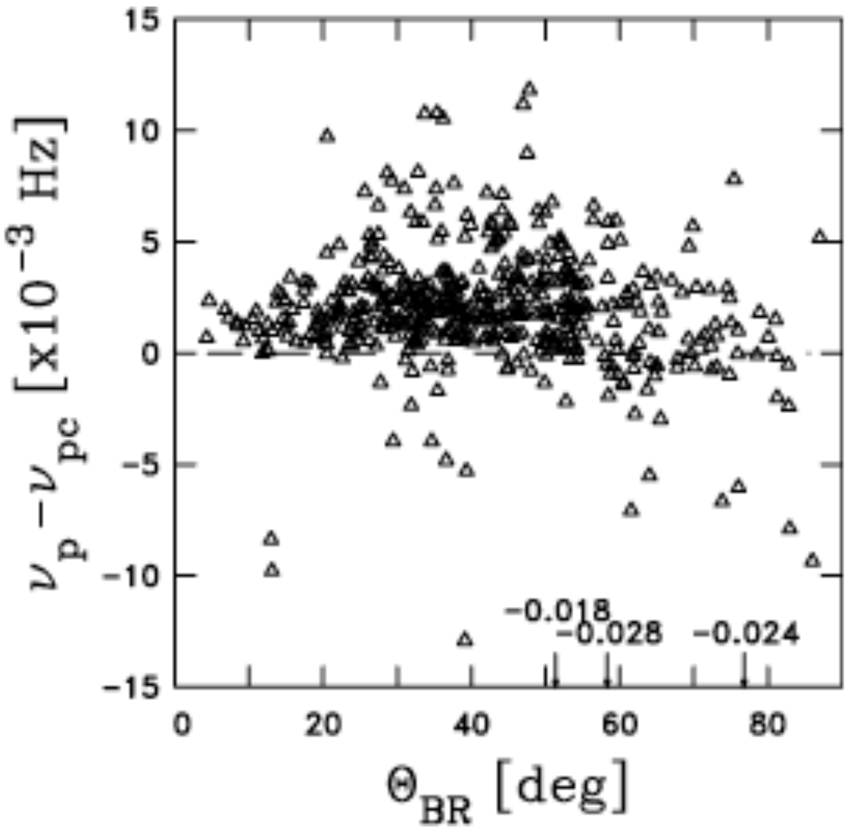
Murphy et al., 1995

The Role of Turbulence

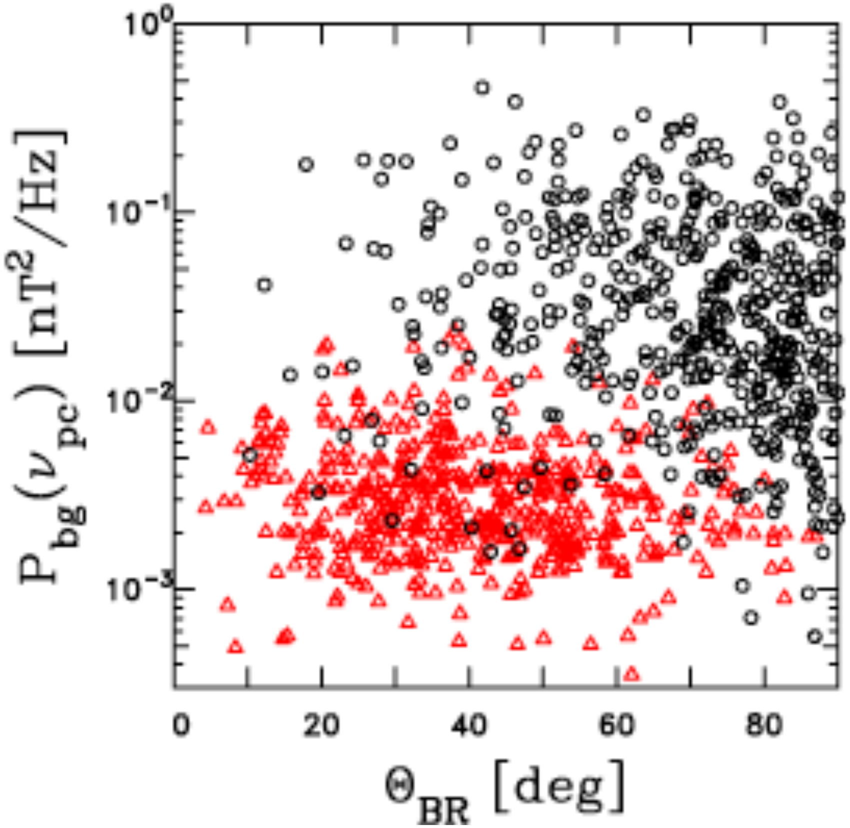


Smith, Matthaeus, Zank, Ness, Oughton & Richardson, 2001
Isenberg,Smith & Matthaeus, 2003
Isenberg, 2005
Isenberg,Smith, Matthaeus, & Richardson, 2005

PUI Wave Properties II

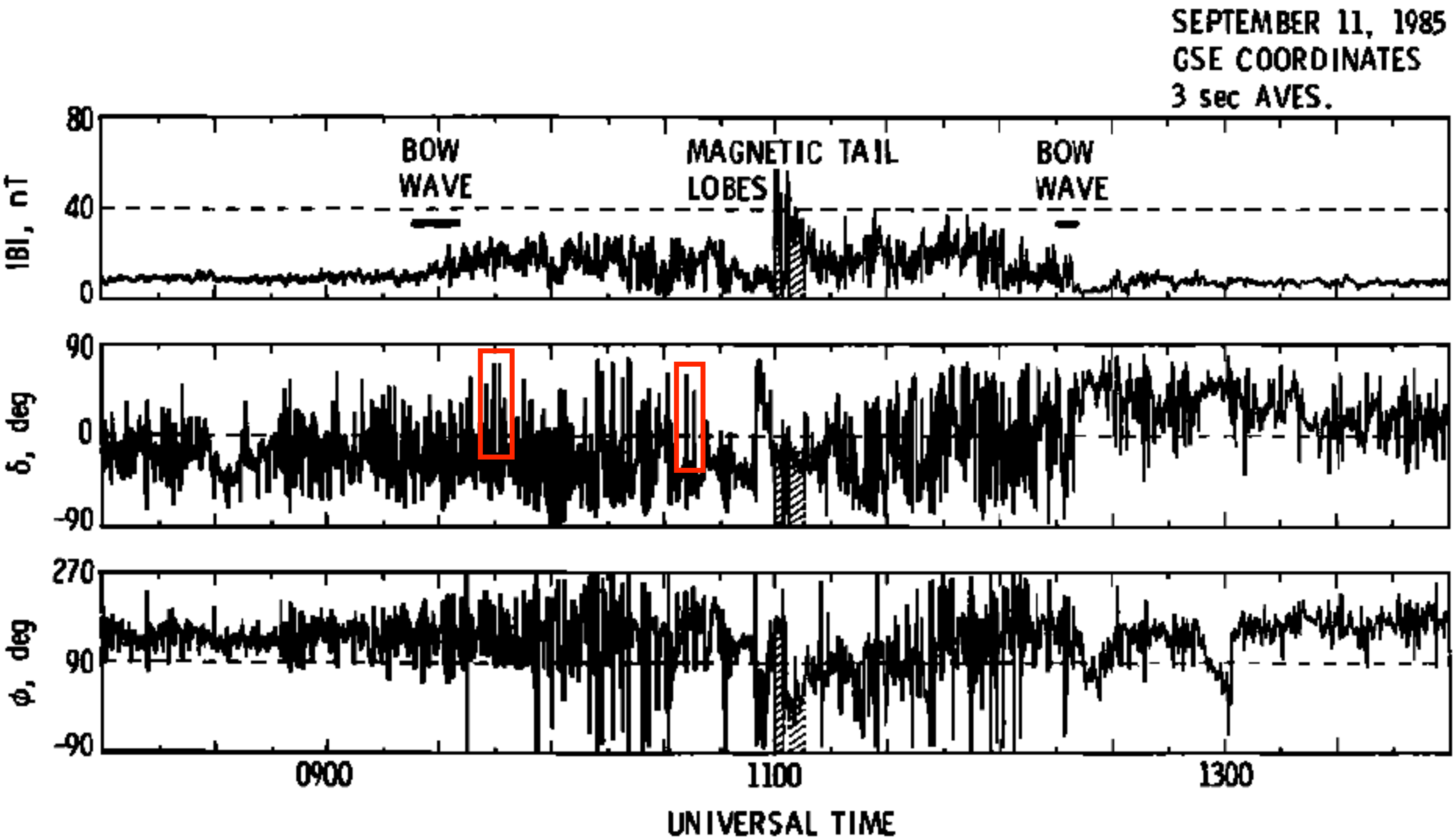


Cannon et al., 2014a



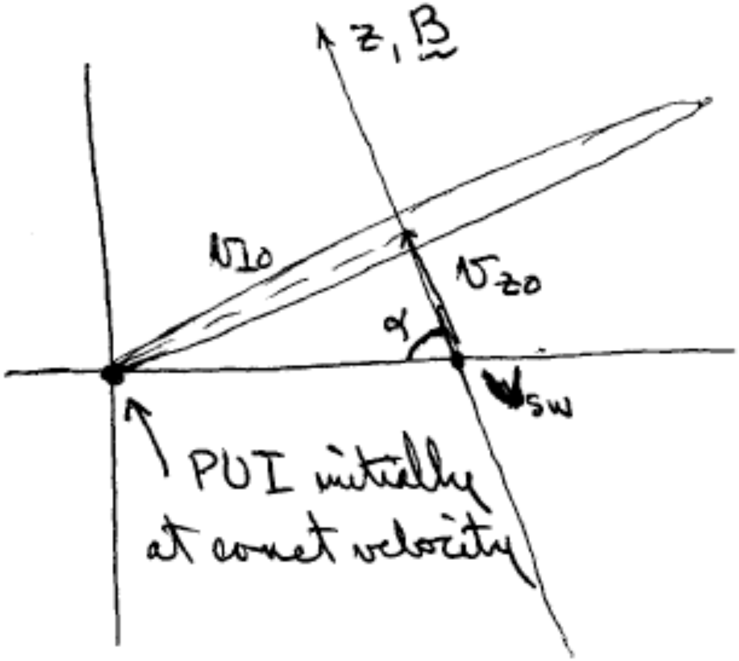
Cannon et al., 2014b

Pickup Ion Excited Waves at Comet G-Z



Tsurutani and Smith, 1986

Cometary Ion Pickup



$$\omega - k_z v_z + \Omega = 0$$

$$\omega - k_z V_{SW} \cos\alpha + \Omega = 0$$

$$\omega + \mathbf{k} \cdot \mathbf{V}_{SW} + \Omega = 0$$

$$\omega_{sc} = -\Omega$$

$$T_{sc} = \frac{2\pi}{|\omega_{sc}|} = \frac{2\pi}{|\Omega_p|} A$$

$B = 8\text{nT}$ $\quad T_{sc} = 8A\,\text{sec} \approx 120\text{ sec} \quad \Rightarrow \quad \text{A} \approx 15$

Shock Waves:
Difficult to Avoid in a Supersonic Flow

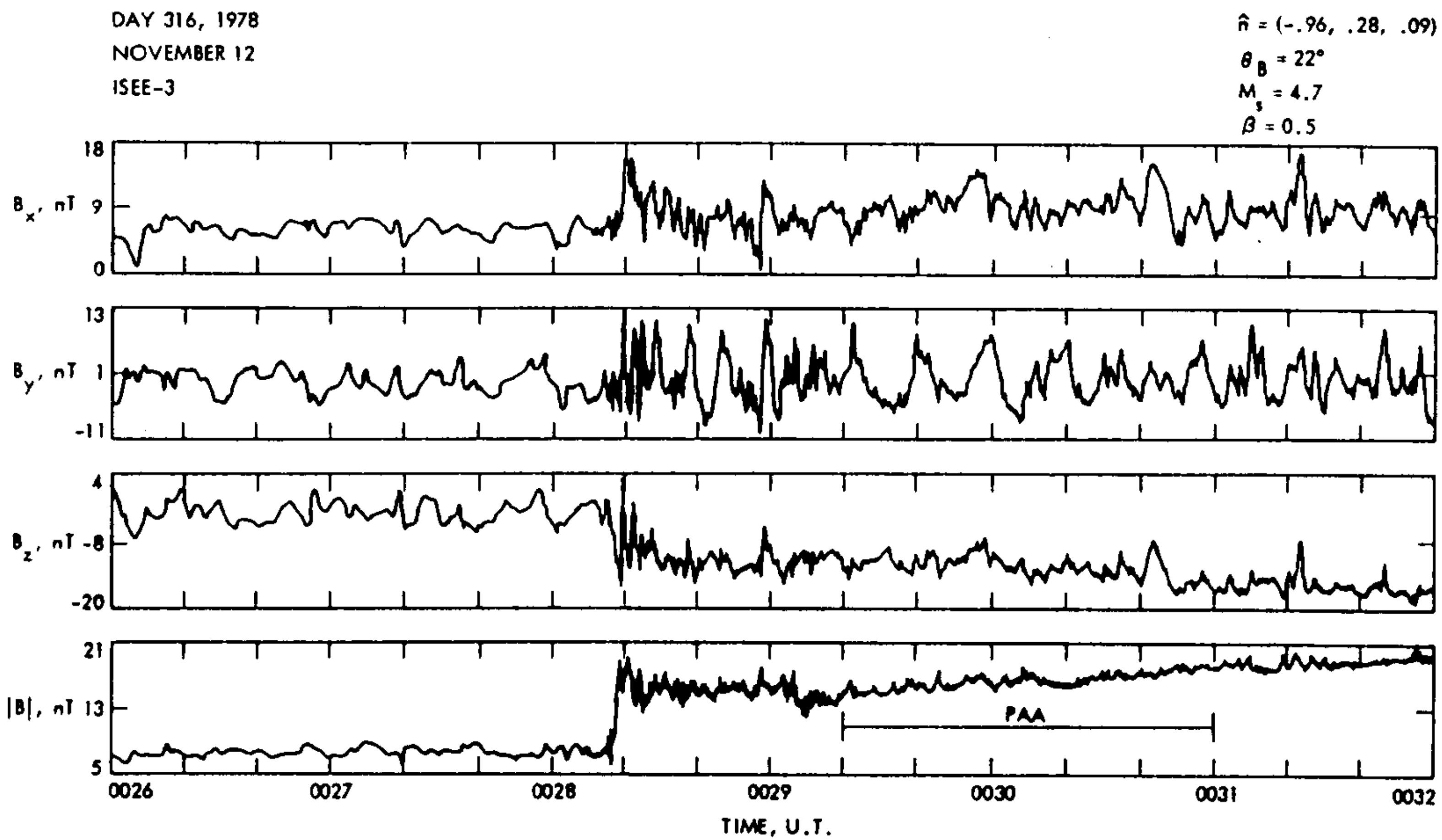
Water Ripples

Fundy Tidal Bore

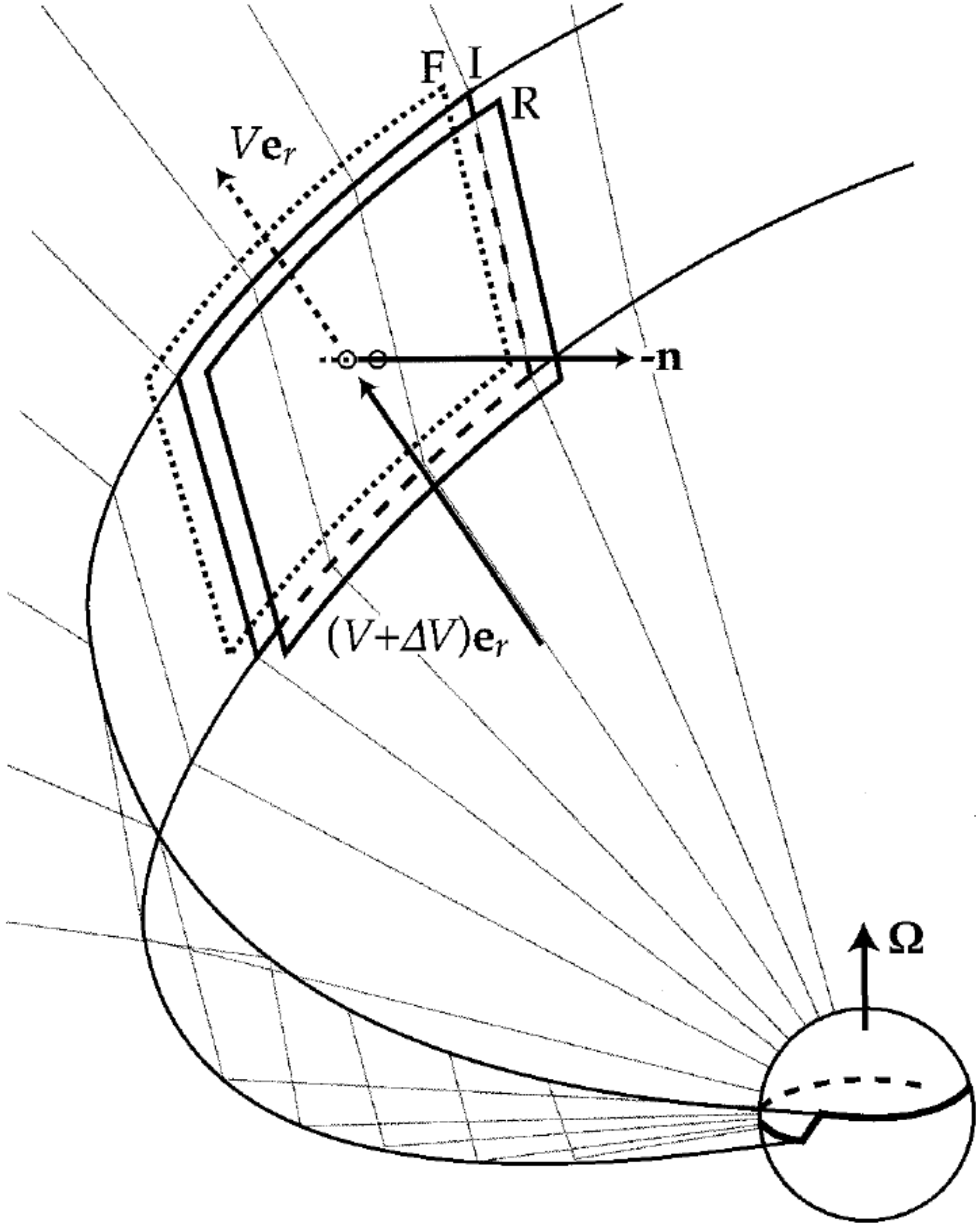
Fundy Tidal Bore

Tsunami Hits Japan, 2011

Upstream Waves I



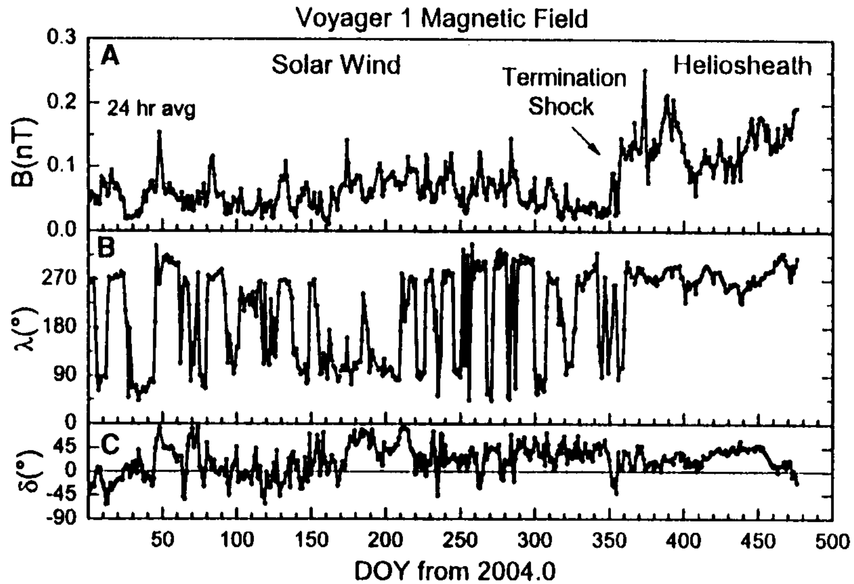
Tsurutani et al., 1983

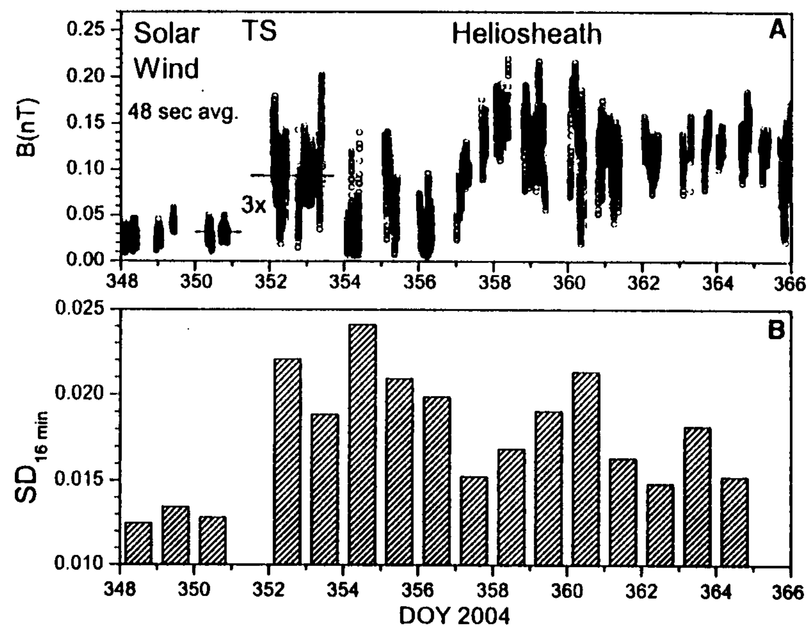


CIR Geometry

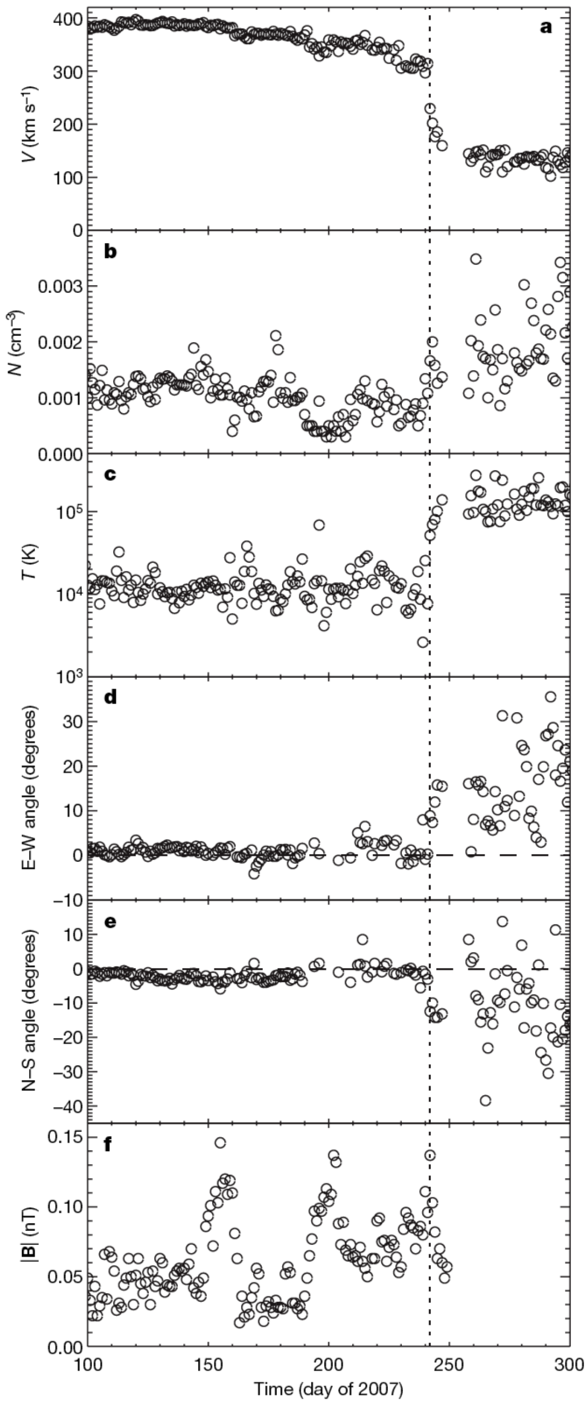
Termination of the Solar Wind

Voyager 1 at the Termination Shock





Burlaga et al., 2005

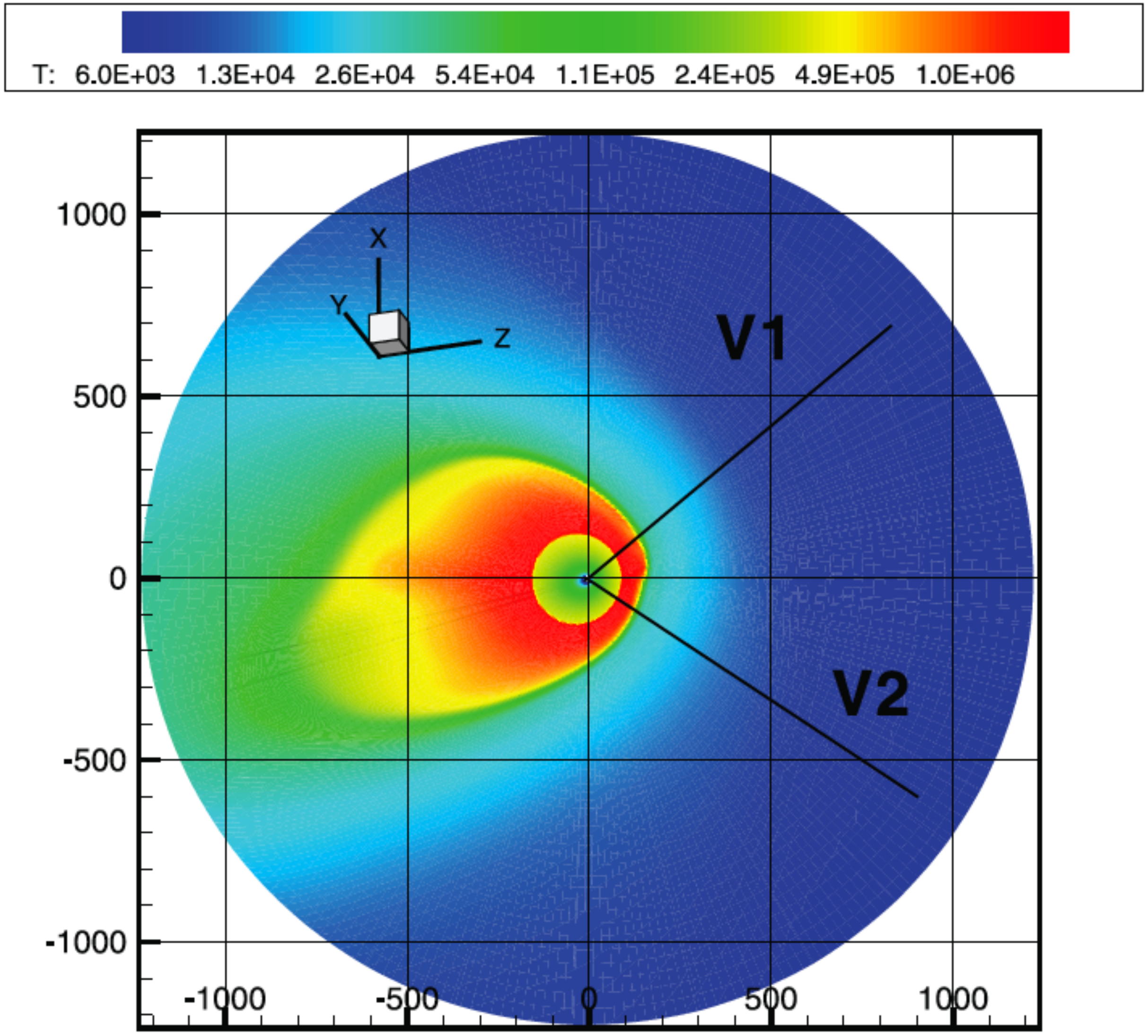


Termination Shock Plasma Data At Voyager 2

Richardson et al., 2008

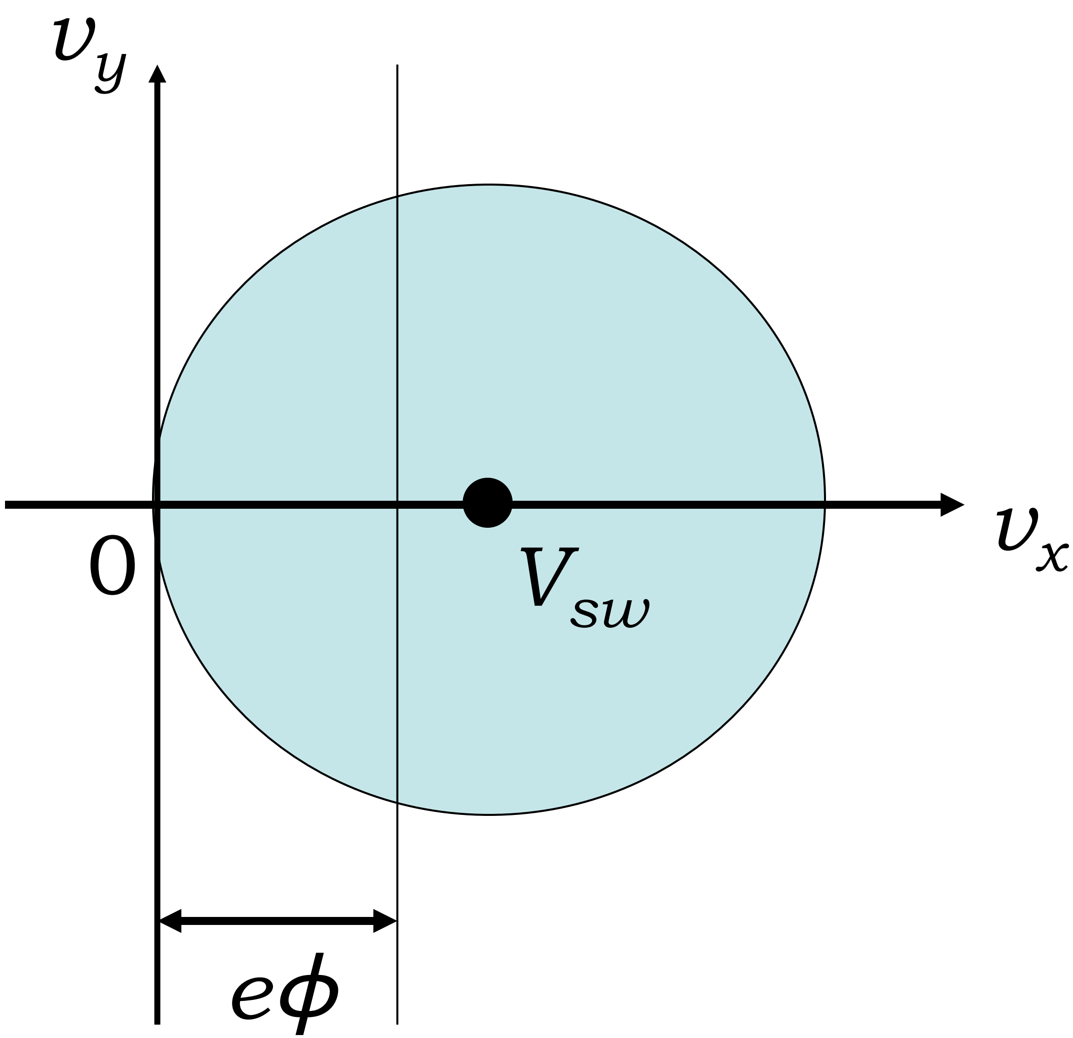
“Termination Shock” in Your Sink

The Heliosphere

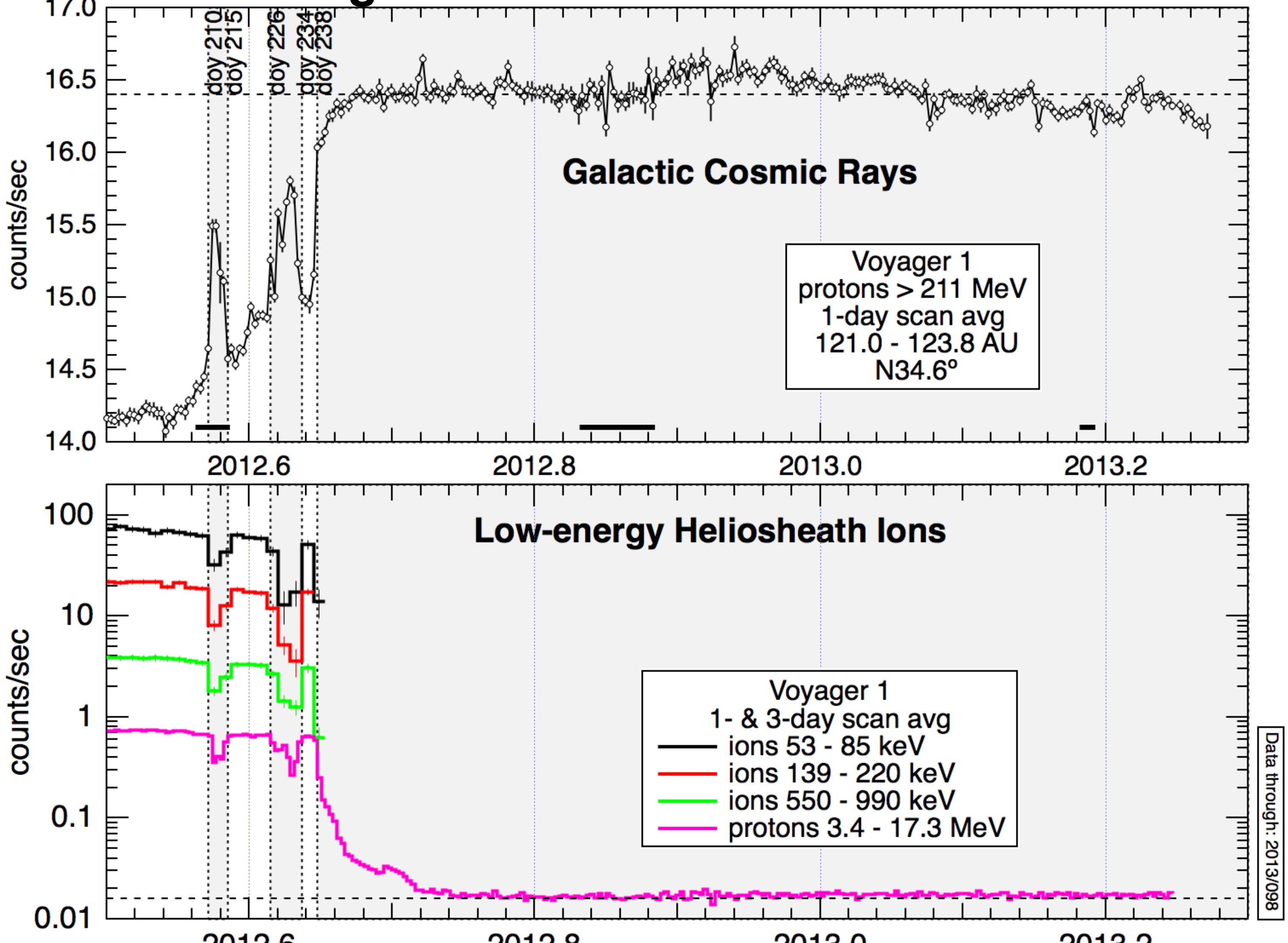


Pogorelov et al., 2008

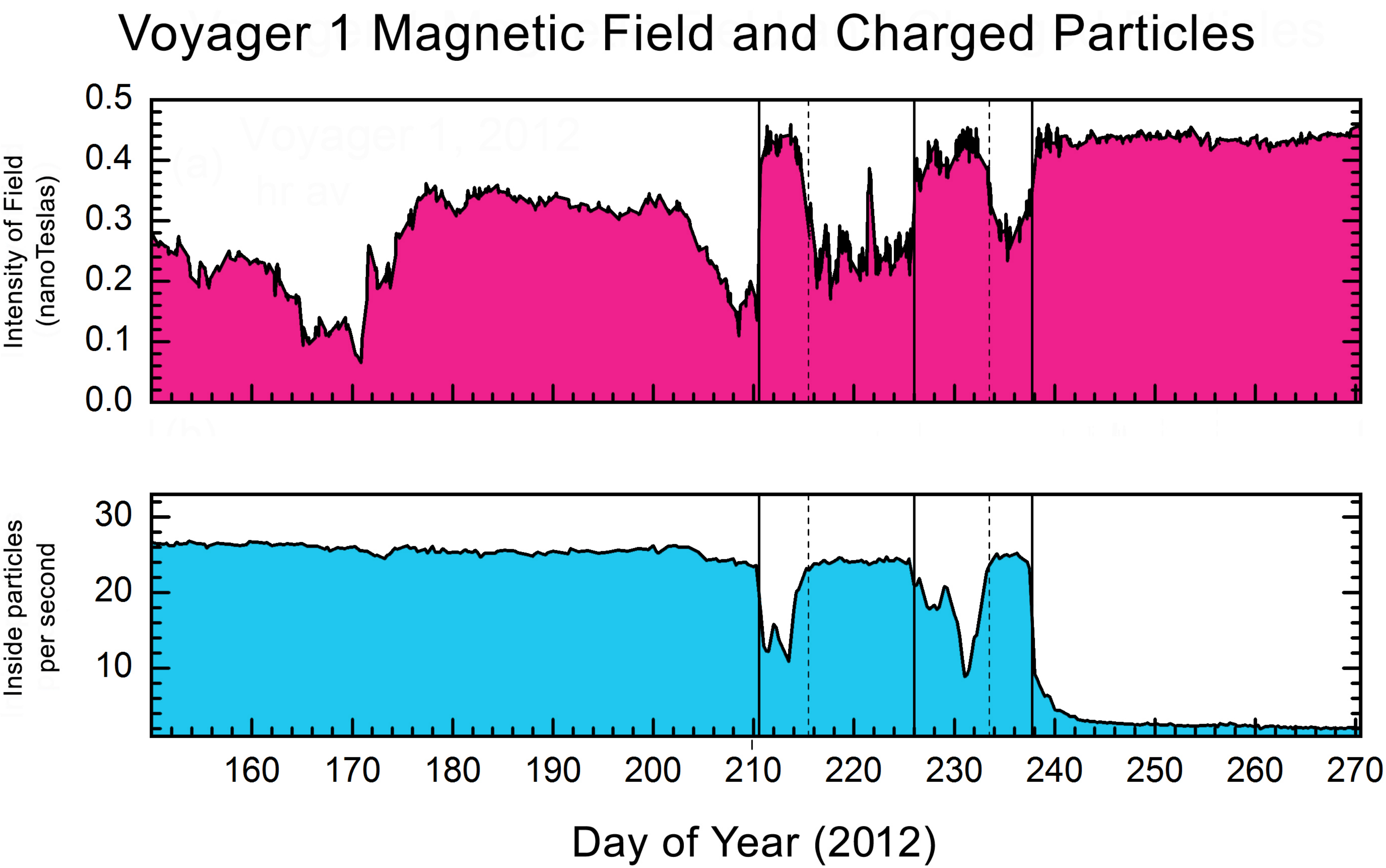
Pickup Ion Mediated Termination Shock



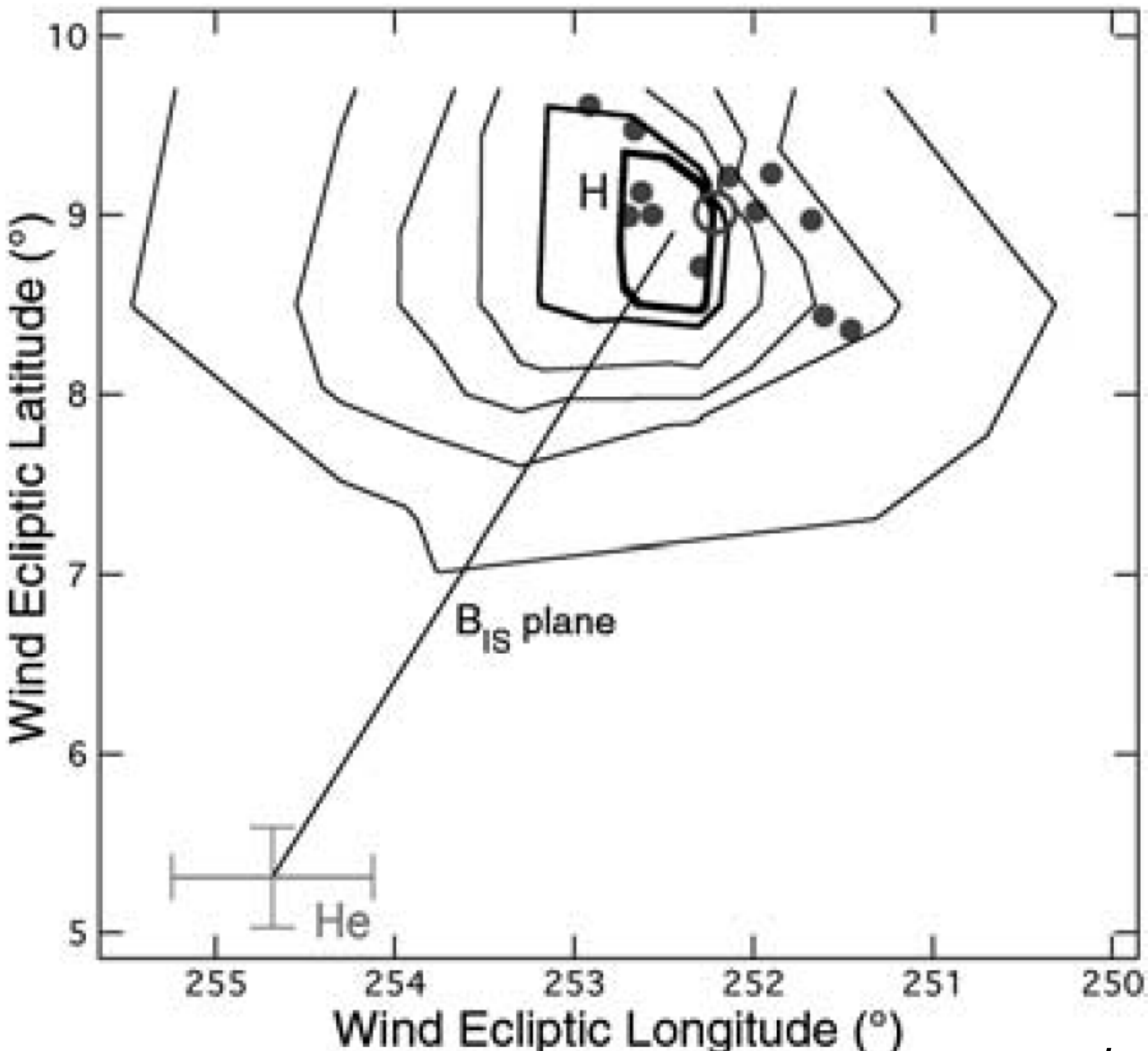
Voyager 1, 2012/183-2013/98: Galactic cosmic rays enter the high-B regions, while low-energy heliosheath particles leave via magnetic connection to LISM



Voyager in the Heliosheath



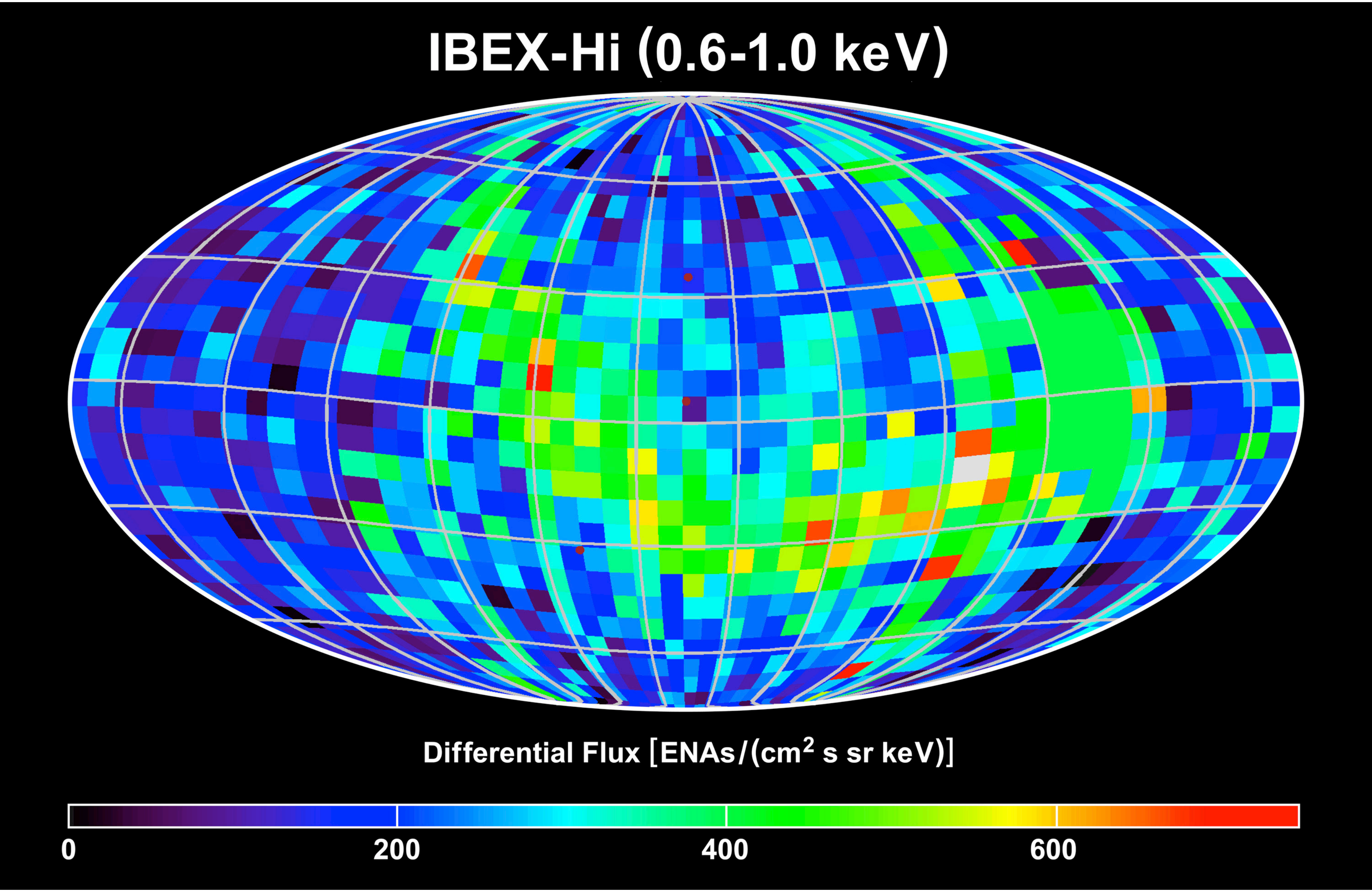
Burlaga et al., 2013 Image credit: NASA/JPL-Caltech/GSFC/ University of Delaware



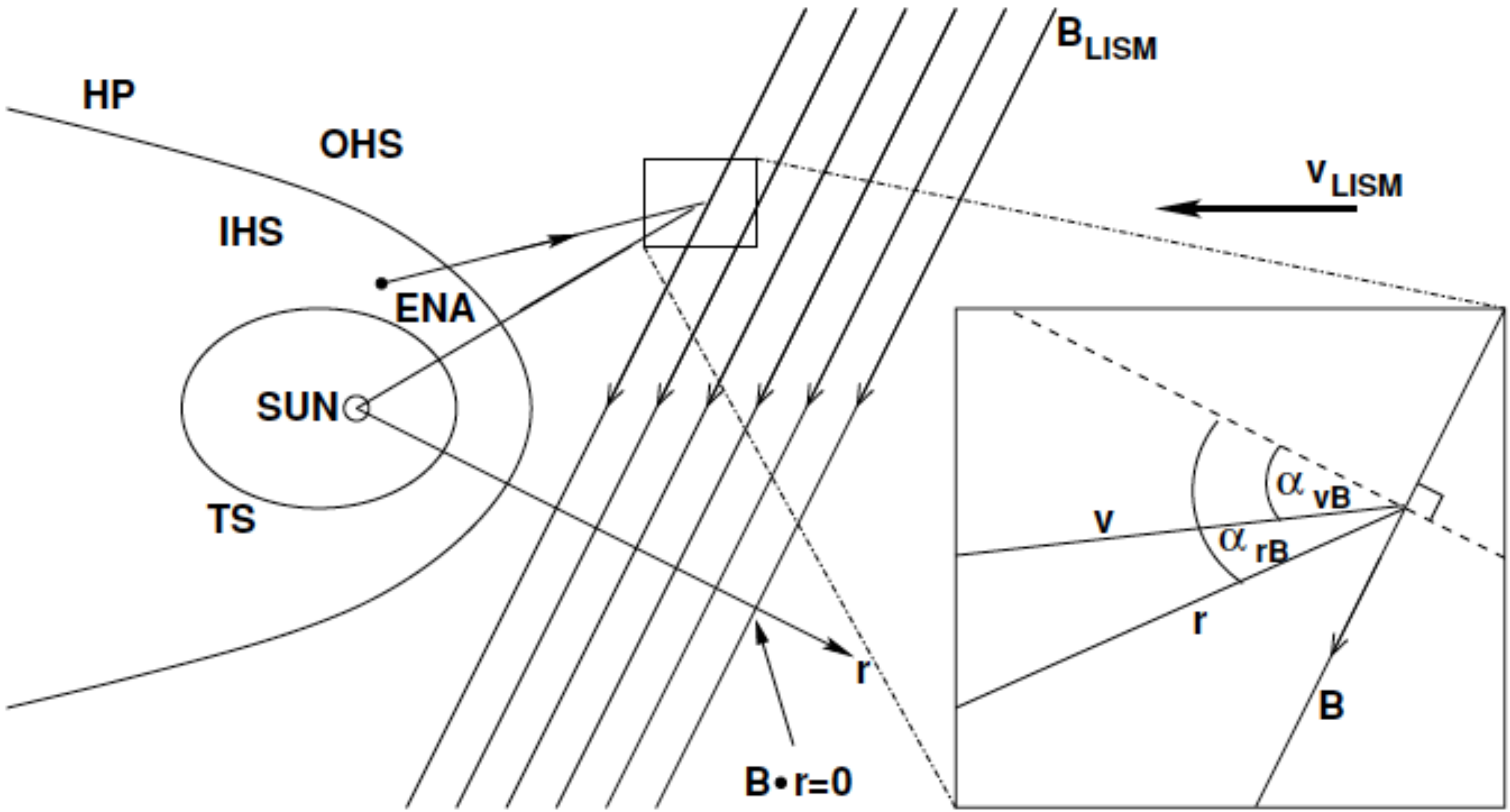
Lyman-α Backscatter

Lallement et al., 2005

The Termination of the Neutral Solar Wind


IBEX-Hi (0.6-1.0 keV)
Differential Flux [ENAs/(cm² s sr keV)]
0
200
400
600

Pickup Ions Beyond Heliosphere



Heerikhuisen et al., 2010