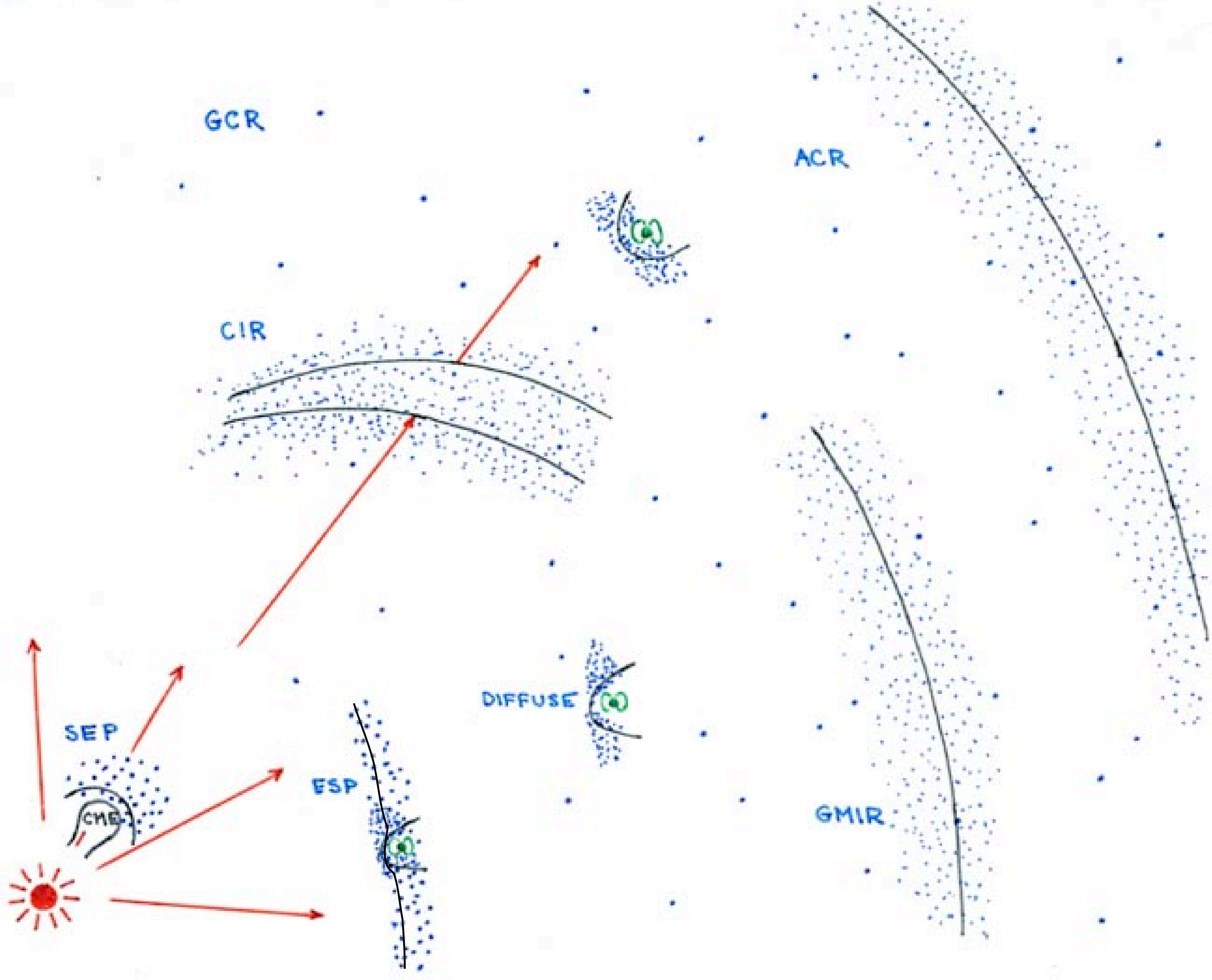
Current Issues Associated with Particle Acceleration in the Heliosphere: Shocks and Stochastic Acceleration

Marty Lee

USA


GCR
ACR
CIR
DIFFUSE
SEP
CME
ESP
GMIR

Current Issues & Challenges

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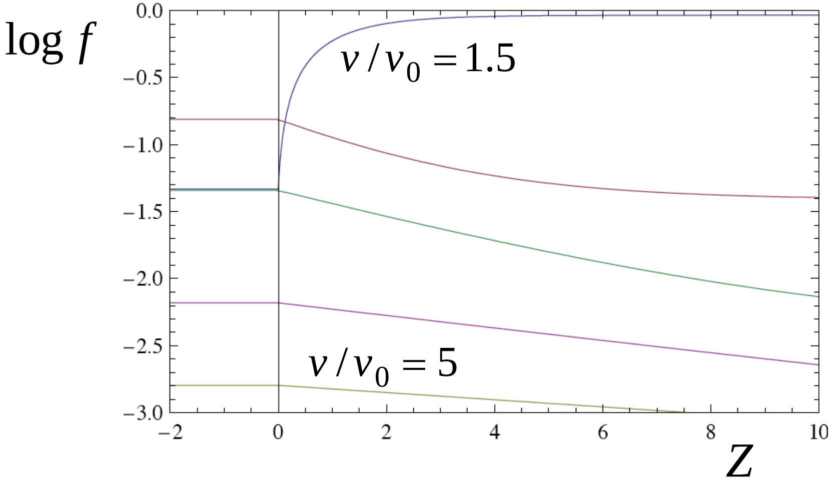
Planar Stationary SA - I

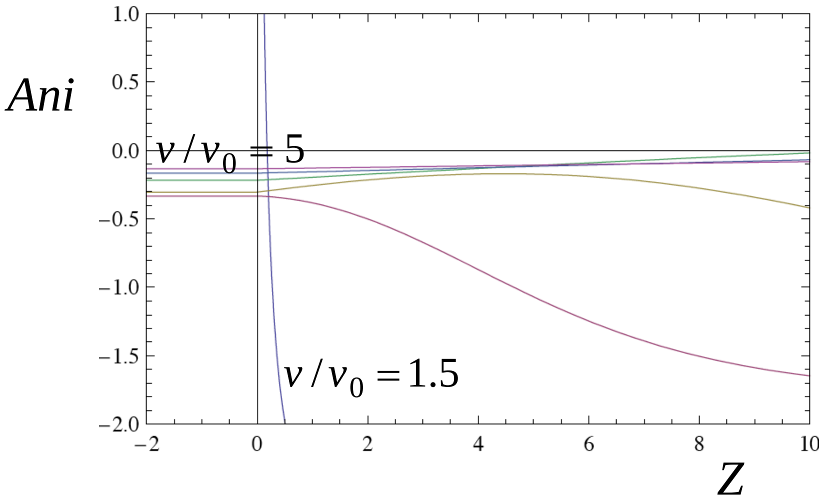


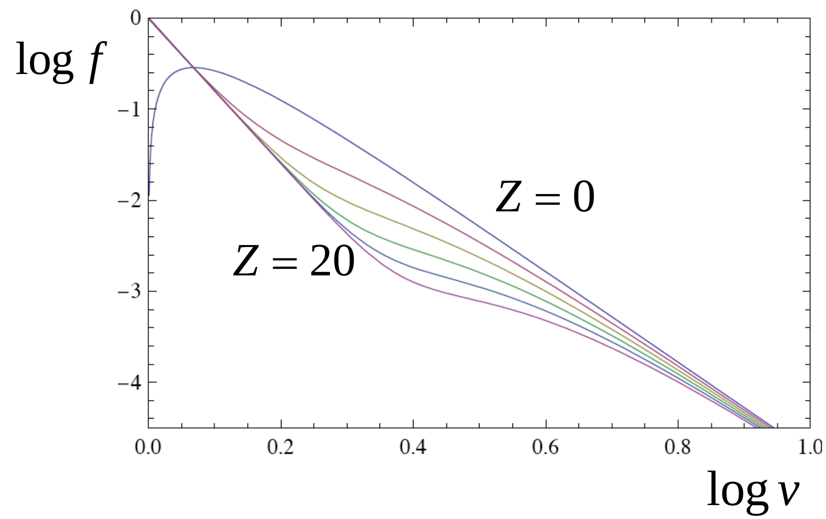
$$f_\infty = (v / v_0)^{-8}$$

$$K_{zz} = K_0 (v / v_0)^2$$

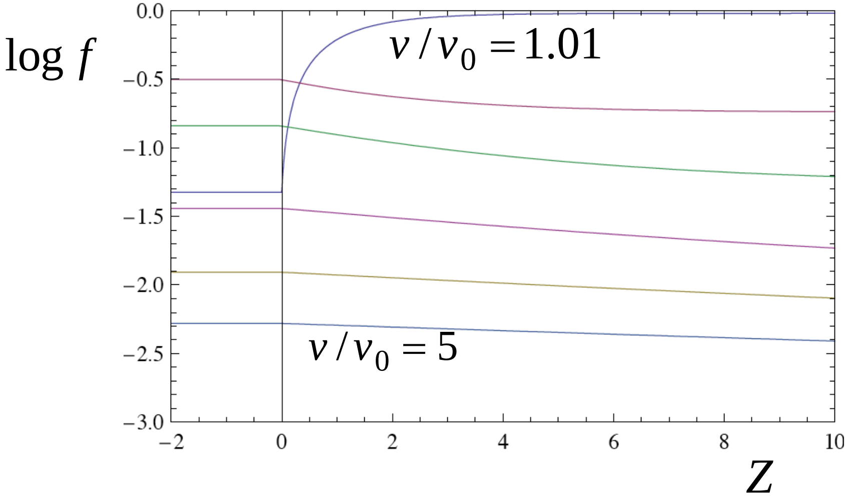
$$Z = Vz / K_0$$

$$\beta = 5$$





Planar Stationary SA - II

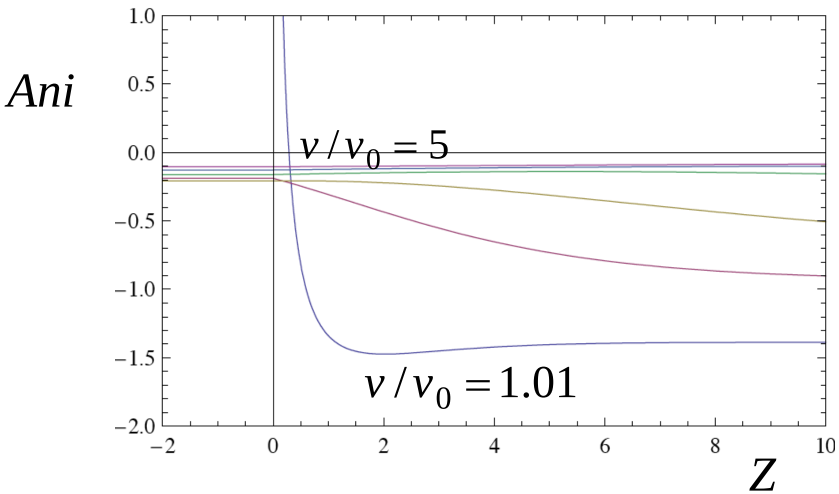


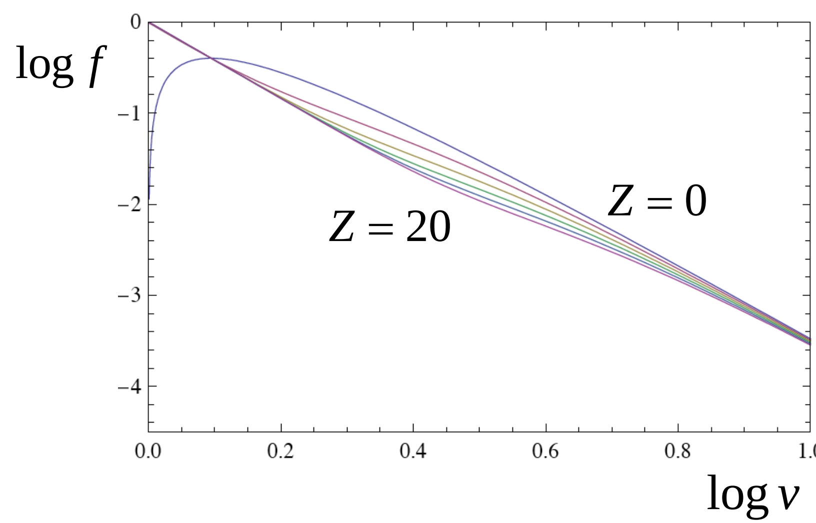
$$f_\infty = (v / v_0)^{-4.2}$$

$$K_{zz} = K_0 (v / v_0)^2$$

$$Z = Vz / K_0$$

$$\beta = 5$$





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Example Event: 1999 / 47-49 (Cold Seeds)

Density compression: $\rho_d/\rho_u \sim 2.9$

Clear proton foreshock of appropriate scale.

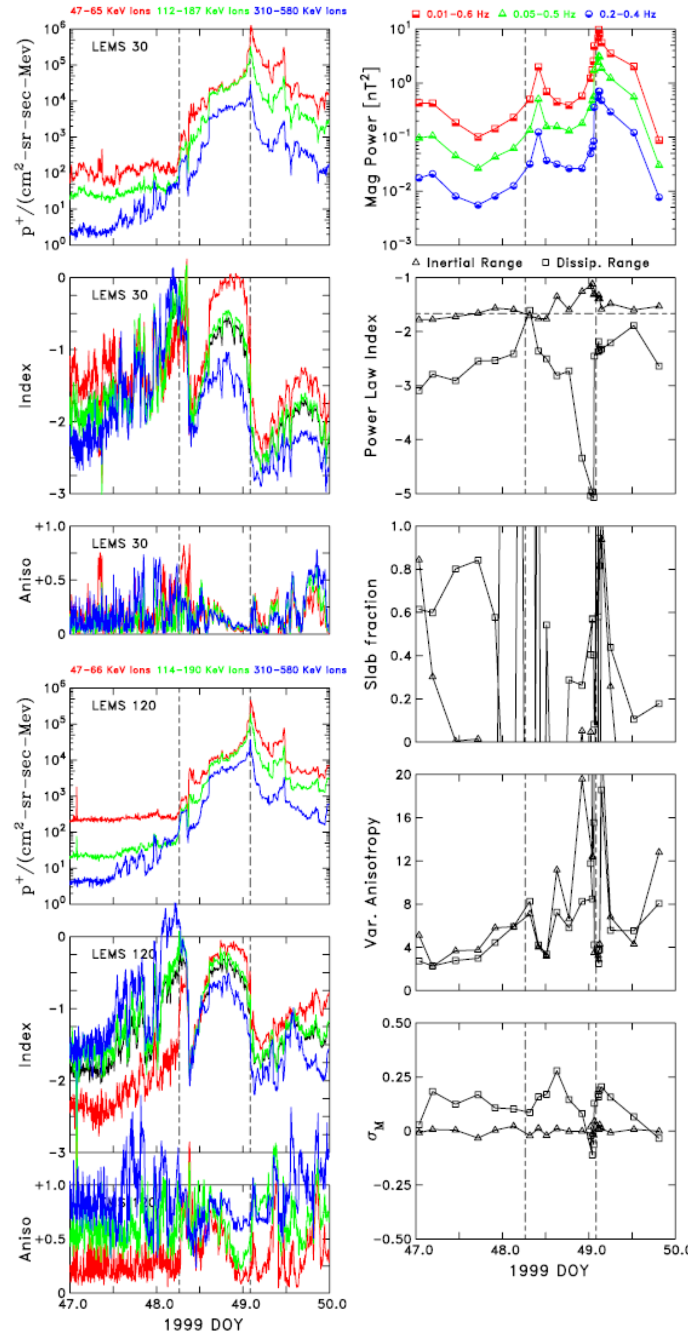
Softening particle spectra on the same ESP scale.

Particle intensity index appropriate to shock strength.

Small proton anisotropy.

Wave foreshock appropriate scale.

Argued and confirmed to be cold ion seed population leading to shock acceleration.



Example Event: 1998 / 217-219 (Hot Seeds)

Density compression: $\rho_d/\rho_u \sim 1.8$

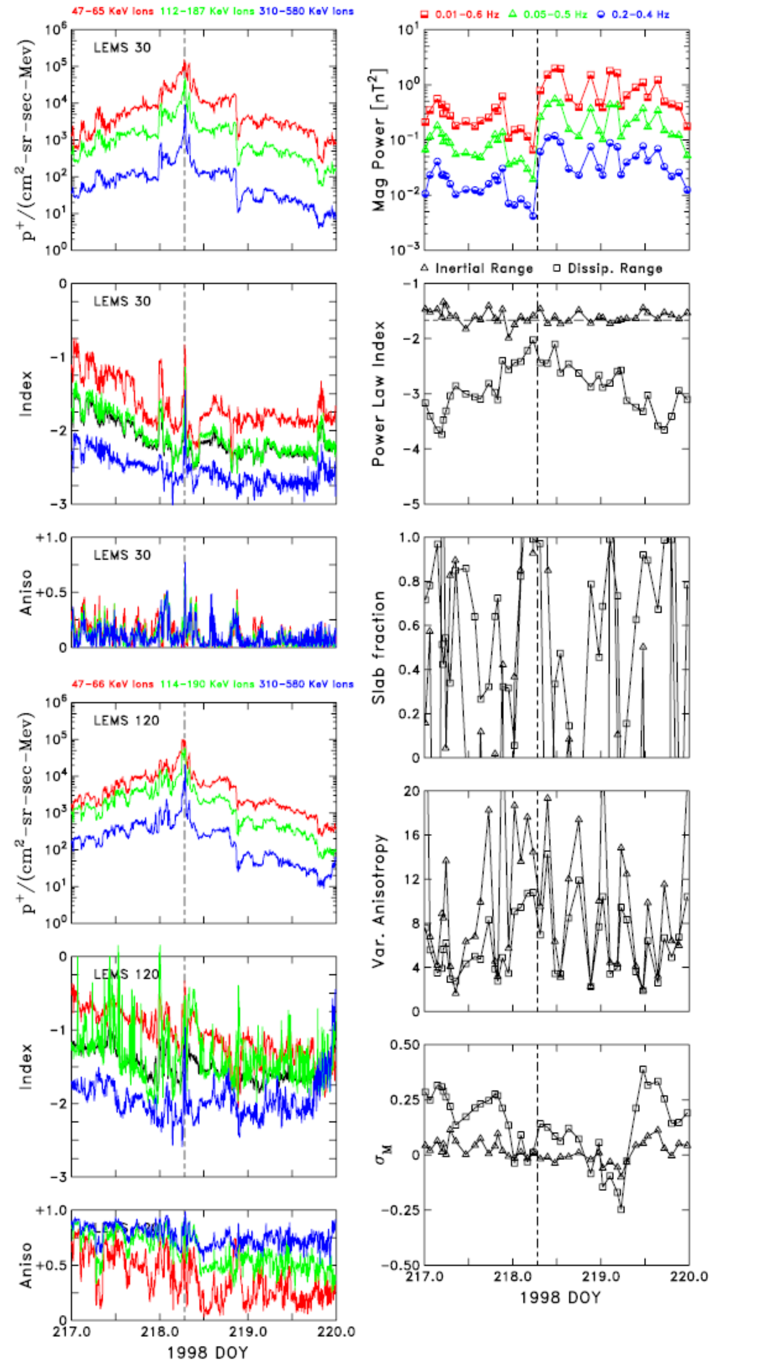
<u>Very modest or questionable</u> proton foreshock if SEP event is properly recognized.

Softening particle spectra on SEP scale.

Moderate proton anisotropy.

Nonexistent wave foreshock.

Argued and confirmed to be hot ion seed population leading to shock acceleration.



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Wave Excitation - I

$$-V\partial I_{\pm} / \partial z = 2\gamma_{\pm} I_{\pm}$$

$$I \cong I_{+} = I_{+}^{\square}(k) + \frac{4\pi^2}{k^2}\frac{V_A}{V}|\Omega_p| m_p \cos\psi \int_{|\Omega_p/k|}^{\infty} dv v^3 \left(1 - \frac{\Omega_p^2}{k^2 v^2}\right)(f_p - f_{p,\infty})$$

$$f_{p,\infty} = \overline{n}_p (4\pi v_{p,0}^2)^{-1} \delta(v - v_{p,0}) + \overline{C} v^{-\gamma} S(v - \overline{v}_{p,0})$$

Wave Excitation - II

$$I = I_{+}^{\square} + \frac{4\pi^2}{k^2}\frac{V_A}{V}|\Omega_p|\, m_p \cos\psi \int_{|\Omega_p/k|}^{\infty} dv\, v^3 \left(1 - \frac{\Omega_p^2}{k^2 v^2}\right) \cdot$$

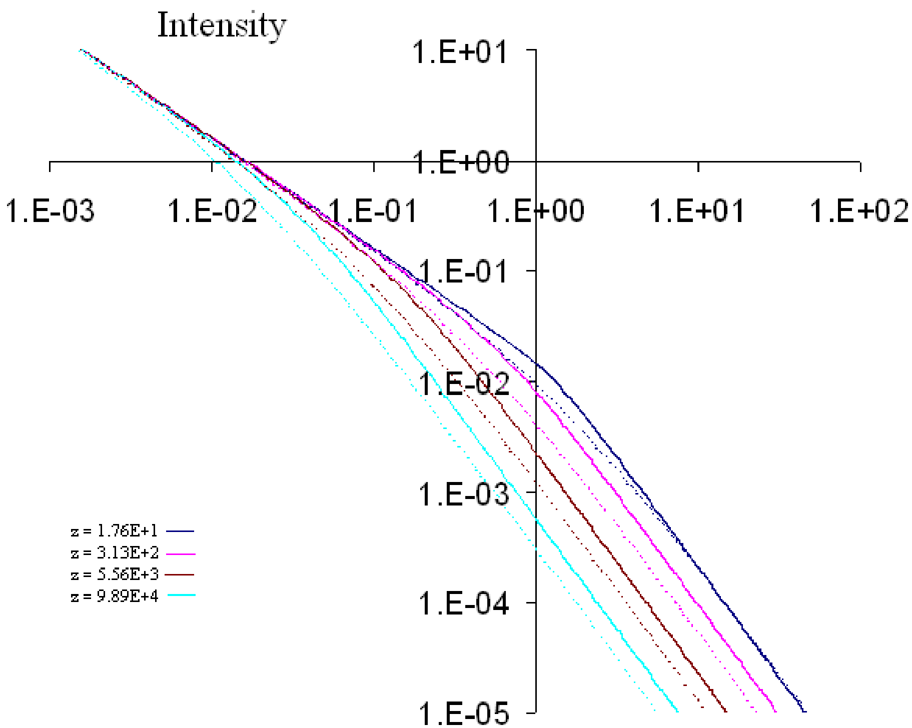
$$\cdot \left\{ \frac{\beta \bar{n}}{4\pi v_{0,p}^3} \left(\frac{v}{v_{0,p}}\right)^{-\beta} S(v - v_{0,p}) - \frac{\bar{n}}{4\pi v_{0,p}^2} \delta(v - v_{0,p}) \right.$$

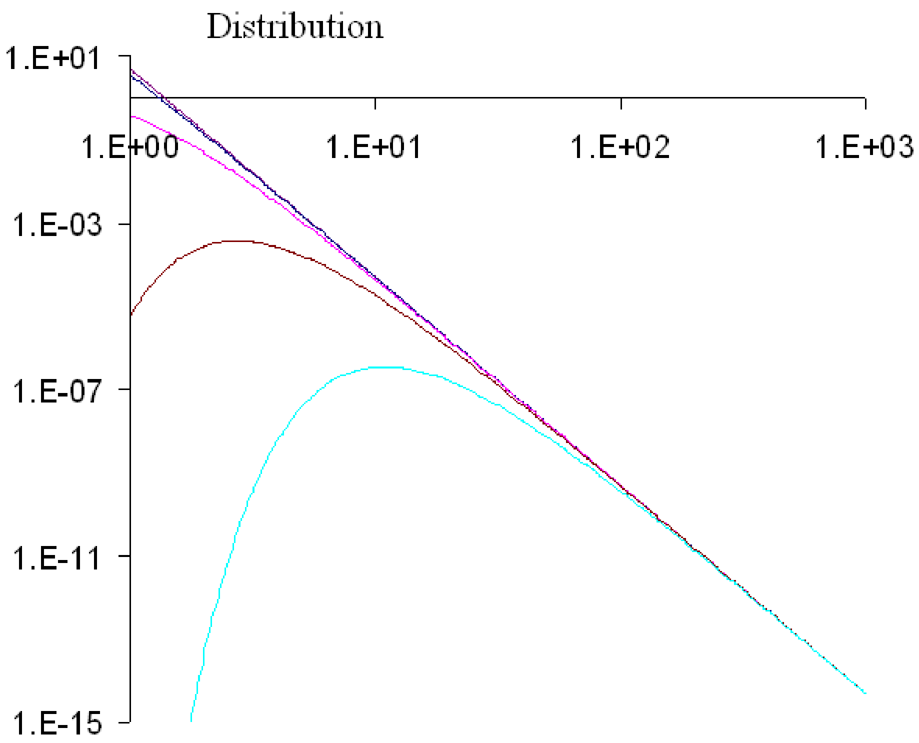
$$\left. + \frac{\bar{C}\,\bar{v}_{0,p}^{-\gamma}}{\beta - \gamma} \left[\gamma \left(\frac{v}{\bar{v}_{0,p}}\right)^{-\gamma} - \beta \left(\frac{v}{\bar{v}_{0,p}}\right)^{-\beta} \right] S(v - \bar{v}_{0,p}) \right\} \cdot$$

$$\cdot \exp\left\{ -V \int_0^z dz' \left[\cos^2\psi \frac{v^3}{4\pi} \frac{B_0^2}{\Omega_p^2} \int_{-1}^{1} d\mu \frac{|\mu|(1-\mu^2)}{I(\Omega_p \mu^{-1} v^{-1})} + \sin^2\psi\, K_\perp \right]^{-1} \right\}$$

Wave Excitation - III

$\beta = 7; \; I_0(k) \approx 0$





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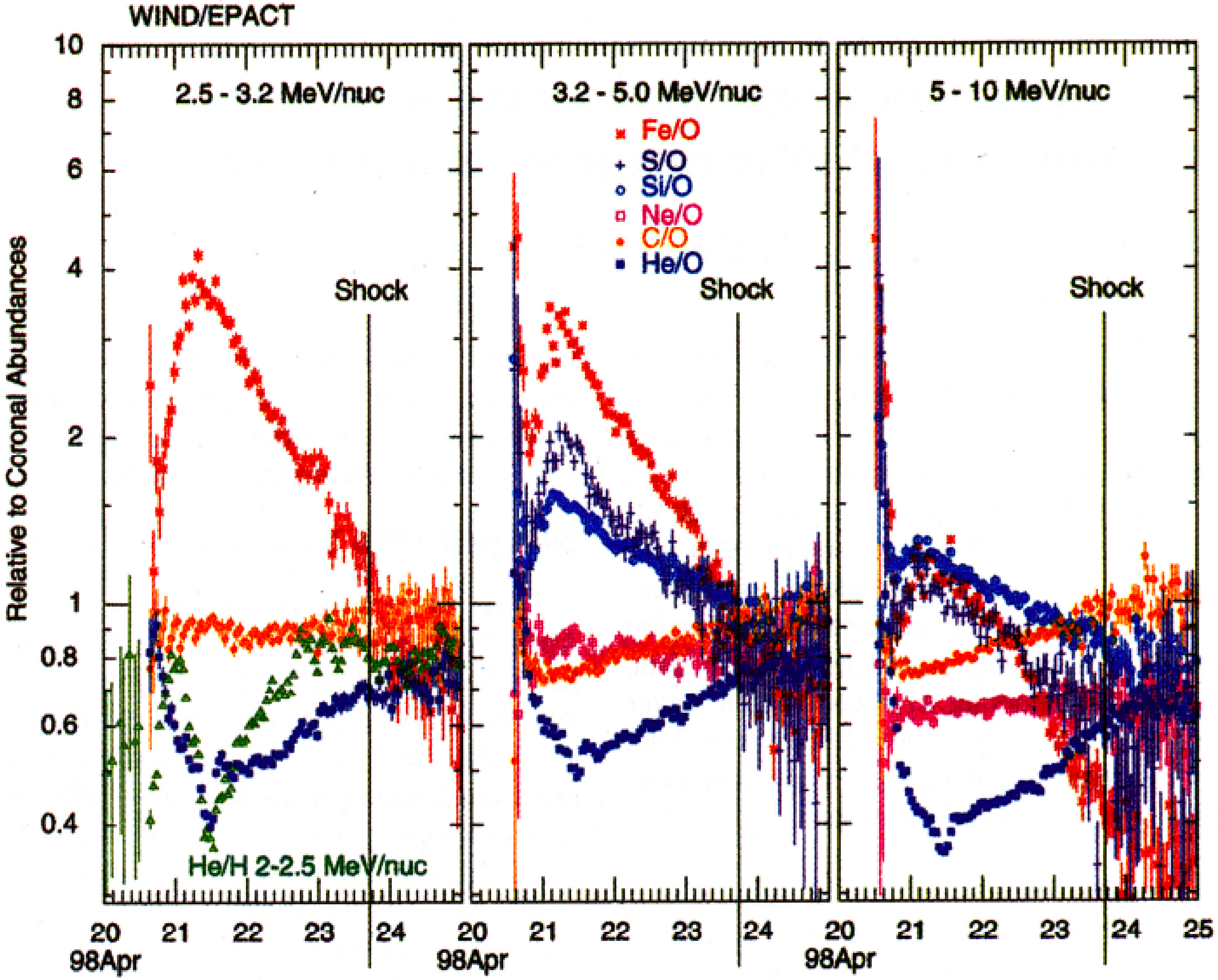
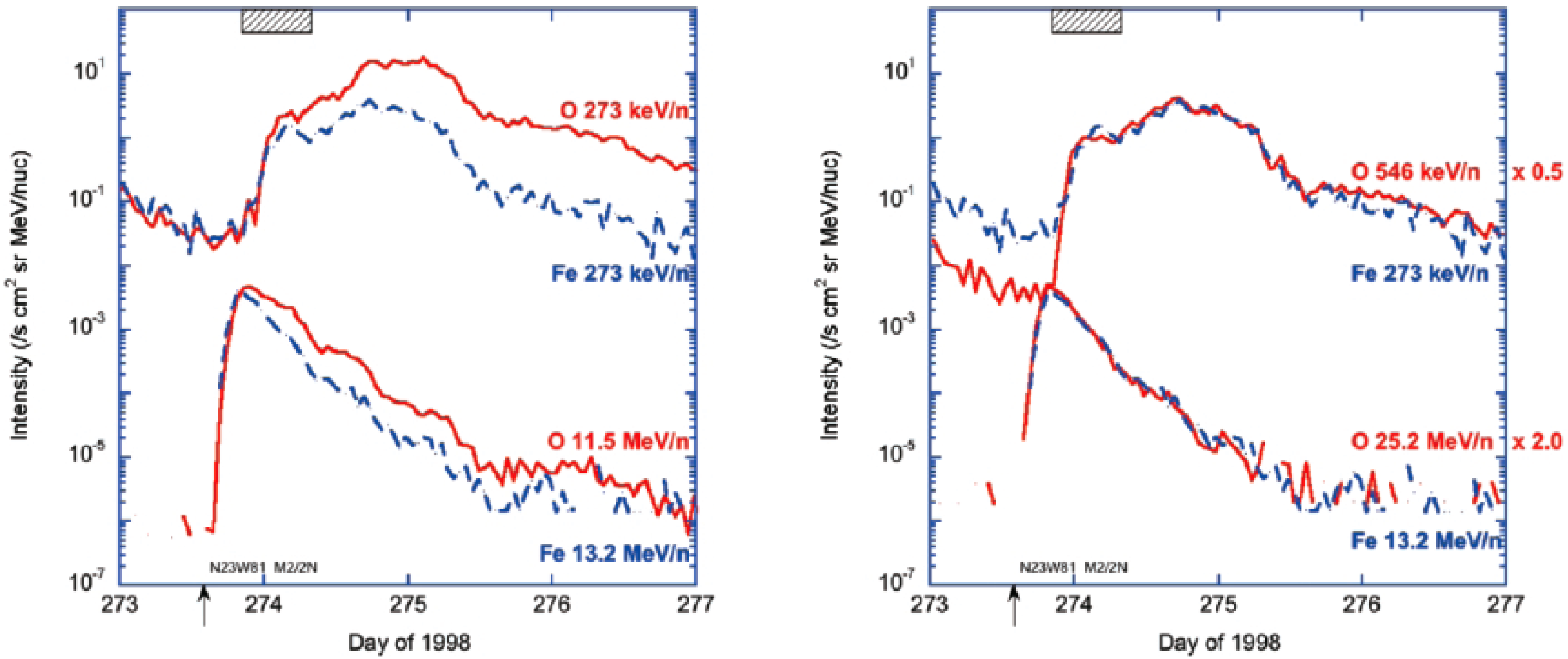
Ion Fractionation



Tylka et al., 1999

Fe and O Time Profiles



Mason et al., 2006

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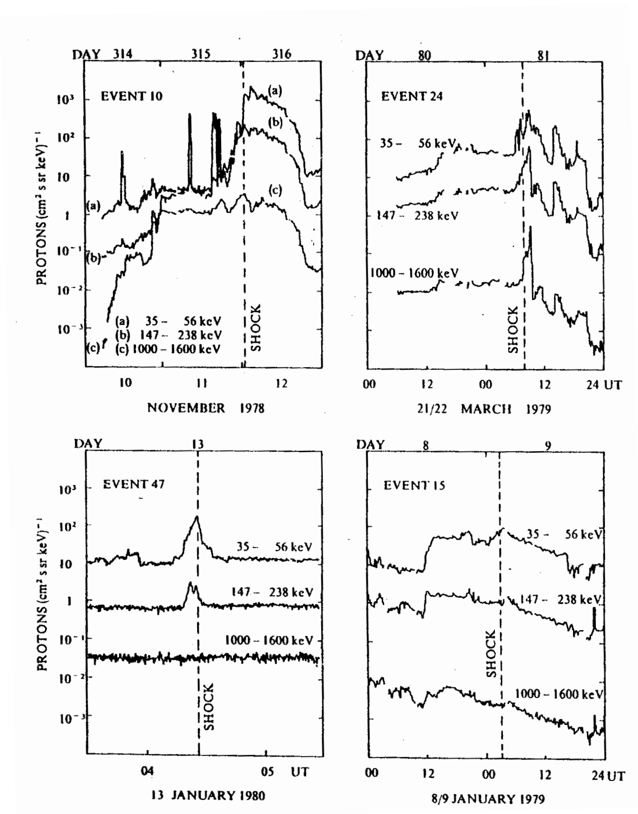
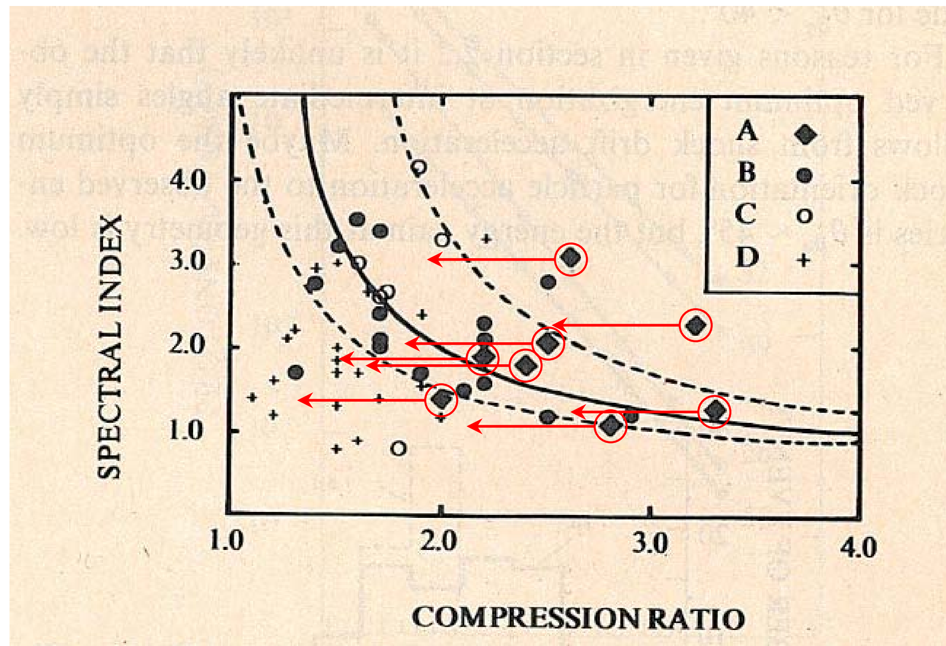
Complications within DSA

Wave-frame compression ratio:





Van Nes et al., 1984

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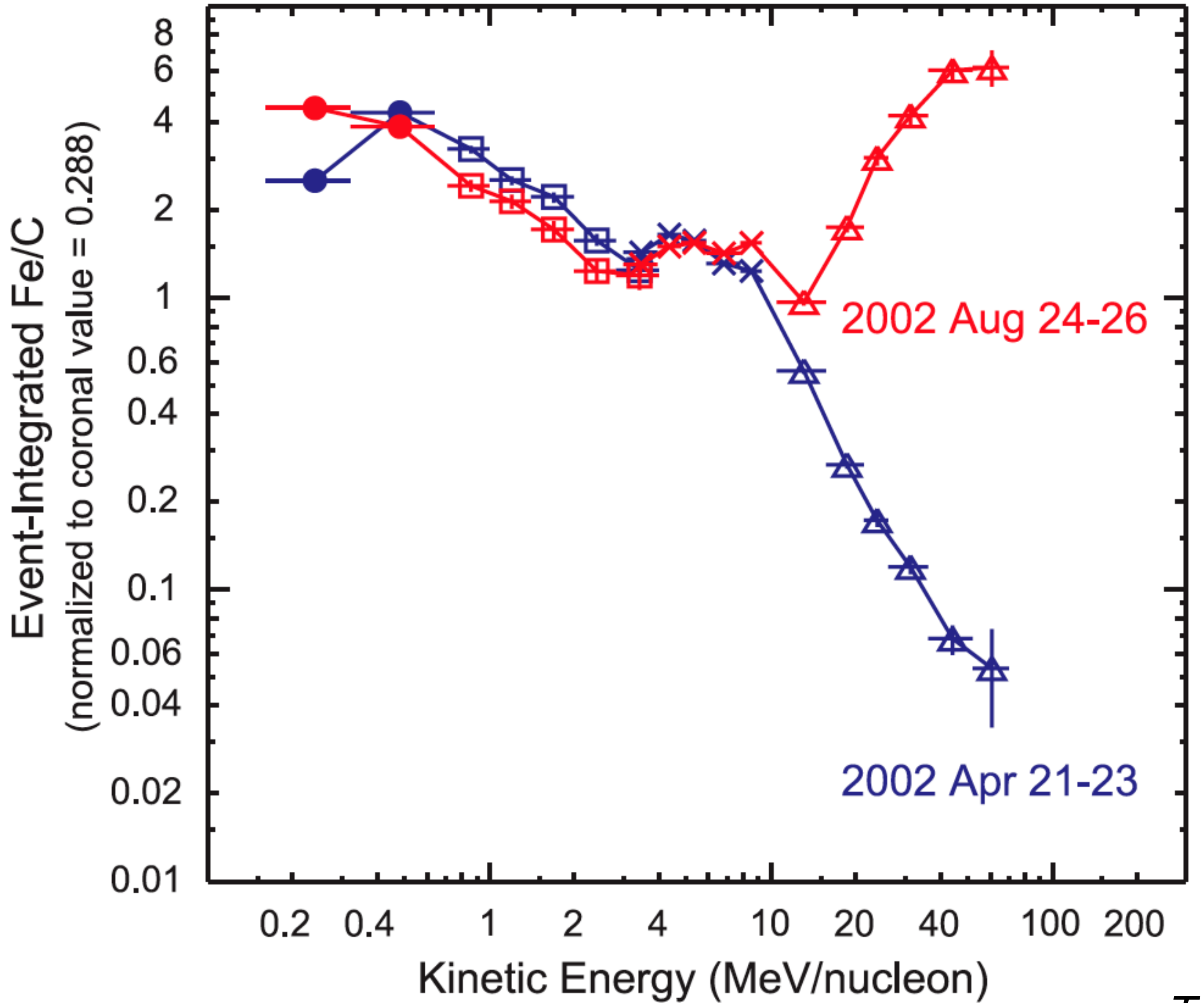
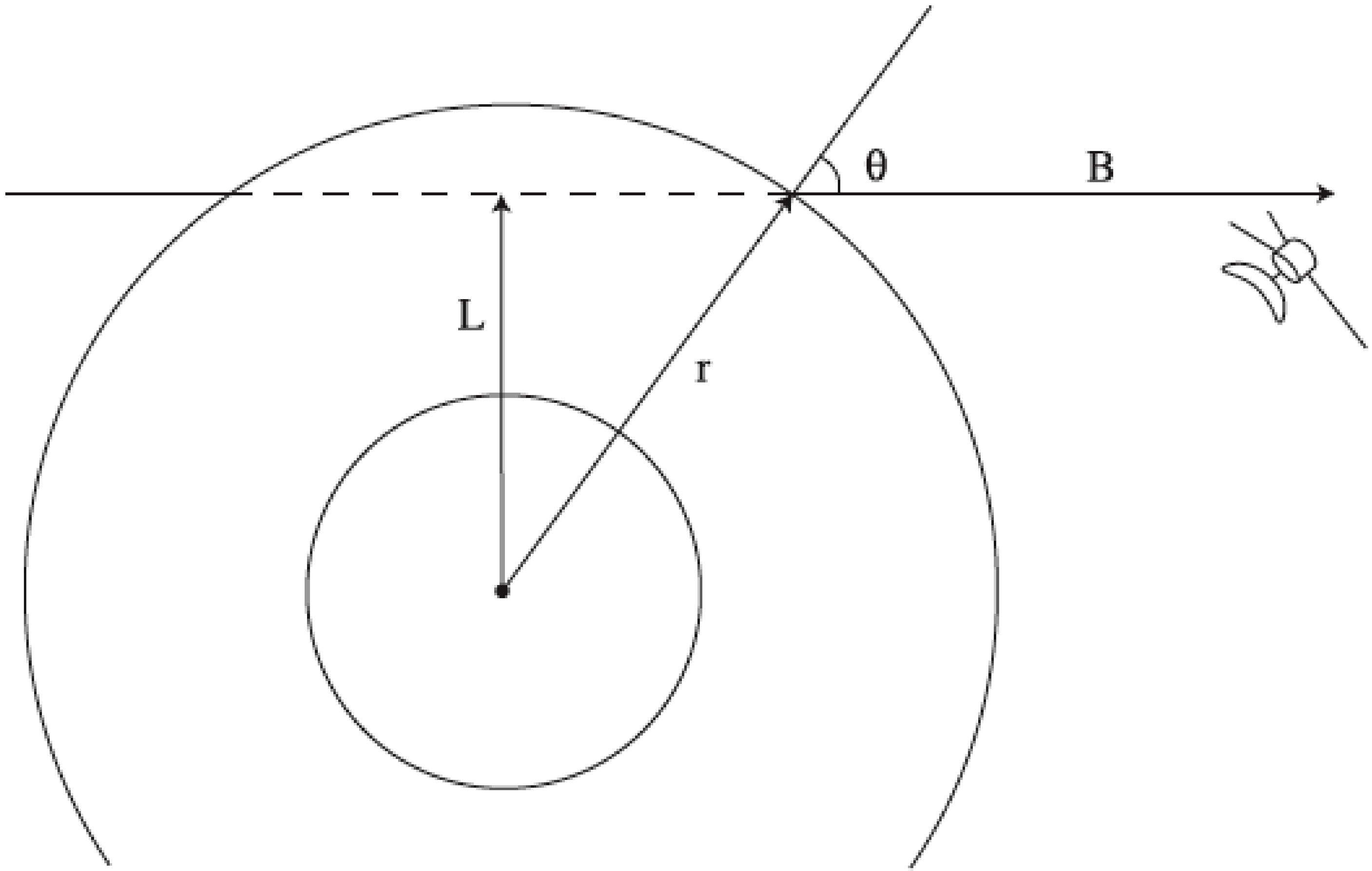
Fe/O Versus Energy



Tylka et al., 2005

Time Evolution



$$v_t \approx V \sec\theta$$

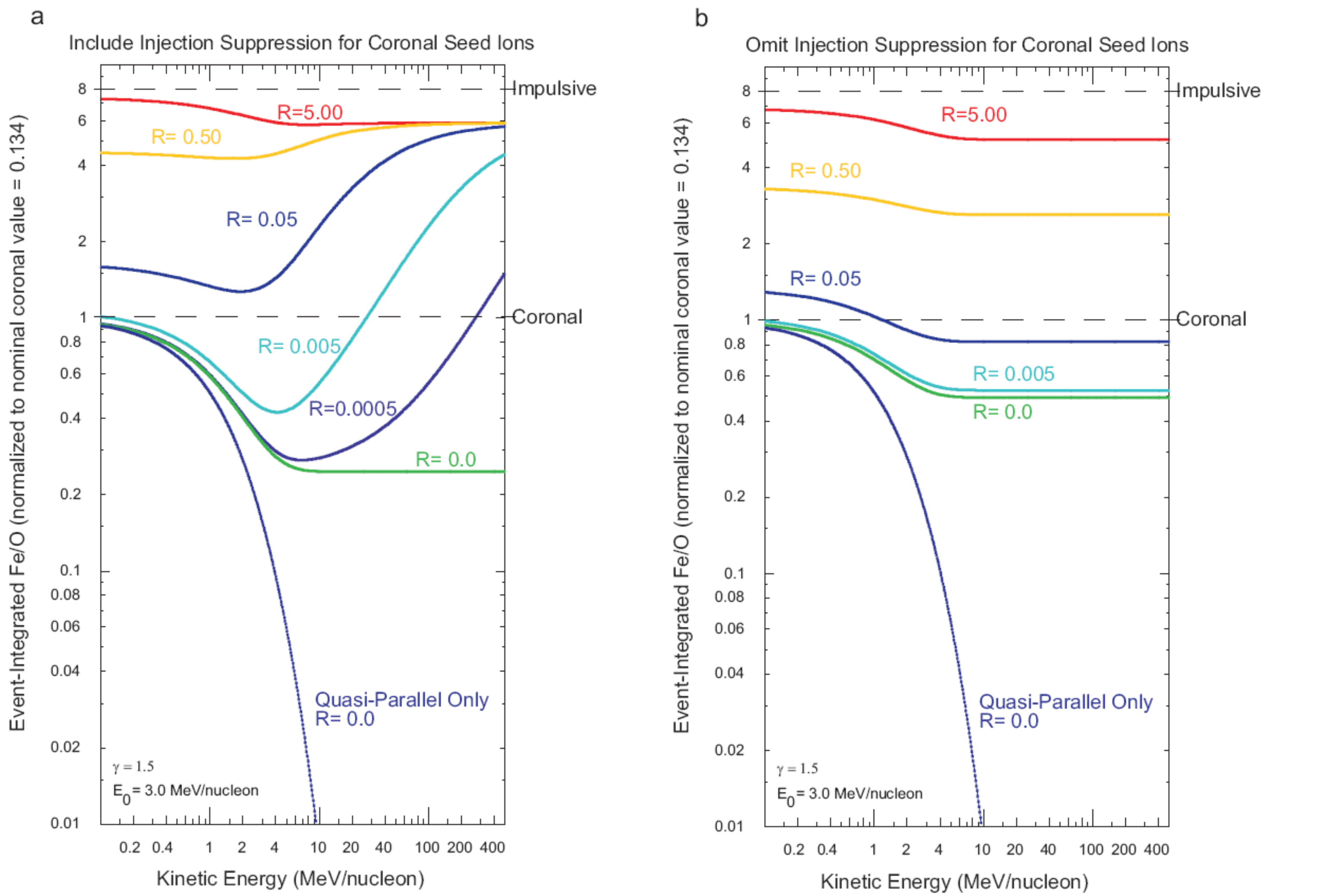
A Simple Model for Composition

$$\overline{F}_{i,flare}(E) = C_{i,flare} E^{-\gamma} \int_{\xi_{min}}^{\xi_{max}} \exp(-E\xi^{2/(2\gamma-1)}/\check{E}_{0i,flare}) d\xi / \int_{\xi_{min}}^{\xi_{max}} d\xi$$

$$\overline{F}_{i,coronal}(E) = C_{i,coronal} E^{-\gamma} \int_{\xi_{min}}^{\xi_{max}} \xi \exp(-E\xi^{2/(2\gamma-1)}/\check{E}_{0i,coronal}) d\xi / \int_{\xi_{min}}^{\xi_{max}} d\xi,$$

Tylka and Lee, 2006

Fe/O Versus Energy



Tylka and Lee, 2006

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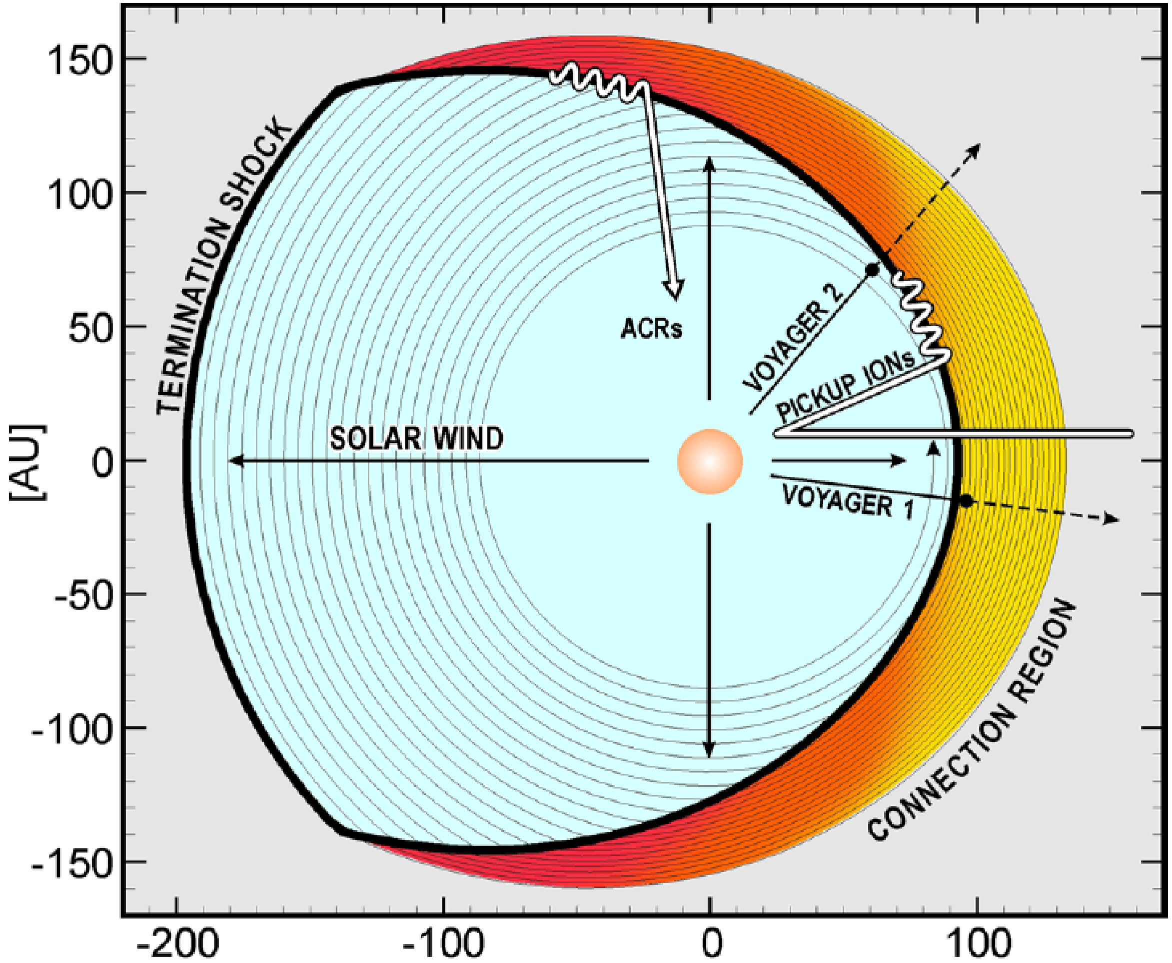
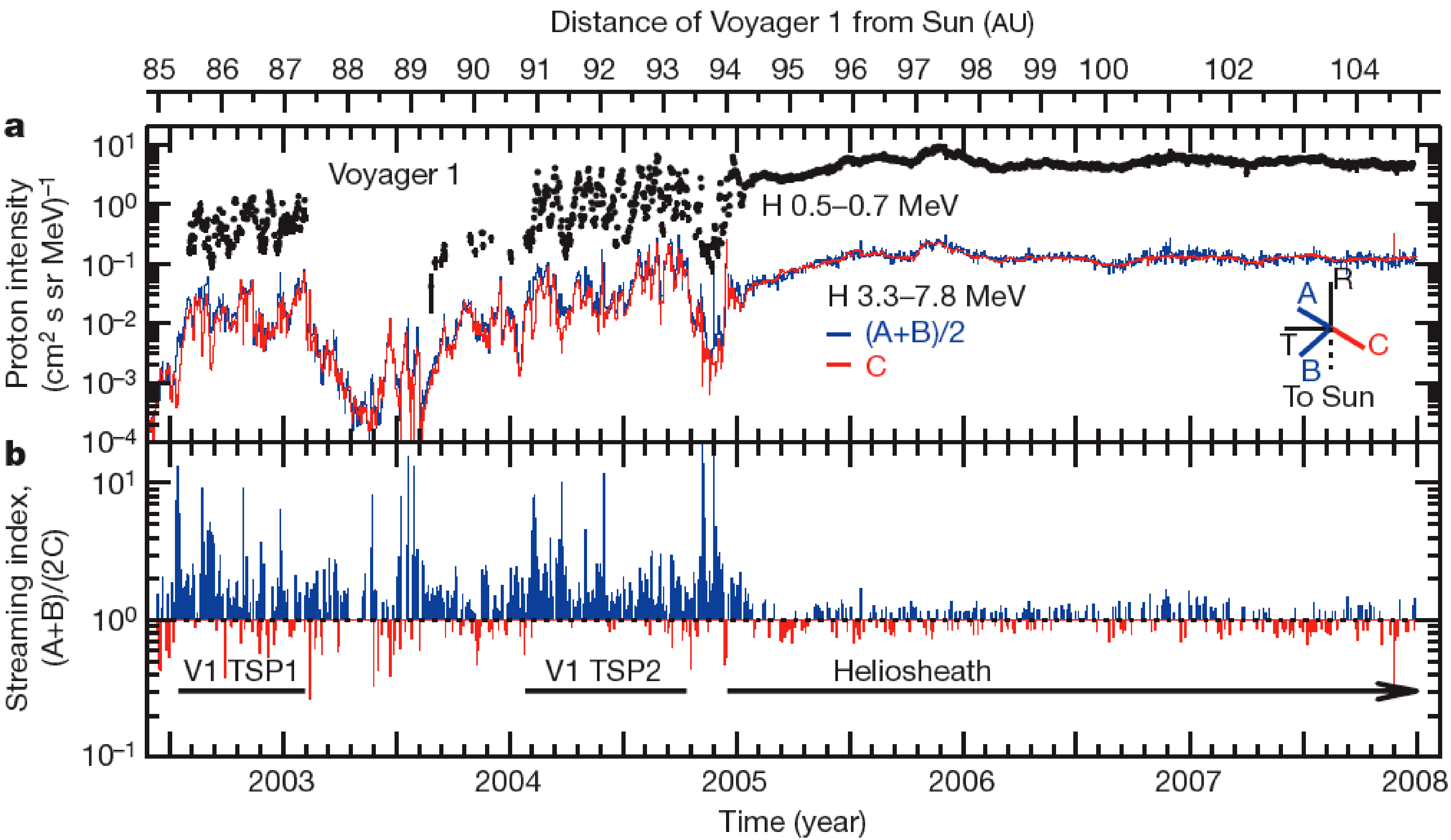
The Blunt Termination Shock

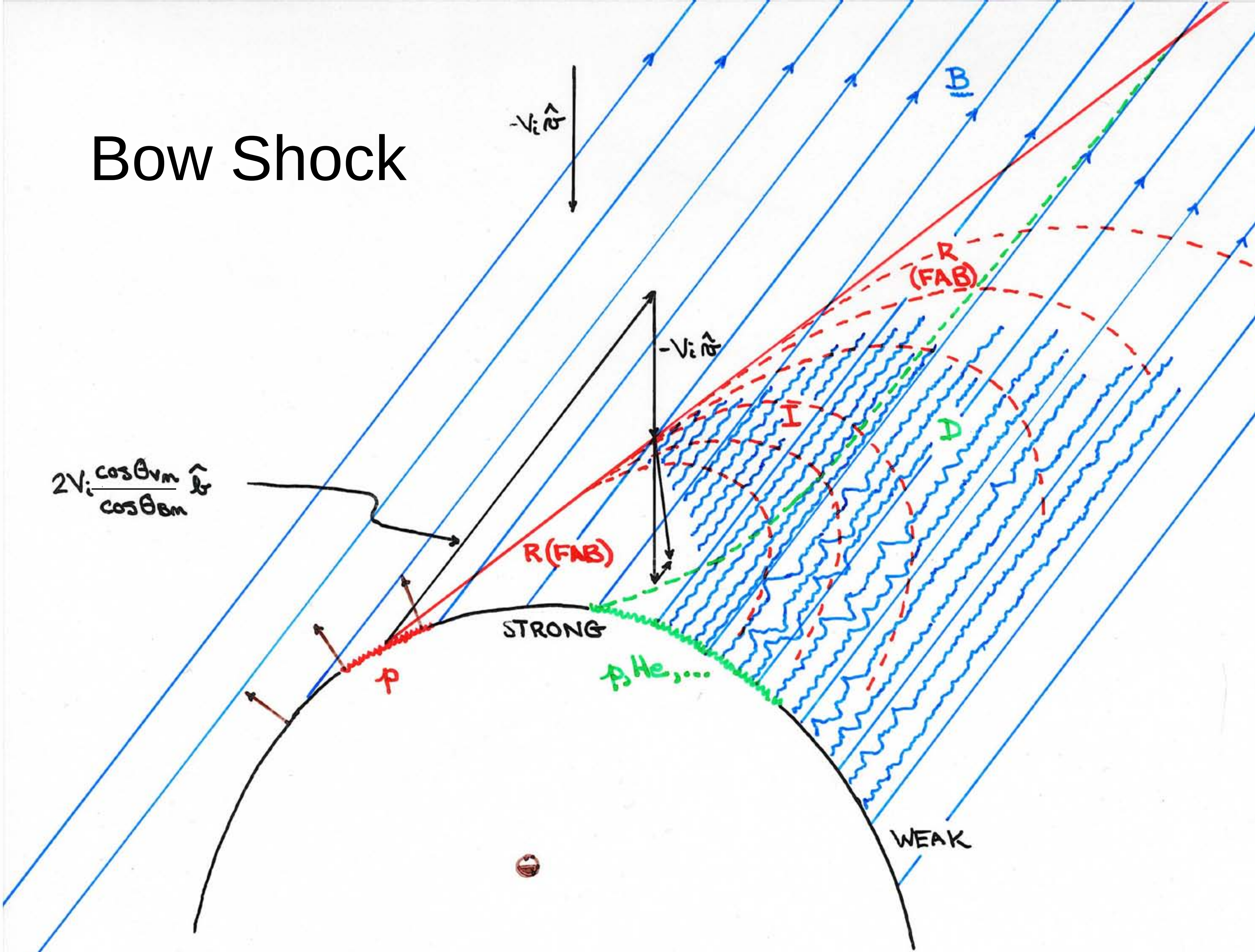


McComas and Schwadron, 2006

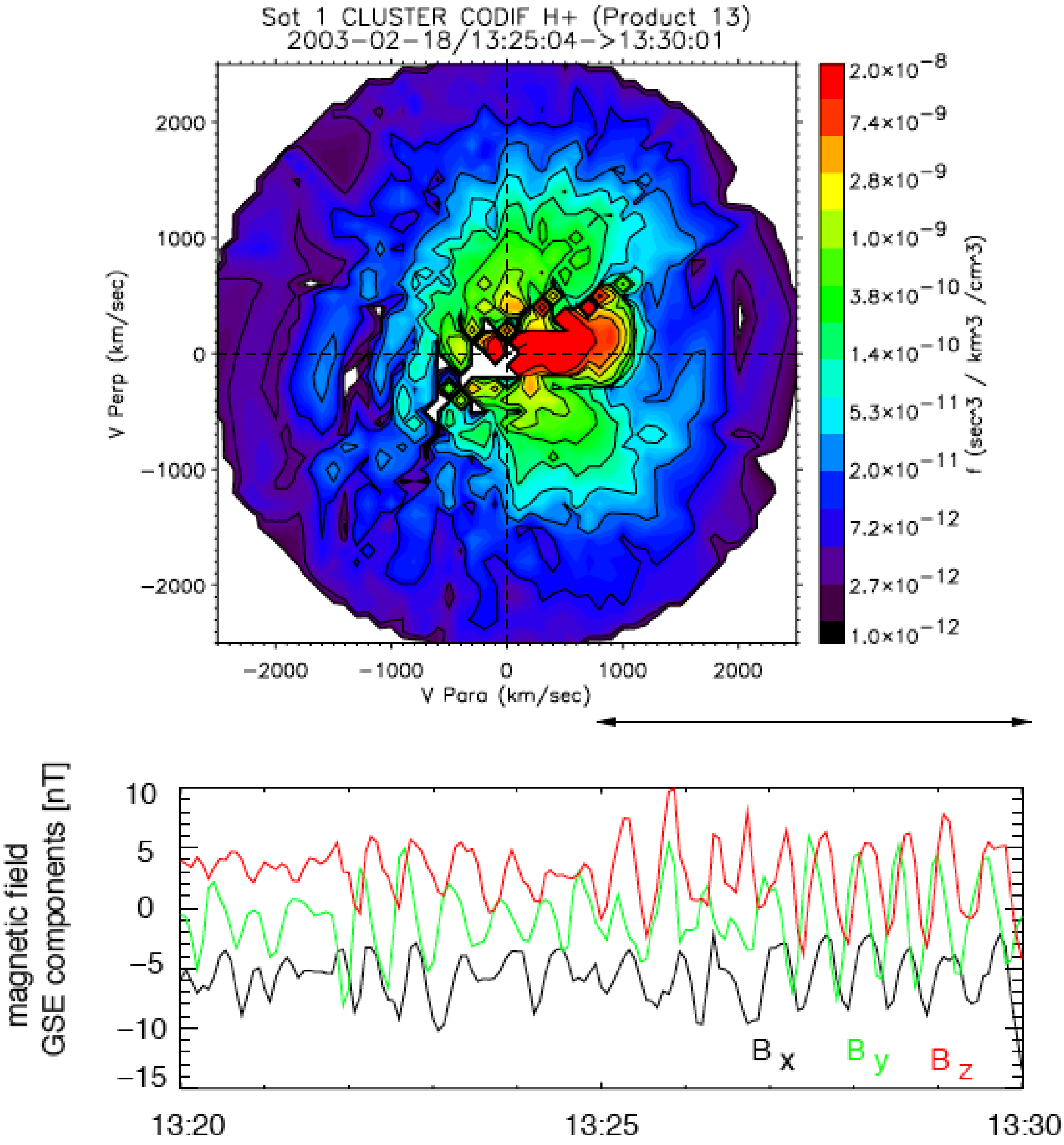


Stone et al., 2008

Bow Shock

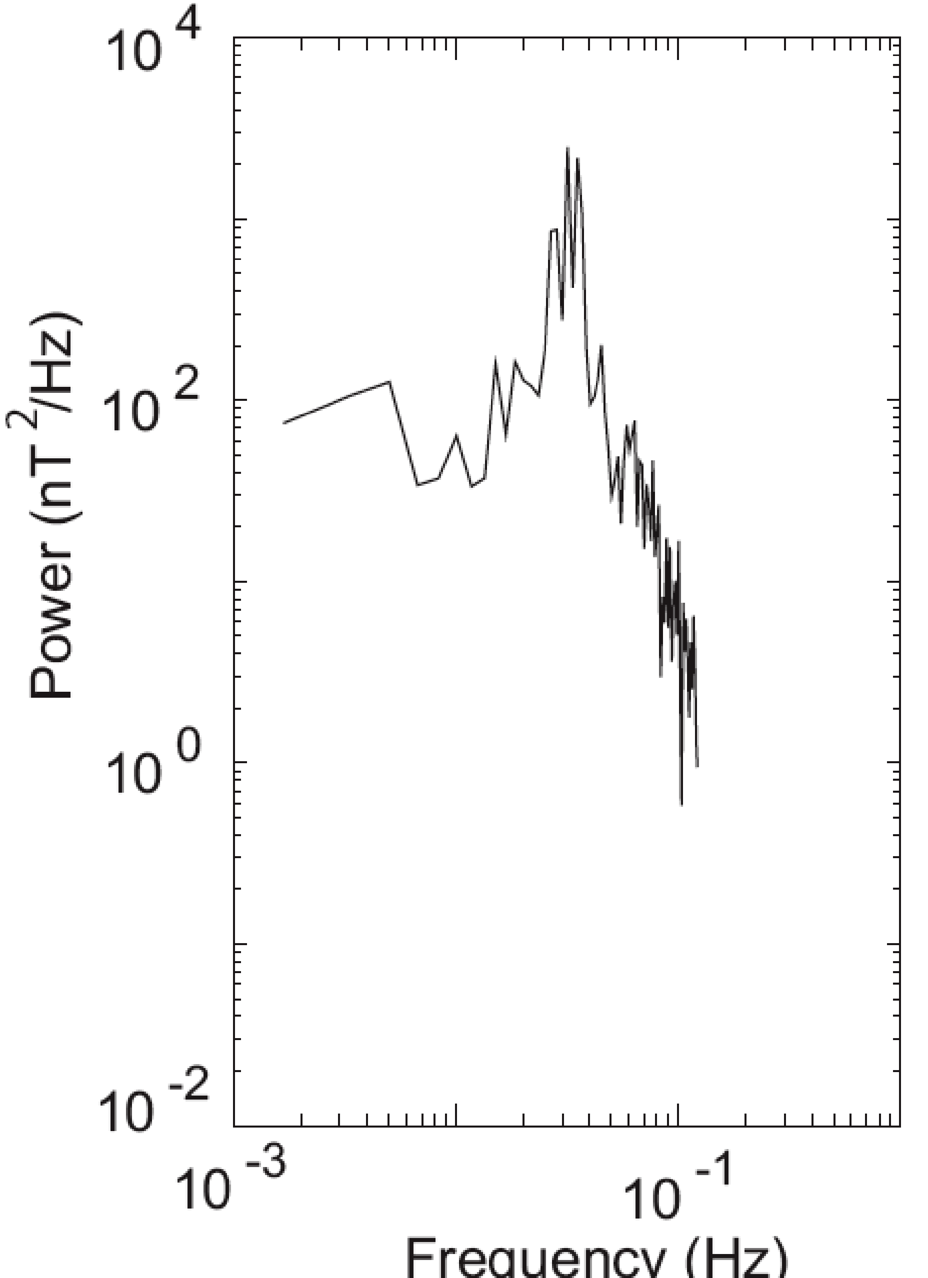


$-V_i\hat{n}$
B
R
(FAB)
$-V_i\hat{n}$
I
D
$2V_i\frac{\cos\theta_{vn}}{\cos\theta_{Bn}}\hat{b}$
R(FAB)
STRONG
p
p, He,...
WEAK



Kis et al., 2007

13:20 - 13:30 UT, February 18, 2003



Kis et al., 2007

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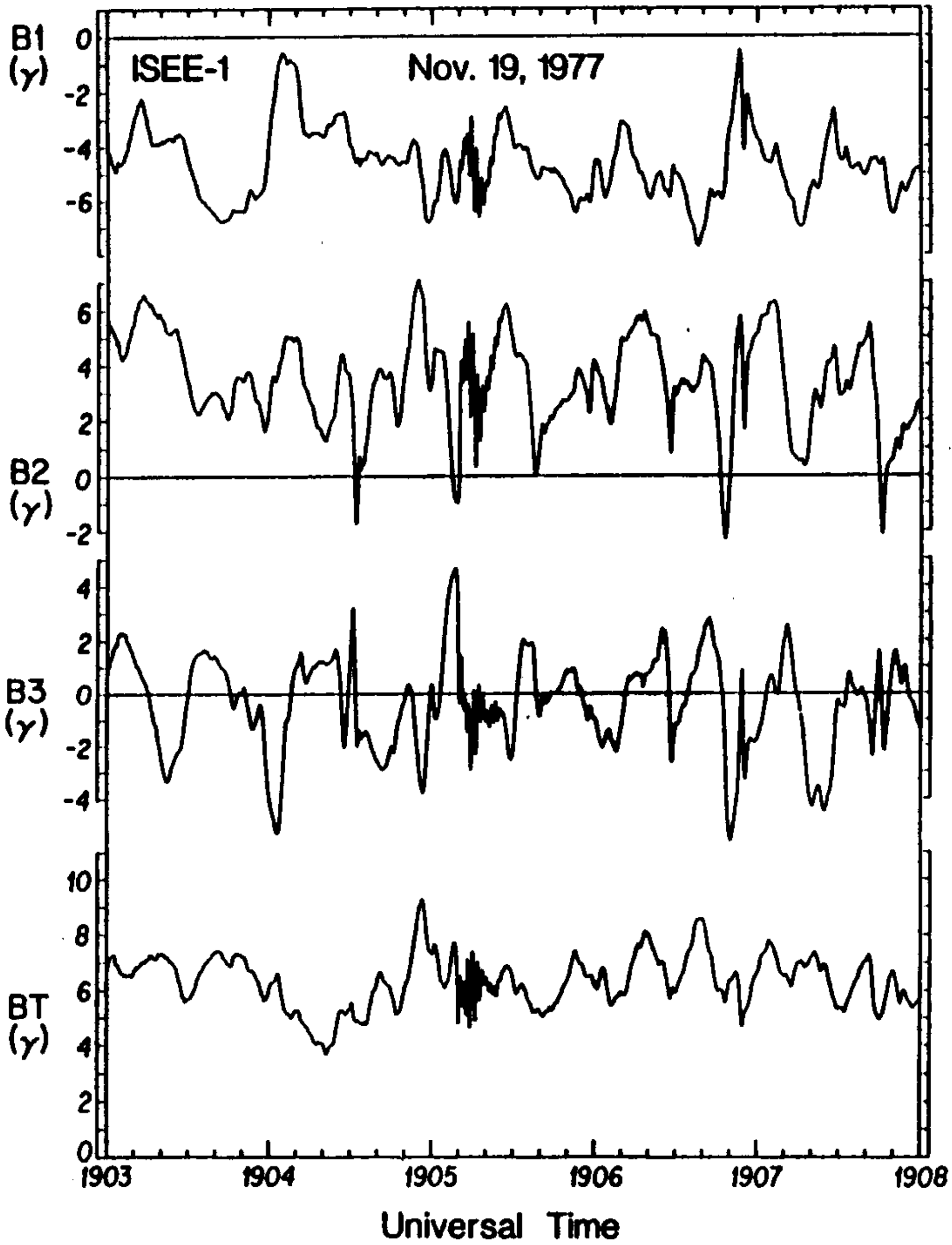
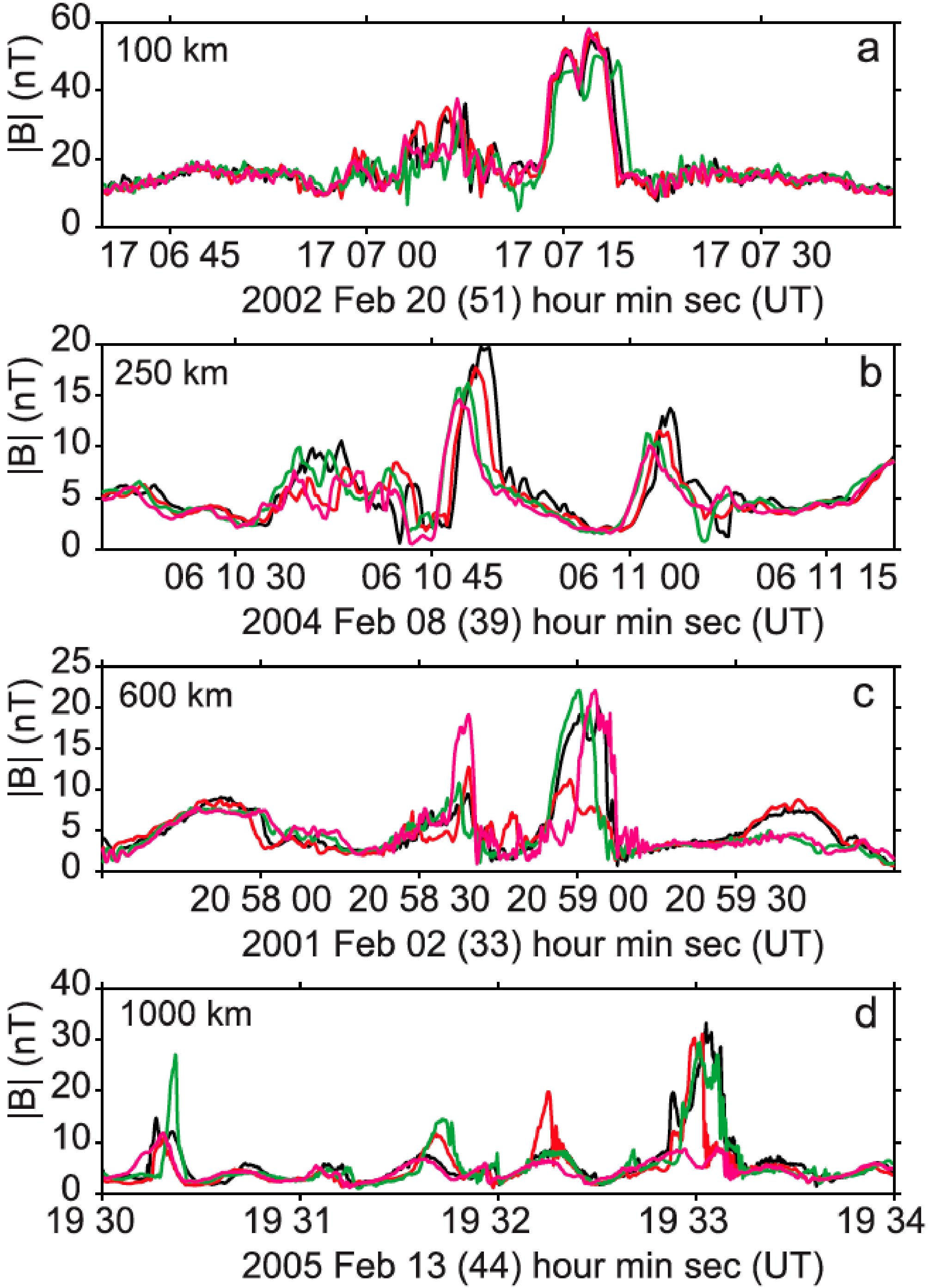


Upstream Waves

Hoppe et al., 1981



SLAMS

Lucek et al., 2008

Growth of a SLAMS

$$\left(V_{sw} - \frac{B}{B_0} V_A\right)\frac{dB^2}{dz} = C\left(1 - \frac{B_0}{B}\right)\frac{B}{B_0} V_A \exp\left(\frac{z}{L}\right)$$

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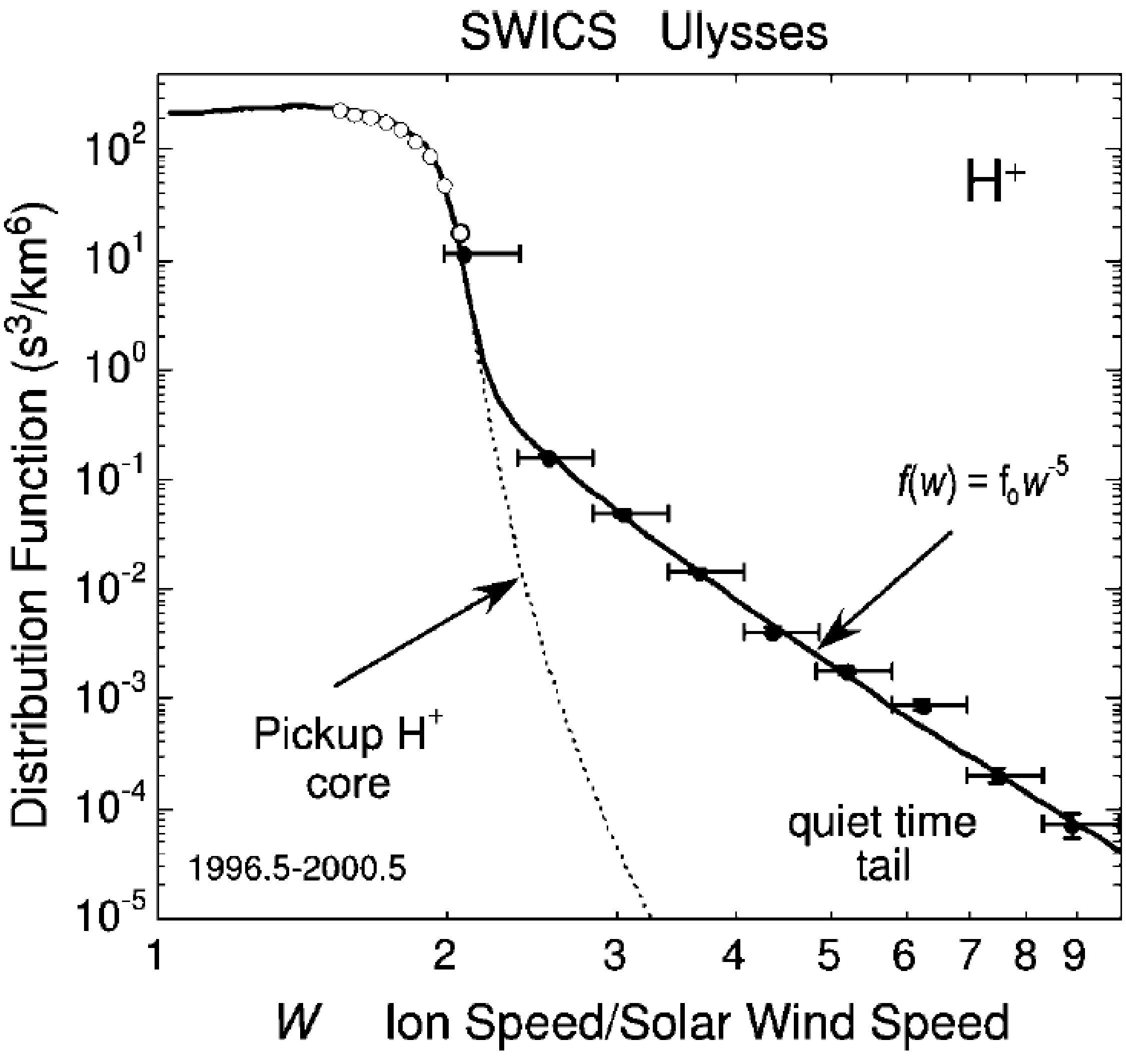
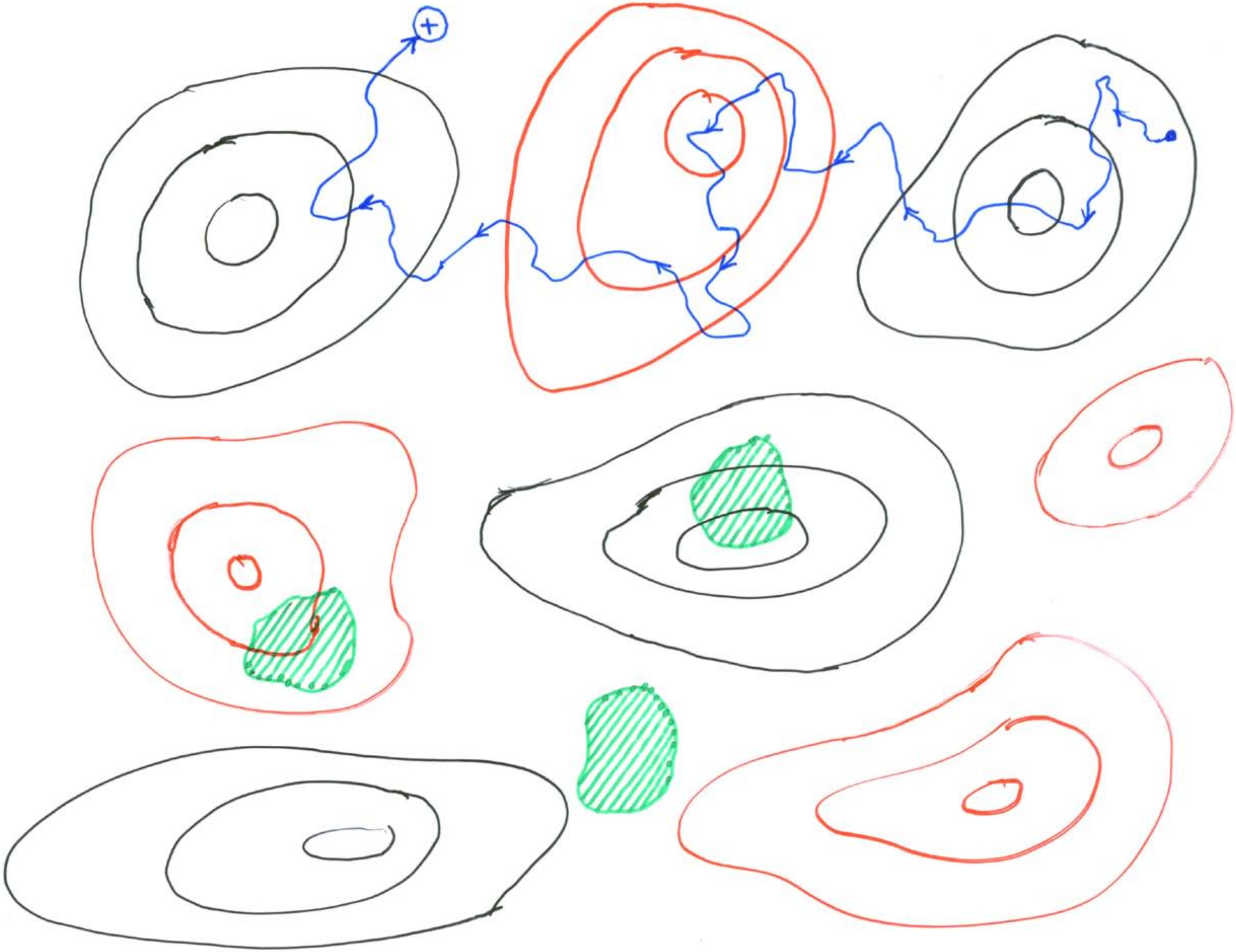
Ubiquitous Suprathermals



Fisk and Gloeckler, 2006

Contours of $\nabla \cdot \mathbf{V} > 0$ and < 0



Compressive Acceleration

Stochastic Compressions and Rarefactions - I

$$\frac{\partial f}{\partial t} + (\mathbf{V} + \mathbf{V}_D) \cdot \nabla f - \nabla \cdot \mathbf{K} \cdot \nabla f - \frac{1}{3} \nabla \cdot \mathbf{V} v \frac{\partial f}{\partial v} = 0$$

$$\frac{\partial f_0}{\partial t} - \frac{1}{3} \frac{1}{v^2} \frac{\partial}{\partial v} \left\langle (\nabla \cdot \delta \mathbf{V}) v^3 \delta f \right\rangle = 0$$

$$\frac{\partial \delta f}{\partial t} - \nabla \cdot \mathbf{K} \cdot \nabla \delta f - \frac{1}{3} (\nabla \cdot \delta \mathbf{V}) v \frac{\partial f_0}{\partial v} = 0$$

Ptuskin, 1988; Jokipii et al., 2003; Webb et al., 2003; Fisk and Gloeckler, 2008

Stochastic Compressions and Rarefactions - II

$$\frac{\partial f_0}{\partial t} = \frac{1}{v^2}\frac{\partial}{\partial v}\left\{\frac{v^4}{9}\int_{-\infty}^{\infty} d^3\mathbf{x}'\int_{-\infty}^{t} dt' G(\mathbf{x},t;\mathbf{x}',t')\left\langle(\nabla\cdot\delta\mathbf{V})(\nabla'\cdot\delta\mathbf{V}')\right\rangle\frac{\partial f_0(v,t)}{\partial v}\right\}$$

$$G(\mathbf{x},t;\mathbf{x}',t') = [4\pi K(t-t')]^{-3/2}\exp\{-|\mathbf{x}-\mathbf{x}'|^2[4K(t-t')]^{-1}\}$$

$$\frac{\partial f_0}{\partial t} = \frac{1}{v^2}\frac{\partial}{\partial v}\left[v^2 D\frac{\partial f_0}{\partial v}\right]$$

Power-law solutions?

Stochastic Compressions and Rarefactions - III

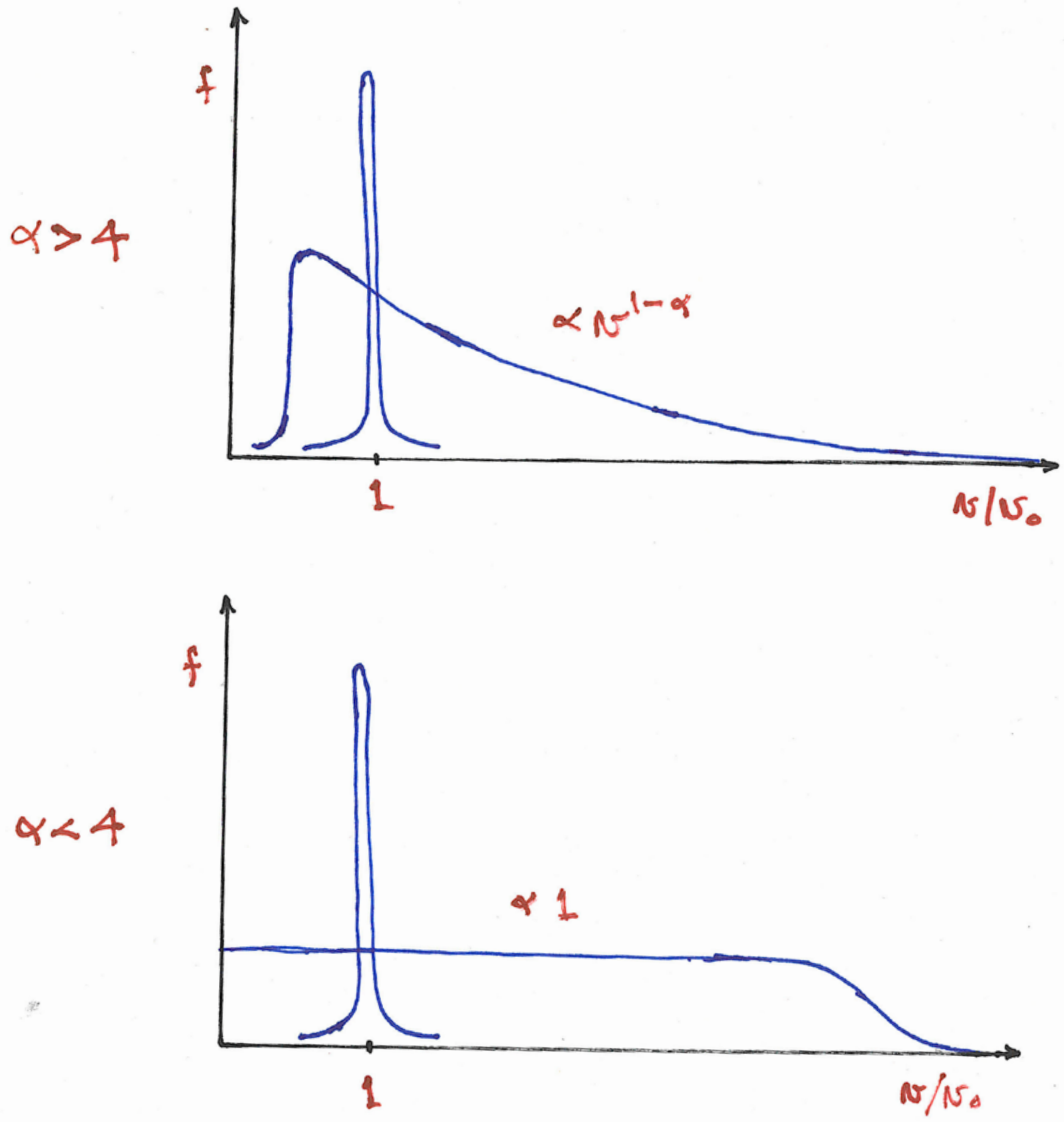
$$\frac{\partial G}{\partial \tau} = \frac{1}{v^2}\frac{\partial}{\partial v}\left[v^{\alpha}\frac{\partial G}{\partial v}\right] + \frac{1}{4\pi}\delta(v-1)\delta(\tau)$$

$$G = \frac{v^{(1-\alpha)/2}}{|4-\alpha|4\pi\tau} I_{\pm p}\left[\frac{2v^{(4-\alpha)/2}}{(4-\alpha)^2\tau}\right]\exp\left[-\frac{1+v^{4-\alpha}}{(4-\alpha)^2\tau}\right]$$

$$p = (1-\alpha)/(4-\alpha)$$

Jokipii and Lee, current

Schematic Plots of Solutions



Stochastic Compressions and Rarefactions - IV

$$\frac{\partial f_0}{\partial t} = \frac{1}{v^2}\frac{\partial}{\partial v}\left\{\frac{v^4}{9}\int_{-\infty}^{\infty} d^3\mathbf{x}'\int_{-\infty}^{t} dt' G(\mathbf{x},t;\mathbf{x}',t')\left\langle(\nabla\cdot\delta\mathbf{V})(\nabla'\cdot\delta\mathbf{V}')\right\rangle\frac{\partial f_0(v,t)}{\partial v}\right\}$$

$$\left\langle(\nabla\cdot\delta\mathbf{V})(\nabla'\cdot\delta\mathbf{V}')\right\rangle = \left\langle(\nabla\cdot\delta\mathbf{V})^2\right\rangle \exp\left[-|\mathbf{x}-\mathbf{x}'|^2\lambda^{-2} - (t-t')T^{-1}\right]$$

$$T << \lambda^2/(4K): \quad D = \frac{v^2}{9}\left\langle(\nabla\cdot\delta\mathbf{V})^2\right\rangle T \qquad \alpha = 4$$

$$T >> \lambda^2/(4K): \quad D = \frac{v^2}{9}\left\langle(\nabla\cdot\delta\mathbf{V})^2\right\rangle \frac{\lambda^2}{2K} \qquad \alpha < 4$$