Proton velocity-space diffusion by waves

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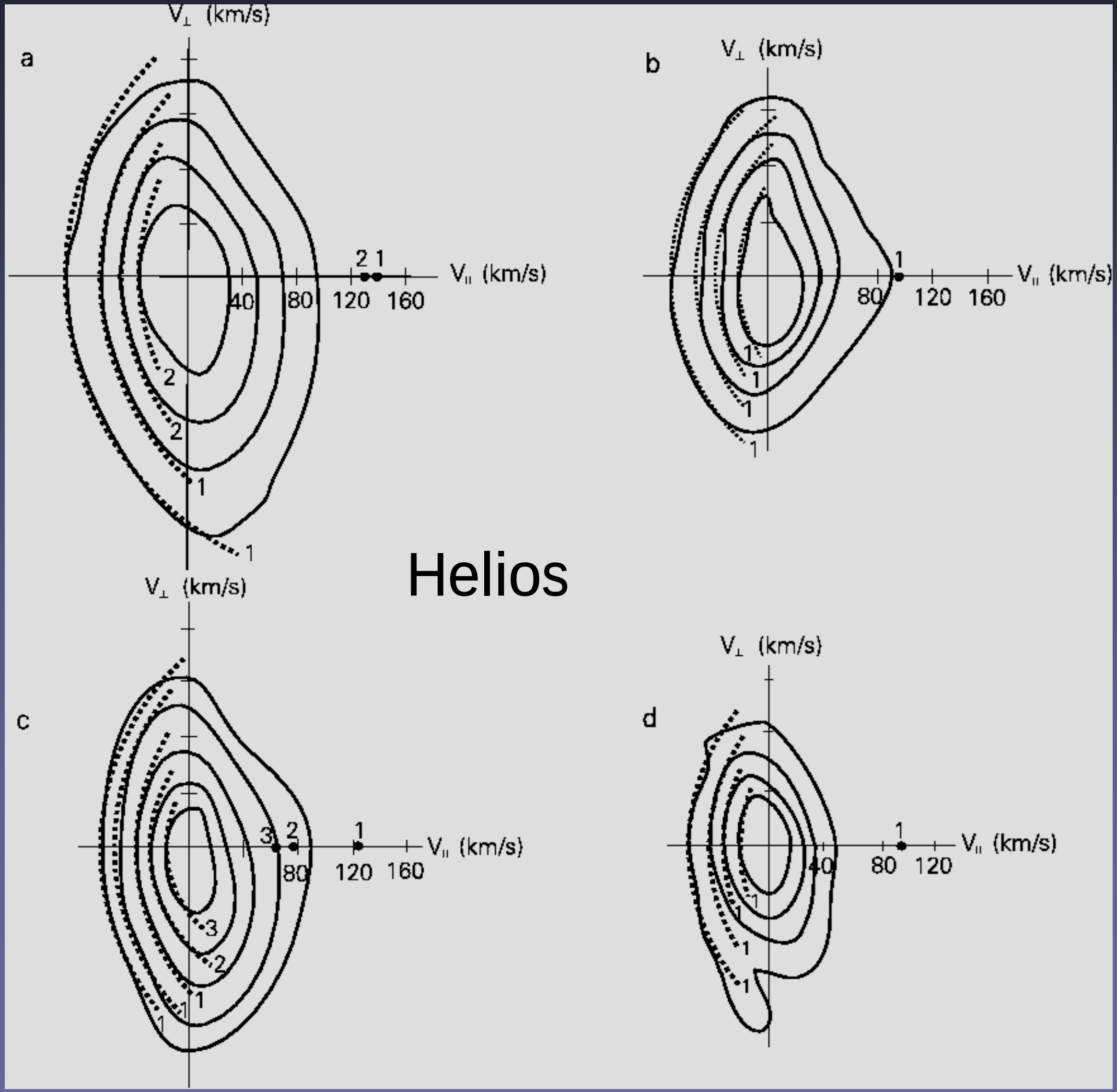
Observation of pitch-angle diffusion



Solar wind proton VDF contours are segments of circles centered in the wave frame ($\omega/k \leq V_A$)

Velocity-space resonant diffusion caused by the cyclotron-wave field

Marsch and Tu, JGR 2001

Quasi-linear pitch-angle diffusion

Diffusion equation

$$\frac{\delta}{\delta t} f_j(v_{||}, v_\perp, t) = \int_{-\infty}^{+\infty} \frac{d^3k}{(2\pi)^3} \sum_M \hat{\mathcal{B}}_M(\mathbf{k}) \frac{1}{v_\perp} \frac{\partial}{\partial \alpha} \left(\hat{\nu}_{j,M}\, v_\perp \frac{\partial}{\partial \alpha} f_j(v_{||}, v_\perp, t) \right)$$

Pitch-angle gradient in wave frame

$$\frac{\partial}{\partial \alpha} = v_\perp \frac{\partial}{\partial v_{||}} - \left(v_{||} - \frac{\omega_M(\mathbf{k})}{k_{||}} \right) \frac{\partial}{\partial v_\perp}$$

Superposition of linear waves with random phases

→ Energy and momentum exchange between waves and particles. Quasi-linear evolution.....

Kennel and Engelmann, 1966; Stix, 1992

Resonant diffusion plateaus

Resonance speed

$$V_{\|} = C(y_{\|}, y_{\perp}) - \frac{s}{y_{\|}} V_{\mathrm{A}}$$

$$C(\mathbf{k}) = \omega(\mathbf{k}) / k_{\|}$$

Phase speed

$$y_{\|} = k_{\|} V_{\mathrm{A}} / \Omega_j$$

$$y_{\perp} = k_{\perp} V_{\mathrm{A}} / \Omega_j$$

Normalized wave vector

$$E(V_{\|}, V_{\perp}) = \frac{1}{2}\left(V_{\perp}^2 + V_{\|}^2\right) - \int_0^{V_{\|}} dV_{\|}' C(V_{\|}')$$

Cyclotron resonance

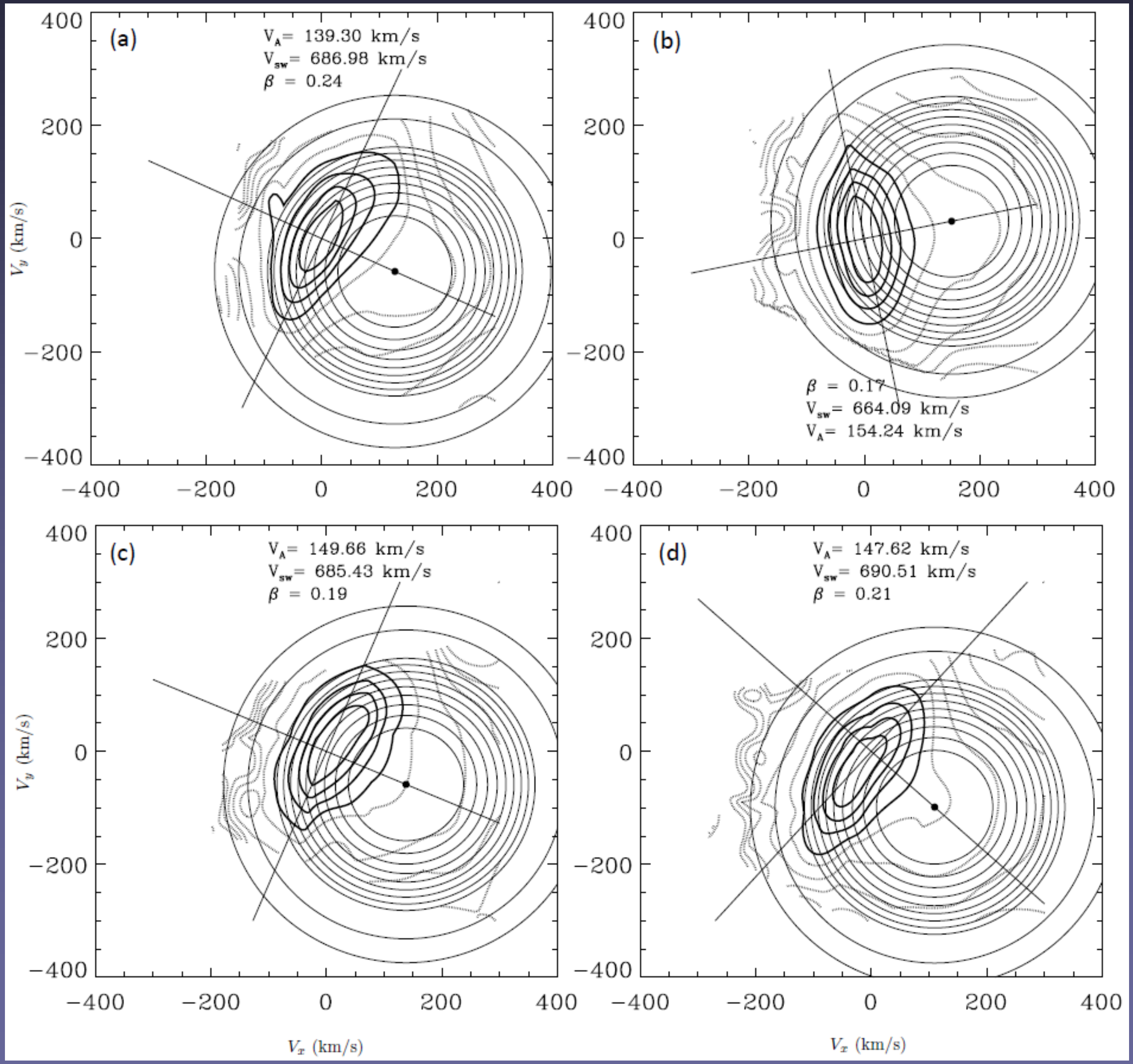
$$V_{\|}(y_{\|}) = V_{\mathrm{A}}(1 - \frac{s}{y_{\|}}) = \frac{V_{\mathrm{A}}}{y_{\|}}(\frac{\omega_{\mathrm{A}}}{\Omega_j} - s)$$

Alfven-ion-cyclotron wave

$$E_{\mathrm{A}}(V_{\|}, V_{\perp}) = \frac{1}{2}\left(V_{\perp}^2 + (V_{\|} - V_{\mathrm{A}})^2\right)$$

Marsch and Bourouaine, Ann. Geophys., 2011

Diffusion in oblique Alfvén/ion-cyclotron and fast-magnetoacoustic waves I



Diffusion circles centered at the local Alfvén speed (dots)

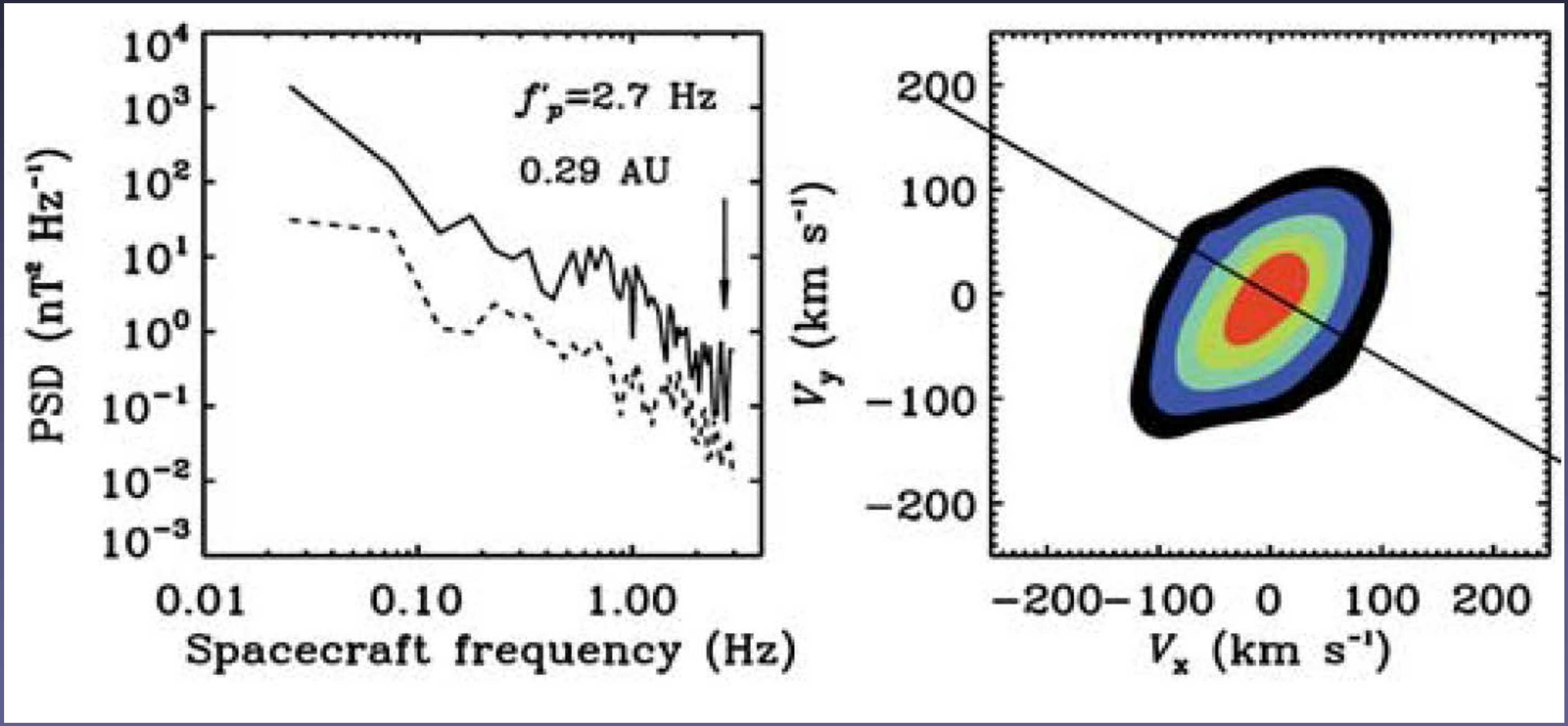
Contour lines:

80, 60, 40, 20, 10. 03, 01, 003, 001 % of the maximum.

Isocontours in plane defined by **V** and **B**

Marsch and Bourouaine, 2011

Transverse Alfvén/ion-cyclotron waves

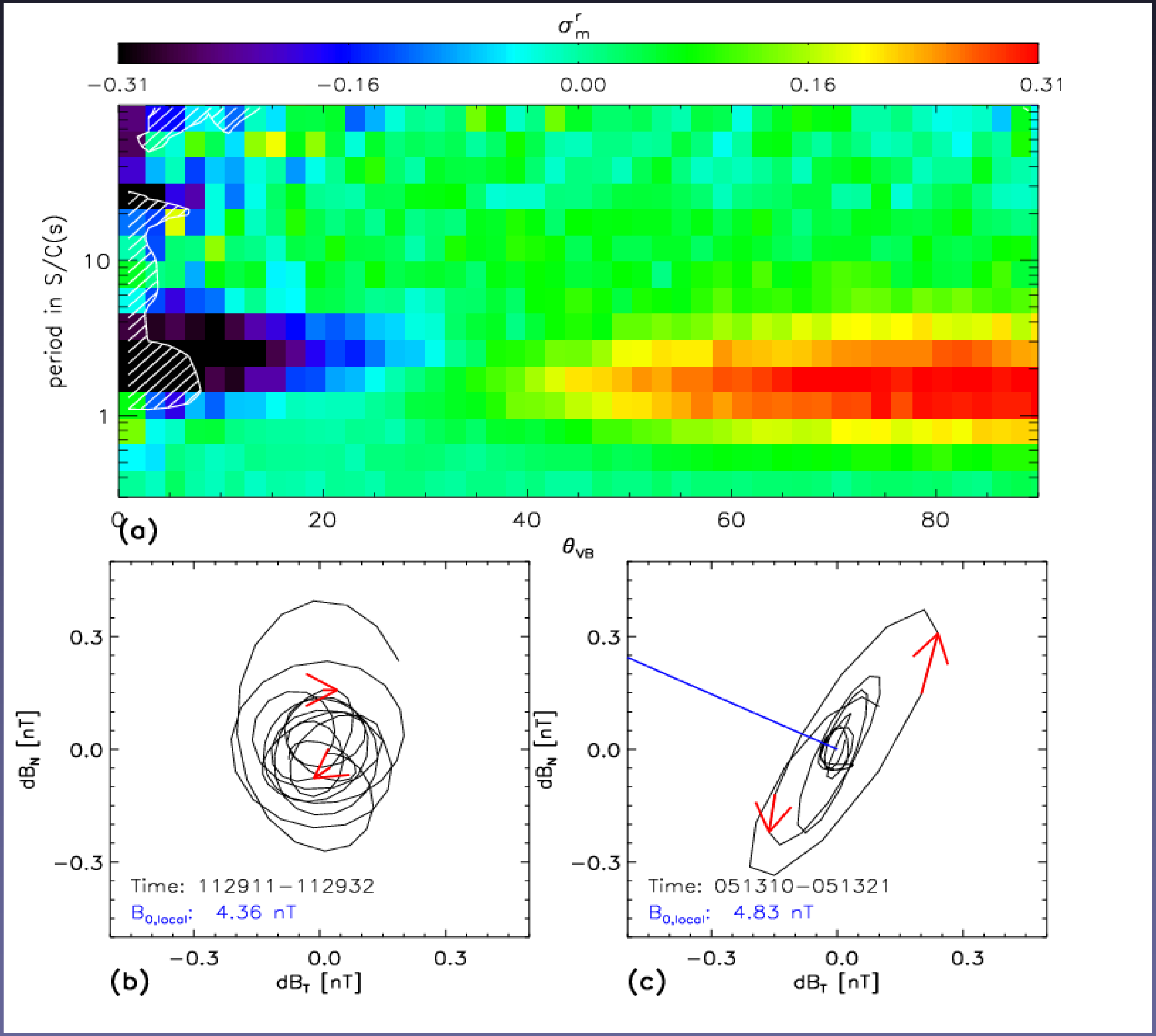


Alfvén-ion-cyclotron waves, 0.02 Hz - 2 Hz from Helios at 0.3 AU

Proton core anisotropy ($T_{\perp}/T_{||}>1$) strongly correlated with wave power

Bourouaine, Marsch, and Neubauer, GRL 2010

Helicity and polarization indicate oblique ICWs

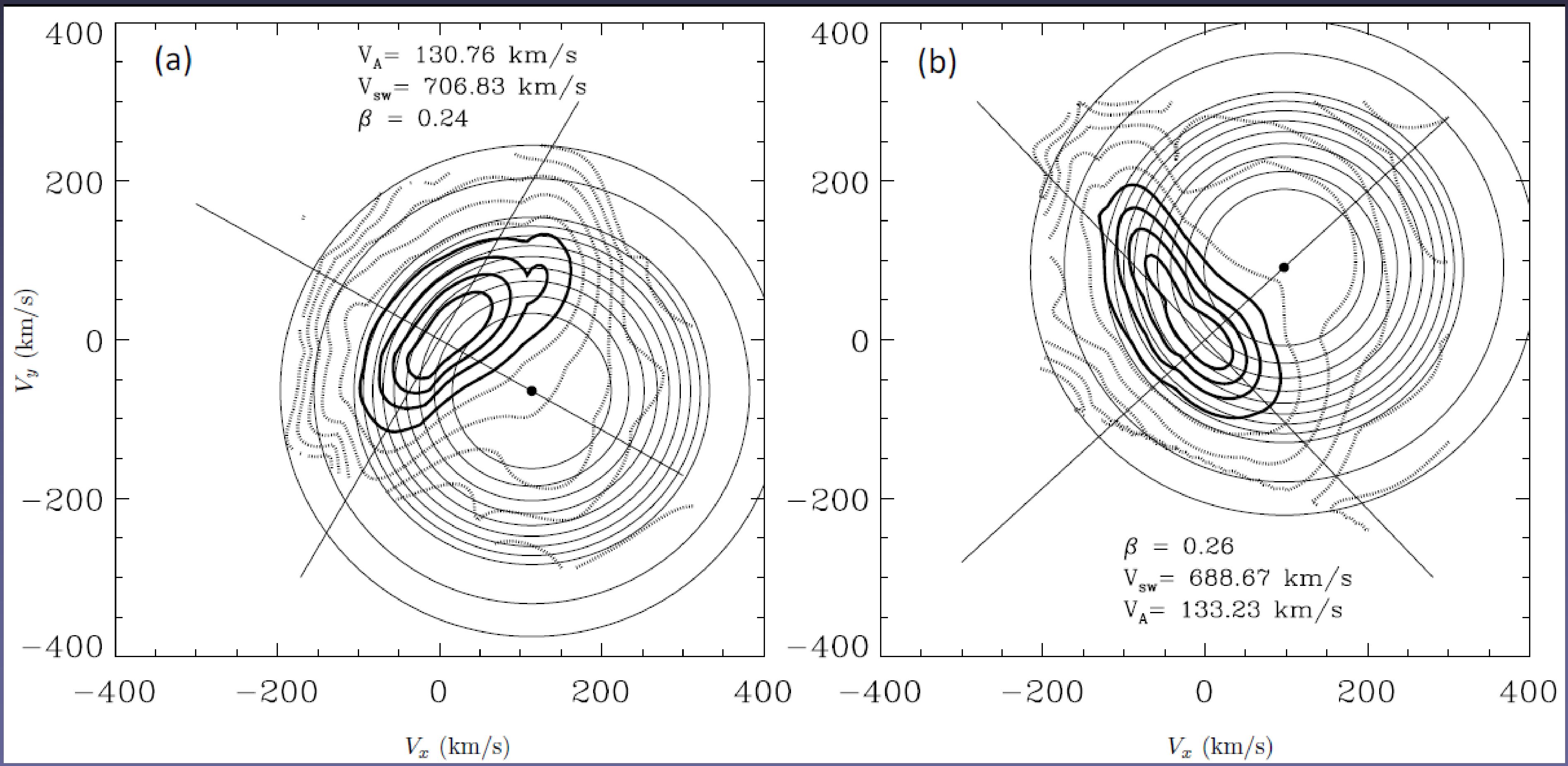


Helicity versus angle between solar wind flow and magnetic field vectors (STEREO, MAG)

Hodograph of normal and transverse magnetic field component, with (b) parallel Left-handed and (c) perpendicular right-handed polarization

He, Tu, Marsch, and Yao, Astrophys.J. 745, 2012

Diffusion in oblique Alfvén/ion-cyclotron and fast-magnetoacoustic waves II



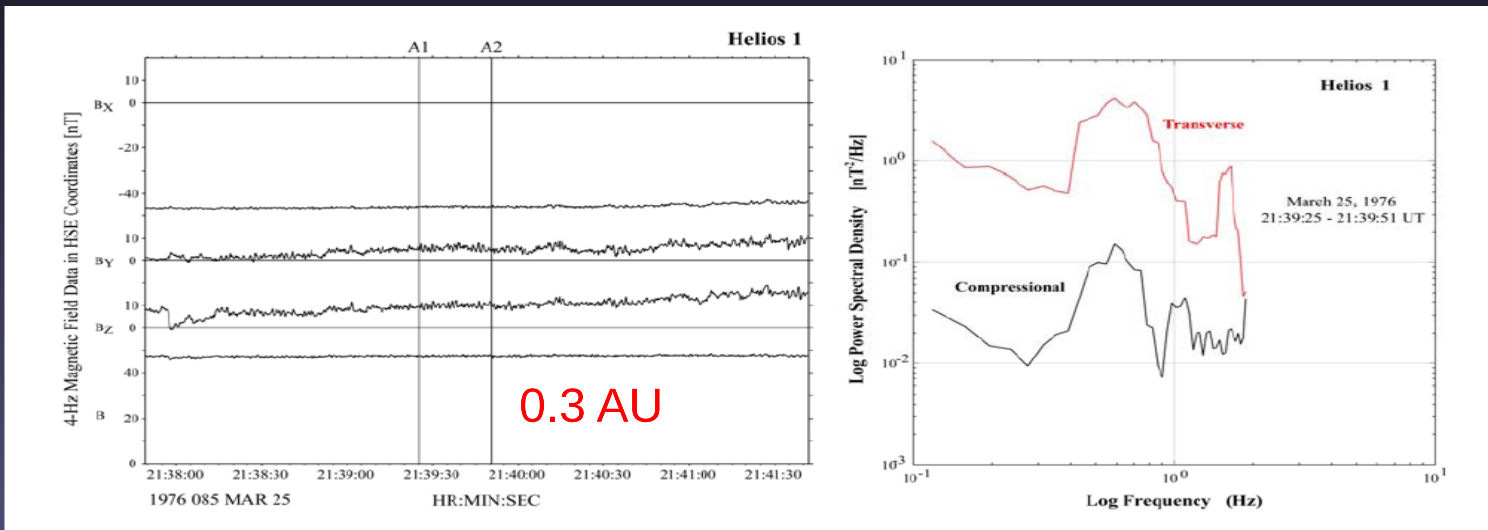
Marsch and Bourouaine, Ann. Geophys., 29, 2011

Conclusions

- Solar wind proton velocity distributions are shaped by resonant interactions with plasma waves.
- The core temperature anisotropy originates mainly from diffusion, involving resonances with parallel and anti-parallel incompressive cyclotron waves.
- The hot proton beam at its outer edges is shaped and confined by proton diffusion in highly oblique compressive Alfvén/ion-cyclotron waves.

- **Diffusion implies inelastic proton scattering by the waves, thus leading to their dissipation.**

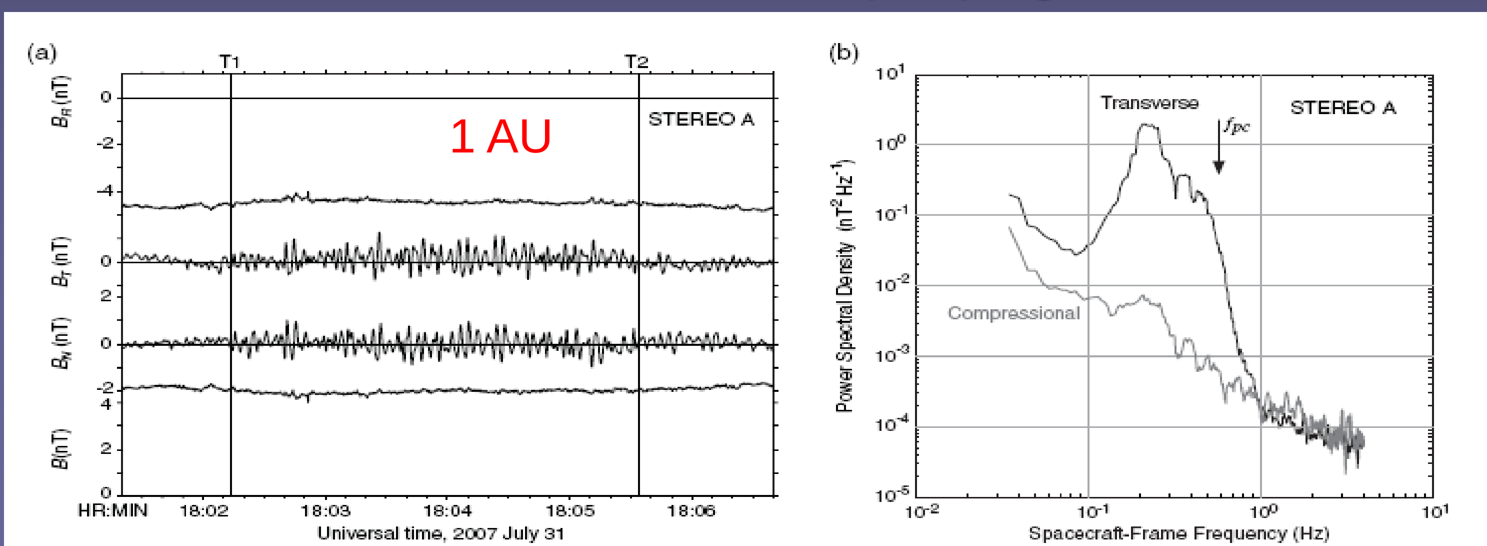
Ion cyclotron waves



Helios

Jian and Russell, The Astronomy and Astrophysics Decadal Survey, Science White Papers, no. 254, 2009

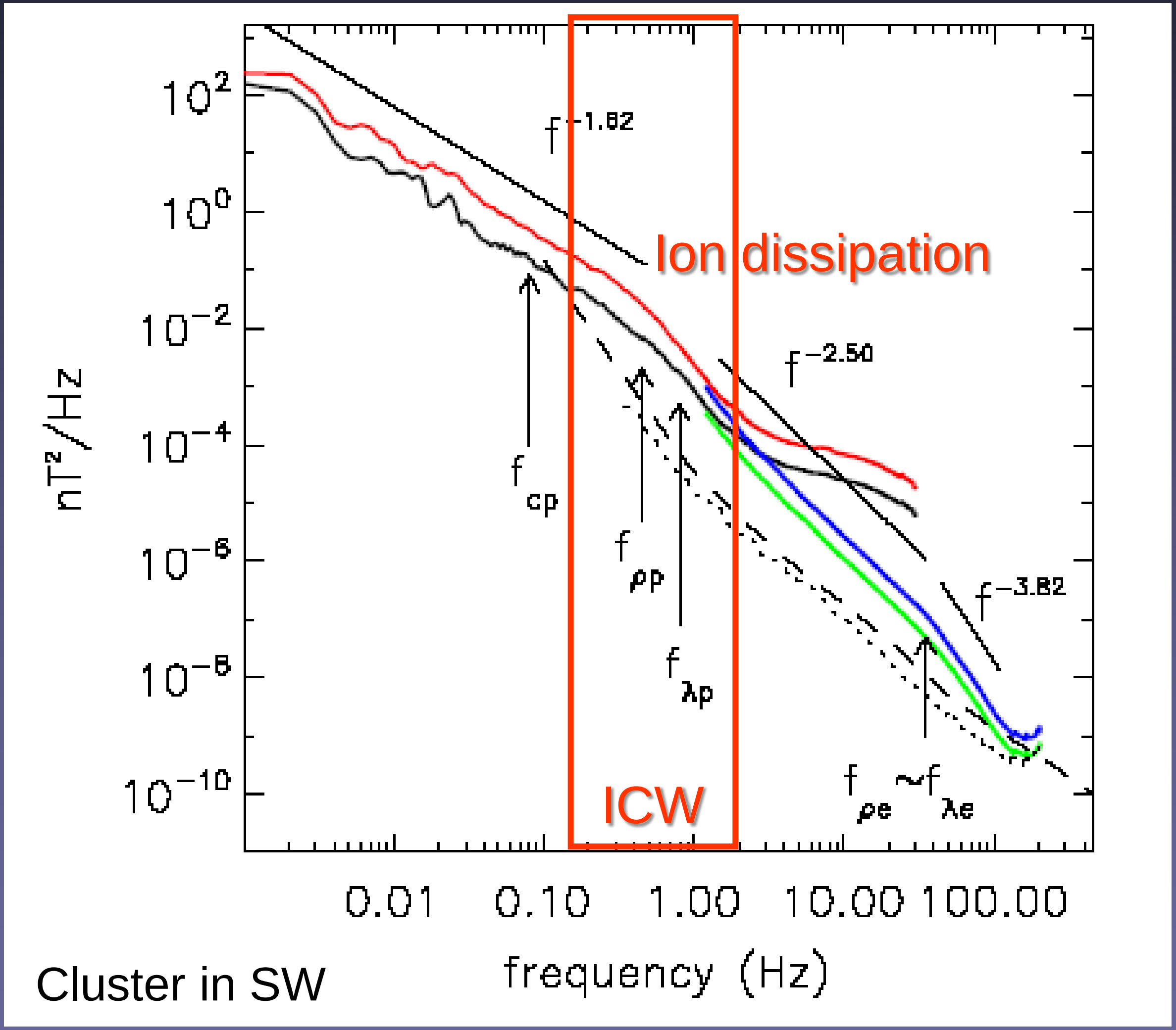
Parallel in- and outward propagation



STEREO

Jian et al., Ap.J. 2009

Magnetic power spectrum



Cascades:

- 5/3 MHD

Ion dissipation

- 2.5 HMHD

- 4

Electron dissipation

Sahraoui et al. PRL, 2009

Ingredients of diffusion operator

$$\hat{\mathcal{B}}_M(\mathbf{k}) = \left(\frac{|\,\mathbf{B}_M(\mathbf{k})\,|}{B_0}\right)^2 \left(\frac{k_{||}}{k}\right)^2 \frac{1}{1-|\,\hat{\mathbf{k}}\cdot\mathbf{e}_M(\mathbf{k})\,|^2}$$

Normalized wave spectrum (Fourier amplitude)

$$V_j(\mathbf{k},s) = \frac{\omega_M(\mathbf{k}) - s\Omega_j}{k_{||}}, \quad J_s = J_s\left(\frac{k_\perp v_\perp}{\Omega_j}\right)$$

Resonant speed, Bessel function of order *s*

Resonant wave-particle relaxation rate

$$\hat{\nu}_{j,M}(\mathbf{k}, v_{||}, v_\perp) = \pi\frac{\Omega_j^2}{k_{||}}\sum_{s=-\infty}^{+\infty}\delta(V_j(\mathbf{k},s)-v_{||})\,\left|\,\frac{1}{2}(J_{s-1}e_M^+ + J_{s+1}e_M^-) + \frac{v_{||}}{v_\perp}J_s e_{Mz}\,\right|^2$$

Marsch, Nonlin. Processes Geophys. 2002