Ion beams formed by Landau damping of waves

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Proton beam velocity distributions

Proton beam

Core temperature anisotropy

Core defined to be above the 20% level of the maximum.

\[ T_{\perp c} > T_{\parallel c} \]

• Firehose instability?
• Mirror instability?

Marsch, Zhao and Tu, Annales Geophysicae 24, 2057, 2006.
The dotted and the dashed lines show the threshold of the Alfven I instability (Daughton and Gary, 1998) with a constant ratio of the proton beam density to the electron density, for the values 0.05 (top) and 0.2 (bottom line).

$$\frac{v_d}{v_A} = (2.16 \pm 0.03) \beta_{\parallel c}^{(0.281 \pm 0.008)}$$

Tu, Marsch and Qin J.G.R, 109, 2004
Numerical hybrid simulations

- 1D, non-linear, homogeneous plasma
- Quasi-neutrality and conservation of longitudinal current 
  Isothermal massless fluid electrons contribute to electric field, but do not participate in dynamics
- Fully kinetic ions

\[
0 = -n_e e E + \mathbf{J}_e \times \mathbf{B} - \nabla P_e .
\]

\[
p_e = n_e k_B T_e.
\]

\[
\left[ \frac{\partial}{\partial t} + \bar{v} \cdot \frac{\partial}{\partial \bar{x}} + \frac{q_s}{m_s} \left( \bar{E}(\bar{x}, t) + \frac{\bar{v} \times \bar{B}(\bar{x}, t)}{c} \right) \right] \cdot \frac{\partial}{\partial \bar{v}} F_s(\bar{x}, \bar{v}, t) = 0,
\]

Typical parameters: \( n_\alpha / n_e = 0.05 \), \( n_p / n_e = 0.9 \), \( \beta_p = 0.1-0.2 \)
Proton core heating and beam formation

VDFs as obtained by numerical simulation of the decay of Alfvén-cyclotron waves and the related ion kinetics

Contour plots of the proton VDF in the $v_x$-$v_z$-plane for the dispersive-wave case at four instants of time. The color coding of the contours corresponds, respectively, to 75 (dark red), 50 (red), 10 (yellow) percent of the maximum.

Numerical simulation results: One-dimensional cuts through the proton VDF as a function of $v_z$ along the magnetic field direction for the dispersive-wave case at three instants of time. Note the formation of a beam with a final relative density of about 7%.
Conclusions

- Beams, diffusion plateaus and temperature anisotropies of ion velocity distributions are interpreted as evidence for ongoing wave-particle interactions in the solar wind.
- They can be either non-resonant fluid-like or more likely of plasma kinetic nature, involving cyclotron and Landau resonances with plasma waves.
- We argue that kinetic instabilities (plasma wave emission and absorption) play a key role in the dissipation of turbulence.

“Kinetic Physics of the Solar Corona and Solar Wind”
http://www.livingreviews.org/lrsp-2006-1
Ion kinetics in the solar wind

- Prominent kinetic features observed by Helios are the proton beam and the core temperature anisotropy, $T_{c\perp} > T_{c\parallel}$
- Evidence for pitch-angle scattering and quasilinear diffusion, microinstabilities and Coulomb collisions

Marsch et al., JGR, 87, 52, 1982
Ion differential heating and acceleration

Ion trapping and scattering in wave field

Magnetic power spectrum

Cluster in SW

Cascades:
- 5/3 MHD
- 2.5 HMHD
- 4 Electron dissipation

Ion dissipation

Sahraoui et al PRL, 2009
Electric power spectrum

Cascades:
- $5/3$ MHD
- $2.5$ HMHD
- $-4$

Electron dissipation

Cluster in SW

Sahraoui et al PRL, 2009
Temperature ratio versus beta

The core temperature anisotropy is regulated by quasilinear diffusion of protons in resonance with thermal cyclotron waves.

Blue line empirical fit:

\[
\frac{T_{\perp}}{T_{\parallel}} = 1.16 \beta^{-0.55}
\]

Marsch, Ao, Tu, JGR, 109, 2004

- Speed \( V > 600 \) km/s
- 36297 proton spectra
Ion cyclotron waves

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

Helios

Jian et al.

Parallel in- and outward propagation

STEREO

Jian et al.
Correlation of anisotropy with transverse Alfvén wave power

\[ f'_p = f_p (1 + M_A); \quad f_p = \frac{eB}{2\pi mc} \]
Temperature ratio versus wave power

Alfvén-cyclotron waves, 0.02 Hz - 2 Hz

Mean $B$ for 40 s; Helios distances: 0.3 - 0.9 AU

$P_{\perp}/P_{\parallel}$

Bourouaine et al., submitted to GRL, 2010
Helios data analysis procedure

- Parameters: Core proton temperatures $T_\perp$ and $T_\parallel$, in the directions perpendicular and parallel to the magnetic field, and parallel plasma beta, $\beta_\parallel$.
- The data are separately analyzed for two distance ranges: $R < 0.4$ AU and $R > 0.4$ AU.
- Division into 24 bins for $\beta_\parallel$, in the range from 0.1 to 10.
- Division into 72 bins for the core temperature anisotropy, $A = 1 - T_\perp/T_\parallel$, in the range from $-0.9$ to 0.9.
- The number of spectra in each bin is determined to obtain colour-coded distributions.
- Statistical results given in two-dimensional histograms.
Anisotropy histogram for \( r < 0.4 \) AU

Data fit:

\[ A = S \beta_{||}^{-\alpha} \]

- \( S = 1.73, \alpha = 1.03 \)
- \( S = 0.96, \alpha = 1.18 \)

Firehose instability

Mirror instability

24856 spectra

Red lines at 8% level

Marsch, Zhao and Tu, Ann. Geophysicae, 24, 2057, 2006
Anisotropy histogram for $r > 0.4$ AU

Data fit: $A = S \beta_{\parallel}^{-\alpha}$
- $S = 1.64, \alpha = 0.71$
- $S = -1.33, \alpha = 1.50$

Firehose instability
Mirror instability

193902 spectra

Red lines at 3% level

Marsch, Zhao and Tu, Ann. Geophysicae, 24, 2057, 2006