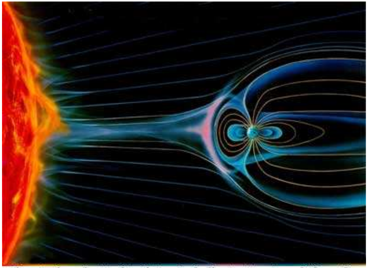
Stability analysis of core-strahl electron distributions in the solar wind

Kosta Horaites*, Patrick Astfalk,
Stanislav Boldyrev, Frank Jenko

AGU 2018

Solar Wind



Solar wind, as depicted in this artist's illustration, travels from the Sun and envelopes the Earth's magnetic field. High-energy pulses of solar wind from sunspot activity ("solar bursts" or "plasma bubbles") travel from the Sun to the Earth at speeds exceeding 500 miles per second. The pulses distort the Earth's magnetic field and produce gemagnetic storms that disrupt the Earth's environment.

Suprathermal electron populations

$$f_m(v_\perp, v_\parallel) = f_c + f_h + f_s$$

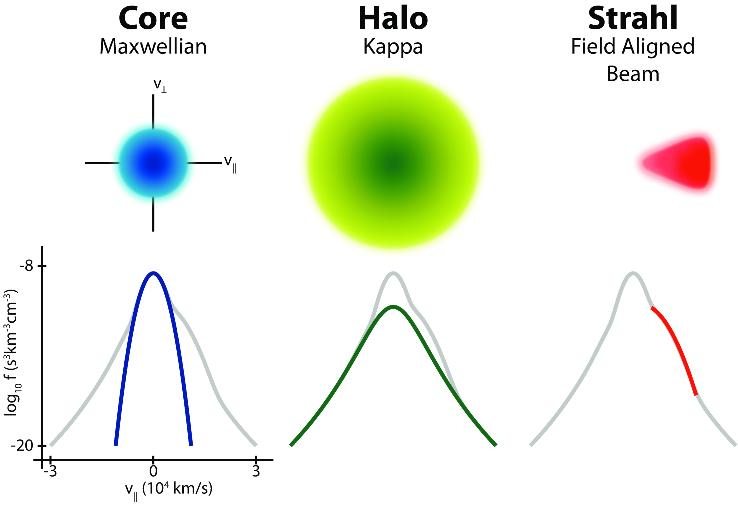


Illustration: M. Pulupa

Angular FWHM of Strahl—Steady-state kinetic theory

$$\mu v \frac{\partial f}{\partial x} - \frac{1}{2}\frac{d \ln B}{dx} v(1-\mu^2)\frac{\partial f}{\partial \mu} - \frac{eE_\parallel}{m}\left[\frac{1-\mu^2}{v}\frac{\partial f}{\partial \mu} + \mu \frac{\partial f}{\partial v}\right] = \hat{C}(f)$$

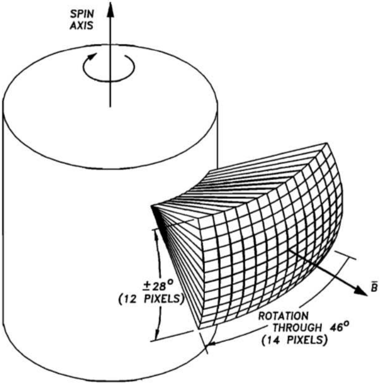
Solution: $f(r_0, v, \theta) \sim g(v) \exp\left(\frac{-Cv^4\theta^2}{n}\right)$.

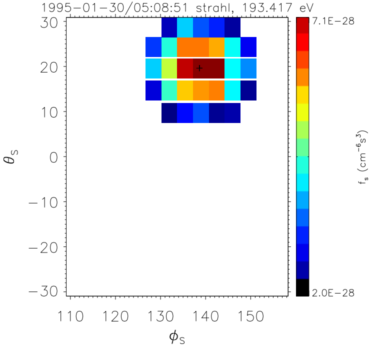
Strahl width: $\theta_{FWHM} \propto \sqrt{n}/v^2$.

Good news experimentally! n and v^2 known to high accuracy (10% and 3%, respectively)

Narrow strahl predicted... need high-res!

SWE Strahl Detector



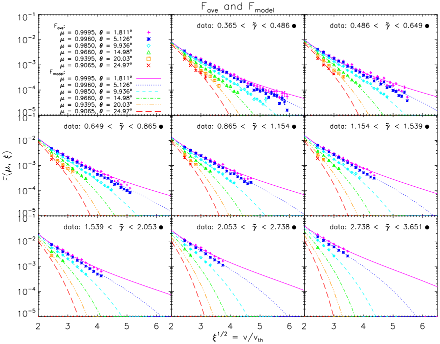


Strahl electron counts measured at 3.5x4.5 degree resolution (Ogilvie et al., 1995, 2000)

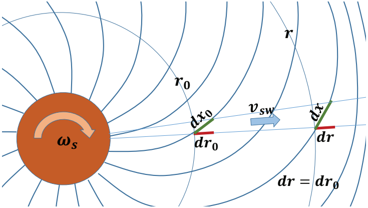
F_{ave}, 2D fits

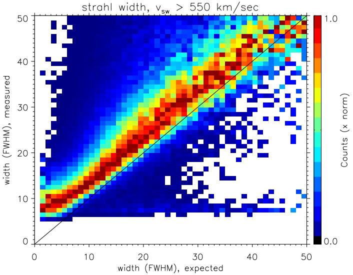
Solution:

$$f(r_0, v, \theta) \sim g(v) \exp\left(\frac{-Cv^4\theta^2}{n}\right).$$



Horaites et al., 2018a





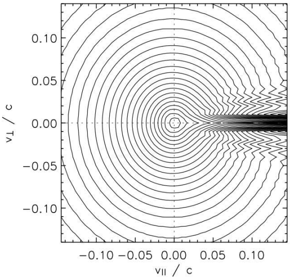
Horaites et al., 2018c (ArXiv)

Fits well to eVDF! But is it stable?

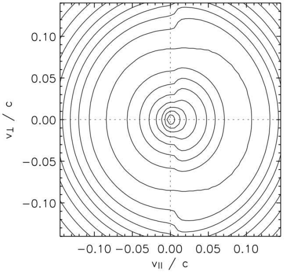
Anomalous Scattering of the Strahl

Some models propose that the strahl is scattered by wave-particle interactions.
Candidate waves:

- Whistler (e.g., Vocks et al., 2005, pictured)
- Langmuir (e.g., Seough et al., 2015)



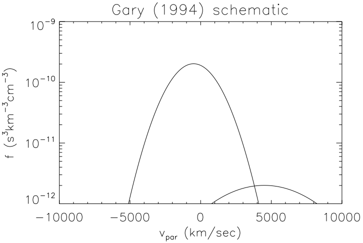
without whistlers

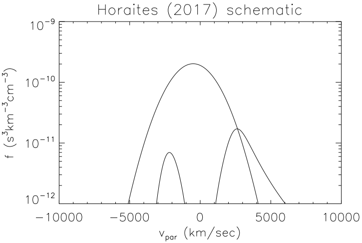


with whistlers

Whistler Heat Flux Instability

Gary et al., (1994) proposed a model, where the electrons are described by 2 drifting Maxwellians.





Core drift v_c follows from current balance:

$$\sum_{\sigma} J_\sigma = 0 \rightarrow v_c = -J_s/n_c$$

How will stability analysis change if we model the strahl more realistically?

Core-strahl model (Horaites et al., 2018b)

Model distribution function as sum of core and strahl components:

$$f = f_c + f_s$$

Core distribution:

$$f_c(\mu, v) = \frac{n_c}{\pi^{3/2} v_{th}^3} \exp\left(\frac{-v^2 + 2\mu v v_c - v_c^2}{v_{th}^2}\right).$$

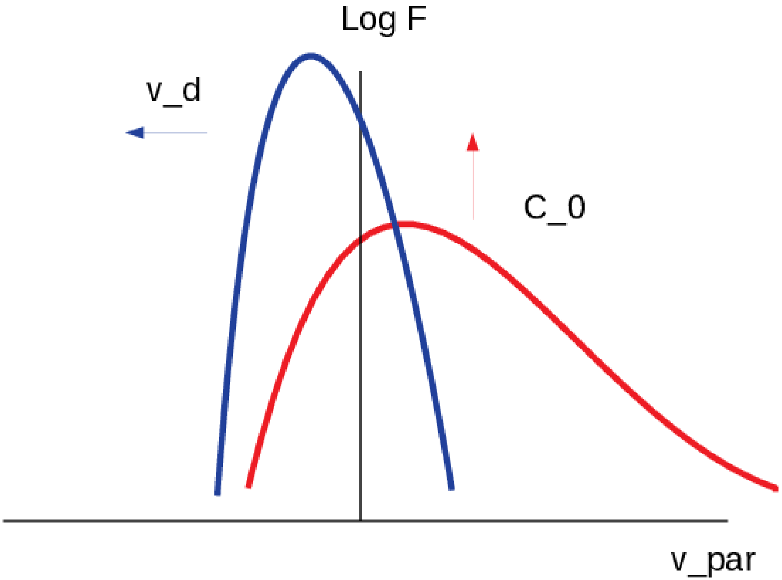
Strahl distribution:

$$f_s(\mu, v) = C_0 A(v) \frac{n_c}{v_{th}^3} \left(\frac{v}{v_{th}}\right)^{2\epsilon} \exp[\tilde{\gamma}\Omega (v/v_{th})^4 (1-\mu)],$$

where we define a truncation function $A(v)$, with $a = 10$, $b = 2\epsilon - 4$:

$$A(v) = \left(\frac{1}{1 + a(v/v_{th})^b}\right).$$

Require $J_\parallel = \int f v_\parallel d^3v = 0$



Dispersion Relation Solver

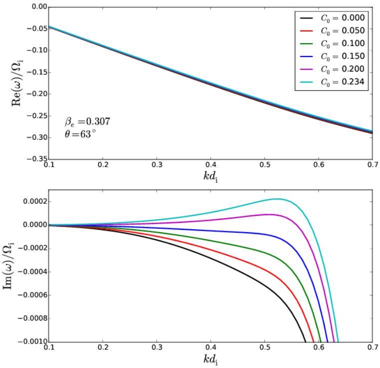
We use the kinetic dispersion relation solver, LEOPARD (Astfalk et al., 2017).

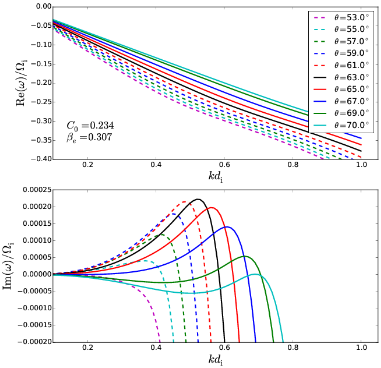
- solves kinetic equation for linear waves in magnetized plasma
- allows for arbitrary (gyrotropic) distribution functions
- can solve for modes with arbitrary propagation angle
- requires an initial guess for $\omega(\mathbf{k}) \rightarrow$ search magnetosonic, kinetic Alfven, Langmuir, and whistler branches

Code computes $\epsilon_{ij}(\omega, \mathbf{k})$ and solves for dispersion relation $\omega(\mathbf{k})$ from:

$$\left\{ k^2 \delta_{ij} - k_i k_j - \frac{w^2}{c^2} \epsilon_{ij}(\omega, \mathbf{k}) \right\} E_j = 0.$$

KAW Instability

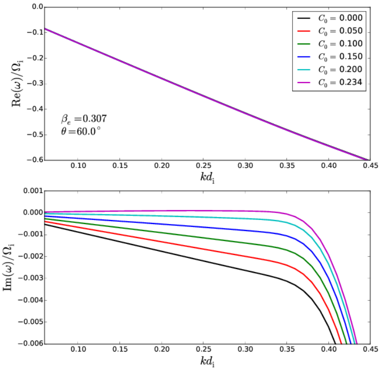


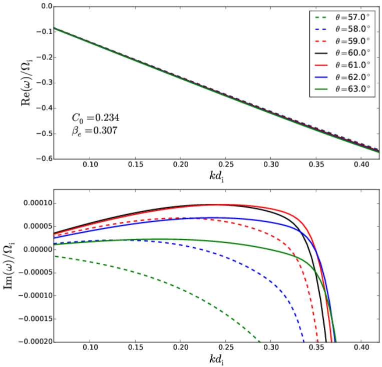


$\mathrm{Im}(\omega)\uparrow$ as $C_0 \uparrow$.

Max. growth rate at $\theta \approx 63^\circ$.

Magnetosonic Instability

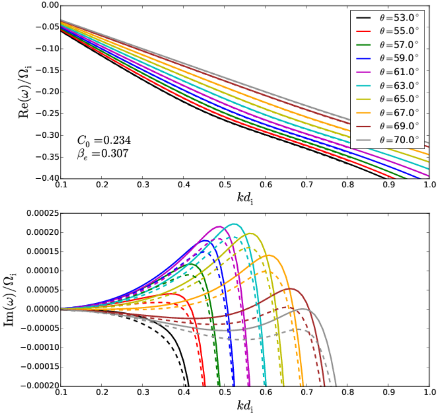




Im$(\omega)\uparrow$ as $C_0 \uparrow$.

Max. growth rate at $\theta \approx 60^\circ$.

Isotropic halo damps growth



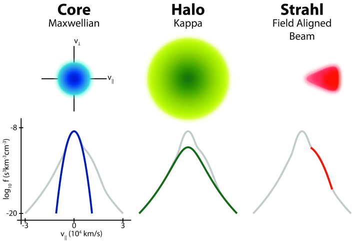
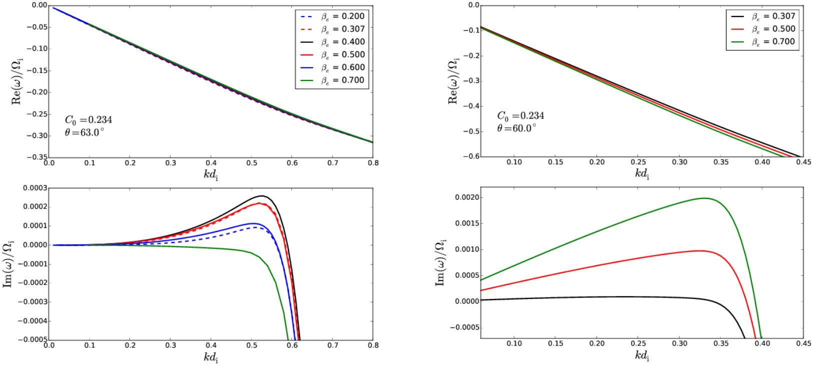


Illustration: M. Pulupa

with halo (dashed), without (solid)

Variation with β_e



KAW: as $\beta_e \uparrow$, $Im(\omega)$ reaches a maximum then stabilizes.

MS: as $\beta_e \uparrow$, $Im(\omega) \uparrow$.

β_e is larger near the sun than at 1 AU, so MS instability may be more important at small heliocentric distances.

Conclusions and future work

- An asymptotic model for the strahl distribution matches the data well at 1 AU.
- Linear analysis shows two growing modes at 1 AU: kinetic alfven and magnetosonic. Modes resonate with sunward-travelling core electrons.
- No whistler instability found!
- Kinetic alfven waves can interact non-linearly and produce whistler waves. May produce a whistler cascade at smaller scales that can then interact with the strahl electrons.