Kinetic theory and simulation of electron-strahl scattering in the solar wind

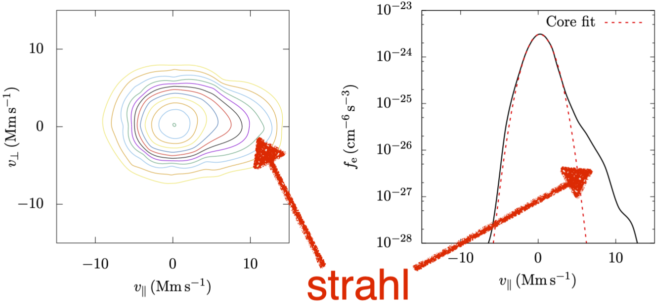
Daniel Verscharen[1,2], Seong-Yeop Jeong[1], Benjamin Chandran[2,3], Chadi Salem[4], Marc Pulupa[4], and Stuart Bale[4,5,6]

1: Mullard Space Science Laboratory, University College London; 2: Space Science Center, University of New Hampshire; 3: Department of Physics and Astronomy, University of New Hampshire; 4: Space Sciences Laboratory, University of California, Berkeley; 5: Physics Department, University of California, Berkeley; 6: The Blackett Laboratory, Imperial College London

@DVerscharen

Properties of the electron distribution function

Helios measurements

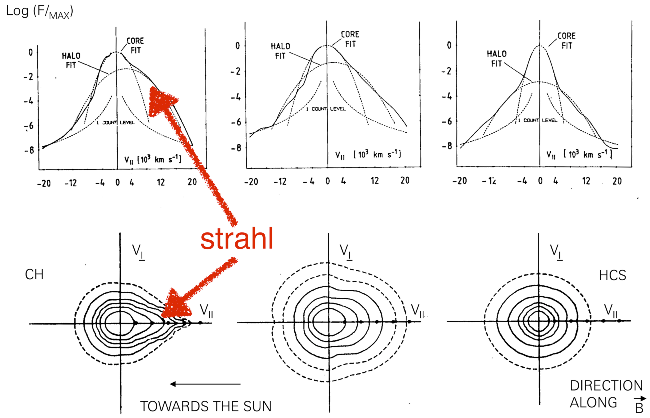


(Verscharen et al., 2019b)

- The electron distribution consists of three parts: core, strahl, and halo.
- The strahl is a field-aligned beam of superthermal electrons.

Properties of the electron distribution function

Helios measurements

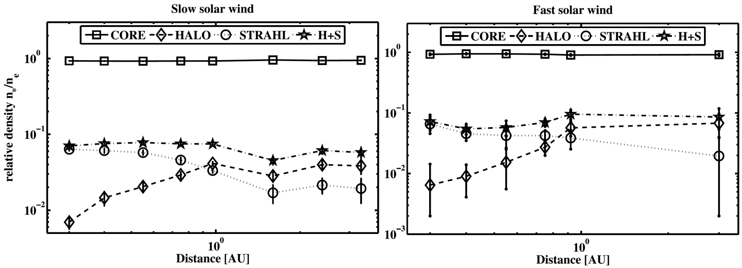


(Pilipp et al., 1987; Marsch, 2006)

- The electron distribution consists of three parts: core, strahl, and halo.
- The strahl is a field-aligned beam of superthermal electrons.

Properties of the electron distribution function

Observed relative densities of thermal and superthermal electrons



(Štverák et al., 2009)

- While the relative strahl density decreases with heliocentric distance, the relative halo density increases.
- This suggests that both populations are linked.
- Strahl electrons are transferred into the halo as the wind expands.

Scenario for the electron evolution in the inner heliosphere

We propose the following scenario:

1. Electrons are energised in the corona.
2. As the wind accelerates, the mirror force in the expanding magnetic field focusses energetic electrons into the strahl.
3. Strahl-driven instabilities regulate the strahl speed (as long as collisions are inefficient).
4. These instabilities scatter the strahl electrons into the halo.

In this presentation, we only address the points 3 and 4 in this scenario.

Certain requirements for instability must be fulfilled:

- polarisation properties
- strahl resonance leads to wave growth
- other particle components do not suppress instability through damping

In linear theory, this means for the total growth rate:

$$\gamma = \sum_j \sum_{n=-\infty}^{+\infty} \gamma_j^n > 0$$

for all species j (protons, electron core, halo, strahl,...). $n = 0$ is the Landau resonance, and $n \neq 0$ are cyclotron resonances.

Fast-magnetosonic/whistler instability

A theoretical framework to describe a scattering instability

The best candidate is an instability of the oblique fast-magnetosonic/whistler (FM/W) wave, which is determined by only *three* contributions to the total growth rate:

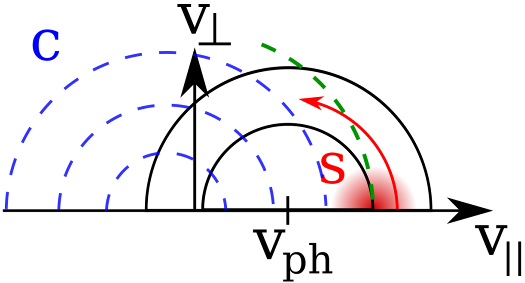
$$\gamma \approx \gamma_{\mathrm{s}}^{n=+1} + \gamma_{\mathrm{c}}^{n=-1} + \gamma_{\mathrm{c}}^{n=0} > 0$$

(strahl cyclotron driving, core cyclotron damping, and core Landau damping)
We use analytical expressions from Kennel and Wong (1967) for these three contributions.

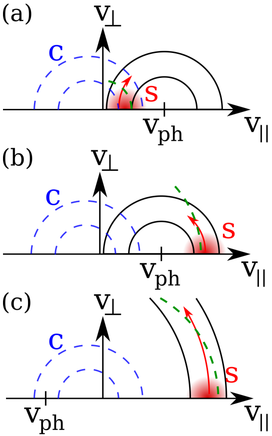
Scattering mechanism

Quasilinear diffusion scatters strahl electrons into the halo

This instability is self-excited by the strahl and scatters strahl electrons into the halo.



(Verscharen et al., 2019a)



<u>Other cases:</u>

Case (a) is stable $\rightarrow$ damping

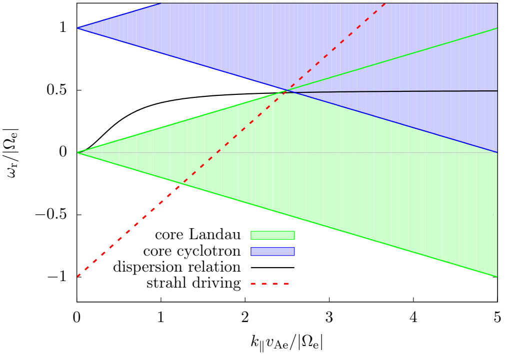
Case (b) is unstable $\rightarrow$ self-induced scattering

Case (c) is stable $\rightarrow$ damping

Regime 1: low β

Resonant strahl driving competes with resonant core damping

At low β, there is a "sweet spot" for instability at $U_s = 3w_c$:



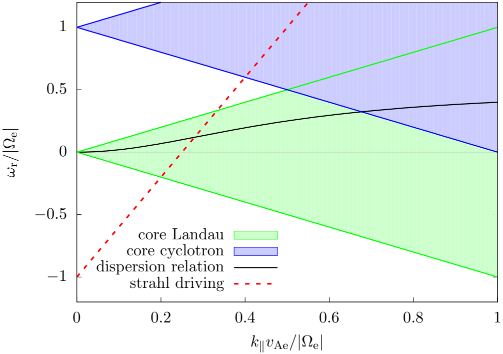
$\omega = \pm k_\parallel w_c, \qquad \omega = |\Omega_e| \pm k_\parallel w_c, \qquad \omega = -|\Omega_e| + k_\parallel U_s$

(Verscharen et al., 2019a)

Regime 2: intermediate to high β

Resonant strahl driving competes with resonant core damping

At higher β, cyclotron damping becomes less important, and the balance between strahl driving and core Landau damping must be evaluated:



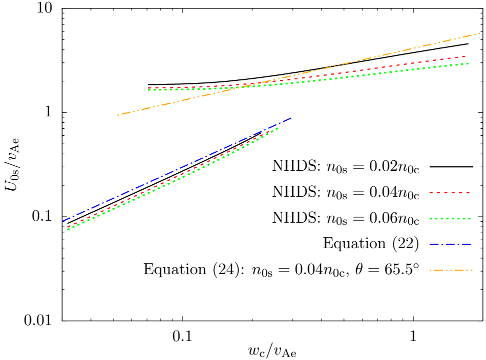
$$\omega = \pm k_\parallel w_c, \qquad \omega = |\Omega_e| \pm k_\parallel w_c, \qquad \omega = -|\Omega_e| + k_\parallel U_s$$

(Verscharen et al., 2019a)

Results: Instability thresholds in both regimes

When does the strahl drive the FM/W instability?

We have developed analytical expressions for the strahl instability thresholds:



(Verscharen et al., 2019a)

Low β:

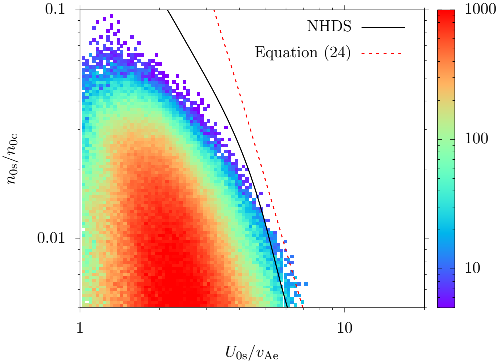
$$U_{\mathrm{s}} \gtrsim 3 w_{\mathrm{c}}$$

High β:

$$U_{\mathrm{s}} \gtrsim \left[\frac{2 n_{\mathrm{c}}}{n_{\mathrm{s}}} w_{\mathrm{c}} w_{\mathrm{s}} v_{\mathrm{Ae}}^2 \frac{1 + \cos\theta}{(1 - \cos\theta)\cos\theta} \right]^{1/4}$$

Results: Comparison with observations

Wind observations at 1 au

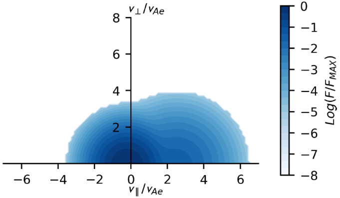


(Verscharen et al., 2019a)

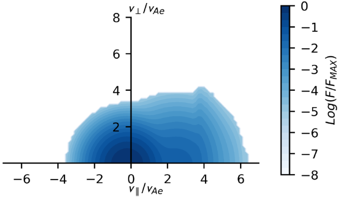
- This plot shows our analytical instability threshold "Equation (24)" and the numerical solution from full hot-plasma theory "NHDS".
- We predict that, in the parameter space to the right of these lines, the oblique FM/W wave is unstable.
- The observations are restricted to stable values in this parameter space.
- This suggests that the instability actually limits the electron distribution.

Results: Kinetic simulation of the oblique FM/W instability

Quasilinear diffusion describes the evolution of the electron strahl



(a) $|\Omega_e|t = 0$

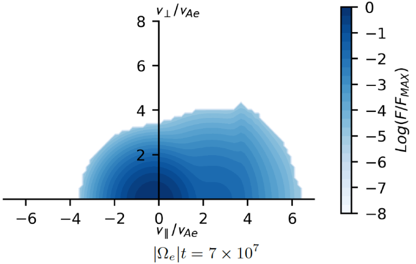


(Jeong, DV, et al., 2020)

- We also simulate the evolution of the VDF by solving the quasilinear diffusion equation numerically.
- We find that the strahl electrons indeed scatter into the velocity space associated with the halo.
- This study confirms the phase-space trajectories of our analytical model and the quasilinear saturation of the oblique FM/W instability.
- PIC simulations can also test this electron-strahl behaviour.

Results: Kinetic simulation of the oblique FM/W instability

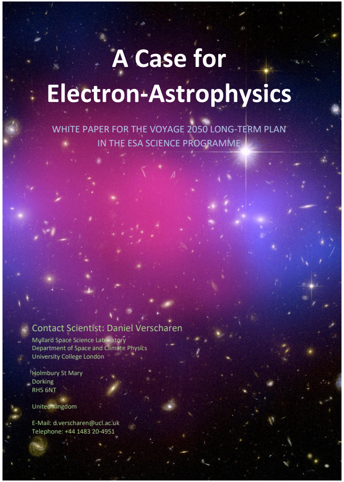
Expansion, focussing, instability, and collisions define the evolution of the electron strahl



(Jeong, DV, et al., 2020)

- The instability creates sharp gradients in velocity space through quasilinear diffusion.
- Collisions relax these gradients, albeit on larger timescales than the growth time of the instability.
- We are currently studying the interplay of expansion, focussing, instability, and collisions in the strahl evolution.
- In this way, we will test our full scenario for the strahl evolution from the Sun to 1 au and beyond.

ESA Voyage 2050 White Paper: A case for electron-astrophysics



Explore the smallest scales: *electron-astrophysics*

The smallest scales in the plasma (d_{e}, ρ_{e}, λ_{e}) determine the large-scale evolution of the system.

Such a mission requires:

- detailed electron distribution functions
- very high cadence
- multi-point measurements

(available on arXiv: Verscharen et al., 2019c)

Conclusions

- The mirror force focusses superthermal coronal electrons into the strahl.
- Strahl electrons excite an instability of the oblique FM/W wave.
- This instability scatters strahl electrons into the halo leading to an increase in $n_{\mathrm{h}}/n_{\mathrm{s}}$ with heliocentric distance.
- We find analytical thresholds for this instability in two different β-regimes.
- **Prediction for PSP and Solar Orbiter:** close to the Sun, the strahl speed is $U_{\mathrm{s}} \lesssim 3w_{\mathrm{c}}$. In normalised units, this means $U_{\mathrm{s}}/v_{\mathrm{Ae}} \lesssim 3\sqrt{\beta_{\mathrm{c}}}$.
- Quasilinear simulations confirm this scenario, but further studies are under way.
- Electron-astrophysics is a new frontier in space physics.

Literature

Seong-Yeop Jeong, Daniel Verscharen, Robert T. Wicks, and Andrew F. Fazakerley. A Quasi-linear Diffusion Model for Resonant Wave–particle Instability. *Astrophys. J.*, page in preparation, Jun 2020.

C. F. Kennel and H. V. Wong. Resonantly unstable off-angle hydromagnetic waves. *Journal of Plasma Physics*, 1:81, February 1967. doi: 10.1017/S0022377800003111.

E. Marsch. Kinetic Physics of the Solar Corona and Solar Wind. *Living Rev. Solar Phys.*, 3:1, July 2006. doi: 10.12942/lrsp-2006-1.

W. G. Pilipp, K.-H. Muehlhaeuser, H. Miggenrieder, M. D. Montgomery, and H. Rosenbauer. Characteristics of electron velocity distribution functions in the solar wind derived from the HELIOS plasma experiment. *J. Geophys. Res.*, 92:1075–1092, February 1987. doi: 10.1029/JA092iA02p01075.

Š. Štverák, M. Maksimovic, P. M. Trávníček, E. Marsch, A. N. Fazakerley, and E. E. Scime. Radial evolution of nonthermal electron populations in the low-latitude solar wind: Helios, Cluster, and Ulysses Observations. *Journal of Geophysical Research (Space Physics)*, 114:A05104, May 2009. doi: 10.1029/2008JA013883.

Daniel Verscharen, Benjamin D. G. Chandran, Seong-Yeop Jeong, Chadi S. Salem, Marc P. Pulupa, and Stuart D. Bale. Self-induced Scattering of Strahl Electrons in the Solar Wind. *Astrophys. J.*, art. arXiv:1906.02832, Jun 2019a.

Daniel Verscharen, Kristopher G. Klein, and Bennett A. Maruca. The multi-scale nature of the solar wind. *Living Rev. Solar Phys.*, 16 (1):5, December 2019b. doi: 10.1007/s41116-019-0021-0.

Daniel Verscharen, Robert T. Wicks, Olga Alexandrova, Roberto Bruno, David Burgess, Christopher H. K. Chen, Raffaella D'Amicis, Johan De Keyser, Thierry Dudok de Wit, Luca Franci, Jiansen He, Pierre Henri, Satoshi Kasahara, Yuri Khotyaintsev, Kristopher G. Klein, Benoit Lavraud, Bennett A. Maruca, Milan Maksimovic, Ferdinand Plaschke, Stefaan Poedts, Chirstopher S. Reynolds, Owen Roberts, Fouad Sahraoui, Shinji Saito, Chadi S. Salem, Joachim Saur, Sergio Servidio, Julia E. Stawarz, Stepan Stverak, and Daniel Told. A Case for Electron-Astrophysics. *arXiv e-prints*, art. arXiv:1908.02206, August 2019c.