Role of Whistler Waves in Regulation of the Heat Flux in the Solar Wind

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Heat flux in the solar wind

there is an upper bound on the electron heat flux that depends on the electron beta

\[
q_e / q_0 \lesssim A \beta_e^{-\alpha}
\]

\[
\beta_e = 8\pi n_e T_e / B_0^2
\]

\[
q_0 = 1.5 n_e T_e (2T_e/m_e)^{1/2}
\]

The collisional Spitzer-Härn law is not applicable in the solar wind and solar corona [e.g., Hollweg, 1974; Scudder, 1992]

The heat flux suppression below the collisional values was demonstrated by direct in-situ measurements in the solar wind (Feldman+, JGR, 1975; Scime+, JGR, 1994; Gary+, Phys. Plasmas, 1999; Tong+, ApJ, 2019)

One of the possible mechanisms of the heat flux regulation in the solar wind is the wave-particle interaction. It was hypothesized that whistler waves driven by the whistler heat flux instability might be responsible for the heat flux regulation (Gary+, Phys. Plasmas, 1999; ApJ, 2000)

Spitzer-Härn law

\[
q_e = -\kappa \nabla T_e
\]
**Whistler heat flux instability (WHFI)**

- consider electron VDF with drifting **core + halo** populations

- the electron heat flux is proportional to drifts of core and halo populations

- heat flux is a free energy capable of driving several so-called heat flux instabilities

- whistler waves grow fastest for a wide range of parameters (whistler heat flux instability)

**WHFI**

- whistler are quasi-parallel propagating, $\mathbf{k} \parallel q_e$

- whistlers are driven by cyclotron resonant halo electrons

- whistlers produced by WHFI were suggested to regulate the heat flux in the collisionless solar wind

*Gary+, JGR, 1975*
Heat flux regulation in the solar wind

the major argument behind Gary+ hypothesis:
beta dependence of the observed upper bound on the electron heat flux is similar to the linear marginal stability threshold of the WHFI

Gary et al., JGR, 1975

Tong+, APJ, 2019
Problems

- no direct evidence of whistler waves generated by WHFI in the solar wind and no detailed understanding of typical whistler wave parameters in the solar wind
  
  - Are whistler waves generated locally by the WHFI in the solar wind?
  
  - What are whistler wave amplitudes, obliqueness, frequency etc.?

- no PIC simulations that would demonstrate that whistler waves generated by the WHFI can regulate the electron heat flux in the solar wind
Observations of whistler waves at 1AU


- ARTEMIS 2011-2013
- clean solar wind, 359 days, ~ 1300 hours
- 800,000 magnetic field spectra (8s res)
- restrict to \( f_{lh} < f < f_{ce} \) and to \([16, 300]\) Hz
- particle moments 3s or 96s cadence

intense whistler wave events
- significant power: \( P_B > 3 P_g \)
- 17,000 spectra, ~ 30 hours
- 2% of all spectra
- \( || \) propagating whistler waves (>80%)

All data

frequencies and e-folding time of the most unstable whistler waves are consistent with linear stability analysis
**PIC simulations**

electrons = Maxwellian Core + Maxwellian Halo:

\[
F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left(-\frac{(\vec{v} - \vec{u}_c)^2}{2v_c^2}\right) + \frac{n_h}{(2\pi v_h^2)^{3/2}} \exp\left(-\frac{(\vec{v} - \vec{u}_h)^2}{2v_h^2}\right)
\]

Zero total current:

\[
n_c\vec{u}_c + n_h\vec{u}_h = 0
\]

Uniform background magnetic field

\[
\vec{B}_0 = \{B_0, 0, 0\}, \quad \vec{u}_h \parallel \vec{B}_0
\]
PIC simulations parameters:

electrons = Maxwellian Core + Maxwellian Halo:

\[ F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left(-\frac{(\vec{v} - \vec{v}_c)^2}{2v_c^2}\right) + \frac{n_h}{(2\pi v_h^2)^{3/2}} \exp\left(-\frac{(\vec{v} - \vec{v}_h)^2}{2v_h^2}\right) \]

\[ n_c = 0.85, n_h = 0.15 \]

\[ \beta_c = 1; 0.4; 2 \& 3 \]

\[ \frac{v_h^2}{v_c^2} = 10 \]

Electron plasma to cyclotron frequency ratio: \( \omega_{pe}/\omega_{ce} \approx 10 - 20 \) (varies within this range for various initial \( \beta_c \))
Linear stability analysis of the WHFI core+halo electron VDF

\[ F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left(-\frac{(\vec{v} - \vec{u}_c)^2}{2v_c^2}\right) + \frac{n_h}{(2\pi v_h^2)^{3/2}} \exp\left(-\frac{(\vec{v} - \vec{u}_h)^2}{2v_h^2}\right) \]

- Most unstable waves \( \omega \leq 0.1\omega_{ce} \); frequency decreases as the drift velocity \( u_c \) increases.

- typical wavelength \( \sim 15 \, c/\omega_{pe} \)

- linear growth rates \( \gamma_L \leq 0.015\omega_{ce} \)
\( \beta_c = 1, u_c = -9 v_A \)

**Results of the simulations**

  1D code (only parallel whistler waves)
  \( dx = 0.2 \frac{c}{\omega_{pe}}; \ dt = 0.09 \frac{1}{\omega_{pe}} \)
  \( N_{\text{particles}} \approx 5.2 \cdot 10^8 \)

- development of whistler wave below \( 0.1 \omega_{ce} \) propagating parallel to the electron heat flux

- the frequencies and initial growth rate are consistent with the linear theory

- whistler waves saturate after a thousand of \( 1/ \omega_{ce} \) at averaged (over the box) amplitudes \( B_w/B_0 \sim 0.03 \) [consistent with spacecraft observations, Tong+, APJL, 2019]

\[ B_w(t) = \sqrt{\langle B_{\perp}^2(t, x) \rangle_x} \]
1\textsuperscript{st} set of simulations
- $\beta_c=1$ and various $u_c/v_A$ or, equivalently, $q_e/q_0$
- whistler waves saturated at averaged amplitudes
  
  \[ B_w/B_0 \sim 0.02 - 0.04 \]

2\textsuperscript{nd} set of simulations
- $q_e/q_0 = 0.45$, various $\beta_c$
- whistler waves saturated at averaged amplitudes
  
  \[ B_w/B_0 \sim 0.01 - 0.05 \]
Saturated amplitude vs. initial heat flux

Simulations

\[ \beta_c = 1 \]

\[ B_w/B_0 \sim (\gamma/\omega_{ce})^\alpha, \alpha \approx 0.7 \]

Observations, solar wind

Tong et al (2019), APJ
Does the heat flux change?

1\textsuperscript{st} set of simulations

$\beta_c = 1$ and various $u_c/v_A$ or, equivalently, $q_e/q_0$

Heat flux variation is less than 1%

2\textsuperscript{nd} set of simulations

$q_e/q_0 = 0.45$, various $\beta_c$

Heat flux variation is less than 3%
Effects of anisotropy on WHFI

\[ F_e = \frac{n_c}{(2\pi v_c^2)^{3/2}} \exp\left( -\frac{(\vec{v} - \vec{v}_c)^2}{2v_c^2} \right) + \frac{n_h}{(2\pi v_h^2)^{3/2}A} \exp\left( -\frac{(v_\parallel - u_h)^2}{2v_h^2} - \frac{v_\perp^2}{2v_h^2A} \right) \]
Results of the simulations

$$\beta_c = 1, \ n_c = 0.85, \ u_c = -3v_A, \ A = 1.3, \ \nu_h^2/\nu_c^2 = 6$$

$$B_w(t) = \sqrt{\langle B^2(t, x) \rangle_x}$$
Saturated amplitude

(a)

(b)
Does anisotropy help with the heat flux?

\[ A = 1.3, \text{ various } u_c/v_A \text{ or, equivalently, } q_e/q_0 \]

Heat flux variation decreases with \( u_c \) (\( \gamma^{anti} \downarrow \))

\[ u_c/v_A = -6 \text{ and different anisotropies (} \gamma^{anti} \text{ increases with } A \)\]
Summary

- We have successfully simulated the generation of whistler waves driven by the whistler heat flux instability combined with anisotropy instability.

- The amplitudes and frequencies of the generated waves are in agreement with the observations of whistler waves in the solar wind.

- For small heat flux, the wave amplitude is positively correlated with the heat flux. For larger heat flux, the correlation becomes negative. This is consistent with the observations.

- We have found a positive correlation between linear increment and saturated wave amplitude.

- Our calculations suggest that parallel whistler-mode waves cannot control the electron heat flux in the solar wind, but anti-parallel waves generated via combined heat flux + anisotropy instability can contribute to the heat flux regulation.
Thank you!
Fastest growing whistler wave at various ($\beta_c, u_c/v_A$)

- core+halo electron VDF
- core density 0.85 $n_0$, $T_h/T_c$=10 or 4
- halo ten times hotter than core in simulations (a bit higher than in reality)
- squares indicate initial conditions for simulations
- two sets of simulations:
  1$^{st}$: $\beta_c$=1 and various $u_c/v_A$ or, equivalently, $q_e/q_0$
  2$^{nd}$: $q_e/q_0$ $\sim$ 0.45 and various $\beta_c$

\[
\tilde{q}_e = \int (\tilde{v} - \langle \tilde{v} \rangle)(\tilde{v} - \langle \tilde{v} \rangle)^2 f(\tilde{v}) d^3v
\]
\[
q_0 = \frac{3}{2}n_eT_e\sqrt{2T_e/m_e}
\]
What leads to the instability saturation?

\[ H = \frac{p^2}{2m_e} + A_{\text{eff}} \sin(kx + \phi_g - \omega t) \]

\[ \frac{d}{dt}(kx + \phi_g - \omega t) = 0 \]

\[ v_R = \frac{\omega - \omega_c}{k} \]

- electrons in the first normal cyclotron resonance \( v \approx v_R \) provide energy for the whistler wave growth

- the scattering of resonant electrons by the growing whistler waves leads to formation of the __plateau__, resulting in saturation of the wave growth