Instability Constraints on Proton Beam Drift Velocity and Temperature Anisotropy in the Solar Wind: Theory meets Observations

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Introduction

In situ measurements of the solar wind reveal that proton Velocity Distribution Functions (VDFs) display distinctly nonthermal kinetic features, including a faster, lower-density, magnetic field-aligned, proton beam alongside a dense core population. The beam is observed to have a drift velocity U_b relative to the core, comparable to the local Alfven velocity v_A.

Proton beams may provide a sufficient source of free energy to excite plasma instabilities. Linear Vlasov theory shows that in a plasma containing a proton core (c), proton beam (b), and electrons (e), the proton beam can induce three types of instabilities: oblique Alfven/ion cyclotron (A/IC), oblique Fast-Magnetosonic/Whistler (FM/W), and parallel FM/W instabilities. If the plasma exceeds the threshold of any of these instabilities, the instability grows. The resulting electromagnetic fluctuations interact with particles, causing a reduction in the free energy that drives the instability.

In this study, we investigate the thresholds of parallel and FM/W instabilities in the presence of an anisotropic proton beam. We derive analytic expressions for the parallel FM/W instability's thresholds, which show the effects of the proton beam temperature anisotropy and parallel proton beta on the real frequency and growth rate of the proton beam instability. We compare the analytical threshold expressions with numerical solutions to the full hot-plasma dispersion relation. By analyzing data from the Parker Solar Probe (PSP) spacecraft, we show how the linear FM/W instability can limit the drift velocity and temperature anisotropy of proton beams observed in solar wind.

Resonance Interaction of Beams and Waves

Considering $|\gamma_k| \ll |\omega_{kr}|$, secondary protons with $v_\parallel = U_b + \sigma w_{\parallel b}$ can resonate with the right-circularly polarized FM/W wave with real frequency ω_{kr}, only if they fulfill the resonance condition below:

$$\omega_{kr} = k_\parallel (U_b + \sigma w_{\parallel b}) - \Omega_p$$

where σ is a constant of order unity.

Conditions for the FM/W wave to be unstable:

- Only solutions of the dispersion relation at $k < k_{max}$ and $\omega_{kr} < \omega_{max}$ can have destabilizing influence on a proton beam at a given temperature anisotropy and drift:

$$\omega_{max}^{FM/W} = \Omega_b \left(\frac{T_{\parallel b}}{T_{\perp b}} - 1\right) + k_\parallel U_b$$

- Only solutions of the dispersion relation at $k > k'$ and $\omega_{kr} > \omega'$ can interact resonantly with a sufficiently large number of protons in the beam to excite an instability.

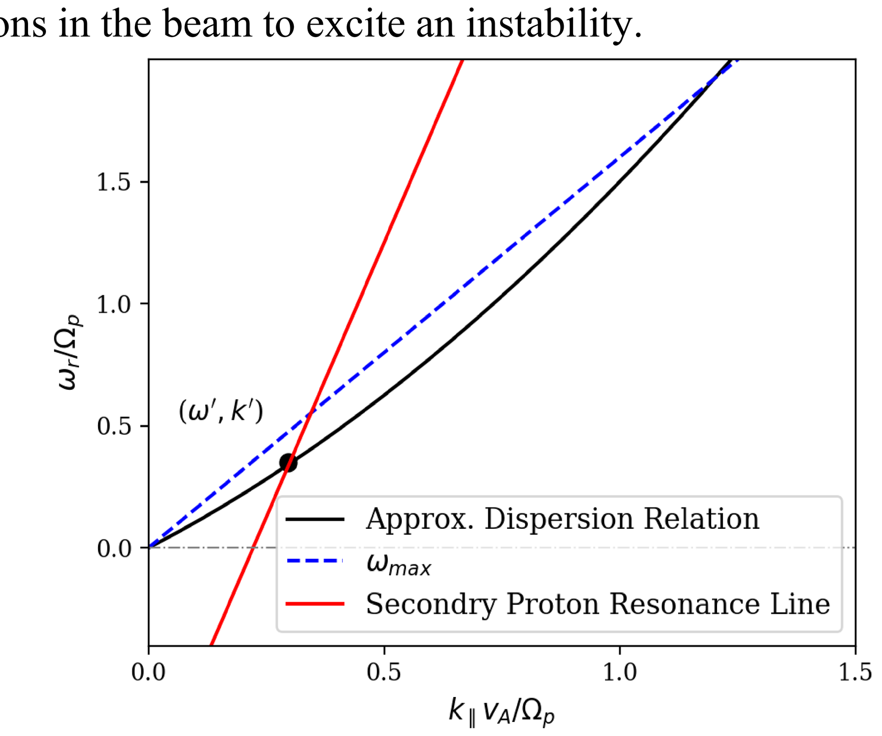

Figure 1: Resonance and instability conditions of the FM/W mode for $U_b = 1.6 v_A$, $\frac{T_{\parallel b}}{T_{\perp b}} = 1$, and $\sigma = 2.45$.

Constraints on Beam Drift Velocity in the Solar Wind

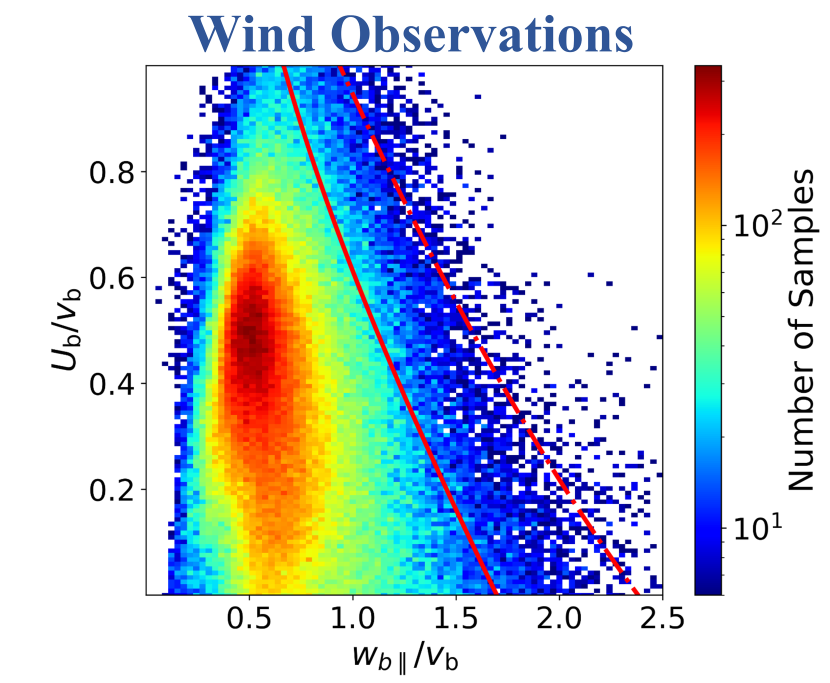

Figure 5: Distribution of Wind (~1 AU) observations and the FM/W instability thresholds for $\frac{T_{\perp b}}{T_{\parallel b}} = 0.7$ for $\gamma_m = 10^{-3}\,\Omega_p$ (dashed line) and $\gamma_m = 10^{-4}\,\Omega_p$ (solid line).

- The distributions of observations for heliocentric distances ranging from ~0.05-1 AU are well constrained by the analytical thresholds defined by parameter conditions corresponding to a maximum FM/W growth rate of $\gamma_m = 10^{-4}\,\Omega_p$ (solid lines).
- PSP observations from Encounter 9 and 11 were analyzed. During the studied intervals, the probe was near the heliospheric current sheet (HCS) and $V_{sw} < 400$ km/s.

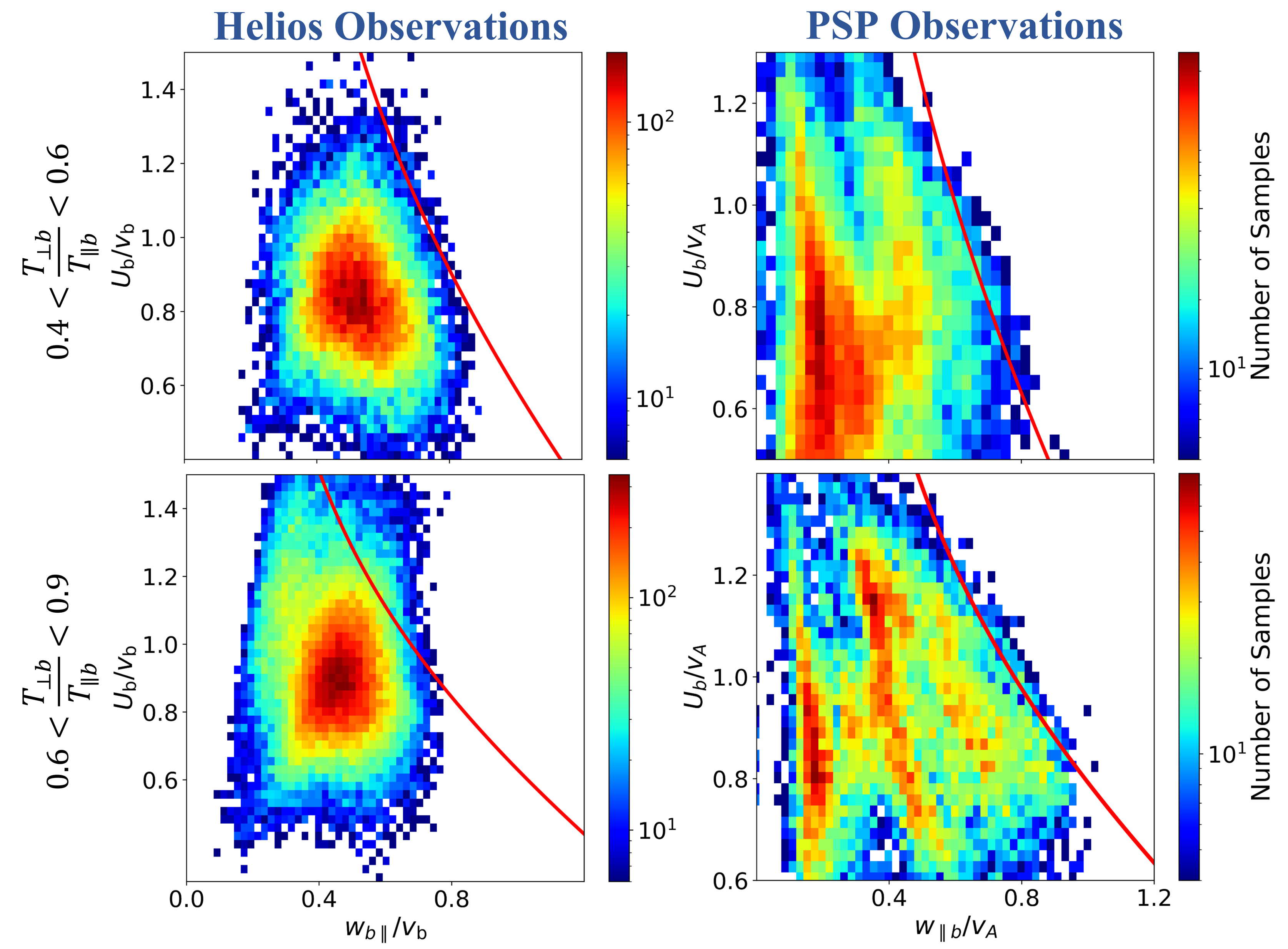

Figure 5: Distribution of observations in the $\frac{U_b}{v_A} - \frac{w_{\parallel b}}{v_A}$ plane for a subset of data with (top) $0.4 < \frac{T_{\perp b}}{T_{\parallel b}} < 0.6$ and (bottom) $0.6 < \frac{T_{\perp b}}{T_{\parallel b}} < 0.9$ from Helios (left; ~0.3-1 AU) and PSP (right; ~0.05-0.1 AU). The FM/W instability threshold (solid line) for (top) $\frac{T_{\perp b}}{T_{\parallel b}} = 0.5$ and (bottom) $\frac{T_{\perp b}}{T_{\parallel b}} = 0.75$ constrains the drift velocity of observed proton beams.

Analytic Instability Thresholds of the Parallel FM/W Instability

- The condition $k_{res} < k_{max}$ defines the lower threshold for U_b:

$$\frac{U_b}{v_A} > 1 + \left(\frac{T_{\parallel b}}{2T_{\perp b}\sigma w_{\parallel b}}\right) + \sigma w_{\parallel b}\left(\frac{T_{\perp b}}{T_{\parallel b}} - 1\right)$$

- Our analytic thresholds match well with numerical solutions to the full-hot plasma dispersion relation.
- The quantity σ defines the range of particle velocities in units of thermal speed that can effectively resonate with the wave and depends weakly upon the density ratio $\frac{n_b}{n_p}$.

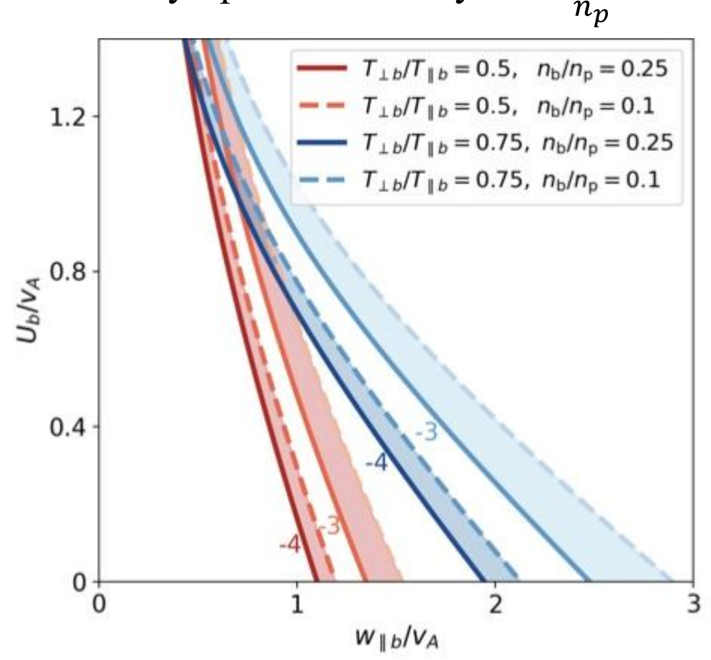

Figure 2: Instability thresholds in the $\frac{U_b}{v_A} - \frac{w_{\parallel b}}{v_A}$ plane for different values of $\frac{T_{\perp b}}{T_{\parallel b}}$, $\frac{n_b}{n_p}$, and maximum growth rate γ_m.

- The lower constrain on beam's drift velocity leads to an upper threshold for the temperature anisotropy at a given drift speed:

$$\frac{T_{\perp b}}{T_{\parallel b}} < \frac{U_b + \sigma w_{\parallel b} - v_A + \sqrt{(U_b + \sigma w_{\parallel b} - v_A)^2 - 2v_A^2}}{\sigma w_{\parallel b}}$$

- The FM/W wave is unstable if U_b and/or $\frac{T_{\perp b}}{T_{\parallel b}}$ are large enough that the resonant interactions with the proton beam are destabilizing within the wavenumber interval $[k_{res}, k_{max}]$.

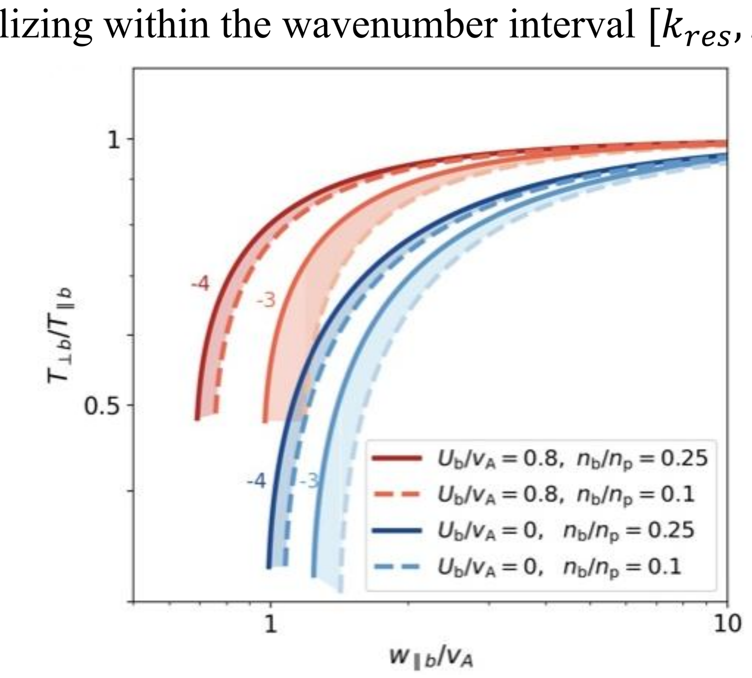

Figure 3: Instability thresholds in the $\frac{T_{\perp b}}{T_{\parallel b}} - \frac{w_{\parallel b}}{v_A}$ plane for different values of $\frac{U_b}{v_A}$, $\frac{n_b}{n_p}$, and maximum growth rate γ_{max}.

Constrain on the Proton Beam Temperature Anisotropy

- A parallel FM/W instability, expected when $\frac{T_{\perp b}}{T_{\parallel b}} < 1$ and $U_b < v_A$, appears to form a lower boundary on the distribution of anisotropic proton beams in the $\frac{T_{\perp b}}{T_{\parallel b}} - \frac{w_{\parallel b}}{v_A}$ plane.
- The distribution shows an upper boundary at $\frac{T_{\perp b}}{T_{\parallel b}} > 1$, suggesting that instabilities operating in this regime may limit the occurrence of strongly anisotropic proton beams.

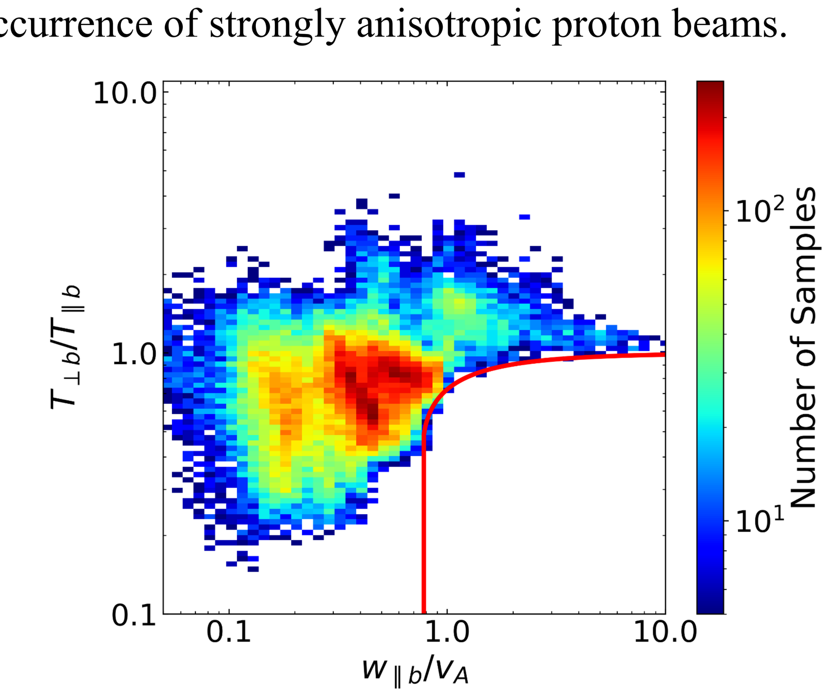

Figure 6: Distribution of data points for the proton beam temperature anisotropy in the $\frac{T_{\perp b}}{T_{\parallel b}} - \frac{w_{\parallel b}}{v_A}$ plane. The red line represents the analytic threshold on the beam temperature anisotropy for $U_b = 0.7 v_A$ and $\frac{n_b}{n_p}$.

Summary and Future Work

Summary:

- Analytic thresholds for the FM/W instability have been derived for the presence of an anisotropic proton beam, consistent with numerical solutions to the full hot plasma dispersion relationship.
- The presence of an anisotropic proton beam with $\frac{T_{\perp b}}{T_{\parallel b}} < 1$ can lead to a reduction of the instability threshold velocity.
- The good agreement between the presented instability thresholds and the distribution of PSP observations near the HCS suggest that proton-beam driven instabilities in this region play an important role in shaping the solar wind distributions.
- The distribution of observations from a range of heliocentric distances (~0.06-1 AU) are all well constrained by the proton-beam driven instability thresholds.

Future Work:

- Investigate how proton-beam instability driven plasma heating and beam deceleration evolve as the solar wind expands.

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