PPPL PRINCETON PLASMA PHYSICS LABORATORY

Two Fluid, Ten Moment Simulations of the Firehose Instability in the Solar Wind

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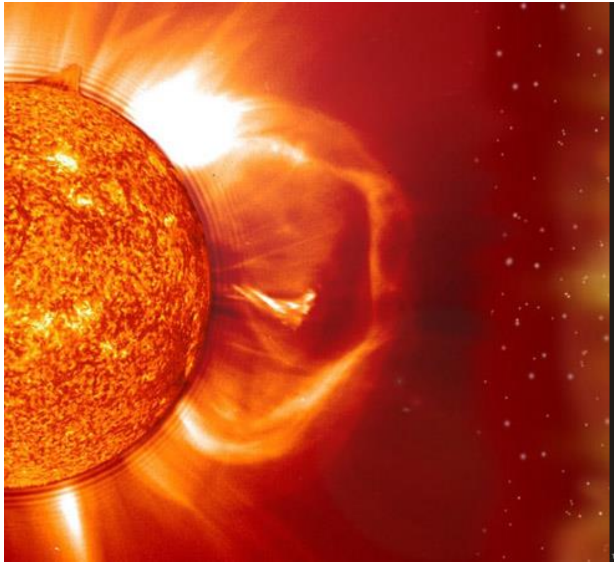
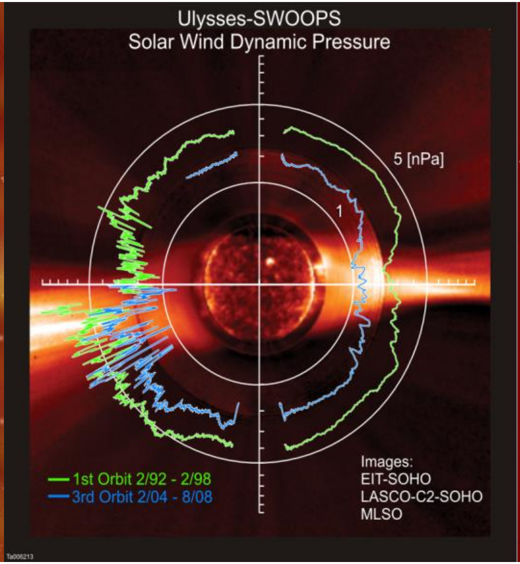
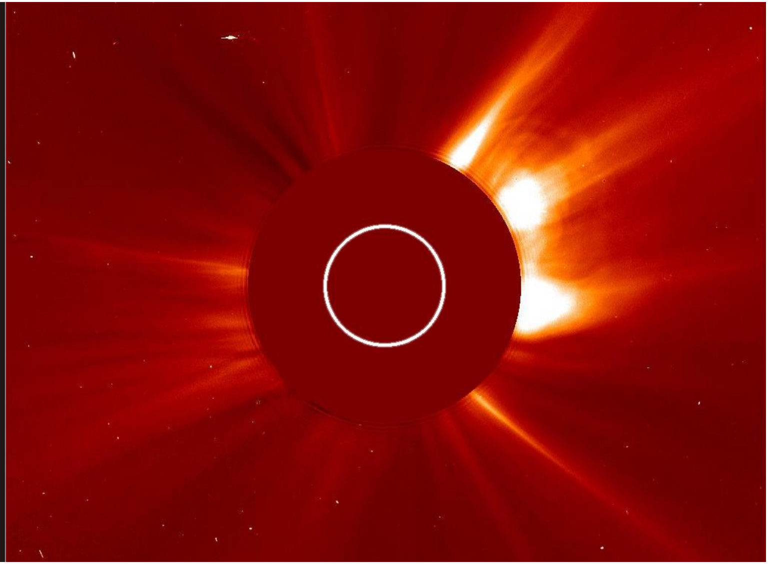
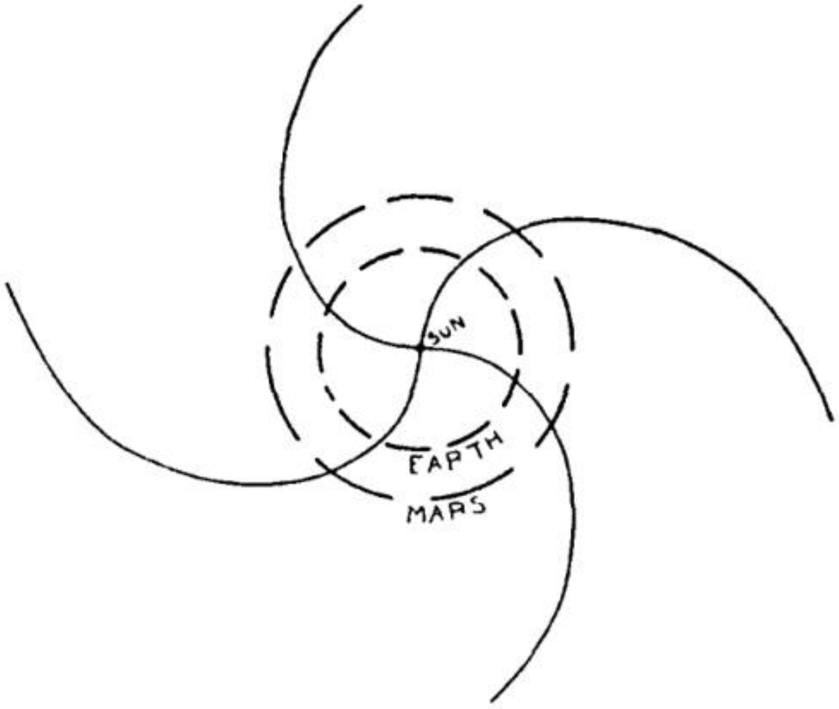






Solar Wind [Parker 1958]

- Plasma continuously emitted from the sun that expands out into heliosphere
- Drags magnetic field lines with it
- Rotation of the sun creates Parker Spiral along field lines



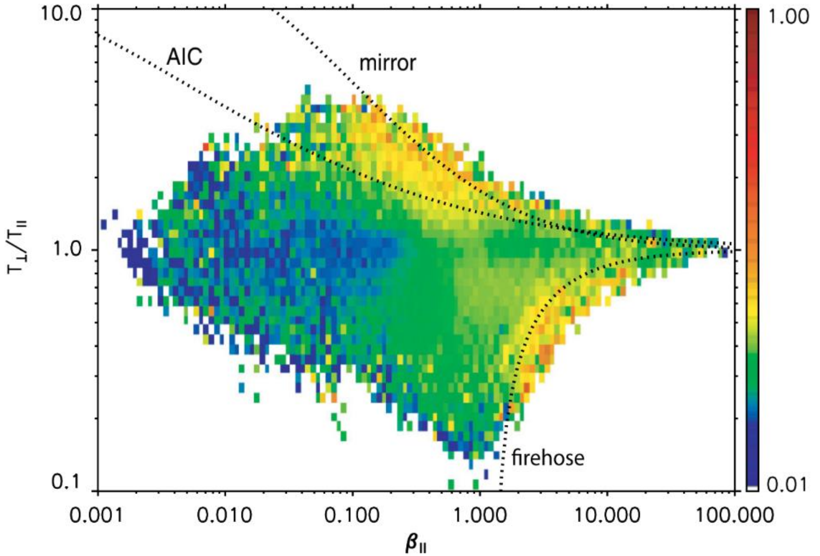
Temperature Anisotropy Driven Instabilities

- Parallel and perpendicular pressures evolve differently
- Leads to anisotropy in pressure
- Source of free energy

In the double adiabatic approximation:

$$\frac{d}{dt}\left(\frac{p_\perp}{mnB}\right) = 0 \qquad \frac{d}{dt}\left[\frac{p_\parallel B^2}{(mn)^3}\right] = 0$$

$$\frac{p_\perp}{mnB} = \text{constant} \qquad \frac{p_\parallel B^2}{(mn)^3} = \text{constant}$$



Data at 1 AU from WIND spacecraft [Bale et al 2009]

Parallel Firehose Instability Criterion: $P_\parallel - P_\perp - \frac{B_0^2}{\mu_0} > 0$

Gkeyll/Ten Moment Equations/Closure

- Simulations Performed in GKEYLL
  - Computational framework with multi-fluid, ten moment solver
- Ten Moment Equations (n,vector(u),tensor(P):
  - Velocity moments of the Vlasov Equation
  - Moments are linked to next order moment equation
  - We use a heat flux approximation as closure

Vlasov Equation:

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} + \frac{q}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right)\frac{\partial f}{\partial \vec{v}} = 0$$

Velocity Moments:

$$\int \left(v_i v_j v_k \ldots\right) f d\vec{v}$$

Closure:

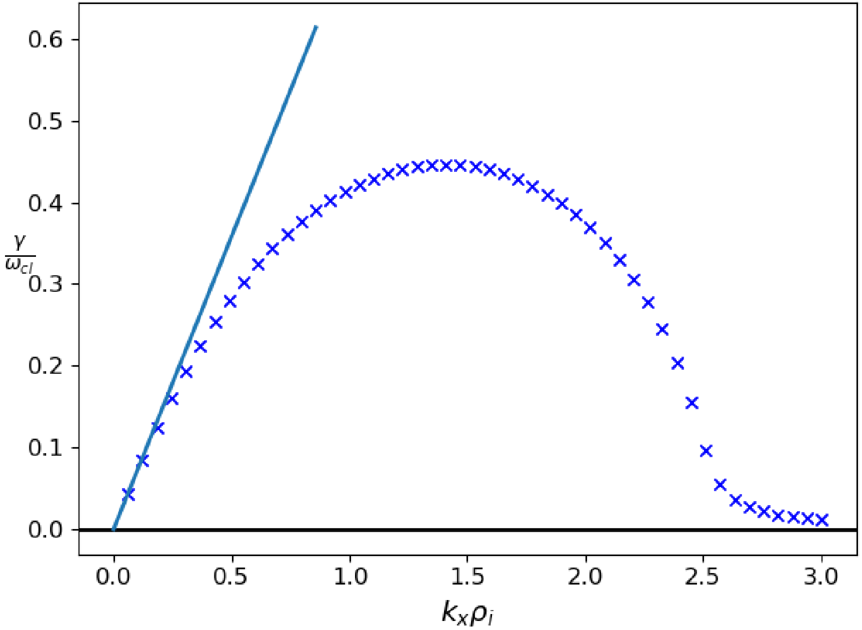
$$\frac{\partial Q_{ijk}}{\partial x_k} \approx v_t k_0 \left(P_{ij} - p\delta_{ij}\right)$$

$$= k_0 \rho_i \omega_{ci} (P_{ij} - p\delta_{ij})$$

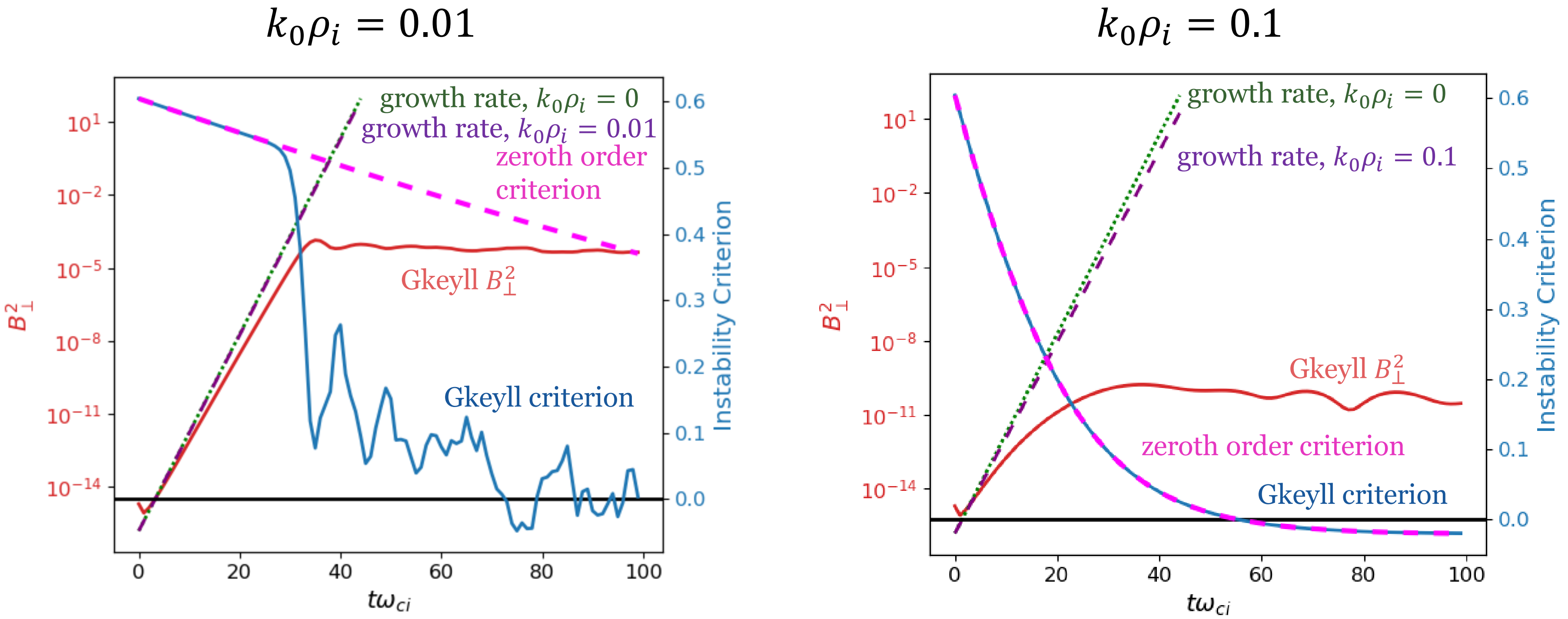
k_0 has units $(\text{length})^{-1}$

Linear Stability Analysis

- Assume perturbations take form $\sim Exp(k_x x - \omega t)$ and linearize ten moment equations to first order
- Can be represented in matrix form $\omega\, \vec{F} = A(k_x)\, \vec{F}$
- Eigenvalue Problem
- To smallest order in k_x with $k_0 = 0$,
$$\omega^2 = k_x^2 v_A^2 \left(1 - \frac{1}{2}(\beta_\parallel - \beta_\perp)\right)$$
$$= k_x^2 \frac{v_t^2}{P_0} \left(\frac{B_0^2}{\mu_0} + P_\perp - P_\parallel\right)$$
- Unstable for growth rate $\gamma = Im[\omega] > 0$



Parallel Ion Firehose Simulations $\left(\beta = \frac{300}{\pi}, \Delta\beta = \beta_{\parallel} - \beta_{\perp} = 100\right)$



- Closure has minimal impact on initial instability growth rate
- Zeroth order evolution: $\frac{\partial \Delta P}{\partial t} + k_0\rho_i\, \Delta P = 0$

Conclusions

- The two fluid, ten moment model can accurately reproduce the parallel firehose instability for ions
- The closure has minimal impact on first order perturbations from the instability
- However there is significant influence from the closure in zeroth order evolution

Closure Comparison

- Hammet-Perkins Closure (what we used) [Hammet, Perkins 1990]
- $\tilde{q}(k) = -\chi_1 \frac{\sqrt{2}}{|k|} ikv_t \tilde{T}(k)$
- Leads to both zeroth and first order dependence

- New Potential Closure [Ng et al 2020]
- $q_{ijk} = -\frac{v_t}{|k_s|} \chi \partial_{[i} T_{jk]}$
- Gradient means there is no explicit zeroth order dependence

Looking at other Posters, Back in a few Minutes