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Cross-scale coupling of the solar-terrestrial plasmas: Novel view on kinetic plasma dynamics

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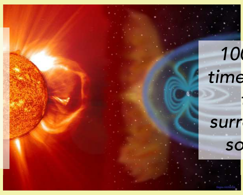
Introduction

How plasmas (ionized gases) get heated and accelerated remains one of the unsolved problems in astrophysics.

The Sun-Earth environments are the most accessible laboratories where the physics at work can be probed in situ.

Understanding how these environments work also help us to mitigate effects from "**space weather**" that can damage space and ground technologies, leading to loss of several billion euros.

Solar corona ***Magnetosphere***



A few 100 times hotter than its surface

100 – 1000 times hotter than the surrounding solar wind

Fig 1. Solar-terrestrial plasmas

A "key" missing piece to solve this problem is the role of kinetic processes (i.e., near particle scales) as they need high-resolution observations in situ.

Plasma kinetic theory

Maxwell-Boltzmann equation is the most powerful tool for investigating plasma kinetic dynamics:

$$\frac{\partial f_s}{\partial t} + \mathbf{v}_s \cdot \nabla f_s + \frac{q_s}{m_s}(\mathbf{E} + \mathbf{v}_s \times \mathbf{B}) \cdot \frac{\partial f_s}{\partial \mathbf{v}_s} = \left(\frac{\partial f_s}{\partial t}\right)_{\mathrm{coll}}$$

where $f_s = f_s(t, \mathbf{v}, \mathbf{r})$, the distribution of a plasma species (s) as a function of time (t), velocity (**v**), and space (**r**).

Measurements of plasma velocity distribution function (VDF) *in situ*

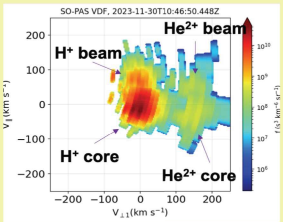


Fig 2. Example of ion VDF from PAS.

Proton-Alpha Sensor (PAS) developed at IRAP onboard SO measures VDF of major solar wind ions (H^+, He^{2+}) with unprecedented resolution[1].

High-resolution ion VDF observations show striking kinetic, non-Maxwellian features (i.e., source of free energy).

Yet, their origins and roles remain poorly understood.

References

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Unsolved problem: Coronal heating and solar wind acceleration

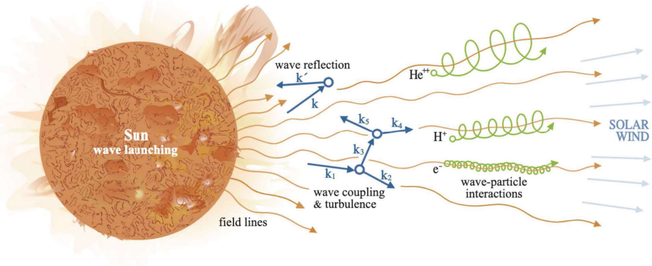


Fig 3. The Sun as an electromagnetic wave launcher.

The Sun continuously launches its matter and electromagnetic waves into space. A leading theory is that the large-scale waves launched by the Sun in Alfvénic form (~ restoring force in a rope), transport the energy outward while transferring energy to smaller-scale waves.

We still do not understand how small-scale waves (i^+, e^- gyroscales) heat and accelerate the solar wind.

Spacecraft radial alignment: unique opportunity for studying solar wind evolution

Parker Solar Probe (PSP) and Solar Orbiter (SO) are two new solar missions, launched in 2018 and 2020, respectively. PSP is the first mission that flies through the corona. SO will probe the Sun from above for the first time. PSP and SO occasionally line up in the radial direction where the solar wind propagates.

How does the solar wind evolve "kinetically" on its way to Earth?

Methodology: identifying a parcel that was intercepted by both spacecraft

On 25 – 27 February 2022, PSP and SO aligned radially (Fig. 4) with PSP being at 0.06 AU while SO being at 0.6 AU. To find an interval that was intercepted by PSP and then SO, we perform the following steps:

1. Ballistic propagation based on proton speed to find plasma origins.
2. Select interval where the He^{2+} to H^+ density ratio is similar.
3. Compare nonlinear similarity of the magnetic fields.

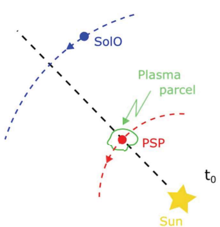


Fig 4. PSP-SO radial alignment

Outcomes: comparison of solar wind stream measured by PSP and SO

We focus on (1) magnetic turbulence, (2) proton instabilities, and (3) VDF of the protons. Magnetic power spectra (Fig. 5) shows that the magnetic field fluctuations show classic turbulent properties with the change of the turbulence cascade rate near the proton gyrofrequency (f_{ci}). The linear instability analysis[2] (Fig. 6) shows proportions of data being unstable to the proton cyclotron instability (above the black dots).

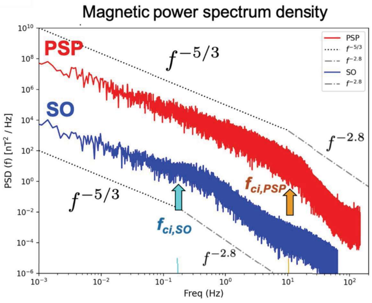
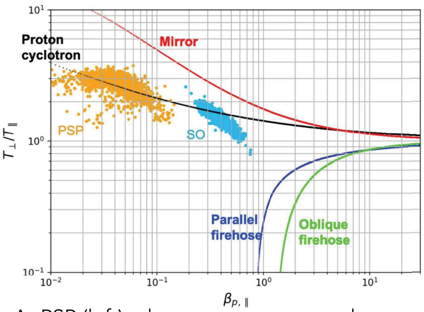
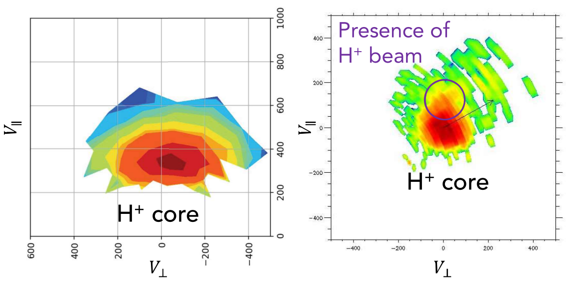


Fig 5 (left). Power spectra of magnetic measurements.

Fig 6 (right). Linear proton instability analysis.



Finally, we compare VDF evolution from PSP to SO in Fig 7. At PSP (left), the protons are strongly scattered along the $V_\perp$ direction (perpendicular to the magnetic field). At SO, the the protons are less scattered along $V_\perp$(i.e. reduced temperature anisotropy).



Surprisingly, we observe a presence of an accelerated population along $V_\parallel$, known as H^+ beam, at SO. This implies that the **accelerated H^+ beam** may be formed on its way while propagating outward from the Sun.

Fig 7. VDF measured at PSP (left) and SO (right) shown in $V_\parallel - V_\perp$ coordinates, i.e., along and perpendicular to magnetic field.

Summary and perspectives

Evolution of kinetic properties:

1. Decrease of proton $T_\perp/T_\parallel$ by half from PSP to SO.
2. Less fraction of protons being unstable to the proton cyclotron instability at SO.
3. Formation of a proton beam, 2 days later, at SO.

On the proton beam (H^+) formation:

The most-likely mechanism is the diffusion of VDF owing to wave-particle (i.e. resonance) interaction[3]. Our analysis suggests that ion cyclotron waves, driven by the instability, might play a key role.

Our work demonstrates a good showcase study for the connection between turbulence, waves, instabilities, and kinetic features, as well as the coupling from large magnetohydrodynamics to small kinetic scales. Future work includes refining the analyses and identification of wave modes.