Solar wind proton and $\alpha$ particle velocity distributions, temperature anisotropies, and heating models guided by Parker Solar Probe perihelia data

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Abstract
We analyze the PSP/Spani data of the proton VDFs with beams during perihelia encounters, as well as plasma moments such as density, anisotropic temperature, and alpha particle data. The FIELDS instrument provides the corresponding kinetic wave activity magnitude, spectra and polarizations that helps identify the dominant kinetic wave modes. Guided by the observations, we use 2.5D and 3D hybrid particle-in-cell (PIC) models of kinetic protons and alpha particles with background electron fluid in an expanding box model to study the kinetic instabilities driven by unstable VDFs such as super-Alfvénic beams and ion relative drifts in the inner solar wind. The model studies the super-Alfvénic as well as sub-Alfvénic solar solar properties. The proton and $\alpha$ particle populations physical properties, such as the drift speeds, anisotropic temperatures, magnetic energy and spectra are modeled and compared to observed PSP solar wind data near perihelia. We find the ion kinetic instabilities associated with the plasma properties and investigate in the conversions between the kinetic energy from ion instabilities to magnetic and thermal energies in the solar wind plasma. In particular, the quantification of the partition the couplings between $\alpha$ particle and proton populations through wave-particle interactions provides insights into the heating and acceleration of the solar wind plasma. We will investigate Artificial Intelligence Machine Learning (AI/ML) data analysis methods for the classification of VDFs produced by the hybrid model with the goal of applying the methods to PSP data.

Hybrid Model

Proton and other ion equations of motion are solved using Particle-in-Cell (PIC).

Temporal Evolution of $T$ anisotropies, energies, and $p-\alpha$ drift

Evolution of the proton $V_p$, $V_{\alpha}$ velocity distributions

Evolution of the $\alpha$ particle $V_{\alpha}$, $V_{\alpha}$ velocity distributions

Temporal Evolution of $T$ anisotropies, energies, and $p-\alpha$ drift

Summary and Conclusions

- We show several examples of sub-Alfvénic solar wind PSP data Spani and FIELDS at $E10$ with moments, proton VDFs and wave analysis.
- Motivated by the PSP observations at $E10$ and $E11$ of ion VDFs and kinetic waves we model proton and $\alpha$ particle populations and study kinetic instabilities with the associated ion-scale wave spectra using 2.5D and 3D hybrid models.
- When protons and $\alpha$ particles are anisotropic in low-$\beta$ plasma the ion-cyclotron instability is produced resulting in perpendicular $\alpha$ particle heating with subsequent relaxation of the temperature anisotropy.
- The models show the evolution of the $\alpha$ temperature anisotropies, kinetic and magnetic energies, and the various forms of VDFs of protons and $\alpha$ particles.
- We demonstrate the wave dispersion spectra modeled in the SW plasma produced by the ion-cyclotron instability in qualitative agreement with linear dispersion branches.
- We extend 2.5D hybrid modeling studies of proton and $\alpha$ beam instabilities and temperature anisotropies to more realistic full 3D hybrid model and find similar results.
- We plan to implement ML/AI methods for automated classification VDFs, and instabilities in PSP data.