Project Title:
Space Plasma Physics: Pickup ions, turbulence, solar wind, and waves

Project Reference Code:
UAH-Zank

Hosting Institution:
The University of Alabama in Huntsville

Hosting Institution Location:
Huntsville, AL

Project Description:
The Sun plays a major role in space plasma physics. The atmosphere of the Sun expands outwards at a supersonic velocity, which we call the solar wind, until the ram pressure of the solar wind is balanced by the interstellar medium pressure. When the expansion of the solar wind stops, a bubble-like region of space is formed in the interstellar medium, known as the heliosphere. The solar wind provides a unique opportunity to study a variety of plasma processes. In the solar wind, waves and turbulence occur everywhere, and is advected by the solar wind flow. Similarly, we can also observe unusual charged particles called pickup ions (PUIs) in the solar wind. PUIs are created by charge exchange between solar wind protons and interstellar neutral atoms that drift from the interstellar medium into the heliosphere. Waves, turbulence, and PUIs have particular properties and can modify the physics of the heliosphere, and the heliospheric termination shock (HTS). Here, we divide our project into four subprojects. The projects are related to investigating the pickup ion distribution function in the distant solar wind, turbulence in the solar wind, solar wind simulations, and waves in the solar wind. The student is free to choose any one of the projects. Students will be involved with state-of-the-art research under the general direction of Dr. Zank and more specifically with his postdocs, Dr’s Laxman Adhikari, Lingling Zhao, Masaru Nakanotani, and Samira Tasnim.

<u>Subproject 1</u>: *Interstellar pickup ions*

As interstellar neutral particles stream into the heliosphere, they are ionized and picked up by the solar wind. These particles are called interstellar pickup ions (PUIs), which are typically singly charged. Although their existence was proposed for decades, direct measurements of PUIs were only available within 5 astronomical units from the Sun until recently. The NASA New Horizon (NH) mission is currently traveling outwards towards the interstellar medium and is currently located about 40 astronomical units from the Sun. NH is the first mission that has the capability of measuring PUIs at such a distance. However, such measurements are showing that our theoretical knowledge of the PUI distribution is not very good. The classical theory assumes that only advection and adiabatic cooling effects the newly born PUI distribution. These assumptions yield a filled-shell distribution. More sophisticated theories and simulations consider also the effects of spatial or momentum diffusion. The goal of this project is to compare different theoretical models to NH observations. The student will learn basic data analysis techniques and apply them to help understand the distinctions between different theoretical models and observations.

<u>Subproject 2</u>: Evolution of magnetic field fluctuations with heliocentric distance

Turbulence occurs everywhere from the small-scale coffee mug to the large-scale universe. Turbulence is common in the solar wind plasma. Turbulence is thought to be responsible for several important phenomena in the solar wind such as the distributed heating of the solar wind, the heating of the solar corona (perhaps one of the most important unanswered questions in heliophysics today and one that the Parker Solar Probe mission seeks to answer), acceleration of the solar wind, scattering of the solar energetic particles, and so on. As the solar wind expands with distance, turbulence evolves with increasing heliocentric distance. In-situ stream-shear and pickup ion sources of turbulence are present and drive the evolution of turbulence throughout the heliosphere. The stream-shear source of turbulence results from the difference between the speed of fast and slow solar wind streams and is a major source of turbulence below ~ 5 astronomical units (au) (1 au is a distance between the Sun and the Earth). Similarly, there is a pickup ion source of turbulence in the distant heliosphere, this related to charge exchange between solar wind protons and interstellar neutrals. This source of turbulence dominates beyond ~ 5 au. These sources drive solar wind turbulence throughout the heliosphere. The evolution of turbulence in the heliosphere can be described by a set of turbulence transport model equation of greater or lesser complexity. For example, Zank et al. (1996) developed a theoretical model comprising just two coupled turbulence transport model equations that describe the evolution of fluctuating magnetic energy and the correlation length of the magnetic field fluctuations throughout the super-Alfvenic solar wind. Measurements from numerous spacecraft allow us to compare the different theoretical models of turbulence transport with detailed spacecraft measurements. This opportunity has furthered our understanding of solar wind turbulence significantly.

The purpose of this project is to understand how turbulent magnetic field fluctuations evolve along the trajectory of the Cassini spacecraft. In this project, the student will analyze both magnetic field and plasma data from the Cassini spacecraft and compare to solutions derived from the simpler Zank et al. (1996) turbulence transport model equations. S/he will calculate the fluctuating magnetic energy density and the correlation length from the Cassini data sets, and compare the observed results with the theoretical results. This project offers a student the opportunity to learn to solve numerically and model turbulence transport equations while comparing the solutions to observations while learning data analysis techniques.

<u>Subproject 3</u>: Comparing Solar Wind Simulations to Observations and Analytic Predictions

The solar wind is the expanding outer atmosphere of the Sun and fills interplanetary space with heated ions and electrons. Studying the solar wind offers unique opportunities to better understand space plasmas, and characterizing the solar wind's global three dimensional (3D) structure is becoming increasingly important for space weather forecasting. The solar wind is the medium through which transients like Coronal Mass Ejections (CMEs), shocks, and fast and slow solar wind streams develop and evolve. These transients lead to space weather events at Earth that can potentially damage satellites and disrupt power grids, and so the monitoring and prediction of such events are of great interest. Magnetohydrodynamic (MHD) simulations, which combine the physics of fluid dynamics and electromagnetism, are one of the most important ways to study this environment. These simulations complement observations and data-driven analytic models, which can then be used to develop improved simulations for forecasting.

In this project, the student will learn to access and utilize data from the Wind and STEREO spacecraft for different solar rotation periods. They will fit these data with an analytic solar wind model and then compare the analytic predictions and observations to a global MHD model generated with the widely used BATS-R-US code. This will be enabled through existing MATLAB and Fortran codes that the student will implement and further develop for their project.

Subproject 4: Computer Simulation: Full Particle-in-cell Simulations (for an advanced student with some prior plasma physics background)

Computer simulations are essential to understand fully the plasma physics of the solar wind. Since there are a huge number of particles in even a collisionless rarefied plasma, it is impossible to trace all particles along with calculating electromagnetic fields by hand. However, a computer can calculate such a many-body system instead of us. Computer simulations have been widely used to study various phenomena (for example, turbulence, magnetic reconnection, shock waves, etc.) and have provided us with important insights. Computer simulations are a powerful tool to study plasma and can be related to experiment, observation, and theory.

Computer simulations are classified depending on their level of approximation. Magnetohydrodynamic (MHD) models, as an example of a high approximation level, treat the plasma as a single fluid. MHD models have been used widely because that can describe large-scale phenomena relatively easily and at a low computational cost. On the other hand, full particle-in-cell (PIC) simulation, in which electrons and ions are treated as particles, can resolve micro scale dynamics and kinetic effects due their low approximation level, but this additional information and insight comes at a high computational cost. We can, however, perform large-scale simulations using a full particle description due to recent improvements in computational power. It has therefore become increasingly important to combine both MHD scale physics and kinetic effects.

This project will have the student writes a full PIC simulation code of their own from scratch. Using the code, s/he will investigate linear waves excited in a full-PIC simulation and compare them with waves derived from an MHD model and observational data. If time permits, another aspect of the project will be to use the code to perform a simulation of the so-called parametric instability, which is considered as a key decay process for low-frequency waves in a turbulent plasma. Through the topic, the student will learn how kinetic effects modify the MHD description.

Disciplines:
Physics, Math, Computer Science, Space Science

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The name and contact information of personnel at the hosting is provided for further assistance with questions regarding the hosting institution or the project.

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