INFLUENCE OF SOLAR-PROBE INHERENT ATMOSPHERE ON IN-SITU OBSERVATIONS

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Abstract

The solar corona is the source of the solar wind, which is responsible for the heliosphere and plays a crucial role in solar/terrestrial phenomena. A comprehensive understanding of these phenomena can be established only by directly measuring ion and electron velocity distributions, plasma waves, and fluxes of energetic particles near the sun. The problem resulting from the inherent atmosphere of a spacecraft moving in the vicinity of the sun and the influence of this atmosphere on in-situ measurements of the solar corona plasma is key to the realization and success of any solar probe mission. To evaluate the influence of the probe-inherent atmosphere on in-situ observations, we have developed comprehensive radiation hydrodynamic models. The physics of plasma/probe/vapor interaction are also being developed in a self-consistent model to predict the effect of probe inherent atmosphere on in-situ measurements of corona parameters during solar flares. Interaction of the ionized atmosphere with the ambient natural plasma will create a turbulent shock wave that can affect in-situ measurements and must be taken into account in designing the spacecraft and its scientific components.

Introduction

Solar-probe missions were recently proposed and studied in the U.S., Europe, and Russia [1]. The success of such missions depends on protecting the spacecraft subsystems and scientific payload from the intense solar heat. For perihelion distances of radius R = 4-10 solar radii, R_s (the values proposed for different options), the power of solar emissions can reach 60-400 W/cm^2. The spacecraft would be protected by a thermal shield made from materials that exhibit low volatility at high temperatures. Surface temperatures of typical graphite thermal shields are estimated to reach 1500-2200 K, depending on heliocentric distance. Outgassing, vaporization, and sputtering of the thermal shield and of the spacecraft will create a probe atmosphere that is partially ionized by solar ultraviolet radiation and fast electrons. Figure 1 is a schematic illustration of solar corona interaction with the probe atmosphere. This partially ionized atmosphere will result in an inherent cloud moving with the spacecraft at a velocity of up to 100-300 km/s. This cloud will interact with the coronal plasma flowing out from the sun at velocities in the hundreds of km/s. Such interaction with the probe environment must be taken into account to correctly interpret in-situ observations of sun perturbations.

Analysis

The Sun probe and its atmosphere crosses the frozen Sun magnetic field into the solar corona plasma at angles, β, that vary from 0 to π/2 at the perihelion. The relative velocity $\vec{V}$ of the solar probe and ambient solar corona plasma, i.e., $\vec{V} = \vec{V}_p - \vec{V}_s$ where $\vec{V}_p$ is the solar probe velocity and $\vec{V}_s$ is the solar wind velocity of about ≈200-300 km/s (which corresponds to the ions relative energy E_0 of several hundred eV). Interaction of the atmospheric plasma of the probe with the natural plasma will result in two-beam instabilities that excite the electromagnetic waves through transformation of the counterstreaming ion beams energy into thermal energy, i.e., a collisionless turbulent shock wave is formed. The conditions in the solar probe are similar to those studied in magnetized plasmas [2].

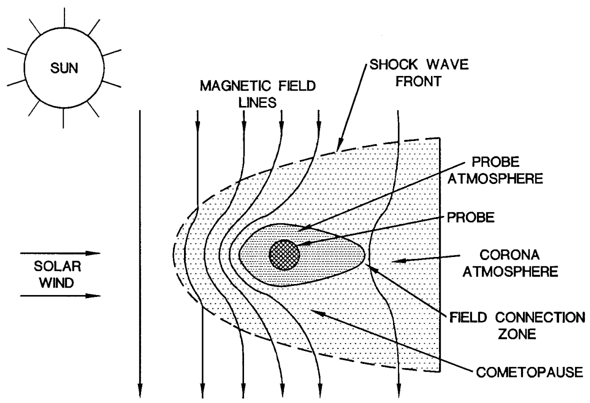

Fig. 1. *Schematic illustration of solar corona interaction with probe atmosphere.*

In the vicinity of the sun at distances R ≈ 4-10 R_s, effective interaction between the two streams occurs in a range approximately equal to the characteristic length of the solar probe L_p ≈ 10 m [3]. Because $r_{Hi} \geq L_p \geq r_{He}$, where $r_{Hi,e}$ is the Larmor radius of ions and electrons in the probe atmosphere, respectively, the magnetic field can affect only the electrons that can be regarded as a fluid. Therefore, the two-beam instability excites magnetosonic waves with frequencies $\omega \leq \omega_{pi}$, $kr_{Hi} > 1$, kr_{He} <1, where k is the wave number, i.e., magnetized electrons and unmagnetized ions. The characteristic time of the streamlining $\tau_u \approx L_p / V$, which determines the interaction time, is comparable to the instability time $\tau_T \approx \gamma^{-1} \approx \omega_{pi}^{-1}$. In the one-dimensional (1-D) solution, all of the kinetic energy, $E_0 = mV_0^2/2$, is transformed into waves energy $W \approx E_0$. However, a more comprehensive 2-D consideration of this problem results in a sharp decrease of W at the end of the interaction [4]. This limitation effect of W in the two-beam instability for nonisothermal and unmagnetized plasmas was studied by both the quasilinear approximation and by particle-in-cell (PIC) methods [5]. It was then shown that $W \leq 0.1 E_0$. The considered case in this study with magnetized electrons is similar because the magnetic pressure $P_\mu = B_0^2 / 8\pi$ plays the role of the hot electron pressure $P_e = n_e T_e$. For this consideration, the following equations are solved:

$$mn_e \frac{d\vec{V}_e}{dt} = -en_e\left[\vec{E} + \frac{1}{c}\left(\vec{V}_e \vec{B}\right)\right],\ \nabla \text{x} \vec{B} = \frac{4\pi}{c}\vec{j}\ ,\ \nabla.\vec{E} = 4\pi e\left(\sum_\alpha \int f_\alpha d\vec{v} - n_e\right),$$

$$\frac{\partial f_\alpha}{\partial t} + \vec{V}\vec{\nabla} f_\alpha + e\vec{E}\frac{\partial f}{\partial t} = 0,\ \alpha = 1,2$$

where α is the beam index and all other terms are conventional. At time t = 0 the ion distribution function is given by

$$f_{\alpha 0} = \frac{1}{(2\pi)^{3/2}}\ n_{\alpha 0} \exp\left[\frac{M_\alpha\left(\vec{V} - \vec{V}_{\alpha 0}\right)^2}{2kT_{\alpha 0}}\right],\ V_{10} = -V_{20} = V_0\ ,\ T_\alpha = T_0.$$

For $T_\alpha = 0$, the dispersion relation for the normal case of $n_1 = n_2$ is given by

$$\left[(1-\lambda u)^2 - \varphi\lambda^2\right]\left[(1+\lambda u)^2 - \varphi\lambda^2\right] = \lambda^4\varphi^2\ ,\ \vec{u} = \vec{V}_0 / c_A,\ c_A^2 = B_o^2 / 4\pi\rho,$$
$$\vec{\lambda} = \vec{k} c_A / \omega\ ,\ \varphi = k_a^2 / \left(k^2 + k_a^2\right)\ k_a = \vec{k}\vec{V} / |kV|\ ,$$

with the instability condition:

$$k^2 \leq \frac{2}{u^2 \cos\theta^2} - 1,\ \cos\theta = \vec{k}\vec{V} / |kV|.$$

The size of the unstable wave region in wave-number space is shown in Fig. 2 for different of beam velocity V. The value of V decreases with time and the thermal energy increases, resulting in a change of the unstable wave region in wave-number space. The mechanism of wave energy limitation was predicted. At a certain t, the unstable standing waves become stable and split into two waves with opposite momentum $\vec{k}_1 = -\vec{k}_2$. Fast damping of these waves transforms the wave energy in to thermal energy. Because $\gamma \propto k$, additional unstable waves arise with time from the low level of the initial waves.

Correct solution of this problem requires full numerical simulation with the PIC method. However, a qualitative solution can be obtained by using a simplified model that takes into account only wave excitation and damping. For a two-temperature (T_x,T_y) approximation, the following equations were solved:

$$\frac{d}{dt}\left(MnV^2/2\right) = -\frac{d}{dt}\sum_{\gamma>0} W_k\ ,\ \frac{dW_k}{dt} = \gamma_k W_k\ ,\ W = \sum_{\vec{k}} W_k\left(\vec{k}\right),$$

$$\frac{d}{dt}\left(nT_y\right) = -\frac{d}{dt}\sum_{\gamma<0} W_k \sin^2\theta_k\ ,\ \frac{d}{dt}\left(nT_x\right) = -\frac{d}{dt}\sum_{\gamma<0} W_k \cos^2\theta_k\ .$$

Results of these calculations are shown in Fig. 3. The wave energy W achieves its maximum, W_{max}, and then decreases sharply to zero, transferring their energy into the thermal energy of ions. The diminishing and collapse of the unstable-wave area is an explosive phenomenon. The maximum value of $W_{max} \approx 0.4E_0$, which is rather large because of this simplification. For a similar problem of unmagnetized plasmas, W_{max} was calculated to be $<0.1E_0$ [5].

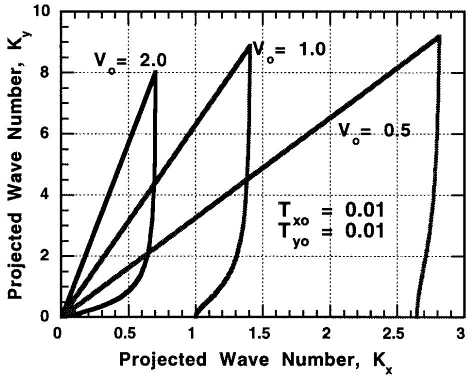

Fig. 2. Size of unstable region in wave-number space during two-beam instabilities.

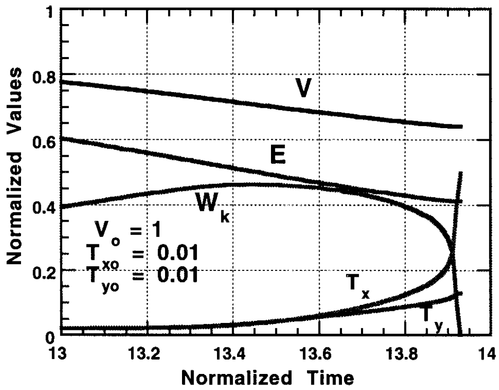

Fig. 3. Time dependence of normalized parameters during two-beam instabilities.

Numerical modeling with the PIC method for real solar probe conditions is currently underway. It will be possible from these calculations to accurately determine the level of the electromagnetic fluctuations due to the two-beam/stream instability and to evaluate the effect on in-situ measurements.

Acknowledgments

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