MICROPHYSICS OF WAVES AND INSTABILITIES IN THE SOLAR WIND AND THEIR MACRO MANIFESTATIONS IN THE CORONA AND INTERPLANETARY SPACE

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Final Report on Sun-Earth Connection Guest Investigator Grant

Microphysics of Waves and Instabilities in the Solar Wind and their Macro-Manifestations in the Corona and Interplanetary Space

Investigations of the physical processes responsible for coronal heating and the acceleration of the solar wind were pursued with the use of our recently developed 2D MHD solar wind code and our 1D multifluid code. In particular, we explored:

(1) the role of proton temperature anisotropy in the expansion of the solar wind,
(2) the role of plasma parameters at the coronal base in the formation of high speed solar wind streams at mid-latitudes,
(3) a three-fluid model of the slow solar wind
(4) the heating of coronal loops
(5) a newly developed hybrid code for the study of ion cyclotron resonance in the solar wind

1. A 2D Alfvén-wave-driven solar wind model with proton temperature anisotropy

In the first two-dimensional Alfvén-wave turbulence-driven solar wind model to take into account the proton temperature anisotropy, we showed that in the fast solar wind the anisotropy is established in the inner corona and yields a ratio of $T_{//}/T_{\perp}$ comparable to measured values in the corona and interplanetary space. However the values of $T_{//}$ and $T_{\perp}$ are only half their observed values. In the slow solar wind, the modeled values for $T_{//}$ and $T_{\perp}$ as well as their ratio are close to those measured in interplanetary space. Curiously, the dip in the velocity that develops near the cusp at the top of the helmet streamer, reduces the effect of transverse expansion, and leads to a realistic electron temperature in the slow wind at 1AU, even though no explicit external heating is applied to electrons

Comparison with models with and without proton temperature anisotropy shows that, by allowing the proton temperature anisotropy to develop, the average proton temperature is lower than the isotropic case due primarily to the cooling in the direction parallel to the magnetic field. These results imply that ion-cyclotron resonance models with isotropic proton temperature are somewhat optimistic in assessing the role of Alfvén-wave turbulence in driving the fast solar wind. Inclusion of the temperature anisotropy of protons and proton thermal conduction are necessary for any physically realistic model.

2. Origin of the fast solar wind at mid-latitudes

The recently developed 2D MHD solar wind code was used to show that the distribution with latitude of density, temperature and magnetic field strength at the coronal base plays a primary role in determining the latitudes at which the fast solar wind originates, while the expansion factor of the flow tubes plays a secondary role. In this model, the wind is driven by the turbulent cascade of high frequency Alfvén-waves in all regions where the magnetic field lines extend into interplanetary space. This parameter study showed how fast streams can originate from mid-latitudes as observed by Ulysses both at solar minimum and maximum.

3. Coronal loops heated by turbulence-driven Alfvén-waves

The heating of long-lived coronal loops by turbulence-driven Alfvén-waves was explored. The novelty of the approach was the use of a two-fluid dynamic model. It was assumed that the nonthermal motions inferred from spectral line observations in the transition region are due to Alfvén-waves. It was also assumed that the turbulence is already developed when the waves are injected at the footpoint of the loop. While the wave/turbulence energy is readily absorbed by the proton gas, the Coulomb coupling between protons and electrons subsequently heats the electron gas. The model reproduces electron densities of $1\text{-}4 10^9$ cm^{-3}, which is in the range inferred from observations, as well as a moderate flow speed around 10 km s^{-1} along the loop.

4. An Ion-Cyclotron Resonance-driven Three-Fluid Model of the Slow Wind near the Sun

A three-fluid slow wind consisting of electrons, protons, and O^{+5} ions is constructed to account for a recent UVCS/SOHO observation. In this model, ion-cyclotron waves, which are assumed to be generated by a Kolmogorov turbulent cascade, are assumed to play a key role in driving the slow solar wind. By reproducing recent measurements on the O^{+5} parameters along a streamer axis and the well-known average proton flux in the slow wind near the Earth, it is demonstrated that the ion-cyclotron resonance mechanism proposed to explain the observations in the coronal hole and fast wind may also be important to the ions in the slow solar wind.

5. A two-dimensional Alfvén wave-driven solar wind model with proton temperature anisotropy

We present the first two-dimensional (2-D) Alfvén wave turbulence-driven solar wind model which takes the proton temperature anisotropy into account. While the modeled proton temperature anisotropy in the fast solar wind is established in the inner corona and yields $T_{p//}/T_{perp}$= 0.57 at 1 AU, which is comparable to measured values, $T_{p//}$and T_{perp} are only about half the observed values. In the slow wind, on the other hand, the modeled values for $T_{p//}$ and T_{perp} as well as their ratio are close to those measured in interplanetary space. Curiously, the dip in the velocity that develops near the cusp at the top of the helmet streamer reduces the effect of transverse expansion and leads to a realistic electron temperature in the slow wind at 1 AU, although no explicit external heating is applied to electrons. Comparison with models with and without proton temperature anisotropy shows that by allowing the proton temperature anisotropy to develop, the average proton temperature is lower than the isotropic case primarily because of the cooling in the direction parallel to the magnetic field. These results imply that ion cyclotron resonance models with isotropic proton temperature are somewhat optimistic in assessing the role of Alfvén wave turbulence in driving the fast solar wind. Inclusion of the temperature anisotropy of protons and proton thermal conduction are necessary for any physically realistic model.

6. Hybrid simulation of ion cyclotron resonance in the solar wind: evolution of velocity distribution functions

Resonant interaction between ions (oxygen ions O+5 and protons) and ion cyclotron waves is investigated using a one dimensional hybrid code. Ion cyclotron waves are self-consistently generated by an ion cyclotron anisotropy instability. We focus on the detailed acceleration process of ions. The non-linear interaction between oxygen ions and ion cyclotron waves is found to have two stages. During the first stage, oxygen ions are accelerated and heated in the direction perpendicular to background magnetic field and can develop extreme high temperature anisotropies with Tperp/Tparallel ~22 in an initially low beta plasma (beta value at 0.01) with very little parallel heating. During this stage, oxygen ions do not show an appreciable bulk acceleration along background magnetic field. In the second stage, a large bulk acceleration of oxygen ions (as large as 0.3 Alfv\'en speed) is observed. Ion cyclotron waves are not able to maintain the high temperature anisotropy as resonant heating continues. The non-linear nature of wave particle interaction makes oxygen ions have highly complex velocity distribution functions. In contrast, the heating and acceleration behavior of the major species, protons, is quite different. The velocity distribution functions of protons are less complex than the oxygen velocity distributions. Protons can also develop an large temperature anisotropy with preferential heating in the perpendicular direction. A bulk acceleration of protons (much smaller than the acceleration of oxygen ions) along background magnetic field is observed to develop simultaneously with the development of proton temperature anisotropy.

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