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PHYSICS OF THE INNER HELIOSPHERE 1-10 R_s:

PLASMA DIAGNOSTICS AND MODELS

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Summary

While the mechanisms responsible for heating the solar corona and accelerating the fast and slow solar wind streams are still unknown, model computations offer the only means for exploring and predicting the properties of such mechanisms in light of the empirical constraints currently available.

During the time covered by this grant, modeling and data analysis efforts were aimed at:

- the study of the propagation and damping of ion-cyclotron waves in the fast solar wind
- the exploration of the role of instabilities in the development of temperature anisotropies in the inner corona
- the coupling of neutral hydrogen and protons in the fast solar wind
- the morphology of the source region of the solar wind

Summarized below are some of the highlights of these studies. Two PhD theses by Xing Li and Lorraine Allen were partially supported by this grant.

Role of Ion Cylcotron Waves in the Fast Solar Wind

Studies of two and three fluid solar wind models concentrated on the effects of heating, momentum addition and Alfvén waves, on the flow of electrons, protons, minor ions and neutral hydrogen. In particular, multi-fluid solar wind models concentrated on the effects of the cascading of Alfvén waves on the heating and acceleration of the different solar wind species and the development of temperature anisotropies in the inner corona.

Models including ion cyclotron waves showed that these waves not only produce strong proton temperature anisotropy in the inner corona but also place a limit on the proton temperature anisotropy in interplanetary space. The set of fluid equations and the wave spectrum equation were solved simultaneously using a newly developed numerical code. Both Kolmogorov and Kraichnan cascade functions, were tested.

The role of proton temperature anisotropy on the energy balance requirements for the solar wind, and the implications for coronal heating processes were also explored. The implications of current inferences of high proton and minor ion temperatures in the inner corona from recent UVCS observations led to the finding that the C II 1036.3367 Å pumping of the O VI 1037 Å line was also in effect. Matching these observations with model computations also proved that the speed of the O^{5+} ions can reach 400 km/s around 3 R_s, and flow much faster than protons at that heliocentric distance.

The preferential acceleration and heating of solar wind alpha particles by the resonant cyclotron interaction with parallel-propagating left-hand-polarized ion cyclotron waves was also investigated. The Alfvén wave spectrum equation was generalized to multi-ion plasmas and a Kolmogorov type of cascade effect was introduced to transfer energy from the low-frequency Alfvén waves to the high-frequency ion cyclotron waves, which are assumed to be entirely dissipated by the wave-particle interaction. In order to distribute the dissipated wave energy among the alphas and protons, the quasi-linear theory of the wave-particle interaction was used along with the cold plasma dispersion relation, and a power-law spectrum of the ion cyclotron waves was assumed, with the spectral index as a free parameter of the model.

The exploration of the proton heat flux was also carried out using a 16-moment bi-Maxwellian fast solar wind model. It was found that the proton heat flux density, which is significantly smaller than the classical heat flux, plays a significant role in shaping the proton temperature anisotropy in the fast solar wind.

The effect of alpha particles on the dispersion relation of ion cyclotron and its influence on the heating of the solar wind plasma were also investigated. The presence of alpha particles was shown to dramatically change the dispersion relation of ion cyclotron waves, and significantly influence the way ion cyclotron waves heat the solar wind plasma. In particular, a spectrum of ion cyclotron waves affects the thermal anisotropy of the solar wind protons and other ions differently in interplanetary space. When alpha particles have a speed $u_\alpha > 0.5 v_A$, and both protons and alpha particles have a thermal anisotropy > 1), ion cyclotron waves heat protons in the direction perpendicular to the magnetic field, coold them in the parallel direction, and exert the opposite effect on alpha particles.

A proton/alpha magnetosonic instability was investigated in the framework of the linear theory of plasma waves for conditions typical of the fast solar wind. Warm streaming alpha particles with a differential, speed, i.e. the speed relative to the major ions/protons, v_α, close to the Alfvén speed, were found to significantly enhance a magnetosonic instability when their temperature anisotropy is less than 1. The possible role of the instability in limiting the relative speed between alpha particles and protons in the fast solar wind was also explored.

The results of the model computations can be summarized as follows:

- Significant temperature anisotropies in the protons and minor ions develop in the inner corona in the presence of Alfvén waves (Hu et al. 1997, Allen et al. 1998, 2000).
- Heavy ions are accelerated earlier than protons in the inner corona (Li et al. 1998).
- Ion cyclotron waves play a critical role in the development and control of the proton temperature anisotropy starting in the inner corona, and limit the growth of the temperature anisotropy in interplanetary space. In addition, this mechanism heats or cools protons in the direction parallel to the magnetic field (Li et al., 1999).
- A bi-Maxwellian-based 16-moment description of the solar wind protons, as well as the high proton temperature anisotropy implied by coronal and in situ observations place strong constraints on the proton heating mechanism: since protons must be heated in the direction perpendicular to the magnetic field, and cooled in the parallel direction (Li, 1999).

- With the Kolmogorov cascade function applicable to regions below 0.29 AU, a properly prescribed Alfvén wave amplitude and spectrum at the coronal base, which determines the total energy deposited via heating and acceleration, and its spatial distribution, can lead to the observed characteristics of the fast solar wind and the evolution of the wave spectrum as well (Hu, Habbal and Li, 1999).

- The effect of alpha particles on the dispersion relation of Alfvén waves is such that these particles can be accelerated to a bulk flow speed faster than the protons by a few hundred kilometers per second and heated by the resonant cyclotron interaction to more than mass-proportional temperature values at several solar radii (Hu and Habbal, 1999; Hu, Esser and Habbal, 2000).

Morphology of the Source Region of the Solar Wind

Analyses of coordinated radio occultation measurements with white light and ultraviolet observations continued to provide very strong evidence for the radial expansion of density structures in the corona.

Observations of the inner corona in polarized brightness by the Mauna Loa Mk III K-coronameter at 1.15 R_s and soft X-rays by Yohkoh at 1.03 R_s were combined with Ulysses radio occultation measurements of the solar wind to demonstrate that the signature of active regions and bright points is present in the heliocentric distance range of 20-30 R_s. The existence of this signature at such distances can be readily accounted for by open field lines rooted within the complex magnetic structures of active regions and bright points.

White-light measurements made by the SOHO LASCO C2 and C3 coronagraphs and the Mk III Mauna Loa K-coronameter, extending from 1.15 to 30 Ro, Kitt Peak daily He I 1083 nm coronal hole maps, and full Sun Yohkoh X-ray images, have been combined to show that the boundaries of polar coronal holes, extend approximately radially into interplanetary space. These results are in contrast with the longstanding view that the boundaries of polar coronal holes diverge significantly beyond radial, evolving around the edges of streamers.

In particular, these studies have shown that:

- The filamentary nature of structures in the solar wind are much smaller in streamer axes than in coronal holes (Woo and Habbal 1997a).

- The quiet Sun is very likely to be a source for the fast solar wind in addition to coronal holes (Woo and Habbal 1997b).

- the fast wind is ubiquitous in the inner corona, the streamer axes are the locus of the slowest solar wind, and a velocity shear exists between the fast and slow solar wind at the boundaries of streamers and along their axes (Habbal et al. 1997).

- The boundaries of coronal holes extend almost radially into interplanetary space, thus drastically changing the longstanding notion of the rapid divergence of the boundaries of polar coronal holes (Woo, Habbal, Korendyke and Howard, 1998).

- Small-scale raylike structures carry the imprint of different density structures of the solar disk approximately radially into the heliosphere with the exception of the small volume of interplanetary space occupied by the heliospheric current sheet that evolves from coronal streamers within a few solar radii of the Sun (Woo and Habbal, 1999a).
- The combined observations show that the corona is dominated by raylike structures as small as a few degrees in angular size with respect to Sun center, originating from both coronal holes and the quiet Sun (Woo and Habbal, 1999b).

PhD Theses

Xing Li, a graduate student from the University of Science and Technology of China, and a predoctoral fellow at the Smithsonian Astrophysical Observatory, completed the first PhD thesis which involved data from the Ultraviolet Coronagraph Spectrometer on SOHO (UVCS) in 1998. His thesis, entitled "On the role of minor ions in the solar wind", was the first comprehensive study of minor ions in the solar wind using multifluid solar wind models. As a consequence of the modeling, the discovery of ions moving faster than protons in the inner corona was made by Li.

Lorraine Allen investigated the coupling between neutral hydrogen and protons in the solar wind for her PhD thesis. Given that the Lyα is the only diagnostic for protons in the corona, the study was essential for the impact of UVCS measurements. The results of her study showed that the coupling between the neutrals and protons was strong out to 3 R_s and decreased thereafter. Hence in the acceleration region of the solar wind, the use of Lyα as a diagnostic for protons is valid. Hers was the second PhD thesis to be triggered by UVCS observations.

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