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The Impact of Ion-Cyclotron Wave Dissipation on Heating and Accelerating the Fast Solar Wind

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Abstract. Using empirical ion velocity distributions derived from UVCS and SUMER ultraviolet spectroscopy, we construct theoretical models of the nonequilibrium plasma state of the polar solar corona. The primary energy deposition mechanism we investigate is the dissipation of high frequency (10–10000 Hz) ion-cyclotron resonant Alfvén waves which can heat and accelerate ions differently depending on their charge and mass. We find that it is possible to explain many of the kinetic properties of the plasma with relatively small amplitudes for the resonant waves. There is evidence for steepening of the Alfvén wave spectrum between the coronal base and the largest heights observed spectroscopically, and it is important to take Coulomb collisions into account to understand observations at the lowest heights. Because the ion-cyclotron wave dissipation is rapid, the extended heating seems to demand a constantly replenished population of waves over several solar radii. This indicates that the waves are probably generated throughout the wind rather than propagated up from the base of the corona.

INTRODUCTION

Ultraviolet spectroscopy of the solar corona provides detailed empirical knowledge about the plasma conditions in the acceleration region of the solar wind. Specifically, the shapes of emission lines probe ion velocity distributions along the optically thin line of sight. In this paper we present a preliminary analysis of spectroscopic measurements from the UVCS instrument aboard SOHO. These observations are interpreted in the context of a specific theoretical mechanism for preferential ion heating: the dissipation of high frequency Alfvén waves via resonance with ion-cyclotron Larmor motions. A more detailed analysis will be presented by Cranmer *et al.* (1).

The steady, nearly uniform high speed wind, which fills the majority of the volume of the heliosphere (2), displays a marked departure from ideal thermal equilibrium. Spacecraft measurements at distances greater than 0.3 AU have found strong temperature anisotropies correlated with the local magnetic field direction, as well as a preferential energization (i.e., faster flow speed and higher temperature) of higher-mass ions [(3), (4), (5)]. Similar plasma properties have also been found in the extended polar corona with UVCS/SOHO (6). Above 2–3 $R_\odot$, O^{5+} ions are measured to have perpendicular kinetic temperatures approaching 2×10^8 K and $T_\perp/T_\parallel \approx$ 10–100 [(7), (8), (9)]. The O^{5+} and Mg^{9+} ion kinetic temperatures are significantly greater than "mass-proportional" when compared with H^0 [i.e., $T_{\rm ion}/T_H > m_{\rm ion}/m_H$; (10)]. A mechanism that naturally and efficiently produces these effects on ion velocity distributions is the dissipation of high frequency gyroresonant waves. This work takes a step toward understanding the importance of this process in the fast solar wind by modeling the observed anisotropic motions in the extended corona.

STEADY STATE MODELS

In this paper we constrain the ion velocity distributions to be bi-Maxwellians and solve the perpendicular energy conservation equation for $T_{\perp i}$,

$$n_i u_i \kappa \frac{\partial T_{\perp i}}{\partial r} + \frac{n_i u_i \kappa T_{\perp i}}{A} \frac{\partial A}{\partial r} =$$

$$Q_{\perp i} + C_{\perp ip}(T_{\perp p} - T_{\perp i}) + m_p J_{\perp ip} \qquad (1)$$

where n_i is the ion number density, u_i is the outflow velocity, κ is Boltzmann's constant, and A is the superradially diverging flux tube area [(11), (12), (13)]. Coulomb collisional energy exchange between the ions and protons ($C_{\perp ip}$) and the Joule heating and isotropization which results from these collisions ($J_{\perp ip}$) are taken into account using full anisotropic rates (14). Collisions between the ions and other species take place typically at much slower rates, and are ignored here for simplicity. Viscosity and ion heat conduction are neglected, and the ion-cyclotron heating rate $Q_{\perp i}$ is discussed below.

The derived perpendicular temperatures are relatively insensitive to variations in parallel temperature and ion outflow velocity, so we constrain these quantities empirically (1). The magnetic field strength B_0 and superradial flux tube divergence over the poles are constrained using the model of Banaszkiewicz *et al.* (15). We adopt the solar minimum electron density n_e of Guhathakurta and Holzer (16) and compute the electron and proton outflow velocity using mass flux conservation. The base boundary condition for the temperature is equilibrium between ions, protons, and electrons with an adopted value of 8×10^5 K. It should be made clear that we are not modeling explicitly the solar transition region between the chromosphere and the corona. Although this decoupled approach does not allow a complete *ab initio* solution for, e.g., the solar wind mass flux (17), the extended ion heating above coronal holes should be relatively insensitive to the structure of the transition region.

We model the powerful wave-particle energy exchange arising from the resonance between high frequency, parallel propagating Alfvén waves and the cyclotron gyromotions of positive ions [(18), (19), (20), (21), (22), (23), (24), (25)]. For coronal hole velocity distributions, this interaction results in a strong (weak) heating in the perpendicular (parallel) direction, as well as preferential acceleration for heavier ions. We use the "quasilinear" approximation for the wave dissipation, which gives an energy deposition rate of

$$Q_{\perp i} \; = \; \int_0^\infty d\omega \, P(\omega, r) \, \mathcal{R}_i(\omega) \left(\frac{\Omega_i}{k_\parallel} \right) \qquad (2)$$

where the frequency dependent momentum transfer rate (per unit wave power) is given by

$$\mathcal{R}_i(\omega) \; = \; \frac{m_i n_i \pi^{1/2} \Omega_i^2 \, e^{-\xi_1^2}}{B_0^2 \, k_\parallel} \left[\frac{\xi_1 T_{\perp i}}{T_{\parallel i}} + \frac{\Omega_i}{w_{\parallel i} k_\parallel} \right] \qquad (3)$$

[(21), (26)]. Above, the wave power (perpendicular magnetic variance) per unit frequency is given by $P(\omega, r)$, the parallel most probable speed is $w_{\parallel i} = (2 \kappa T_{\parallel i} / m_i)^{1/2}$, and the ion-cyclotron frequency is $\Omega_i = q_i B_0 / m_i c$. The heating arises only from waves within a small range of frequencies determined by the resonance factor

$$\xi_1 \; = \; \frac{\omega - u_i k_\parallel - \Omega_i}{w_{\parallel i} k_\parallel} \qquad (4)$$

where $k_\parallel$ is the wavenumber of the parallel-propagating waves. We assume the magnetic fluctuation spectrum is maintained in a self-similar power law form $[P(\omega) \propto \omega^{-\eta}]$ over the resonant frequencies of interest, and that the radial evolution of wave power is governed by the linear conservation of wave action [(27), (28), (29), (30)]. The dispersion of the waves is modeled in the cold plasma limit with only the proton cyclotron resonance affecting the phase speed [(20), (23)].

COMPARISON WITH SPECTROSCOPIC MEASUREMENTS

Cranmer *et al.* (1) present a detailed analysis of measurements made by the SUMER and UVCS instruments, and compare them to models similar to those described above (but with $T_{\parallel i}$ computed self-consistently as well). The relevant SUMER observations are the $1/e$ emission line widths presented by Tu *et al.* (31) and Hassler *al.* (32) between 1.01 and 1.06 $R_\odot$. These have been modeled by the dissipation of relatively *shallow* power law wave spectra, with $\eta \approx 0.5$–1. Steeper slopes cannot produce the observed dependence of line width on the charge-to-mass ratio Z/A of the ions. For lines of iron and silicon, which have been observed in more than one ionization state, smaller charge states have broader widths; this is consistent with those ions having a weaker Coulomb collision rate [proportional to Z^2/A; (33)].

Measurements of emission lines at higher heights with UVCS have revealed unexpectedly broad profiles of the O VI $\lambda\lambda$ 1032, 1037 doublet over the poles. The most-probable speeds $w_{\parallel i}$, $w_{\perp i}$, and outflow velocities u_i have been empirically modeled by Kohl *et al.* (8) and Cranmer *et al.* (9), and in Figure 1 we plot a comparison between the empirical values of $w_{\perp i}$ and model integrations from 1 to 4 $R_\odot$. The normalization of the wave power law $P(\omega)$ was varied for each value of η to match the empirically derived $w_{\perp i}$ at 3 $R_\odot$. Interestingly, the best agreement with the observed radial variation comes from a model with a *steep* power law ($\eta \approx 2$), in contrast to the shallower value constrained by the SUMER measurements at lower heights.

The magnitude of the resonant wave power required to heat the O^{5+} ions is small when compared with the mean magnetic field energy and the thermal ion energy (21), and is also several orders of magnitude smaller than simple extrapolations of *in*

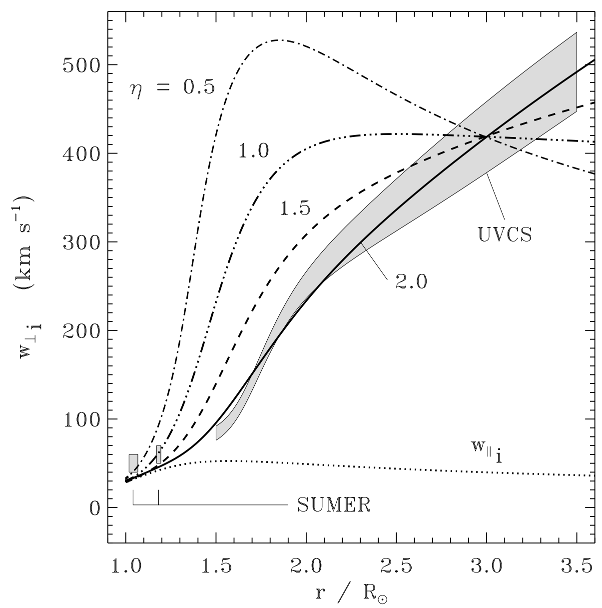

FIGURE 1. Radial dependence of the O^{5+} perpendicular most-probable speed $w_{\perp i} = (2\kappa T_{\perp i}/m_i)^{1/2}$. Empirical constraints from SUMER and UVCS are denoted by gray regions bordered by thin solid lines. Also plotted is the assumed parallel most-probable speed (*dotted line*) and model results for a range of spectral power law exponents η.

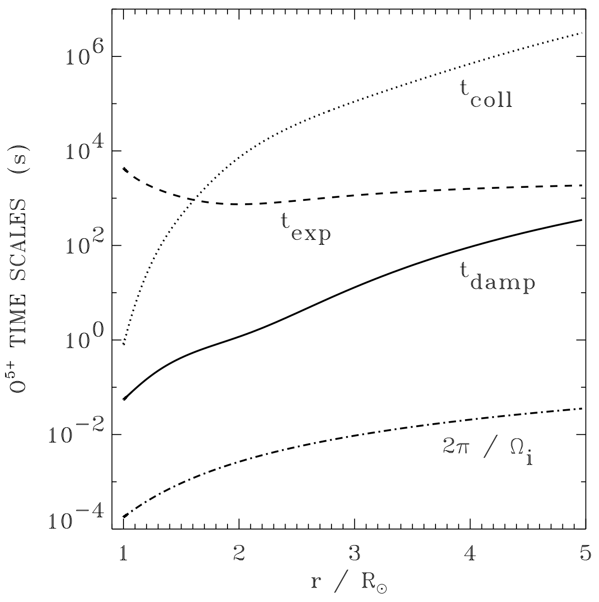

FIGURE 2. Time scales for O^{5+} ion dynamics in the extended corona: mean ion-proton collision time (*dotted line*), wind expansion time, derived from the density scale height (*dashed line*), quasilinear wave damping time (*solid line*), and the ion-cyclotron resonant wave period (*dot-dashed line*).

situ wave power down to the corona. There is thus ample room for some resonant damping of the wave amplitudes to occur and still have enough power to heat the minor ions (1). We find that resonant wave damping times are long relative to the local ion-cyclotron periods (see Figure 2), thus confirming the validity of the quasilinear approximation for minor ions. Also, it is clear from Figure 2 that the damping times are very short when compared to macroscopic wind expansion times. These waves would tend to decay rapidly (over $\sim 10^{-3}\ R_\odot$) if not otherwise maintained at their modeled amplitudes. Thus, a purely self-consistent model of the propagation and decay of ion-cyclotron waves (from, e.g., the base of the corona) should not be able to deposit heat into the extended corona, and some kind of *gradual wave generation* over several solar radii seems to be required.

The generation and maintenance of a high-frequency coronal Alfvén wave spectrum remains a major unresolved issue. Standard MHD turbulent cascade may not be sufficient to replenish the resonant wave power on time scales short enough to compete with the ion-cyclotron damping. Kinetic microinstabilities arising from nonequilibrium velocity distributions may play an important role [(34), (35), (36)], as may the coupling of different wave modes in inhomogeneous shear flows [(37), (38)]. The existence of a self-organized power-law spectrum points to fundamentally nonlinear processes, and even the observed (*in situ*) onset of dissipation near the cyclotron frequency does not guarantee the dominance of parallel propagating wave resonances [(39), (40)]. If ion-cyclotron wave dissipation is indeed the solution to the problem of extended coronal heating in the fast solar wind, then this solution gives rise to many new questions concerning the kinetic physics of the plasma and the origin of its fluctuation spectrum.

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