SPECTROSCOPIC CONSTRAINTS ON MODELS OF ION-CYCLOTRON RESONANCE HEATING IN THE POLAR SOLAR CORONA

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Abstract. Using empirical velocity distributions derived from UVCS and SUMER ultraviolet spectroscopy, we construct theoretical models of anisotropic ion temperatures in 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 the observed high perpendicular temperatures and strong anisotropies with relatively small amplitudes for the resonant waves. There is suggestive evidence for steepening of the Alfvén wave spectrum between the coronal base and the largest heights observed spectroscopically. Because the ion-cyclotron wave dissipation is rapid, even for minor ions like O^{5+}, the observed extended heating seems to demand a constantly replenished population of waves over several solar radii. This indicates that the waves are generated gradually throughout the wind rather than propagated up from the base of the corona.

Key words: Alfvén waves, Corona, Ion Cyclotron Resonance, Spectroscopy, UV radiation

1. 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 transverse line of sight. In this paper we present a preliminary analysis of 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 is presented by Cranmer *et al.* (1999a).

The high speed solar wind 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 (e.g., Feldman and Marsch 1997). Similar plasma properties have also been found in the extended polar corona with UVCS/SOHO (Kohl *et al.* 1995). 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 (Kohl *et al.* 1997, 1998a; Cranmer *et al.* 1999b). The O^{5+} and Mg^{9+} ion kinetic temperatures are significantly greater than "mass-proportional" when compared with H^0 (i.e., $T_{\rm ion}/T_H > m_{\rm ion}/m_H$; see also Kohl *et al.* 1998b).

2. Steady State Models

In this work we model the ion velocity distributions as bi-Maxwellians and solve the perpendicular energy conservation equation for $T_{\perp i}$. The derived perpendicular temperatures are relatively insensitive to variations in parallel temperature and ion outflow velocity, so we constrain these quantities empirically (see also Cranmer *et al.* 1999a). Ion heat conduction is neglected, but Coulomb collisions between the ion and proton distributions are taken into account (Barakat and Schunk 1981). The magnetic field strength and superradial flux tube divergence over the poles are constrained using the model of Banaszkiewicz *et al.* (1998). The empirical electron temperature T_e of Ko *et al.* (1997) is adopted, and the proton temperature is modeled as $T_p = T_e(r/R_\odot)^{0.75}$. We use the solar minimum electron density n_e of Guhathakurta and Holzer (1994) and compute the proton outflow velocity u_p using mass flux conservation. The ion outflow speed u_i is set equal to the proton outflow speed, and a test with $u_i = 2u_p$ produced no more than a 30 km s^{-1} change in the resulting most probable speed $w_{\perp i} = (2kT_{\perp i}/m_i)^{1/2}$. The parallel random ion motions are assumed to be in thermal equilibrium with the protons, and the lower boundary condition at $r = R_\odot$ is simply $T_{\perp i} = T_{\parallel i} = T_p$.

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 (e.g., Hollweg and Turner 1978; Marsch *et al.* 1982; Isenberg 1984; Tu and Marsch 1997). We use the “quasilinear” approximation for the wave damping rate, and have verified its consistency for minor ions in the corona. 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 (Isenberg and Hollweg 1982).

3. Comparison with Spectroscopic Measurements

Cranmer *et al.* (1999a) 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.* (1998) and Hassler *et al.* (1997) between 1.01 and 1.06 $R_\odot$. These are modeled effectively using 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 Fe and Si, which have been observed in more than one ionization state, lower charge states have broader widths; this is consistent with those ions having a weaker Coulomb collision rate ($\propto Z^2/A$; Spitzer 1962).

Measurements of emission lines at higher heights with UVCS have revealed unexpectedly broad profiles of O VI $\lambda\lambda$ 1032, 1037 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.* (1998a) and Cranmer *et al.* (1999b), and in Figure 1 we plot a comparison between the empirical values of $w_{\perp i}$ and model integrations from 1 to 3.5 $R_\odot$. 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

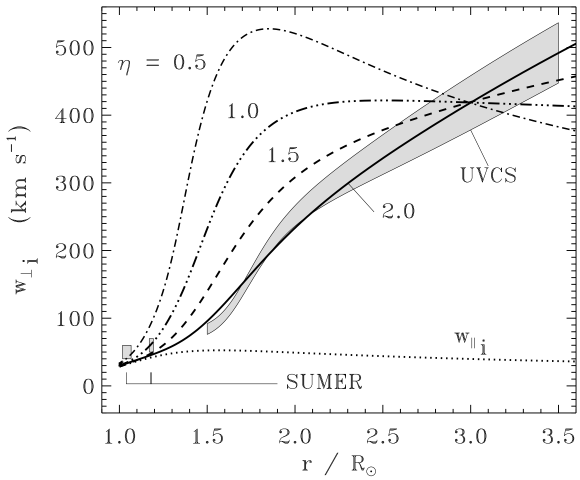

Figure 1. Radial dependence of the perpendicular most-probable speed $w_{\perp i}$ for O^{5+} ions. Empirical constraints from SUMER and UVCS are denoted by gray regions bordered by thin solid lines. Also plotted is the assumed parallel most-probable speed (*dotted line*) and model results for a range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

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 and the thermal ion energy (see Marsch *et al.* 1982), and is also several orders of magnitude smaller than simple extrapolations of *in 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 (Cranmer *et al.* 1999a). We find that resonant damping times are very short when compared to macroscopic wind flow times, so waves will damp rapidly if not otherwise maintained at their modeled amplitudes. Thus, a purely self-consistent model of their propagation (from, e.g., the base of the corona) and decay should not be able to deposit heat *gradually* into the extended corona as seems to be required. Such a self-damped model would produce a strong impulse of heating at low heights, followed by an extended region of ineffective and negligible energy deposition. It seems clear that some kind of additional wave generation over several solar radii is required to produce agreement with the observations.

It remains to be seen if the majority ions in the solar corona (protons and He^{2+}) can be heated by the same mechanisms that power the minor species. Quasilinear theory may not be sufficient to model their stronger ion-cyclotron damping, and the required gradual production of waves proposed above may not be rapid enough to stop the dissipation arising from proton and He^{2+} resonances.

4. Conclusions

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 (Schwartz 1980). 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 (e.g., Goldstein *et al.* 1995; Leamon *et al.* 1998). 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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