# Proton Temperature Anisotropy in the Fast Solar Wind: Turbulence-Driven Dispersive Ion Cyclotron Waves

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**Abstract.** The effects of parallel propagating ion cyclotron waves on the solar wind plasma are investigated in an attempt to reproduce the observed proton temperature anisotropy. The model calculations presented here assume that a nonlinear cascade process, at the Kolmogorov rate, transports energy from low-frequency Alfvén waves to the ion cyclotron resonant range. The energy is then picked up by the plasma through the resonant cyclotron interaction. Ion cyclotron waves are found to play an important role in shaping the proton temperature anisotropy starting in the inner corona and extending to interplanetary space. Dispersive ion cyclotron waves are able to cool protons more significantly than nondispersive ones.

## INTRODUCTION

The development of a temperature anisotropy of both protons and minor ions (1,2) in the inner corona, which was observed by the Ultraviolet Coronagraph Spectrometer (UVCS) (3) on board SOHO, and its persistence into interplanetary space (4) have important implications for the mechanisms responsible for coronal heating and solar wind acceleration. The importance of incorporating thermal anisotropy in solar wind models was recognized earlier by *Leer and Axford* (5) and more recently by *Sandbæk and Leer* (6) and *Hu et al.* (7). In these studies an ad hoc heating function was used. While the *Leer and Axford* and *Sandbæk and Leer* studies reproduced conditions typical of the slow solar wind, the work by *Hu et al.* tried to match the characteristics of the fast solar wind. *Hu et al.* concluded that the inclusion of a proton temperature anisotropy in the models requires that either the protons be highly anisotropic in the inner corona, or that a mechanism, in addition to adiabatic expansion, must exist to cool protons in the direction parallel to the magnetic field.

Numerical simulations of magnetized plasmas showed that ion cyclotron waves not only heat ions in the direction perpendicular to the magnetic field but, interestingly enough, also cool them in the parallel direction when the wave frequency is lower than the ion cyclotron frequency (8). This phenomenon could be accounted for by the quasi-linear theory of ion-cyclotron-resonant interaction in the resonant limit (9). The process basically involves the transfer of energy from the parallel to the perpendicular motions when the energy in the waves is below the energy available at the ion cyclotron resonance frequency.

Based on the these studies, *Li et al.* (10) found that turbulence driven nondispersive ion cyclotron waves can cool protons significantly in the direction parallel to the magnetic field. Turbulence dissipation can heat protons to temperatures which are in accord with the UVCS data, and provide the energy for high-speed solar wind. In this paper, we study both nondispersive and dispersive ion cyclotron waves for comparison. A nonlinear cascade process, namely, the Kolmogorov dissipation of Alfvénic turbulence, transports energy from the low-frequency waves to the ion cyclotron resonant range, where it is picked up by the plasma through the resonant cyclotron interaction. The dissipated energy was distributed to protons according to the resonant cyclotron interaction of these species with a spectrum of parallel-propagating ion cyclotron waves.

## MODEL DESCRIPTION

In the presence of a temperature anisotropy, the dispersion relation of outward propagating nondispersive and dispersive Alfvén waves in a cold plasma can be written as (11)

$$\frac{\omega}{k_\parallel} = \begin{cases} v_\parallel + A^{1/2} v_A & \text{nondispersive} \\ v_\parallel + A^{1/2} v_A \left[1 - \frac{\omega - k_\parallel v_\parallel}{\Omega_p}\right]^{1/2} & \text{dispersive} \end{cases} \tag{1}$$

with

$$A = \left[1 + \frac{4\pi(p_\perp - p_\parallel)}{B^2 + \langle \delta B^2 \rangle}\right] , \tag{2}$$

where $\omega$ and $k_\parallel$ are the wave frequency and wave number, respectively. Alfvén speed is $v_A = B/\sqrt{4\pi\rho_p}$, $p_\perp$ and $p_\parallel$ are the proton pressures in the direction perpendicular and parallel to the magnetic field, $\langle \delta B^2 \rangle^{1/2}$ is the magnetic field fluctuation in the Alfvén waves, and $B$ is the average local magnetic field strength.

The time-dependent wave energy equation can be written as (12)

$$\frac{\partial}{\partial t}[(1+A)p_w] + \nabla \cdot \mathbf{F} + vF_w + Q_p = 0, \tag{3}$$

where

$$\mathbf{F} = 8\pi p_w \left[\frac{\rho_p v_\parallel (\omega/k_\parallel - v_\parallel)^2}{2B^2} + \frac{(p_\perp - p_\parallel)\omega}{(B^2 + 8\pi p_w)k_\parallel} + \frac{\omega}{4\pi k_\parallel}\right] \mathbf{B}/B. \tag{4}$$

is the wave energy flux, $\omega/k_\parallel$ represents the nondispersive phase speed in eq. (1), and $p_w = \langle \delta B^2 \rangle / 8\pi$ is the magnetic pressure exerted by Alfvén waves when $A = 1$. The velocity fluctuations $\langle \delta v^2 \rangle$ of Alfvén waves in an anisotropic fluid are then given by

$$\langle \delta v^2 \rangle = \frac{A \langle \delta B^2 \rangle}{4\pi\rho_p} = \frac{2Ap_w}{\rho_p}. \tag{5}$$

The total heating rate, $Q_p$, is distributed to protons in the parallel, $Q_{p\parallel}$, and perpendicular, $Q_{p\perp}$, directions according to the quasi-linear theory of the ion cyclotron resonant interaction of particles with a wave power spectrum $P_B(k_\parallel) \propto k_\parallel^{-\eta}$ (9,12,13,14), and $\eta$ is the spectral index in the dissipation range. In the following we assume that the proton distribution function can be approximated by a bi-Maxwellian. The parallel and perpendicular heating of the protons from the waves can then be written as

$$Q_{p\parallel} = Q_p \frac{Q^w_{p\parallel}}{Q^w_{p\parallel} + Q^w_{p\perp}}, \; Q_{p\perp} = Q_p \frac{Q^w_{p\perp}}{Q^w_{p\parallel} + Q^w_{p\perp}}, \tag{6}$$

with (12)

$$Q^w_{p\perp} = \int_0^\infty dk_\parallel \; k_\parallel^{-(\eta+1)} \frac{\Omega_p}{k_\parallel} H_p \tag{7}$$

$$Q^w_{p\parallel} = \int_0^\infty dk_\parallel k_\parallel^{-(\eta+1)} \left(\frac{\omega - \Omega_p}{k_\parallel} - v_\parallel\right) H_p \tag{8}$$

where

$$H_p = \{\Omega_p/k_\parallel + [(\omega - \Omega_p)/k_\parallel - v_\parallel]/\Gamma_p\} \cdot \exp\{-m_p(2k_B T_{p\parallel})^{-1}[(\omega - \Omega_p)/k_\parallel - v_\parallel]^2\}. \tag{9}$$

The cyclotron frequency of the protons is $\Omega_p = q_p B/m_p$, $q_p$ is the proton charge, $\Gamma_p$ is the anisotropy $T_{p\parallel}/T_{p\perp}$, $v_\parallel$ is the solar wind speed in the frame corotating with the Sun.

In a spherically symmetric flow, when the Alfvén waves damp, the wave force $F_w$ on the protons can be written as (15)

$$F_w = F^{nr}_w + F^r_w \tag{10}$$

where

$$F^{nr}_w = \rho_p \frac{\mathrm{d}}{\mathrm{d}r} \left[\frac{4\pi p_w}{B^2}(\omega^2/k_\parallel^2 - v_\parallel^2)\right] \tag{11}$$

is the nonresonant wave force, and $\omega/k_\parallel$ is the nondispersive Alfvén wave phase speed. The resonant force $F^r_w$ can be calculated in the same way as $Q_{p\parallel}$ and $Q_{p\perp}$

$$F^r_w = \frac{Q_p v_\parallel}{(Q^w_{p\parallel} + Q^w_{p\perp})v} \int_0^\infty dk_\parallel \; k_\parallel^{-(\eta+1)} H_p, \tag{12}$$

where $Q_p$ is the proton heating rate due to the dissipation of Alfvén waves, $v$ is the solar wind speed.

The remaining governing equations are given in (10). The nondispersive and dispersive phase speed in (1) will be applied to equations (7)-(10) and (13) to study the effects of these ion cyclotron waves on the solar wind plasma.

## NUMERICAL RESULTS

Model computations with proton heating at the Kolmogorov dissipation rate are presented here. The heating of the protons at the Kolmogorov rate is given by (16,17)

$$Q_p = \Gamma \rho_p \langle \delta v^2 \rangle^{3/2} / L_c, \tag{13}$$

Here $L_c$ is the correlation length of the fluctuations, $\Gamma$ is a dimensionless parameter, and $\rho_p$ is the proton mass density. The correlation length is chosen to scale as the distance between flow tubes (16,17)

$$L_c \propto \sqrt{a} \propto r, \tag{14}$$

for the radial geometry adopted in this paper.

For all models, the density and temperature at the coronal base are fixed at

$$n_e = 2.5 \times 10^8 \mathrm{cm}^{-3}, \quad T_e = T_{p\parallel} = T_{p\perp} = 6 \times 10^5 \mathrm{K}. \tag{15}$$

The corresponding base pressure $n_e T_e$ is consistent with values in coronal holes (18,19). The magnetic field at the coronal base is computed from the conservation of magnetic flux for a given value $B_{rE}$ at 1 AU, and a cross-section $a$, i.e.,

$$B = 215^2 \; B_{rE} \; f_m \quad \mathrm{G} \tag{16}$$

with $B_{rE} = 5 \times 10^{-5}$ G (or 5 $\gamma$).

In addition, the following choice of adjustable parameters is made:

$$\begin{gathered} \eta = 5/3, \;\; (L_c/\Gamma)_{1_{R_s}} = 9 \times 10^4 \text{ km}, \\ \left(\langle \delta v^2 \rangle^{1/2}\right)_{1_{R_s}} = 25 \text{ km/s} \end{gathered} \tag{17}$$

$\left(\langle \delta v^2 \rangle^{1/2}\right)_{1_{R_s}}$ is chosen below the upper limit of 35 km/s currently inferred from remote sensing observations (20).

The corresponding solar wind parameters for nondispersive (top panel) and dispersive waves (bottom panel) are shown in Figure 1 together with the empirical values currently available from remote sensing observations of the inner corona. The velocity and electron density (left panels), and temperatures (middle panels), match as closely as possible the empirical constraints on electron density in the inner corona (21), perpendicular and parallel components of proton temperature (3), and flow speeds and temperature components in interplanetary space (22). With the exception of electrons, the solar wind parameters of both models at 1 AU are in good agreement with observations. The wind velocity of 270 km s$^{-1}$ at 4 $R_s$ is at the lower limit of the recent UVCS observations (3).

Since the total proton heating rate is determined by the Kolmogorov dissipation rate, the two models have almost identical density and velocity profiles. Most of the dissipated energy goes to heat protons in the direction perpendicular to the magnetic field. Hence $T_{p\perp}$ in the 2 cases are not very different ($T_{p\perp}$ in the dispersive case is higher at 1AU than in the nondispersive case). However, the wave dispersion makes it possible to cool protons much more in the direction parallel to the magnetic field than the nondispersive case. This is not surprising. In fact, as described by equations (7)-(10), and studied in detail (8,13), the cooling occurs primarily when the wave frequency is smaller than the cyclotron frequency. In the solar wind frame, the dispersive wave frequency can never exceed the proton cyclotron frequency. The effect of the ion cyclotron resonance can also be followed from the changes in the heating rates $Q_{p\perp}$ and $Q_{p\parallel}$ as a function of heliocentric distance, as shown in the right panels of Figure 1. The solid lines correspond to positive values, while the dashed lines correspond to negative values. We note that $Q_{p\perp}$ is always positive; hence protons always get heated in the perpendicular direction. But $Q_{p\parallel}$ is very different. Protons get cooled at the coronal base and beyond 70 $R_s$ (nondispersive case) or 36 $R_s$ (dispersive case), when $Q_{p\parallel} < 0$. However, at some heliocentric distances (see the solid lines of $Q_{p\parallel}$ in the right panels of Figure 1) protons are also heated in the parallel direction. According to (8), $Q_{p\parallel}$ can be positive when $T_{p\parallel} \ll T_{p\perp}$. At 1 AU, $Q_{p\parallel}$ has the same order of magnitude as $Q_{p\perp}$. Since $Q_p = Q_{p\parallel} + Q_{p\perp}$, is fixed by equation (14) at a given heliocentric distance, the negative $Q_{p\parallel}$ leads to a larger heating in the perpendicular direction. The thermal energy of protons in the parallel direction has thus been transferred to the perpendicular direction. Hence ion cyclotron waves not only produce a strong proton temperature anisotropy in the inner corona but also limit the growth of the proton temperature anisotropy in interplanetary space.

## CONCLUSIONS

This study demonstrates that turbulence driven parallel propagating ion cyclotron waves in the fast solar wind can play a significant role in shaping the proton temperature anisotropy in both the inner corona and interplanetary space. Dispersive ion cyclotron waves are more efficient than nondispersive waves in cooling protons in the direction parallel to the magnetic field. Turbulence dissipation can heat protons to temperatures which are in accord with the UVCS data, and provide the energy for the high-speed solar wind. We note that the electron temperature at the coronal base is lower than observed (23), and the temperatures suffer an initial decrease at the coronal base. This indicates that the electrons cannot get enough heating from the Coulomb collisions with protons.

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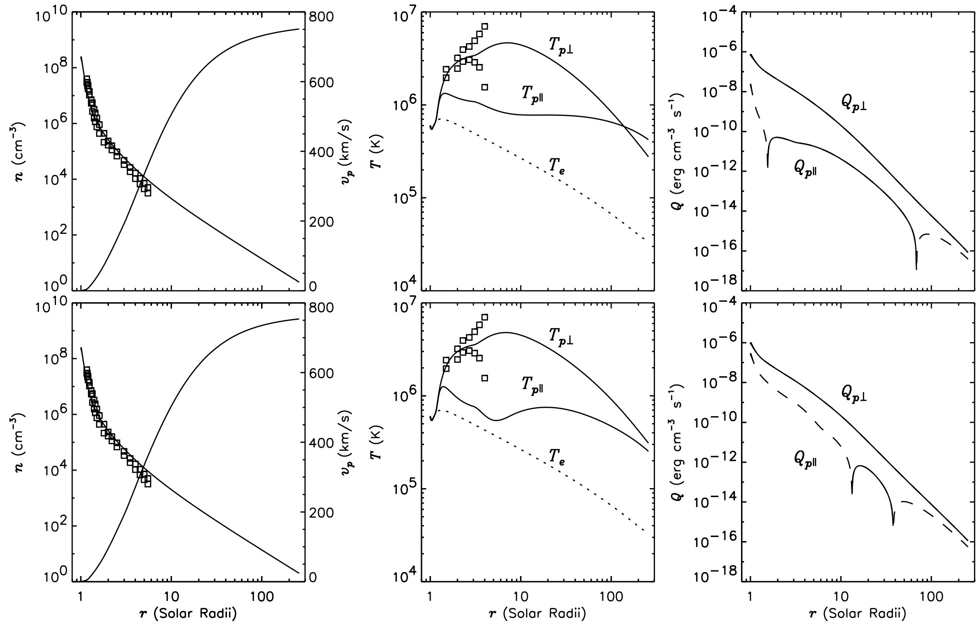


**FIGURE 1.** Two-fluid solar wind models: with nondispersive (top panels) and dispersive (bottom panels) waves: Left panels: velocity and electron density (the open boxes represent the observed upper and lower electron density limits (22); Middle panels: proton and electron temperatures (the open boxes represent the observed upper and lower perpendicular temperatures of neutral hydrogen derived from the line-width measurements of H I Ly$\alpha$ in coronal holes (3). Right panels: parallel and perpendicular heating rates of protons used in the model (solid and dashed lines correspond to positive and negative values, respectively).

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