Alfvén-Cyclotron Scattering of Solar Wind Ions: Hybrid Simulations

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The heating of the solar corona is one of the most important unsolved problems of space physics. SOHO observations support the scenario in which Alfvén-cyclotron fluctuations propagating away from the Sun scatter and heat protons and the various heavy ions. But there are no quantitative predictions for the ion heating rates, or even for the relative heating rates of the various ion species. We are using Los Alamos hybrid simulations (particle ions, fluid electrons) in a homogeneous, collisionless plasma model to compute the scattering and heating of protons and alpha particles by given spectra of Alfvén-cyclotron fluctuations. Our goal is to eventually predict proton and heavy-ion heating for comparison against both remote observations of the corona and in situ measurements of the solar wind.

1. Introduction

Alfvén-cyclotron fluctuations at sufficiently short wavelengths and at propagation approximately parallel or antiparallel to a background magnetic field B, in a relatively uniform, collisionless plasma can resonate with protons and heavy ions. If the heavy ions are alpha particles and are a minority species, as they are in the solar wind, the proton and alpha resonance conditions are sensitive functions of the alpha/proton relative speed \( v_{\alpha p} \) parallel or antiparallel to \( B_0 \). A strong ion cyclotron resonance enables strong pitch-angle scattering, indicating that the resonant species is likely to exhibit \( T_{\perp}/T_{\parallel} > 1 \) if Alfvén-cyclotron fluctuations of sufficiently large amplitude are present.

In our opinion, computer simulations offer a more complete self-consistent solution to this wave-particle scattering problem than analytic-based theories. Several hybrid simulation studies have addressed the interaction of given spectra of Alfvén-cyclotron fluctuations with both protons and heavy ions [Liever et al., 2001; Ofman et al., 2002, 2005; Xie et al., 2004]. All of these simulations demonstrate that scattering by representative spectra of Alfvén-cyclotron fluctuations yields strong perpendicular heating of alpha particles and heavy ions, relatively weaker perpendicular heating of protons, and very weak acceleration of alpha particles relative to the protons.

The primary purpose of the research described here is to better understand Alfvén-cyclotron scattering of alpha particles and protons in the solar wind. Our goal is to quantify and parameterize this process so that its consequences might be incorporated into large-scale fluid models of the solar corona and solar wind. We here consider only alpha particles (hereafter “alphas”) as the heavy ion species.

We use subscripts \( \parallel \) and \( \perp \) to denote directions relative to the background magnetic field \( B_0 \). The species subscripts are \( p \) for protons, \( \alpha \) for doubly ionized helium ions, and \( e \) for electrons. For the \( j \)th species we define \( \tilde{\beta}_{\parallel j} \equiv 8\pi n_e k_B T_{\parallel j}/B_0^2 = (n_e/n_j)\beta_{\parallel j} \); the plasma frequency based on the total electron density, \( \omega_j = \sqrt{4\pi n_e e^2/m_j} \); the cyclotron frequency, \( \Omega_j = e_j B_0/m_j c \); the thermal speed,
as stated in Table 1. Alfvén-cyclotron fluctuations at \( k \times B_0 = 0 \) are not likely to arise from a turbulent cascade, so we consider a frequency sweeping scenario in which \( |\delta B|^2 \sim k^{-1} \). The amplitudes of the four waves also stand in the same ratio for each run; the only initial parameter we have varied is the total fluctuating magnetic field energy density:

\[
|\delta B_{ext}|^2 / B_0^2 = 0.02, 0.05, 0.10, 0.15, 0.20, \text{ and } 0.25
\]

The fluctuation amplitudes of Table 1 correspond to a representative simulation in which \( |\delta B_{ext}|^2 / B_0^2 = 0.10 \).

For these simulations, we have chosen \( v_{\alpha p} / v_A = -0.50 \) so that, for most wavenumbers we have chosen, the alphas are resonant (i.e., \( |\zeta_\alpha| \lesssim 3 \)), whereas the protons are non-resonant (\( |\zeta_p| \gtrsim 3 \)). As a result, the protons are scattered weakly, and are not illustrated here. Figure 1 shows the relative changes in the perpendicular alpha temperatures, the parallel alpha temperatures, and the alpha/proton relative speed between the final state (\( \Omega_p t = 100 \)) and the initial state (\( t = 0 \)) of each run. In agreement with previous simulations, each run shows that scattering yields the strongest increase in the perpendicular alpha temperature; the increase in the parallel alpha temperature is relatively smaller, and reduction of the alpha/proton relative speed is a relatively small effect.

### 3. Conclusions

We have presented preliminary results of hybrid simulations in a homogeneous, collisionless plasma model to demonstrate the scattering and heating of protons and alpha particles by given spectra of Alfvén-cyclotron fluctuations under solar-wind-like parameters. Our results show that the scattering increases as the fluctuation amplitude increases, that the strongest response is increased perpendicular energies in the resonant alphas, and that the decrease in the alpha/proton relative speed due to scattering is relatively weak. Each of these results is expected, if not demonstrated by previous simulations.

We intend to carry out further such simulations in which we vary other parameters such as \( \beta_{||} \) to represent coronal, as well as solar wind, conditions, \( v_{\alpha p} / v_A \) to allow the Alfvén-cyclotron fluctuations to resonate with protons instead of alphas, and larger values of the heavy-ion mass to study how the very tenuous heavy ions of the corona and solar wind respond to such fluctuations.

### References


