Solar wind ion scattering by Alfvén-cyclotron fluctuations: ion temperature anisotropies versus relative alpha particle densities

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Abstract. Analysis of plasma data from the ACE spacecraft for 4 months of solar wind observations shows negative statistical correlations between the $T_{\perp}/T_{\parallel}$ of alpha particles and the relative alpha particle density, as well as between the $T_{\perp}/T_{\parallel}$ of the protons and the relative alpha particle density. Here, the subscripts refer to directions perpendicular and parallel to the background magnetic field. Hybrid computer simulations of the interaction between an applied spectrum of steady Alfvén-cyclotron fluctuations and a solar-wind-like plasma also show negative correlations between the alpha particle and proton temperature anisotropies and the relative alpha particle density. These results imply that these correlations are signatures of ion scattering by Alfvén-cyclotron fluctuations, and that such scattering occurs sporadically in the solar wind near Earth.

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1. Introduction

It is sometimes claimed that the solar wind is a useful laboratory for the study of fundamental physics of hot, tenuous collisionless plasmas, but few observational studies of the interplanetary medium actually pursue questions of basic plasma physics. Current trends in solar wind research emphasize the study of large-scale events, with the goal of providing global pictures, both steady and dynamic, of the interplanetary plasma. In contrast, relatively little current solar wind research addresses fundamental small-scale problems which also can be studied by particle-in-cell simulations and/or laboratory experiments.

One example of solar wind research which has addressed fundamental plasma physics questions has been the study of shocks, and especially the Earth's bow shock, which, in conjunction with particle simulations, has led to substantially increased scientific understanding of how collisionless shocks work. This research has been framed in terms of a limited number of local parameters such as the magnetosonic Mach number, the plasma $\beta$, and the angle of propagation relative to the background magnetic field $B_0$, so its results may be applied to collisionless shocks beyond the domain of present-day spacecraft, indeed throughout the universe.

Turbulence studies are another category of solar wind research which has yielded fundamental knowledge that has potential application to plasmas far beyond the local interplanetary medium. The damping of collisionless plasma fluctuations generally increases as wavelengths decrease, so turbulent dissipation, or more generally the exchange of energy between magnetic fluctuations and ion species in the interplanetary medium, is a fundamental issue requiring study of relatively small-scale kinetic physics. Here we specifically consider the interaction between Alfvén-cyclotron fluctuations (that is, left-hand polarized electromagnetic waves with ion cyclotron resonances at frequencies somewhat below the proton cyclotron frequency) and ions in the solar wind. Comparing in situ plasma and magnetic field measurements gathered by spacecraft against the results of computer simulations, we seek improved understanding of this basic process, so that we may better apply this knowledge to more distant plasmas (such as the anisotropically heated ions of the high latitude solar corona) which now can be measured only by remote sensing.

Low-frequency, long wavelength Alfvén fluctuations abound in the solar wind. Although there is current debate about the processes which lead such magnetic fluctuation energy to the relatively short wavelengths where ion cyclotron resonances arise (Hollweg and Isenberg 2002), there is good evidence that such transport does take place. Observations of proton velocity distributions have shown distinct anisotropies in the sense of $T_\perp/T_\parallel > 1$ (e.g., Bame et al 1975, Marsch et al 1982a, Feldman et al 1996, Neugebauer et al 2001); these anisotropies have been interpreted as due to scattering by Alfvén-cyclotron fluctuations (Marsch and Tu 2001, Tu and Marsch 2002, Marsch et al 2004). Based on such evidence, we here assume that the frequency sweeping scenario (Hollweg and Turner 1978, Schwartz et al 1981, Leamon et al 2000) holds: Alfvén-like fluctuations propagating approximately parallel or antiparallel to the background magnetic field $B_0$, (that is, at $k \times B_0 = 0$) move predominantly outward in the solar wind. As $B_0$ decreases, these fluctuations encounter cyclotron resonant frequencies of successively larger charge-to-mass ratio ions, scattering these ions at successively greater distances from the Sun.

Unfortunately, a critical piece of evidence which would confirm the presence of Alfvén-cyclotron scattering is missing from observations near 1 AU; there is no statistical correlation between enhanced magnetic fluctuations in the ion cyclotron frequency domain and ion...
temperature anisotropies (Gary et al 2005b). A possible explanation for this is that this scattering is a stochastic, sporadic process which happens infrequently. Moreover, it also happens rapidly; as many simulations have shown (Liewer et al 2001, Ofman et al 2002, Xie et al 2004, Lu and Wang 2005, Hellinger et al 2005, Gary et al 2006), even relatively weak Alfvén-cyclotron fluctuations cause appreciable scattering within a small number of proton cyclotron periods. So observations of such enhanced fluctuations may be rare. But the consequences of the scattering are irreversible; the particle signatures persist until much slower process (e.g. ion–ion collisions) acts to erase them. Thus observations of such particle signatures should be much more frequent.

Earlier studies mentioned above indicate that protons are scattered by Alfvén-cyclotron fluctuations in the solar wind. But until recently, similar evidence had not been presented concerning the possible scattering of alpha particles. Linear theory (Gomberoff et al (1996)) and analytic-based quasilinear models (Dusenberg and Hollweg 1981, Li and Habbal 1999, Gary et al 2001) showed that the cyclotron resonance properties of minority alpha particles (hereafter simply ‘alphas’) in solar-wind-like collisionless plasmas are sensitive functions of $v_{ap}/v_A$, the dimensionless alpha/proton relative speed parallel or antiparallel to $B_0$. (All symbols used here are defined in the appendix.) If an Alfvén-cyclotron fluctuation at $k \times B_0 = 0$ has $\omega_r/k_\parallel > 0$, the alpha cyclotron resonant speed determined by the resonance condition $\omega_r - k_\parallel v_\parallel = -\Omega_\alpha$ lies in the thermal regime of the alpha reduced velocity distribution if $v_{ap}/v_A < 0$. As $v_{ap}/v_A$ becomes zero and then positive, the alpha cyclotron resonance moves into the tail of $f_\alpha(v_\parallel)$ so that most of the alphas become non-resonant. The opposite is true for the protons; at negative alpha/proton relative speeds, they are non-resonant, but as $v_{ap}/v_A$ becomes positive, the proton cyclotron resonant speed moves into the thermal body of $f_p(v_\parallel)$, so that the protons become the resonant ion species. Theoretical arguments (Marsch et al 1982b) and simulation results (Liewer et al 2001, Ofman et al 2002, Gary and Saito 2003) show that Alfvén-cyclotron resonant ions are pitch-angle scattered, so that the lowest order consequence of this interaction is an increase in the effective $T_\perp/T_\parallel$ of an initially isotropic resonant species. Thus, if Alfvén-cyclotron fluctuations are scattering ions, $T_{\perp\alpha}/T_{\parallel\alpha}$ should decrease and $T_{\perp p}/T_{\parallel p}$ should increase as $v_{ap}/v_A$ varies from negative to positive. Gary et al (2005a, b) carried out the first statistical study of solar-wind data which demonstrated both such correlations, and Gary et al (2006) used hybrid simulations to provide the first self-consistent computations demonstrating this expected relationship between $T_{\perp\alpha}/T_{\parallel\alpha}$ and $v_{ap}/v_A$. These observational and simulation results provided good evidence that Alfvén-cyclotron scattering of alphas operates in a statistical sense in the solar wind near 1 AU.

Although ion cyclotron resonance properties as determined by linear dispersion theory are sensitive functions of $v_{ap}/v_A$, they are relatively insensitive to variations in $n_\alpha/n_e$ (e.g., figure 3 of Gary et al (2005b)). However, if the fluctuating magnetic field energy density available for ion scattering is, on average, constant, then smaller values of $n_\alpha/n_e$ should correspond to larger average values of $T_{\perp\alpha}/T_{\parallel\alpha}$, because fewer alphas imply that there is more field energy per particle available for scattering.

Particle–particle collisions, shocks, reconnection, large-scale changes in the interplanetary magnetic field, wave-particle scattering by enhanced field fluctuations from instabilities and wave-particle scattering by background field fluctuations may all contribute to the observed values of ion anisotropies. Untangling the consequences of each of these processes from observations is a huge task; our more modest goal is to separate observed properties due to processes independent of $n_\alpha/n_e$ from those which depend upon this ratio. To this end, we carry out statistical data analysis of plasma and magnetic field data gathered in situ by the ACE spacecraft in the solar wind near 1 AU, in particular seeking correlations between ion temperature
anisotropies (hereafter ‘ion anisotropies’) and the relative alpha density, \( n_\alpha/n_e \). We fit the data with the simple fitting function

\[
\frac{T_{\perp,j}}{T_{\parallel,j}} = a_j + b_j \frac{n_\alpha}{n_e}, \quad j = p, \alpha
\]

which ascribes the consequences of processes independent of \( n_\alpha \) to the fitting parameters \( a_j \) and uses the \( b_j \) to characterize the effects of those processes dependent upon the alpha particle relative density.

Given fitting parameters from our data analysis, we then turn to computer simulations to attempt to reproduce the observed values of \( b_p \) and \( b_\alpha \). To choose the specific process to simulate, we argue as follows: kinetic processes which are likely to be functions of \( n_\alpha/n_e \) include alpha-ion and alpha-electron collisions, scattering due to enhanced fluctuations from alpha/proton instabilities, and scattering by background field fluctuations. Collisions generally act to isotropize particle velocity distributions, and are not likely sources of the enhanced ion anisotropies considered here. We discount electromagnetic alpha/proton instabilities as sources of the correlations analysed here because their typical threshold conditions demand \( v_{\alpha p}/v_A > 1 \) for significant growth (e.g. Gary et al 2000) which condition is satisfied by a very small fraction of the data analysed (Gary et al 2005b). Electrostatic alpha/proton instabilities require \( T_{\parallel e}/T_{\parallel p} \gg 1 \) to show appreciable growth; as this is an untypical solar-wind condition, we regard such growing modes as unlikely sources of these anisotropies. So the most likely drivers of the proton and alpha anisotropies examined here are background electromagnetic fluctuations; as many have argued (for a very comprehensive review, see Hollweg and Isenberg (2002)). Alfvén-cyclotron scattering is the most likely wave-particle process to cause \( T_{\perp}/T_{\parallel} > 1 \) on the ions, and it is this process which we simulate here.

Section 2 describes the observations, section 3 describes results from our hybrid simulations and section 4 summarizes our conclusions. The spatially homogeneous model used for our computations is appropriate because the average gradient scale lengths near 1AU \((n_{sw}/(dn_{sw}/dr) \sim 10^8 \text{ km})\) are far larger than the typical wavelengths used in our simulations \((\lambda \sim 2\pi/k_\parallel \sim 4\pi c/\omega_p \sim 30 \text{ km})\).

2. ACE observations

Instrumentation on the ACE spacecraft includes the Solar Wind Electron Proton Alpha Monitor (SWEPAM) (McComas et al (1998)) and the Magnetic Field Experiment (MAG) (Smith et al (1998)). SWEPAM consists of two fully independent sensors: one for electrons and one for ions. Both instruments are based on spherical section electrostatic analysers followed by sets of channel electron multiplier detectors. Each can make full three-dimensional measurements of the particle velocity distributions with 64s time resolution. Here, we used the proton and alpha densities as well as parallel and perpendicular proton and alpha temperatures derived by integration in velocity over the observed ion distributions. As in Gary et al (2005a, b), we considered each 64s ion measurement to constitute a single datum, but excluded from our analysis data which implied non-gyrotropic distributions or appeared to represent inconsistencies in the data reduction. Details of this exclusion process, as well as a more thorough discussion of
Table 1. ACE observations: fits to ion anisotropies as functions of alpha relative densities.

| Month    | Proton anisotropies | Alpha anisotropies |
|----------|---------------------|--------------------|
|          | $(n_{α}/n_{e} < 0.08)$ | $(n_{α}/n_{e} < 0.06)$ |
| Jan 2001 | $T_{\perp p}/T_{\parallel p} = 0.82–4.66n_{α}/n_{e}$ | $T_{\perp α}/T_{\parallel α} = 0.99–3.59n_{α}/n_{e}$ |
| Apr 2001 | $T_{\perp p}/T_{\parallel p} = 0.86–1.84n_{α}/n_{e}$ | $T_{\perp α}/T_{\parallel α} = 1.21–7.37n_{α}/n_{e}$ |
| May 2002 | $T_{\perp p}/T_{\parallel p} = 1.03–8.99n_{α}/n_{e}$ | $T_{\perp α}/T_{\parallel α} = 1.09–5.99n_{α}/n_{e}$ |
| Dec 2002 | $T_{\perp p}/T_{\parallel p} = 1.14–9.08n_{α}/n_{e}$ | $T_{\perp α}/T_{\parallel α} = 0.83–0.14n_{α}/n_{e}$ |

Errors to fitting parameters.

| Month    | $b_{p}$      | $b_{α}$      | $R_{p}$ | $R_{α}$ |
|----------|--------------|--------------|---------|---------|
| Jan 2001 | $-4.66 \pm 0.21$ | $-3.59 \pm 0.49$ | $0.18$  | $0.06$  |
| Apr 2001 | $-1.84 \pm 0.22$ | $-7.37 \pm 0.53$ | $0.07$  | $0.12$  |
| May 2002 | $-8.99 \pm 0.23$ | $-5.99 \pm 0.29$ | $0.26$  | $0.15$  |
| Dec 2002 | $-9.08 \pm 0.18$ | $-0.14 \pm 0.27$ | $0.32$  | $0.004$ |

the data reduction method, are presented in section 4 of Gary et al. (2005b). We analysed data from 4 months of ACE observations: January 2001, April 2001, May 2002 and December 2002. For each of these months we plotted ion temperature anisotropies as functions of the relative alpha density, and then carried out least-squares fits of each plot to equation (1). The monthly averages of the relative alpha density range over $0.029 \lesssim n_{α}/n_{e} < 0.035$ and distributions of this quantity show non-statistical tails at $n_{α}/n_{e} \gtrsim 0.06$. We found that the fitting coefficients which reflect the consequences of wave-particle scattering, $b_{p}$ and $b_{α}$, are consistently negative if we consider only those data points corresponding to $n_{α}/n_{e} \lesssim 0.06$, but that these coefficients become uniformly less negative as we raise the constraint on the relative alpha densities used in the plots. In our analysis of proton anisotropies, we rejected outlying points at $n_{α}/n_{e} > 0.08$, and our analysis of alpha anisotropies ignored outlying points corresponding to $n_{α}/n_{e} > 0.06$.

Figure 1 illustrates statistical plots of proton anisotropies as functions of the relative alpha density for ACE observations during January 2001 and May 2002. The dashed lines indicate least-squared fits to the data in each case; we find similar correlations (not shown here) for data from April 2001 and December 2002. Least-squares fits to the observations for all 4 months are summarized in table 1. Although the correlations between $T_{\perp p}/T_{\parallel p}$ and $n_{α}/n_{e}$ are weak ($R_{p} \ll 1$), they are consistently negative and consistently significant. If we include the outlying points at $n_{α}/n_{e} > 0.08$, the slopes of the fits are reduced, but $b_{p}$ remains negative in each case.

Figure 2 illustrates statistical plots of alpha anisotropies as functions of the relative alpha density for ACE observations during January 2001 and May 2002. The dashed lines indicate least-squared fits to the data in each case. Least-squares fits to the observations for all 4 months are summarized in table 1. Although the correlations between $T_{\perp α}/T_{\parallel α}$ and $n_{α}/n_{e}$ are weak ($R_{p} \ll 1$), they are consistently negative and (except for December 2002) consistently significant. If we include the outlying points at $n_{α}/n_{e} > 0.06$, the slopes of the fits become less negative or, in the cases of April 2001 and December 2002, positive.
Figure 1. ACE observations: $T_{\perp \parallel} / T_{\parallel \parallel}$ as a function of $n_{\alpha} / n_{e}$, for $n_{\alpha} / n_{e} \leq 0.08$ during (a) January 2001 and (b) May 2002. Every tenth point is plotted. The data has been reduced as described in the text. The dashed lines represent least-squares fits to the data; the errors to the fitting parameters $b_j$ and the correlation coefficients $R$ are given in table 1.

3. Hybrid simulations

This section describes hybrid computer simulations upon which we have imposed a spectrum of Alfvén-cyclotron fluctuations which propagate only in the direction parallel to $B_0$ (that is, $\omega_r / k_{\parallel} > 0$). In these simulations the initial plasma is collisionless, homogeneous, steady and magnetized with $B_0 = \hat{x}B_0$. The ions consist of an initially Maxwellian majority proton component and an initially Maxwellian minority alpha component. Table 2 states the initial parameters for all simulations described here.
Figure 2. ACE observations: $T_{\perp\alpha}/T_{\parallel\alpha}$ as a function of $n_{\alpha}/n_e$, for $n_{\alpha}/n_e \leq 0.06$ during (a) January 2001 and (b) May 2002. Every tenth point is plotted. The data has been reduced as described in the text. The dashed lines represent least-squares fits to the data; the errors to the fitting parameters $b_j$ and the correlation coefficients $R$ are given in table 1.

We use the same code as described in Gary et al (2006). Periodic boundary conditions are used with a simulation box length $L\omega_p/c = 40\pi$; we choose the wavenumbers of the applied fluctuations to satisfy $k_{\parallel}c/\omega_p = 0.050n$ with $n$ an integer, so the applied modes each satisfy the periodic boundary conditions. The simulations are carried out on a two-dimensional grid, but in effect are one-dimensional, with 256 cells in the $x$-direction, 4 cells in the $y$-direction, and 256 particles per cell for each ion species. Note that, unlike Liewer et al (2001), Gary and
Table 2. Initial plasma parameters: all simulations.

| Dimensionless parameter       | Symbol | Initial value |
|-------------------------------|--------|---------------|
| Alpha mass                    | $m_\alpha/m_p$ | 4             |
| Alpha charge                  | $q_\alpha/q_p$  | 2             |
| Alpha/proton relative speed   | $v_{\alpha}/v_A$ | 0.0           |
| Electron temperature          | $T_e/T_\parallel p$ | 1.0          |
| Alpha parallel temperature    | $T_{\alpha}/T_\parallel p$ | 4.0           |
| Proton parallel $\beta$      | $\tilde{\beta}_{\parallel p}$ | 0.50 (Ensemble N) |
| Proton anisotropy             | $T_{\perp p}/T_\parallel p$ | 1.0           |
| Alpha anisotropy              | $T_{\perp \alpha}/T_\parallel \alpha$ | 1.0           |

Saito (2003), Lu and Wang (2005) and Hellinger et al (2005) who apply fluctuations as initial conditions to their simulations, we apply the following fluctuations throughout our simulations:

$$\delta B(x, t) = -\hat{y} \sum_{n=1}^{4} \delta B_n \sin [k_n x - \omega_r(k_n)t] + \hat{z} \sum_{n=1}^{4} \delta B_n \cos [k_n x - \omega_r(k_n)t],$$

$$\delta E(x, t) = +\hat{y} \sum_{n=1}^{4} \delta E_n \cos [k_n x - \omega_r(k_n)t] + \hat{z} \sum_{n=1}^{4} \delta E_n \sin [k_n x - \omega_r(k_n)t]. \quad (2)$$

Here $k \times B_0 = 0$ for all modes and we drop the subscript $\parallel$ on the wavenumbers. The $k_n$ are chosen as appropriate cyclotron resonant wavenumbers and the real frequencies $\omega_r(k_n)$ satisfy the Vlasov dispersion equation for left-hand polarized Alfvén-cyclotron fluctuations. From Faraday’s equation and $|\gamma| \ll \omega_r$, we use $\delta E_n = [\omega_r(k_n)/k_n c] \delta B_n$.

To emphasize the role of resonant fluctuations in ion heating, we choose spectra consisting of relatively narrow ranges of wavenumbers, $\Delta k/k \ll 1$, and $k$-values corresponding to the onset of cyclotron damping. The narrow range of wavenumbers implies that the detailed distribution of energy among the modes is not important, so we choose each mode to have the same initial value of $|\delta B_n|^2/B_0^2$. Liewer et al (2001) and Hellinger et al (2005) also assumed initially flat distributions of magnetic fluctuation amplitudes in their simulations. Furthermore, a series of test computations described in Gary et al (2006) led us to conclude that the model of four applied modes used here provides a plausible approximation to the multi-mode conditions observed in the solar wind.

We apply relatively weak fluctuating fields such that the total fluctuating magnetic field energy density $|\delta B|^2/B_0^2 = \sum_n |\delta B_n|^2/B_0^2 \ll 1$. This is consistent with typical observations of fluctuating field energy densities at wavenumbers near the onset of alpha cyclotron damping (Smith et al 2004). So, under many circumstances, as has been demonstrated by Gary et al (2006), the scattered reduced velocity distributions of both protons and alphas remain Maxwellian-like. This implies that it is approximately valid to analyse simulation results in terms of relative average velocities and perpendicular and parallel temperatures, and that is the procedure which we follow here.

The first computation described here is our characteristic simulation, with $n_\alpha/n_e = 0.02$, other initial plasma parameters as described in table 2, and applied fluctuation parameters as described for Run N−3 in table 3. Figure 3(a) illustrates the total dimensionless fluctuating...
magnetic field energy densities as functions of time, where the applied fields of equation (2) are represented as a dashed line, and the resulting self-consistent fields are shown as a solid line. From figures 3(b) and (c) the strongly resonant alphas show a much greater response than the weakly resonant protons, and the late-time increase in $T_{\perp\alpha}/T_{\parallel\alpha}$ is much greater than the late-time increase in $T_{\perp p}/T_{\parallel p}$, which in turn, is substantially larger than the increase in $v_{\alpha p}/v_A$. These results are all

Figure 3. Results from our characteristic simulation. (a) The imposed and self-consistent total dimensionless fluctuating magnetic field energy densities, (b) $T_{\perp\alpha}/4T_{\parallel p}$, $T_{\perp p}/T_{\parallel p}$ and $T_{\perp\alpha}/T_{\parallel\alpha}$ and (c) the dimensionless alpha/proton relative speed as functions of time.
consistent with previous simulations of Alfvén-cyclotron fluctuations interacting with solar wind ions at $v_{\alpha p} = 0$ (Liewer et al 2001, Ofman et al 2002, Lu and Wang 2005, Hellinger et al 2005). The self consistent field energy, denoted by $|\delta B(\text{self})|^2/8\pi$, as well as the plasma parameters, all attain a quasi-steady late time state. Linear Vlasov theory results discussed below show that the ion anisotropy increases lead to a reduction of damping or weak instability growth at the driving wavenumbers, consistent with the evolution of a quasi-steady state.

Figure 4 shows the relative amplitudes of four self-consistent modes in the characteristic simulation. The two solid lines represent modes at the same wavenumbers as those of the applied spectrum; their early, rapid growth indicates they are driven directly. The other two curves represent the time dependence of modes at wavelengths shorter than (the dotted curve) and longer than (the dashed curve) the four modes of the driving spectrum. The maximum growth rate of the helium cyclotron anisotropy instability (Gary et al 2003), calculated using linear Vlasov theory and late-time average values of plasma parameters from the simulation, is $\gamma_m/\Omega_p \simeq 2 \times 10^{-4}$ at $k_{\parallel c}/\omega_p = 0.25$; such a slow growth is not discernable in the relatively brief interval of this simulation, so it is likely that other nonlinear processes such as wave–wave coupling are more important than the wave-particle processes associated with instability growth. Nevertheless, linear Vlasov dispersion theory predicts that the increases in $T_{\perp p}/T_{\parallel p}$ and $T_{\perp \alpha}/T_{\parallel \alpha}$ act to reduce the damping rates of fluctuations at resonant wavelengths (e.g. figure 8 of Gary et al (2006)), allowing the self-consistent fields to persist to late times in this simulation. It is the total fluctuation field which scatters the ions, with both the applied fields and the self-consistent fields contributing.

Figure 5 illustrates results from an ensemble of simulations in which all initial plasma parameters except $n_\alpha/n_e$ were held constant. There were eight runs overall in Ensemble N;
Figure 5. Simulation results from Ensemble N: the late-time averaged values of (a) $T_{\perp\alpha}/T_{||\alpha}$ ($\blacktriangle$), $T_{\perp p}/T_{|| p}$ ($\blacklozenge$) and $T_{||\alpha}/4T_{|| p}$ ($\blacktriangleleft$) and the dimensionless maximum growth rate of the alpha cyclotron anisotropy instability ($\blacktriangleleft$) as functions of $n_\alpha/n_e$. All initial plasma variables except $n_\alpha/n_e$ are stated in table 2; applied fluctuation parameters for sample runs are stated in table 3.
Table 3. Applied fluctuation parameters: Ensemble N

| n   | δBrms^2 / B0^2 | kx c / ωp | ωr(kx) / Ωp | Re(ζ−) | Re(ζ+)|
|-----|----------------|-----------|--------------|--------|--------|
| Run N–1 : nα/ne = 0.005 |
| 1   | 0.0025         | 0.45      | 0.3010       | −2.20  | −0.63  |
| 2   | 0.0025         | 0.50      | 0.3132       | −1.94  | −0.53  |
| 3   | 0.0025         | 0.55      | 0.3236       | −1.74  | −0.45  |
| 4   | 0.0025         | 0.60      | 0.3331       | −1.57  | −0.39  |
| Run N–3 : nα/ne = 0.02 |
| 1   | 0.0025         | 0.45      | 0.2994       | −2.20  | −0.63  |
| 2   | 0.0025         | 0.50      | 0.3127       | −1.94  | −0.53  |
| 3   | 0.0025         | 0.55      | 0.3235       | −1.74  | −0.45  |
| 4   | 0.0025         | 0.60      | 0.3332       | −1.57  | −0.39  |
| Run N–5 : nα/ne = 0.04 |
| 1   | 0.0025         | 0.45      | 0.2952       | −2.21  | −0.64  |
| 2   | 0.0025         | 0.50      | 0.3106       | −1.95  | −0.54  |
| 3   | 0.0025         | 0.55      | 0.3224       | −1.74  | −0.46  |
| 4   | 0.0025         | 0.60      | 0.3325       | −1.57  | −0.39  |
| Run N–8 : nα/ne = 0.075 |
| 1   | 0.0025         | 0.45      | 0.2805       | −2.26  | −0.69  |
| 2   | 0.0025         | 0.50      | 0.3019       | −1.97  | −0.56  |
| 3   | 0.0025         | 0.55      | 0.3170       | −1.76  | −0.47  |
| 4   | 0.0025         | 0.60      | 0.3286       | −1.58  | −0.40  |

Table 3 describes the applied fluctuation parameters of four of these computations. The scalings which result from these computations are functions of the choice of the applied wavenumber spectrum. Here our choice is based on the observational result that, among the 4 months of data examined in section 2, we find no consistent statistical correlation between |δBrms|^2 / B0^2 and nα/ne, where δBrms is a relatively high-frequency (f ∼ 1 Hz) measurement of the rms value of the magnetic fluctuations (Smith et al 2001). We conclude that there is no present evidence that solar-wind magnetic power spectra in the ion cyclotron damping regime have a clear dependence on the relative alpha density. Based on this conclusion, we apply the same wavenumbers and mode amplitudes to each simulation, as indicated in table 3.

Figure 5 shows late-time averages (over 80 \( \leq \Omega_p t \leq 100 \)) of several dimensionless quantities from the simulations of Ensemble N. As for the simulations of Gary et al (2006), perpendicular alpha scattering is the strongest consequence of the wave-particle interactions, with perpendicular proton scattering considerably weaker, and changes in the alpha/proton relative speed smaller yet. The late-time averaged values of \( T_{⊥α} / T_{||α}, T_{⊥p} / T_{||p}, v_{αp} / v_{A} \) and |δB(self)|^2 / B0^2 all decrease monotonically as nα/ne increases. Three of these computational results show the same trends with relative alpha density as do our analyses of ACE observations: \( T_{⊥p} / T_{||p} \) versus nα/ne as in figure 1, \( T_{⊥α} / T_{||α} \) versus nα/ne as in figure 2, and \( v_{αp} / v_{A} \) versus nα/ne which is not shown here.

Earlier we argued that Alfvén-cyclotron scattering should yield a negative correlation between \( T_{⊥α} / T_{||α} \) and nα/ne because there is a smaller energy density per particle available to the heavy ions as nα/ne increases. The simulations show that the fraction of applied field energy which goes into the alphas decreases as nα/ne decreases, leaving more energy available...
for scattering the protons, thus providing a plausibility argument for the associated increase in $T_{\perp p}/T_{\parallel p}$. In summary, if all fluctuation parameters except the frequencies and all plasma parameters except $n_\alpha/n_e$ are held fixed, then it is plausible to expect that the Alfvén-cyclotron scattering of both alphas and protons should increase as $n_\alpha/n_e$ decreases, and that is exactly what the simulations yield.

Figure 6 illustrates late-time ion anisotropies as functions of $n_\alpha/n_e$ from two ensembles of simulations, Ensemble NN with $\tilde{\beta}_{\perp p}(0) = 0.125$, initial $|\delta B|^2/B_0^2 = 10^{-3}$, and $k_1 c/\omega_e = 0.50$,
Table 4. Hybrid simulations: fits to ion anisotropies as functions of alpha relative densities

| Month | Proton anisotropies $(n_a/n_e \leq 0.075)$ | Alpha anisotropies $(n_a/n_e \leq 0.075)$ |
|-------|------------------------------------------|------------------------------------------|
| Ensemble NN | $T_{\perp p}/T_{\parallel p} = 1.43$–$4.32n_a/n_e$ | $T_{\perp a}/T_{\parallel a} = 3.01$–$12.47n_a/n_e$ |
| Ensemble N  | $T_{\perp p}/T_{\parallel p} = 1.32$–$1.54n_a/n_e$ | $T_{\perp a}/T_{\parallel a} = 1.82$–$3.73n_a/n_e$ |

Errors to fitting parameters

| Month | $b_p$ | $b_a$ | $R_p$ | $R_a$ |
|-------|-------|-------|-------|-------|
| Ensemble NN | $-4.32 \pm 0.31$ | $-12.47 \pm 2.06$ | 0.98 | 0.93 |
| Ensemble N  | $-1.54 \pm 0.02$ | $-3.73 \pm 0.13$ | 0.999 | 0.996 |

and Ensemble N with $\bar{\beta}_p(0) = 0.50$, initial $|\delta B|^2/B_0^2 = 10^{-2}$ and $k_1c/\omega_e = 0.45$. Although these responses are not precisely linear functions of the relative alpha density, we have fit them using equation (1) to facilitate comparison of observations and simulations. Table 4 states the fitting parameters and their errors for ion anisotropies as functions of alpha relative densities from the two simulations of ensembles. Those solar wind plasma processes which are independent of $n_a$ (e.g. proton–proton collisions) may contribute to the values of $a_j$ determined from the observations. But our simulations do not represent such processes, so it would be inappropriate to compare observational and computational values of this fitting parameter. In contrast, resonant wave-particle interactions are likely functions of $n_a/n_e$ and therefore, are likely contributors to the $b_j$-values fit to the observations. So comparisons of observational and computational values of this parameter are appropriate.

For the proton anisotropy there is a clear, consistent negative correlation with the relative alpha density for all 4 months of observations and for both simulations. For the alpha anisotropy, the simulations show a consistently negative correlation with $n_a/n_e$, in agreement with all 4 months of alpha observations discussed in section 2 if outlying points are rejected.

4. Conclusions

We studied relationships between ion temperature anisotropies and relative alpha densities using both data analysis and computer simulations. The observations are from the ACE spacecraft, operating in the solar wind at the L1 point near earth. Our statistical data analysis shows a weak but consistent negative correlation between $T_{\perp p}/T_{\parallel p}$ and $n_a/n_e$, as well as a weak and less consistent negative correlation between $T_{\perp a}/T_{\parallel a}$ and $n_a/n_e$ if outlying values of the relative alpha density are excluded from the data analysis. The simulations use a hybrid code with protons and alphas as the ion species and parameters characteristic of average solar-wind parameters. The computations demonstrate that imposed spectra of Alfvén-cyclotron fluctuations scatter both protons and alphas so as to increase their effective $T_{\perp}/T_{\parallel}$ and at $v_{ap} = 0$ the alphas are scattered more strongly than the protons. The simulations also yield negative correlations between $T_{\perp p}/T_{\parallel p}$ and $n_a/n_e$ as well as between $T_{\perp a}/T_{\parallel a}$ and $n_a/n_e$. New Journal of Physics 8 (2006) 17 (http://www.njp.org/)
Thus the observations and the simulations are consistent, but this consistency is qualitative; although most values of the fitting parameters \( b_\alpha \) and \( b_p \) lie between \(-1\) and \(-10\), we have not demonstrated a quantitative relationship between values from simulations, which correspond to precise values of all initial conditions, and the values analysed from the observations, which correspond to a broad range of plasma parameters including \( \tilde{\beta}_{\parallel p} \), \( v_{ap}/v_A \) and \( T_{\parallel a}/T_{\parallel p} \). It would be useful to carry out further analysis in which the data were restricted to narrow ranges of the plasma parameters in order to seek more quantitative agreement with the simulation results.

Nevertheless, this consistency between observations and computations leads us to conclude that the observed statistical correlations are signatures of Alfvén-cyclotron scattering of the ions. With the previous demonstration that the negative statistical correlation observed between \( T_{\perp a}/T_{\parallel a} \) and \( v_{ap}/v_A \) (Gary et al 2005a, b) is also a signature of this process (Gary et al 2006), there is now substantial evidence that both proton and alpha scattering by Alfvén-cyclotron fluctuations occurs sporadically in the solar wind near Earth.

The major uncertainty in the interpretation of our simulations is the link between the applied magnetic fluctuations and the self-consistent magnetic fluctuations which they excite. This coupling requires further study because it appears to be the primary factor in determining the efficacy of both the proton and alpha scattering which arise in the simulations.

Appendix

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, \( \omega_j \equiv \sqrt{4\pi n_e e_j^2/m_j} \); the cyclotron frequency, \( \Omega_j \equiv e_j B_0/m_j c \); the thermal speed, \( v_j \equiv \sqrt{k_B T_{\parallel j}/m_j} \); and the average flow velocity parallel or antiparallel to \( B_0 \), \( v_{o_j} \).

We define the Alfvén speed as \( v_A \equiv B_0/\sqrt{4\pi n_e m_p} \), and the alpha/proton relative flow velocity as \( v_{ap} \equiv v_{o\alpha} - v_{op} \). The complex frequency is \( \omega = \omega_r + i\gamma \), and the cyclotron resonance factors of the \( j \)th species are \( \zeta_j^\pm \equiv (\omega - k \cdot v_{o_j} \pm \Omega_j)/\sqrt{2|k_\parallel|v_j} \).

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