Nonlinear evolution of EMIC waves in a uniform magnetic field:
2. Test-particle scattering

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Received 27 April 2010; revised 29 July 2010; accepted 14 October 2010; published 18 December 2010.

[1] The trajectories of individual proton test particles are computed as they traverse a temporally and spatially evolving electromagnetic ion cyclotron (EMIC) wavefield. This EMIC wavefield is simulated using a hybrid code, which is described in a companion paper, with parameters representative of those found in the dawnside outer magnetosphere ($L \sim 9$). The scattering of a representative group of hot protons ($E_0 = 4$ keV, $\alpha_0 = 60^\circ$) and cool protons ($E_0 = 30$ eV, $\alpha_0 = 20^\circ$) is analyzed in configuration space, velocity space, $E$, $\alpha$, and phase. Results indicate that the hot protons are scattered by the EMIC wave in a manner consistent with resonant wave-particle interactions, that they are constrained to move along single-wave-characteristic curves, and that the particles experience moderate phase bunching. On the other hand, the cool protons are not scattered by the EMIC wave resonantly and experience strong phase bunching, which results in large positive advective motion in both $E$ and $\alpha$, as well as large relative diffusion. The phase bunching and heating of the cool proton population is consistent with observations of cool, heavy-ion heating in space, and the phasing of the particle $v_{\perp}$ and EMIC wave’s $E$ field is consistent with a previously described mechanism known as electric phase bunching, which results in efficient energization of cool particles.


1. Introduction

[2] Electromagnetic ion cyclotron (EMIC) waves are naturally occurring plasma emissions found predominantly on the day and dusk sides of the Earth, and extend all the way from the plasmapause to the magnetopause [e.g., Anderson et al., 1992a, 1992b; Anderson and Hamilton, 1993; Meredith et al., 2003]. Such waves occur in the Pc1–Pc2 range of pulsations, ~0.1–5 Hz [e.g., Kozyra et al., 1984; Horne and Thorne, 1994] and are excited by the temperature anisotropy ($T_{\perp} > T_{\parallel}$) of the energetic ion population, for example the ring current in the inner magnetosphere ($E \sim 10$–100’s of keV), or the convecting plasma sheet in the outer magnetosphere ($E \sim 1$–10 keV) [Cornwall, 1965; Kennel and Petschek, 1966]. The linear growth rates of EMIC waves tend to maximize where the hot, anisotropic ions drift into regions of cool, dense plasma such as the plasmapause or plasmaspheric drainage plume [Cornwall et al., 1970; Horne and Thorne, 1993], and the net amplification can be further enhanced if the cool plasma is highly structured and guides the wave along its magnetic field line resulting in an extended growth region [Horne and Thorne, 1993; Chen et al., 2009].

[3] EMIC waves play an important role in magnetospheric dynamics, in that they are able to transfer energy and momentum between particles in different energy ranges, as well as between different particle species [e.g., Gendrin, 1983]. For example, EMIC waves extract energy from the hot, anisotropic ring current ions, and in the process cause ion pitch angle scattering into the loss cone, and excitation of the proton aurora [Cornwall et al., 1970; Jordanova et al., 2007]. As the EMIC waves propagate away from their equatorial source region, they can impart a large portion of their energy to suprathermal (a few eV) electrons through Landau resonant interactions, which then precipitate into the dense upper atmosphere and form stable auroral red arcs [Cornwall et al., 1971; Thorne and Horne, 1992; Gurgiolo et al., 2005]. They can resonantly heat heavy ion populations [Thorne and Horne, 1993, 1994], as well as parasitically scatter relativistic electrons very rapidly [e.g., Thorne and Kennel, 1971; Lyons and Thorne, 1972; Friedel et al., 2002, and references therein; Meredith et al., 2003; Shprits et al., 2008, and references therein], which is currently considered one of the leading candidates for causing radiation-belt dropouts [Blake et al., 2001; Onsager et al., 2002, 2007; Green et al., 2004; Bortnik et al., 2006; Borovsky and Denton, 2009].

[4] Of particular interest to the present study is the observed modulation and heating of the suprathermal (<100 eV) ion populations (both H$^+$ and He$^+$) in response to EMIC waves [Young et al., 1981; Roux et al., 1982; Mauk et al., 1981], which is believed to be a nonresonant process.

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of energy transfer, acting predominantly in the direction perpendicular to the background magnetic field [Gendrin et al., 1984]. We note in passing that this is a distinct process from the resonant ion heating at the bi-ion frequency, which is associated with the formation of ion conics [Horne and Thorne, 1997].

The present paper is part of a series of studies focusing on the nonlinear excitation of EMIC waves, their saturation, and interaction with the ion populations. In a companion paper, Omidi et al. [2010, hereafter P1] describe the growth, excitation, and saturation of EMIC waves in a four-component plasma (e−’s, and three ion species: cool H+, hot H+, and cool He+) with a homogeneous background magnetic field, as well as the energy transfer between hot and cool ions. Here, we trace test particles through the electromagnetic fields computed in P1 to study the microphysics of the wave-particle interactions during the wave growth and nonlinear saturation phase. In section 2 we describe the test-particle tracing technique used in this paper, in sections 3 and 4 we study the response of the resonant and nonresonant particles, respectively, and we give a summary of the results for a range of initial energies and pitch angles in section 5.

2. Aim of This Study and Approach

A principal aim of this study is to understand the process of energy transfer from the hot proton population to the cool, heavy ions via the EMIC waves. The heating of the cool ions was demonstrated in P1, and clearly shown to be an efficient process which does not obey the usual resonance condition for wave-particle interactions. Moreover, similar energization of cool, heavy ions was observed in space [Young et al., 1981; Roux et al., 1982; Mauk et al., 1981], which gives us confidence that a real, physical process is being reproduced in the numerical simulations, that should be understood.

The parameters of the simulation are given in P1 and only summarized below for convenience. A four-component plasma is simulated using a hybrid code [Winske and Omidi, 1993, 1996] with a massless, charge-neutralizing fluid of electrons (N_e = 5 cm⁻³), and 3 ion species modeled as super particles: (1) cool H+ (N_{H+} = 4.66 cm⁻³, T_{H+} = 30 eV, T_\perp = 10 eV), (2) cool He+ (N_{He+} = 0.04 cm⁻³, T_{He+} = 20 eV, T_\perp = 3 eV), and (3) hot H+ (N_{H+} = 0.3 cm⁻³, T_{H+} = 1300 eV, T_\perp = 4T_{H+} = 5200 eV). The background field was taken to be B = 42.634 nT, corresponding to L = 9. All the above parameters were chosen to be representative of high-L, duskside conditions, and modeled after Horne and Thorne [1997] (which were, in turn, based on Anderson and Fuselier [1994] and Anderson et al. [1996]).

During the period of initial wave growth to saturation (i.e., tΩ_p = 0–200 in P1 Figure 2) corresponding to 0–50 s in real time) the energetic H+ population experiences a rapid loss of T_\perp and a modest gain in T_\perp in a manner consistent with quasi-linear scattering. The hot ion anisotropy, A = T_\perp/T_\perp, is reduced from A = 3 at tΩ_p = 0 to A = 1.6 at tΩ_p = 200, with a concomitant net loss in hot ion energy density comparable to ~9.0 × 10⁻¹¹ ergs/cc. It is instructive to compare this energy loss to the net gain in energy density of the excited EMIC waves, δB_p^2/8π ~ 1.6 × 10⁻¹¹ ergs/cc. During this growth of the waves the cool H+ population is strongly heated primarily in the direction perpendicular to B_0 with a concomitant increase in cold ion energy density comparable to ~7.1 × 10⁻¹¹ ergs/cc. Cold He+ ions are also heated but the net change in the He+ energy density (~0.3 × 10⁻¹¹ ergs/cc) is small due to their low concentration. Clearly, the major energy transfer occurs between the hot and cool H+ ions, with less than 20% of the energy being stored in the EMIC waves. The waves however, play a pivotal role in transferring the energy to the cool ion population. During the nonlinear saturation of the EMIC waves in the period tΩ_p = 200–400 the hot ion anisotropy is further reduced to A ~ 1.0, but the net change in hot ion energy density is relatively modest, and the cool H+ heating is also greatly reduced.

To understand the microphysical processes responsible for the energy transfer described above, we launch test particles of a given charge (q) and mass (m) into the simulated EMIC wavefield starting at a given location r_0, and integrate the Lorentz force equation which governs the particle motion:

\[
\frac{dv}{dt} = \frac{E}{q} + v \times B
\]

where v is the velocity vector (v in m/s) normalized to the Alfven speed v_A, t = tΩ_p is time (t in sec) multiplied by the proton gyrofrequency Ω_p, E = E/qB_0 is the electric field (E in V/m) normalized to the Alfven speed and background magnetic field intensity B_0, and B' = B/B_0 is the normalized magnetic field vector (B in T). Since the energies of the test particles we deal with in this study are <10 keV, relativistic effects are neglected. The configuration space in which the particle moves is 128 × 128 proton skin depths (where each proton skin depth = c/ω_p = v_A/Ω_p ~ 100 km), with doubly-periodic boundary conditions (similar to the hybrid code in P1), and the precise wavefield values are interpolated to the time and location of the particle at every time step of the particle motion.

To illustrate the motion of a typical test particle, we show in Figure 1 a portion of the trajectory of a proton with initial energy E_0 = 40 eV, and initial pitch angle \alpha_0 = 60°, launched at the initial position r_0 = (X_0, Y_0, Z_0) = (33, 33, 0) at time t = 0. The trajectory is shown in the time interval tΩ_p = 200–240, where the superimposed red and black arrows represent the local B fields and E fields encountered by the particle. Figure 1a shows the particle propagating in the background field alone, without the presence of the EMIC wave, whereas Figure 1b shows the same particle propagating in the presence of the EMIC wave from the simulation in P1. The difference in the particle trajectories is dramatic, with significant changes in both E and α. For reference, we note that even though the total amplitude of the wave compared to B_0 is relatively large (in the range of a few percent (cf. P1, Figures 1 and 2), the absolute value of the wavefields is only ~1–2 nT, which is entirely consistent with observed values [e.g., Meredith et al., 2003]. The behavior of the test particles in this study is thus representative of what could be expected in space.

3. Resonant Particle Scattering

In order to understand the detailed response of the test particles to the EMIC wavefield, we begin by analyzing
the motion of the energetic component of the proton population, since these particles are expected to exhibit the more typical resonant behavior that has been studied extensively in the past [Horne and Thorne, 1997]. We select an energy ($E_0 = 4$ keV) and pitch angle ($\alpha_0 = 60^\circ$) which is roughly representative of the typical energy and anisotropy of the hot proton population, and launch a group of 12 proton test particles which are uniformly distributed in Larmor phase, and all having the same guiding center (i.e., they are uniformly distributed on a circle with a radius equal to a Larmor radius). The equations of motion are integrated over a period of $t\Omega_p = 0$–400, which is the period of most intense wave growth, hot proton cooling, and cool particle energization (P1, Figures 2, 5, and 6).

The trajectories of the 12 protons are shown in configuration space in Figure 2a, color-coded according to the particles' initial Larmor phases. The protons are seen to leave and reenter the simulation space (black line at the top of Figure 2a) twice, and in the course of the simulation, the gyroradii of the group of particles are seen to diverge sig-

![Figure 1](image1.png)

**Figure 1.** Trajectory of a proton test particle shown as the blue line, with superimposed local magnetic field vectors (red arrows) and local electric field vectors (black arrows), for (a) a uniform $B$ field only and (b) a uniform $B$ field, with simulated EMIC wavefield. The coordinate system is shown in Figure 1a, where $B_0$ is aligned with the $x$ axis.

![Figure 2](image2.png)

**Figure 2.** Trajectories of 12 proton test particles color-coded according to their initial Larmor phase, shown in (a) configuration space and (b) velocity space.
nificantly (scatter), indicating a change in energy and/or pitch angle. The velocities of these protons are shown in velocity space in Figure 2b, where we have superimposed the initial pitch angle line (dashed radial line), the constant $E_0$ circle (solid circle), and the single-wave characteristic lines (dashed ellipses) [Summers et al., 1998], calculated for a range of initial energies, for the representative wave frequency $\omega = 0.4 W_p$, which is the largest amplitude spectral component (P1, Figure 3). As expected, the particles roughly follow the nominal single-wave characteristic curve which is indicative of resonant wave-particle interactions, but due to the presence of other spectral components, are occasionally seen to switch the particular single wave characteristic curve on which they are constrained to move. This is aided by the fact that the EMIC waves are confined to narrow spatial packets (P1, Figure 1), through which the particles propagate, and which have their own particular representative wave frequencies. Figure 2b also shows that the pitch angle variation of the protons is dramatic, it fills virtually the entire pitch angle space from $\alpha = 0^\circ$ to $\alpha = 90^\circ$, which is indicative of strong scattering. That is, the wave-induced scattering in $\alpha$ is no longer very small relative to $\alpha_0$, and thus cannot be represented as a mere first-order perturbation to the usual helical 0th-order trajectory of a charged particle in a background magnetic field, which is the basic assumption of linear (or quasilinear) scattering.

[13] The wave-induced scattering in energy and pitch angle for this set of particles is shown as a function of time in Figures 3a and 3b, where the pitch angle variations are clearly seen to fill the entire space from $\Omega_p \sim 160$, which is roughly when the EMIC waves reach their saturation amplitudes. The variation in energy is also large, and varies roughly by $\pm 2$ keV from its nominal 4 keV energy (i.e., $\pm 50\%$ normalized variation).

[14] As a final step in the analysis, we examine the extent to which gyrophase bunching takes place during the wave-particle interaction since this bunching is believed to be important for the wave growth process. In Figure 4b we show the instantaneous Larmor phase $\tan^{-1}(v_z/v_y)$, where $B = B_0x$, of each of the 12 test particles, together with the instantaneous phase of the EMIC wave $\tan^{-1}(B_z^w/B_y^w)$, evaluated dynamically at the location of test particle 1. For comparison, we also show in Figure 4a the kinetic energy $K$ absorbed by one of the test particles (where $K = \int_0^t (v \cdot E) dt$), which can be thought of as crudely representing the intensity of the EMIC waves when the wave and particle are roughly corotating. It is interesting to note that the EMIC wave’s phase occasionally reverses direction and does not rotate smoothly, due to the superposition of two counterstreaming, superimposed waves, which also correspond to the regions of density enhancement discussed in P1. The expanded portion of the wave and particle phases in Figures 4c and 4d show that there is a moderate degree of phase bunching, which is indicated by the nonuniform separation between the 12 particle phases (if the particles continued to be uniformly distributed in gyrophase throughout the simulation, as they were at $\Omega_p = 0$, the colored lines would be uniformly spaced as a function of time and no grouping would be visible). As shown, the particles are no longer uniformly distributed in Larmor phase by the time the EMIC waves saturate ($\Omega_p \sim 170$ (from P1, Figure 2)). Regions of enhanced phase bunching are roughly coincident with enhancements in wave intensity, and hence $K$.

[15] Except for the effects of strong scattering, the energetic particles in the above example behave roughly as
Figure 4. Phase bunching of the 12 proton test particles in Figures 2 and 3. (a) The integrated kinetic energy of 1 particle, (b) the instantaneous particle Larmor phase as a function of time for each test particle, color-coded by initial Larmor phase, with the instantaneous phase of the EMIC wave in black. (c) Blow-up of the time range $t\Omega_p = 150$–$200$ showing the kinetic energy and (d) particle Larmor phases.
would be intuitively expected for resonant wave-particle interactions. Having developed some techniques to analyze the particle behavior, we proceed to examine the response of nonresonant proton scattering next.

4. Nonresonant Particle Scattering

[16] The analysis presented in section 3 is repeated for a group of 12 proton test particles, uniformly distributed in Larmor phase, with $E_0 = 30$ eV, and $\alpha_0 = 20^\circ$, which is roughly representative of the typical energy and anisotropy of the cool proton population. For reference, the minimum first-order cyclotron resonant energy of protons interacting with an EMIC wave having $\omega = 0.4 W_p$, is $>2$ keV, so the particles being considered presently are well below the energy required for resonant interactions.

[17] Figure 5a shows the trajectories of the group of 12 test particles in configuration space. Compared to Figure 2, these particles only propagate about 60 skin depths ($X = 33–90$) instead of the ~350 skin depths for the energetic H$^+$ population (Figure 2a), due to their low parallel velocity, and the guiding center of the group of particles exhibits large offsets from its initial value. The trajectory of the protons in velocity space (Figure 5b) shows that the particle velocities are no longer constrained to move along the single-wave characteristic curves, but instead undergo dramatic changes in their motion, predominantly in the $v_\perp$ direction, with some small spreading in $v_\parallel$ due to the presence of multiple wave frequencies.

[18] The energy and pitch angle of the test particles is shown as a function of time in Figure 6, and shows that the scattering in pitch angle is not as dramatic as in Figure 3, but that the excursions in energy scattering shown in Figure 6a reach $E \sim 80$ eV, i.e., 260% of its initial value, which is far greater than the value of ~50% for the resonant particles. The cold H$^+$ energization occurs predominantly over the interval $t \Omega_p = 100–200$, namely, during the nonlinear wave-growth phase just prior to wave saturation.

[19] Figure 7 shows the phase bunching of the particles and EMIC wave in the same format as Figure 4, where it is clear that the particle phases have bunched into a very tight group that rotates together with the wave magnetic vector, and is strongly modulated by the intensity of the wave’s electric field (Figures 7a and 7c).

[20] Even though the cool protons are unable to cyclotron-resonate with the EMIC waves, they are nevertheless seen to be strongly affected by the wave from the foregoing example. The energy of the test particles is scattered predominantly in the perpendicular direction, there is a large amount of relative energization of the particles, and strong phase bunching, all of which are consistent, point for point, with the observations of suprathermal heavy ions modulated by EMIC waves in space [Young et al., 1981; Roux et al., 1982; Mauk et al., 1981].

[21] This interaction mechanism has been described previously as an “electric phase bunching” process [Mauk et al., 1981], which is the low-energy analog of the “magnetic phase bunching” process. In magnetic bunching, the wave ‘nudges’ the particle’s $v_\parallel$ in such a way that particles drift along the wave train to locations where the relative wave-particle phase oscillates about the equilibrium position, such that $v \times B \sim 0$. In electric bunching, the EMIC wave’s E field nudges the phase of $v_\perp$, such that it becomes increasingly more parallel to E, and the particle is efficiently
accelerated. The factor that determines whether electric or magnetic bunching will dominate in the wave-particle interaction, is the magnitude of the velocity relative to $v_A$. If $v/v_A \gg 1$, then the $v \times B$ term will dominate in equation (1), whereas if $v/v_A \ll 1$, then the $v \times B$ term will be negligible compared to $E$, and electric bunching will dominate.

5. Total Scattering

[22] The representative examples presented in sections 3 and 4 were used to highlight some of the key features inherent in the wave-particle interaction between EMIC waves and energetic and cool protons, respectively. However, in order to better understand the behavior of the whole plasma population, it is instructive to study the test-particle response of a range of pitch angles and energies. We do this by quantifying the scattering as follows: for a given initial $E_0$ and $\alpha_0$, 12 proton test particles are run through the EMIC wavefields for the time range $\Omega_p = 0$–400, as in the examples above. At every time step, the mean energy and pitch angle is calculated $\mu_E = 1/12\Sigma_{i=1}^{12}E_i$, $\mu_\alpha = 1/12\Sigma_{i=1}^{12}\alpha_i$, as well as the variance of the spread, $\sigma_E^2 = 1/12\Sigma_{i=1}^{12}(E_i - \mu_E)^2$, $\sigma_\alpha^2 = 1/12\Sigma_{i=1}^{12}(\alpha_i - \mu_\alpha)^2$.

[23] Figure 8 illustrates this process, where we have again shown the scattering in energy and pitch angle of the non-resonant particle as a function of time (identical to Figure 6), with the means $\mu_E$, $\mu_\alpha$ (black line) and $\mu_{E,\alpha} \pm \sigma_{E,\alpha}$ (red lines) superimposed in Figures 8a and 8b. To quantify the net scattering, we average the quantities $\mu_E$, $\mu_\alpha$, $\sigma_E$, and $\sigma_\alpha$ over the period $\Omega_p = 360$–400 (i.e., the last 5% of the interaction) to minimize the effect of the fluctuations, and obtain final ‘scattered’ values. The final scattering in energy and pitch angle are then summarized using 4 quantities as

$$
\Delta \mu_E = (\mu_E^{\text{final}} - E_0)/E_0, \quad \Delta \sigma_E = \sigma_E^{\text{final}}/E_0, \quad \Delta \mu_\alpha = \mu_\alpha^{\text{final}} - \alpha_0, \quad \Delta \sigma_\alpha = \sigma_\alpha^{\text{final}}.
$$

[24] The four quantities described above are calculated for the range of initial conditions $\alpha_0 = 0^\circ$–90$^\circ$ and $E_0 = 1$ eV to 10 keV, and displayed in Figure 9. Figures 9a and 9b show that by far the largest relative scattering in energy occurs for the cool protons, with $E_0 < 100$ eV. This population experiences diffusive spreading in $E_0$ that can be as large as $\sigma_E \sim 3E_0$ (Figure 9a), which increases with increasing $\alpha_0$, and decreases $E_0$. There is also a large positive advection of the mean energy (Figure 9b), indicating that the entire group of 12 proton test particles can increase in energy by a factor of up to $\sim 10E_0$. Also evident in Figure 9b is a distinct separation into a low-energy ($E_0 < 100$ eV) and high-energy ($E_0 > 100$ eV) behavior. The high-energy region (few keV) experiences positive advection in energy by up to a factor of 1 at low $\alpha_0$ and small negative advection in energy for $\alpha_0 > 50^\circ$. Due to the large anisotropy of the high-energy proton population (i.e., many more particles at high $\alpha$ than at low $\alpha$), the small relative energy loss of the high-energy, large-$\alpha_0$ particles is sufficient to compensate for the acceleration of low-energy and high-energy low-$\alpha_0$ protons.

[25] The behavior of $\sigma_\alpha$ and $\mu_\alpha$, shown in Figures 9c and 9d reflects the trends observed in sections 3 and 4, in that the high-energy protons experienced large scattering in $\alpha_0$ and tended to isotropize quickly, whereas the low-energy protons experienced smaller scattering in $\alpha_0$, and tended to phase bunch rapidly, thus behaving more as a single particle, with concomitant large changes in $\mu_\alpha$ and small changes in $\sigma_\alpha$. Since the high-energy protons isotropize quickly, i.e., fill the entire $\alpha = 0^\circ$–90$^\circ$ space within $\Omega_p \sim 200$ (e.g., Figure 3), the mean $\alpha$ will tend to $\sim 45^\circ$, and so those test particles that are initiated with $\alpha_0 \sim 0^\circ$ will show positive
advection of $\sim 45^\circ$, as is indeed observed in Figure 9d. For high-energy test particles with $\alpha_0 \sim 90^\circ$, advective terms are smaller since the EMIC waves scatter particles to both positive and negative directions symmetrically.

Finally, we observe that there is a structure apparent in the low-energy proton scattering, where a crest or trough of scattering (e.g., Figure 9d), extends all the way from low $\alpha_0$ to high $\alpha_0$ and increases in $E_0$ as it does so. This is
explained by observing that within the crest (or trough), the particle’s initial $v_k$ is kept approximately constant, and thus the test particle traverses roughly the same number of wave periods, which results in either a maximum, or minimum of net scattering. To illustrate this point, we superimpose 4 lines of constant $v_k$ corresponding to $E_0 = 1, 4, 7, \text{ and } 10 \text{ eV}$ at $\alpha_0 = 0^\circ$ on Figure 9d that show how the striations follow these lines (lines of constant $v_k$ increase in energy as $\alpha_0$ increases, since $v_\perp$ increases with increasing $\alpha_0$). The consecutive striations then simply correspond to the particles traversing an increasing number of EMIC wave periods.

6. Summary and Conclusions

[27] The trajectories of individual proton test particles were computed, traversing a temporally and spatially evolving EMIC wavefield, superposed on a homogeneous, background magnetic field. The EMIC wavefield was simulated using a hybrid code, with realistic inputs representative of a high-L, dawnside EMIC event, which is described in a companion paper, P1. The purpose of the present paper was to examine the microphysical wave-particle interactions, that lead to the rapid relative heating of the cool (<100 eV) proton population, which is believed to involve a nonresonant mechanism. For comparison, we showed the scattering of a representative group of hot protons ($E_0 = 4 \text{ keV, } \alpha_0 = 60^\circ$) in configuration space, velocity space, $E$, $\alpha$, and phase. The same analysis was then used to examine the behavior of a representative group of cool protons ($E_0 = 30 \text{ eV, } \alpha_0 = 20^\circ$), and then the scattering of the entire hot and cool proton population was examined.

[28] The results of our study show the following.

[29] 1. The hot protons were scattered by the EMIC wave in a manner consistent with resonant wave-particle interactions. The velocities of the particles were roughly constrained to move along the single-wave characteristic curves, the particle guiding centers remained roughly constant, and the particle phases experienced a moderate degree of bunching. The scattering of the particles was described well by linear theory in the initial part of the simulation ($\tau \omega_p < 100$), but at the later times ($\tau \omega_p > 100$) the large amplitude of the EMIC waves (relative to the background $B$ field) tended to isotropize the particle distribution rapidly and produced scattering in $E$ and $\alpha$ that was not linear.

[30] 2. The cool protons were not scattered by the EMIC wave resonantly, but rather favored scattering in $v_\perp$. The EMIC wave strongly bunched the test particles in phase, which resulted in large positive advective motion in both $E$ and $\alpha$, as well as large relative diffusion. The phase bunching, and heating of the cool proton population is consistent with observations of cool, heavy-ion heating in space, and the phasing of the particle $v_\perp$ and EMIC wave’s $E$ field is consistent with a previously described mechanism known as electric phase bunching, which results in efficient energization of cool particles. This mechanism becomes effective when the particle velocity is sufficiently low (compared to $v_A$), to make the $E$ term dominate over the $v \times B$ term in the Lorentz force equation, and is the low-energy analog of magnetic phase bunching.

[31] 3. The scattering of the entire (hot and cool) proton population showed that the scattering tended to maximize in two distinct regions, above and below $\sim 100 \text{ eV}$. In the low-energy region, very strong advection was evident in both $E$ and $\alpha$, for all $\alpha_0$, accompanied by strong diffusion. In the
high-energy region, advection was moderate in $E$ and $\alpha$, but diffusion remained strong for moderate $\alpha_0$. The effects of the strong isotropization of the high-energy protons were evident in the large advection of the pitch angle for $\alpha_0 \sim 0^\circ$. The low-energy scattering showed evidence of striations in the $E_0 - \alpha_0$ plane, due to the finite number of wave periods encountered by the streaming test particles.

Figure 9. Net scattering of the hot and cool protons as a function of initial energy and pitch angle, after $t \Omega_p = 400$. (a) Normalized standard deviation of the particle energy $\Delta \sigma/E_0$ indicating diffusive scattering, (b) normalized change in the mean energy $\Delta \mu/E_0$ indicating advective scattering, (c) diffusive scattering $\Delta \sigma_\alpha$, and (d) advective scattering $\Delta \mu_\alpha$ in pitch angle. The 4 dashed lines in Figure 9d have constant $v||$ corresponding to $E_0 = 1, 4, 7$, and 10 eV at $\alpha_0 = 0^\circ$.

Acknowledgments. This work was supported by NASA grants NNX08A135G and NNX08AM17g.

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