GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 6, PAGES 1063-1066, JUNE 1991

PITCH ANGLE SCATTERING OF COMETARY IONS INTO MONOSPHERICAL AND BISPHERICAL DISTRIBUTIONS

Ronald H. Miller

Space Physics Research Laboratory, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan

S. Peter Gary

Space and Science Technology Division, Los Alamos National Laboratory

Dan Winske

Applied Theoretical Physics Division, Los Alamos National Laboratory

Tamas I. Gombosi

Space Physics Research Laboratory, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan

Abstract. Low frequency magnetic fluctuations generated by solar wind/cometary ion distributions cause pitch-angle scattering of cometary ions. The nature of this pitch angle scattering is examined by means of one-dimensional hybrid simulations, in which newborn ions are created at a constant rate, and for various injection angles, α, relative to the magnetic field. Pitch angle scattering in the quasi-perpendicular regime (α>60°) results in a bispherical velocity distribution while in the quasi-parallel regime (0≤α≤60°), pitch angle scattering can result in either a mono or bispherical distribution depending on the injection angle and initial beam velocity.

1. Introduction

Cometary neutral atoms and molecules escape from the surface of the comet and migrate outwards until they become ionized. The introduction of these newborn cometary ions represents a source of free energy in the solar wind which allows for the growth of instabilities out of the thermal background of fluctuations. The instabilities are a function of the plasma parameters, particularly on the velocity of the solar wind (v_{ob}) and the angle α between the solar wind velocity and the magnetic field. (In the solar wind frame v_{ob} is thus the velocity of the newborn ions and α is the injection angle.) The predominant electromagnetic instability propagating parallel to the beam in the quasi-parallel regime (0°≤α≤60°) is the electromagnetic ion/ion right-hand resonant instability [Gary et al., 1984; Winske and Gary, 1986; Gary et al., 1988; Gary and Madland, 1988]. In the quasi-perpendicular regime (α>60°), the left-hand electromagnetic ion cyclotron anisotropy instability is dominant, which consists of two ion cyclotron modes: a positive helicity mode which propagates anti-parallel to the beam and a negative helicity mode which propagates parallel to the beam [Gary and Schriver, 1987; Miller et al., 1991]. In the limit α=90°, both right- and left-traveling instabilities grow at the same rate but for α<90° the positive helicity anti-beamward propagating mode is dominant. The fact that the instability physics changes with α suggests that pitch angle scattering of newborn ions from these instabilities and consequently the resulting ion velocity distribution should be functions of α.

Paper number 91GL01047
0094-8534/91/91GL-01047$3.00

Two simple models of pitch-angle scattering have been used to estimate the long-term consequences of these instabilities. Lee [1989] assumes that a single wave propagates in the direction of the beam, and scatters cometary ions uniformly over a sphere centered at the phase speed of the wave. We term this result a "monospherical distribution." Lee also calculates the energy loss associated with the energy transferred to the fluctuating magnetic field. In contrast, Galeev and Sagdeev [1987] assume fluctuations of equal amplitude propagate in opposite directions relative to the solar wind, and that cometary ions are scattered forward by backward travelling waves and scattered backward by forward traveling waves to form what is termed the "bispherical distribution." This model has been used by Coates *et al.* [1990] to compute an average cometary ion streaming speed which was compared against the observed cometary ion bulk speed.

Miller et al. [1991] has demonstrated that the wave assumptions of both monospherical and bispherical models apply only in the fully parallel and fully perpendicular limits; i.e., at α=0° the waves are all propagating in the beam direction, while at α=90° waves of roughly equal intensity propagate in both directions. At intermediate values of α, left and right traveling waves are present, but with different amplitudes and different dispersion properties. The purpose of this paper is to combine the fluctuation diagnostics of Miller et al. [1991] with a detailed examination of pitch-angle scattering over a range of values of α to understand the conditions under which the mono and bispherical distributions may be regarded as valid approximations.

To address these issues, we have used the simulation model of Gary et al. [1986, 1988, 1989] with improved diagnostics

[Miller et al., 1991]. We vary only the injection angle α, to study in more detail the properties of wave generation and the subsequent development of mono/bispherical pick-up ion distributions due to pitch-angle scattering. Specifically, we look at three cases: α=35°, representative of a monospherical distribution where the scattering waves are due to the ion/ion right-hand resonant instability; α=55°, representative of a bispherical distribution where the scattering waves are due to both the ion/ion right-hand resonant instability ($v_{ph} \approx v_A$) and the ion cyclotron anisotropy instability ($v_{ph} \approx -v_A$); and α=85°, which also represents a bispherical distribution but where the scattering waves are due to the two ion cyclotron anisotropy modes propagating in opposite directions ($v_{ph} \approx \pm v_A$). We examine pitch angle scattering along diffusion paths centered at the phase velocities of the waves that are responsible for the scattering of the beam protons and which ultimately determine whether the distribution function is monospherical or bispherical.

The simulation model and results for the three cases are presented in Section 2. In Section 3 we summarize our principal findings and discuss the consequences of pitch-angle scattering in the quasi-parallel and quasi-perpendicular regime

2. Simulation Results

The hybrid simulation code used in this paper and in earlier simulations of Gary et al. [1986, 1988, 1989], Winske et al. (1984) and Miller et al. [1990, 1991] treats the electrons as a massless, charge neutralizing fluid and the ions as discrete particles [Winske and Leroy, 1985]. The simulations involve three species: solar wind protons, solar wind electrons, and a tenuous injected proton component. The injected protons are assumed to be cold and are distributed randomly through one-dimensional space (taken to be the x-axis here) with constant injection rate L_b and injection velocity, v_{ob}=x $v_{ob}\cos\alpha$+y $v_{ob}\sin\alpha$, thus simulating the ionization of cometary neutrals, and the subsequent appearance of new cold ions in the solar wind. The solar wind plasma is assumed to be Maxwellian, characterized by β_j=1.0 ($\beta j=8\pi n_o T_j/B^2$) for both the protons (j=p) and electrons (j=e). The simulation domain is taken to be 100 c/ω_p (proton inertial lengths), longer than the wavelength of the instabilities of interest. We only consider the case when $\mathbf{k}\times\mathbf{B}_o=0$, because the instabilities of interest have linear growth rates which maximize at this angle of propagation, as discussed earlier. The calculations also use 128 computational cells, 10000 simulations particles to represent the solar wind protons, and 10 simulation particles injected per time step ($\Omega p \Delta t$=0.1) which corresponds to an injection rate of $\Lambda_b=2.0\times10^{-4}\Omega_p$. This injection rate is higher than that seen experimentally [Neugebauer et al., 1989, 1990] and subsequently the pitch-angle scattering will be faster. The injection rate was chosen so that a dominant mode in the system would be excited quickly not allowing for background noise in the simulation to scatter the protons. One can then identify the modes responsible for the pitch-angle scattering in the quasi-parallel and quasi-perpendicular regime.

All three simulations have the same initial beam velocity, v_{ob}= 5v_A where v_A is the Alfven speed with $v_A/c=10^{-4}$; however, the injection angle is taken as 35, 55, and 85 degrees. The fluctuating magnetic field energy density in the simulations are all in the linear temporal growth regime. We believe pitch-angle scattering is a process which proceeds gradually as a parcel of solar wind plasma approaches the comet, and the quantification of this process is more appropriately done in the context of linear temporal growth regime.

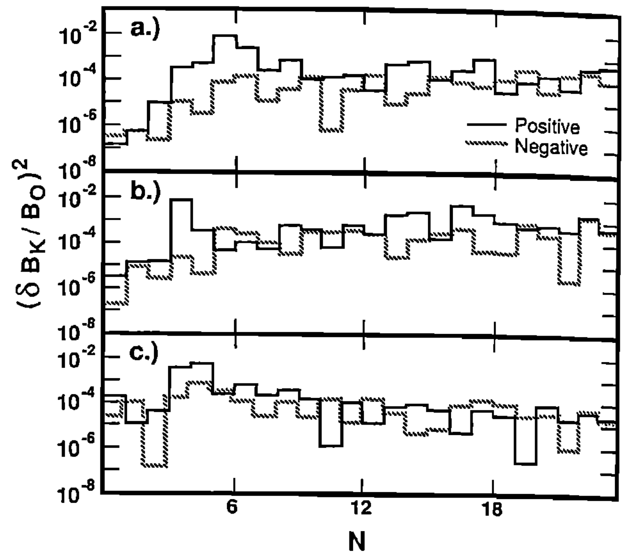

Fig. 1. Fourier spectral plots of the fluctuating magnetic field separated into positive (top histogram) and negative (bottom histogram) helicity components, at Ω_pt=51.2, for an injection angles of (a) 35° and (b) 55° and at Ω_pt=128.0 for (c) α=85°. The initial parameters used in these simulations are $m_b=m_p$, $v_{ob}=5v_A$, $\Lambda_b=2.0\times10^{-4}\Omega_p$, $T_e=T_p$, $\beta_p=1.0$, $v_{op}=0$, $v_A/c=10^{-4}$ with $\Omega_p\Delta t=0.1$, NZ=128, and $L\omega_p/c=100$: b denotes the proton beam population and p represents the proton core constituent and e is for the electrons.

Figure 1 shows the histogram plots of the fluctuating magnetic field for the three injection angles; 35, 55, and 85 degrees. The fluctuating magnetic field has been decomposed into positive (top histogram) and negative (bottom histogram) helicity components. Note that the top curve in each panel has been multiplied by a factor of 100 for clarity. Figure 1a and 1b display results for injection angles of 35 and 55 degrees, respectively, at Ω_pt=51.2. Figure 1c corresponds to an injection angle of 85 degrees and is displayed at a later time in the simulation, Ω_pt=128.0, since the growth rate of the

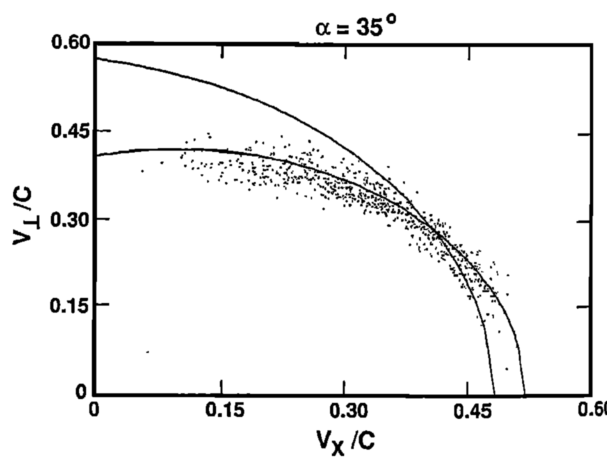

Fig. 2. Pitch angle scattering of newborn ions in velocity space for α=35° at Ω_pt=51.2.

negative helicity component of the ion cyclotron anisotropy instability decreases as a is decreased from 90° [Gary and Schriver, 1987].

In the quasi-parallel regime ($\alpha \leq 60°$), the dominant mode is the ion/ion right-hand resonant instability [Gary et al., 1986, 1988, 1989, Miller et al., 1991; Winske et al., 1984] which has positive helicity and propagates parallel to the beam. Figure 1a shows the Fourier mode, N=6, with positive helicity as the dominant mode at 51.2 Ω_p^{-1}. The corresponding negative helicity modes are much smaller in amplitude and essentially correspond to the level of background of noise. This ion/ion right-hand resonant mode scatters the pick-up ions resulting in a monospherical velocity distribution since there are no waves with scattering centers at $-v_A$. However, running the simulation longer leads to higher beam densities and eventually negative helicity waves with $v_{ph}<0$ due to the development of the nonresonant ion/ion instability [Miller et al., 1991].

Pitch-angle scattering of the beam particles can be seen by displaying the constant energy paths in the wave frame, $(v_{\|} \pm v_{ph})^2 + v_{\perp}^2 = const.$ [Galeev and Sagdeev, 1987], where v_{ph} is the phase velocity of the wave which is scattering the particles. Figure 2 shows the distribution of proton beam particles in velocity space at $\Omega_p t=51.2$ for $\alpha=35°$. The two solid circular lines are the diffusion path for pitch-angle scattering. Most of the particles are scattered forward and backwards along the forward shell which centered around v_A, thus tending towards a monospherical velocity distribution for the pick-up ions.

Figure 1b shows there are two positive helicity modes with comparable relative amplitudes at $\Omega_p t=51.2$ for an injection angle of 55°. The N=4 mode is the left-hand polarized ion cyclotron anisotropy instability with a scattering center at $-v_A$ and N=17 is the ion/ion right-hand resonant instability with a scattering center located at v_A. Again, there are no negative helicity modes of significant amplitude generated at 55° at this time. Figure 3 shows the velocity diffusion paths at $\Omega_p t=51.2$ for $\alpha=55°$. In this case the beam protons have scattered forward on the backward ($-v_A$) shell by ion cyclotron anisotropy modes and scattered backwards on the forward (v_A) velocity shell by ion/ion right-hand resonant modes. The scattering is clearly progressing towards a bispherical distribution.

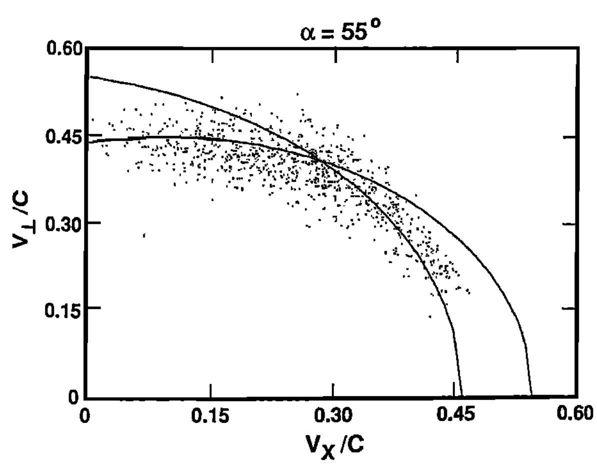

Fig. 3. Pitch angle scattering of newborn ions in velocity space for $\alpha=55°$ at $\Omega_p t=51.2$.

The simulation with an injection angle of 85° differs from the other two simulations presented earlier due to the presence of the negative helicity ion cyclotron waves. Figure 1c shows that the Fourier mode, N=5, of the positive and negative helicity components have the largest relative amplitudes at $\Omega_p t=128.0$. The positive helicity mode has the larger amplitude, consistent with its larger growth rate [Gary and Shriver, 1987; Gary and Madland, 1988] and propagates antiparallel to the beam ($-v_A$) where the negative helicity anisotropy mode propagates parallel to the beam (v_A) [Miller et al., 1991].

Figure 4 shows the velocity distribution for this case at $\Omega_p t=128.0$, at somewhat later times than the other two cases. Again, the beam ions are scattered into a bispherical distribution. The spread of the pitch angle on backward shell in the forward direction is larger than that found on the forward shell in the backward direction. This is a consequence of the larger amplitude of the positive helicity waves.

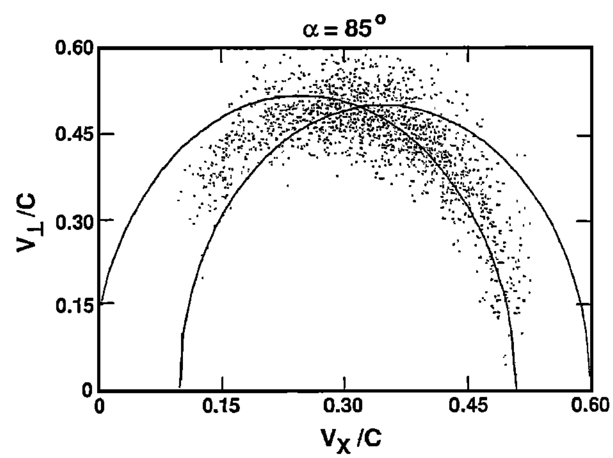

Fig. 4. Pitch angle scattering of newborn ions in velocity space for $\alpha=85°$ at $\Omega_p t=128.0$.

We can also make some quantitative statements concerning the rate of pitch angle scattering from figures 2-4 (and other runs we have carried out). The comparable rate of spreading of the ions by the resonant ion/ion instability for $\alpha=35°$ and 55° (as well as for small α, not shown) suggests the pitch angle scattering rate is nearly constant for $0° \leq \alpha \leq 60°$. The comparable amount of scattering by the anisotropy mode at 55°, in spite of its smaller amplitude and larger diffusion in velocity space at 85° indicate that pitch angle scattering is enhanced for $\alpha>60°$. These results are consistent with the oxygen-ion results of Gary et al. [1991]. The velocity diffusion (perpendicular to the pitch-angle diffusion paths) also increases with α, as is evident from a comparison of Figures 2 and 3. We have also run a number of other cases varying the beam injection velocity. For larger beam velocities, on the order of 7-10v_A, the distribution of pick-up protons becomes bispherical at approximately the same angle, $\alpha \sim$ 45°-55°.

3. Conclusion

In conclusion we have used 1-D electromagnetic hybrid simulations to study the consequences of wave growth due to the injection and subsequent pitch angle scattering of newborn cometary ions. We find two types of velocity distributions result, depending on the injection angle α. For $\alpha<40°$, the distribution of pick-up ions is monospherical. The scattering is due to the ion/ion right-hand resonant instability, which scatters the pick-up ions on the forward velocity shell in both the forward and backward directions.

For $\alpha>40°$, the velocity distributions are bispherical because of the presence of waves propagating along and against the beam direction. However, the source of these waves can be different depending on α. In the quasi-parallel regime, $\alpha\leq60°$, the waves with $v_{ph}>0$ are due to the resonant ion/ion instability, whereas the ion cyclotron anisotropy instability excites left-hand polarized positive helicity waves with $v_{ph}<0$. In the quasi-perpendicular regime ($\alpha>60°$), the ion/ion right-hand resonant instability becomes stable, while the negative helicity ion cyclotron anisotropy instability becomes excited and assumes the role of scatterer for the forward velocity shell.

From our results, we also verify the findings of Gary et al. [1991] that the rate of pitch angle scattering is nearly constant for $\alpha\leq60°$ and becomes larger for $\alpha>60°$. We also conclude that the assumption of Galeev and Sagdeev [1987] and Coates et al. [1990] that the distribution of pick-up ions is bispherical is supported by our simulation results at $\alpha>40°$. Even though our simulations yield monospherical distributions for $\alpha<40°$, the difference between mono- and bispherical distribution is small at these α values. As a consequence, the total bispherical bulk speed derived by Coates et al. [1990] is not significantly changed by the assumption that the distribution of pick-up ions is bispherical for all angles of injection.

Acknowledgments: This work was supported at the University of Michigan by NASA grants NAGW-2162 and NAGW-1366. Research at Los Alamos was done under the auspices of the U.S. Department of Energy and was supported in part by the NASA Research and Analysis Program at the Laboratory.

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T. I. Gombosi and R. H. Miller, Department of Atmospheric, Oceanic and Space Sciences, Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109-2143.

S. P. Gary and D. Winske, Space and Science Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545.

(Received April 4, 1991;
accepted April 11, 1991.)