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Toroidal distributions in the polar wind plasma

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Abstract : The energization of charged particles, due to interaction with electromagnetic turbulence, has an important influence on the plasma outflow in space. The effect of wave-particle interaction (WPI) on O^+ and H^+ velocity distributions in the polar wind was investigated by using Monte Carlo method. The Monte Carlo simulation included the effect of WPI, gravity, polarization electrostatic field, and the divergence of geomagnetic field within the simulation tube (1 7–10 earth radii, *Re*) as the ions are heated due to WPI and move to higher altitudes, the ion's Larmor radius a_L may become comparable to the perpendicular wave length $\lambda_\perp$ of the electromagnetic turbulence. As the ratio $a_l / \lambda_\perp$ becomes $\gtrsim 1$, the quasi-linear perpendicular diffusion coefficient becomes velocity dependent, the heating rate becomes self-limited and the ion ditribution displays toroidal features. This result is consistent with observations of O^+ toroidal distribution in the auroral region.

Keywords : Toroidal distributions, polar wind, auroral region, Monte Carlo simulation

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1. Introduction

The polar wind is an ambipolar outflow of plasma a long 'open' geomagnetic field lines, it is well known that the classical polar wind undergoes four major transitions including a transition from chemical to diffusion dominance, a transition from collision dominated region to collisionless region, and a transition from a heavy to a light ion dominance [1]. In the classical picture of the polar wind, the O^+ ions are gravitationally bounded, and the H^+ ions are continually blown out to higher altitudes where they become supersonic and develop very large anisotropy $(T_\parallel > T_\perp)$ [2] Several studies were devoted to include the non-classical features of the polar wind. The escape flux of O^+ was found to be greatly enhanced due to elevated electron temperature, elevated ion temperature, and energetic magnetosphere electrons [3, 4]. Wu *et. al* [5] used European Incoherent Scatter (EISCAT) VHF radar to study the vertical flux of O^+ and H^+ ions in the topside high-latitude ionosphere; they were able to determine the vertical velocities and fluxes of the H^+ and O^+ ions

Theoretical studies [6,7] indicated that the polar wind could become unstable. Significant levels of electromagnetic turbulence were observed, for example, by the plasma wave instrument (PWI) aboard the Dynamics Explorer 1 (DE1) satellite [8]. The ion heating due to ion cyclotron resonance with these turbulences has an important effect on the escape of the heavy ionospheric ions into the magnetosphere.

In a series of papers [9-12], Monte Carlo simulation has been used to investigate the effect of Wave-Particle Interactions (WPI) on the O^+ velocity distribution at 2 *Re* in the auroral region. The model they adopted, ignored the effect of body forces (gravitational and polarization electrostatic) and assumed an altitude, and velocity independent perpendicular diffusion coefficient $(D_\perp)$. They obtained the conic distribution for O^+ ions.

Another series of papers [13-17], used a Monte Carlo approach to study the effect of wave-particle interactions (WPI) on the H^+ and O^+ outflow in the polar wind and in the auroral region. As the ions drift upward along the geomagnetic field lines, they interact with the electromagnetic turbulence and, consequently get heated in the direction perpendicular to the magnetic field. The mirror force converts some of the gained ion energy in the perpendicular direction into parallel kinetic energy. These effects combine to form an ionconic distribution. They

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included the effect of body forces and an altitude-dependent perpendicular diffusion coefficients ($D_\perp$). They found the effect of body forces is more important in the polar wind case and for O^+ ions than it is for the auroral region and the H^+ ions respectively, O^+ ions were preferentially energized in both regions, and H^+ and O^+ were energetic in the auroral region at most altitudes.

The above mentioned studies that handled WPI, used Retterer *et al* [12] form for the perpendicular diffusion coefficients $D_\perp$ which is velocity independent, and Barghouthi [17] form for $D_\perp$ which is altitude dependent.

In this study, we computed new form of the perpendicular diffusion coefficients $D_\perp$ and we found it is velocity and altitude dependent. We used this new $D_\perp$ to investigate the effect of WPI on the H^+ and O^+ velocity distribution in the polar wind plasma.

2. Theoretical formulation

The interaction between the ions and the electromagnetic ion cyclotron waves can be represented by particle diffusion in the velocity space : that is ;

$$\left(\frac{\delta f}{\delta t}\right)_{WPI} = \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp} D_\perp v_\perp \frac{\partial f}{\partial v_\perp} \qquad (1)$$

where $D_\perp$ is the quasi-linear velocity diffusion rate perpendicular to the geomagnetic field lines. The perpendicular diffusion rate for resonant wave particle interaction with a spectrum of electromagnetic turbulence is given by the following expression [12]

$$D_\perp = \frac{q^2}{m^2}\sum_{n=-\infty}^{\infty}\int\frac{d\omega}{2\pi}\int\frac{d^3k}{(2\pi)^3}\left[\frac{n\Omega}{\omega}\right]^2 A_n\pi\delta(\omega - n\Omega - k_\parallel v_\parallel) \qquad (2)$$

with

$$A_n = \frac{1}{2}J_{n-1}^2|E_L|^2(k,\omega) + \frac{v_\parallel J_n^2}{v_\perp}|E_\parallel|^2(k,\omega) + \frac{1}{2}J_{n+1}^2|E_R|^2(k,\omega). \qquad (3)$$

In these equations, q is the ion's charge, m is the ion's mass, ω is the angular frequency, k is the wave vector, Ω is the ion gyrofrequency, $J_n = J_n\left(\frac{k_\perp v_\perp}{\Omega}\right)$ is the standard Bessel function. $|E_L|^2$ and $|E_R|^2$ are the spectral densities of the electric field in the two perpendicular polarizations.

To simplify $D_\perp$, Retterer *et al* [12] assumed $k_\parallel v_\parallel << \Omega, n = 1$ and $\frac{k_\perp v_\perp}{\Omega} << 1$, and found that

$$D_\perp = \frac{\varsigma q^2}{4m^2}|E_x|^2(\omega = \Omega), \qquad (4)$$

where $|E_L|^2(\omega) = \varsigma|E_x|^2(\omega)$, $|E_x|^2$ is the measured spectral density of the wave, and ς is the proportion of the measured spectral density by plasma wave instrument (PWI) on board DE-1 satellite that corresponds to a left-hand polarized wave.

It is worth while to point out that $D_\perp$ is species-dependent since both m and Ω depend on the type of the ion. Retterer *et al* [12] assumed $k_\perp v_\perp << \Omega$ (*i.e.* the ion Larmor radius a_L to be much less than the perpendicular wavelength $\lambda_\perp$ of the electromagnetic turbulence). However, as an ion drifts upward along a geomagnetic field line, it heats up due to WPI, and geomagnetic field intensity B decreases, the combined effect of these two factors results in a rapid increases in a_L with altitude. At higher altitudes, the Larmor radius a_L may become comparable to or even more than $\lambda_\perp$ and consequently $\frac{k_\perp v_\perp}{\Omega}$ becomes greater than 1, and hence the velocity independent expression for $D_\perp$ given in eq. (4) becomes inaccurate. At these altitudes, we need to modify the form of the diffusion coefficient $D_\perp$. To do this, we divide the general form of $D_\perp$ as given in eq. (2) by the simplified form given in eq. (4) to obtain a ratio denoted by R:

$$R = \frac{\frac{q^2}{m^2}\sum_{n=-\infty}^{\infty}\int\frac{d\omega}{2\pi}\int\frac{d^3k}{(2\pi)^3}\left[\frac{n\Omega}{\omega}\right]^2 A_n\pi\delta(\omega - n\Omega - k_\parallel v_\parallel)}{\frac{\varsigma q^2}{m^2}|E_x|^2(\omega = \Omega)} \qquad (5)$$

We now plot the ratio R against the argument of Bessel function $\left(\frac{k_\perp v_\perp}{\Omega}\right)$ as shown in Figure 1. When the argument $\left(\frac{k_\perp v_\perp}{\Omega}\right)$ is less than 1, the ratio R is one which means that $D_\perp$ needs no modification, and we reproduce Retterer *et al* [12] form, but as the argument $\left(\frac{k_\perp v_\perp}{\Omega}\right)$ becomes greater than 1 then

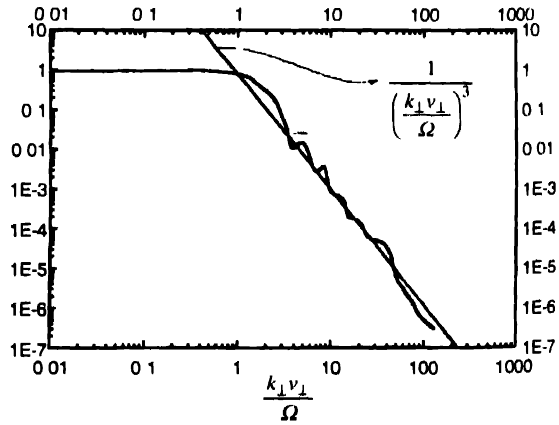

Figure 1. The ratio given in eq. (5) *versus* $\frac{k_\perp v_\perp}{\Omega}$. The straight line is the adopted dependence of the ratio R when $\frac{k_\perp v_\perp}{\Omega}$ greater than 1.

the ratio decreases as $\left(\frac{k_\perp v_\perp}{\Omega}\right)^{-3}$. Therefore when $\frac{k_\perp v_\perp}{\Omega} \geq 1$ we need to multiply $D_\perp$ given in eq. (4) by $\left(\frac{k_\perp v_\perp}{\Omega}\right)$. As we mentioned earlier, $\frac{k_\perp v_\perp}{\Omega} > 1$ at higher altitudes. The modified form of the diffusion coefficient is consistent with the suggested form given by Crew and Chang [18].

3. Monte Carlo model

The Monte Carlo model used in this study is described in details by Barghouthi [17]. Only a brief description is given here with emphasis on new features relative to the model adopted in Refs. [11,12]. We considered the steady state flow of a three components plasma composed of H^+, O^+ and the electrons. The simulation region was a geomagnetic tube extending from the exobase $r_0 = 1.7$ Re to 10 Re. The ions were injected at r_0 with velocity consistent with a drifting Maxwellian distribution function. The ion motion was followed for a 'small' time interval (Δt) as it moved under the effect of gravity (g), polarization electric field (E_p), and diverging geomagnetic field B. The influence of WPI during Δt was simulated by incrementing the ion's velocity ($v_\perp$) perpendicular to $\boldsymbol{B}$ by a randomly chosen $\Delta v_\perp$ [17] such that

$$\left\langle (\Delta v_\perp)^2 \right\rangle = 4 D_\perp \Delta t \qquad (6)$$

According to eq. (4), the dependence of $D_\perp$ on altitude is due to the dependence of Ω on altitude. Barghouthi [17] computed an altitude dependence form for $D_\perp$ by analyzing experimental data collected by PWI instrument on board DE-1 satellite. In this paper, we used $D_\perp$ from Barghouthi [17] *i.e.*

$$D_\perp(H^+)\left[cm^2 \sec^{-1}\right] = 5.77\times10^3 \left(\frac{r}{Re}\right)^{7.95}, \qquad (7)$$

$$D_\perp(O^+)\left[cm^2 \sec^{-3}\right] = 9.55\times10^2 \left(\frac{r}{Re}\right)^{13.3} \qquad (8)$$

and whenever $\frac{k_\perp v_\perp}{\Omega} \geq 1$, we multiplied the above altitude dependent $D_\perp$ by its velocity dependence $\frac{k_\perp v_\perp}{\Omega}$.

In the simulation, a large number of test ions (10^5) were followed (one at a time) as they moved until they exit the simulation region. The O^+ and H^+ velocity distribution functions were computed at different altitudes. Since the data collected by the PWI do not include information about $\lambda_\perp$. We considered a wide range ($\lambda_\perp = 1, 10, 100$ km) that covers the conditions expected to occur above the polar cap.

4. Results

Now, we report the effect of self-limiting heating on O^+ and H^+. In Figure 2, the top panel shows the O^+ velocity distribution $f(O^+)$ and the bottom panel shows the H^+ velocity distribution $f(H^+)$ at 10 Re for $\lambda_\perp = 1$ km. At high altitudes, the distribution function displays toroidal features. This toroidal shape can be explained if we remember that $D_\perp$ peaks near $\frac{k_\perp v_\perp}{\Omega} \approx 1$ and decreases rapidly for large values of $\frac{k_\perp v_\perp}{\Omega}$ as shown in Figure 1. Therefore the O^+ ions tend to move out of the region of large diffusion ($k_\perp v_\perp/\Omega < 1$) and accumulate in the region of relatively low $D_\perp$, $k_\perp v_\perp/\Omega > 1$ forming the aforementioned toroidal distributions. The toroidal features for O^+ ion distribution appear earlier at 4.3 Re, and they are well pronounced at 10 Re. However, H^+ toroidal features appear at 10 Re. The O^+ ions are heated more efficiently than H^+ ions, especially at low altitudes due to pressure cooker effect [13]. The argument $\frac{k_\perp v_\perp}{\Omega}$ approaches 1 for O^+faster than H^+, consequently, O^+ ions get heated before H^+ ions and their toroidal features appear at low altitude. In an on-going study, the above mechanism may be the first theoretical explanation of the O^+ toroidal observations in the auroral region [19].

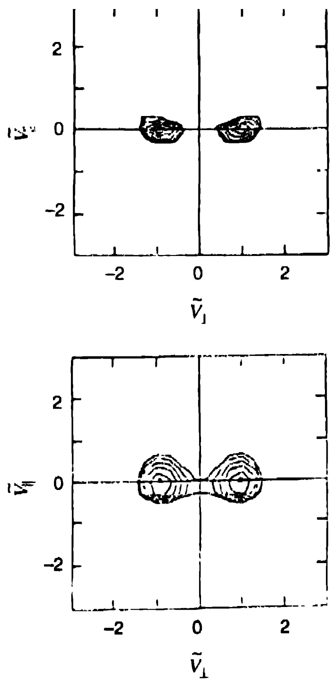

Figure 2. The top panel shows the O^+ velocity distribution $f(O^+)$ and the bottom panel shows the H^+ velocity distribution $f(H^+)$ at 10 Re for the electromagnetic turbulence wavelength $\lambda_\perp = 1$ km $f(H^+)$ and $f(O^+)$ are represented by equal-value contours in the normalized velocity$(\tilde{v}_\parallel, \tilde{v}_\perp)$ plane, where

$$\tilde{v}(H^+) = \left[v(H^+)\right] / \left[2KT(H^+)/m(H^+)\right]^{1/2}$$

and

$$\tilde{v}(O^+) = \left[v(O^+)\right] / \left[2KT(O^+)/m(O^+)\right]^{1/2}.$$

The contour levels decrease successively by a factor $e^{1/2}$ from the maximum (marked by dot).

5. Conclusion

In conclusion, the effect of self-limiting heating on $f(H^+)$ and $f(O^+)$ velocity distribution functions was studied for conditions representative of the polar wind. We used the Monte Carlo simulation for polar wind, in addition to WPI, we considered the body forces (gravitational and polarization electrostatic) and the divergence of geomagnetic field [17]. As the ions were heated at high altitudes, their gyro-radius a_L increases and exceeds the wavelength $\lambda_\perp$ of the electromagnetic turbulence. This result in a velocity and altitude-dependent quasi-linear perpendicular diffusion coefficient $D_\perp$. The effect of the above phenomena (*i.e.* self-limiting heating) was investigated at 10 *Re* and for $\lambda_\perp$ = 1km. Finally, we have illustrated the process of toroidal formation through self-limiting heating by electromagnetic turbulence ($\lambda_\perp$ = 1 km). We explicitly considered H^+ and O^+ ions in the calculations presented here.

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