GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 23, PAGES 2289-2292, DECEMBER 2, 1992

ANISOTROPIC ION HEATING AND PARALLEL O^+ ACCELERATION IN REGIONS OF RAPID E x B CONVECTION

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Abstract. A numerical solution to the 20-moment set of transport equations has been found in order to study subauroral ionospheric outflows during periods of enhanced perpendicular ion drifts. The numerical model solves the time-dependent O^+ density, momentum, and both the parallel and perpendicular energy and heat flow equations in the 200–6000 km altitude range. Assuming perpendicular drifts of 3 km/s relative to the neutral atmosphere, we have found that anisotropic heating of O^+ (a result of ion-neutral collisions) leads to a temperature anisotropy, with perpendicular temperatures exceeding 8000 K and parallel temperatures greater than 5000 K (near 200 km altitude). Above approximately 2000 km, transport processes dominate the effects of collisions and wavelike oscillations in O^+ velocity, temperature and heat flux were noted.

Introduction

Since the discovery of O^+ ions in the magnetosphere by Shelley et al. [1972], a great deal of interest has been placed on understanding the ionospheric sources of these ions. The classical polar wind [Axford, 1968] is not likely to be a major contributor of O^+ ions to the magnetosphere, because the thermal energy of these ions is insufficient for a significant fraction of them to escape the gravitational attraction of Earth. Ion outflows frequently contain a heated component [Gurgiolo and Burch, 1982] and this also suggests an additional energization source. Upward ion beams with energies exceeding 0.5 keV were first observed by the ion mass spectrometer on the S3-3 satellite [e.g., Ghielmetti et al., 1978] and acceleration of ions transverse to the magnetic field has also been inferred from observations of ion conics [Sharp et al., 1977].

There are even indications that some energization of O^+ occurs at relatively low altitudes in the ionosphere. Observations of upward ion velocities, associated with subauroral ion drift (SAID) events reaching 1000 m/s near 400 km altitude have been reported by Anderson et al. [1991]. These drifts events were colocated with narrow regions of rapid (4 km/s) convection. Lockwood et al. [1985] mapped ion trajectories from the high-altitude cleft ion fountain down to a low-altitude ion upwelling observed by the DE-2 spacecraft. Yeh and Foster [1990] published Millstone Hill radar observations during a large magnetic storm when the cleft region reached that latitude. They observed heavy ion outflows exceeding 3 km/s at 1000 km altitude. There are similar observations in the auroral region [e.g., Wahlund et al., 1992], though they may be influenced by precipitation fluxes and by high convection velocities.

Several mechanisms are proposed for the energization of O^+. Ion outflows observed in conjunction with large perpendicular electric fields are likely to be a result of frictional heating caused by a relative drift between O^+ and the neutral atmosphere [e.g., Jones et al., 1988; Sellek et al., 1991]. This heating can lead to anisotropic ion distributions if the relative drift is of the order of the neutral thermal speed (see review by St-Maurice and Schunk [1979]). Perpendicular acceleration associated with observations of ion conics is believed to be due to ion cyclotron waves [e.g., Sharp et al., 1977; Whalen et al., 1978] or lower hybrid waves [e.g., Retterer et al., 1986]. Slow electric field fluctuations may also be responsible for the acceleration O^+ [e.g., Hultqvist et al.,, 1988]. Another mechanism may be parallel electric fields associated with anomalous resistivity [e.g., Papadopolous, 1977], in regions of field-aligned current.

Description of the Model

In order to better understand the physical processes leading to the heating and subsequent expulsion of O^+ ions into the magnetosphere, we have developed a numerical model describing plasma transport in regions where anisotropic velocity distributions may arise [Körösmezey et al., 1992]. This model solves the 20-moment set of generalized transport equations [e.g., Gombosi and Rasmussen, 1991] to describe the time-dependent transport of O^+ density, field-aligned velocity , ion and electron parallel and perpendicular temperatures, and parallel and perpendicular heat fluxes, in one dimension along the magnetic field . For these equations to be valid the magnetic field must be large enough so that the gyration period for ions is much smaller than any other time scales of interest, including the collisional ones. This means that the ion distribution is always gyrotropic. The numerical method used is an extension of high-order Godunov schemes and is third-order accurate in space and second-order accurate in time [see Körösmezey et al., 1992].

Although models based on moment-expansions have limitations as they can not describe fine details of distribution functions, they can describe the most important properties even in regions where kinetic models are not suitable because of very short mean free paths. Demars and Schunk [1991] have demonstrated good agreement between the results of a polar wind model based on the 16-moment set of equations and another one using a semikinetic simulation up to altitudes of 12,000 km. For the specific purpose of the present paper we expect our technique be adequate as long as the convection

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Paper number 92GL02489
0094-8534/92/92GL-02489$03.00

velocity is not large enough to form conic ion distributions. A drawback of the present model is that we neglect the presence of H^+ ions. This can effect our results at higher altitudes and we are planning to incorporate them in a later version of the model.

What makes the model unique is the wide parameter regime in which it is applicable. Moments of the O^+ distribution function are calculated from 200 km to 6000 km (or higher) in altitude. A special numerical technique [described in Rasmussen and Greenspan, 1992] is employed to handle the stiff charged particle–neutral collision terms at low altitudes. The collisions terms that were employed are specified in Gombosi and Rasmussen [1991] with two notable exceptions:

(1) To calculate the total collision frequency we use equation (42) of Gombosi and Rasmussen [1991] with the mass ratio omitted. With this correcton the relaxation model used by that paper gives comparable results to a more accurate model for low-speed isotropic flows.

(2) The energy transfer collision terms of Konikov and Khazanov [1982] were adopted to permit anisotropic heating due to the ion-neutral drag force.

Because the lower boundary is at 200 km, boundary conditions here are relatively straightforward: O^+ density was assumed to be in photochemical equilibrium; the field aligned velocity and temperatures were set equal to the those of the neutrals, which were obtained from the MSIS-86 empirical model [Hedin, 1987]; and heat fluxes were assumed to be zero. At the upper boundary, fewer boundary conditions are required, because typically, all but one of the ion Mach numbers are greater than one. At the upper boundary, an O^+ density gradient of 6%/100 km was assumed and the parallel and perpendicular electron heat fluxes were assumed to be 6×10^{-3} and 2×10^{-3} erg cm^{-2} s^{-1}, respectively.

Results

Initial values for the start of the model run were obtained from equilibrium O^+ distributions near local noon at 290° geographic longitude for an L-shell of $L = 5$. The footprint of the modeled tube of plasma was then allowed to corotate with the Earth until 2400 LT, at which time a 3 km/s westward drift (turned on with a 10 minute transient time) was applied. The westward drift was maintained until the tube of plasma reached sunlight again, near 1800 LT.

The F-peak O^+ density (hmF2) is decreasing in time even before the start of rapid westward convection due to recombinaton processes and the lack of photoionization. The recombination is accelerated by the turn-on of rapid convection partly due to the higher O^+ temperatures partly due to the large ion-neutral velocity difference [Schunk et al., 1975], we note that hmF2 decreases nearly an order of magnitude to 2×10^4 in about 35 minutes.

Profiles of ion and electron temperatures are shown in Figure 1 at 0439 UT, at the starting time of westward convection (denoted by $t = 0$ in the figure) and 23 minutes later. It is seen that initially electron temperatures are higher than ion temperatures at all altitudes. Electron temperatures were found to be relatively constant during the model run and are not discussed further.

The initial ion temperature increases with altitude from 200 to roughly 1300 km as a result of collisions with the electron population. Above 2500 km the ion temperature decreases and $T_{i\perp}$ becomes somewhat higher than $T_{i\|}$. The decrease in ion temperature is primarily a result of a nearly adiabatic expansion of the plasma as O^+ is accelerated upward.

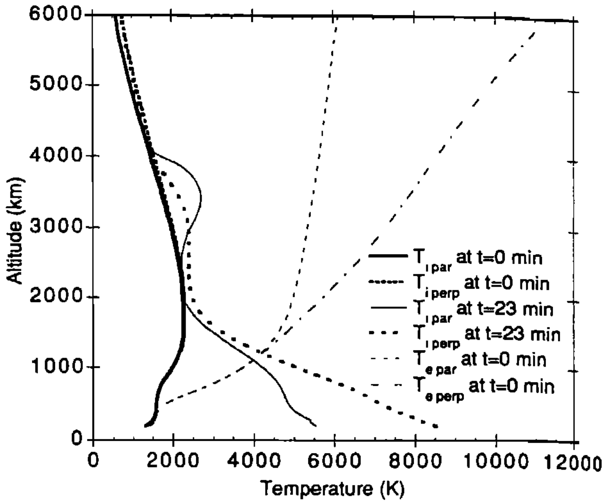

Fig. 1. Profiles of ion and electron temperature just prior to the onset of enhanced convection and 23 minutes after convection began.

At the onset of westward convection, both the parallel and perpendicular ion temperatures increase rapidly with time and remain relatively constant thereafter. In the region of frictional heating, $T_{i\perp}$ is greater than $T_{i\|}$ because the heating rate is larger in the perpendicular direction. Examining the different terms in the energy equations reveal (see Figure 2) that the heating caused by the neutral drag is almost fully compensated by Coulomb collisions with ions and electrons. Other terms, like convective derivates or heat flows contribute only about 10–15%. The $t = 23$ min curves of Figure 1 show that the ion anisotropy is largest near the lower boundary, where it is roughly equal to 2. Above 200 km, the anisotropy decreases with increasing altitude as a result of the effects of Coulomb collisions. Note, however, that the O^+ distribution is never completely isotropized; even at 1200 km a small ion anisotropy

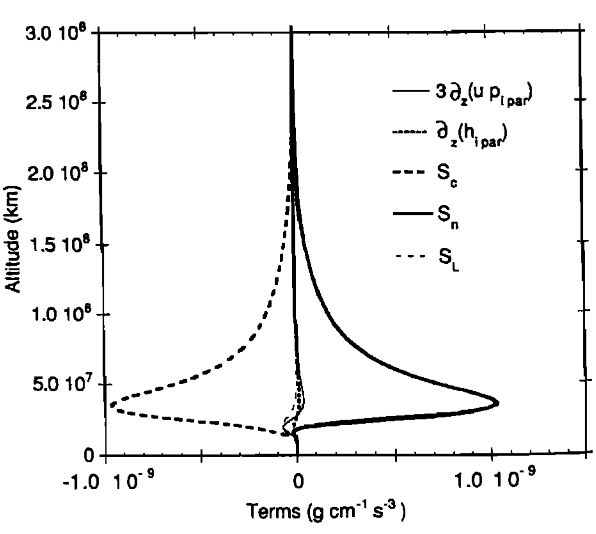

Fig. 2. Dominant terms in the parallel ion energy equation. S_c, S_n and S_L are the sources corresponding to Coulomb collisions, ion-neutral collisions and ion loss/creation processes, respectively.

exists. Above 2000 km the temperature variations are due to a wave front propagating upward.

The upward propagating wave can clearly be seen in Figure 3, where velocity profiles are shown at 5 different times. At $t = 0$ ion velocities are mostly downward below 3000 km, as a result of ion losses at the bottom of the tube of plasma. At $t = 5$ min, frictional heating has accelerated ions upward to a peak velocity of about 100 m/s near 900 km. As the wave front created by the heating propagates upward, ions within the wave are continually accelerated. By $t = 23$ min the wave front has reached 3000 km with a peak velocity of nearly 1000 m/s. Eventually the wave progresses through the simulation domain and leaves the system through the upper boundary (not shown). At $t = 23$ min, ion velocities are downward below about 700 km. Ion velocities down the field line are driven by a downward pressure gradient which exists below the F-region peak. The downward velocity is seen to increase with time because rapid decay of the F region increases the downward pressure gradient.

Another run with 4 km/s drift velocity was also modeled. This yielded about 50% higher temperatures at 200 km. The outflow velocity exceeded 2 km/s at 3000 km and an outward moving shock wave was created at that altitude. Like in the run with 3 km/s drift velocity, the flow velocities were downward below 700 km. We must note, however, that even though the results seem to be realistic Winkler et al. [1992] has shown that the O$^+$ distribution function becomes toroidal at this high ion-neutral relative velocity and our moment expansion is not valid anymore. Therefore we concentrate on the physically well-established 3 km/s drift results and indicate only the possible effect of higher drift speeds.

Discussion

A clear outcome of the modeling effort is that ion velocities are downward throughout much of the F-region ionosphere. This is true especially after the pulse of upwelling ions has had time to propagate to substantial altitudes. Observations, however, indicate that ion acceleration and upward flows can exist at relatively low altitudes in the F region [e.g., Anderson et al., 1991; Yeh and Foster, 1990]. Sellek et al. [1991] used a hydrodynamic model to examine the effects of large zonal plasma drifts on the subauroral ionosphere and obtained similar results, namely, that ion drifts are downward below about 400 km. They suggested two possible explanations for the differences between the observations and their results: (1) the initial F layer height in their model may have been too high; and (2) Joule heating may have caused an upwelling of the neutral atmosphere which would have provided an additional upward momentum source for the ions. Recent observations have shown that it is unlikely that an error in the modeled height of the F layer is the explanation; Wahlund et al. [1992] observed ion upflows of around 100 m/s below 500 km, where the pressure gradient was downward. They found that an additional momentum source of approximately 1.5×10^{13} kg m^{-2} s^{-2} at 400 km was needed to explain the observed ion upflows. Although this is auroral observation, the subauroral region is similar in many respects: Anderson et al. [1991] found even higher upward velocities (900 m/s) at 400 km.

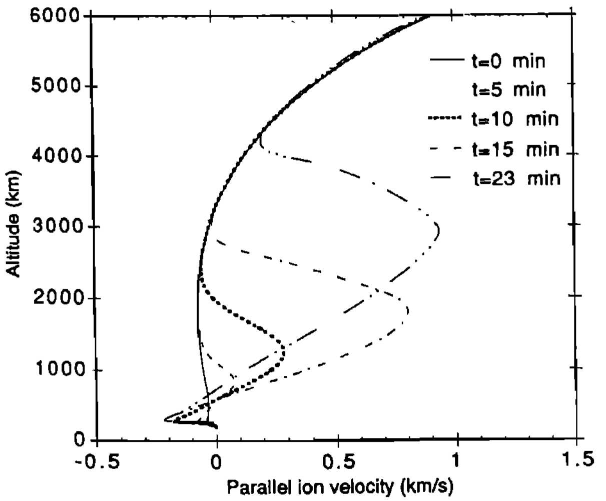

Fig. 3. A series of ion velocity profiles at 5 different times. Positive velocities are upward and in the direction of the magnetic field.

Sellek et al. [1991] expected that an upward neutral air upwelling due to E-layer Joule heating could change the flow direction of the plasma below 400 km. To model this scenario a 75 m/s upward neutral wind was added during the drift event. There was no noticable difference in our results.

Increasing the westward drift velocity to 4 km/s raises the perpendicular ion temperature to about 1.3×10^4 K and increases the slope of the ion velocity profile yielding a peak outflow velocity around 400 m/s at 1000 km altitude but leaves the profile unchanged below 700 km.

Our parallel and perpendicular ion temperatures compare favorably with the observations of Anderson et al. [1991] who reported ion temperatures exceeding 10^4 K during a SAID of 4 km/s. Ion temperatures depend strongly on the magnitude of the perpendicular drifts, thus, Wahlund et al. [1992] observed substantially lower ion temperatures of about 2800 K in conjunction with perpendicular drifts approaching 2 km/s (ion temperature anisotropies with $T_{i\perp} > T_{i\parallel}$ were also observed during this time). Sellek et al. [1991] assumed 2 km/s drifts in their study and predicted ion temperatures somewhat above 4000 K.

Sellek et al. [1991] found that ion temperature decreased with altitude between 250 and 750 km altitude, as do the temperature profiles reported here (see Figure 1). However, Yeh and Foster [1990] found that ion temperature increases with altitude in the 200–800 km range. This is another indication that physical processes are present in nature which are not included in the models.

There are strong indications that enhanced perpendicular drifts of this magnitude are relatively short-lived. Anderson et al. [1991] found SAID lifetimes to be less than 3 hours, although the time that any one tube of plasma spends within the region of enhanced drifts is likely to be much less than this. Tsunoda et al. [1989] found that the average latitudinal width of the observed thermal-ion upwellings (at 800 km in the vicinity of the dayside cleft) was only about 4°, on the average. Thus, plasma on convection paths traveling through the region of upwellings, would only be heated for a short period of time. The impulsive nature of these strong heating events suggests that the temporal evolution of ion upflows along field lines would be transient in nature, with a wavelike pulse of ions created, propagating upward along a field line. This is substantially the signature seen in Figure 3. However, we note that a transient pulse is created, even if heating is constantly applied and is not turned off after a period of time, as seen in Figure 3.

The temperature anisotropy produced at lower altitudes by frictional heating leads to an upward force on the ions. For the temperature profiles shown Figure 1, the maximum value this force attains is approximately 5–10% of gravity. A similar estimate was made by Suvanto et al. [1989]. Sellek et al. [1991] estimated the effect that a 10% reduction in gravity would have on their modeled results and found little effect. Thus, for the results shown here, the temperature anisotropy has little effect on the ion density and velocity.

Gombosi and Killeen [1987] modeled the effect of frictional heating on the polar wind using a 5-moment approach. Their results are consistent with the present calculations but it is hard to draw concluison about the difference between the 5-moment and 20-moment approaches, as they have used dayside ion densities and different heating rates.

Acknowledgements. This research was supported in part by NASA grants NAGW-2162 and NAGW-1619, and NSF grant ATM-9114409.

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(Received: August 18, 1992;
Accepted: September 30, 1992)