Large-Scale Counterstreaming of H^+ and He^+ Along Plasmaspheric Flux Tubes

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An interhemispheric plasma transport model has been used to study the flow characteristics of H^+ , He^+ , and O^+ along closed geomagnetic field lines for solstice conditions at noon local time. The calculations were carried out for the flux tube that passes through Millstone Hill. Both symmetric and asymmetric neutral winds in the conjugate ionospheres were considered. Initially, the flux tube content was partially depleted, and the subsequent refilling was studied until a steady state flow was established between the winter and summer hemispheres. The main conclusion to be drawn from this study is that H^+ - He^+ counterstreaming can be expected along a large segment of a plasmaspheric flux tube at solstice. For both symmetric and asymmetric wind patterns, the He^+ flow is from the winter to the summer ionosphere not only in the steady state, but during flux tube refilling owing to the winter helium bulge and the depletion of N_2 . For symmetric poleward neutral winds in both hemispheres, H^+ and O^+ flow up from the conjugate ionospheres during flux tube refilling, which leads to large-scale H^+ - He^+ counterstreaming in the summer hemisphere. In the steady state, both H^+ and He^+ flow from the winter to the summer ionosphere and no light-ion counterstreaming occurs. When the neutral wind in the summer hemisphere is set to zero, which acts to reduce the F region 'winter anomaly,' H^+ - He^+ counterstreaming occurs in the summer hemisphere during refilling and along the entire flux tube in the steady state. The H^+ and He^+ counterstreaming velocities obtained are too small to excite plasma instabilities, but large enough to be measured.

1. INTRODUCTION

Since the incoherent scatter measurements of H^+ - O^+ counterstreaming on closed geomagnetic field lines by Vickrey *et al.* [1976, 1979a], considerable attention has been given to this subject. The counterstreaming, with H^+ downward and O^+ upward, was measured in the topside ionosphere above Arecibo near twilight. Subsequent modeling efforts by Bailey *et al.* [1977a, b; 1979] for a flux tube refilling situation have shown that such counterstreaming is primarily a nighttime phenomenon. However, Young *et al.* [1979] showed that this type of counterstreaming should also occur in the steady state under conditions of field tube symmetry if the ion and neutral temperatures are not equal. More recently, Bailey [1980] has shown the H^+ - O^+ counterstreaming, with H^+ downward and O^+ upward, should occur in the topside ionosphere above Arecibo during most of the day at equinox near sunspot maximum, which is in general agreement with the measurements of Vickrey *et al.* [1979b]. Since the different modeling efforts were for different conditions, the main conclusion to be drawn is that H^+ - O^+ counterstreaming is a common feature of the mid to low latitude ionosphere.

The purpose of this paper is to show that large-scale H^+ - He^+ counterstreaming should also occur on closed geomagnetic field lines at solstice both during flux tube refilling and in the steady state. The interhemispheric plasma transport model used in this study is based on a low-speed collision-dominated formulation of the ion

transport equations, and therefore, only a partially depleted flux tube condition could be modeled. For large density depletions, such as those following magnetic storms, supersonic flow and collisionless plasma characteristics are expected on depleted flux tubes [cf. Schulz and Koons, 1972; Singh and Schunk, 1983], which invalidates our interhemispheric transport model.

2. INTERHEMISPHERIC MODEL

The model, which has been described in detail by Young *et al.* [1980a, b], uses a Newton iterative procedure to minimize the functions

$$F_i(n_i, n_{3-i}) = Q_i - L_i - \frac{\partial n_i}{\partial t} - B V \cdot \left(\frac{n_i V_i}{B} \right) \quad (1)$$

where $i = 1, 2$, Q_i is the sum of the production processes for ion i , L_i is the sum of the loss processes for ion i , B is the magnetic field strength, and V_i is the velocity of ion i . The velocities of the ions are obtained from the diffusion and heat flow equations for the midlatitude topside ionosphere presented by St.-Maurice and Schunk [1977].

Young *et al.* [1980a, b] were able to solve these equations throughout the entire plasmasphere from 120 km in one hemisphere to 120 km in the other hemisphere by introducing the flux preserving concept. This technique allowed for an arbitrary choice of step size so that the large distances in the plasmasphere could be covered in a single spatial step. This procedure significantly improves the stability of the solution and is especially helpful in starting the solution procedure from poor initial conditions. However, all the calculations in this paper were performed throughout the plasmasphere on a variable spatial grid. The grid point spacing varied

smoothly from 5 km at 120 km to several thousand kilometers near the equatorial plane. In the interest of economy, the solution of the equations for the three ions was carried out in 2 steps. First the coupled O^+ and H^+ equations were solved simultaneously for densities and velocities. Then, the coupled He^+ and H^+ equations were solved simultaneously for densities and velocities.

Since O^+ is not a minor ion for a significant portion of the altitude region over which the He^+H^+ solution is obtained, two O^+ terms were included in the He^+ and H^+ momentum equations. These terms were the O^+H^+ and O^+He^+ collision and thermal diffusion terms [St.-Maurice and Schunk, 1977]. Also, O^+ affects H^+ and He^+ through its contribution to the electron density. Extensive tests were carried out to make sure that differences in the densities of H^+ between the two solutions resulted from the presence of He^+ rather than program problems. It was found that when He^+ was an insignificant minor ion the H^+ densities obtained from the O^+H^+ portion of the model were in excellent agreement with the H^+ densities and velocities obtained from the H^+He^+ portion of the model. When He^+ was not an insignificant minor ion, its influence on the H^+ densities and velocities was approximately in proportion to its significance. That is, if the equatorial He^+ density is 10% of the equatorial H^+ density, the effect on the H^+ densities and velocities is about 10%.

One of the aims of this paper is to show how small changes in the electron and ion temperature profiles can affect the O^+ velocity in the equatorial plane. In this paper the electron and ion temperatures have been obtained by solving the time dependent energy flow equations by using the method described by Young *et al.* [1980a, b]. The ions were assumed to have a common temperature. The electron and ion temperatures are somewhat arbitrary because of the uncertainty in the electron heating rates, especially in the plasmasphere. No suitable method currently exists for calculating the amount of plasmaspheric heating due to photoelectrons which escape the ionosphere. The plasmaspheric electron heating rates used in this study were obtained by assuming that half of the escaping electrons are trapped in the plasmasphere and lose their energy there.

The calculations were carried out for the field line that passes through Millstone Hill ($L = 3.2$). This is the longitude of maximum latitudinal displacement of the magnetic and geographic poles. Although Millstone Hill is at a latitude of $40^\circ N$, its conjugate point is $60^\circ S$. The neutral atmosphere was obtained from the MSIS model [Hedin *et al.* 1977a, b] for $AP = 12$ and $F10.7 = 150$. Although the equations were solved in a time-dependent mode, the neutral atmosphere was kept constant for noon conditions.

2.1. Basic Chemistry

For O^+ , He^+ , and H^+ , the dominant photochemical reactions in the plasmasphere are

where the photoionization frequencies and chemical rate coefficients are given in the reviews by Torr and Torr [1982] and Schunk and Nagy [1980].

To some extent, the sources and sinks of ionization listed above can explain the direction of the ion flow in a given hemisphere. For example, at noon and for steady state conditions the O^+ flux reverses its direction at about 600 km. That is, below 600 km the O^+ ions produced by photoionization diffuse downward to the low altitude sink provided by the molecular neutrals, while above 600 km they diffuse upward to the high altitude sink provided by neutral hydrogen [cf. Schunk and Walker, 1972]. However, when the ion densities vary with time or when there is an appreciable interhemispheric flow, the determination of the ion flow direction is more complicated. This topic will be discussed in more detail in a later section.

2.2. Neutral Atmosphere

Figure 1 shows the neutral atmosphere composition used in this solstice interhemispheric study. The northern winter hemisphere and southern summer hemisphere densities are shown as solid and dashed curves, respectively.

Fig. 1. Neutral densities versus altitude for both the winter (solid curves) and summer (dashed curves) hemispheres. The densities were calculated for Millstone Hill and its conjugate point by using the MSIS model of the neutral atmosphere [Hedin *et al.*, 1977a, b]. Note the large seasonal variation in both N_2 and He.

Fig. 2a

Fig. 2b

Fig. 2. (a) Ion densities versus altitude for equal poleward winds in both hemispheres and for a flux tube refilling situation. The solid curves are for the winter hemisphere and the dashed curves are for the summer hemisphere. Note the winter anomaly in the peak O^+ density. (b) Field-aligned ion drift velocities versus altitude. These velocities correspond to the ion densities shown in Figure 2a. Positive velocities are directed from the northern (winter) to the southern (summer) hemisphere. The crosshatch area shows the region where H^+ and He^+ are counterstreaming. (c) Ion and electron temperatures versus altitude for both the winter (solid curves) and summer (dashed curves) hemispheres. These temperatures correspond to the ion densities and drift velocities shown in Figures 2a and 2b.

These densities were obtained from the MSIS neutral atmosphere model [Hedin *et al.* 1977a, b] for noon conditions at Millstone Hill in the northern hemisphere and for the magnetically conjugate point in the southern hemisphere. As noted earlier, the solar and magnetic condi-

tions for the neutral atmosphere were set at $F10.7 = 150$ and $AP = 12$, respectively. The seasonal differences in the neutral atmosphere have a major effect on the ionosphere. He^+ is produced by photoionization of $[He]$ and lost through charge exchange reactions with $[N_2]$ and $[O_2]$ (see previous section on chemistry). In winter there is an order of magnitude more $[He]$ (the winter helium bulge) and an order of magnitude less $[N_2]$ and $[O_2]$ above 500 km than in summer. Hence, even with lower solar fluxes in winter (increased solar zenith angle), a significantly enhanced He^+ density is expected in the winter hemisphere [Raith *et al.*, 1978; Ottley and Schunk, 1980].

Below 400 km, the atmosphere conditions favor enhanced O^+ densities in winter, which is the winter anomaly where $N_m F_2$ is greater in winter than in summer (see, for example, Schunk and Raith, [1980]). This occurs because the production of O^+ is greater owing to the higher winter $[O]$ densities, and the O^+ loss rate is lower owing to the smaller winter $[N_2]$ and $[O_2]$ densities. At low altitudes, H^+ should also display enhanced densities in winter, since $[H]$ and $[O^+]$ are both higher in winter. On this basis one might expect an H^+ flow from the winter to the summer hemisphere. However, in this low altitude region H^+ is in chemical equilibrium, and therefore, the variations of the H^+ density in this region cannot be used to deduce the direction of the interhemispheric H^+ flow. At altitudes above 400 km, $[O]$ is higher in summer than in winter and this tends to counter the lower $[H]$ in summer. Also, the H^+ interhemispheric flow will be sensitive to high altitude winds, diffusion, and temperatures.

Fig. 2c

Fig. 3a

Fig. 3b

Fig. 3. (a) Steady state ion densities versus altitude for equal poleward winds in both hemispheres. The solid curves are for the winter hemisphere and the dashed curves are for the summer hemisphere. (b) Steady state, field-aligned ion drift velocities versus altitude. These velocities correspond to the ion densities shown in Figure 3a.

3. INTERHEMISPHERIC FLOW

At Millstone Hill, which is on an $L = 3.2$ magnetic field line, both neutral winds and storm associated flux tube depletion mechanisms are important in determining the direction of the interhemispheric flow in addition to the photochemistry already discussed. In order to study the effects of neutral winds, we selected two wind configurations: (1) Equal poleward winds of 200 m/s in the conjugate ionospheres, and (2) A northern hemisphere poleward wind of 200 m/s and no neutral wind in the southern hemisphere. For the solstice conditions used in this study, realistic wind patterns are expected to span the range given by configurations (1) and (2).

To allow for depleted flux tube situations as well as for dynamic equilibrium (steady state) conditions, model results will be presented for both partially depleted (refilling) flux tube and steady state situations for both wind configurations. Since our model solves the energy equation self-consistently, which in general has not been done in previous studies, a comparison will be given in which we used a fixed set of temperature profiles in order to demonstrate the flow dependence upon temperature.

3.1. Equal Poleward Winds

Figures 2a, 2b, and 2c show density, flow velocity, and temperature profiles, respectively, for equal poleward winds and for a depleted flux tube situation. Under these conditions upward plasma flows from both ionospheres are expected to refill the flux tube. In Figure 2a, the H^+ , He^+ , and O^+ densities are shown as a function of altitude from both the winter (solid curves) and summer (dashed curves) ionospheres to the equator. The three ions all

show higher densities in winter below 1000 km, indicating that $N_m F_2$ is higher in the winter hemisphere than in the summer hemisphere ($[N_m F_2]_w = 7.9 \times 10^5 \text{ cm}^{-3}$, $[N_m F_2]_s = 2.9 \times 10^5 \text{ cm}^{-3}$). This appears as the winter anomaly; however, technically the winter anomaly is a term used to contrast peak F region densities at the same geographic location. For both H^+ and He^+ , higher winter densities are present to above 2000 km. As expected from the earlier discussion of the seasonal variations of the neutral atmosphere, He^+ shows a larger seasonal variation than H^+ ; at 500 km $[He^+]_w/[He^+]_s = 300/26$, while $[H^+]_w/[H^+]_s = 413/105$.

Figure 2b shows the ion flow velocities along the flux tube that correspond to the densities shown in Figure 2a. The horizontal axis represents altitude from the northern ionosphere (left side) through the equator (center) to the southern ionosphere (right side). Flow velocities are positive if the flow is from the northern ionosphere to the southern ionosphere. The He^+ flow velocity is positive along the entire flux tube, indicating that He^+ is flowing from the higher density northern ionosphere to the lower density southern ionosphere. For both H^+ and O^+ the flow velocity is positive in the northern hemisphere and negative in most of the southern hemisphere. This corresponds to H^+ and O^+ flowing up from both ionospheres to the equator, a flux tube refilling situation. Hence, in most of the southern hemisphere He^+ and H^+ are counterstreaming; this region is shown in Figure 2b by the cross hatching. The relative counterstreaming velocity is about 20–25 m/s. Counterstreaming is also present in the southern hemisphere between He^+ and O^+ .

The above discussion has primarily focused on the region above 2000 km. Below this altitude in the topside ionosphere, very steep gradients in the flow velocities and

Fig. 4a

Fig. 4b

Fig. 4. (a) Ion densities versus altitude for a flux tube refilling situation but with a change in the wind pattern. For this case, the wind in the northern (winter) hemisphere was doubled and the conjugate wind was set to zero. The solid curves are for the winter hemisphere and the dashed curves are for the summer hemisphere. Note that the winter anomaly still persists, although it is reduced. (b) Field-aligned ion drift velocities versus altitude corresponding to the ion densities shown in Figure 4a. The plotting format is similar to that used for Figure 2b.

velocity reversals are present, i.e., the H^+ outflow from the winter ionosphere reaches 550 m/s at about 1500 km, but below this altitude it decreases rapidly and even flows downward below 1000 km. A detailed discussion of this effect is given by Schunk and Walker [1972]. Clearly, this large variation of the H^+ flow velocity with altitude in the topside ionosphere indicates that incorrect deductions about refilling rates could occur if ionospheric escape fluxes are evaluated at altitudes between 500 and 2000 km.

Figure 2c shows the electron and ion temperatures that correspond to the densities and flow velocities shown in Figures 2a and 2b. Winter and summer hemisphere temperatures are shown as solid and dashed curves, respectively. At all altitudes the electron temperature is greater than the ion temperature, by 200 to 300° K at the equator and by about 1500° K at 500 km. In our model all three ions are assumed to have the same temperature. This temperature below 1000 km is largest in summer, whereas above 1000 km it is largest in winter, and then above 3000 km it reverses again and is largest in summer. The electron temperature in contrast is always largest in summer, by as much as 500° K below 1000 km.

The steady state conclusion of the time dependent study illustrated in Figures 2a-2c is shown in Figures 3a and 3b. Figure 3a shows the H^+ , He^+ , and O^+ densities as a function of altitude in both hemispheres after a steady state interhemispheric flow has been established. Since the flux tube is now full, the equatorial densities have reached their maximum values (compare with Figure 2a); the equatorial H^+ density has increased from 1.5×10^3 to 2×10^3 cm^{-3} and the equatorial He^+ density from 3×10^1 to 1.3×10^2 cm^{-3} . At low altitudes the composition and

seasonal characteristics are very similar to those shown in Figure 2a, with only He^+ being significantly enhanced in the steady state at all altitudes. Figure 3b shows the steady state ion flow velocities in a format identical to that used for Figure 2b. The light ions H^+ and He^+ flow from the northern ionosphere to the southern ionosphere, and therefore, no longer counterstream in the southern hemisphere. In addition, their flow speeds in the northern hemisphere are considerably lower than in the earlier refilling case. However, both light ions counterstream with O^+ along most of the field line, since O^+ still flows out of both ionospheres. In the steady state the ion and electron temperatures are within 25° of those shown in Figure 2c at all altitudes.

3.2. Asymmetric Poleward Winds

In contrast to the symmetric neutral wind case shown in Figures 2 and 3, Figures 4 and 5 show the refilling and steady state results for the case of asymmetric poleward neutral wind conditions. Figure 4a shows the summer hemisphere (dashed lines) and winter hemisphere (solid lines) ion density profiles for flux tube refilling assuming a poleward wind in the northern hemisphere and no wind in the southern hemisphere. The O^+ profiles are now considerably different in the summer and winter hemispheres. With the different neutral winds $h_m F_2$ is at 327 km in the summer hemisphere and at 233 km in the winter hemisphere. In addition to this 100 km difference in the altitude of the F_2 peak, the peak densities are now comparable in the summer and winter hemispheres, in contrast to the previous case. At higher altitudes the O^+ seasonal difference increases; however, although not

Fig. 5. (a) Steady state ion densities versus altitude for the wind pattern used for Figure 4. The solid curves are for the winter hemisphere and the dashed curves are for the summer hemisphere. (b) Steady state, field-aligned ion drift velocities versus altitude for the ion densities shown in Figure 5a. The plotting format is similar to that used for Figure 2b. Note that He^+ and H^+ counterstream throughout the plasmasphere.

shown, both hemispheres have the same O^+ density at the equator.

H^+ and He^+ show similar characteristics to those in the previous equal poleward wind study. The corresponding ion flow velocities are shown in Figure 4b in a similar format to that used for Figures 2b and 3b. The He^+ and H^+ flow velocities are very similar to those for the equal poleward wind case (see Figure 2b) with counterstreaming between the two ions in the southern hemisphere. However, in contrast, the heavy O^+ ion flows from the southern (summer) ionosphere to the northern (winter) ionosphere at speeds as large as 1.6 km/s near the equator. This flow reversal from the previous study is entirely due to the change in the adopted neutral wind.

The steady state density profiles are shown in Figures 5a. The O^+ density profile is similar to that obtained for the refilling case (Figure 4a). However, the H^+ and He^+ densities at high altitudes have increased, reaching their full flux tube values (compare with the other steady state case shown in Figure 3a). Under the influence of different neutral winds, the O^+ steady state density shows quite different seasonal characteristics to those shown in Figure 3a. The flow velocities in steady state are quite different to those shown earlier (compare Figures 3b and 5b). Now, He^+ and H^+ counterstream along the whole field line, with He^+ flowing from winter to summer and H^+ flowing from summer to winter. At steady state, O^+ flows rapidly from summer to winter, therefore O^+ also counterstreams with He^+ along the entire field line.

3.3. Effect of Thermal Structure

In order to determine the effect of using self-consistent temperature profiles versus fixed temperature profiles,

we repeated our time dependent study for equal poleward neutral winds, but we kept the temperature profiles fixed during the refilling of the flux tube. The steady state ion-density profiles were practically the same as those shown in Figure 3a; however, the flow velocities were significantly different (compare Figures 3b and 6). The light ions H^+ and He^+ show similar winter to summer ionosphere flows to those shown in Figure 3b, although with reduced speeds. However, O^+ has changed its flow characteristic from one of summer to winter flow across the equator to a winter to summer flow. At the equator the difference in O^+ flow speed for the two cases is 400 m/s. It should be noted, however, that this increased flow speed is associated with extremely low densities, hence no significant O^+ flux is transported across the equator. The chosen fixed temperature profiles for this study were within 100 ° K of the self-consistent temperatures shown in Figure 2c. Thus, although the steady state densities are not particularly sensitive to the temperature distribution, be it analytical, empirical or self-consistently computed, the ion flow velocities are highly sensitive, with 10-100% velocity differences occurring for very small changes in the shape of the ion and electron temperature profiles.

4. SUMMARY

We have used an interhemispheric plasma transport model to study the flow characteristics of H^+ , He^+ , and O^+ along closed geomagnetic field lines for solstice conditions. The model corresponds to a time dependent solution of the coupled continuity, momentum, and energy equations for the ions and electrons. The equations were solved along an entire flux tube from 120

Fig. 6. Steady state, field-aligned ion drift velocities versus altitude for the case when the temperature profiles were kept fixed. Note the large change in the velocity profiles.

km in one hemisphere to 120 km in the other hemisphere. For this study the calculations were carried out for noon conditions for the flux tube that passes through Millstone Hill ($L = 3.2$). Initially, the total content of the Millstone Hill flux tube was depleted by a factor of 2, and the subsequent refilling was studied until a steady state flow was established between the summer and winter hemispheres. Since the neutral wind has an important effect on the F region ion densities and on the direction of the interhemispheric flow, two cases were considered; equal poleward winds in both hemispheres, and a poleward wind in the northern winter hemisphere and no wind in the southern summer hemisphere.

For the case of equal poleward winds in both hemispheres, a winter anomaly situation occurs in that $N_m F_2$ is greater in the northern winter ionosphere than in the southern summer ionosphere. Also, since the production of H^+ in the F region is directly proportional to the O^+ density, the H^+ density in the winter ionosphere is greater than that in the summer ionosphere. Therefore, during the time of flux tube refilling, when both O^+ and H^+ flow up from the conjugate ionospheres, the upward flux from the winter ionosphere is larger than that from the summer ionosphere. However, the situation for He^+ is different. Because of the winter helium bulge, the He^+ density in the winter ionosphere is much greater than that in the summer ionosphere, and consequently, He^+ flows from the winter to the summer ionosphere even when the flux tube is refilling. Hence, in most of the southern hemisphere, He^+ and H^+ counterstream with a relative velocity of about 20-25 m/s during flux tube refilling. After a steady state has been established, both He^+ and H^+ flow from the winter to the summer ionosphere and no light-ion counterstreaming occurs.

For the case of a poleward neutral wind in the northern winter hemisphere and no wind in the southern summer

hemisphere, the most important change involves O^+ owing to the changes in $N_m F_2$ and $h_m F_2$. Without the poleward wind in the summer hemisphere, $h_m F_2$ is increased by nearly 100 km and the 'winter anomaly' is significantly reduced. At altitudes above about 300 km, the O^+ density in the summer ionosphere is much greater than that in the winter ionosphere, which produces an O^+ flow from the summer to the winter hemisphere both during flux tube refilling and in the steady state. Although the O^+ flow is considerably different from that obtained for the case of equal poleward winds, the He^+ and H^+ flows are qualitatively similar during refilling, with light-ion counterstreaming in the summer hemisphere. In the steady state, however, the He^+ and H^+ flow characteristics are quite different from those obtained for the case of equal poleward winds. Now, He^+ and H^+ counterstream along the entire field tube, with the He^+ flow being from the winter to the summer hemisphere and the reverse flow for H^+ .

We have also studied the effect of the thermal structure on the ion flow characteristics and we found that the ion flow velocities are fairly sensitive to the thermal structure. Therefore, self-consistent ion and electron temperatures must be calculated in order to obtain reliable estimates for ion counterstreaming velocities. However, the ion density distributions are not very sensitive to small changes in the ion and electron temperature profiles.

Finally, we note that the H^+ - He^+ and O^+ - He^+ counterstreaming velocities that we obtained are too small to excite plasma instabilities [cf. Singh and Schunk, 1983], but large enough to be measured.

Acknowledgements. This research was supported by NASA grant NAGW-77 and NSF grant ATM-8217138 to Utah State University. The computer modelling effort was supported by the National Center for Atmospheric Research, which is sponsored by the National Science Foundation.

The Editor thanks G. J. Bailey and J. F. Vickrey for their assistance in evaluating this paper.

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(Received March 21, 1983;
revised May 9, 1983;
accepted May 10, 1983.)