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IONOSPHERIC ORIGIN OF MAGNETOSPHERIC O^+ IONS

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Abstract. Flows of thermal atomic oxygen (O^+) ions are deduced from topside ionospheric plasma density profiles. The mean flux within most of the polar cap is of the order of 10^{12} m^{-2} s^{-1}, a figure which is consistent with both theoretical and experimental estimates of the light ion polar wind at greater altitudes. Larger flows (up to 6 x 10^{12} m^{-2} s^{-1}) are observed near the poleward edge of the night-side statistical auroral oval, a feature not reproduced in the light ion flux. The implication is one of a low altitude acceleration mechanism, acting upon the O^+ ions at these latitudes and at heights above that at which the fluxes are observed. Such a process would enable ions to escape from the ionosphere because they do not exchange charge with neutral hydrogen. The observations are in general agreement with energetic O^+ ions as previously observed in various parts of the magnetosphere.

Introduction

Observations of large populations of energetic O^+ ions in the magnetosphere (reviewed by Johnson, 1979) have lead to recent suggestions of low altitude auroral acceleration of cold ionospheric plasma (Klumpar, 1979; Ungstrup et al., 1979). Neither the variability of magnetospheric composition, as observed with the S3-3 satellite by Kintner et al., (1979), nor the numbers of O^+ ions present can be explained by thermal polar wind escape with subsequent heating.

The polar wind flux of thermal light ions is observed to be of the order of 10^{12} m^{-2} s^{-1} (Hoffman and Dodson, 1980), and this agrees well with the theory of thermal plasma escape (Banks and Holzer, 1969). Observations in the magnetotail near 35 Re imply an O^+ flux of this magnitude out from the ionosphere (Frank et al., 1977) which is consistent with observations made nearer to earth at 1 Re (Klumpar, 1979). However the fraction of O^+ ions in the polar wind is predicted to be about 10^{-3} and hence this flow is an insufficient source for the magnetosphere. Moore (1980) has extended polar wind theory to allow for parallel or transverse acceleration mechanisms at low altitudes. These allow O^+ ions, with sufficiently elevated energies, to escape from the ionosphere because they do not exchange charge with neutral hydrogen, the effect which restricts the thermal O^+ outflow. This theory accounts for the variability of the energetic O^+ flows by invoking variations in the height of the acceleration region, relative to the O/H neutral transition altitude. Observations made using the S3-3 satellite (Ghielmetti et al., 1978; Kintner et al., 1979) indicate that in the majority of cases most of the acceleration occurs above 4000 km. This is too high to cause escape of ionospheric O^+ ions. However observations by the ISIS satellites (Ungstrup et al., 1979; Klumpar, 1979) have shown that some acceleration must occur below 1400 km and a rocket observation by Whalen et al., (1978) detected acceleration in the 400-500 km range during the expansive phase of an auroral substorm.

The threshold for O^+ escape due to parallel acceleration is lower than that for transverse, provided that the forcing is continued. For transverse accelerations the full escape energy must be provided at once (Moore, 1980). The low altitude accelerations which have been observed have all been transverse and are thought to be due to ion cyclotron waves. Escape of O^+ due to a transverse mechanism requires an initial energy of at least 10 eV be imparted to the ion. Recent results from the thermal plasma composition experiment on ISEE 1 (Baugher et al., 1980) reveal magnetospheric O^+ ions outside the plasmasphere with energies elevated, by not less than 10 eV, above that which would be obtained by adiabatic mapping from the high latitude ionosphere. The broad pitch angle spread indicates that the process is a transverse acceleration.

This letter presents observations of thermal O^+ ion fluxes in the lower topside ionosphere. Upward flows near the auroral oval are found to be sufficiently large at night to act as a source of both the light ion polar wind (via charge exchange) and observed magnetospheric O^+ ions of a wide range of energies (via an acceleration mechanism at low altitudes).

Analysis

The data base used in this study consists of 60,000 ionospheric plasma scale height profiles, observed within three years of sunspot minimum by the Alouette I satellite. Departures from diffusive equilibrium conditions in the topside ionosphere alter the scale height only at altitudes near the F2 peak, where frictional drag between O^+ ions and O atoms is a significant term in the equation of motion of the ions (Banks and Holzer, 1969). Figure 1 shows model scale height profiles produced using the model by Titheridge (1976a) for a given set of steady-state conditions and various values of ϕ, the field-aligned O^+ ion flux. Values of ϕ are positive for upward flows and are expressed as a function of ϕ_L, the maximum, 'limiting' flux to which ϕ is restricted by the ion-neutral frictional drag (Banks and Holzer, 1969).

The observed profiles were each fitted with a model profile by assuming diffusive equilibrium conditions (Titheridge, 1976a). A flow of O^+ ions causes a deviation between observed and

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best fit profiles at altitudes where the frictional drag is large. The maximum, d, of this deviation can be calibrated (by applying the same fitting procedure to model profiles of the kind shown in Fig. 1) as a function of : (ϕ/ϕ_L); the neutral temperature, T_n; the plasma temperature of the best fit profile at the peak deviation, T_t; and the gradient of T_t (Lockwood and Titheridge, 1981). T_n is taken to be independent of height as it is close to its exospheric value, and steady state conditions are assumed to apply. The value of (ϕ/ϕ_L) can then be calculated for each profile from the values of d, T_t and (dT_t/dh), which are taken from the best-fit profile (Titheridge, 1976b), and the value of T_n predicted by the MSIS neutral atmosphere model.

Above the ion transition height (Titheridge, 1976a) Coulomb drag between O^+ and H^+ sets a limit to the outflow of thermal ions which is an order of magnitude smaller than ϕ_L. Hence values of (ϕ/ϕ_L) are usually less than about 0.2 and the error introduced by use of the MSIS model neutral temperature is less than one per-cent in this range. By making additional use of MSIS neutral composition prediction, the value of ϕ for each sounding can also be deduced (Lockwood and Titheridge, 1981). The value of ϕ however, is much more dependent on the model values and any errors introduced must be averaged out by taking the mean of sufficient observations. Values of ϕ are given here in $m^{-2}\ s^{-1}$ normalised to a height of 1000 km.

Results and Discussion

Figures 2 and 3 show the mean values of the moduli ϕ and (ϕ/ϕ_L) in 2.5 geomagnetic latitude bins with error bars of plus and minus one

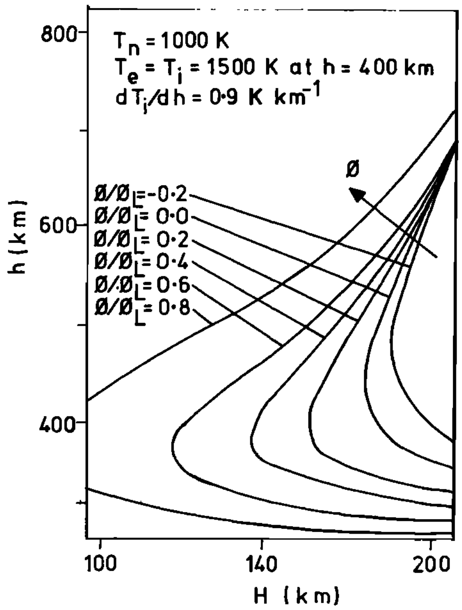

Fig. 1. Model steady-state, scale height profiles for various O^+ ion fluxes. The neutral temperature and plasma temperature gradient are independent of height and equal to 1000 K and 1.8 K km^{-1} respectively. The plasma temperature at 400 km is 3000 K.

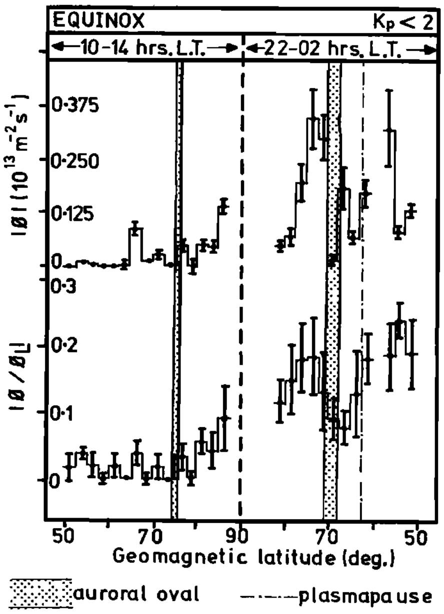

Fig. 2. Mean of modulus ϕ and ϕ/ϕ_L as a function of geomagnetic latitude, for noon and midnight during equinox and K_p < 2.

standard error. The left hand sides of these plots show the means for all observations within two hours of local midday, and the right hand side those for within two hours of local mid-night. The geomagnetic latitude scale is reversed on the right hand side of the diagram so that the polar cap appears as the region between the two shaded areas, denoting the statistical auroral oval. The mean of the statistical location of the nocturnal plasmapause, calculated for each observation by the regression equation of Köhnlein and Raitt (1977), is indicated. The mean latitudes of the edges of the auroral oval were calculated using the equations of Holzworth and Meng (1975). The means in Fig. 2 are for all observations taken when the planetary K_p index was less than 2 and Fig. 3 is for all greater magnetic activity levels. The results shown in Figs. 2 and 3 are for within 50 days of the equinoxes, for which there were sufficient observations to give reliable means of ϕ at most latitudes. Solstice means, where available, show the same general features with a few seasonal variations which will not be discussed in detail here. The analysis is restricted to the two local time ranges shown in order to minimise transient effects associated with sunrise and sunset. Within the polar cap plasma is moved by the convection electric field and it is difficult to assess the error which may be introduced by any departures from steady state conditions caused by this motion. Schunk et al., (1976) have used a full time-dependent model to determine the evolution of the topside F layer profile under model increases in the electric field, both with and without polar wind outflow. In some of their examples the departure from steady state conditions does make a small contribution to the scale height profile 'signature' which is calibrated here, but this is much smaller than that made by the ion outflow.

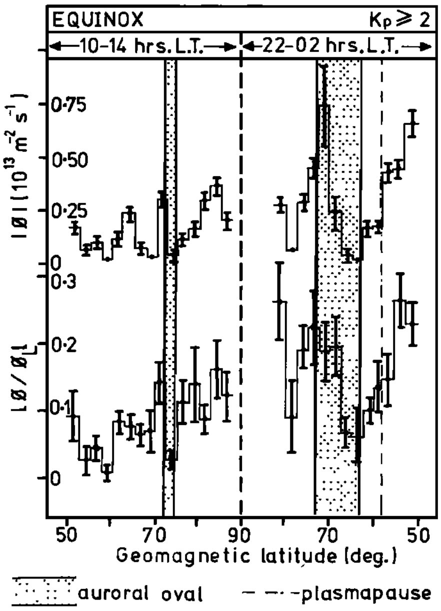

Fig. 3. Mean of modulus of $\emptyset$ and $\emptyset/\emptyset_L$ as a function of geomagnetic latitude, for noon and midnight, during equinox and Kp $\geq$ 2.

Within the polar cap the flows were always found to be upward, the mean dayside flux being of the order of 0.1 x 10^{13} m^{-2} s^{-1} for $K_p < 2$, rising to roughly twice this value for $K_p \geq 2$. Hence the mean fluxes agree well with the proton flux observed by the roll modulation of results from the mass spectrometer on board ISIS II at 1400 km (Hoffman and Dodson, 1980) and theoretical values of the ion escape flux (Banks and Holzer, 1969). At times of upward flow the O^+ flux is expected to be a good indicator of the light ion flow which it supports (Evans and Holt, 1978). Equatorward of the plasmapause fluxes are large and generally upward by day and downward at night, and are consistent with theoretical estimates of plasma exchange between the ionosphere and protonosphere (e.g. Bailey et al., 1979). This diurnal flow pattern is subject to considerable modification by the depletion of the protonosphere following magnetic storms, especially at outer plasmaspheric latitudes, and will be discussed in detail elsewhere.

The feature of interest here is the large upward fluxes consistently observed on the night-side at the poleward edge of the auroral oval and in the lower latitude region of the polar cap. Analysis of the other four, four-hour local time sectors shows that this peak is largest before midnight, although results nearer sunrise and sunset must be treated with more caution because of the assumption of steady state conditions. The peaks coincide with maxima in ($\emptyset/\emptyset_L$) and hence are not due to an enhanced F region plasma density increasing $\emptyset_L$. Satellite observations of the light ion flow show no such peak, the flow being limited by the O^+-H^+ Coulomb drag and having a roughly constant value of 0.1 x 10^{13} m^{-2} s^{-1} across the polar cap (Hoffman and Dodson, 1980). The peak flux near the edge of the auroral oval is of the order of 0.3 x 10^{13} m^{-2} s^{-1} at low Kp, rising to 0.6 x 10^{13} m^{-2} s^{-1} for Kp $\geq$ 2. The ion transition level is high under these conditions of outflow, and this enables the observation to be made at greater altitudes, where production and loss terms are negligible. Under such conditions the above values must equal the total ion (of all energies) flux into the magnetosphere. These fluxes are therefore sufficiently large to support both the thermal light ion flows (via charge exchange) and energetic O^+ outflows (via a low altitude acceleration mechanism), both of which require a component of the order of 0.1 x 10^{13} m^{-2} s^{-1}. The frequency with which Ghielmetti et al., (1978) observed upward flowing energetic ions, using the S3-3 satellite, was greatest at altitudes above 6000 km in the pre-midnight sector. The major difference between their results and those presented here is that the frequency was greatest in the centre of the statistical auroral oval, whereas in Figures 2 and 3 the peak is near the poleward edge of the oval, moving nearer the centre of the oval, and becoming larger, at higher K_p values. The S3-3 satellite's energetic ion mass spectrometers do not detect ions of energies below 500 eV. This is well above the threshold for transverse acceleration escape of O^+ from the ionosphere as derived by Moore (1980) and hence the S3-3 experiment is only sampling the high energy end of the possible O^+ escape by parallel or transverse accelerations at low altitudes. This may explain the latitudinal difference between the two studies, the lower energy O^+ ions (Baugher et al., 1980) arising from higher latitudes. However the effect on the plasma scale height of the rapid motion towards dawn in the auroral oval (Schunk et al., 1976) may also cause this discrepancy.

Conclusions

The upward flows of thermal O^+ ions in the topside ionosphere, observed in the vicinity of the pre-midnight auroral oval, are larger than those required to support the polar wind outflow of thermal light ions. The fluxes are large enough to act as a source of the high energy ionospheric O^+ ions observed in the magnetosphere and of lower energy ions as well, and are not restricted by the charge-exchange barrier presented by neutral hydrogen atoms. These results therefore support the hypothesis of a low altitude acceleration mechanism active in these regions.

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References

Bailey, G. J., R. J. Moffett, and J. A. Murphy, Calculated daily variations of O^+ and H^+ at mid latitudes - II sunspot maximum results, J. Atmos. Terr. Phys., 41, 417, 1979.

Banks, P. M., and T. E. Holzer, High latitude plasma transport: The polar wind, J. Geophys. Res., 74, 6317, 1969.
Baugher, C. R., C. R. Chappell, J. L. Horwitz, E. G. Shelley, and D. T. Young, Initial thermal plasma observations from ISEE-1, Geophys. Res. Lett., 7, 657, 1980.
Evans, J. V., and J. M. Holt, Nighttime proton fluxes at Millstone Hill, Planet. Space Sci., 26, 727, 1978.
Frank, L. A., K. L. Ackerson, D. M. Yeager, Observations of atomic oxygen (O^+) ions in the earth's magnetotail, J. Geophys. Res., 82, 129, 1977.
Ghielmetti, A. G., R. G. Johnson, R. D. Sharp, and E. G. Shelley, The latitudinal, diurnal and altitudinal distributions of upward flowing energetic ions of ionospheric origin, Geophys. Res. Lett., 5, 59, 1978.
Hoffman, J. H., and W. H. Dodson, Light ion concentrations and fluxes in polar regions during magnetically quiet times, J. Geophys. Res., 85, 626, 1980.
Holzworth, R. H., and C. I. Meng, Mathematical representation of the auroral oval, Geophys. Res. Lett., 2, 377, 1975.
Johnson, R. G., Energetic ion composition in the earth's magnetosphere, Rev. Geophys. and Space Phys., 17, 696, 1979.
Kintner, P. M., M. C. Kelley, R. D. Sharp, A. G. Ghielmetti, M. Temerin, C. Cattell, and P. Mizera, Simultaneous observations of upstreaming ions and electrostatic hydrogen cyclotron waves, J. Geophys. Res., 84, 7201, 1979.
Klumpar, D. M., Traversely accelerated ions: An ionospheric source of hot magnetospheric ions, J. Geophys. Res., 84, 4229, 1979.
Kohnlein, W., and W. J. Raitt, Position of the mid-latitude trough in the topside ionosphere as deduced from ESRO 4 observations, Planet. Space Sci., 25, 600, 1977.
Lockwood, M., and J. E. Titheridge, Global morphology of departures from diffusive equilibrium in the topside ionosphere observed at altitudes near the F2 peak, to be published in J. Atmos. Terr. Phys., 1981.
Moore, T. E., Modulation of terrestrial ion escape flux composition (by low altitude acceleration and charge exchange chemistry), J. Geophys. Res., 85, 2011, 1980.
Schunk, R. W., Banks, P. M., and Raitt, W. J., Effects of electric fields and other processes upon the nighttime high-latitude F layer, J. Geophys. Res., 81, 3271, 1976.
Titheridge, J. E., Ion transition heights from topside electron density profiles, Planet. Space Sci., 24, 229, 1976a.
Titheridge, J. E., Plasma temperatures from Alouette I electron density profiles, Planet. Space Sci., 24, 247, 1976b.
Ungstrup, E., D. M. Klumpar, and W. J. Heikkila, Heating of ions to superthermal energies in the topside ionosphere by electrostatic ion cyclotron waves, J. Geophys. Res., 84, 4289, 1979.
Whalen, B. A., W. Bernstein, and P. W. Daly, Low altitude acceleration of ionospheric ions, Geophys. Res. Lett., 5, 55, 1978.

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