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QUANTITATIVE PARAMETRIZATION OF ENERGETIC IONOSPHERIC ION OUTFLOW

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Abstract. The magnitude and composition of energetic upflowing ionospheric ions are key parameters in a merged magnetospheric-ionospheric model. Their magnetic and solar activity dependences have been parametrized in terms of the magnetic Kp and AE indices and the solar radio flux index $F_{10.7}$ using data from the Lockheed energetic ion composition spectrometer on Dynamics Explorer 1 between September 1981 and May 1986. The data period extends from near the maximum to the minimum of solar cycle 21 when $F_{10.7}$ varied between ~70 and ~300. For a given solar activity level, the ion outflow rate of H^+ and O^+ in the 0.01-17 keV range was found to increase exponentially with the magnetic Kp index, by a factor of 4 and 20, respectively, from Kp = 0 to 6. The exponential dependence prevails at all solar activity levels. Empirically, $F_{O^+} \propto \exp(0.50\ Kp)$, $F_{H^+} \propto \exp(0.23\ Kp)$. In addition, it approximately follows a power law dependence with the AE index. Empirically, $F_{O^+} \propto AE^{0.8}$ and $F_{H^+} \propto AE^{0.4}$ for AE above 100 nT. From solar minimum to near maximum ($F_{10.7}$ from ~70 to ~250), the O^+ rate for a given magnetic activity level (Kp, Dst, or AE) increases by a factor of ~5 while the H^+ rate decreases by a factor of ~2, resulting in an order of magnitude increase in the O^+/H^+ upflowing ionospheric ion composition ratio.

Introduction

The magnetosphere and the ionosphere were previously treated as two essentially separate entities consisting of plasmas of distinctly different origins and characteristics, and the charged particles in the terrestrial environment were accordingly classified as magnetospheric and ionospheric. In contrast, energetic ion composition measurements from satellites in the last decade have brought forth the realization that (a) ionospheric ions (ions of ionospheric origin) constitute a substantial fraction of the magnetospheric plasma population under certain geomagnetic and solar conditions, and (b) the magnetosphere and the ionosphere are in fact two intimately coupled parts of the terrestrial environment. The realization points to the merger of current magnetospheric and ionospheric models as the necessary next step in our quantitative understanding of the near earth space.

At Dynamics Explorer 1 (DE 1) altitudes, a variety of ion outflow populations from the polar ionosphere have been observed, including the supersonic polar wind (Nagai et al., 1984); the upwelling ions, which are ions of different species transversely heated to 10-20 eV in the dayside cusp and then upwelling and convecting anti-sunward across the polar cap, forming a cleft ion fountain under the combined influence of gravitation and convection electric fields (Lockwood et al., 1985; Moore et al., 1986); polar cap O^+ ions, which appear to originate from inside the polar cap distinct from the cleft ion fountain (Shelley et al., 1982; Waite et al., 1985; Lockwood et al., 1986); and auroral upflowing ion beams and conics, in energies up to several kiloelectron volts (Klumpar et al., 1984; Yau et al., 1984; Collin et al., 1987) and down to a few electron volts (near the gravitational escape energy). The few electron volt auroral upflowing ionospheric ions (UFIs) are expected to follow parabolic trajectories unless they are further energized at higher altitudes (see, for example, Cladis, 1986), resulting in an auroral ion fountain in analogy to the cleft ion fountain.

The morphology and occurrence characteristics of energetic UFIs have been the subject of a number of statistical studies using data on S3-3 below 8000 km (Ghielmetti et al., 1978; Gorney et al., 1981; Collin et al., 1981, 1984; Ghielmetti et al., 1987) and data from the energetic ion composition spectrometer (EICS) on DE 1 up to

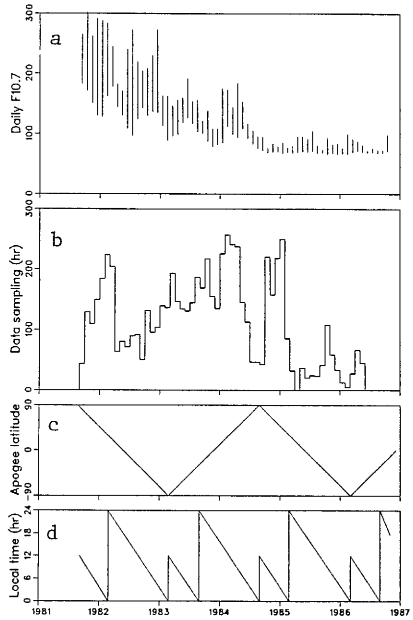

Fig. 1. (a) Monthly minimum and maximum of daily solar radio flux at 10.7 cm, $F_{10.7}$ (10^{-22} Wm^{-2} Hz^{-1}) at 1 AU. (b) Monthly EICS data coverage in present study (auroral data only). (c) Geographic latitude of DE 1 apogee. (d) Local time of DE 1 orbital plane. As a result of the 18-month apsidal cycle and the 12-month local time drift period, apogee latitude and local time visited in a particular season in the first apsidal cycle are revisited in the same season in the subsequent cycles.

23,300 km (Yau et al., 1984, 1985a,b; Collin et al., 1987). The morphology of upwelling ion events up to ~50 eV was also studied using data from the retarding ion mass spectrometer (RIMS) on DE 1 (Lockwood et al., 1985).

The Yau et al. (1985a,b) studies, in particular, were based on data from a 3-year period between 1981 and 1984 and were focussed on the occurrence morphology and outflow of energetic (0.01-17 keV) UFIs near the solar maximum and in the early declining phase of the solar cycle. These studies revealed systematic changes in the UFI occurrence morphology and mass composition with geomagnetic activity, as well as significant long-term variations which were correlated with variations in the solar activity. The present study is a follow-on to these studies; its aim is to quantify and empirically parametrize these variations and to explore the physical consequences of the parametric dependences.

UFIs from the high-latitude (auroral and polar cap) ionosphere represent the primary source of energetic ionospheric ions in the magnetosphere. Therefore, their magnitude, composition, and energy distributions are key parameters in a quantitative magnetospheric-ionospheric model. The present study represents a first step toward the synthesis of quantitative observational results into analytic inputs for such a model.

Data Analysis

DE 1 was launched on August 3, 1981, into a highly elliptic orbit. The DE 1 orbit has an apogee of 4.6 R_E geocentric and an inclination of 90°. Its orbital plane has a local time drift period of 12 months and a line-of-apsides drift period of 18 months. Consequently, the latitude and local time of the apogee for a given season in the first apsidal cycle are revisited in the same season in subsequent cycles. The revisits make it possible to readily delineate long-term variations in the observed data from seasonal and other variations.

Data in the present data base have been acquired from the EICS on DE 1 between September 15, 1981, and May 31, 1986, from near the maximum to the minimum of solar cycle 21. On DE 1, EICS typically measures ions in the ~0.01-17 keV/q range and operates in a number of specialized modes (see Shelley et al., 1981 for details). Data in this study were acquired when the instrument was operating in its fast and drum modes in which the instrument steps through 15 energy steps in the 0.01-17 keV/q range and completes a full instrument (mass-energy-angular) scan in 24 s (fast modes) or 96 s (drum modes).

The data base in the present study consists of 96-s averages of integral ion fluxes of H^+ and O^+ in three energy bands (0.01-1, 1-4, and 4-17 keV) and nine pitch angle bins. At auroral and polar cap latitudes, data coverage was fairly complete at high altitude (above 16,000 km, within ~1 R_E of DE 1 apogee) for all magnetic local times. The data base includes over 10^4 hours of data. Figure 1 shows the monthly data sampling distribution (a) and the solar radio flux index $F_{10.7}$ (monthly minimum and maximum of daily values) (b) from 1981 to 1986 inclusive, together with the apogee latitude (c) and local time (d). Over the data period, $F_{10.7}$ varied from a high of >300 in October 1981 to a low of <70 in 1986. Near the solar maximum and in the early declining phase, it exhibited large variations within a given month. The solar radio flux is correlated with the solar EUV flux and is therefore also an indicator of solar EUV activities. Naturally, the month-to-month data coverage is not uniform, peaking in periods when the apogee was at auroral latitudes, and typically ranges from ~50 to 200 hours of data per month.

The total ion outflow rate of UFIs between 10 eV and 17 keV was determined as a function of geomagnetic and solar activity conditions using the data base and following the computational procedure in Yau et al. (1985b). Briefly, data samples acquired within a particular data period and during specific magnetic (one of Kp, Dst, and AE) and solar activity (daily $F_{10.7}$) conditions were binned into 2°-invariant latitude and 3-hour

MLT bins. For each 96-s data sample, the net ion flux J was computed from the measured pitch angle distributions of H^+ and O^+ ion fluxes at 0.01-17 keV, and then normalized to a reference altitude (1000 km),

$$J = 2\pi \int_{\beta_{1c}}^{\pi} I(m,\beta)\cos(\pi - \beta)\sin\beta d\beta \qquad (1)$$

$$J_r = JB_r/B , \qquad (2)$$

where $I(m,\beta)$ is the integrated ion flux, β is the pitch angle, m is the ion mass, β_{1c} is the loss cone angle, J_r is the normalized net ion flux, and B and B_r are the magnetic fields at the observation and reference altitudes, respectively. In equation (1), an energy-independent loss cone angle was assumed. Also, where the pitch angle sampling did not extend to 180°, approximate corrections were made to take into account ion fluxes in unsampled pitch angle regions. The normalized flux J_r was averaged over all data samples in a given bin. The bin-averaged normalized flux $\bar{J}_r$ was integrated over all invariant latitudes (above 56°) and MLT in both hemispheres to obtain the total ion outflow rate F as a function of magnetic and solar activity indices.

$$F = (\pi/6)\Delta\tau R_r^2 \sum_{MLT,\Lambda} \bar{J}_r(MLT,\Lambda) \{[- (R_r R_E)\cos^2\Lambda_2]^{1/2} - [1 - (R_r/R_E)\cos^2\Lambda_1]^{1/2} \} , \qquad (3)$$

where $\Delta\tau$ is the range of MLT bin in hours, Λ_1 and Λ_2 are the limits of the invariant latitude bin Λ, R_E is the earth radius, and R_r is the geocentric distance at the reference altitude.

Insofar as UFI activities are concerned, the relative merit between the magnetic Kp, Dst, and AE indices as a primary magnetic activity indicator is by no means established. Each index has its inherent limitations (see, for example, Rostoker, 1972). To the extent that energetic auroral UFI events are associated with auroral substorms, the auroral electrojet (AE) index, being a measure of the auroral electrojet and therefore of the auroral substorm, is theoretically the most appropriate indicator. However, the index is not as readily available as the Kp and Dst indices. Also, it tends to underestimate the strengths of auroral electrojets associated with small, highly localized substorms (that are situated between the sparsely spaced auroral observatories) and those associated with substorms well equatorward of the observatories. On the other hand, the Kp index contains contributions from both the auroral electrojet and the ring current, while the Dst index is primarily an indicator of ring current strength (level of magnetic storm). In the earlier studies, the Kp and Dst indices were used as the magnetic activity indicator in the absence of available AE data. Strong correlation was found between O^+ UFI occurrence and intensity with the Kp index. However, the correlation in itself does not necessarily mean that the index is the primary magnetic activity indicator insofar as UFI activity is concerned. In the present work, the three indices were used where available on a purely empirical basis (Kp and Dst for the full data period and AE up to December 1983), and no attempt was made to establish their a priori theoretical relevance to UFI.

The solar radio flux index $F_{10.7}$ was used as an indicator of solar activity since it is known to correlate with the solar EUV flux, and the latter modulates the upper atmospheric and ionospheric densities and temperatures. Theoretically (Moore, 1984), the change in atmospheric scale heights during the solar cycle results in a corresponding change in the UFI composition. Qualitatively, Yau et al. (1985a) found that near solar maximum, O^+ UFIs occur more frequently and are statistically more intense. Also, the conic-to-beam ratio in UFIs was higher, consistent with the S3-3 results (Ghielmetti et al., 1987). In contrast, the H^+ UFI morphology did not display similar long-term variations.

In Yau et al. (1985b), the H^+ and O^+ ion outflow rates were computed as a function of the magnetic Kp index, independently for each of the first two apsidal cycles. It was found that for O^+, the rates in the two periods had similar Kp dependences, but the rate in the first period (near solar maximum) was consistently a factor of 2 larger than that of the second period (in the early declining phase of the solar cycle) for all Kp. In contrast, the H^+ rates in the two periods were equal within statistical errors. The decrease in the O^+ rate in the second period was correlated with the corresponding decrease in the solar EUV flux.

In the present study, the ion outflow rates were computed for the third apsidal cycle (June 1984 to January 1986) near the solar minimum. A factor of ~4-5 decrease in the O^+ rate relative to the first apsidal cycle was found, while the H^+ rate remained near its earlier value. The consistent, quantitative decrease in the O^+ rate with decreasing solar activity ($F_{10.7}$) and the consistent lack of corresponding decrease in the H^+ rate point to a quantitative dependence of the ion outflow composition on $F_{10.7}$ and on the magnetic activity indices.

In the following, ion outflow rates are computed as a function of $F_{10.7}$ for selected ranges of Kp, Dst, or AE, and conversely as a function of Kp, Dst, or AE, for selected ranges of $F_{10.7}$. Note that despite the large size and

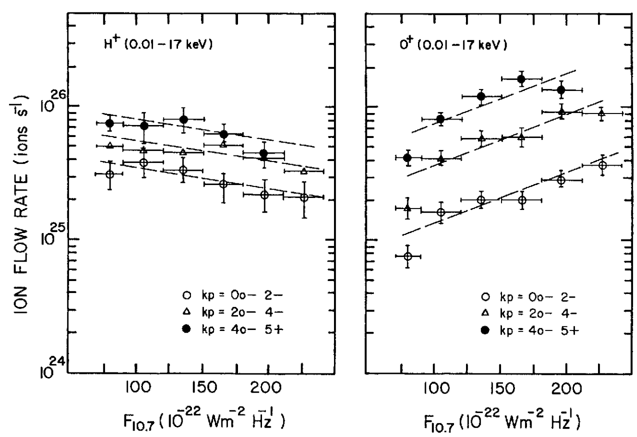

Fig. 2. Ion outflow rate of H^+ and O^+ ions at 0.01-17 keV, as a function of the solar radio flux index $F_{10.7}$, for different ranges of Kp values.

the generally uniform invariant latitude and magnetic local time coverage of the full data base, data gaps in invariant latitude MLT bins exist for some of the $F_{10.7}$-Kp, $F_{10.7}$-Dst, and $F_{10.7}$-AE parameter pairs. The computation was limited to parameter pairs where all invariant latitude bins between 66° and 86° invariant were sampled in each of the four 6-hour MLT sectors.

Ion Flow Dependences

In Figure 2, the ion outflow rate of energetic (0.01-17 keV) H^+ and O^+ was computed as a function of $F_{10.7}$, for three different Kp ranges. In O^+, there is a clearly statistically significant, factor of ~5 increase in the outflow rate from near solar minimum ($F_{10.7} \approx 70$) to near solar maxium ($F_{10.7} \approx 250$). For all three Kp ranges, the dependence of the rate on $F_{10.7}$ is very similar. In contrast, the H^+ rate displays a statistically marginal decrease with $F_{10.7}$. The choice of displaying the flow rate in logarithmic scale versus $F_{10.7}$ in linear scale is somewhat arbitrary in that (a) there is not a known theoretical functional relationship between the two quantities, and (b) other $F_{10.7}$-related quantities (such as the exospheric temperature) may be just as appropriate as the independent parameter. However, a simple exponential dependence appears to be adequate for empirical representation of the data. Explicitly,

$$F_{O^+} \propto \exp(+1.0 \times 10^{-2} F_{10.7}) \quad (4)$$

$$F_{H^+} \propto \exp(-2.7 \times 10^{-3} F_{10.7}) \quad . \quad (5)$$

In Figure 3, the H^+ and O^+ outflow rates were computed as a function of Kp for three $F_{10.7}$ ranges. For clarity, the error bars in this and the succeeding figures have been omitted. The O^+ rate increases exponentially witht Kp by a factor of 20 from Kp = 0 to 6. The rate exceeds 3 x 10^{26} ions s^{-1} at times of high magnetic (Kp = 6) and solar ($F_{10.7} > 150$) activity. As may be anticipated from Figure 2, the rate at low solar activity ($F_{10.7}$ between 70 and 100) is about a factor of 4 smaller than that at higher activity ($F_{10.7}$ between 150 and 250). For all three $F_{10.7}$ ranges, the dependence of the rate on Kp is similar. The similarity justifies the separated treatment of the magnetic (Kp) and solar activity ($F_{10.7}$) variations in the ion outflow rate. In comparison, the H^+ rate increases with Kp more moderately, by a factor of 4, from Kp = 0 to 6. Also, the rates for the three $F_{10.7}$ ranges are similar.

Since the Kp index is a quasi-logarithmic measure of magnetic disturbance, the exponential increase of the H^+ and O^+ outflow rates suggests a quasi-linear dependence of UFI outflow with magnetic activity (as measured by magnetic field perturbation). Empirically, the dependence may be represented as

$$F_{O^+} \propto \exp(0.50 \text{ Kp}) \quad (6)$$

$$F_{H^+} \propto \exp(0.23 \text{ Kp}) \quad . \quad (7)$$

In Figure 4, the H^+ and O^+ outflow rates were computed as a function of the Dst index for $F_{10.7}$ in the range of 70-100 and 100-150, respectively. Again, the rates for the two $F_{10.7}$ ranges are equal within statistical errors for H^+ but significantly different for O^+. Given the large scatters in the data, part of which were attributed to nonuniform data sampling, the O^+ rates for the two $F_{10.7}$ ranges exhibit qualitatively

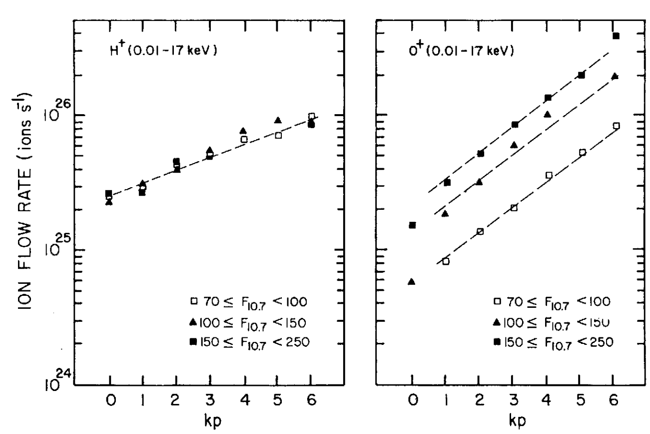

Fig. 3. Ion outflow rate of H^+ and O^+ ions at 0.01-17 keV, as a function of the magnetic Kp index, for different ranges of $F_{10.7}$ values.

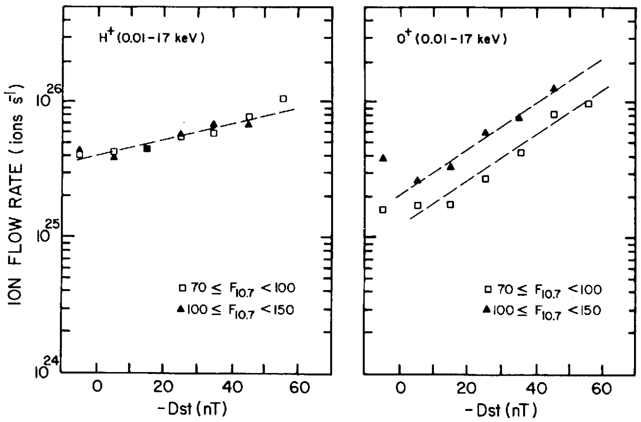

Fig. 4. Ion outflow rate of H^+ and O^+ ions at 0.01-17 keV, as a function of the magnetic Dst index, for different ranges of $F_{10.7}$ values.

similar Dst dependences. The similarity further supports the separation of the magnetic Kp and the solar $F_{10.7}$ dependences in Figures 2 and 3. As noted earlier, the Dst index is primarily a measure of the ring current strength. A quantitative relationship between UFI activity and Dst is not expected theoretically, and the reason for the apparent, exponential correlation between the rates and the Dst index under negative Dst conditions (dashed lines in figure) is not clear. Note that the exponential trend does not appear to extend to positive Dst conditions.

In Figure 5, the outflow rates were computed as a function of the AE index for $F_{10.7}$ below and above 150, respectively, using data samples acquired in the period between September 1981 and December 1983 for which AE index data were available. For all AE values, the rate for high solar activity ($F_{10.7}$) is consistently higher for H^+ and marginally lower for H^+ than the corresponding low $F_{10.7}$ value. In both H^+ and O^+, the rate increases with AE and, except for low AE values, approximately follows a power law dependence. Over the range of AE between 10 and 10^3 nT, the O^+ rate varies between 2×10^{25} and 2×10^{26} ions s^{-1} and the H^+ rate between 2×10^{25} and 7×10^{25} ions s^{-1}. Empirically,

$$F \propto AE^{\alpha} \, , \qquad (8)$$

where $\alpha \approx 0.8$ for O^+ and ≈ 0.4 for H^+. Since the AE index is an approximate, linear measure of the auroral electrojet strength, and UFI events are associated with auroral substorms, a simple, quasi-linear statistical correlation between the UFI outflow rate and the AE index is perhaps not surprising. From the point of view of energy input-to-output ratio (the free energy flux associated with a substorm available for ionospheric ion energization to the energy flux associated with the outflowing ions), a power law index of unity would be expected if the input energy flux was the only controlling factor of UFI production and the overall efficiency of the ion energization process was independent of the input source strength. Empirically, a power law index slightly less than unity simply reflects that such is probably not the case, and that other factors play a significant role in moderating the total throughput. These include, for example, possible changes in the relative importance of parallel and perpendicular energization, changes in the acceleration altitude distribution, and corresponding changes in the amount of ambient ions available for energization, for changing levels of substorm activity. The factor of 2 difference between the H^+ and O^+ power law indices is likely to be related to these factors.

The apparent dependence of the outflow rates at low AE values must be interpreted with caution. As explained earlier, the AE index may underestimate the actual auroral substorm activity, particularly in the case of small, highly localized substorms that are situated between two sparsely spaced auroral observatories, and of very large substorms that are highly equatorward of the observatories. Thus, whereas a large AE value indicates the presence of high substorm activity, a small AE value does not necessarily imply the absence of activity. Also, the transit time for a 10-eV (low-energy limit of the observed ions) O^+ originating as a transversely accelerated ion at 1000 km altitude to reach the DE 1 apogee (23,300 km) is of the order of 1 hour. Thus, UFIs injected at low altitudes during the late recovery phase of a substorm may be present at DE 1 altitude for up to the order of 1 hour following the substorm, when the hourly AE index may have returned to near zero values. For these two reasons, nonnegligible ion outflow may exist at times of near zero AE values, despite the fact that ionospheric

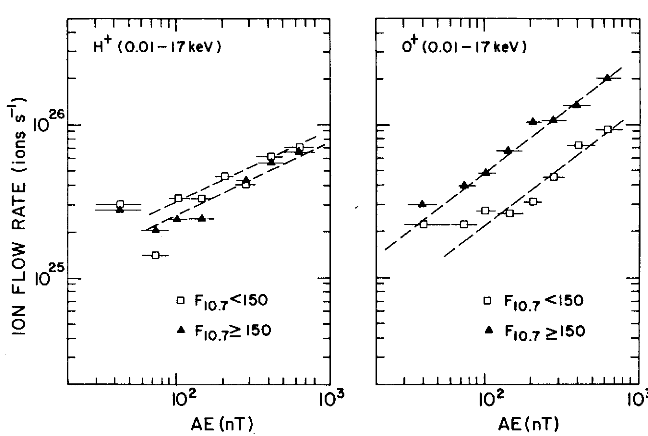

Fig. 5. Ion outflow rate of H^+ and O^+ ions at 0.01-17 keV, as a function of the auroral electrojet index AE, for different ranges of $F_{10.7}$ values.

ion energization may not be occurring at times of no substorm activity.

Conclusions and Discussions

Observed UFI data from the DE 1 EICS, acquired from near the maximum to the minimum of solar cycle 21 ($F_{10.7}$ from <70 to >300), were used to determine the UFI outflow rate as a function of geomagnetic and solar activity conditions and to empirically parametrize its solar ($F_{10.7}$) and magnetic (Kp and AE) dependences. In both H^+ and O^+, ion outflow rate was calculated for ions in the 0.01-17 keV range using the computational procedure described in Yau et al. (1985b). The ion outflow rate increases exponentially with Kp by a factor of 20 for O^+ and 4 for H^+ from Kp = 0 to 6. The exponential dependence prevails at all solar EUV flux levels. Similar exponential increase is found with the Dst index. Also, the rate increases with the hourly AE index. The increase is proportional to AE^{α} where $\alpha \approx 0.8$ and 0.4 for O^+ and H^+, respectively. For a given magnetic activity condition, the O^+ rate increases by a factor of ~5 in the $F_{10.7}$ range of 70-250. In contrast, the H^+ rate displays a statistically marginal factor of 2 decrease with increasing $F_{10.7}$. The very different magnetic and solar activity dependences between the H^+ and O^+ rates result in an order of magnitude increase in the O^+/H^+ UFI composition ratio from solar minimum to maximum for a given magnetic activity level, as well as from magnetically quiet to active time for a given solar EUV activity level. The variations may be empirically parametrized as follows:

$$F_{O^+}(Kp, F_{10.7}) = 1.0 \times 10^{25} \exp[+1.0 \times 10^{-2} (F_{10.7} - 100)] \exp(0.50\ Kp) \quad (9)$$

$$F_{H^+}(Kp, F_{10.7}) = 2.5 \times 10^{25} \exp[-2.7 \times 10^{-3} (F_{10.7} - 100)] \exp(0.23\ Kp) \quad (10)$$

$$F_{O^+}(AE, F_{10.7}) = 4.2 \times 10^{25} \exp[+1.0 \times 10^{-2} (F_{10.7} - 100)] (AE/100)^{0.8} \quad (11)$$

$$F_{H^+}(AE, F_{10.7}) = 4.3 \times 10^{25} \exp[-2.7 \times 10^{-3} (F_{10.7} - 100)] (AE/100)^{0.4} \quad (12)$$

in the ranges of Kp = 0-6, $F_{10.7}$ = 70-250, and AE $\geq$ 100.

Young et al. (1982) found similar $F_{10.7}$ dependence of 0.9-16 keV equatorially trapped O^+ density at geosynchronous altitudes. They found an exponential coefficient between 1.0×10^{-2} (all Kp data) and 1.8×10^{-2} (Kp $\leq$ 2 data) for O^+ and a coefficient between ~0 (all Kp data) and 3.2×10^{-3} (Kp $\leq$ 2 data).

The magnitude and composition of energetic UFI are key parameters in a coupled magnetospheric-ionospheric model. Equations (9)-(12) represent important input terms to such a model. The equations do not include UFIs below 10 eV or above 17 keV. The contribution of >17-keV ions is believed to be small since the outflow in the 0.01-17 keV range is dominated by <1-keV ions. On the other hand, the contributions from ions below 10 eV, particularly the cleft ion fountain, are probably non-negligible. Recently, Chappell et al. (1987) inferred the relative contribution between ions below and above 10 eV to the cleft ion fountain, using typical upwelling ion energy spectra taken near solar maximum. They found a ratio of about 4 for O^+ and about 0.25 for H^+. Furthermore, they made a rough estimate of the contribution of the <10-eV cleft ion fountain to the total ion outflow by equating the observed outflow of UFI above 10 eV (by EICS) near the dayside cusp to the >10-eV component of the cleft ion fountain. A quantitative determination of the contribution of upwelling ions below 10 eV to the total ion outflow (as well as their fate at high altitude) will be very useful for the model.

The empirically separate dependences of UFI outflow rate on magnetic and solar activities in equations (9)-(12) simply reflect the fact that overall UFI activity--and ultimately the coupling between the ionosphere and the magnetosphere--are intimately modulated by the neutral atmosphere.

Finally, the quantitative AE and $F_{10.7}$ dependences of UFIs above may be related to their magnetospheric ion composition counterparts. On ISEE 1, Lennartsson and Shelley (1986) found order of magnitude changes in energetic O^+ ion densities in the plasma sheet with AE, and lesser but nevertheless significant changes with moderate change in $F_{10.7}$. Quantitative comparison of the dependences between the present UFI and the ISEE 1 plasma sheet results provides a definitive means with which to assess the terrestrial contribution to the hot magnetospheric plasma population.

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