Auroral Ionospheric Ion Feeding of the Inner Plasma Sheet during Substorms

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During the last decade, satellite observations in the nightside magnetosphere have confirmed the presence of energetic (>20 keV) ionospheric-origin ions in the near-Earth magnetotail. Observations also imply that the feeding of the equatorial magnetosphere with ions from the high-latitude ionosphere can be very fast and intense at times. In the present paper we use observations from the Combined Release and Radiation Effects Satellite (CRRES) to investigate the characteristics of ion energy density variations. Multispecies studies of the energy density give important clues on the coupling of the different plasma sources and their participation in the substorm energization. The measurements, coming from the Magnetospheric Ion Composition Spectrometer (MICS), confirm previous results obtained from the AMPTE/CCE-CHEM spectrometer, with regard to the timing of the high-latitude ionosphere response to the equatorial magnetosphere disturbances. The energy density profile of the ionospheric-origin O^+ follows the intensity enhancements of the westward electrojet very closely in time, exhibiting a continuing increase, contrary to the behaviour of the other major ion species H^+ and He^{++} . This feature, which is consistent with statistical studies of AMPTE/CCE observations, points towards a fast activation of an extraction/acceleration mechanism which feeds the inner plasma sheet with ions of ionospheric origin during the substorm expansion.

1. Introduction

Measurements by mass/charge-discriminating energetic plasma instruments on board several spacecraft in the late 1970s (e.g., Balsiger *et al.*, 1980) and the 1980s (e.g., Gloeckler and Hamilton, 1987) confirmed the early observations of O^+ ions by Shelley *et al.* (1972). Observations from both equatorial and polar orbiting spacecraft (e.g. Hultqvist, 1991) have demonstrated that the high-latitude terrestrial ionosphere is a significant hot plasma source for the magnetosphere. The two most important ionospheric outflow regions are the auroral region and the dayside cleft; statistical studies by Yau *et al.* (1984) and Lockwood *et al.* (1985) concluded that the auroral ionosphere is the major source of magnetospheric O^+ ions.

Statistical studies of AMPTE/CCE observations in the nightside magnetosphere during substorms (Daglis *et al.*, 1991, 1992, 1994a) have shown that the energy density of the ionospheric-origin O^+ ions correlates strongly with the auroral electrojet intensity. This is a feature of the O^+ ions only; the He^{++} ions (of solar wind origin) show a very poor correlation with the auroral electrojet intensity. The trend of O^+ is presented in Fig. 1 and is indicative of a fast extraction/acceleration mechanism closely related to the energy dissipation at the nightside auroral ionosphere. The parameters that appear on top of Fig. 1 refer to the fit applied to the original data. The regression coefficient is equal to $b = 2.3 \cdot 10^{-3}$, so that we have $ED(O^+) = -0.04 + 2.3 \cdot 10^{-3} \cdot AL$, where AL is given in nT and ED in keV/cm³. The correlation coefficient is $r = 0.73$, with an F -ratio value of 143.26, which (for 126 observations) yields

Fig. 1. The diagram demonstrates the strong correlation between the O^+ energy density and the auroral electrojet intensity during substorm expansion phase on timescales of minutes.

a confidence level higher than 99.99%. The corresponding fit for He^{++} (not shown here) gave $ED(He^{++}) = 0.29 + 0.39 \cdot 10^{-3} \cdot AL$, with a correlation coefficient of 0.29 and an F -ratio value of 11.09, showing that the energy density of the solar wind origin He^{++} correlates very poorly with the auroral electrojet intensity, in contrast to the ionospheric-origin O^+ ions.

The time resolution used by Daglis *et al.* in these studies was 15 min, which is far better than the time resolution of previous relevant statistical studies. Most of the previous studies had used long-time averages of AE indices or the Kp index (e.g. Young *et al.*, 1982; Lennartsson and Sharp, 1985; Lennartsson and Shelley, 1986). However, within a time interval of 3 or more hours, several substorms can take place and both the magnetospheric conditions and the ionospheric state can undergo a series of dramatic changes. The use of several-minute averages of AE data guarantees that the substorm features are not *a priori* smoothed out (Baker *et al.*, 1986).

Furthermore, the above mentioned studies of AMPTE/CCE observations were the first statistical studies of energy density in the near-Earth magnetotail with multi-species ion data extending into the higher energy range (≥ 20 keV/e). A large gap in multispecies ion measurements between 20 and 200 keV existed until the middle of the 1980s; this was considered critical in the effort to assess the makeup of magnetospheric populations (Young, 1983). Furthermore, the energy range between 20 and 200 keV was suggested (Williams, 1981) and later shown (Krimigis *et al.*, 1985; Hamilton *et al.*, 1988) to be the most important energy range during the main phase of geomagnetic storms, because the bulk of the ring current energy density is contained within this range. Later, Daglis *et al.* (1994b) showed that the high-energy range is also the most important range during the substorm expansion phase: they showed that the energy density is essentially carried by the high-energy (≥ 20 keV) ions during substorm expansion (see Fig. 11 of Daglis *et al.* (1994a)). It is obvious that measurements in the high energy range (≥ 20 keV) are critical for

Fig. 2. The diagram shows the time profile of the average energy density gain for 131 substorms observed by AMPTE/CCE in the nightside magnetosphere, near $r/R_E = 8$ and around local midnight (after Daglis (1991)). The two main features are the continuing increase of O^+ energy density gain, contrary to H^+ and He^{++} , and the maximum reached by O^+ , which is about double the maximum of the other two ion species.

substorm studies.

A remarkable statistical difference between the ionospheric-origin O^+ and the solar wind origin He^{++} during substorms was presented by Daglis (1991): after the substorm onset the O^+ energy density is gradual and continuous while the energy density gain of He^{++} is like a step function, that is it takes place only just after onset. The continuing rise in energy density gain of O^+ , in contrast with the step-wise gain of H^+ and He^{++} energy density indicates a source of O^+ which remains active for some time after the substorm expansion onset. Furthermore, O^+ reaches the highest relative energy density gain among the major ion species (Fig. 2).

The CRRES mission followed the AMPTE mission and its orbit configuration made it very suitable to cross-check the AMPTE results. During the 13 months of the mission lifetime, the eccentric orbit of CRRES permitted the exploration of the inner magnetosphere, from the outer radiation belts up to the inner boundary of the plasma sheet, over magnetic local times from 0800 (through 2400) to 1600 hours. The substorm observations that we present here, indicate a fast ionospheric ion feeding of the inner plasma sheet during the substorm expansion. Observations implying direct injection of ionospheric ions into the mid-tail plasma sheet ($15 \leq r/R_E \leq 30$) were previously presented by Möbius *et al.* (1987) and Orsini *et al.* (1988, 1990).

2. Observations

We shall present substorm observations from the CRRES mission. CRRES was launched on 25 July 1990, and was operational until 9 October 1991; it had an elliptic orbit with geocentric

apogee at $\sim 6.3 R_E$, a perigee altitude of 370 km and an orbital inclination of $\sim 18.1^\circ$. The orbital period was ~ 10 hours, and the spin period was approximately 30 s with the spin axis pointing roughly toward the Sun. A detailed description of CRRES is given by Johnson and Kierein (1992).

For this study we have used particle data from the Magnetospheric Ion Composition Spectrometer (MICS), which belongs to a class of advanced instruments providing full characterization of incident ions by determining their mass A , charge Q and velocity V (Wilken *et al.*, 1992). MICS determines the ion identity from a combination of electrostatic deflection, post acceleration (improving the resolution at low particle energies) and time-of-flight and energy measurements. The time-of-flight/energy detector geometry was matched to an electrostatic analyzer of an unusual ogive design to achieve high system sensitivity coupled with a rather narrow collimation angle of 1.1° . The double and triple coincidence technique used by MICS provided inherent immunity to background.

We shall present three substorm events observed by CRRES within the first three months of 1991. We deliberately selected events from this time period, because of the availability of provisional AE indices prepared by Alexander G. Yahnin (Polar Geophysical Institute, Apatity, Russia). The first substorm event was observed on 14 to 15 February 1991, with CRRES located in the premidnight magnetosphere. As already reported by Grande *et al.* (1992), CRRES observed a multiple ion injection during this event, with the first onset at 2352 UT. A remarkable variation was observed with regard to the relative abundance of the solar wind origin He^{++} and the ionospheric-origin O^+ ions: in the first injection the He^{++} abundance was higher, while in the second injection the O^+ proportion increased greatly and surpassed He^{++} . Grande *et al.* (1992) also reported that the count rate of all ions with a charge greater than two (of predominantly solar wind origin) followed a very similar pattern to that of He^{++} . The ratio of He^{++} to the higher charge state material was shown to remain constant throughout that day.

Our main interest has been to investigate the features of energy density, because they constitute valuable diagnostics of the participation of the different plasma sources in the substorm energization process. We have calculated the energy density for the energy range from 20 to 426 keV for H^+ and from 50 to 426 keV for O^+ . Although the useful energy range of MICS extends from 426 keV/e down to about 1 keV/e, due to insufficient calibration data the rates we used could be confidently converted to fluxes for the above mentioned energy ranges only.

We show the time profile of the energy density of the three major ion species (H^+ , O^+ , He^{++}), along with the contribution of H^+ and O^+ to the total energy density, in Fig. 3. What is readily recognizable is the time-shifted increase of O^+ energy density. It is also evident that H^+ is the dominant ion species, contributing more than 75% of the total energy density at all times. After the onset of the substorm however, the contribution of O^+ rises from zero to above 15% (panel 5), which is also reflected in the fall of the corresponding H^+ line (panel 4). These features are consistent with a time-shifted (delayed) feeding of the near-Earth magnetotail with, and subsequent injection to the inner magnetosphere of, ionospheric-origin O^+ ions as a fast response of the high-latitude ionosphere to the onset of the substorm.

Comparison of the energy density time profile with the AL index time profile (Fig. 3) reveals a most interesting similarity between the AL and the O^+ patterns. The first drop in AL is concurrent with the enhancement in the energy density of both O^+ and He^{++} . The second AL drop however, is concurrent with the second enhancement in the O^+ energy density and the increase of its contribution to the total energy density from $\sim 6\%$ to 12% . Another most interesting feature is that during the second enhancement of O^+ , the AU index exhibits a jump from the level of the past 30 minutes, which is equivalent to an enhancement of the convectional DP2 current system, a signature of driven energy dissipation. Hence, in this case we see an isolated, transient increase of O^+ energy density, at the time of coexistence of DP1 and DP2 systems. The global geomagnetic activity during this event was low to moderate ($Dst = -13$ nT,

Fig. 3. Energy density time profile and provisional AE indices for the event on 14 February 1991. The seven panels show: 1. the H^+ energy density (in keV/cm^3), 2. the O^+ energy density, 3. the He^{++} density, 4. the contribution of H^+ to the total energy density (in %), 5. the contribution of O^+ to the total energy density, 6. the AL index, 7. the AU index.

Fig. 5. Energy density time profile and provisional AE indices for the event on 23 March 1991. The format is the same as in Fig. 3.

is initially common for all three ion species (H^+ , O^+ , He^{++}), and the subsequent intense second enhancement of O^+ energy density only. Again the O^+ enhancement is concurrent with a simultaneous increase of both AL and AU . The global geomagnetic activity during this event was moderate ($Dst = -30$ nT, $Kp = 4+$ to $5-$). The energy density of all ion species was

substantially higher in this event, as compared to the event of 14 February 1991. The energy density of O^+ in particular, reached rather high values (~ 15 keV/cm³), contributing about 40% of the total energy density (panel 5 of Fig. 4).

The third substorm event was observed by CRRES on 23 March 1991. The onset was at 0222 UT and the energy density time profiles and *AE* indices are shown in Fig. 5, in the same format as in Fig. 3. The enhancements of energy density in this event are not quite as remarkable as in the previous one. However, one can identify again the striking similarity of the O^+ and the *AL* time profiles on a short timescale. During this event however, there has been no increase in the *AU* magnitude, showing the absence of a combined DP1-DP2 enhanced current system. The global activity in this case was low to moderate (*Dst* = -15, *Kp* : 3- to 3+).

3. Discussion

The substorm events we have presented have a common feature: the O^+ energy density time profile closely follows the *AL* index time profile, in contrast with the other two major ion species H^+ and He^{++} . This is most evident in the concurrent continuing increase of O^+ energy density and continuing drop in the *AL* index. In the two out of the three cases presented here, the extraordinary second rise in O^+ pressure is concurrent with a combined DP1-DP2 enhanced current system, as shown by the *AL* and *AU* indices. Clauer and Kamide (1985) and Kamide and Baumjohann (1985) showed that direct dissipation (DP2 current system) and explosive dissipation (DP1 current system) of energy may coexist during the expansion phase with the direct dissipation being decreased or enhanced as compared to that during the growth phase. Since energy dissipation through ionospheric currents presumably is a critical parameter in the process of ionospheric ion extraction, the relation of direct to explosive energy dissipation may well influence or even determine the morphology of ionospheric ion outflow. However, further research on this issue is needed before conclusions are drawn.

The results of this CRRES case study are very much consistent with the implications of the statistical studies of AMPTE/CCE observations by Daglis *et al.* (1992) and Daglis *et al.* (1994b). There is not simply a tendency of higher O^+ abundance during periods of higher geomagnetic activity (e.g. Young *et al.*, 1982), but rather a concurrent enhancement of the O^+ energy density and the westward (and, occasionally, the eastward) auroral electrojet. We suggest a fast feeding of the inner plasma sheet with ions of ionospheric origin, initiated by the increased geospace activity and associated magnetosphere reconfigurations ("dipolarizations") after substorm onset (Daglis and Axford, on print, 1996). Although the structure of the near-Earth magnetotail and its connection to the polar ionosphere are still far from clear (Galperin, 1995), it is assumed that the auroral ionosphere is magnetically connected with the inner plasma sheet during substorm expansion, as suggested by Lassen and Friis-Christensen (1991), Galperin and Feldstein (1991) and Jordan *et al.* (1992). The increased concentration of ionospheric O^+ ions in the inner plasma sheet may regulate the triggering of successive substorm onsets (e.g., Lakhina, 1995) during periods of continuing solar wind-magnetosphere coupling.

A limitation of the set of events presented here is that all three events were observed by CRRES in the premidnight near-Earth magnetosphere; it has been suggested that this region (rather than the postmidnight region) is more likely to couple with the upper ionosphere during substorms (e.g., Baker *et al.*, 1985).

The outflow of ionospheric ions and their concentration in the plasma sheet is generally transient and localized, as indicated by the studies of Strangeway and Johnson (1983), Heelis *et al.* (1984) and Stokholm *et al.* (1985). By "transient" we do not mean that the overall response of the ionosphere to enhanced geospace activity is temporally limited, but rather that different (localized) regions of the upper ionosphere successively respond and feed different parts of the inner magnetotail with outflowing ions for relatively short time intervals (as compared with the duration

of the substorm expansion). The "intermittent" one-spacecraft observations of the ionospheric outflow and of the ionospheric ion feeding of the inner magnetotail are not sufficient to resolve the spatial/temporal characteristics of magnetosphere-ionosphere coupling during substorms. A useful tool in this context would be energetic neutral atom imaging of the auroral outflow (e.g., Daglis and Livi, 1995) and coordinated composition measurements by more than one spacecraft in the inner magnetotail.

There are obviously various factors influencing the transition from a weak feeding to a strong feeding of the magnetosphere with ionospheric ions, as during great magnetic storms for example (Daglis *et al.*, 1995). Such factors should be the following: the solar UV radiation level influencing the scale height of oxygen in the upper atmosphere, the magnitude of solar wind velocity (Lundin *et al.*, 1995), the auroral current dissipation (Daglis *et al.*, 1994b), the magnitude of induced electric fields during substorm onset dipolarization (Daglis *et al.*, 1994a), and certainly the prior history of geomagnetic activity. A future study will investigate the relation between these factors and the ionosphere-magnetosphere coupling through the outflowing ions.

4. Summary

We have presented observations of the major ions' energy density by the CRRES satellite during three substorms. We have been interested in energy density variations because they are valuable diagnostics of the participation of the two main sources of magnetospheric plasma in the substorm energization process. There are two conditions that have to be fulfilled for such studies: first is a high time resolution (of the order of several minutes) and second is the information on the high energy range. A high time resolution is crucial, because only a time resolution of the order of several minutes can assure that information on the dynamics of substorm phases will not be masked (Baker *et al.*, 1986). Higher energy range means energies above 20 keV/e, which have been shown to be most critical during substorm expansion (Daglis *et al.*, 1994b).

The CRRES-MICS measurements show that the time profiles of O^+ energy density and AL index are strikingly similar, in contrast to the other major ion species H^+ and He^{++} . The feature of continuing increase of the O^+ energy density for some time after substorm onset and after H^+ and He^{++} have reached their final value, known from statistical studies of AMPTE/CCE observations (Daglis *et al.*, 1994b), is also present in the substorms observed by CRRES. These characteristics suggest a fast response of the ionosphere to increased solar wind-magnetosphere coupling and associated dynamic reconfigurations, in the form of enhanced feeding of the inner plasma sheet by ion outflow from the auroral ionosphere.

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