



Influence of Interplanetary Disturbances on the Terrestrial Ionospheric Outflow

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Abstract. Following the discovery of the terrestrial ionospheric outflow in the early 1970s, and the confirmation of its significance in the late 1970s and the 1980s, a large number of studies investigated the processes leading to the escape of ionospheric ions to the magnetosphere. In general, ionospheric outflow was found to increase proportionally with geomagnetic activity. In the late 1980s and the 1990s several studies showed that whenever the abundance of ionospheric origin ions in the magnetosphere is extraordinarily high, their effects on geospace activity are substantial. It has been suggested that the large abundance of ionospheric origin ions regulates major dynamic processes like storms and substorms. This appears to be the case during great magnetic storms. A number of factors have been identified, which have a critical influence on the extent and the characteristics of ionospheric outflow. There are certainly several internal geospace factors, but a major influence on ionospheric outflow presumably originates in certain interplanetary structures. Such structures are for example high-speed streams, magnetic clouds, and coronal mass ejections. We will discuss the relationship between interplanetary structures and ionospheric outflow, on the basis of both theoretical expectations and observational facts. © 1998 Elsevier Science Ltd. All rights reserved.

1 Introduction

A bulk of observational and theoretical work exists on the escape of ions from the ionosphere to the magnetosphere of the Earth. The first considerations of the significance of ionospheric outflow (Dessler and Hansson, 1961; Axford, 1970) were not welcomed by the early space community (e.g., Hill, 1974). However, after the discovery of energetic ionospheric O⁺ ions by the Lockheed group (Shelley et al., 1972), a number of missions confirmed the presence of significant amounts of ions of ionospheric origin in the magnetosphere (e.g., Geiss et al., 1978; Lennartsson and Sharp, 1982; Daglis et al., 1991).

Ionospheric-origin ions have been observed in a wide range of energies, from hundreds of eV to hundreds of keV (Kaye et al., 1981; Ipavich et al., 1984; Strangeway and Johnson, 1984; Stokholm et al., 1985; Lennartsson and Shelley, 1986; Daglis et al., 1993) and in a variety of locations, from the inner magnetosphere to the distant magnetotail (Candidi et al., 1982; Daglis et al., 1991; Wilken et al., 1995; Zong et al., 1997).

Most investigations relevant to ionospheric outflow focused on O⁺, because it is the major ionospheric-origin ion species in the magnetosphere. The abundance of O⁺ is most variable: Daglis et al. (1993) showed that its contribution to the total energy density in the energy range 1–300 keV is well below 10% during quiet times, while it exceeds 50% during great storms (e.g. Hamilton et al., 1988; Daglis et al., 1998b).

What makes the O⁺ abundance in the magnetosphere so variable? There is a large variety of processes that have been suggested to cause or influence the acceleration of ionospheric O⁺ and its extraction to the magnetosphere. Suggested processes include field-aligned electric fields (Mizera and Fennell, 1977; Cladis, 1986), hydrogen cyclotron waves (Kintner et al., 1979), various instabilities (e.g., Lakhina and Bhatia, 1984), low-frequency wave heating (Temerin and Roth, 1986), resonant heating due to Alfvén waves (Chang et al., 1986), large-amplitude low-frequency electric field fluctuations (Lundin and Hultqvist, 1989; Hultqvist, 1996), lower hybrid dissipative cavitons (Shapiro et al., 1995), etc. A rich literature on this topic exists.

The present paper addresses the possibility that the extent of ionospheric outflow is additionally influenced, or even controlled, by interplanetary parameters. In particular, we suggest that particular interplanetary conditions, such as a strong and prolonged southward IMF, will allow the internal extracting and accelerating processes to remain active for an extended time interval. The result would be an accumulation of extracted ionospheric O⁺, and eventually an O⁺ dominance during intervals of very high geospace activity, as observed during intense storms.

2 Observations/Discussion

Here we refer to a number of large storms observed with the Magnetospheric Ion Composition Spectrometer (MICS, Wilken *et al.*, 1992) on board the Combined Release and Radiation Effects Satellite (CRRES) in 1991. The storms started on March 24, June 4, July 8, and July 12, respectively. All four storms had a minimum $Dst \leq -200$ nT at their maximum epoch; they were presented in detail, along with a medium size storm (which took place in February 1991) by Daglis (1997).

The common characteristic of these intense storms was the prominent dominance of O^+ at their maximum epoch, as well as the prolonged extraordinarily high values of O^+ concentration. The contribution of O^+ to the total energy density in the L -range 5 to 6, measured in the energy range 50-425 keV, was more than 50% around storm maximum for all cases. In the June 4 and the July 12 storms the O^+ contribution stayed above 20% for more than 36 hours (see lower panels of Figs. 1 and 2). In the March storm, which was the greatest of all, reaching a deep Dst of -300 nT, the O^+ contribution stayed above 20% for about 4 days!

Considering the fact that the O^+ contribution to the total energy density in this region and energy range does not exceed 10% (Daglis *et al.*, 1993) during quiet times, it becomes clear that an explosive ionospheric feeding of the inner magnetosphere took place. What could be the cause of such an explosive O^+ enhancement? The basic mechanisms of ionospheric ion extraction and acceleration are more or less known and have been observed by many polar orbiting spacecraft. Relevant observations have been made by S3-3 (Collin *et al.*, 1984), Dynamics Explorer 1 and 2 (Heelis *et al.*, 1984; Chandler *et al.*, 1991), Viking (Hultqvist *et al.*, 1988), Akebono (Abe *et al.*, 1993), ISEE 1 (Cattell *et al.*, 1993), Freja (André *et al.*, 1994), and FAST (Klumpar *et al.*, 1997).

The two major source regions in the ionosphere are the cusp/cleft ion fountain and the auroral ionosphere. It is not clear yet if the two sources are concurrently active or not, and if they are more (or less) active during particular processes (as for example substorms). The auroral arc related outflows seem to be more frequent and result in larger values of ion fluxes during periods of intense auroral activity, that is during substorms (e.g., Gazey *et al.*, 1996).

Some of the mechanisms responsible for ionospheric upflow and outflow operate either more efficiently or exclusively during geomagnetically active periods, i.e. during substorms and storms. The resulting effect is the well known general enhancement of O^+ abundance with increasing geomagnetic activity (e.g., Geiss *et al.*, 1978; Young *et al.*, 1982; Lennartsson and Shelley, 1986; Daglis *et al.*, 1991). During substorms however, all these mechanisms, although very efficient in energizing the rather cold ionospheric ions, result in only transient enhancements of O^+ in the magnetosphere.

How can we explain the remarkable difference of intense storms? Are there any common features among these storms, except for the high and long-lived O^+ abundance?

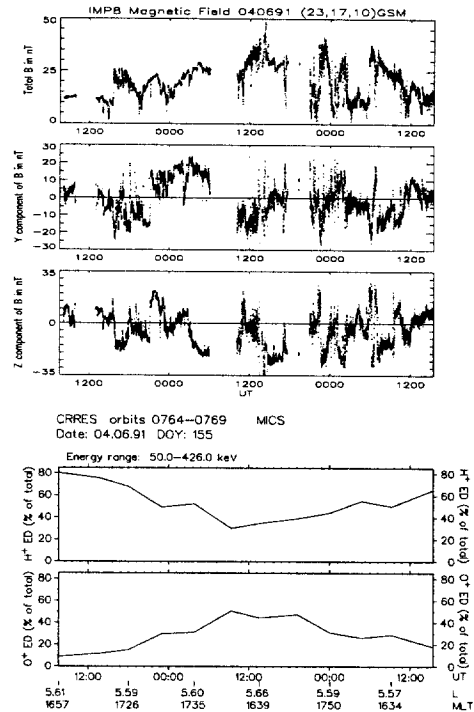


Fig. 1. The storm of June 4, 1991. The three upper profiles show the time profile of the three components of the interplanetary magnetic field (IMF) from IMP 8, while the lower two panels show the time profile of the H^+ and the O^+ contribution to the total ion energy density. The period of maximum O^+ is preceded by a period of prolonged southward IMF.

Figures 1 and 2 (lower panels) show, as already mentioned, the time profile of the contribution of H^+ and O^+ to the total energy density in the inner magnetosphere. The upper panels of the Figures show the three components (x , y , z) of the interplanetary magnetic field, as measured by IMP 8. It is remarkable that the periods of maximum O^+ contribution are preceded by several-hours intervals of southward IMF. Daglis *et al.* (1995) counted southward IMF among the factors regulating the supply of ionospheric ions to the magnetosphere during geomagnetically active times. It is plausible that southward IMF will promote ionospheric outflow, since it increases the rate of energy input from the solar wind into the magnetosphere via dayside merging, and therefore drives magnetospheric substorms. Which in turn are associated with increased ionospheric outflow. However, as we already mentioned, O^+ never reaches such high and long-lived abundance during non-storm-substorms, as it reached during the storms under discussion.

Tsurutani and Gonzalez (1997) have empirically shown that intense storms ($Dst \leq -100$ nT) are primarily caused by $B_z \leq -10$ nT fields with duration greater than 3 hours. This is the case in all four intense storms of 1991. However there is no consensus yet, as to how/why these prolonged southward IMFs result in intense storms. The major question is if intense storms are the result of the enhanced magnetospheric convection driven by the prolonged southward IMF, or if they are the result of successive strong substorms, which involve internal magnetospheric dynamics and are not directly driven (Kamide *et al.*, 1998).

We suggest that substorm series initiated and continuously supplied with solar wind energy due to prolonged southward IMF, keep ionospheric outflow enhanced for a long time period, unlike isolated substorms, and result in heavy loading of the inner magnetosphere with O^+ ions. It is assumable that during such periods of intense substorm activity (see Figure 1 of Daglis *et al.*, 1998b), the two major ionospheric source regions (cusp/cleft and auroral zone) are simultaneously and highly active and that more than one acceleration mechanisms operate. Such differences from isolated substorms would explain why storm-time substorms are much more O^+ -rich.

Certainly the fact that CRRES operated around solar maximum is also, at least partially, a reason for the exceptionally high O^+ abundance, as compared for example with the February 1986 storm (studied by Hamilton *et al.*, 1988) near solar minimum. Young *et al.* (1982) examined GEOS 1 and 2 measurements and found that the O^+ density exhibits striking correlation with solar EUV as measured by F10.7. The observed correlation has been interpreted as a result of increased ionospheric and atmospheric scale heights at solar maximum (caused by the increased solar EUV irradiation), which effectively shift the O^+ -H charge exchange altitude upward and facilitate O^+ injection to higher altitudes.

Yau *et al.* (1985, 1988) showed on the basis of Dynamics Explorer I measurements that the O^+ outflow increases by a factor of 5 between solar minimum and solar maximum.

Barakat *et al.* (1987) found that limiting outflowing fluxes exist for both ionospheric H^+ and O^+ , but the O^+ limiting fluxes increase with solar EUV due to the enhanced neutral temperature and resulting changes in density profiles. The authors argued that the H^+ flow would approach its limiting value everywhere outside the plasmapause, while the O^+ flux would vary strongly with the amount of plasma heating present in the topside ionosphere, from essentially zero to its limiting value.

Hence the heating rate of the topside ionosphere due to the dissipation of energy, both driven and unloading, exerts primary control over the O^+ flux. However, the heating is greater during substorms.

Lundin *et al.* (1995) suggested that according to Viking measurements, it is the solar wind velocity that influences outflow characteristics (namely the energy), not the

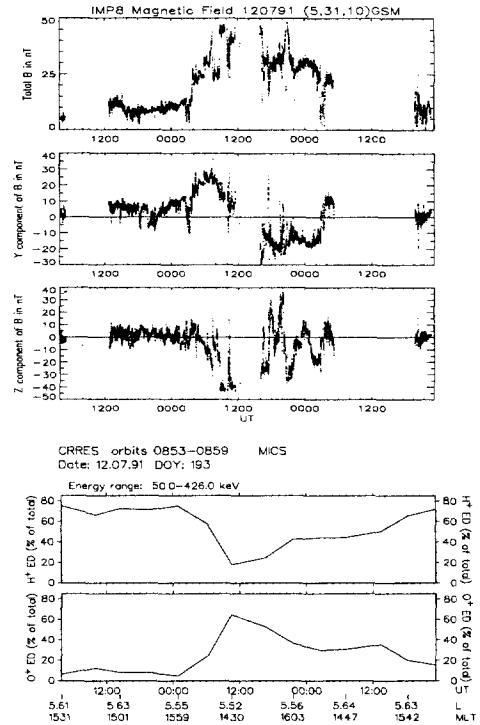


Fig. 2. The storm of July 12, 1991 (format same as in Fig. 1).

orientation of the IMF. An example of an intense storm with a period of high-speed solar wind and a high abundance of O^+ in the inner magnetosphere was the February 1986 storm (Hamilton *et al.*, 1988). The great February 1986 storm started with an SSC on February 6, at 1200 UT. Late on February 8, the solar wind reached very high speeds (~ 1200 km/s), O^+ became the dominant ion species in the inner magnetosphere and Dst reached its minimum (approx. -300 nT). Unfortunately we have not examined the solar wind velocity profiles for the 1991 storms yet. However, a more detailed study is under preparation.

3 Summary

It is clear that although many internal magnetospheric factors regulate ionospheric outflow, a substantial if not major influence on ionospheric outflow presumably originates in certain interplanetary structures. Such structures are for example high-speed streams, magnetic clouds, and coronal mass ejections (Daglis *et al.*, 1997).

These interplanetary structures are also candidates for being responsible for the "envelope-phenomenon" of the very high O^+ concentrations, namely the intense magnetic storms (Daglis *et al.*, 1998a; Tsurutani *et al.*, 1998). Coronal

mass ejections, in particular, have been shown to be associated with the vast majority of intense storms (Gosling *et al.*, 1992).

The main "geoeffective" characteristics of these interplanetary structures seem to be: 1. The prolonged southward magnetic fields, which presumably increase the merging rate at the dayside magnetopause, and 2. The prolonged high speed solar wind flow, which presumably increases the solar wind-magnetosphere viscous-type coupling through the boundary layer dynamo (as suggested by Lundin *et al.*, 1995), and/or increases the convection electric field (whenever there is a concurrent negative B_z).

In summary, we suggest that particular interplanetary conditions, such as a strong and prolonged southward IMF, or high-speed solar wind, which are encountered in certain structures such as interplanetary coronal mass ejections, allow the magnetospheric processes of ionospheric ion extraction and acceleration to remain active for an extended time interval. The result is an exceptionally high abundance of ionospheric ions in the storm-time inner magnetosphere, which in great storms is responsible for the bulk of the ring current.

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