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Review Article

On the Dynamics of the Ring Current*

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Abstract. The present knowledge of the ring-current population is first briefly summarized, with emphasis on the lower energies. It is then shown that in the February 1979 magnetic storm O^+ ions of $\leqq 17$ keV energy contributed considerably to the energy density of the ring current in its entire altitude range. They probably dominated the dayside ring current, from an energy density point of view, in the early phase of the storm. It is argued that these O^+ ions, observed in the dayside magnetosphere in the early phase of the storm, were extracted directly from the dayside ionosphere over a wide latitude interval. The likely importance, from an energy density point of view, of O^+ ions in the ring current at higher energies (>17 keV) where the composition has not, as yet, been investigated, is finally discussed.

Key words: Ring current – Energetic particles in magnetosphere – O^+ ions

Introduction

The cause of the world-wide depression of the geomagnetic field intensity during the main phase of magnetic storms, which has been studied for more than a hundred years (Adams, 1880; 1881; Ellis, 1880), is a westward-directed ring current flowing around the Earth. In the last two decades spacecraft borne instruments have demonstrated that the ring current is due to strong increases, in the range $L=2$–7, in the fluxes of electrons and ions which drift around the earth and give rise to the westward current (Hoffman and Brachen, 1967). The ions contribute most to the current and the magnetic field depression is proportional to the energy density of the ring-current plasma (Sckopke, 1966). A fairly complete distribution function for the ring-current ions, determined as a function of L, was first obtained less than ten years ago by Explorer 45 (Williams and Lyons, 1974).

When the Explorer 45 payload was planned and built the ring-current ions were assumed to be virtually all protons, so the lack of a composition-determining instrument on board was not considered to be important. The first energetic-ion mass-spectrometer measurements in space, made by the Lockheed group on low-orbiting satellites, were reported in 1972 (Shelley et al., 1972) and the then astonishing result was that, during magnetic storms, the precipitated energetic-ion fluxes in the 0.7–12 keV energy range sometimes contained even higher fluxes of O^+ ions than of H^+. These observations raised the question of whether the then dominating view, of the ring-current particles as brought into the inner magnetosphere by convection and diffusion from greater distances on the night side (the plasma sheet and the tail), was the whole truth or whether direct injection from the ionosphere might contribute significantly (Shelley et al., 1972, and others later).

Williams (1979; 1981) has recently summarized the development of our understanding of the ring current during the seventies. He has emphasized the importance of composition determinations in a figure and a table reproduced here (Fig. 1 and Table 1). Both Fig. 1 and Table 1 demonstrate effectively the lack of knowledge of the composition of the majority of the ring-current particles. Only for the low and high energy tails of the ring-current ion population have direct measurements of the composition been possible hitherto. Figure 1 also indicates the effect of part of the ions being O^+ instead of H^+ (dashed curve) and demonstrates that the quiet-time ring current has a harder energy spectrum than the storm-time one. It should be emphasized that the profiles in Fig. 1 are based on Explorer 45 observations before and during one single magnetic storm, in December 1971, which was a large one (Dst reached -190 nT), and that smaller storms may show different profiles, especially in the inner part of the ring-current region where differences in the penetration depth of the injected particles become apparent.

After Explorer 45 only a few satellites have provided detailed ring current information. Balsiger et al. (1980) and Balsiger (1981) have analysed GEOS 1 data for two storms covering the energy range from a few tens of eV to a few hundreds of keV. The ring current composition below 17 keV, during the recovery phase of magnetic storms, has been studied by Balsiger et al. (1980) on the basis of GEOS observations and by Lundin et al. (1980) with Prognoz-7 data, with slightly different emphasis. Their results are summarized by Williams (1981). Lennartsson et al. (1981), Peterson et al. (1981), Sharp et al. (1983) and others have recently published results of ISEE 1 measurements of the composition of the ions below 17 keV in the ring-current region as well as in the plasmasheet, adjacent to the ring current and at great distances. They have all demonstrated

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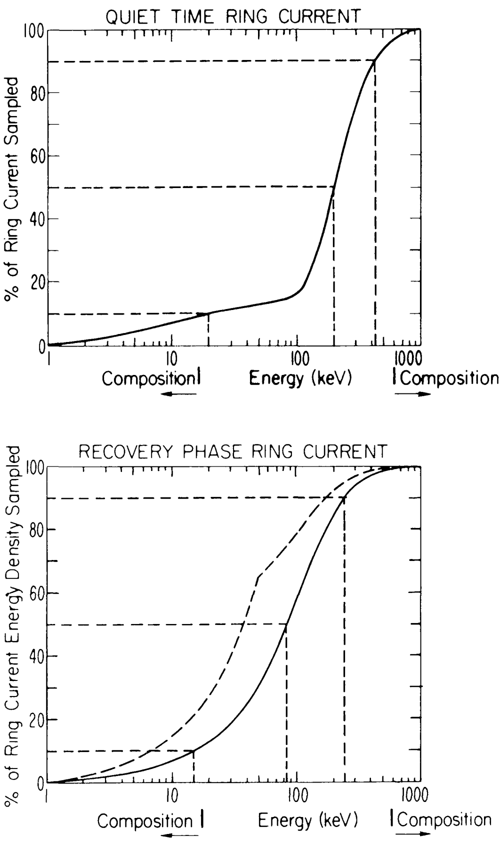


Fig. 1. Cumulative percentage of ring current energy density vs energy for pre-storm and early recovery phases of the major geomagnetic storm on 17 December 1971, as observed by means of Explorer 45 (After Williams, 1981). Solid curves assume all ions are protons. For the dashed curve in the lower diagram all ions below 50 keV have been assumed to be O^+ ions and all ions above 50 keV, protons.

that, in the energy range studied, O^+ ions of ionospheric origin constitute an important part of the hot magnetospheric plasma, from a number density point of view, during disturbed conditions.

None of these authors have dealt with the question of the importance of the observed, fairly low-energy, ring-current ions for the magnetic effects of the ring current, i.e. of the variation of the energy density distribution with energy and L. This review addresses that question as one of its main concerns (although the data available is very limited). In fact there is very little data published on this matter, which may be partially due to the fact that, in order to obtain a cross cut through the whole ring-current region, eccentric orbit satellites are needed. Most satellites in recent years have had very eccentric orbits, which means long orbital periods and generally only one passage through a storm-time ring current per magnetic storm (GEOS-1 is the exception). With highly-eccentric-orbit satellites one thus needs good luck to have a good satellite passage through the ring-current population in the appropriate phase of a storm. The present report is largely based on a fairly detailed analysis of one single such "lucky" observation of the day-side ring current in the early main phase of the 21 February 1979 magnetic storm by means of Prognoz 7. The approach is different and complementary to those of the studies referred to above.

Energy Density Distributions

For the reasons mentioned above (and possibly others) very few observations of the distribution of the energy density in the ring current against energy and radial distance have been published. The question we address in this section is the following: Are the heavy ions of ionospheric origin in the ring current, observed hitherto only below 17 keV for technical reasons, of any importance for the magnetic

Table 1. Ring current composition summary (after Williams, 1979)

Energy (keV)	Technique	H	He	C	O	Comments[a]	Source preference
$\lesssim$17	Direct observation	×	×		×	Low altitude; synoptic surveys; trapped and precipitated; energy, latitude, and time dependence in relative abundances	Ionosphere
$\lesssim$30–50	Inference	×	×		×	Equatorial decay rates-charge exchange comparisons; recovery phase; time dependence in relative abundances	?
50–100						No information; centrum of ring current energy distribution is in 50–100 keV range	?
~100–1,000	Inference	×				Equatorial intensity profile-cross L diffusion comparisons; steady state and recovery phase	?
$\gtrsim$600	Direct observation	×	×	×	×	High altitude; energy, altitude, and time dependence in relative abundances	Solar Wind

[a] Depending on energy, altitude, and time of observation, it is possible for any of the ions indicated to dominate the ion distribution

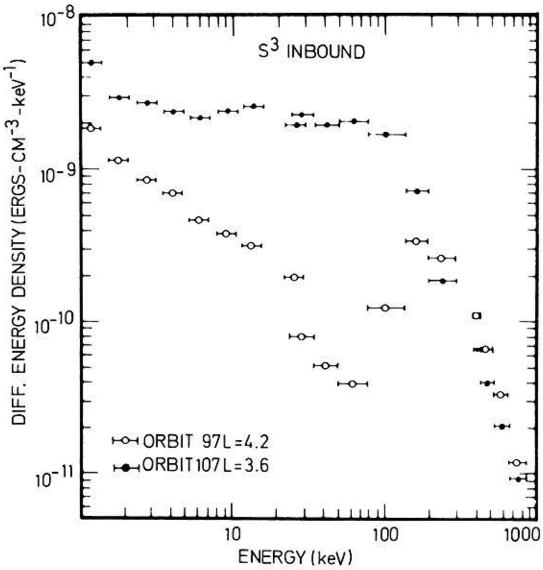


Fig. 2. Ion energy density spectra (protons assumed) measured by Explorer 45 during pre-storm quiet-time (orbit 97) and during early recovery phase (orbit 102) for the 17 December 1971 geomagnetic storm. (From Smith and Hoffman, 1973)

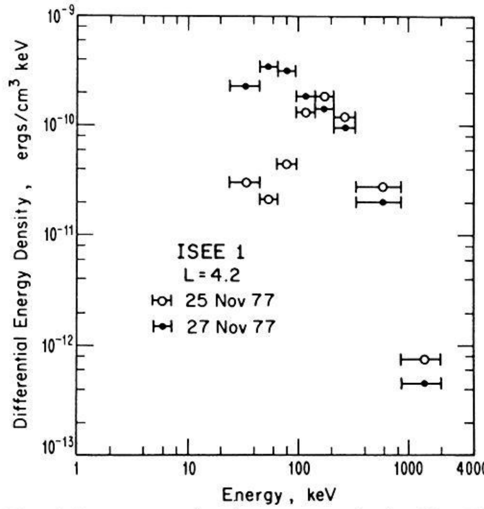


Fig. 4. Ion energy density spectra obtained by ISEE 1 during pre-storm quiet-time (25 November 1977) and during recovery phase (27 November 1977). (After Williams, 1981)

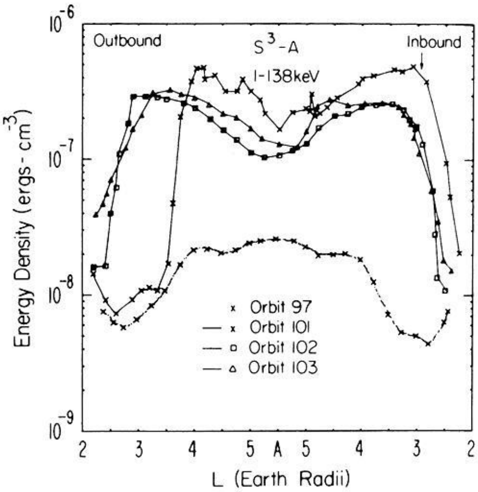


Fig. 3. Proton energy density radial profiles as measured by Explorer 45 (S^3-A) during pre-storm quiet (orbit 97), main phase injection (orbit 101), and recovery phase (orbits 102 and 103) for the 17 December 1971 geomagnetic storm. (From Smith and Hoffman, 1973)

effect associated with the storm-time ring current, or is the magnetic disturbance completely dominated by the higher energy ions in the main part of the ring-current energy range. As this question is of some general interest we will discuss how far we can get in answering it on the basis of the limited published data available.

The most complete data set (except for composition) for the energy density distribution, as a function of energy and L, during different phases of a magnetic storm is that obtained with Explorer 45 during the December 1971 storm (Smith and Hoffman, 1973). This was a large storm ($|Dst|_{max} = 190$ nT). The observations were made in the evening-midnight sector. This storm is also discussed by Williams (1979). Two figures of Smith and Hoffman (1973) are reproduced here as Fig. 2 and 3, as they summarize well the energy density distribution as function of energy (Fig. 2) and of L and the variations of the energy density distribution in the course of such a large storm (Fig. 3). The values shown in these two figures are based on the assumption that the ions were protons. If the ions were heavier than protons the energy density values were higher (Williams, 1979).

During the smaller geomagnetic storm in November 1979 ($|Dst|_{max} = 100$ nT), the ISEE-1 medium energy experiment measured the differential energy density distributions above 24 keV (protons assumed) shown in Fig. 4 before the storm and in its recovery phase (Williams, 1981). The observations were made near noon (1030 LT in the first pass). The quiet-time data before the storm agree well with the quiet-time data before the big storm shown in Fig. 2. The recovery-phase energy densities in Fig. 4 are an order of magnitude lower than in the large storm case in Fig. 2. This may, to some smaller extent, be due to the fact that the Fig. 4 data were obtained somewhat later in the storm than the data in Fig. 2, but mainly to the lower intensity of the storm.

Energy densities as a function of L for the November 1977 storm are shown in Fig. 5 (after Williams, 1981). It corresponds to Fig. 3 for the December 1971 storm but covers only energies $\geqq 24$ keV. The ions are assumed to be protons. Fig. 5 also provides information about how the changes of the energy density are distributed between the 24–210 keV and 210–2,080 keV energy ranges. The energy density increases at lower energies (24–210 keV) and decreases at higher energies. This behaviour is similar to that shown in Fig. 2 and is discussed in detail by Lyons and Williams (1976). The main storm-time effect in phase space is an enhancement of densities at values of the first adiabatic invariant (μ) below the μ-value of the density maximum seen in the quiet-time data. Above this μ-value of maximum density (corresponding to ~150 keV energy at $L \sim 4$) phase space densities remain constant (Williams, 1981).

Whereas there are very large increases of 1–138 keV ions at $L = 3$ in the large storm case of Fig. 3, there is no increase in the 24–210 keV range at $L = 3$ in the smaller storm data

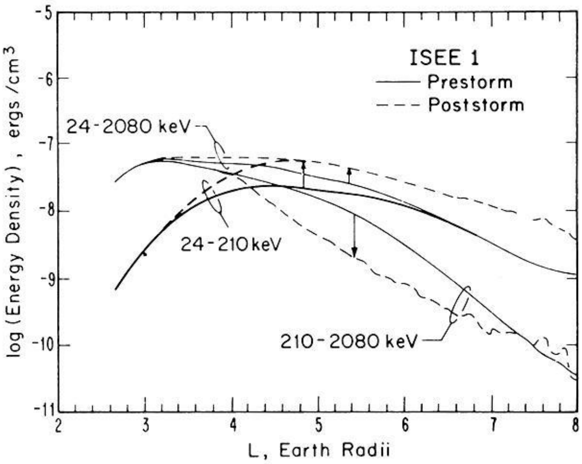


Fig. 5. Pre-storm (25 November 1977) and post-storm (27 November 1977) energy densities vs L value. (After Williams, 1981)

in Fig. 5. This illustrates that the injection depth of the ring-current plasma is strongly related to the intensity of the magnetic storm.

Detailed observations of the ion distributions below 30 keV, including composition (0.2–17 keV), in the dayside magnetosphere, near noon, during a $|Dst|_{max} = 100$ nT storm were made by means of Prognoz-7 on 21 February 1979 (Lundin et al., 1982a; Hultqvist, 1982, 1983). The Prognoz-7 measurements were taken before Dst reached its minimum value, whereas the ISEE-1 measurements shown in Figs. 4 and 5 were obtained after the Dst minimum. One may expect the obtained density values in both cases to be somewhat lower than the peak value during the storm. According to Fig. 3, order of magnitude differences between densities in main phase and (early) recovery phase are not expected in the central part of the ring current, during several hours around the storm peak.

It is somewhat unclear how low in energy O^+ ions could be detected by means of the solid state detectors on ISEE 1 used by Williams (1981). The lower energy limit may have been as high as 100 keV. We may therefore assume, as an extreme alternative, that William's data give practically only the proton content of the ring current. As the heavy ions of ionospheric origin most likely decrease in relative importance with energy above the present measuring limit of the mass spectrometers (17 keV), this limitation is not likely to affect the comparisons of ring current energy density contributions from different energy ranges very much. Even if it should turn out in the future that O^+ ions play a major role in the main part of the ring current energy density distribution (50–100 keV) also a comparison of the relative contribution to the magnetic effect by the presently observed ring-current ions of ionospheric origin (of energies below 17 keV) to that of the proton component of the ring current is of interest. In fact, if ionospheric ions should turn out to be of major importance in magnetic storms near the peak of the energy density distribution also, the general conclusion of the discussion in this section concerning the importance of ionospheric ions in the ring current is only amplified.

The fact that the ISEE data and Prognoz 7 data were obtained in two different storms is of course a serious drawback. However, as the Dst value is considered to be a rather good measure of the total energy in the ring current, we may expect that the two storms were quite equal in this respect at the storm peaks. If there were a higher O^+ content in the ring current in February 1979 than in November 1977 because of the solar cycle effect on the O^+ density below 17 keV energy demonstrated by Young (1980) and Young et al. (1982), we have in the discussion below compared the energy density of the O^+ ions below 17 keV with a too high energy density of protons above 24 keV and the relative figures of the importance of O^+ ions for the magnetic effect of the ring current should rather be somewhat higher than found. Unless O^+ ions play a dominating role in the 50–100 keV range (which is unlikely) this difference is not expected to change the general qualitative conclusions we draw.

Prognoz-7 data from the early main phase of the February 1979 storm are shown in Fig. 6a. The format is quite different from that in earlier figures, partly due to the inclusion of composition information, but the energy density in the units of Figs. 3 and 5 (erg/cm^3) of H^+ and O^+ ions can easily be obtained from the data in Fig. 6 by combining the density (N_i m^{-3}) and temperature (T_i K) values according to $\varepsilon_i(\text{erg/cm}^3) = 2.07 \cdot 10^{-22}\, N_i(\text{m}^{-3}) \cdot T_i(\text{K})$. The characteristic energy of each ion species is given as a temperature (although the distributions are generally not Maxwellian). More detailed energy distribution data is contained in Fig. 7a. Prognoz-7 crossed the ring current boundary inbound at 1130 UT at a geocentric distance of 8.6 R_E. The solar magnetic (SM) latitude was 35° and the SM longitude 350° (i.e. MLT ~1120).

Figures 6b and 7b show the similar data sets for a fairly undisturbed period. Dst had the values −23, −25, −21, −14, −11, −14 nT in the six hour interval centered on the time of the satellite crossing of the magnetopause (~1750 UT). The magnetopause crossing occurred at a geocentric distance of 11 R_E, at 10° SM longitude (i.e. MLT ~1240) and at ~45° SM latitude. The only major difference between the conditions in which the two data sets of Figs. 6a and 6b were obtained was evidently the magnetospheric disturbance level. The main differences between the storm main phase and the low disturbance data are the higher number densities (for the energy range 0.2–17 keV) in the storm situation both inside (~2 cm^{-3} and ~0.4 cm^{-3} respectively) and outside (30 cm^{-3} and 10 cm^{-3}) the ring current boundary and – more remarkable – the complete domination during the storm time passage of O^+ ions below 17 keV in the entire dayside magnetosphere. The O^+ density in the outer magnetosphere is an order of magnitude higher in Fig. 6a than in Fig. 6b and there is an O^+ density increase at least in as far as $L \sim 3$, whereas the H^+ density is not very much changed. Nor are the H^+ (crosses) and O^+ (circles) temperatures (0.2–17 keV) very much different in the storm main phase from those in the undisturbed situation, except in the innermost part where the O^+ temperature is lower in the storm than in the undisturbed situation (MeV electrons give rise to a strongly dominating background along part of the low altitude trajectory in Fig. 6a, UT ~1545 – ~1635, which has not been eliminated from the data.)

Let us now compare the energy density information for $\leqq 17$ keV contained in Figs. 6a and 6b with that for $\geqq 24$ keV in Fig. 5.

At $L = 3$ the *prestorm* energy density value (ε) is shown in Figure 5 to be $\sim 2 \cdot 10^{-9}$ erg/cm^3 for 24–210 keV ions (assumed to be protons) and $\sim 5 \cdot 10^{-8}$ for 210–2,080 keV

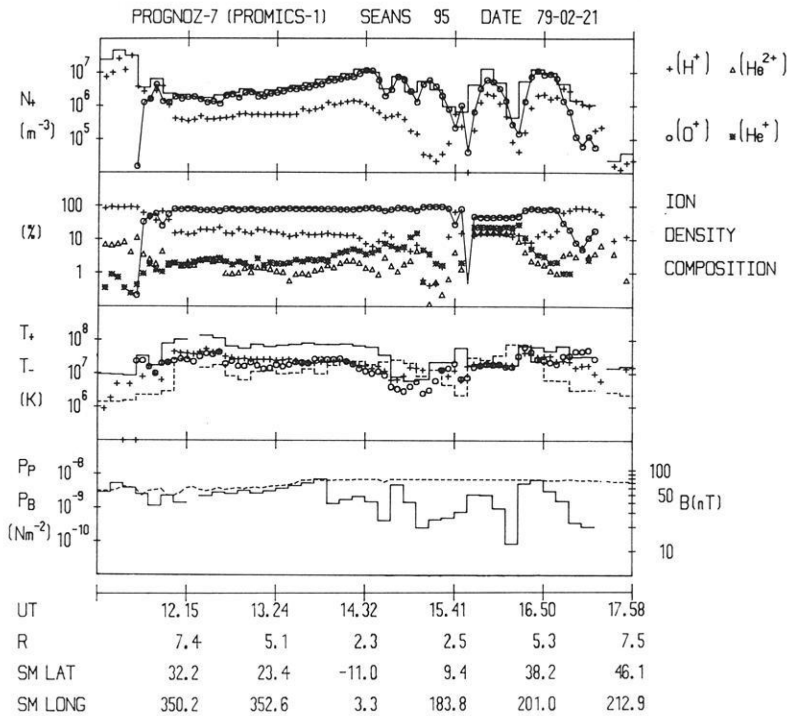
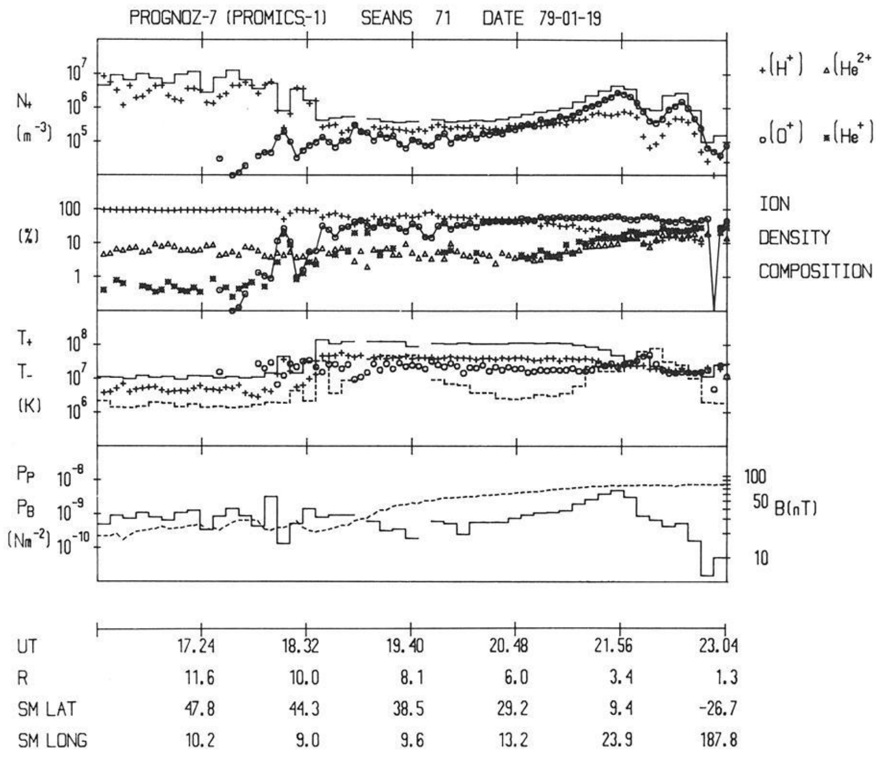


Fig. 6. a An example of a storm time situation in the dayside magnetosphere when O^+ ions dominated over other ion species. Between ~1545 and ~1635 UT MeV electrons gave rise to a dominating background which has not been eliminated from the data shown. The upper panel shows the ion number density (N_+) as deduced from the E/q spectrometers assuming the ions were all protons (solid lines). Plus signs (+) represent the density of H^+ as deduced from the perpendicular ICSs (assuming isotropy) and circles (○) represent the number density of O^+ using all ICSs. The second panel from the top represents the percentages of the four major ion constituents with respect to the total number density (logarithmic scale used). The third panel shows the temperatures of ions (*solid line*) and electrons (*broken line*) as deduced from the E/q electron and ion spectrometer data fitted onto Maxwellians. In the same panel the "perpendicular" H^+ (+) and O^+ (○) temperatures have been plotted. The fourth panel shows the ion plasma pressure (*solid line*) and magnetic field pressure (*dotted line*). The time and space coordinates (in Solar Magnetic, SM, coordinates) are given along the horizontal axis.



b An example of observations in the dayside magnetosphere during fairly low disturbance conditions. At the lowest altitudes MeV electrons produce a dominating background which has not been eliminated from the data shown in the figure. The format is the same as in **a**

ions. The 0.2–17 keV ion data for the low disturbance level in Fig. 6 give a value of $\sim 4 \cdot 10^{-9}$ erg/cm^3, i.e. comparable with, but somewhat larger than, the 24–210 keV energy density and an order of magnitude lower the energy density of the higher energy ions ($\geqq 210$ keV).

Whereas at $L=3$ there is no change from prestorm to recovery phase for 24–210 keV ions in Fig. 5, the 0.2–17 keV ions in Fig. 6 show an increase of ε to $4 \cdot 10^{-8}$ erg/cm^3 in the *early main phase,* practically all carried by O^+ ions. This value is about the same as the energy density of the entire high energy part of the ring current plasma at that L value. The Prognoz observations thus indicate that in (small) magnetic storms there is an injection even at $L=3$ of O^+ ions into the dayside ring current in the early main phase of the storm, representing about as much energy density as the quiet-time (and storm-time; small storms) high-energy particles (>210 keV). That Williams did not see any increase at all in his low energy

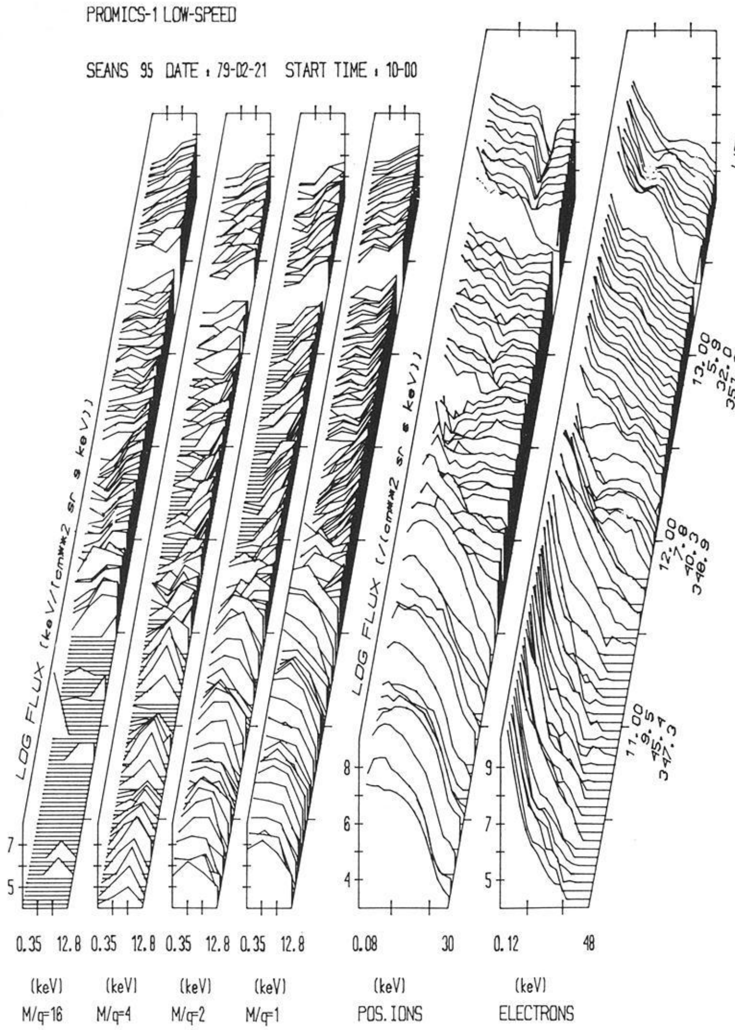


Fig. 7a and b. Energy spectrum as a function of time, measured with spectrometers pointing perpendicularly to the spin axis, i.e. to the sun direction, for that passage through the dayside magnetosphere for which data are shown for **a** in Fig. 6a and for **b** in Fig. 6b. To the left, individual four point energy spectra for the four major ion constituents are depicted (using differential energy flux units). To the right, 16 point energy spectra for positive ions and electrons (from E/q spectrometers), using differential flux units, are plotted. Time and space coordinates (in Geocentric Solar-Magnetospheric Coordinates, GSM) are given along the inclined time axis.

Fig. 7a

range (>24 keV) is, as mentioned before, likely to be due to his detectors not being able to detect fairly low energy O^+ ions.

At $L=5$ the O^+ and H^+ ions in the energy range 0.2–17 keV provide, in the *prestorm* situation, almost as big a contribution to the total ring-current energy density ($\sim 9 \cdot 10^{-7}$ erg/cm^{-3}) as the 24–210 keV ions (protons assumed) do ($\sim 2 \cdot 10^{-8}$ erg/cm^3; see Fig. 5). The *early main phase* data in Fig. 6a correspond to an energy density of O^+ ions in the 0.2–17 keV energy range of $\sim 3 \cdot 10^{-8}$ erg/cm^3 at $L=5$, less than a factor of two below the ε-value of $\sim 5 \cdot 10^{-8}$ erg/cm^3 for the ring-current plasma above 24 keV (protons assumed) in the recovery phase (shown in Fig. 5). The early main phase values for the November 1977 storm, corresponding to the Prognoz-7 data, may possibly have been somewhat higher than the value shown in Fig. 5, so the energy density contribution from the lowest energy range ($\leqq 17$ keV) may have been less than the 3/8 of the total energy density found here, especially if a substantial part of the ions were O^+ ions also above 24 keV. Whether it were low enough to correspond to the relative contribution of O^+ ions shown in Fig. 1 (22%) for the big storm case, we do not know, but it does not appear unlikely and we can at least conclude that the Prognoz-7 and the Explorer 45 observations are generally consistent in respect of relative contribution to the ring current energy density by O^+ ions below 17 keV energy.

On the other hand, as O^+ injection into the dayside magnetosphere had already occurred in the early main phase of the storm, when particles, which were originally injected into the inner magnetosphere on the night side at the beginning of the storm, had not had time to drift to the noon sector, the low energy O^+ ions may very well have dominated the dayside ring current in terms of energy density for some hours.

The ISEE-1 and Prognoz-7 observations at $L=8$ in the noon sector show that the *prestorm* energy density of $\geqq 24$ keV ions (protons assumed) contributed $(1–2) \cdot 10^{-9}$ erg/cm^3 (Fig. 5), whereas lower energy H^+ ions ($\leqq 17$ keV) contained $\sim 2 \cdot 10^{-9}$ erg/cm^3 and O^+ ions $\sim 5 \cdot 10^{-10}$ erg/cm^3 (Fig. 6a).

In the *early main phase* the O^+ ions contained $\sim 10^{-8}$ erg/cm^3 at $L=8$, whereas the H^+ ions were an order of magnitude lower. The recovery phase value obtained from ISEE-1 for ions of $\geqq 24$ keV energy (protons assumed) amounted to $4 \cdot 10^{-9}$ erg/cm^3. If these poststorm ions of $\geqq 24$ keV energy were to a significant degree O^+ ions we end up with energy density contributions from ions above and below ~ 20 keV at L$=8$ of very similar magnitudes. At these great distances from the earth it is difficult to

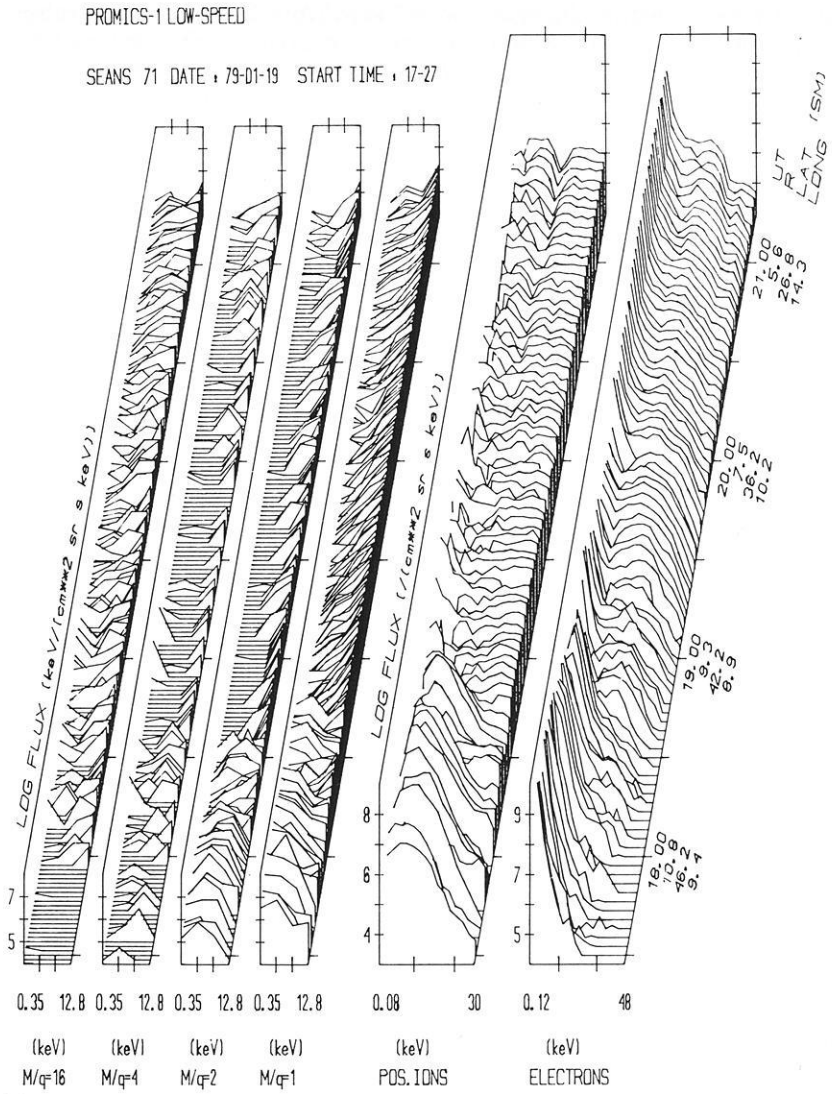


Fig. 7b

predict quantitatively what effect the difference in storm time between the ISEE-1 and Prognoz-7 observations may have. At $L=8$ we are outside the main part of the ring current and the contribution to the magnetic field depression at the Earth's surface is generally small.

To summarize this section: We have, in the main part of the dayside ring current ($L=5$) of a small storm, found rough agreement with Williams' (1979, 1981) results for the nightside ring current in a large storm concerning the contribution to the total ring current energy density by O^+ ions below 17 keV energy ($\sim 20\%$). At the inner edge ($L=3$) we have found an O^+ population of $\leqq 17$ keV energy contributing about as much as all ions above 24 keV (protons assumed) to the energy density. At the outer edge ($L=8$) the low energy O^+ ions have also been shown to be a major contributor to the energy density. On the whole, the $\leqq 17$ keV O^+ ions have thus been found to play a considerable role in the magnetic effect in the early main phase of the small-storm, dayside ring current investigated.

The Prognoz-7 observations were made in the rising phase of solar activity. There is a strong solar cycle variation of the average O^+ density below 17 keV at the geostationary orbit with O^+ ions playing a larger role the higher the solar activity (Young, 1980; Young et al., 1982). Near solar activity minimum, the O^+ contribution to the ring current energy density is therefore expected to be lower than in the example discussed above and in peak years of the solar cycle it is expected to be higher.

On the Sources of the Ring Current

For a discussion of the composition, with source considerations, of the high energy part of the ring current population, which may be an important component of the quiet-time ring current, the reader is referred to Spjeldvik and Fritz (1978a, b, d) and Williams (1979). Here we shall only deal with the observations of the low energy part of the storm-time ring current distribution in the dayside magnetosphere by means of Prognoz-7, which were discussed from an energy density point of view in the previous section. As justification for the origin of the ions we use the fact that there are very few O^+ ions in the solar wind and very many of them in the ionosphere.

As mentioned earlier, the possibility of the ionosphere being an important source of magnetospheric ions was suggested after the first observations by the Lockheed group of <12 keV O^+ ions being precipitated into the atmosphere during magnetic storms, even at fairly low magnetic latitudes (Shelley et al., 1972). The first ion mass spectrometer flown to great altitudes on GEOS-1 by the Bern group demonstrated the occurrence of substantial fluxes of ionospheric O^+ ions in the ring current (Geiss et al., 1978; Balsiger et al., 1980). Lundin et al. (1980) demonstrated the dominance of O^+ ions for energies less than 17 keV in the inner part of the ring current ($L \leqq 4$) during the recovery phase of magnetic storms, in agreement with the inference by Lyons and Evans (1976) of heavy ion dominance below 50 keV in the later part of storms. That ionospheric O^+ ions are ejected locally with high fluxes into the magnetosphere along auroral latitude magnetic field lines, was first demonstrated convincingly by the S3-3 measurements (Shelley et al., 1976; Ghielmetti et al., 1978).

Even against the background of the previous observations outlined above, the data in Fig. 6a are rather surprising in that the number density and energy density of O^+ ions below 17 keV are an order of magnitude higher than the corresponding densities of protons in practically the entire dayside magnetosphere, from near the magnetopause to an L-value well below 3. (In the innermost part MeV-electron background counts are present in Fig. 6a). A comparison with the low disturbance situation illustrated in Fig. 6b demonstrates, as mentioned before, that the storm-time situation differs from it in that the O^+ density has been increased by an order of magnitude whereas the H^+ density and the temperatures are not very much changed.

That the O^+ ions below 17 keV energy in the dayside ring current during the early main phase of a fairly small magnetic storm, which are shown in Figs. 6a and 7a, are of ionospheric origin, is of course without doubt. But we can say a lot more about their path to where they were observed by analysing the observations in some detail (Lundin et al. 1982a, Hultqvist, 1982, 1983).

First, the $\leqq 17$ keV ionospheric ions shown in Fig. 6a are not likely to have reached the inner magnetosphere via the plasma mantle (fairly generally supposed to be a major source of the plasma sheet and, by inward convection, of the ring current). Lundin et al. (1982a) have analysed observations of the plasma mantle during the same passage of Prognoz-7 through the magnetosphere in which the Figure 6a data were taken and have found that the O^+ density in the mantle was of the order of 10% or less as compared with $\sim 90\%$ in the dayside magnetosphere.

Secondly, the O^+ ions in the dayside magnetosphere, at least in the inner part, are not likely to originate in a plasma injection population on the nightside associated with the magnetic storm, because there was not enough time for them to drift to the noon sector (unless the convection field was unreasonably high). The Dst decrease started only at 06 UT and Dst reached -90 nT between 08 and 09 UT after which it increased again, indicating a low convection field intensity after 09 UT.

Thirdly, the Prognoz-7 observations on the nightside during the same passage showed that the O^+ density was lower there than on the dayside.

It can therefore be concluded that the O^+ ions observed by Prognoz-7 in the dayside magnetosphere on February 21, 1979 were extracted from the ionosphere on the dayside (Hultqvist, 1982, 1983).

Hultqvist (1983) has also concluded that the source region on the dayside had a very wide extension in L, arguing that if the source were limited to a fairly narrow L range one would expect to see an uneven O^+ distribution over L along the satellite trajectory, unless the limited L range source were at the inner edge of the ring current, i.e. at $L = 2$–3, or if the convection electric field in the dayside magnetosphere were dominantly dusk-dawn directed instead of dawn-dusk directed, both of which alternatives are highly unlikely, according to all experience. Observations of source regions for ionospheric ions which are very wide in L have been reported (Lundin et al., 1982b).

On the basis of a comparison of the observations summarized in Figure 6a with existing knowledge about the altitude distribution of cold ionospheric ions, Hultqvist (1983) has found that the hot O^+ ions in the dayside ring current cannot have been produced by accelerating cold O^+ ions in the outer parts of the field tubes. There are not sufficient numbers of cold O^+ ions available in the magnetosphere. In order to find sufficient numbers of cold O^+ ions to accelerate, the extraction has in fact to occur below 1,000 km altitude in the ionosphere. Moore (1980) has presented strong arguments, based on basic charge exchange considerations, for the main extraction region being located below the neutral O/H cross-over altitude (500–1,500 km). Hultqvist's (1983) observational results thus confirm his basic arguments.

We therefore conclude that the $\leqq 17$ keV O^+ ions, which dominated the dayside ring current from an energy density point of view, in the early main phase of the February 1979 storm (see previous section), were directly injected from the dayside ionosphere. This does not mean that ions directly extracted and accelerated out of the ionosphere were likely to carry most of the total ring current energy. For that part of the ring current ions which have energies near the peak of the differential energy density distribution, acceleration processes are required that produce ions well above the energies that characterize the dayside O^+ population shown in Figs. 6a and 7a.

On the Acceleration Processes

Most of what we know about the processes that accelerate ions out of the ionosphere has been learnt from the measurements of the S3-3 satellite (see Mozer et al., 1980, and Sharp and Shelley, 1981, for reviews) but recently Prognoz-7 has also contributed (Lundin et al., 1982b). A very brief summary of the results may be as follows:

– Strongly field aligned outflowing ion beams are produced by electrostatic acceleration, mainly above 5,000 km altitude along high-latitude magnetic field lines (Ghielmetti et al., 1978; Gorney et al., 1981). The composition of the upflowing ions has been found to vary from more than 90% protons to more than 90% oxygen ions.

– There are also mechanisms that accelerate ions perpendicularly to the magnetic field lines and give rise to conical pitch angle distributions (conics). These processes are assumed to be associated with ion cyclotron waves (Ungstrup et al., 1979, and others).

– The accelerated ions generally do not move adiabatically to the equatorial plane (and on towards mirroring or precipitation). Pitch angle scattering or transverse acceleration occurs between an altitude of an earth radius, or less, and the equatorial plane which is sufficiently strong to make the beams wide (Borg et al., 1978; Kaye et al., 1981). The processes may work differently on various ion species (Collin et al., 1981). The largest altitude at which narrow (adiabatically moving) beams have been observed hitherto is $\sim 5\ R_E$ (Lundin et al., 1982b).

Although the processes mentioned above can both extract O^+ ions below 1,000 km altitude and give them keV energies at greater altitudes, the observations do not fit very well to a model with low-altitude perpendicular acceleration due to ion-cyclotron waves and field-aligned acceleration in a simple potential drop at greater heights. Some of the problems are the following: Field aligned electron distributions coming together with field aligned ions from the same hemisphere, reported first by Borg et al. (1978), have been found in a large fraction of ion bursts near the equatorial plane by means of the SCATHA satellite (Kaye et al., 1981); The wide energy spectra observed, illustrated in Fig. 7, are not consistent with the main acceleration occurring in a simple potential drop, where all ions obtain the same energy increase. If a potential drop acceleration is important strong secondary effects must exist that modify energy spectra (and pitch angle distributions) greatly.

Even if, as we have seen in previous sections, direct extraction and acceleration of ions out of the ionosphere contribute significantly to the ring current and plasma sheet energy content, it is obvious, as mentioned before, that different kinds of acceleration processes from those discussed above are required for providing the higher energy particles of the ring current. The energy of charged particles can be increased only by electric fields. The electric fields may have different characteristics in different phases of magnetic storms. When there are fast variations in the geomagnetic field, induced electric fields may be important. They may well produce ions in the entire energy range up to the highest energies in the ring current (Heikkila and Pellinen, 1977; Pellinen and Heikkila, 1978; Heikkila et al., 1979). There does not seem to be any favouring of heavy ions over protons in the acceleration due to induced electric fields.

The potential dawn-dusk electric field generated by the solar wind flowing by the Earth gives rise to inward convection of the plasma on the nightside. When the convection electric field decreases after the injection period the particles find themselves in trapped orbits. Substorms generally inject plasma to $L=4$–5, while flux increases at $L<4$ are significant only during magnetic storms. The adiabatic energy increase cannot be larger than that corresponding to the entire voltage difference between the dawn and dusk sides of the magnetosphere. This is, of the order of 50 kV in substorms but it may be much larger during magnetic storms, up to a few hundred kV in the most intense injection period. The ratio of the particle energy in the original and final location is, for equatorially mirroring ions, the same as the ratio of the magnetic field intensities in the two locations (adiabatic compression). This is also the energy increase associated with loss-free radial diffusion of such particles. For equatorial pitch angles different from 90°, the energy increase is lower. By non-adiabatic diffusion processes some particles may reach L values lower than those corresponding to the potential difference over the magnetosphere and thereby obtain higher energies, but this is a slower process than convection.

Lyons and Williams (1980) have suggested, on the basis of Explorer 45 observations, that the flux increases of ring current particles at $L \leqq 4$ during geomagnetic storms result simply from an inward displacement of the pre-existing trapped particle distribution a few R_E further out and that ions need not be brought from greater distances in the plasmasheet or the tail as has been generally thought (Axford, 1969; Williams, 1972).

The observation by means of the ISEE 1 satellite of large amounts of ionospheric ions in the plasma sheet during magnetic storms (Peterson et al., 1981) makes it natural to expect that the high energy ions in the central ring current region come from the plasmasheet, having been accelerated during the inward transport (e.g. Balsiger, 1983). We shall therefore consider briefly some relations between the main part of the ring current ion population (from an energy density point of view) and the observations of the plasmasheet composition by Peterson et al. (1981).

The ISEE 1 measurements have shown the existence of percentages even above 50 of O^+ ions in the plasmasheet, out to 20 R_E, during magnetic storms. During the 21 February 1979 storm, 71% O^+ ions (below 17 keV) were recorded at 20 R_E (Peterson et al., 1981), whereas only one to a few tens of percent O^+ ions were observed at closer distances (Lennartson et al., 1981). During quiet conditions only one or a few percent of O^+ ions have been found in the plasmasheet. The O^+ ions observed in the plasmasheet during the February 1979 storm obviously had been extracted from the ionosphere on the night side of the earth in a similar way to that discussed for the dayside above. Although no characteristic energy values are reported for the greatest distances, we may assume that the O^+ ions had a mean energy of a few keV, as further in (Lennartsson et al., 1981).

If an ion mixture of the kind mentioned were brought, by convection, into the central ring-current region ($L=4$–5 for small storms; see Fig. 5) their mean energy would be increased by adiabatic compression. The amount of energy increase depends on the origin of the ions. Those which are brought into the central ring current in the expansive phase of the storm were located only a few earth radii further out before the storm ($L=5$–7, say; Lyons and Williams, 1980). The plasmasheet ions from greater distances, which were extracted from the ionosphere in the early phase of the storm may, if they are pitch angle scattered away from the loss cone, take up a smaller or larger fraction of the electric potential difference over the magnetosphere. This energization is expected to work identically on all ions of equal energy irrespective of mass. This is brought about by the gradient and curvature drift of the ions across equipotential surfaces of the convection field. Before the storm the ionospheric ion content in this region was generally low (e.g. Balsiger et al., 1980; Petersen et al., 1981; Balsiger, 1983) unless there had been significant disturbances well before the storm. We may thus expect that the ion mixture that is injected into the central part of the ring current by the strong convection field existing in the early storm phase before Dst reaches its minimum value, contains relatively low percentages of O^+ ions. Those ions which arrive in the $L=5$–7 region by extraction from the ionosphere in the early phase of the storm have typical mean energies of a few keV and they have their energy increased, by the convection to $L=4$–5, by less than an order of magnitude. Thus, they do not reach the central part of the energy density versus energy distribution of the ring current (50–100 keV). Most ions located in the plasmasheet at greater distances than 7 R_E at or after the storm onset convect past the earth at fairly great distances and never reach the trapped orbit region, even after its expansion, when Dst has passed its minimum.

We thus expect the main part of the ring current ion population (50–100 keV) in the $L \sim 4$–5 range to consist of ions of energies of a few tens of keV located in the L range 5–7 when the storm main phase starts. Those ions have generally reached the source region mentioned in a period with a lower activity level than during the storm and have thus obtained a lower potential energy increase from the convection electric field than storms provide. The highest energies present between $L=5$ and 7 have reached there from outside by non-adiabatic diffusion processes, as their forbidden regions at low activity level are likely to be larger than 7 R_E (or they have been accelerated locally by some unknown process). Most of the ions are however expected to have reached the source region ($L=5$–7) by convection and have therefore obtained energy increases from the adiabatic motion in a fairly low disturbance convection field. As the potential difference between the dawn and dusk flanks of the magnetosphere in fairly quiet conditions is typically only a few tens of kV, the typical ion energy increase when reaching the source region is expected to be of the order ten keV. The original energy of the ions at great distances in the plasmasheet may thus be the determining factor in whether ions, at least some of them, reach energies between 50 and 100 keV when they arrive in the central ring-current region after further acceleration in the storm convection electric field of the magnetosphere. That is the basis for the following discussion of the possible importance of an acceleration process which favours heavy ions entering the plasmasheet from the mantle. Its real importance remains to be determined.

Charged particles may get into the inwardly convecting part of the magnetospheric tail, the plasma sheet, by way of the plasma mantle, reaching the neutral current sheet where they may be accelerated before they start convecting towards the Earth. To reach the mantle they either have to enter the dayside boundary layer, where they may be accelerated in the magnetopause current layer, or they may be extracted from the ionosphere in the cusp region more or less directly into the mantle. Having entered the mantle they are expected to stay in it, provided they have a field aligned speed that is not higher than the flow speed of the plasma and the magnetic field lines at the magnetopause of the open magnetosphere (see Cowley, 1980, for a detailed discussion of the open magnetosphere model). (If the magnetic field lines along the high-latitude nightside magnetopause do not pass through the magnetopause into the magnetosheath, as Prognoz-7 observations indicate that they generally do not do (Lundin et al., 1982a), this limiting velocity condition does not apply directly. Even then there should be some velocity criterion for the ions to meet in order to reach the current layer in the tail at distances where convection towards the Earth occurs.) After the current layer acceleration, the adiabatic compression follows (discussed above) as an effect of the convection electric field.

A circulation process thus exists in the magnetosphere which "pumps up" the energy of the particles. This process tends to provide more energy to heavy ions than to protons, because the acceleration process in the current layers gives approximately the same velocity increase to the ions independently of mass.

As mentioned before, in order to stay in the magnetospheric circulation loop, the particles have to have sufficiently low field aligned velocities. As the acceleration in the current sheets at the magnetopause and in the neutral sheet of the tail tends to be directed along the field lines, the majority of the ions are not expected to make more than one round trip through the convection cycle, if the limiting field aligned velocity condition applies. Some of them may be scattered into the cycle again by nonadiabatic processes after having made one (or more) round trips and may thereby achieve very high energies. We shall briefly consider, a little more quantitatively, what effect the ion mass may have on this energization process associated with the magnetospheric circulation.

A typical flow velocity along the mantle magnetopause of plasma and magnetic field lines is 250 km/s. This corresponds to an energy of O^+ ions moving along the field lines of 5.2 keV. O^+ ions in the mantle with lower energies will certainly not leave the magnetosphere but higher energy O^+ ions may, if the field lines are open. For protons the corresponding energy is 16 times lower: 0.32 keV. In a neutral sheet current layer with a flow velocity of say 200 km/s (e.g. $E=0.2$ mV/m and $B=1$ nT) O^+ and H^+ ions with the above-mentioned energies, along the field lines, may be accelerated up to a maximum field-aligned velocity of 650 km/s (Cowley, 1980) which corresponds to an energy of 35 keV for O^+ ions but only 2.2 keV for H^+ ions. If such ions are convected inward by a potential convection electric field, which may correspond to a potential difference across the magnetosphere of one or a few hundred kilovolts during the early intense injection phase of magnetic storms but to only a few tens of keV in fairly quiet conditions, they will pick up a larger or smaller fraction of that potential difference, depending upon where they start out. This means that ions of energies near the peak in the differential energy density distribution of the ring current (50–100 keV depending upon ions mass and storm strength; see Fig. 1) can be produced in one round trip through the magnetospheric circulation system more easily if the ions are O^+ than if they are H^+ ions. We therefore may expect that the relative energy density contribution to the ring current of O^+ is larger than the O^+ number density fraction of the plasma mantle, if acceleration in one or more current layers is important anywhere in the circulation loop through the magnetosphere. The O^+ ions are also expected to achieve higher energies than H^+ ions in all diffusive transport processes into the ring-current region, provided there is a current layer acceleration to start with. For inctance, if a 35 keV O^+ ion (accelerated as mentioned above) is scattered to 90° pitch angle and brought from the tail with $B=10$ nT, say, to a distance of ~ 5 R_E in the equatorial plane ($B \sim 250$ nT) it will obtain an energy of almost an MeV, whereas a proton transported to the same place after maximum acceleration in the current layer would have an energy of only 55 keV. Radial diffusion is a much slower process than the convection and is not expected to play a major role in determining the temporal development of the ring current during the more active phases of magnetic storms.

Lundin et al. (1980) have shown that the plasma mantle contains O^+ during disturbed conditions but not during quiet conditions. The peak relative abundances of O^+ amount to a few tens of percent (number density). 5–10% O^+ is rather representative for disturbed conditions. The number density distribution within the plasma mantle is generally very uneven in time/space. According to what has been argued above, concerning the favouring of O^+ ions compared to protons in current layer acceleration, we may thus expect that, of those ions which get into the plasmasheet and ring current from the mantle, a larger fraction of the O^+ ions than of the H^+ ions achieve energies in the range 50–100 keV. Those plasmasheet ions which have not experienced any current layer acceleration region are generally not likely to have energies in this range, according to the above discussion, unless they have had time to diffuse into the central ring current region. Also ions streaming into the tail in the magnetospheric high latitude lobes (Sharp et al., 1981) may reach the current layer of the neutral sheet in the tail and be accelerated in the way discussed.

The O^+ ions in the storm-time mantle may come more or less directly from the ionosphere (Lundin et al., 1982a) or they may originate in the dayside ring-current population, which has been extracted from the ionosphere in the early phase of the storm, as described in earlier sections. Such ions drift to the dayside magnetopause in the dawn-dusk directed convection field. There they are accelerated and ejected along the field lines, some of them in the direction of the earth. After mirroring in or near the cusp they enter the plasma mantle and stay there (provided their field-aligned velocity component is not larger than the flow velocity at the magnetopause; see above) until they finally reach the tail neutral sheet. As the convection cycle time of magnetic field lines from the dayside magnetopause through mantle, tail and plasma sheet, back to the dayside is expected to be several hours, even for moderate penetration into the magnetosphere of the field lines (not reaching the permanently trapped ring-current region) during storm conditions (see e.g. Cowley, 1980), we may expect to see more energetic O^+ ions (which have passed through the circulation process, after extraction from the ionosphere at the beginning of the storm) in the dayside ring current only several hours after the start of the storm main phase and mostly only in the outer parts of the ring-current region where the ions are not permanently trapped.

If the high energy ions in the storm-time ring current are accelerated mainly by inductive electric fields there does not seem to be any strong favouring of heavy ions within the energy range where the majority of the ring-current ions are found, as mentioned above. Observations of the composition of the ring-current ions above 20 keV may thus also tell us something about the dominating acceleration process(es).

Concluding Remarks

In this report the importance of ionospheric ions in the ring current has been emphasized. The observational basis for the above discussion is very recent and quite limited in some respects. It suffers in particular from the lack of composition determinations for the main part of the ring-current population (between 17 and ~ 200 keV). Several of the conclusions drawn above are therefore rather hypothetical. It will be most interesting to see the results of the mass determination of the entire ring-current population which the AMPTE and Viking satellits are expected to carry out in the fall of 1984.

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