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Review Article

Heavy Ion Plasmas in the Outer Magnetosphere*

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Abstract. This brief review discusses heavy ions (below 30 keV/Q) in magnetospheric plasmas from two points of view: heavy ions as minor species or "tracers", and heavy ions as major plasma constituents. At present some 12 species of heavy ions have been detected in concentrations ranging from nearly 100% of the total ion density to $<10^{-2}$%. Tracer ions detected thus far include $^4He^{2+}$, O^{2+}, N^+ and N^{2+}; whereas the species O^+ and $^4He^+$ very often appear as major ions, i.e., they make up a large enough fraction of the plasma to significantly alter its dynamical properties. Still other ion species, such as high charge state solar wind oxygen or ionospheric molecular species, may be present in the high altitude magnetosphere but have not yet been detected. Some discussion of future prospects in this field is included.

Key words: Ion composition – Magnetosphere – Mass spectrometry

Introduction

The era of heavy ions (i.e. ions other than H^+) in the Earth's magnetosphere began in 1969 with two events: Axford's paper, given in 1969, suggesting the utility of heavy ions as tracers of magnetospheric plasma origins (Axford, 1970), and the Lockheed group's initial measurements of precipitating heavy ion fluxes in the Earth's upper ionosphere (Shelley et al., 1972). In view of later developments, these two events also serve to establish a useful physical distinction between heavy ions as tracers, and heavy ions as major constituents of magnetospheric plasmas. Over the past decade, ion composition has grown to be a key ingredient in the study of magnetospheric plasma and dynamics. At the present time, an even dozen ion species, including two isotopes, have been identified at energies per charge $\leqq 30$ keV/Q (Fig. 1).

During the 1960's, experiments carried on board sounding rockets succeeded in identifying H^+ and $^4He^{2+}$ ions in auroral fluxes (Reasoner, 1973). This tended to confirm the conventional wisdom of the time which identified the solar wind as the expected source of auroral particles. The only competing source was the polar wind, which could have been distinguished by the presence of $^4He^+$ in measurements made at high altitudes (Reasoner, 1973). Solar wind helium could also be traced by its distinctive $^3He/^4He$ ratio (Axford, 1970; Bühler et al., 1976). In the late 1960's, the Lockheed group began flying a series of satellite-borne ion mass spectrometers of the Wien filter type (see the review by Balsiger, in press, for a discussion of instrumentation). These instruments were able to distinguish the major ion species and were responsible for the discovery that large fluxes of O^+ ions are present in the ring current during geomagnetic storms (Shelley et al., 1972). A second obser-

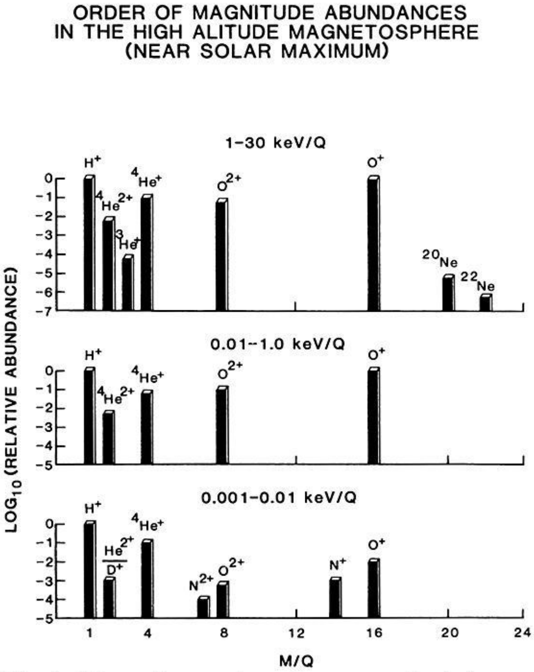

Fig. 1. Schematic overview of magnetospheric ion composition in three energy ranges. The two isotopes of neon as well as ^3He, were detected in foils (Lind et al., 1979) and have not yet been observed by charged particle detectors. They are included here because their abundances suggest a solar wind ion source, which in turn implies that these species entered the magnetosphere as ions.

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vational breakthrough (not dealt with in this review) occurred with the detection of kilovolt ions flowing upward out of the auroral regions (Shelley et al., 1976).

In 1970, groups at the University of Bern and the Max-Planck-Institut in Garching began developing the first in a series of focusing mass spectrometers that were optimized for space plasma measurements (Balsiger et al., 1976). This design first saw service on GEOS-1 and has since been flown on GEOS-2, ISEE-1 (Shelley et al., 1978), and DE-1 (Shelley et al., 1981). GEOS provided the first in situ measurements of trapped magnetospheric ions of ionospheric origin, including composition of the ring current up to 17 keV (Geiss et al., 1978; Balsiger et al., 1980). With ISEE-1, composition observations have been extended out to 22 R_E in the magnetotail (Sharp et al., 1981). The Wien filter design also continues to provide important measurements, having been flown on S3-3, PROGNOZ-7 and SCATHA, the latter instrument reaching energies of 32 keV (Johnson et al., in press).

New instrument designs have been proposed for NASA's OPEN mission. They will push magnetic mass spectrometers to still higher energies (~40 keV) and provide better time resolution with complete mass-energy-pitch angle scans once per spacecraft spin period, or ≈3 s.

Following this abbreviated background survey, we discuss in the remainder of this review the most significant composition observations and a few of the consequences for magnetospheric plasmas. The paper is divided along lines mentioned earlier, namely (1) heavy ions as tracers, and (2) heavy ions as major constituents.

Heavy Ions as Tracers

The following section presents a list of ion species detected thus far in the high-altitude magnetosphere. Three energy ranges may be distinguished: *energetic* (1–30 keV/Q, where Q is the ionization state), *suprathermal* (0.01–1.0 keV/Q), and *thermal* (1–10 eV/Q). Roughly speaking, five ion species can be detected with good reliability by present day instrumentation. The capability of these detectors is typified by the averaged GEOS-2 spectrum shown in Fig. 2.

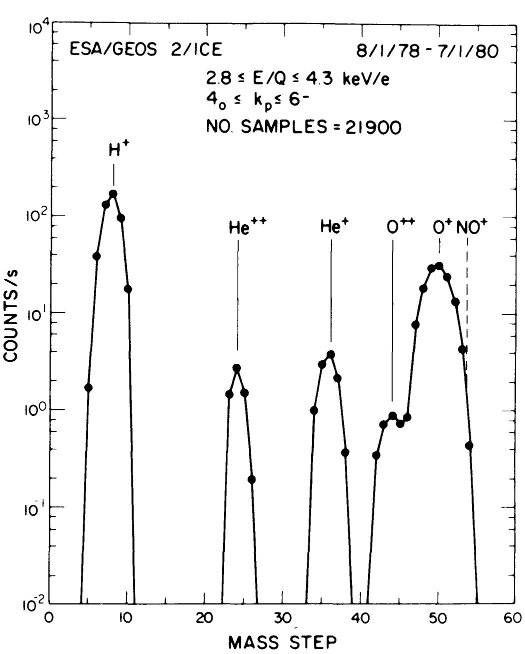

Fig. 2. Integrated mass spectrum based on 11 months of GEOS 2 data. Four energy steps have been summed over and a total of 21,900 samples of 0.1505 s have gone into each data point. The average background subtracted was 6.78 counts/s. The mass step scale extends to 63 but the last 3 steps are not shown. Note that 5 ion species are easily seen and resolved, and also the absence of any 'ghost' or other spurious peaks. If NO^+ were present it would be located in mass channel 53.5 (dashed line). On the basis of the analysis of the O^+ peak shape it is estimated that $NO^+/O^+ < 0.03$. (From Young et al., 1982)

1–30 keV/Q (Energetic Plasmas)

$^4He^{2+}$. Detected throughout the magnetosphere, usually at concentrations from a few tenths of a percent to a few percent. Typical differential fluxes near geostationary orbit ($L \approx 6.6$) are 3–30 ions $(cm^2\ s\ sr\ eV)^{-1}$ (Balsiger et al, 1980). $^4He^{2+}$ has been detected (at lower flux levels) out to ~20 R_E in the tail on ISEE-1 (Peterson et al., 1981). Although low-energy $^4He^{2+}$ of terrestrial origin has also been detected (see below), at the measured $^4He^{2+}$ mean energies of 5–10 keV/Q and above, we have every reason to believe that the solar wind is the source of $^4He^{2+}$. Several studies have been initiated to trace the temporal signature, and hence the transport, of solar wind $^4He^{2+}$ into the magnetosphere (cf. Balsiger et al., in press) thus far without conclusive results. Generally speaking, the densities of H^+ and $^4He^{2+}$ increase with increasing distance from the Earth (Fig. 3) as might be expected of ions whose source region is at the outer boundary of the magnetosphere.

$^3He^{2+}$. Because of its very low flux, $^3He^{2+}$ has not been detected by satellite-borne mass spectrometers. Instead, ^3He has been observed using the foil-trapping technique both in the aurora (Bühler et al., 1976) and on Skylab at $L<4$ (Lind et al., 1979). The Skylab $^4He/^3He$ ratio at ~30 keV was found to be 3,100±200, similar to that of the solar wind (2,350±150), with perhaps a small admixture of terrestrial ^4He. Based on Skylab results we might expect typical ^3He fluxes near $L \approx 6.6$ to be 10^{-3} to 10^{-2} ions $(cm^2\ s\ sr\ eV)^{-1}$, well below current state-of-the-art in ion mass spectrometer sensitivity.

$^4He^+$. Detected throughout the magnetosphere (Figs. 3 and 4), it is most intense near the inner edge of the ring current (Balsiger et al., 1980; Lennartsson et al., 1981; Lundin et al., 1980) but has also been observed in the subsolar magnetopause boundary layer and magnetosheath (Peterson et al., 1982). Within the magnetosphere it is found that $^4He^+$ and $^4He^{2+}$ have dissimilar energy spectra, with $^4He^{2+}$ having a higher mean energy and $^4He^+$ a higher mean density (Balsiger et al., 1980). This suggests that, at least in the 1–15 keV/Q energy range, the two species are unrelated, i.e. $^4He^+$ does not originate from $^4He^{2+}$ by charge exchange. Furthermore, long term studies with GEOS (Young et al., 1982) show no correlation of averaged $^4He^+$ and $^4He^{2+}$ densities, again suggesting independent sources for the two species: $^4He^+$ being terrestrial, $^4He^{2+}$ being solar.

$^{16}O^{6+,\ 5+\cdots}$. Have not been detected by any means, except in the magnetosheath (Geiss et al., 1978), and are expected to be present only at low flux levels (cf. Fig. 2). Typically the relative solar wind O/He elemental abundance ratio is

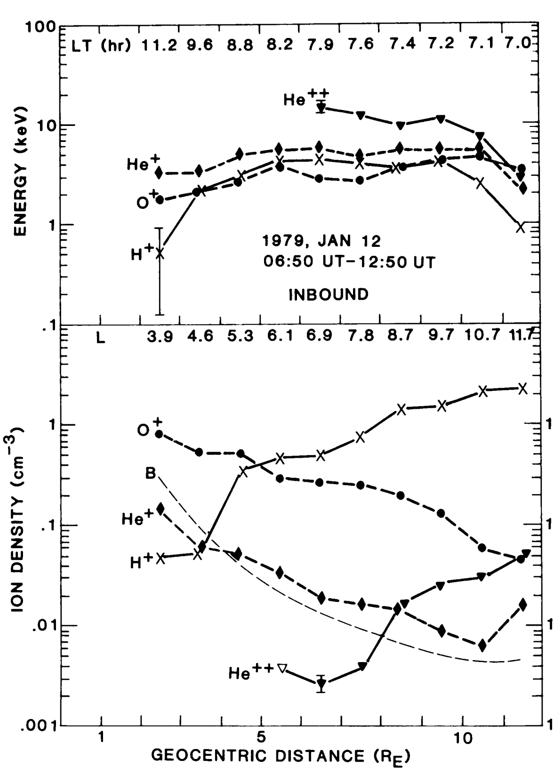

Fig. 3. Characteristic energies (*upper panel*) and number densities (*lower panel*) sampled during a magnetically quiet day, plotted versus the distance of ISEE-1 from the center of the Earth. The local time of each data point is shown at the top of the figure, the corresponding L parameter (dipole) is shown in the middle. The $\pm 1\sigma$ uncertainty carried over from the counting statistics is shown as an error bar when larger than the data symbol. The open data symbol on the He^{2+} density graph (*bottom*) represents an upper limit. The He^{2+} was below background at $L<6$ (corresponding to a density of less than a few percent of the total density). The thin dashed curve labelled B (*lower panel*) shows the measured magnetic field with the scale to the right. Qualitatively similar trends in composition during storms has been reported by Balsiger et al. (1980). (From Lennartsson and Sharp, 1982.)

~ 0.01 (Bame et al., in press). In GEOS-type instruments, which are currently the most sensitive, $^4He^{2+}$ approaches the detection limit for isotropic fluxes except during disturbed periods. Moreover, solar wind oxygen should have roughly four times the total energy of $^4He^{2+}$, or about 1.5 times its energy per charge, which places the bulk of it above the ~ 20 keV/Q energy per charge limit of most plasma mass spectrometers. Routine detection of $^{16}O^{6+}$ would nonetheless be of some interest because it, together with $^4He^{2+}$, represents a second solar wind ion species pair (after the H^+–$^4He^{2+}$ pair) on which to base studies of magnetospheric ion transport. The high percentage of terrestrial H^+ in the magnetosphere greatly detracts from the usefulness of the H^+–$^4He^{2+}$ ion pair as a tracer.

$^{16}O^{2+}$. Detected under disturbed conditions and in long-term averages (Fig. 2) which increase the signal to noise ratio of the data (Young et al., 1982). O^{2+} has been detected in magnetotail ion beams (Sharp et al., 1981), and Young et al. report that it, like O^+, has a strong solar cycle dependence (see below). At low levels of magnetic activity ($K_p<2o$) the long term O^{2+}/O^+ ratio is ~ 0.05 in kilovolt plasmas located near geostationary orbit.

$^{16}O^+$. Detected under nearly all conditions at fractions ranging from a few percent to over 80% of the total density (Figs. 3, 4). Often kilovolt O^+ is too abundant to be called a tracer (see below) although its presence at any measurable concentration indicates an ionospheric source. The bulk of composition observations have been made near the maximum of the current solar cycle (Fig. 5) and, as a result, some bias undoubtedly affects our present thinking about "average" magnetospheric composition. One example of the consequences of heavy ion enriched plasmas has been suggested by Baker et al. (1982): the presence of O^+ in the tail plasma sheet may promote growth of the ion tearing mode instability, thereby facilitating the onset of magnetospheric substorms.

^{20}Ne, ^{22}Ne. Lind et al. (1979) report the detection of neon isotopes trapped in Al and Pt foils on the Skylab experiment. Typical measured values of $^{20}Ne/^{22}Ne$ were 13–20. This is reasonably near the solar wind ratio of 13.7 and rules out a terrestrial source for which the ratio is 9.8. Furthermore, the $^{20}Ne/^3He$ ratio was found to be 0.1–0.2, again very close to the solar wind value of 0.23 ± 0.05. Measurement of the neon isotopes demonstrates the power of the foil technique for detecting and identifying rare noble gas ions since typical magnetospheric fluxes would be $\sim 10^{-4}$ to 10^{-3} (cm^2 s sr eV)$^{-1}$.

0.01–1 keV/Q (Suprathermal Plasma)

There are now considerable data in the literature to show that this category of plasma population exists (Young, 1982). Figure 6, taken from Balsiger et al. (1980), shows several instances of <1 keV populations found near $L=6.6$. Generally, suprathermal plasmas are found outside the plasmapause with typical densities of ~ 0.1–10 cm^{-3}. They are characterized by a tendency to exhibit highly anisotropic pitch angle distributions (cf. Horwitz, 1982). These may be field-aligned or pancake (flux maximum at 90° pitch angle) or conical (flux maxima at some pitch angle between 0° and 90° or 90° and 180°). Composition of this population is both energy and pitch angle dependent, with the field-aligned and conical components dominated by O^+ and H^+ and the trapped component characterized very roughly by $H^+ > He^+ > O^+$ ordering. The reader is directed to recent reviews by Horowitz (1982) and Young (1982) for further details.

$^4He^{2+}$. Detected at concentrations such that $^4He^{2+}/^4He^+$ is usually below a few percent. Because of its low mean energy and the shape of its energy distribution, it is clear that this component of $^4He^{2+}$ is of terrestrial origin (Fig. 6). Although acceleration of $^4He^+$ to suprathermal energy by wave-particle interactions has been observed (see below), similar observations of $^4He^{2+}$ are problematic due to its low concentration. However, since waves near Ω_{He^+} (the He^+ cyclotron frequency) are quite intense and exhibit harmonics as well, there is no reason why $^4He^{2+}$ could not also be accelerated in a manner similar to $^4He^+$.

$^4He^+$. Nearly always present in the suprathermal plasma at levels of a few percent to a few tens of percent. Investigation of intense ULF waves near Ω_{He^+} on the GEOS satellites has established that $^4He^+$ plays a critical role in the generation and amplification of these waves and is in turn heated

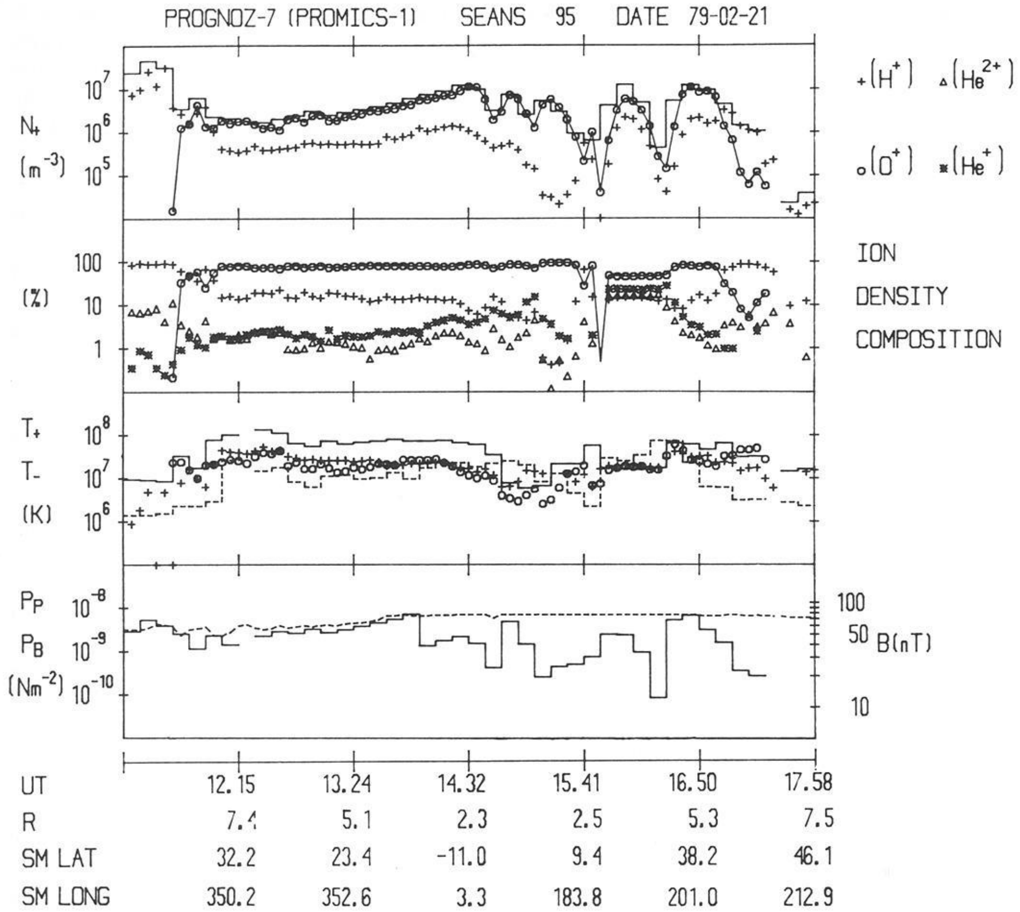

Fig. 4. An example of a storm time ring current observed on PROGNOZ, when O^+ ions dominated completely over the entire dayside magnetosphere and also part of the nightside ring current. Between ~1545 and ~1635 UT, radiation belt MeV electrons produced a background that dominated the detectors. The upper panel shows the ion number density (N_+) as deduced from E/q spectrometers, assuming the ions to be protons (solid line). Plus signs represent the density of H^+ as deduced from the perpendicularly oriented mass spectrometer assuming isotropy, and circles represent the number density of O^+ derived from the measurements of both the perpendicular mass spectrometer and one pointing 25° from the direction to the sun. The second panel from the top represents the percentages of the four major ion constituents. The third panel shows the temperatures of ions (*solid line*) and electrons (*dashed line*) as deduced from E/q electron and ion spectrometer data fitted to Maxwellians. In the same panel the 'perpendicular' H^+ (*pulses*) and O^+ (*circles*) temperatures have been plotted. The fourth panel gives the ion plasma pressure (*solid line*) and magnetic field pressure (*dashed line*). The lower part contains the magnetic field and flow velocity components in the xy and yz solar ecliptic coordinate planes. Flow velocity components represented by solid lines refer to H^+ ions, and dashed lines to O^+ ions. The time and space coordinates (in solar magnetic (SM) coordinates; R in earth radii) are given along the horizontal axis. (From Hultqvist, 1982.)

by them (Roux, 1982). In this case one cannot consider $^4He^+$ as a tracer ion, rather it becomes an active ingredient of the plasma as discussed below. The presence of $^4He^+$ is, however, useful as a tracer of plasmaspheric-like ion composition signatures (Balsiger et al., 1980). The plasmaspheric ordering of composition ($H^+ > He^+ > O^+$), which is the result of either diffusion or polar wind-like flow, can be distinguished from ionospheric ordering (H^+, $O^+ > He^+$), which is usually associated with kilovolt plasmas. A critical issue now under investigation is the extent to which near-equatorial acceleration processes, such as the interaction of $^4He^+$ with ULF waves, contribute to more energetic plasma populations such as the storm time ring current.

O^{3+}. Has been observed a few times (Fig. 6) in conjunction with high He^{2+} and O^{2+} abundances (Balsiger, 1981; Balsiger et al., in press). Its source is thought to be the same as that of O^{2+} (see below).

O^{2+}. Detected at concentrations of $O^{2+}/O^+ \sim 0.1$ and higher, although we emphasize that O^{2+} and $^4He^{2+}$ are both highly variable. The generally higher O^{2+}/O^+ ratios in comparison to those of He^{2+}/He^+ may be understood largely in terms of production rates for the respective doubly charged ions (Geiss et al., 1978). Transport processes also play an important role in determining these ratios, particularly within the plasmasphere (see below). As ion detectors evolve towards greater sensitivity with future space missions, it should become practical to employ the doubly charged species as diagnostics of magnetospheric wave-particle interactions in a situation analogous to the role of multiply-charged species used to study heavy ion acceleration in the solar wind.

O^+. Commonly detected, particularly in the field-aligned plasma component. For example, Kaye et al. (1981) have argued that because the field-aligned component of so-called "zipper" events is O^+ dominated, these ions are

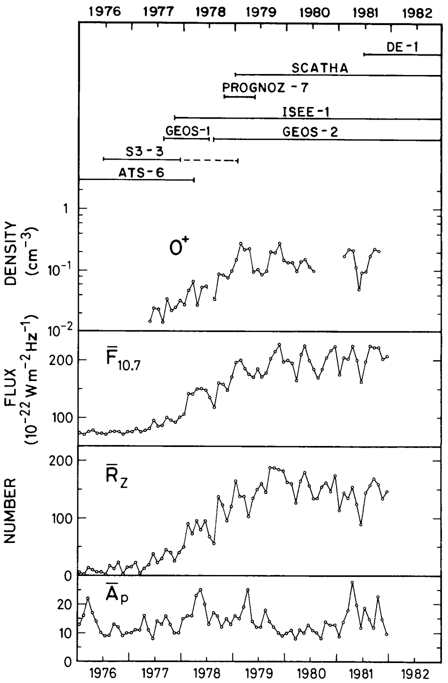

Fig. 5. Upper panel shows spacecraft which carried ion composition experiments over the past seven years (ATS-6 carried only solid state detectors sensitive to heavy ions $\geqq 100$ keV/nucleon, all others carried plasma composition and most had solid state experiments as well). The bottom four panels are taken from Young et al. (1982). Upper panel is the density of 1–14 keV O$^+$ ions measured near geostationary orbit with the GEOS-1 and -2 satellites. The GEOS data are monthly averages restricted to intervals of $K_p < 2o$ in order to remove variations caused by geomagnetic activity. The bottom three panels are monthly averages of (from top to bottom) the 10.7 cm solar radio flux, the Zurich sunspot number, and the global magnetic activity index (these data are taken from J. Geophys. Res.)

being injected directly from the ionosphere into the near-Earth portion of the plasma sheet. There is also some evidence for the existence of ULF waves, and presumably wave-particle interactions as well, near Ω_{O^+} (Fraser and McPherron, 1982).

1–10 eV/Q (Thermal Plasma)

Routine ion measurements within the plasmasphere are somewhat problematic for experimental reasons, primarily the limited angular coverage of mass spectrometers. Outside the plasmasphere these difficulties are exacerbated by high positive spacecraft potentials ($\sim +5$ V) and the nonequilibrium state of the lower density plasma (<10 cm^{-3}). Remarks in this section are therefore confined to thermal plasma within the plasmasphere.

$^4He^{2+}$. Has been detected at concentrations $\leqq 10^{-3}$ relative to total ion density. Typically the ^{4}He^{2+}/^{4}He$^+$ ratio is less than a few percent. This points toward an enrichment of ^{4}He^{2+} relative to ^{4}He$^+$ in comparison to its ionospheric value. Geiss et al. (1978) have suggested that enrichment is driven by the temperature gradient between the equatorial plane and the ionosphere (roughly several thousand degrees K) through the mechanism of thermal diffusion. This process is discussed in more detail below in connection with O^{2+}.

$^2D^+$. Assuming the different plasmaspheric ion species to be in thermal equilibrium, then it is possible to determine whether the $M/Q = 2$ peak is predominantly ^{4}He^{2+} or ^{2}D$^+$. On one occasion, at $L \approx 3.5$ in the plasmasphere, Geiss et al. (1978) found that the $M/Q = 2$ peak was most likely ^{2}D$^+$ since this gave the most consistent result for the temperatures of all species (i.e., because of its extra charge, the assumption that ^{4}He^{2+} was present would have yielded twice the temperature of the other species). Geiss et al. have argued that ^{2}D$^+$ is the dominant $M/Q = 2$ ion if the abundance of $M/Q = 2$ ions is $\leqq 5 \times 10^{-4}$ that of H$^+$, whereas ^{4}He^{2+} is dominant if the abundance is $\geqq 10^{-3}$ that of H$^+$.

$^4He^+$. Is typically the second most abundant plasmaspheric ion (after H$^+$) with relative concentrations of $\sim 10\%$. Earlier studies based on OGO-5 data gave the impression that ^{4}He$^+$ comprised only $\sim 1\%$ of the total, a result that may have been due partly to data selection and partly to instrumental effects (see Young, 1979 for discussion of the latter). Modeling efforts are now under way that should aid in our understanding of plasmaspheric ^{4}He$^+$ which, in this regard, can be treated as a minor ion species (Murphy et al., 1979). What is presently lacking are good synoptic measurements that accurately describe the distribution and dynamic behavior of ^{4}He$^+$.

N^{2+}, N^+. Have been observed with the Retarding Ion Mass Spectrometer on DE-1 by Chappell et al. (1982). Both species were seen in the plasmasphere where the N$^+$/O$^+$ ratio was ~ 0.1 during one spacecraft orbit, with a corresponding N^{2+}/N$^+$ value of 0.01 to 0.05. Over the polar cap N$^+$ was observed at similar concentrations and at altitudes up to 3 R$_\mathrm{E}$. Near the equator at $L \sim 6.6$, Young et al. (1977) placed an upper limit of 0.3 on the N$^+$/O$^+$ ratio.

The observation of thermal nitrogen ions opens up the question of what percentage of the "oxygen" seen at kilovolt energies is in fact nitrogen. Are we witnessing another example of the situation described previously for protons, in which we will later find that most of the magnetospheric oxygen is in fact nitrogen? From the point of view of ionospheric chemistry one can argue that this cannot be the case since atomic oxygen, the main source of O$^+$ and O^{2+} ions, is the dominant neutral constituent over a wide range of altitudes. Secondly, the relative difference in the masses of O$^+$ and N$^+$ is small and should not alter plasma behavior even at concentrations above the presently observed N$^+$/O$^+$ ratio of ~ 0.1. Nitrogen may nonetheless play an important observational role, for example as a tracer of the influence of ionospheric chemistry on magnetospheric composition.

O^{2+}. Detected in the plasmasphere in varying concentrations. Of particular interest is the observation that the O^{2+}/O$^+$ ratio increases with time as the plasmasphere fills following a magnetic disturbance (Geiss et al., 1978). Over a few days O^{2+}/O$^+$ rises from ~ 0.01 to concentrations $\geqq$ 0.3, the latter being ~ 100 times the value found in the topside ionosphere. Geiss and Young (1981) explain the O^{2+} enrichment relative to O$^+$ as being the result of thermal diffusion of the doubly charged ion species in a background gas of singly charged ions. This has been tested by solving the time-dependent diffusion equation between the topside ionosphere (~ 300 km) and the equatorial plane. Their results show that the temperature gradient between

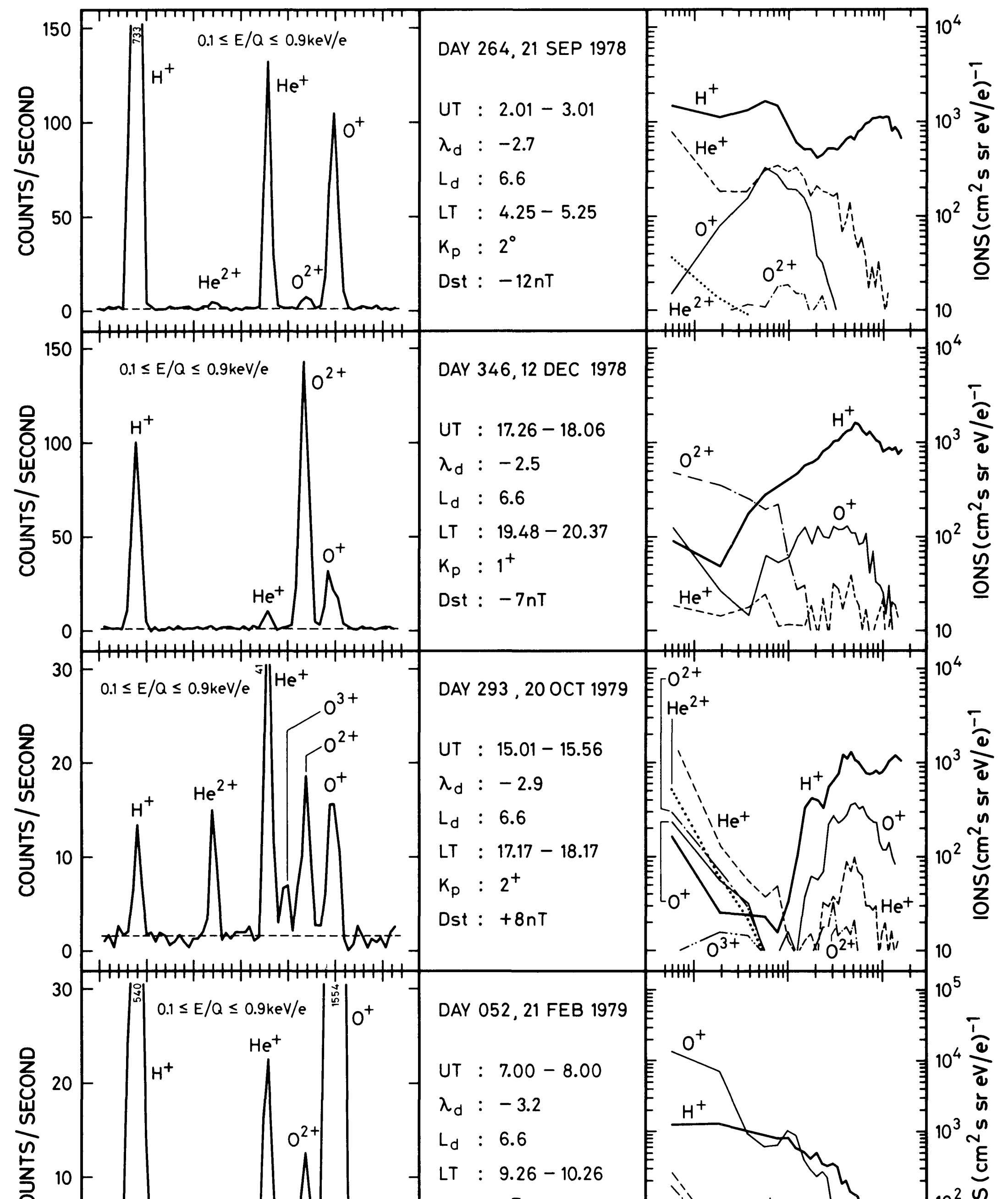

Fig. 6. Ions from "plasmaspheric" source (see text). Mass and energy spectra measured at geostationary orbit by the GEOS-2 mass spectrometer. Mass spectra (*left*) are averaged over the energy per charge range 0.1–0.9 keV/*e*. Counts per second are proportional to differential flux. Where mass peaks exceed the scale, the corresponding counting rates are given. Energy spectra (*right*) cover the full range of the mass spectrometer. In all four examples a plasmaspheric source is clearly recognizable by the source specific ions He^+ and/or O^{2+} The O^{3+} ion, resulting from further ionization of O^{2+}, is clearly recognizable on 20 October 1979; at the same time plasmaspheric He^{2+} is exceptionally high ($He^{2+}/He^+ \simeq 0.3$). (From Balsiger, 1981.)

the topside ionosphere ($T_i = 1{,}000$ K) and equatorial magnetosphere ($T_i \geq 5{,}000$ K) plays an important role in determining the build-up of doubly charged ions (Fig. 7). In this way, O^{2+} has served in exemplary fashion as a tracer of transport processes.

O^+. Detected in the plasmasphere, typically at concentrations of ~ 0.01 of the total ion density. An interesting point about O^+ is that its very presence in the high altitude plasmasphere is difficult to explain and no models presently exist which include O^+ transport. Geiss and Young (1981)

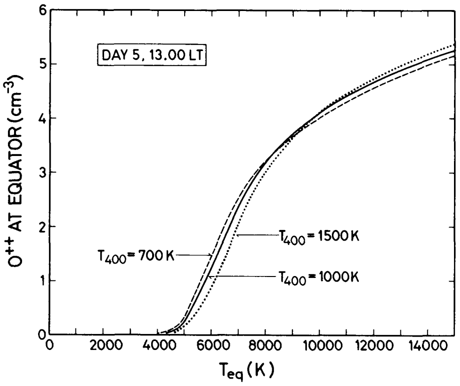

Fig. 7. Computed density of O^{2+} at the $L=3$ equator as a function of equatorial temperature. Data are for 1,300 LT on the fifth day of plasmasphere filling. The three curves demonstrate that the effect of varying ion temperature at the ionospheric boundary is quite small. Note that the threshold temperature at which thermal diffusion becomes effective is $\simeq 5000$ K for all three curves. (From Geiss and Young, 1981.)

have solved the transport problem only for minor ions, and their models of the major ions H^+ and O^+ were based on observational data.

NO^+, N^{2+}... Not detected. Young et al. (1977) estimated the sum of NO^+, N_2^+ and O_2^+ to be less than 10% of the O^+ density. Both chemistry and gravity work against molecular ions escaping into the high altitude plasmasphere, although this may not always be the case. For example, during the large magnetic storm of August 1972, high concentrations of molecular species were seen at altitudes of 1,400 km by Hoffman et al. (1974).

Heavy Ions as Major Constituents

A major constituent is one which is sufficiently abundant to alter plasma properties in a significant way. Evidence for two phenomena that fall into this category has been found with data from the GEOS spacecraft: the participation of He^+ ions in the propagation and amplification of ULF waves, and the presence of large quantities of O^+ ions in the magnetosphere. The subject of He^+ in wave-particle interactions is treated in more detail by Roux (1982).

He^+ and Wave-Particle Interactions

Intense, nearly monochromatic ULF waves near $\Omega_{He}{}^+$ are often observed on GEOS-1 and 2 and on ATS (Mauk and McPherron, 1980). The free energy source for the waves is the pitch angle anisotropy of energetic protons above ~ 20 keV. When thermal (~ 1 eV) He^+ ions are present at concentrations $\geqq 0.05$ the waves are destabilized. Although details of the instability are rather complicated (Roux et al., 1982) He^+ may play a further role in the amplification process by creating a laser-like effect in which waves propagating away from the equator are reflected when they reach a value of the magnetic field such that

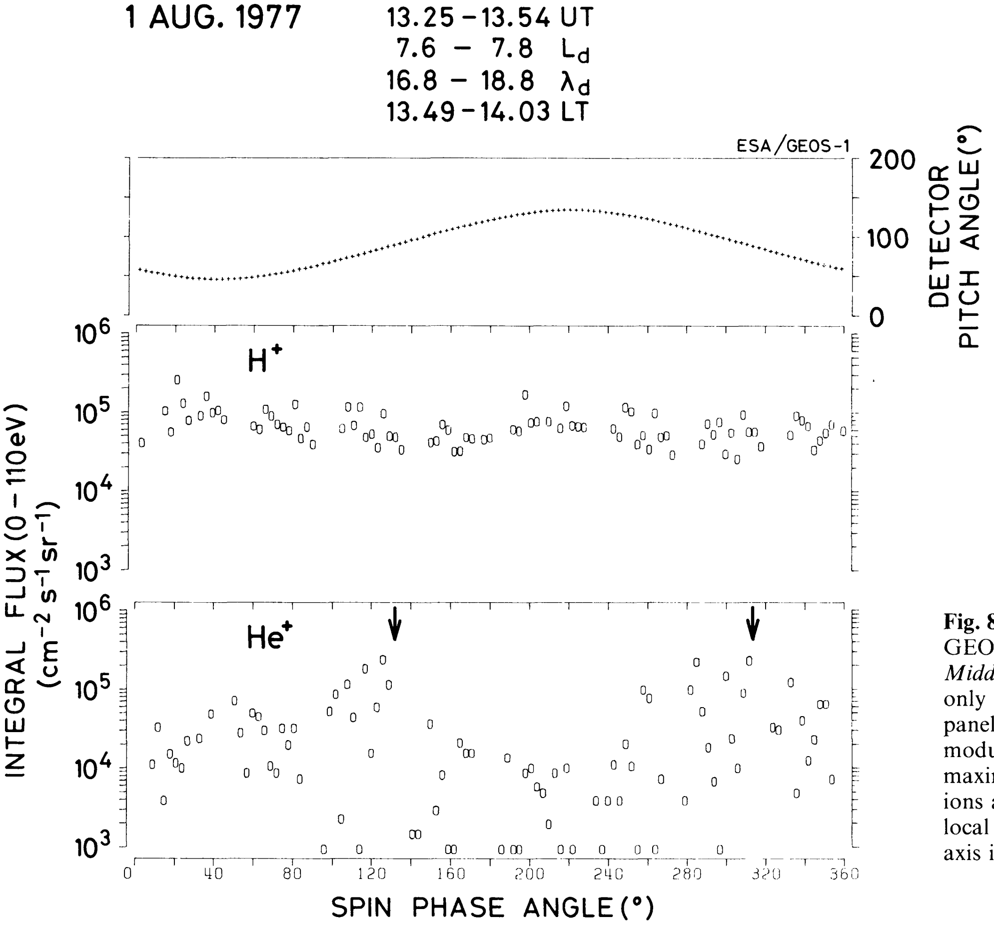

Fig. 8. *Top* Pitch angle sampled by the GEOS Ion Composition Experiment. *Middle* The H^+ flux, showing that it is only weakly modulated. On the lower panel the He^+ flux is strongly spin modulated due to ULF waves; it is maximum when 90° pitch angle He^+ ions are sampled. The angle between the local magnetic field and the satellite spin axis is 44°. (From Roux et al., 1982.)

the wave frequency is equal to the local bi-ion hybrid frequency (Young et al. 1981b)

$$f_{bi}=[f_{He^+}]\cdot[(1+3\eta)/(1-3\eta/4)]^{1/2}$$

where η is the He^+ concentration. Upon reflection the wave again passes through the amplification region and growth is sustained. A final point of interest is that the waves are apparently intense enough to trap cold He^+ ions and accelerate them to energies up to ~100 eV (Fig. 7). Roux (1982) has pointed out that this heating represents an effective friction between the hot (≧20 keV) protons and cold (~1 eV) He^+.

The point to be stressed here is that the presence of He^+ in sufficient quantities (≧5%) alters plasma characteristics and causes new phenomena to appear. Similar phenomena may also occur near the O^+ gyrofrequency, and ULF waves indeed been observed in this range (Fraser and McPherron, 1982).

O^+ and Solar-Cycle Induced Variations in Magnetospheric Composition

Beginning with GEOS-1 operations in 1977 and continuing with GEOS-2, it has been possible to obtain nearly complete coverage of ion composition in the vicinity of geostationary orbit ($L\approx 6.6$) through the end of 1982. This $5^1/_2$ year period brackets the current solar cycle maximum, during which the O^+ content of the equatorial magnetosphere has been observed to increase dramatically (Fig. 2). Detailed analysis of $3^1/_2$ years of GEOS data has shown that the abundance of terrestrial heavy ion species (O^+, O^{2+} and He^+) increases with increasing solar EUV flux, apparently due to increased scale heights of ions in the upper atmosphere and ionosphere as well as to increased ion production (Young et al., 1981a; 1982). One possible consequence of this phenomenon is a systematic variation in the decay time of the storm ring current due to changes in the proportions of major ion species which are present. A second consequence is suggested by the work of Baker et al. (1982) who find that O^+ has a destabilizing effect on the magnetotail, and the presence of O^+ may facilitate the occurrence of substorms. One might therefore look for a solar cycle dependence in either the frequency or onset characteristics of substorms, based on variations in the abundance of O^+ in the outer magnetosphere.

Discussion

Figure 1 gives a very qualitative overview of typical magnetospheric abundances. The reader should keep in mind, however, that large variations are observed, and in particular that the data refer primarily to a period near solar maximum (cf. Fig. 5).

We have tried to show in this brief resume how our knowledge of magnetospheric heavy ions has expanded both qualitatively and quantitatively in the past 5–10 years. The discovery that heavy ions are major participants in the dynamics of magnetospheric plasmas represents an important qualitative departure from earlier concepts. Likewise the growing number of ion species observed in the magnetosphere is a real quantitative expansion of the ion family, somewhat reminiscent of the proliferation of subatomic particles in the field of nuclear physics with the advent of large accelerators. At this juncture, and with the planning of the next spacecraft mass spectrometers for the OPEN mission already upon us, we might pause to ask what composition measurements are most important and will lead to real progress in this field.

Minor Ions

One question is whether it is useful to push for *routine* detection of new and even rarer species, e.g. for solar wind O^{6+} or O^{5+} or for ionospheric N^+ or NO^+. As mentioned above, one can argue that a second, uniquely solar wind species would be most useful if it could be detected together with $^4He^{2+}$ on a routine basis. This would require ~100 times the present sensitivity of GEOS-type instruments. Since the GEOS-type has a geometric factor of $\sim 10^{-2}$ cm^2 sr, which is already quite large for a plasma analyzer, an order of magnitude increase in this parameter is difficult to achieve without some radical design breakthrough such as mass spectrometers which focus in both azimuthal and polar directions. Increases in detector signal-to-noise ratio also present a feasible avenue for improvement. Thus far only passive shielding has been used and active shielding by anti-coincidence techniques needs to be investigated. Unfortunately, this requires some investment in detector mass and in electronic complexity. At present, 2-dimensional focusing devices, but no methods of active shielding, are being considered for the next generation of plasma instruments being studied for OPEN.

Major Ions

Improvements in this area can and will be made in the future. Emphasis will be placed on obtaining rapid pitch angle-energy measurements of several major ion species simultaneously. The OPEN era should see the development of both mass spectrograph and time-of-flight techniques. The former requires an ion optical design capable of imaging all ion species simultaneously on a microchannel plate detector. These instruments are planned to be imaging in two dimensions, e.g. mass and polar angle. Time-of-flight relies on nearly simultaneous detection of ions of nearly equal energy per charge but different mass according to their time-of-flight over a fixed distance of a few cm. Both techniques are well known in the laboratory although neither has been applied to satellite-borne plasma instruments.

We may conclude by saying that the reign of the "proton" is at an end. Its demise is not regretted, although as a result magnetospheric particle populations have become even more complex than previously imagined.

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References

Axford, W.I.: On the origin of radiation belt and auroral primary ions. In: Particles and fields in the Earth's magnetosphere, by B.M McCormac, ed.: p. 76. Dordrecht, Holland: D. Reidel 1970

Baker, D.N., E.W. Hones, Jr., D.T. Young, Birn, J.: The possible role of ionospheric oxygen in the initiation and development of plasma sheet instabilities. Geophys. Res. Lett. **9**, 1337, 1982

Balsiger, H.: Composition of hot ions (0.1–16 keV/e) observed by the GEOS and ISEE mass spectrometers and inferences for the origin and circulation of magnetospheric plasmas. Adv. Space Res. Vol. 1, 289, 1981

Balsiger, H.: Recent developments in ion mass spectrometers in the energy range below 100 keV. Adv. Space Res., in press

Balsiger, H., P. Eberhardt, J. Geiss, A. Ghielmetti, H.P. Walker, D.T. Young, H. Loidl, Rosenbauer, H.: A satellite-borne ion mass spectrometer for the energy range 0 to 16 keV. Space Sci. Instrum. **2**, 499, 1976

Balsiger, H., P. Eberhardt, J. Geiss, Young, D.T.: Magnetic storm injection of 0.9- to 16-keV/e solar and terrestrial ions into the high-altitude magnetosphere. J. Geophys. Res. **85**, 1645, 1980

Balsiger, H., J. Geiss, Young, D.T.: The composition of thermal and hot ions observed by the GEOS-1 and -2 spacecraft. In: Energetic ion composition in the Earth's magnetosphere, R.G. Johnson, ed. Tokyo: Terra Scientific Publishing Co. and Dordrecht, Holland: D. Reidel (in press)

Bame, S.J., W.C. Feldman, J.T. Gosling, D.T. Young, Zwickl, R.D.: What magnetospheric workers should know about solar wind composition. In: Energetic ion composition in the Earth's magnetosphere, R.G. Johnson, ed. Tokyo: Terra Scientific Publishing Co. and Dordrecht, Holland: D. Reidel (in press)

Bühler, F., W.I. Axford, H.J.A. Chivers, Marti, K.: Helium isotopes in an aurora. J. Geophys. Res. **81**, 111, 1976

Chappell, C.R., R.C. Olsen, J.L. Green, J.F.E. Johnson, Waite, J.H. Jr.: The discovery of nitrogen ions in the Earth's magnetosphere. Geophys. Res. Lett. **9**, 937, 1982

Fraser, B.J., McPherron, R.L.: Pc-2 magnetic pulsation spectra and heavy ion effects at synchronous orbit: ATS 6 results. J. Geophys. Res. **87**, 4560, 1982

Geiss, J., H. Balsiger, P. Eberhardt, H.P. Walker, L. Weber, D.T. Young, Rosenbauer, H.: Dynamics of magnetospheric ion composition as observed by the GEOS mass spectrometer. Space Sci. Rev. **22**, 537, 1978

Geiss, J., Young, D.T.: Production and transport of O^{++} in the ionosphere and plasmasphere. J. Geophys. Res. **86**, 4739, 1981

Hoffman, J.H., W.H. Dodson, C.R. Lippincott, Hammack, H.D.: Initial ion composition results from the Isis 2 satellite, J. Geophys. Res. **79**, 4246, 1974

Horwitz, J.L.: The ionosphere as a source for magnetospheric ions. Rev. Geophys. Space Phys. **20**, 8174, 1982

Hultqvist, B.: Recent progress in the understanding of the ion composition of the magnetosphere and some major question marks. Rev. Geophys. Space Phys. **20**, 589, 1982

Johnson, R.G., R.J. Strangeway, E.G. Shelley, J.M. Quinn, Kaye, S.M.: Hot plasma composition results from the SCATHA spacecraft. In: Energetic ion composition in the Earth's magnetosphere, R.G. Johnson, ed. Tokyo: Terra Scientific Publishing Co. and Dordrecht, Holland: D. Reidel (in press)

Kaye, S.M., E.G. Shelley, R.D. Sharp, Johnson, R.G.: Ion composition of zipper events. J. Geophys. Res. **86**, 3383, 1981

Lennartsson, W., R.D. Sharp, E.G. Shelley, R.G. Johnson, Balsiger, H.: Ion composition and energy distribution during 10 magnetic storms. J. Geophys. Res. **86**, 4628, 1981

Lennartsson, W., Sharp, R.D. A comparison of the near equatorial ion composition between quiet and disturbed conditions. J. Geophys. Res. **87**, 6109, 1982

Lind, D.L., J. Geiss, Stettler, W.: Solar and terrestrial noble gases in magnetospheric precipitation. J. Geophys. Res. **84**, 6345, 1979

Lundin, R., L.R. Lyons, Pissarenko, N.: Observations of the ring current composition at $L<4$. Geophys. Res. Lett. **7**, 425, 1980

Mauk, B.H., McPherron, R.L.: An experimental test of the electromagnetic ion cyclotron instability within the Earth's magnetosphere. Phys. Fluids **23**, 2111, 1980

Murphy, J.A., G.J. Bailey, Moffett, R.J.: Helium ions in the midlatitude plasmasphere. Planet. Space Sci. **27**, 1441, 1979

Peterson, W.K., R.D. Sharp, E.G. Shelley, R.G. Johnson, Balsiger, H.: Energetic ion composition of the plasma sheet. J. Geophys Res. **86**, 761, 1981

Peterson, W.K., E.G. Shelley, G. Haerendel, Paschmann, G.: Energetic ion composition in the subsolar magnetopause and boundary layer. J. Geophys. Res. **87**, 2139, 1982

Reasoner, D.L.: Auroral helium precipitation. Rev. Geophys. Space Phys. **11**, 169, 1973

Roux, A. Anomalous friction between various magnetospheric components through ion cyclotron waves. EOS, Trans. Am. Geophys. U. **63**, 1319, 1982

Roux, A., S. Perraut, J.L. Rauch, C. de Villedary, G. Kremser, A. Korth, Young, D.T.: Wave-particle interactions near Ω_{He^+} observed onboard GEOS-1 and -2: 2. Generation of ion cyclotron waves and heating of He^{+} ions. J. Geophys. Res. **87**, 8174, 1982

Sharp, R.D., D.L. Carr, W.K. Peterson, Shelley, E.G.: Ion streams in the magnetotail. J. Geophys. Res. **86**, 4639, 1981

Shelley, E.G., R.G. Johnson, Sharp, R.D.: Satellite observations of energetic heavy ions during a geomagnetic storm. J. Geophys. Res. **77**, 6104, 1972

Shelley, E.G., R.G. Johnson, Sharp, R.D.: Satellite observations of an ionospheric acceleration mechanism. Geophys. Res. Lett. **3**, 654, 1976

Shelley, E.G., R.D. Sharp, R.G. Johnson, J. Geiss, P. Eberhardt, H. Balsiger, G. Haerendel, Rosenbauer, H.: Plasma Composition Experiment on ISEE-A. IEEE Trans. Geosci. Elec. Vol. **GE-16**, 266, 1978

Shelley, E.G., Simpson, D.A., T.C. Sanders, E. Hertzberg, H. Balsiger, Ghielmetti, A.: The Energetic Ion Composition Spectrometer (EICS) for the Dynamics Explorer-A. Space Sci. Instrum. **5**, 443, 1981

Young, D.T.: Ion composition measurements in magnetospheric modeling. In: Quantitative modeling of magnetospheric processes, Geophys. Monogr. Ser. Vol. **21**, W.P. Olson, ed.: p 340. Washington, D.C.: AGU 1979

Young, D.T.: Near-equatorial magnetospheric particles between ~1 eV and ~1 MeV. Rev Geophys Space Phys. (in press)

Young, D.T., J. Geiss, H. Balsiger, P. Eberhardt, A. Ghielmetti, Rosenbauer, H.: Discovery of He^{2+} and O^{2+} ions of terrestrial origin in the outer magnetosphere. Geophys. Res. Lett. **4**, 561, 1977

Young, D.T., H. Balsiger, Geiss, J.: Observed increase in the abundance of kilovolt O^{+} in the magnetosphere due to solar cycle effects. Adv. Space Res. Vol. 1, No. 1, 309, 1981a

Young, D.T., S. Perraut, A. Roux, C. de Villedary, R. Gendrin, A. Korth, G. Kremser, Jones, D.: Wave-particle interactions near Ω_{He^+} observed on GEOS 1 and 2:1. Propagation of ion cyclotron waves in He^{+}-rich plasma. J. Geophys. Res. **86**, 6755, 1981b

Young, D.T., H. Balsiger, Geis, J.: Correlations of magnetospheric ion composition with geomagnetic and solar activity. J Geophys. Res. **87**, 9077, 1982

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