Recent and future space missions will reveal why the ionosphere is a very significant plasma source in all regions of magnetospheres.

The Composition of Magnetospheric Plasmas

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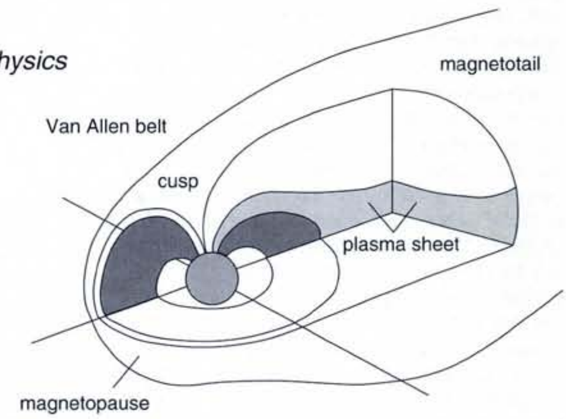

Fig. 1 — A schematic illustration of the Earth's magnetosphere. The Sun is off to the far left and the solar wind flows strongly towards to the right. The magnetopause — the magnetosphere's outer surface — separates the solar wind from the physically distinct, magnetized plasma of the magnetosphere.

iMagnetospheres are cosmic plasma systems organized to a significant degree by magnetic fields of external origin, such as the Earth's magnetic field, and shaped by the interaction with another plasma system moving at a different speed. For magnetospheres in the solar system, the moving plasma is the solar wind coming from the Sun. In the case of the Earth, the magnetosphere filled with a tenuous gas of ionized particles extends about 10 Earth radii (some 64000 km) on the day-side of the planet towards the Sun, and stretches in a long magnetotail on the night-side (Fig. 1).

Magnetospheric physics was the first, new scientific discipline to be born in the space age, although it was called space plasma physics, auroral physics or ionospheric physics as the concept of the magnetosphere did not exist. The word "magnetosphere" was introduced by Thomas Gold in 1959 and in the 35 years the concept has existed, magnetospheric physics has reached a certain degree of maturity. However, it remains a young research field in the sense that the most important new results from practically all space missions continue to be unexpected and surprising. This is because magnetospheres are so complex that it is very difficult, if not impossible, to derive more than a limited amount of information from basic principles; only *in situ* observations can reveal what happens and theory needs strong guidance from experiments to find its way.

Early Surprises

The story behind efforts to understand the composition of the magnetospheric plasma is a good example of surprising results. Up until the early 1970s it was taken more or less for granted by the magnetospheric physics community that practically all plasma in magnetospheres originates from the solar wind. The first measurements with ion-mass spectrometers in the Earth's magnetosphere (carried out in 1968 by a group at the Lockheed Palo Alto Research Laboratories, USA) gave such astonishing results that the group did not dare to publish them until 1972 after they had been confirmed by a second spacecraft [1]. They showed evidence for precipitating energetic oxygen ions which could only have come from the ionosphere and not from the solar wind (the ionosphere is the region close to Earth which contains charged particles resulting from ionization of neutral gases by high-energy solar radiation).

These first two ion-mass spectrometers were flown aboard small American military satellites. The next major step was also taken using an inexpensive military satellite when an ion-mass spectrometer (again provided by the Lockheed group) aboard the satellite S3-3 discovered in 1976 outward flowing O^+ ion beams above the ionosphere at the auroral zone — the region near the Earth's pole where auroral activity is at a maximum [2]. This result was perhaps not quite so surprising given the earlier observations of precipitating energetic O^+ ions, but it was in some respects even more important.

An Historic Breakthrough

The first ion-mass spectrometer to probe the magnetosphere to high altitudes belonged to a group at the University of Bern. It flew aboard the European Space Agency satellite GEOS-1 in 1977 to altitudes of the geostationary orbit (6.6 R_E where R_E is the Earth's radius). Significant abundances of ionospheric ions in the outer magnetosphere were expected, but the discovery by the Bern group [3] that the ionosphere is a source for the magnetospheric plasma of comparable importance to the solar wind came as a big surprise. The ionospheric source sometimes dominates completely, as is shown Fig. 2 giving data on the ion composition during a magnetic storm (a

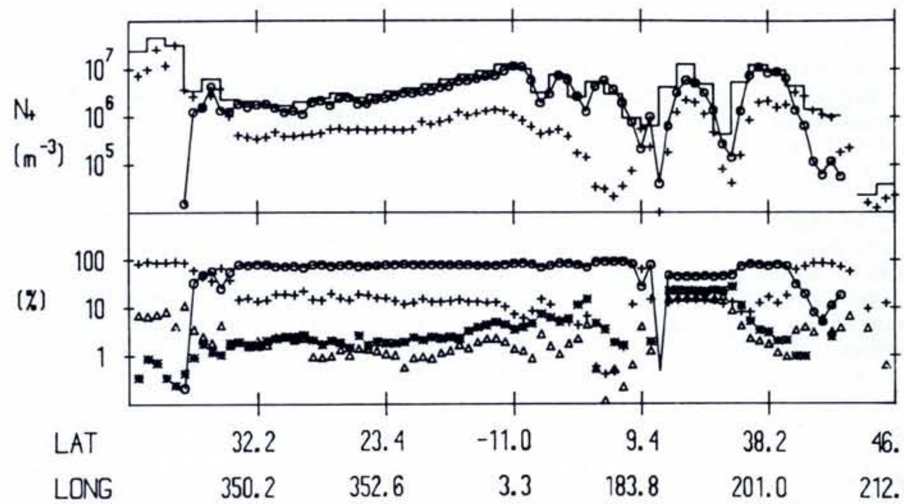

Fig. 2 — An example of the complete dominance of O^+ ions (of ionospheric origin) in the day-side magnetosphere during a relatively small magnetic storm [4]. Upper panel: histogram (solid line) based on total-ion measurements and the number densities (ions per m^3) of H^+ (crosses +), He^{++} (triangles △), He^+ (asterisks ✻), and O^+ (circles ○) in the magnetosphere plotted as a function of time (in hours) and position on 21 February 1979. The position is given in terms of the latitude and longitude corresponding to different distances from the Earth (in units of R_E). The data show that the O^+ density was an order of magnitude higher than the H^+ density in the entire day-side of the magnetosphere. Lower panel: the number densities plotted as a percentage of the total ion density to show that number density of O^+ is an order of magnitude higher than that of H^+ for the entire day-side.

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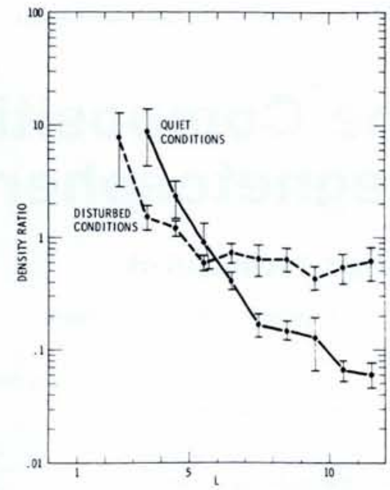
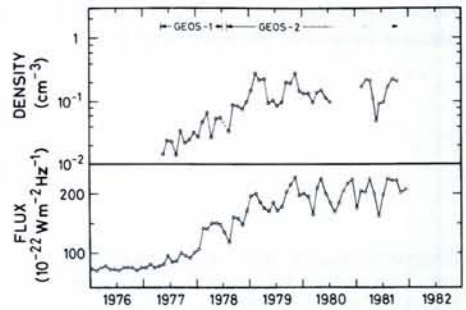
disturbance in the magnetosphere). There is seen to be an order of magnitude higher number density of O^+ ions than of H^+ ions in the entire day-side part of the magnetosphere during the storm.

The 1980s thus saw a revolution in our understanding of the interaction between the ionosphere and magnetosphere with respect to ion exchange. The efficiency with which the magnetosphere injects energy into, and extracts plasma from, the ionosphere had been greatly underestimated. After summarising what is known about the composition of the Earth's magnetosphere, I shall discuss the origin of the acceleration and extraction of ionospheric plasma since the mechanisms by which the ionosphere's heavy ions escape into the magnetosphere is today a topic of intense research in space physics. The major unanswered questions will be reviewed, together with some of the partial answers that have been found during the last 10 to 15 years. In particular, it will be shown that the ionospheric ions are accelerated not only along the magnetosphere's magnetic field lines by a parallel electric field component, but also perpendicularly to the field lines. This perpendicular acceleration gives rise to so-called conical distributions (conics) of ion velocities at altitudes well above those where the acceleration takes place (such distributions were first reported by the Lockheed group in 1982 [5]).





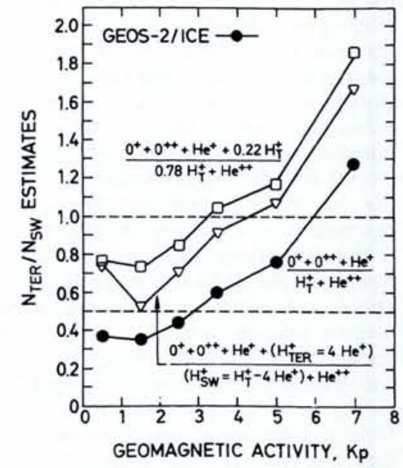


Fig. 3 — Some characteristics of the composition of the Earth's magnetosphere.
a, upper left) The average O^+/H^+ number density ratio for quiet and disturbed conditions as a function of the distance L from the Earth's centre of the geomagnetic field line in the equatorial plane, measured in Earth radii [6].
b, upper right) Upper panel: the variation of the average number density of O^+ ions (with energies of 1-14 keV) from the ionosphere in the magnetosphere for magnetically quiet conditions ranging from a near minimum of the solar cycle in 1976 to the maximum in 1980/81 [7]. Lower panel: the solar activity is given in terms of the average radio flux at a wavelength of 10.7 cm.
c, lower right) Estimates (open symbols), plotted as a function of the geomagnetic activity at high latitudes, of the ratio of the number densities of hot ions (0.9-16.4 keV/q) of ionospheric origin, NTER, to those of solar-wind origin, NSW, at the geostationary orbit [8]. The curves are calculated for different values of H_T^+, the total (observed) proton number density.

The Earth's Magnetosphere

General characteristics

Satellite measurements have demonstrated that the main ionospheric source lies in the auroral zone, with the cusp region where the magnetic field lines converge (see Fig. 1) playing a major rôle. But contributions are also provided by the polar-cap region (the polar region within the auroral zone) and by the polar wind. The latter is an ion outflow of thermal origin occurring at all latitudes and longitudes poleward of the innermost region of the magnetosphere where the magnetic field lines are permanently closed.

The best information about the average composition variations in the Earth's magnetosphere for most of a solar cycle out to a distance of 23 R_E was obtained by the GEOS and ISEE satellites. Fig. 3a shows, for instance, that the O^+/H^+ ratio decreases with increasing distance from the Earth and increases with increasing magnetospheric disturbance (except close to the Earth). Fig. 3b illustrates that the ionospheric component of the magnetospheric plasma increases with increasing solar activity, from near a minimum in the solar cycle in 1977 to the maximum in 1980-81. Fig. 3c illustrates that the increase of ions of ionospheric origin in the magnetospheric plasma is closely related to high-latitude magnetic disturbances. The various curves in the figure correspond to different assumptions concerning the fraction of H^+ ions that are of ionospheric origin. The curves increase with increasing geomagnetic activity and exceed unity at medium to high activity.

Ion expulsion

Oxygen ions are found everywhere in the magnetosphere, even in the thin boundary layer between the magnetosphere and the solar wind. In the lower part of the boundary layer, ionospheric ions frequently occur as beams of low temperature. An especially intense outflow of ionospheric ions has been found in the cusp region at latitudes above 70° (near noon) of the magnetosphere. This ion "fountain" [9] has been investigated in detail using measurements taken by the satellites Dynamics Explorer 1 and Viking.

The exchange of ions between the Earth's ionosphere and the magnetosphere is characterised by total fluxes of 2 x 10^{26} ions/s for ionospheric ions of various types. Such fluxes are consistent with the amounts of O^+ ions that have been observed in the magnetosphere during storms, with the observed rates of precipitation of particles in the auroral regions, and with the total rate at which ions are circulated through convection in the magnetosphere. The extraction of ionospheric plasma corresponds to an energy flow of from one to a few 10^9 W, which is between a few percent and a few tens of percent of the energy flux associated with the precipitation of energetic particles into the upper atmosphere (10^{10}-10^{11} W), and a few percent of the power input, in the form of Joule heating, into the neutral upper atmosphere.

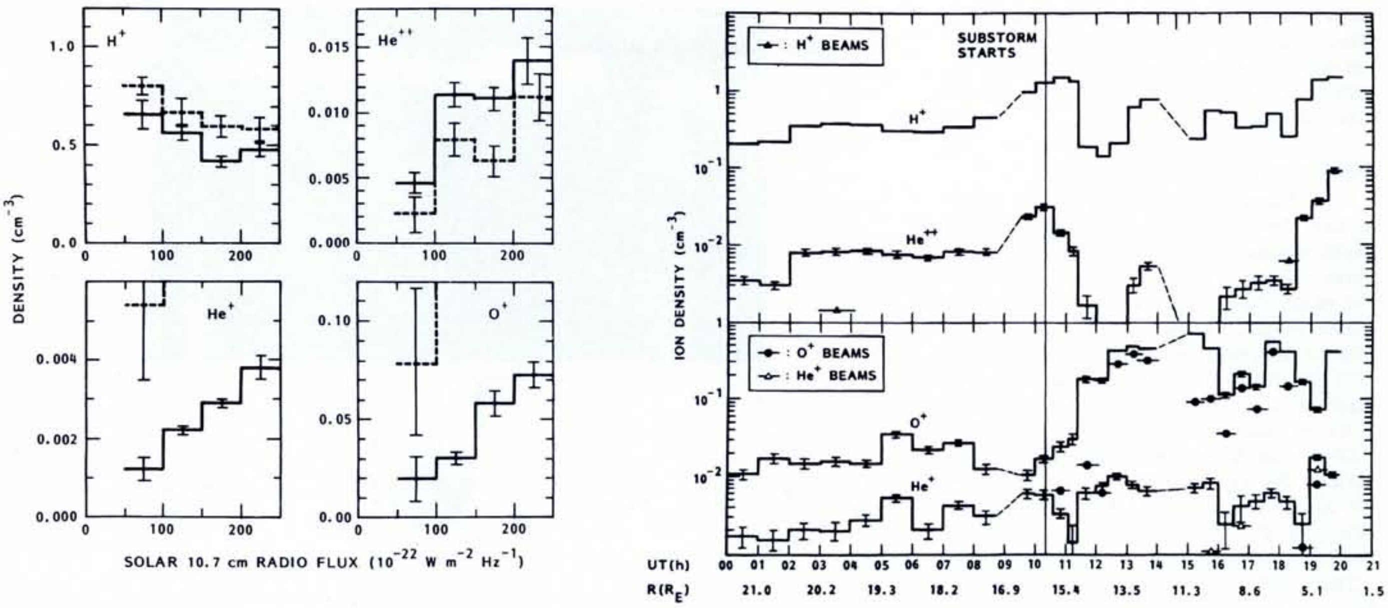
Plasma sheet

The main "storage" region of the magnetosphere, namely the plasma sheet in the magnetotail, has been investigated with respect to the composition of the hot plasma using mainly the ISEE-1 satellite. Ionospheric O^+ ions were also found to dominate in the innermost part for both quiet and disturbed magnetospheric conditions. At larger distances, H^+ densities dominate the hot plasma, but in disturbed conditions, ionospheric ions (O^+ and H^+) are at least as numerous as solar-wind ions out to some 12 R_E, where the data ends in Fig 3c.

Fig. 4a shows how the densities of the four major ion species depends on solar activity (given by the radio flux at a wavelength of 10.7 cm) in the magnetotail at distances greater than 10 R_E (also compared with distances less than 10 R_E). The ionospheric ions increase in density with increasing solar radio flux, but the proton density (also believed to be partly of ionospheric origin) decreases.

Fig. 4b demonstrates that the average O^+ density is closely correlated with the polarization electric field in the solar wind within 10 R_E. The lower panel in this figure shows that the average energy decreases with increasing electric field. Such a relation has also been found between the average energy of O^+ and solar and geomagnetic activities in general. Moreover, the Geotail spacecraft launched in the summer of 1992 into a highly eccentric orbit has recently sent back data indicating that O^+ ions are present in the tail out to 60 R_E (corresponding to the satellite's apogee). Geotail was injected into an orbit with an apogee of about 220 R_E in early-September 1992 so further results are expected.

The composition of the hot plasma in the plasma sheet is very dynamic, as is illustrated by Fig. 4c. Before the onset of a so-



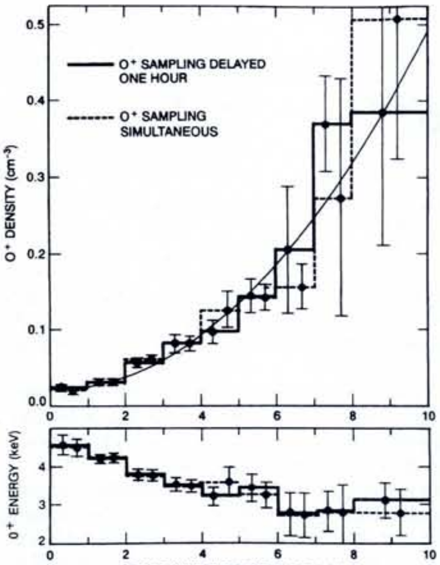


Fig. 4 — The composition of the main storage region of the Earth's magnetosphere, namely the plasma sheet in the magnetotail.
a, upper left) Number densities of the four dominant ion species (H^+, He^{++}, He^+, O^+) in the magnetotail near the equatorial plane as a function of the solar activity measured by the solar 10.7 cm radio flux [10]. The solid lines are for the tail region at a radius $R > 10\ R_E$ and the dashed lines for $R < 10\ R_E$.
b, lower left) The average density (upper panel) and energy (lower panel) of 0.1-16 keV/q O^+ ions as function of the polarization electric field (in mV/m) in the solar wind during the period O^+ was sampled (dashed lines) and during the preceding hour (solid lines). The data were obtained by the ISEE-1 satellite [11] and the parabola is a least-squares fit.
c, upper right) Changes of ion densities in the plasma sheet immediately before and during a substorm measured by ISEE-1 on 22 March 1979 [12]. The data are plotted in terms of time (in hours) and position (radius R) and the circular and triangular symbols indicate the fractions of the density of the ion species (H^+, O^+, He^+) which are attributed to narrowly collimated beams.

called substorm (a sort of elementary magnetospheric disturbance involving a macroscopic instability), the plasma consisted of 90-95% of H^+ and He^{++}, mostly of solar-wind origin. About half an hour after the substorm started, the H^+ and He^{++} densities dropped sharply at 15 R_E. At the same time the O^+ density increased by an order of magnitude at all energies over a period of about 10 minutes, and stayed high thereafter. A significant proportion of the O^+ ions was contained within strongly collimated beams flowing tailward with energies mostly below 1 keV, but sometimes as high as 6-8 keV. This seems to indicate a fundamental change in the flow pattern which is possibly associated with a diversion through the polar ionosphere of the electric current that flows across the tail.

Ring current

The first experimental investigation of the composition of the highly energetic ring current plasma circulating the Earth in the magnetosphere within about 7 R_E was made using the AMPTE satellite in the second half of 1980 [13, 14]. The energy range 1-310 keV/*q* was covered by the ion-mass spectrometer on one of the three AMPTE satellites, whereas earlier satellites had only reached some 30 keV for protons (the energy density of the ring current plasma generally reaches a maximum between 100 and 200 keV/*q*). The average number-density fractions of the various ring current species for 20 magnetic storms of moderate intensity was found to be 77% for H^+ and 21% for O^+ (and N^+) in the inner ring current (radii less than 3-5 R_E). In none of these storms was O^+ more abundant than H^+. However, in a severe magnetic storm, a so-called "great magnetic storm", O^+ was found to dominate over H^+ during a period close to the storm's maximum phase. Near maximum, some three times more of the ring current's energy was associated with ionospheric ions than with ions of solar-wind origin [14].

Unanswered Questions

Outflow mechanisms

As mentioned earlier, the remarkably high efficiency with which the magnetosphere pumps ionospheric plasma out into the magnetosphere was unexpected until the mid-1970s. The physical processes responsible for the energizing and expulsion of the ionospheric plasma remain a topical field of research.

Except under quiet conditions, mechanical forces such as those due to thermal effects (the polar wind) or pressure gradients are not the primary ones; electromagnetic acceleration processes are clearly the most important. There are, however, many different mechanisms whereby electric and magnetic fields can accelerate ionospheric ions and electrons, and today's research mainly considers which processes could contribute significantly to the outflow of ionospheric ions. For instance, early satellites only measured the upcoming ions and electrons well above the ionosphere, where the ions and electrons have already been accelerated to final or close to final energies. Hence Freja, the most recent satellite designed to probe the magnetosphere, has as one of its main tasks the acquisition of data about acceleration processes in the source regions of the upper ionosphere below an altitude of 1700 km.

From the research conducted in the last decade we can conclude that the acceleration of ions and electrons is both parallel and perpendicular to the magnetosphere's magnetic field lines. To what extent the parallel acceleration is due to a quasistatic electric field or to waves remains unclear, but the importance of potential differences along magnetic field lines has been fairly clearly demonstrated. However, electromagnetic wave fields are generally also present; they cause spreading of the angular distributions caused by the potential fields.

That the perpendicular acceleration is due mainly to waves is generally accepted. Since a magnetized plasma with both hot and cold inhomogeneous components can sustain a very large number of wave modes, much effort has gone into identifying the dominant modes. The acceleration has been associated mainly with ion-cyclotron waves [15] and with lower hybrid waves [16], but many other mechanisms have been invoked [17], among them various non-linear wave processes.

Field fluctuations

One observational result is that the acceleration and extraction processes work simultaneously on electrons and ions, forcing them to flow out of the ionosphere together, the electrons as beams and the ions as cones or beams, sometimes with narrow angular distributions around the magnetic field lines for both electrons and ions [18]. Such joint outflow of energized electrons and ions has been found to be strongly correlated with slow, large-amplitude fluctuations of the electric field with a power-density spectrum that peaks below 1 Hz, *i.e.*, below all the characteristic frequencies of the ion species present in the upper ionosphere and lower magnetosphere [18-20]. An example of this strong correlation between ion beams and electric field fluctuations is shown in Fig. 5, where a roughly perpendicular electric field component is shown in the middle frame. In the periods when ion beams (06.2815-06.2915 hours) and ion conics (from 06.3025 hours onward) were observed, there were also fluctuations in the electric field component of the order of 100 mV/m. Such fluctuations (with large amplitude) did not exist outside these time intervals.

Both the nature and origin of these electric field fluctuations are uncertain. Most likely they are some sort of Alfvén waves generated on auroral zone magnetic field lines well beyond the region of intermediate altitudes which have been investigated by the satellites S3-3, Dynamics Explorer I, Viking, and Akebono (*i.e.*, beyond an altitude of 25000 km).

Paths to the tail

There are also a number of unanswered questions about how the ionospheric ions reach various parts of the magnetosphere, especially its tail. The ions may be transported to the large region of stored plasma in the plasma sheet of the magnetospheric tail either *via* the cusp region through the high-latitude boundary layer (the plasma mantle) or through the low-latitude boundary layer along the flanks of the tail. The mantle was the first path to be proposed, but observations seem not to fit the theoretical expectations. On the other hand, the route into the plasma sheet through the low-latitude boundary layer is not well supported by either direct observations or theory. So paths to the tail will probably be on the research agenda for quite some time.

Other sources

We have here discussed two sources of the magnetospheric plasma, the solar wind and the ionosphere. An interesting result from the visits of spacecraft to the other planets in the solar system (except Pluto) is that two other kinds of sources are important in some planetary magnetospheres, namely gases from volcanoes on moons (*e.g.*, Jupiter's moon Io) and sputtering

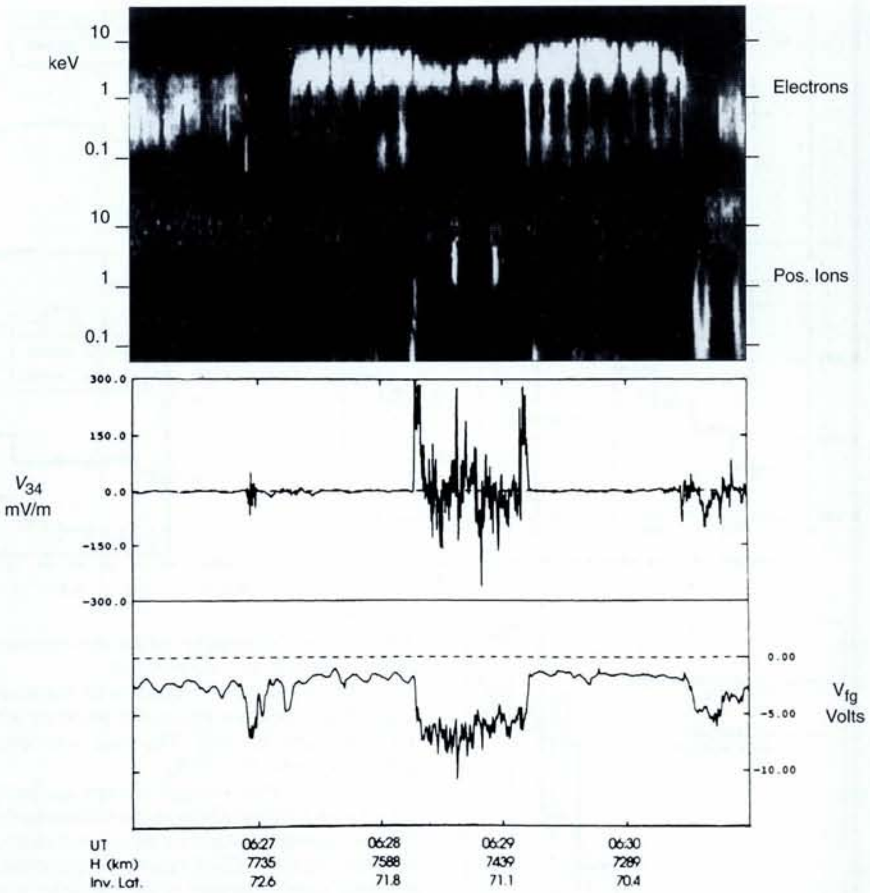


Fig. 5 — Data from the Viking spacecraft showing the strong correlation between the joint outflow of energized electrons and ions and electric field fluctuations in the magnetosphere [20]. The data are plotted as a function of position corresponding to different times UT (in hours), heights H (in km), and latitude (in degrees).

Upper panel: energy-time spectrograms for electrons (top) and positive ions (bottom). Middle panel: one of the corresponding perpendicular electric field components (v_{34} in mV/m). Lower panel: the density V_{fg} (in volts), an approximate measure of the density of cold electrons, decreased in the periods during which the ion beams and conics were observed.

When the slow, electric field fluctuations (middle panel) have very large amplitudes, the ions generally show conic angular distributions around the magnetic field lines, and narrow, upward directed electron beams of energies of the order of hundreds of eV to several keV are frequently seen. It appears that the acceleration of both the ions and the electrons is caused by the electric field fluctuations: the ions are affected mainly by the fluctuation component perpendicular to the magnetic field lines but the (much smaller) field-aligned electric field component is the most important one for producing the narrow, field-aligned electron beams. So whereas the ions experience the fluctuations as a complex wave field, the electrons experience them as a quasistatic field and are accelerated out of the acceleration region in one (or a few) reversals of the field. Also, for the ions the acceleration process due to the slow, large-amplitude electric field fluctuations seems to be at least partly a non-resonant process associated with a few shock-like field structures which give a large fraction of the perpendicular energy to the ions, causing them to pass upwards through the acceleration region owing to the increasing magnetic moment that the perpendicular acceleration produces. It is still unclear to what extent this non-resonant process contributes relative to the various resonant-wave acceleration mechanisms which are also certainly present.

PLANNED SPACE MISSIONS

FAST: a small NASA Explorer-class satellite which will be launched into an orbit with an apogee of a few thousand kilometres to carry out measurements at high resolution in time at low and intermediate altitudes.

Polar: in NASA's GGS programme. Will be sent into a polar orbit with an apogee altitude of about 10 R_E.

Interball: a Russian four-spacecraft mission, with one spacecraft in a polar orbit reaching some 10 R_E in altitude and one in a tail orbit with an apogee of about 40 R_E. Two of the four satellites are small sub-satellites, with one staying relatively close to each of the two main spacecraft.

Cluster: the European Space Agency's main space-physics project for the 1990s, planned for launching in late-1995. It will be the first mission comprising a group of (four) spacecraft close to each other so there will be some possibilities for separating time and space variations and for investigating the fine structure in the plasma field, even in the thin boundary layers between different plasma regions.

by energetic particles of heavy ions from surfaces of moons or ring particles (*e.g.*, Saturn). However, these sources are negligible in the Earth's magnetosphere.

Prospects

Two satellites which are currently contributing major new observations about the composition of the Earth's magnetospheric plasma are the Japanese-US Geotail mission launched in July 1992 into a highly eccentric orbit, and the Swedish-German Freja satellite with an apogee of 1750 km launched in October 1992. The former will make measurements in the deep tail up to October 1994 before being moved into an orbit with an apogee of 30 R_E for studies of the near tail. Freja is aimed at investigations of the source region of the magnetospheric ions of ionospheric origin. Geotail will make the first detailed studies of the tail and Freja will carry out for the first time measurements at high resolutions in time using several new instruments.

In the period up to the end of 1995, four other satellite projects will reach their launch phase (see insert). So there is some hope that several of the open questions will be answered by the end of the decade. On the other hand, we can expect that more detailed measurements of all kinds of plasma and field variables will provide new surprises, thus raising new questions about fundamental properties of the Earth's highly complex magnetospheric plasma system.

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Heavy-Ion Therapy at GSI

Gerhard Kraft from the Gesellschaft für Schwerionenforschung, Darmstadt, describes how new approaches and a novel scanning technique to be implemented at GSI's planned ion-therapy unit will offer biologically efficient, tumour conform treatment.

Beams of heavy charged particles beginning with protons represent the most advanced tools for external, subcutaneous therapy of deep-seated tumours in humans. Compared to electromagnetic radiation, they offer an improved distribution of the dose with depth owing to their small lateral and angular scattering; they travel in virtually straight lines and stop at a definite depth (or "range"). More importantly, the dose profile is inversed in that the energy deposition increases from a plateau with increasing penetration distance up to the Bragg maximum, and then cuts off sharply within a few millimetres. By combining overlapping Bragg peaks it is possible to achieve a homogeneous energy deposition over a defined volume (Fig. 1).

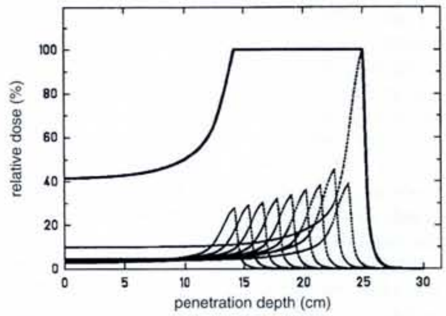


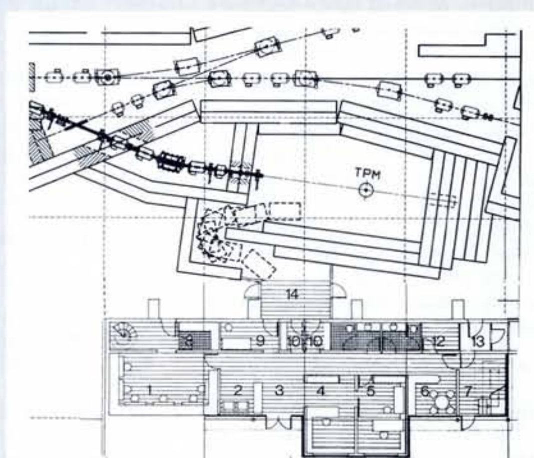
Fig. 1 — The superimposition of Bragg curves to give a uniform dose over a spherical volume. For each Bragg curve, the ionization density rises from a plateau value as the ions slow down, until at the very end of the ion's range the ionic charge is reduced by electron pick-up and the ionization falls rapidly to zero.

The lateral and range scattering decreases with the square of the atomic number so the precision of beam delivery increases as the atomic number increases. But the nuclear interaction rate also increases yielding lighter nuclear fragments having a longer range than the primary particles. An optimum is reached for ions around carbon where lateral scattering is small and nuclear fragmentation tolerable [1]. Moreover, nuclear fragmentation of ions heavier than protons and helium has strongly forward-peaked reaction kinematics. By measuring the γ-annihilation quanta of β^+-radioactive ions using positron emission tomography (PET) one can therefore correlate the range distribution with the primary beam in order to localize on-line the beam inside the patient [2].

The increased biological efficiency of heavy ions providing high ionization density in certain types of tumours opens up new dimensions in the treatment of radio-resistant

HEAVY-ION THERAPY UNIT AT GSI

The creation of a heavy-ion therapy unit at GSI (HITAG) was proposed to the German government in May 1993 by the GSI together with the Heidelberg Radiological Clinic and the German Cancer Research Centre, both these institutes having a long tradition in conventional therapies, neutron therapy and the development of advanced treatment techniques. The proposed 13.2 MDM unit (with some 60% coming from government and other external sources including insurance companies) will consist of a dedicated therapy care and an annex housing a control room, waiting rooms and the like (diagnosis and treatment planning will be in Heidelberg).



The ion beam from the beam line is guided by two dipole magnets and a pair of focussing quadrupoles. Symmetry and achromatism of the beam line is important for safety because the final focus in the patient corresponds to a focus intermediate between the two dipoles. Scintillators used as a beam scratcher at the intermediate focus allow the beam to be controlled nondestructively. Other safety features include an asymmetric layout for the raster scanning magnets so that the beam passes above the patient when the magnets are not powered (in the case of a power failure, the beam will automatically move outside the patient). A high-speed position sensitive counter just in front of the patient will monitor on-line the beam position and compare it with the settings of the scanner magnets in less than a millisecond. Finally, the PET system mentioned in the text will monitor the location of the beam inside the patient.

The cave is under construction and most of the beam-line components have been ordered; construction of the annex starts next year. An extended experimental campaign to characterize carbon and oxygen beams both biologically and physically will allow a choice before the end of 1994. Beam testing in the treatment cave, including exposure to anthropomorphic phantoms, will start in 1995 in preparation for the start of therapy in 1996. The aim is to treat about 100 patients a year suffering from local and inoperable cancers, mostly in the head and neck regions.