'RAPID'
RESEARCH WITH ADAPTIVE PARTICLE IMAGING DETECTORS

B. Wilken, W.I. Axford, P. Daly, A. Korth, G. Kremser, W.H. Ip, V.M. Vasyliunas[1]; J.B. Blake, J.F. Fennell, L.R. Lyons, M. Schulz[2]; H. Fisher, G. Wibberenz[3]; H. Borg, B. Hultquist[4]; D.N. Baker, R.D. Belian, T.A. Fritz[5]; K. Mursula, P. Tanskanen[6]; D. Hall[7]; S. McKenna-Lawlor[8]; F. Gliem, W. Rieck[9]; M. Scholer[10]; E.T. Sarris[11]; F. Soraas & S. Ullaland[12]

[1] Max-Planck-Institut für Aeronomie, Lindau, FRG; [2] Aerospace Corp., Los Angeles, USA; [3] Institut für Kernphysik, Kiel, FRG; [4] Swedish Institute of Space Physics, Kiruna, Sweden; [5] Los Alamos National Lab., USA; [6]Univ. of Oulu, Finland; [7] Rutherford Appl. Lab., Chilton, UK; [8] St. Patrick's College, Maynooth, Ireland; [9] IDA/TU Braunschweig, FRG; [10] MPI für Extraterrestr. Physik, München, FRG; [11] University of Thrace, Greece; [12] University of Bergen, Norway

ABSTRACT

The RAPID spectrometer for the CLUSTER mission is an advanced particle detector for the analysis of suprathermal plasma distributions in the energy range from 20-400 keV and 2 keV/nuc - 1500 keV for electrons and ions, respectively. Novel detector concepts in combination with pin-hole acceptance allow the measurement of angular distributions over a range of 180° in polar angle for either species. The detection principle for the ionic component is based on a two-dimensional analysis of the particle's velocity and energy. Electrons are identified by the well known energy-range relationship. The detection techniques are briefly described and selected areas in geospace highlight the scientific objectives of this investigation.

Keywords: Energetic particle spectrometer, plasma dynamics, reconnection field line

1. INTRODUCTION

Energetic particles are sensitive probes of the global state of the magnetosphere. Full energy spectra and complete pitch angle distributions of energetic particles can be used as an indicator of stresses in the magnetic field of the magnetosphere; they can be used to investigate the physics of acceleration processes of which they themselves are the product; they can be used to investigate the physics of wave-particle interactions; they can be used for entry studies of particles into the magnetosphere. Hence, comprehensive measurements of the properties of energetic particles can be used to trace the flow of mass and energy momentum through geospace and the physics associated with that concept.

The scientific goals of the CLUSTER program have been determined within the context of nearly three decades of extensive satellite exploration through which important physical processes of the geospace environment have been identified. Many remaining questions can be resolved using multipoint input from several fully coordinated, appropriately instrumented spacecraft. Extensive analysis identified measurements of the energetic particle distribution functions as essential to the achievement of the program objectives. Not only do energetic particles serve to couple different elements of geospace as they are injected, accelerated, transported and precipitated, but also by virtue of the spatial scale of their adiabatic motion, they serve as probes of regions remote from the spacecraft at which they are measured.

The energetic particle experiment RAPID (Research with Adaptive Particle Imaging Detectors) onboard CLUSTER and as part of the complement of particle and field instruments will contribute to a significant expansion of our understanding of solar-terrestrial physical processes in all principle regions of the magnetosphere. The following is a brief report on the instrumental techniques employed in RAPID and the prime scientific objectives pursued with this investigation.

2. INSTRUMENTATION

The RAPID spectrometer is designed for the fast analysis of energetic electrons and ions with a complete coverage of the unit sphere in phase space. Dedicated sensor systems for electrons and ions cover the unit sphere with comparable angular resolution for either particle species. Both systems employ state-of-the art techniques to accomplish particle discrimination and three dimensional velocity analysis. The instrument consists of the Imaging Electron Spectrometer (IES), the Imaging Ion Mass Spectrometer (IIMS), and the common Digital Processing Unit (DPU). Figure 1 illustrates configuration, orientation and viewing angles of RAPID.

2.1 The Sensorsystem

2.1.1 The Imaging Ion Mass Spectrometer (IIMS) IIMS is an energetic ion spectrometer which derives its particle identifier function $M \sim E \bullet T^2$ from a time-of-flight/energy measurement (particle mass M in amu). Figure 2 is an illustration of the two-dimensional analysis showing the mass sorting along hyperbolic curves in the E–T plane. Comprehensive description of this detection technique and its application in space research have been published in the literature (Ref. 45 & Ref. 16). The IIMS is a generic derivative of the family of instruments which uses secondary electron emission (SEE) for timing: The flight time T of a swift particle is obtained by detecting secondary electrons (SE) released from a thin START foil (thickness 5-20 $\mu g/cm^2$) and the surface of a solid state detector (SSD) which is located at a distance s behind the foil. Secondary electrons ejected from the foil and the SSD are deflected onto microchannel plates (MCP) to obtain timing signals for the T measurement. An essential step in the technical evolution of this family of instruments is the addition of position sensing on the entrance foil (START foil). The secondary electron transport to the MCP is not only isochronous but also image forming. The principle of proximity focussing is used to create an one-to-one image of the foil on the MCP. The particle's direction of incidence is then obtained from the pin-hole effect associated with the small geometry of the SSD as the back element.

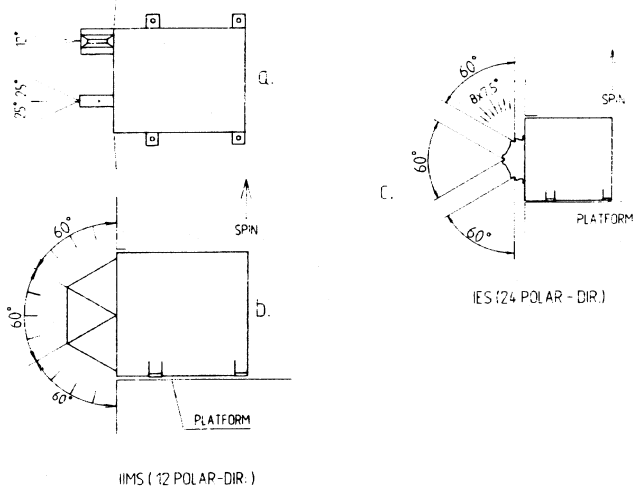

Fig. 1 Instrument configuration, orientation on the spacecraft, viewing angles, and field of views. (a) Top view with the IIMS and IES azimuthal openings. (b) Side view with the IIMS 12 angular intervals in the 180° polar segment. (c) Side view with the IES 24 angular intervals in the 180° polar segment.

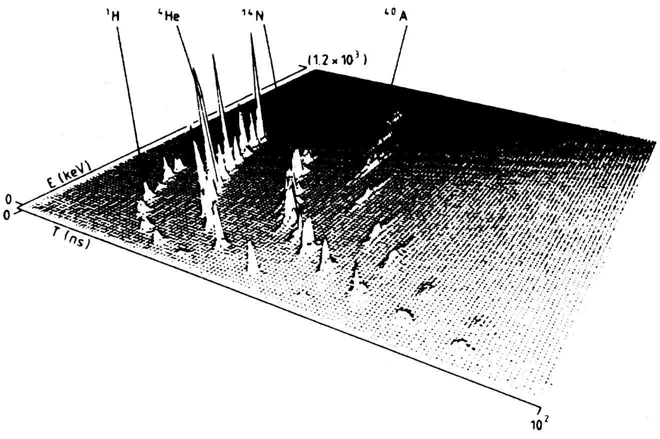

Fig. 2 Illustration of the two-dimensional mass analysis with a time-of-flight/energy spectrometer. Particles with equal masses are sorted along hyperbolic curves.

A schematic representation of the time-of-flight detector is shown in Fig. 3. Secondary electrons released from the foil (or from the SSD) are accelerated over a distance of 3 mm to about 1 keV. Except for the 90° reflection in the electrostatic mirror field the electrons drift in a potential free cavity towards the respective MCP. Before striking the entrance surface of the microchannelplate the electrons are decelerated by about 0.1 keV in order to suppress background signals from migrating low energy secondary electrons which may be released from surfaces other than the foil or SSD.

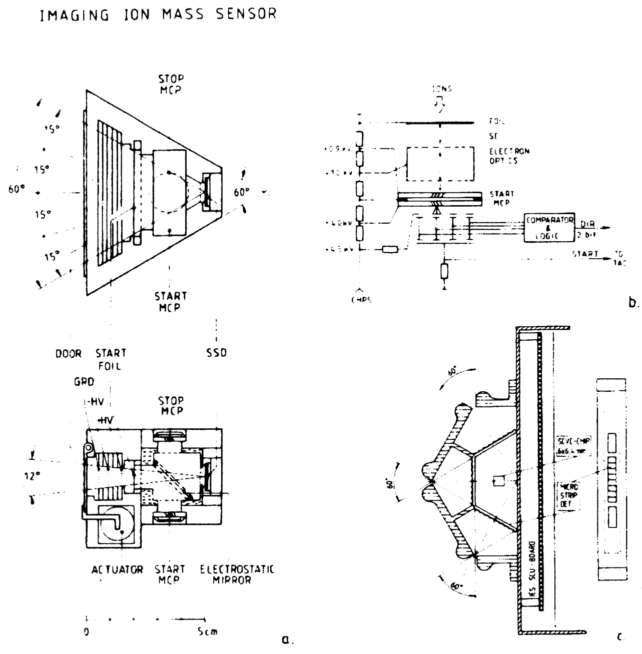

Fig. 3 (a) Cross-sectional view of an IIMS 60° sensor element. One-dimensional position sensing on the START foil devides the foil/solid state detector (SSD) geometry into four angular intervals. (b) Principle signal read-out system for the START assembly. (c) Cross-section of the IES sensor assembly with three 60° pinhole/micro strip detector systems. The principle lay-out of micro strip detector is shown on the right side. The monolythic SCVC device is integrated into the sensor system.

The number of secondary electrons arriving at the MCP is amplified in a two-stage channelplate assembly by a factor of $\sim 5 \bullet 10^6$. A one dimensional four-element anode array behind the START channelplate with a digital read-out system determines the position of the electron cloud on the exit side of the MCP. Each anode element corresponds to an area on the MCP face which in turn projects back to an area on the START foil by virtue of the electron optics. The particular potential distribution in the IIMS detector requires novel design approaches for the signal read-out system. The mandatory condition to keep the solid state detector at ground potential results in a high positive voltage for the exit surface of the microchannelplate. As a result the fast channelplate output pulses have to be isolated from this high potential before timing and position information can be extracted. The principle of the capacitor coupled read-out system is shown in Fig. 3 (b). The position of the activated anode element is obtained from a slow power-saving charge analysis whereas the timing pulse is derived from the fast waveform generated by the channelplate. The time constant for the position determination is about 1 μs. If only a single anode was stimulated by the particle the follow-on electronics encodes the event in a 2 bit binary address. Events for which the MCP output current is split between two adjacent anodes are eliminated from the evaluation process. The fast timing pulse for the time-of-flight measurement is obtained from the common signal path as indicated in Fig. 3 (b). At the end of the flight path (s = 3 cm) the incident particle impinges on the small solid-state detector (SSD) as shown in Fig. 3. Secondary electrons ejected from the SSD surface upon impact of the ion are transferred to a circular STOP microchannel plate without position sensing. The residual ion energy is deposited in the SSD and provides the energy (E) signal for the mass analysis.

The START foil with position sensing and the narrow SSD (active diameter 8 mm) form a particle imaging system similar to a pin-hole camera: The position of intersection on the entrance foil and the SSD define the particle's direction of incidence. The position sensing system forms four angular intervals over a range of 60° as sketched in Fig. 3. This only moderate angular resolution is in good agreement with the scientific requirements.

The described system allows the identification of ions over an energy range of 5 keV/nuc to 1500 keV total energy with a mass resolution of about 4 (at A = 16 amu). The mass-energy range covered by the detector is shown in Fig. 4.

The integrated sensorsystem of IIMS consists of three identical sensor units which cover a 180° fan in the polar plane with 12 contiguous angular intervals (15° x 12° each). The collimator of each detector unit has a built-in plasma rejector and the sensor sensitivity can be adjusted to the particle flux by an adaptive aperture system.

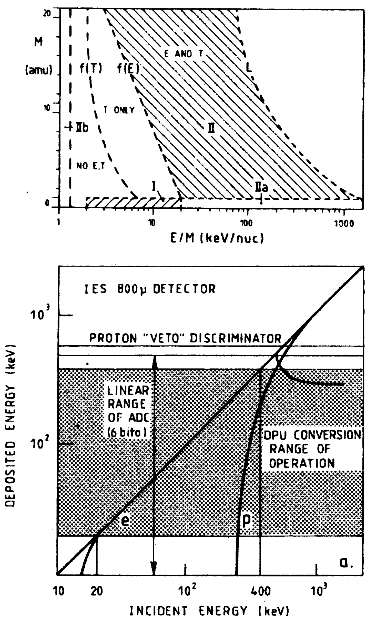

Fig. 4 (a) Energy characteristic for an IES micro strip detector with an 450 $\mu g/cm^2$ absorbing window. (b) Mass versus energy per nucleon range for the IIMS sensor. The prime region for analysis with unique ion mass information is marked with II. The curve f(T) indicates the lower limit for time-of-flight measurements.

2.1.2 The Imaging Electron Spectrometer IES Electrons with energies from 20 keV to 400 keV are measured with the Imaging Electron Spectrometer (IES). Advanced microstrip solid state detectors having a 0.5 cm × 1.5 cm planar format with eight individual elements form the image plane for three acceptance "pin-hole" systems. Each system divides a 60° segment into 8 angular intervals. Three of these detectors arranged in the configuration shown in Fig. 3 (c) provide electron measurements over a 180° fan.

The 800 micron thick ion-implant solid state devices are covered with a 450 microgram/cm^2 (Si eq) absorbing window which eliminates ions up to 350 keV through the mass dependent range-energy relationship. The principle energy range for IES is shown in Fig. 4.

The 24 individual strips on the three focal plane detectors are interrogated by a multichannel switched-charge/voltage-converter (SCVC) in monolythic technology. The SCVC provides for each particle coded information on the strip number and particle energy. This primary information is transferred to the DPU for further evaluation.

2.1.3 The Digital Processing Unit (DPU) The intrincically high data rate of RAPID must be reduced to a level compatible with the limited telemetry capacity. The prime task of the DPU is to transform the measured quantities into physical parameters such as particle mass and pitch angle and to apply effective data compression techniques prior to ground transmission.

Azimuthal resolution in velocity space is obtained by dividing the spin plane into 32 equally spaced sectors (highest resolution). Combined with the angular division of the 180° segment in polar angle a complete coverage of the unit sphere with 384 and 768 contiguous angular bins is obtained for ions and electrons, respectively.

The conversion and compression is done by event driven preprocessors, IPP for the ion sensor and EPP for the electron sensor. These preprocessors are served and controlled by a microprocessor system. The preprocessed data will be further compressed to the following data categories: Three-dimensional angular distributions, ion mass and energy spectra, electron energy spectra, fast measurements of ion and electron front-to-back intensities from sensor elements with fields of view in opposite directions, ion and electron flux obtained at specific pitch angles such as 0°, 90° and 180° with respect to the magnetic field (the latter process requires an inter-instrument link to the magnetometer).

3. SCIENTIFIC OBJECTIVES

The energetic particle measurements on RAPID will be able to expand significantly our understanding of solar-terrestrial physical processes in most principle regions of the magnetosphere. These are in particular the: 1) Middle Magnetosphere; 2) Low Latitude Boundary Layer; 3) Auroral Zone extension to high altitude; 4) Plasma Sheet and its associated Boundary Layer; 5) Plasma Mantle/Tail Lobes;
6) Magnetopause; 7) Cusp/Magnetosheath, and 8) Bow Shock Upstream Region.

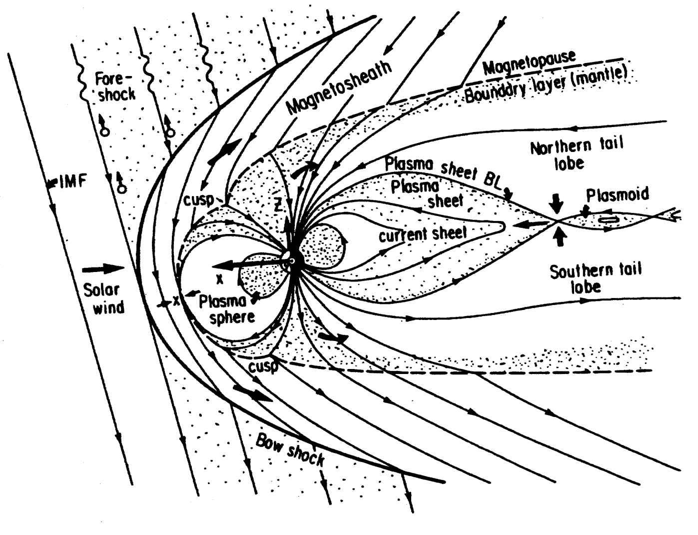

Fig. 5 A noon-midnight meridional cut through the magnetosphere showing the various regions to be studied by CLUSTER. (Ref. 41)

Figure 5 illustrates a noon-midnight meridional cut through the magnetospheric system, showing most of the plasma regions and boundaries presently believed to exist in geospace. The microphysical processes occurring within these key regions – especially during the times of major dynamical reconfigurations – are areas in which RAPID will provide absolutely essential information. These studies are particularly dependent upon the 4-spacecraft CLUSTER configuration. The remainder of this scientific section will be restricted to the discussion of three selected regions which place emphasis on the most outstanding physical processes:

1) Bow Shock structure and upstream particle sources;
2) The Dayside Magnetopause, Magnetosheath, and Cusp regions; and
3) Plasma Sheet Dynamics and Magnetotail Boundary.

The description of these selected regions of geospace are meant to highlight the scientific contributions that can be made with RAPID but can by no means give a complete picture of the return expected from this instrument.

3.1 Bow Shock and Upstream Phenomena

One prominent feature in the solar wind interaction with the magnetosphere concerns the various particle acceleration processes occurring upstream of and at the bow shock. The ISEE 1 and 2 observations have shown that these regions are very rich in small- and large-scale phenomena directly related to the generation of plasma turbulence and particle energization, and hence are most important for testing theories of different shock acceleration mechanisms and wave-particle interactions. Some of the ISEE results and the advances expected from the CLUSTER mission are outlined in the following.

Particle acceleration at MHD-shocks has become one of the key topics in space plasma physics during the last decade, stimulated by both extensive theoretical studies and in situ measurements within the solar system. In this field, the earth's bow shock has attracted particular attention because of its proximity. The energetic particle population near the bow shock has been related to diffusive Fermi acceleration (Ref. 18, Ref. 37 & Ref. 44) and compared with model calculations (Ref. 21 & Ref. 11). Recently, the bow shock origin of the diffusive upstream ions has been questioned (Ref. 1 & Ref. 34) and it has been proposed that this energetic particle population is due to escape of magnetospheric ions into the upstream region. The question is of considerable importance.

Diagnostic tools to distinguish these two origins are the following: (a) simultaneous measurements of ions and electrons at different positions inside and outside the earth's magnetosphere, (b) check for the simultaneous occurrence of an electron component (the bow shock acceleration in the energy range above 20 keV is restricted to ions), (c) correlation with the momentary directions of the interplanetary magnetic field and flow direction of the solar wind, (d) measurement of the energy spectrum over a wide range, throughout various phases of individual events, (e) measurement of the chemical composition, (f) correlation with the simultaneous occurrence of an increased level of turbulence in the magnetic field, (g) study of anisotropies in three dimensions.

Apart from the question of the origin of upstream particles, a number of fundamental problems in the interaction between the bow shock and energetic particles are still unsolved. These include: the injection of thermal solar wind ions into the diffusive shock acceleration mechanism, in relation to the shock structure; the efficiency of shock acceleration as a function of the shock Mach number, the shock normal angle, the position on the bow shock etc.; the escape mechanism (upstream, downstream, perpendicular to the average field) which finally determines the shape of the energy spectrum; conditions for the growth of wave turbulence; the scattering of particles by hydromagnetic turbulence, in particular, the variation of the mean free path with particle parameters like velocity and/or energy/charge; the conditions for the appearance of limiting fluxes in a steady state situation; the influence of the accelerated particles on the ambient medium.

Recent AMPTE/IRM observations (Ref. 26) show the advantage of measurements of complete spectra of ions of different species from thermal energies up to above 100 keV. It is an interesting observation that for quasi-parallel shocks maximum attainable energy seems to be limited. Some authors relate this as well as the deviation of the energy spectrum from a power law, to the finite size of the bow shock combined with lateral escape (Ref. 10). This is not at all clear because the upstream turbulence decays with distance from the bow shock and finally leads to free streaming of particles away from the bow shock at some finite distance generally simulated by a free escape boundary (Ref. 44 & Ref. 12).

Previous studies established, depending on the location around the shock front, two separate populations of suprathermal ions. The so-called beam ions, observed predominantly in the quasi-perpendicular bow shock regime (Ref. 3, Ref. 17 & Ref. 28) were identified as beams of particles streaming along the interplanetary magnetic field, with energies that seldom exceed 20 keV. However, at higher energies, a reflected diffuse ion population exists in the quasi-parallel shock regime (Ref. 24 & Ref. 17). The diffuse ions (protons, alphas and CNO) have energies in the range 30-100 keV, and exhibit rather isotropic distribution, indicating a process of random scattering. Diffuse shock acceleration might be at work here. Another population intermediate between the beam ions and the diffuse ions has also been identified (Ref. 29).

It is possible that, while the beam ions have their origin in the specular reflection of solar wind ions at the quasi-perpendicular shock front (Ref. 40 & Ref. 28) some of them could act as seed particles for the diffuse ions via further acceleration. The energy density of the reflected diffuse ions is about 1/3 of the solar wind energy density (Ref. 19), the shock acceleration is thus a very efficient mechanism. Mitchell and Roelof (Ref. 25) have made the interesting suggestion that the acceleration of the diffuse ions is self-limiting in the sense that the parallel energy ($E_{||}$) of the 30-200 keV energy ions cannot exceed the magnetic field energy density ($B^2/2\mu_o$) by more than a factor of 2. This effect can be investigated in detail with the RAPID instrument as it has comprehensive pitch-angle (4π) as well as energy (20 keV to 1 MeV) coverage for different ion species (p, α, and CNO). Observations at the 4 different positions relative to the shock will specifiy the boundary conditions for models of the processes occuring.

The appearance of the diffuse energetic ions is usually accompanied by large-amplitude low-frequency waves in the magnetic field as well as the solar wind plasma. The presence of ULF waves is essential in the theoretical model of first-order Fermi acceleration (Ref. 4 & Ref. 22). The Fermi acceleration mechanism requires that the ions be resonantly scattered between the converging upstream magnetic irregularities and the shock front or the downstream waves. Several ingredients are important in the diffuse shock acceleration process. First of all, the diffusion coefficient ($K_{||}$) should have a certain energy dependence such that the scale length λ for the e-folding distances for the upstream distribution of the diffuse ions should be different for ions of different energies. While Ipavich et al. (Ref. 18) have determined $\lambda = 7.2$ R_E for 30 keV-protons, Wibberenz et al. (Ref. 44) have found λ = const. (6.5 ± 1.5 R_E) for 25-36 keV protons without significant energy dependence. With the energy window of the RAPID experiment covering the full energy width of the upstream diffuse ions and with multiple measurements at the different positions of the spacecraft, this outstanding issue will be thoroughly addressed by the CLUSTER mission.

The time scale for diffuse acceleration is of the order of $K_{\|}/V_1^2$ (Ref. 4) where V_1 is the upstream solar wind velocity. This means that the Fermi-acceleration is a time-dependent process, an effect that can be clearly seen by comparing the temporal profile of diffuse ions of different energies. Usually the low energy (30 - 60 keV) ions have a flat-topped distribution with the onset and dropout modulated by the magnetic field direction. On the other hand, the profiles of the energetic ($E > 100$ keV) population have a more gradual rise and fall (Ref. 19). This is thought to be due to the longer magnetic field connection time necessary for higher energy increases. As mentioned earlier, besides diffusive streaming along the magnetic field lines, with an escape boundary at large upstream distances (Ref. 38), cross-field diffusion has also been suggested to be of importance in shaping the spatial distribution and energy spectra of the diffuse ions (Ref. 10). Theoretical modelling predicts that the e-folding energy per charge, Eo/Q, is determined by the lateral dimension of the magnetic flux tube. The multipoint measurements of the CLUSTER/RAPID experiment will scrutinize small-scale structures in three dimensions, permitting an exact determination of the bow shock and its motion, necessary for the proper performance of the calculations. Consequently, the comparative importance of the two directional diffusions, parallel and perpendicular to the magnetic fields, should be established, as a test of the corresponding models.

Since the temporal and directional variations of the interplanetary magnetic field have strong effect on the upstream particle population. The simultaneous observations of the solar wind by the SOHO spacecraft at the L1 libration point will be of great importance in correlating the various magnetospheric phenomena with the interplanetary condition.

3.2 The Magnetopause, Magnetosheath, and Cusp Regions

After deceleration at the bow shock, the solar wind plasma continues to travel through the magnetosheath until it reaches the magnetopause, the actual separation between the solar wind and terrestrial magnetic field lines. Here it is deflected to the sides and over the poles into the magnetotail. The interesting physical questions in this region are what processes occur during the propagation of the plasma from the bow shock to the magnetopause; to what extent is the magnetopause penetrated by the solar wind; where and under what conditions does entry occur; what happens to the solar wind plasma once it is in the magnetosphere; and what becomes of the magnetospheric particles that are released to the magnetosheath?

3.2.1 Magnetic Field Line Reconnection and Flux Transfer Events (FTE) Over a quarter century ago it was suggested that the magnetic field lines in the solar wind could combine with those of the earth to provide direct entry and acceleration of solar wind plasma into the magnetosphere. This process, known as 'reconnection', or 'merging', has been confirmed by the ISEE project (Ref. 27 for plasma and Ref. 20 for energetic electrons). The process has turned out to be far more complicated than originally imagined. The multi-point measurements of the CLUSTER experiments will be able to probe the complex structure of reconnection events in terms of spectra, composition, and flow directions, thus yielding information on energisation, sources, and motion of the particles. In addition, the ability to use finite gyroradius effects, described below, is a powerful tool to detect the motion of the structure as a whole.

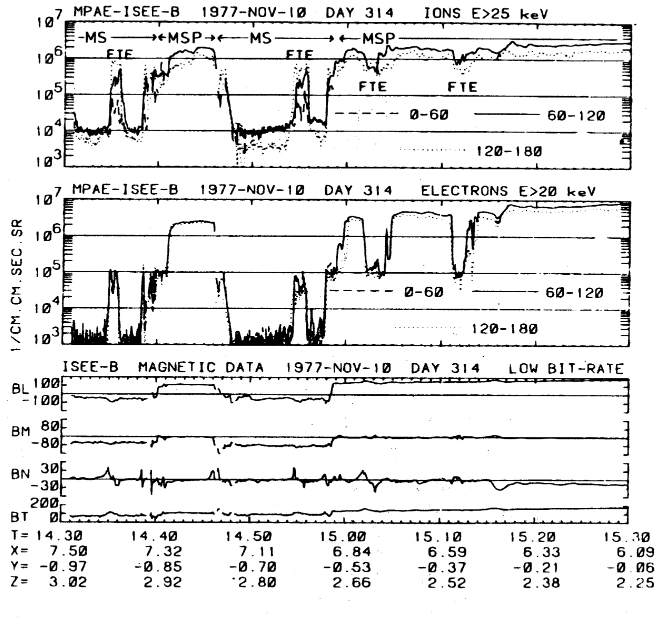

Fig. 6 Ion, electron, and magnetic data from an inbound passage of ISEE-2 across the magnetopause, from Daly and Keppler, (Ref. 7). The different types of curves give the particle intensities in different pitch angle ranges. Magnetic data are given as components in the boundary normal system (LMN) of Russell and Elphic (Ref. 32), plus the total magnetic field strength, BT. FTEs are found both in the magnetosheath (MS) and magnetosphere (MSP).

The principle observational features of FTEs are shown in Fig. 6, for an inbound crossing of the magnetopause by ISEE-2. One first sees that the magnetopause is not a stationary boundary, since the spacecraft crosses it several times, first at UT 1440, then at 1447, and lastly at 1459. On this day, the magnetosphere (MSP) is distinguished from the magnetosheath (MS) by the sign of BL, the northern component of the magnetic field. The FTEs are indicated by a positive then negative fluctuation in BN, the component of magnetic field normal (and outwards) to the magnetopause. In the magnetosheath, the FTEs are accompanied by isotropic electrons and streaming ions. Field-aligned anisotropies of the energetic ions uniquly identifies the magnetospheric hemisphere to which the magnetosheath field line is connected.

In the magnetosphere, the particle intensities are reduced during FTEs, to slightly more than those levels in the magnetosheath FTEs. This indicates that the FTEs have a continuity through the magnetopause permitting magnetospheric energetic particles to escape into the magnetosheath, and possibly into interplanetary space. Conversely, it has also been demonstrated by Paschmann et al., (Ref. 30) that magnetosheath plasma is to be found within the magnetospheric FTEs. These phenomena have first been observed by GEOS and STARE (Ref. 39).

Surveys of the occurrence and properties of FTEs (Ref. 31 & Ref. 9) demonstrate that they are a persistent feature of the dayside magnetopause during times when the interplanetary field is directed southward, which is further confirmation that they are a reconnection phenomenon. These surveys, however, suffer from a lack of coverage in the southern hemisphere and near the cusps and poles. The polar orbit of CLUSTER will be able to investigate these poorly explored regions.

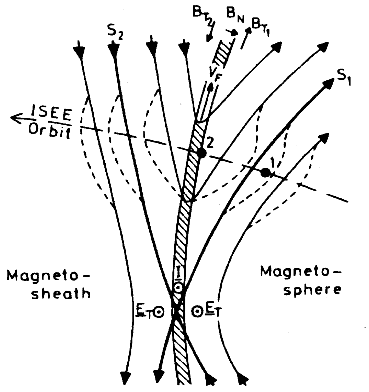

Fig. 7 Meridian cross-section of the dayside magnetopause illustrating the signatures of steady subsolar reconnection for antiparallel external and internal magnetic fields. The field lines are shown as solid lines, with the dashed lines denoting the field distortions which may occur following a short pulse of stronger reconnection which erodes extra flux. (after Ref. 35)

Using ISEE-1 and 2 to make two-point measurements of FTEs, Saunders et al. (Ref. 36), have shown that the events are highly structured, possessing twisted field lines and vortex plasma motion. Infact, based on these measurements alternate interpretations of FTE signatures have been proposed by Saunders (Ref. 35) and Southwood et al (Ref. 42). According to the suggestion by Saunders (Ref. 35) in Fig. 7 FTE signals will be observed if a flux bulge due to transient changes in the rate of quasi-steady reconnection passes across the satellite. It is quite clear that four-point measurements will greatly add to our understanding of these complex features by probing in detail their cross-sectional structure and temporal variations.

That FTEs are spatially and temporally localized reconnection events is now widely (although not universally) accepted. It is even believed that there is a continuous spectrum of reconnection event sizes covering the range from quasi-stationary reconnection to the fastest FTEs. Another possibility is that FTEs are very large scale features of the magnetopause that only appear to be localized due to wave motion of the magnetopause surface and the (at best) two point measurements previously available. The four-point measurements of CLUSTER will be able to answer this question in ways that the two-point measurements of ISEE could not. Energetic particle measurements are vital to any investigation of reconnection events because: 1) they are the only reliable indicator in the magnetosheath of the hemisphere to which the flux tube is connected (necessary for source determination); 2) that the particles exist for longer than their bounce time (about 1 min for 25 keV protons) means that there is a resupply process, which is still one of the mysteries of reconnection observations for which multi-point spectral measurements are required; 3) composition measurements are essential for the resupply and source determination; 4) the use of energetic particles as remote sensing probes (described below) can determine orientation and motion of the events, needed to discover their ultimate destination and four-point measurements will be necessary if the radius of curvature of the event surface is comparable to the ion gyroradius, as appears most likely.

3.2.2 Remote Sensing of Boundaries using Energetic Particles Finite gyroradius effects in the ion angular distribution function have been successfully used on ISEE to probe the dayside magnetopause (Ref. 15), FTE motion (Ref. 8), and plasma sheet motion in the geotail (Ref. 2). The remote sensing method can be applied in many ways, both for step function gradients and for finite density gradients.

Although this method has the advantage that boundary orientations and motions can be determined by a single spacecraft, it does contain some problems and ambiguities. The application of the step function gradient is often complicated, being tailored to each event individually. The finite gradient permits an analytical application by means of particle anisotropy measurements, but the additional Compton-Getting (motional) anisotropies must also be corrected for.

In both cases, a rotation of the magnetic field during the analysis period introduces intractable complications.

A necessary assumption in all applications of remote sensing is that the particle boundaries have a radius of curvature much greater than the ion gyroradius, i.e. that they be planar. Departures from this assumption have been found at the magnetopause (Ref. 13) and in the geomagnetic tail (Ref. 2). In such situations only multi-spacecraft analyses will be able to determine the complicated surface wave motion of the boundary in question.

3.3 Magnetotail Dynamics

A major topic to be addressed using energetic particle measurements is that of acceleration processes in the tail. Energetic particles have been observed continuously over time periods of hours with impulsive time variations on time scales < 1 min. However, because of the motion of the plasma sheet over single spacecraft and the limited intensity thresholds in the instrument, it has not been possible to distinguish the continuous plasma sheet energetic particle population and its sources from the population produced by impulsive acceleration associated with substorms. Such distinctions are vital to theories of substorms and related induced electric fields such as those associated with tearing mode instability theory. A cluster of four spacecraft will make it possible to address this problem by simultaneously sampling nearby regions within the relatively narrow plasma sheet and its boundary layer.

The best direct evidence for particle acceleration and probably the most important energetic phenomena in the magnetosphere are the high intensity field-aligned "impulsive" bursts, displaying inverse velocity dispersion (IVD). These events are usually detected at the high latitude plasma sheet boundary during thinnings of the plasma sheet. However, a number of cases have been found where 'impulsive' bursts with inverse velocity dispersion were observed well inside the plasma sheet (PS) or during PS expansions. These observations suggest that for some events the IVD may be a temporal rather than spatial effect. However, the most straigtforward explanation is that the events are caused by accelerations at a neutral line (Ref. 33). CLUSTER is a perfect mission for resolving spatial from temporal effects. The RAPID high resolution electron measurements can provide an extra "fingerprint" of the acceleration mechanism, which is missing from all previous observations of impulsive bursts because of instrumental limitations.

The passage of a "source" of energetic particles over a spacecraft inside the PS has been inferred on the basis of reversals in both the streaming of the energetic particles and the plasma flow. However, severe objections have been raised to such interpretations of the observations. CLUSTER must search specifically for such events with good time resolution, since the expected "reversal" must be observed simultaneously at all energies (within ~ few secs.) at each spacecraft. If such an encounter with the "source" is observed, then the RAPID measurements on the multiple CLUSTER spacecraft will be able to measure its size and speed.

Single spacecraft measurements of the time evolution of the angular distributions of energetic particle intensities during cases of counterstreaming between energetic ions and electrons have been used to infer the presence of transient (~ 10-20 sec) $\vec{E}$-fields parallel to the magnetic field. From simultaneous measurements of the variations in the energy spectra of the ambient energetic proton and electron populations under the influence of the $\vec{E}_{||}$-field, the "effective" potential traversed by the energetic particles, has been estimated to be a few tens of keV. The region over which the inferred transient $\vec{E}_{||}$-field extends may be determined using multipoint observations of such events. Furthermore, such multipoint measurements of various species with different charges will provide an excellent self-consistency test for the assumed existence of the field-aligned $\vec{E}$-field.

The $\vec{B}$-field microstructure (i.e. magnetic loops or islands with lengths of a few R_E) which develops in the magnetotail following acceleration events has been inferred mostly on the basis of single spacecraft measurements. Suspected neutral line formation in the near-earth tailregion and the subsequent plasma acceleration has led Baker et al. (1979) to propose the substorm sequence reproduced in Fig. 8. Energetic electron anisotropies were used to indicate whether field-lines were open or closed, but such mapping cannot be certain given the spatial scale sizes and temporal variation. Multiple spacecraft measurements of energetic particles, plasma and field with good time resolution ($\leq$ few secs.) can contribute to resolve these uncertainties.

Pulsations of the PS boundary with periodicities of ~ 2-9 min have been detected from measurements of the energetic particle intensities. Such oscillations are not apparent in the measurements of the $\vec{B}$-field alone. There is strong evidence that these pulsations are due to a standing (and not a travelling) wave at the PS boundary.

Energetic particle measurements will also be useful in the tail lobes during periods of observable solar particles. Regions of open lobe field lines can be identified, and using timing comparisons with SOHO, the length of open field lines can be estimated. In the past, incorporating 2 spacecraft inside and outside the magnetosphere, the time delay in the entry of solar particles in the lobes of the magnetotail was used in order to infer the "effective" length of the geotail (Ref. 43 & Ref. 14). However, the entry of solar particles inside the PS has not been studied in detail. Recent results have indicated that the access of solar particles inside the PS is prompt near the neutral sheet and delayed at high PS latitudes, being always considerably faster than the particle access in the lobes of the magnetotail. With simultaneous multispacecraft observations by CLUSTER (with spacecraft located at various distances from the neutral sheet as well as inside the lobes) it will be possible to examine directly the access of solar particles to the different regions under distinct configurations of the upstream field. Furthermore, the study of the expected dawn-dusk asymmetries in the time delay for the access of solar particles into the PS will become possible by multispacecraft observations across the magnetopause.

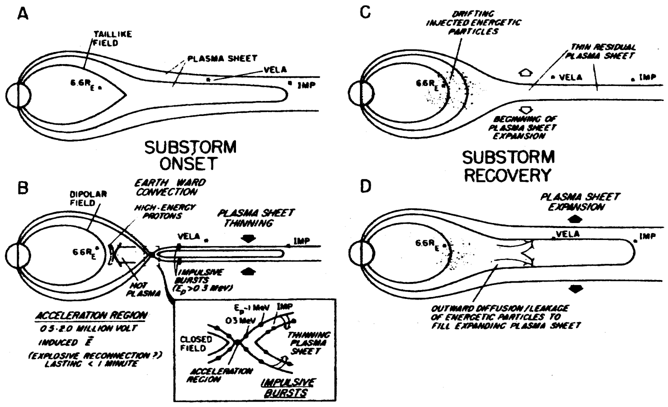

Fig. 8 Schematic sequence of energetic particle events predicted by the model of Baker et al. (Ref. 6). (a) The inner magnetosphere just prior to substorm onset showing the buildup of stress evidence by the taillike field. (b) The magnetosphere just after onset showing a dipolar field configuration and the accelerated ion bunches streaming sunward toward the trapped radiation zones and antisunward along the thinning plasma sheet. (c) Conditions just prior to substorm recovery and the beginning of the plasma sheet expansion. (d) Expansion of the plasma sheet and the subsequent filling of the expanding sheet with energetic protons diffusing out of the trapped region.

4. Summary

The dual sensorsystem in the RAPID spectrometer identifies energetic electrons and ions in the energy range 20 - 400 keV and 5 keV/nuc - 1500 keV, respectively. Moderate ion mass resolution of about 4 (for oxygen ions) allows the identification of all ions and ion groups with significance in geospace plasmas.

Novel concepts are employed in the sensorsystems to achieve angular resolution over a 180° range in polar angle. The imaging-ion-mass-spectrometer IIMS uses two-dimensional time-of-flight/energy analysis to determine the ion's mass. Addition of position sensing techniques on the entrance foil (START foil) is a major evolutionary step which, in combination with a geometrically small STOP detector (at the end of the flight path), provides direction sensitivity by virtue of the pin-hole effect as the optical principle. This approach divides the 180° polar segment in 12 contiguous angular intervals. Sectoring the satellite spin plane with a maximum of 32 azimuthal intervals covers the unit sphere in velocity space completely with a total of 384 angular bins.

The imaging-electron-spectrometer IES achieves directional sensitivity by using novel microstrip solid state devices in combination with a pin-hole acceptance. This technique divides the 180° polar range into 24 angular intervals which, with 32 sectors in the spin plane, corresponds to a total of 768 bins on the unit sphere.

The advanced RAPID concept represents an important scientific tool in the complement of plasma instruments onboard the four CLUSTER spacecrafts. New capabilities of the novel spectrometertyp permit a variety of studies in all regions of geospace visited by CLUSTER. Three selected areas, the bow shock and upstream events, reconnection at the magnetopause and FTEs, and the dynamics in the magnetotail, are discussed in detail to highlight outstanding physical problems to be addressed by the RAPID investigation, and to emphasise specific contributions expected from studies of the suprathermal plasma component.

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