THE IMS SATELLITE PROGRAMME: SCIENTIFIC OBJECTIVES

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Abstract

The International Magnetospheric Study is a proposed international co-operative enterprise during the years 1976–1978 whose aim is a quantitative understanding of the dynamic plasma and field environment of the Earth. Satellite programmes play a key role in this study, together with co-ordinated ground-based, balloon and rocket observations. Herein we review the presently announced IMS satellite programmes, and illustrate many of the objectives of the IMS satellite investigations with examples drawn from current research.

1. Introduction

The key to success during the International Magnetospheric Study lies in the ability to perform synoptic studies, i.e. co-ordinated observation programmes, including ground-based, balloon, rocket and satellite measurements. Satellites form a vital element of this programme for without them we could do little but repeat the IGY. Their role is both to provide the in-situ data required to understand magnetospheric behaviour and, just as importantly, to act as monitors of the state of the solar wind and the magnetosphere, in order that the ground-based, balloon and rocket data may be placed in their proper context.

Before discussing the specific objectives of the IMS satellite programme, we will first examine what satellites are scheduled for launch during the IMS and what instruments will be carried on board these satellites. Next, we will present a brief overview of the magnetosphere and how it works. Then we will present a sample of problems to be attacked during the IMS period with these satellites. Some of these problems are illustrated with examples of data obtained during fortuitous alignments of two or more satellites. The fact that these few multisatellite studies

have each provided a new level of understanding of magnetospheric processes bodes well for the co-ordinated programme of IMS satellites.

2. The IMS Satellites

During the International Magnetospheric Study, there will be a series of IMS-related satellites launched by the ESA, Japan, the USA and the USSR. In addition to these spacecraft, there will be a number of satellites still operating carrying one or more instruments capable of contributing to IMS investigations, and satellites launched primarily for nonmagnetospheric applications, such as communications, or weather monitoring. We will not discuss these latter spacecraft here, but defer this discussion to the paper by Vette [1975]. We have no guarantees that the pre-IMS magnetospheric spacecraft will still be operational during the IMS. Further, the applications spacecraft do not carry sufficient instrumentation to perform the detailed investigations required during the IMS. Certainly, their measurements will be of some use, but to list them as IMS satellites suggests an opulence that the IMS does not possess.

**TABLE 1**

IMS Satellite Programme

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Launch Date</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOS</td>
<td>February 1977</td>
<td>Geosynchronous</td>
</tr>
<tr>
<td>ISEE-A</td>
<td>October 1977</td>
<td>Apogee 23 $R_e$</td>
</tr>
<tr>
<td>ISEE-B</td>
<td>October 1977</td>
<td>Apogee 23 $R_e$</td>
</tr>
<tr>
<td>ISEE-C</td>
<td>July 1978</td>
<td>Solar, 1 AU</td>
</tr>
<tr>
<td>EXOS-A</td>
<td>January 1978</td>
<td>350-4500 km</td>
</tr>
<tr>
<td>EXOS-B</td>
<td>August 1978</td>
<td>Apogee 5.7 $R_e$</td>
</tr>
<tr>
<td>ISS</td>
<td>February 1976</td>
<td>1000 km circular</td>
</tr>
</tbody>
</table>

Table 1 lists the satellites whose launch during the IMS seems assured. The first satellite listed is GEOS, scheduled for launch by the ESA in February 1977. Although there have been several slips in the scheduled launch date of GEOS, there is good reason to be confident in this launch date. This will be the first IMS satellite launched into the outer magnetosphere and the first strictly scientific spacecraft launched into geostationary orbit, at a geocentric distance of 6.6 Earth radii ($R_e$).

The next three satellites listed form a joint NASA-ESA programme called ‘ISEE’, the International Sun Earth Explorers. The first two spacecraft ISEE A and B will be launched in October 1977 by the same vehicle into the same highly elliptical orbit, having an apogee of 23 $R_e$. The orbit is very similar to that of the OGO-1, 3 and 5 spacecraft. ISEE A and B will have a variable separation in this orbit ranging from 100 km to 5000 km near apogee, with a much greater separation near perigee where
the satellite velocities are greater. The separation distance is increased or decreased by firing gas jets on the smaller of the two spacecraft, ISEE-B, and allowing the spacecraft to slowly drift apart or together from orbit to orbit. Enough gas will be carried to cycle between 100 km and 5000 km, two or three times per year. The launch window for this mission repeats every six months. The initial line of apsides is planned to be on the dawn side of local noon and apogee will be in the northern hemisphere. For the April launch window, the initial line of apsides remains fixed, but apogee switches to the southern hemisphere.

The next satellite, ISEE-C, will serve as a monitor of the behaviour of the Sun and the solar wind as well as making measurements fundamental to understanding the Sun and the solar wind themselves. Unfortunately, this satellite will not be launched until mid-1978, whereas it is needed throughout the IMS period.

The last three satellites form the Japanese contribution to the IMS. The first, EXOS-A, will be launched into a low-altitude, high-inclination orbit. The second, EXOS-B, will be launched into a moderate-eccentricity, low-inclination orbit. The final satellite listed, ISS, is principally an ionospheric sounder, launched into a low-altitude moderate-inclination orbit. If it is launched on schedule, it will be the first ‘IMS’ satellite, preceding the second ‘IMS’ satellite by over a year.

Although the plans have yet to be announced, there will also be a series of Russian spacecraft. Attractive possibilities to complement the existing programme would include a solar-wind monitor much earlier in the IMS than ISEE-C, a mission similar to ISEE A/B, but at high latitudes to study the polar cusp, and more low- and mid-altitude polar orbiting satellites to study the coupling of the magnetosphere to the ionosphere and the upper atmosphere.

3. The IMS Satellite Instrumentation

Having satellites in the proper orbits is a necessary condition for success during the IMS, but it is not sufficient. These satellites must also carry the proper instrumentation. Fortunately, as we will see, the planners of the IMS satellites have shown much wisdom in this regard. In this section we examine the instrumentation of each of the IMS satellites in turn. This will assist us in assessing the capabilities of the satellite programme.

3.1 GEOS

The first ESA contribution to the IMS will be GEOS, located in a geostationary orbit on the Earth’s geographic equator at a geocentric distance of 6.6 $R_e$. Most of the time it will be stationed so that its northern conjugate point will be in Northern Scandinavia, but manoeuvres are planned to co-ordinate with ground-based and balloon campaigns from Iceland.

Table 2 shows the payload of GEOS. There is a plasma wave experiment covering both electric and magnetic components. Of the 100 kbit/s data rate, 90 kbit/s are assigned to the plasma wave experiment. There are electrostatic analysers covering
**TABLE 2**

GEOS Instrumentation

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search coil</td>
<td>GRI/CNET, ESTEC, DSRI</td>
</tr>
<tr>
<td>Electric dipoles</td>
<td></td>
</tr>
<tr>
<td>Electrostatic analysis (Thermal)</td>
<td>Mullard</td>
</tr>
<tr>
<td>Crossed fields analyser</td>
<td>Univ. of Bern / MPE</td>
</tr>
<tr>
<td>Electrostatic analysers (0.2-20 keV)</td>
<td>Kiruna</td>
</tr>
<tr>
<td>Energetic particles</td>
<td>MPA</td>
</tr>
<tr>
<td>Electron gun</td>
<td>MPE</td>
</tr>
<tr>
<td>Fluxgate magnetometer</td>
<td>Univ. of Rome</td>
</tr>
</tbody>
</table>

Orbit: Geostationary

*Figure 1. Artist's impression of the ISEE mission. The ISEE-C, or Heliocentric spacecraft, monitors the solar wind while the ISEE-A and -B spacecraft, or Mother and Daughter, orbit the Earth, passing through the Van Allen belts, the magnetopause and shock front.*
the energy range from thermal to 20 keV. There is an energetic-particle experiment, an electron gun which will be used to measure the electric field, and finally a fluxgate magnetometer. This is an excellent and very complete set of wave particle and field experiments. For a more complete description of the GEOS payload, operation and shift plan, the interested reader is referred to the paper by Knott [1975].

3.2. ISEE A-B AND C

Figure 1 shows an artist’s impression of the ISEE mission. While GEOS is circling the Earth well inside the magnetosphere every 24 h, the ISEE-A and -B spacecraft, also called ‘Mother’ and ‘Daughter’, will be making measurements of the radial gradients in tandem every 2½ days in a near-equatorial, highly elliptical orbit with an apogee of 23 $R_e$. These spacecraft will leave the magnetosphere whenever apogee is on the dayside of the magnetosphere and make measurements of the magnetopause, magnetosheath and solar wind. The use of two satellites close together in the same orbit permits the separation of temporal from spatial changes, a determination of the velocity of propagation or convection of wavefronts and boundaries, and thus permits the conversion of the time profile of these boundaries into thicknesses, current densities, etc. While Mother and Daughter are probing the magnetosphere, ISEE-C, or the ‘Heliocentric’ spacecraft, will be in orbit about the Sun in synchronism with the Earth’s motion about the Sun, thus providing knowledge of the boundary conditions imposed on the magnetosphere by the solar wind.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrispherical analysers</td>
<td>LASL</td>
</tr>
<tr>
<td>LEPEDEA</td>
<td>Univ. of Iowa</td>
</tr>
<tr>
<td>Triaxial electrostatic analysers</td>
<td>GSFC</td>
</tr>
<tr>
<td>Energetic particles 1-200 keV</td>
<td>UCB</td>
</tr>
<tr>
<td>Energetic particles 20-2000 keV</td>
<td>NOAA, MPI Lindau</td>
</tr>
<tr>
<td>Particle telescopes 5-6000 keV</td>
<td>MPI, Garching</td>
</tr>
<tr>
<td>Fluxgate magnetometer</td>
<td>UCLA</td>
</tr>
<tr>
<td>Electric dipole</td>
<td>GSFC</td>
</tr>
<tr>
<td>Electric dipole</td>
<td>UCB</td>
</tr>
<tr>
<td>Electric dipole and search coils</td>
<td>Univ. of Iowa</td>
</tr>
<tr>
<td>Plasma resonance and propagation</td>
<td>Observatoire de Paris</td>
</tr>
<tr>
<td>Ion mass spectrometer</td>
<td>Lockheed, Univ. of Bern, MPE</td>
</tr>
</tbody>
</table>

Orbit: Eccentric, Apogee 23 $R_e$

Table 3 shows the payload of the ISEE-A, or Mother, spacecraft, which is the larger of the two vehicles. First, there is a series of low-energy plasma experiments.
The first listed experiment will be capable of measuring the solar wind. Next, there are a set of energetic particle experiments covering up to low-energy cosmic-ray energies. There is a fluxgate magnetometer, two long dipole antennas for measuring the DC electric field, and an AC electric and magnetic plasma wave experiment. The cold plasma density will be measured in two ways: first with a plasma resonance and radio propagation experiment supplied by Meudon, and second with a modification of the Lockheed heavy-ion experiment to allow it to also measure the thermal protons.

**TABLE 4**
ISEE-B Instrumentation (Daughter)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energetic particles 1-200 keV</td>
<td>UCB</td>
</tr>
<tr>
<td>Energetic particles 20-2000 keV</td>
<td>NOAA</td>
</tr>
<tr>
<td>Quadrirpherical electrostatic analyser</td>
<td>MPI, Garching</td>
</tr>
<tr>
<td>LEPEDEA</td>
<td>Univ. of Iowa</td>
</tr>
<tr>
<td>Solar-wind experiment</td>
<td>Univ. of Rome</td>
</tr>
<tr>
<td>Electric dipole and search coils</td>
<td>Univ. of Iowa</td>
</tr>
<tr>
<td>Plasma propagation</td>
<td>Observatoire de Paris</td>
</tr>
<tr>
<td>Fluxgate magnetometer</td>
<td>UCLA</td>
</tr>
</tbody>
</table>

Orbit: Eccentric, Apogee 23 $R_e$

**TABLE 5**
ISEE-C Instrumentation (Heliocentric)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-wind</td>
<td>LASL</td>
</tr>
<tr>
<td>Vector helium magnetometer</td>
<td>JPL</td>
</tr>
<tr>
<td>Solar X-ray/solar electrons</td>
<td>UCB</td>
</tr>
<tr>
<td>Energetic protons 30-1500 keV</td>
<td>Utrecht, IC, ESTEC</td>
</tr>
<tr>
<td>Solar-wind composition</td>
<td>GSFC</td>
</tr>
<tr>
<td>Particle telescopes 5-6000 keV</td>
<td>MPE</td>
</tr>
<tr>
<td>Cosmic-ray isotopes</td>
<td>UCB</td>
</tr>
<tr>
<td>Cosmic-ray isotopes</td>
<td>CalTech</td>
</tr>
<tr>
<td>Solar and galactic cosmic rays</td>
<td>GSFC</td>
</tr>
<tr>
<td>Radio emissions</td>
<td>Observatoire de Paris</td>
</tr>
<tr>
<td>Plasma waves: E and B</td>
<td>TRW</td>
</tr>
</tbody>
</table>

Orbit: Solar, 1 AU
Table 4 shows the ISEE-B, or Daughter, instrumentation. There are two energetic-particle experiments, two low-energy plasma experiments, a solar-wind experiment, a plasma-wave experiment, the receiver for the radio-propagation experiment, and a fluxgate magnetometer.

Table 5 shows the ISEE-C, or Heliocentric, instrumentation. There is a solar-wind experiment, a vector helium magnetometer, a solar X-ray experiment, energetic-particle experiments, solar-wind composition experiments, cosmic-ray experiments, a radio-emission experiment and a plasma-wave experiment. For further details, see the paper by Wenzel [1975].

### TABLE 6
EXOS-A Instrumentation

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Principal Investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma probe</td>
<td>Oyama</td>
</tr>
<tr>
<td>Energetic particles</td>
<td>Mukai</td>
</tr>
<tr>
<td>UV auroral TV</td>
<td>Kaneda</td>
</tr>
<tr>
<td>Plasma wave</td>
<td>Yoshino</td>
</tr>
<tr>
<td>UV spectrometer</td>
<td>Nakamura</td>
</tr>
</tbody>
</table>

Orbit: Apogee, 4500 km; Perigee, 350 km

### EXOS-B Instrumentation

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma resonance 3 kHz-10 MHz</td>
<td>Tohoku Univ.</td>
</tr>
<tr>
<td>VLF, LF and MF electric field</td>
<td>Tohoku Univ.</td>
</tr>
<tr>
<td>VLF propagation</td>
<td>Kyoto Univ.</td>
</tr>
<tr>
<td>DC electric field</td>
<td>Tokyo Univ.</td>
</tr>
<tr>
<td>Fluxgate magnetometer</td>
<td>Tokai Univ.</td>
</tr>
<tr>
<td>Low-energy particles (0.05-20 keV)</td>
<td>Tokyo Univ.</td>
</tr>
<tr>
<td>Electron gun</td>
<td>Tokyo Univ.</td>
</tr>
</tbody>
</table>

Orbit: Eccentric, Apogee, 5.7\\(R_e)\\n
### ISS Instrumentation

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swept-frequency sounder</td>
<td>RRL, Tokyo</td>
</tr>
<tr>
<td>Radio noise</td>
<td>RRL, Tokyo</td>
</tr>
<tr>
<td>Retarding potential trap</td>
<td>RRL, Tokyo</td>
</tr>
<tr>
<td>Bennett, ion mass spectrometer</td>
<td>RRL, Tokyo</td>
</tr>
</tbody>
</table>

Orbit: 1000 km circular
3.3. EXOS-A, EXOS-B AND ISS

The Japanese contributions to the IMS satellite programme are shown in Table 6. The first satellite, EXOS-A, will be launched into a low-altitude high-inclination orbit. It will carry a plasma probe, an energetic-particle experiment, a UV auroral TV, a plasma-wave instrument, and a UV spectrometer, but no DC magnetometer or electric-field probe. There is still much to be learned about the low-altitude convection pattern and so a DC electric-field experiment is a high-priority item for low-altitude high-inclination spacecraft. A DC magnetometer is essential for probing the field-aligned currents in the magnetosphere.

The EXOS-B satellite will probe the inner magnetosphere - plasmasphere region. It does include a magnetometer and a DC electric-field experiment, but it does not include an energetic-particle experiment or a cold-plasma measurement. On the other hand, the plasma-resonance experiment may provide a measure of the density, but as far as I am aware this technique has yet to be proven in the outer magnetosphere. For more information on this technique, which is also being implemented on GEOS and ISEE-A, the interested reader is referred to the paper by Bitoun et al. [1975].

The last satellite listed, ISS, is an ionospheric sounder and is not directed towards the same objectives as the other two missions. I should like to point out that because of the limited size of these spacecraft, many compromises have had to be made and a full complement of experiments could not be flown. The mission planners should not be faulted for that, but it is important to point out at this stage what those compromises were.

![Diagram](image)

Figure 2. Noon-midnight meridional cross-section of the magnetosphere [after Russell, 1972].
4. The Magnetosphere

Having seen what we have to work with, let us quickly review the morphology of the magnetosphere and examine a simple model for how it works, to prepare for our later examination of a sampling of what we can do during the IMS. Figure 2 shows a noon-midnight meridian cross-section of the magnetosphere. There is a bow shock in front which slows, deflects and heats the solar wind and allows it to flow around the magnetosphere. There are phenomena upstream from the shock: plasma waves and counter-streaming particles, but they little affect the macroscopic properties of the solar wind. Behind the shock is the magnetosheath, and between the magnetosheath and the magnetosphere is a layer of current called the magnetopause. The magnetopause is the most important boundary in the magnetosphere and is the most poorly understood, both observationally and theoretically. Understanding the nature and behaviour of the magnetopause is one of the primary objectives of the IMS.

The magnetosheath plasma gains direct access to the ionosphere in the polar-cusp region. This plasma then expands and flows down the sides of the lobes of the tail to form the plasma mantle. It appears that the mantle plasma and the magnetosheath plasma, entering on the flanks of the magnetosphere, both supply the plasma sheet. There is a neutral point sitting on a reconnection line somewhere deep in the tail. There is a current sheet, which is seldom neutral, residing in the plasma sheet which reverses the field from the north to south lobes. Deep in the magnetosphere is a torus of cold dense plasma maintained by the ionosphere and called the plasmasphere. Figure 3 shows a representation of the three-dimensional magnetosphere [Heikkila, 1972].

Figure 3. Cutaway sketch showing the various magnetospheric regions [Heikkila, 1972].
The most important process occurring in the magnetosphere is reconnection or merging, in which two opposing magnetic field lines join together to form two new field lines. Figure 4 shows Dungey’s sketches of the topology of merging [Dungey, 1963]. I should stress that these sketches show only the topology of merging and are not to scale. Dungey [1965] fully realised the tail would be of the order of 500 $R_e$ long. The top panel illustrates merging between a south pointing interplanetary field and the magnetosphere. Interplanetary field lines join with magnetospheric fields and are carried back behind the Earth. This process removes magnetic flux from the dayside magnetosphere and adds it to the tail. To maintain a steady state, field lines must then reconnect in the tail and add closed field lines to the night-time magnetosphere. These field lines then flow around both sides of the auroral oval to the dayside.

For an exactly northward field, the situation is quite the reverse. Field lines merge with tail field lines and add flux to the dayside and then there is flow antisunward around the auroral oval. If this merging takes place with open field lines, it reduces the number of open field lines. If all the field lines in the tail were closed, it essentially moves field lines from the nightside to the dayside.

In general, the interplanetary field is not exactly north-south and the field line that connects to the north tail lobe does not connect to the south tail lobe. This process is sketched in Figure 5 for merging with the north lobe only [Russell, 1972]. Other field lines must connect with the south lobe. The connected field lines exert a stress on the magnetosphere which causes a circulation in the tail and in the polar cap, but no exchange of open and closed fields. The sense of flow is down along the flanks towards the plasma sheet and away from the plasma sheet in the centre of the tail. In the ionosphere, the flow is sunward in the centre of the polar cap, and antisunward at the edges. We note that only in this process which replaces an open field line with another, can the merging rate in the two tail lobes be unequal. In merging or reconnection processes which form open lines from closed lines, or vice versa, both tail lobes are affected equally.

Figure 6 illustrates schematically the possible polar-cap flows. If there is dayside merging as illustrated in the top left panel, closed field lines open up and are connected into the polar cap near noon. The polar cap increases in area, i.e. the area enclosed by the ‘last closed field line’ (LCF) is increasing. If flux is reconnected at the neutral sheet, the open polar-cap flux closes and is convected out of the polar cap near midnight. Then the polar cap defined by the last closed field line decreases. Neither process can proceed alone indefinitely, for the polar cap cannot expand or shrink indefinitely. However, they can proceed simultaneously in the steady state. If the interplanetary field is close to being perpendicular to the magnetospheric equator and directed southward, the expected flow is essentially directly over the polar cap. This is simply because the north polar cap is connected to the solar wind north of the magnetosphere and the south polar cap is connected to the solar wind south of the magnetosphere. In this situation, newly reconnected field lines are piled on top of old field lines, resulting in a sinking of field lines into the lobes of the tail.

If the interplanetary field is northward and there is no dayside merging, then the situation sketched in the middle two panels exists, in which the size of the polar cap remains fixed, but an asymmetric convective flow exists. The sign and strength of this asymmetry depends on the magnitude and direction of the east-west component of the interplanetary magnetic field.
Figure 4. Topology of merging for southward fields (top panel) and for northward fields (bottom panel) [Dungey, 1963].

Figure 5. Temporal sequence of events occurring when field line B-b merges with the north-tail lobe, but does not connect to the southern tail lobe [Russell, 1972].
Figure 6. Expected flow patterns in the polar cap associated with merging on the dayside, closed lines reconnection between the open tail lobes and merging between the interplanetary lines and the open tail lobe field lines [Russell, 1972].
Finally, the bottom left panel shows the case for dayside merging with interplanetary fields having sizeable east-west components. As in the previous case, there will be a dawn-dusk asymmetry in the flow. However, here the polar cap increases in size and thus night-time reconnection must eventually occur. Thus, the average convection pattern would resemble the sum of the left-hand and right-hand bottom panels, and no sunward polar-cap flows would be present. The only situation in which we expect sunward directed flows on open field lines is when the interplanetary magnetic field merges with the tail-lobe field.

Many of these expectations based on the geometry of the merging process have been confirmed. The asymmetry of the polar-cap convection pattern and its dependence on the east-west component of the interplanetary magnetic field has been observed directly by Heppner [1972] and indirectly using magnetic records by Friis-Christensen & Wilhjelm [1975] and Maezawa & Obayashi [1975]. The dependence of the strength of the polar-cap electric field on the interplanetary magnetic field has been studied by directly observing the polar-cap electric field with balloon measurements [Mozer et al., 1974; Mozer, 1975] and indirectly from magnetic records by Friis-Christensen & Wilheljm [1975] and Maezawa & Obayashi [1975]. Finally, the existence of sunward flow for northward interplanetary fields has been deduced from ground-based magnetic records by Maezawa & Obayashi [1975].

Our next task is to examine how merging and reconnection leads to substorms. Figures 7 and 8 illustrate this schematically. In Figure 7, the magnetospheric flux has been arbitrarily divided into three regions: the dayside closed flux $\Phi_{\text{Day}}$, the tail lobe open flux, $I_{\text{Lobe}}$, and the nightside closed flux, $\Phi_{\text{PS}}$ [McPherron, 1974].

![Changes in Magnetic Flux](image)

\[
\Delta \Phi_{\text{Day}} = \int_0^t [R-M] \, dt \\
\Delta \Phi_{\text{Lobe}} = \int_0^t [M-R] \, dt \\
\Delta \Phi_{\text{Plasma sheet}} = \int_0^t [R-R] \, dt
\]

*Figure 7. Flux bookkeeping in the open magnetosphere [McPherron, 1974].*
Figure 8. Conceptual model of a substorm based on the temporal behaviour of the amount of magnetic flux on the dayside, the nightside and in the tail lobes [McPherron, 1974].

The change in flux on the dayside is the integral of the difference between the return of flux from the nightside and the dayside merging rate. The change in the lobe flux is the integral of the difference between the merging rate and the reconnection rate in the tail. The flux in the nightside magnetosphere is the integral of the difference between the reconnection rate and the return rate to the dayside.

Figure 8 shows how these integrals may be associated with a substorm. The top panel shows the rate of change of the flux in the three regions. Initially, there is a steady state, and in this simple model we suddenly increase the merging rate, the return rate $R$ increases slightly to replace the lost flux, but this rate is controlled by the ionosphere and magnetospheric pressure gradients which build up in proportion to the amount of missing flux. In the bottom panel we see that the amount of flux in the dayside decreases, that in the tail lobe increases and that on the nightside decreases. Eventually, the stresses on the tail become too great and reconnection begins. Perhaps this is due to the fact that the plasma sheet becomes too thin. Then the tail lobe loses flux and the nightside magnetosphere gains flux.

These ideas are somewhat controversial, although I believe there is strong observational evidence in favour of every one of them. In fact, there are even some who still maintain that the magnetosphere is closed [Michel & Dessler, 1975]. However, many of the differences between the open and closed ‘camps’ are more apparent than real.
5.1. MACROSCOPIC BEHAVIOUR OF THE MAGNETOSPHERE

The above model of the magnetospheric substorm process leads to our first set of objectives for the IMS. How does the merging rate depend on interplanetary parameters? Why is reconnection in the tail delayed with respect to dayside merging? What is the trigger that starts the substorm? Does the magnetospheric substorm sketched here correspond one-to-one to the auroral substorm seen from the ground?

The heliocentric spacecraft can aid in attacking these problems by monitoring the solar-wind conditions while we observe the magnetospheric response. Figure 9 shows an example of what can be done using Explorer 33 and 35 magnetic-field and solar-wind data [Burton et al., 1975]. Here we have plotted the rate of change of the ring current as a function of the dawn-to-dusk component of the interplanetary electric field. This is simply the product of the north-south component of the interplanetary magnetic field times the radial component of the solar-wind velocity. When the electric field is from dusk to dawn, the $D_{st}$ index does not change, but when it is from dawn to dusk it does change and in fact appears to be linear in $E$. Thus, the magnetosphere seems to be an efficient rectifier of the solar-wind electric field.

We have used this relationship together with the known dependence of $D_{st}$ on the solar-wind dynamic pressure and with a constant 8 h decay time for the ring current to predict $D_{st}$ from solely the solar-wind dynamic pressure and dawn-dusk electric field. Figure 10 shows the results for a double main phase storm. The top panel shows the square root of dynamic pressure, the middle panel the electric field, and the bottom panel the observed and predicted $D_{st}$ values. The dashed line is the prediction.

![Graph showing ring-current injection rate as a function of $E_y$](image)

**Figure 9.** Ring-current injection rate as a function of the dawn-dusk component of the interplanetary electric field [Burton et al., 1975].
Figure 10. Square root of the solar-wind dynamic pressure (top panel), the dawn-dusk component of the interplanetary electric field (middle panel) and the predicted and measured $D_{st}$ index (bottom panel), during a complex geomagnetic storm on February 7 and 8, 1967. The predicted curve is the dashed line [Burton et al., 1975].
Figure 11. Solar-wind dynamic pressure, interplanetary electric field and predicted and measured $D_{st}$ index during a moderately disturbed period from March 3-5, 1968.

Figure 11 shows the results for an interval in which there was no storm but rather a continuous period of disturbance. Again good agreement. These results show that the ISEE-C measurements can be used as a predictor of the state of the magnetosphere if one requires such knowledge one hour in advance and replaces the need to acquire ground-based data from around the world, if only a rough measure of activity is required.

This is only one of the possible monitor functions of ISEE-C. It will also provide the interplanetary cosmic-ray flux measurements essential to polar particle entry studies, for example. It is also essential for monitoring solar-wind conditions while we are probing the structure of the shock front and the magnetopause.

5.2. MICROSCOPIC PROCESSES

In addition to examining the macroscopic response of the magnetosphere to exter-
nal conditions, we are also interested during the IMS in the microscopic processes and how they vary when solar-wind conditions change. The ISEE A-B, or Mother-Daughter, spacecraft are ideally suited for this purpose. In addition to having sufficiently high data rates so that the structure of the boundaries can readily be resolved, they permit an assignment of dimensions to this structure. In the past, there have been a limited number of boundary studies when two or more spacecraft by chance assumed a favourable configuration for such studies. However, with ISEE A and B, these studies will be undertaken on a regular basis.

![Diagram of magnetic field strength observed at HEOS-1 and OGO-5](image)

**Figure 12.** Magnetic field strength observed at HEOS-1 and OGO-5 (middle two panels) while nearly aligned along a radius vector from the Earth as the bow shock repeatedly moved back and forth, first crossing one and then the other. The inserts show high-resolution snapshots of the field as measured by the OGO-5 satellite [Greenstadt et al., 1975].

**The Bow Shock**

Figure 12 shows magnetic field measurements taken during a chance alignment of OGO-5 and HEOS-1 along a radius vector in the vicinity of the Earth’s bow shock [Greenstadt et al., 1975]. The middle two panels show the magnetic field strength at HEOS and OGO-5. The panels surrounding these data show high-resolution snap
shots of the shock crossings using the OGO-5 data. The inner two panels illustrate the motion of the shock: it moves back and forth crossing HEOS then OGO; OGO then HEOS, etc. We can then use the relative timing to get shock velocities and hence thicknesses. At this time, the velocities ranged from 10 to over 100 km/s and the thicknesses roughly twice the ion inertial length, $c/\omega_{pi}$, or about 300 km. The durations of the crossings were about 10 s.

The shock studied was a 'quasi-perpendicular laminar' shock. By 'quasi-perpendicular', we mean that the local angle between the interplanetary magnetic field and the shock normal was between 50° and 88°, and by 'laminar' we mean that the solar wind Mach number was below a critical value close to 3 and the magnetic energy density was much greater than the thermal energy density, i.e. $\beta << 1$. The results for the thickness obtained for this one class of shocks should not be applied to other conditions. For example, Formisano et al. [1975a] have studied, with a single satellite, a shock crossed in less than 0.3 s. If this had a thickness of 300 km, then the velocity must have been greater than 1000 km/s. Such high velocities are not expected theoretically [Völk & Auer, 1974] and thus the thickness must be much less than 300 km. The determination of dependence of thickness on solar-wind conditions must await the ISEE A-B investigations.

If one is interested in only the qualitative dependence of the shock structure on the upstream solar-wind conditions, and not in the scale length of the structure, then two satellite studies with one satellite at the shock and another somewhere in the solar wind in the near vicinity of the Earth will suffice. A number of such studies have been performed. They show that the bow shock does not possess a well-defined structure when either the thermal pressure becomes much greater than the magnetic pressure [Formisano et al., 1975b] or when the interplanetary field is parallel to the shock normal [Greenstadt et al., 1975]. In the latter case, a pulsation region at least 2Re thick has been identified using simultaneous HEOS-1 and OGO-5 measurements. Defining the dimensions of this pulsation region and its dependence on the field direction is ideally suited to the Mother-Daughter mission. The existence of this broad pulsation region suggests that a wide range of interspacecraft separations should be used in shock studies.

The Magnetopause

Although the physics of the magnetopause is quite different from the physics of the bow shock, the same types of studies must be performed at the magnetopause also. Figure 13 shows the three components of the magnetic field and the total field for a 6 h period during which there were many magnetopause crossings, as indicated by the reversals in some of the components at the crossings [Aubry et al., 1970]. The multitude of crossings at this time is due both to an average inward displacement of the magnetopause roughly matching, averaged over the 6 h period, the inward motion of the satellite, and to oscillations of the boundary about this inward moving equilibrium position at a velocity much exceeding the spacecraft velocity. There are only two unambiguous means of deducing the relative velocity between the spacecraft and the boundary, the use of gradients in the energetic particle populations [Kaufman et al., 1973], and the use of two satellites. The former method which uses only one satellite is limited to times when large fluxes of energetic magnetospheric or solar protons are available as tracers. We note that this
technique has also been used to probe successfully the velocity of the plasma sheet [Buck et al., 1972] and of the lobe field lines during a solar-particle event [Palmer et al., 1974]. The occasional availability of this technique to cross-check the velocities derived from two-satellite studies permits a testing or the relaxation of the basic assumptions used in reducing the two-satellite data, i.e. that the boundaries are planes with known normals.

It is becoming increasingly evident that the magnetopause is a complex boundary whose structure is very sensitive to solar-wind conditions. As observed in the plasma data, the magnetopause is not thin, but can be up to an Earth radius thick [Bezrukovkh et al., 1975; Haerendel & Paschmann, 1975; Formisano, 1975]. On the other hand, the magnetopause at times can assume a simple structure. Figure 14 shows the
Figure 14. Magnetic field in boundary system during magnetopause crossing (top panel) and current parallel and perpendicular to the field [Neugebauer et al., 1974].

field structure through such a simple magnetopause [Neugebauer et al., 1974]. In the uppermost panel, the top and bottom traces are the field variation in the boundary. The middle trace is the variation along the normal to the boundary. The bottom two traces show the derived current densities along the field and perpendicular to it. The parallel component shows a region of negative current and a region of positive current. This is most easily interpreted in terms of the proton turning radius and the electron turning radius. Since they are not equal, the charge separation electric field must have been largely shorted out. The current densities are given in arbitrary units because we have no measure of the velocity as would be possible with ISEE A-B.

Substorm-Associated Boundaries

Figure 15 shows a conceptual sketch of a popular model of the expansion and recovery phase of an isolated substorm [Russell, 1972; McPherron et al., 1973; Nishida & Nagayama, 1973; Hones et al., 1974]. In this model, the neutral point forms in the tail close to the Earth and then moves rapidly away from the Earth. Two satellites closely spaced can test whether the predicted temporal sequence of events is in fact seen as a function of distance from the Earth.

A fortunate alignment of the OGO-5 and ATS-1 spacecraft in the night-time magnetosphere permitted detection of another feature of this model, the inward-moving compressional wave associated with the return of magnetospheric field lines to a more dipolar shape. The three components of the magnetic field in solar magnetospheric co-ordinates together with the total field as measured at both OGO-5 and ATS-1 are given in Figure 16 [Russell & McPherron, 1973]. At this time both OGO-5
and ATS-1 were near midnight: OGO-5 at 8 $R_e$ and ATS-1 at 6.6 $R_e$. Shortly after the initiation of a substorm expansion phase, a compression of the field occurs first at OGO-5 and then at ATS-1, 94 s later. Without the two satellites, we would not have known the propagation direction of the disturbance, its velocity, or the thickness of the boundary.

**Wave-Particle Interactions**

One of the highest priority objectives of the IMS is to determine what wave-particle interactions are operative, what is the relative importance of each one, and how this relative importance changes with time during a storm with spatial location in the magnetosphere, and with changing plasma conditions. One of the most fruitful means of studying wave-particle interactions is the examination of the change in plasma-wave properties in response to the rapid change in a single parameter of the magnetospheric plasma. There are two ways in which this occurs at moderately frequent intervals in the magnetosphere.
First, sudden compressions of the field such as that shown in Figure 16 alter the pitch-angle anisotropies of energetic particles. Kivelson et al. [1973] have studied the pitch-angle anisotropy changes in >50 keV electrons during an event similar to the event discussed in Figure 16. When the pitch-angle anisotropy was in such a direction that $T_{\parallel}$ was greater than $T_{\perp}$, i.e. there were larger fluxes at small pitch angles than at large (near 90°) pitch angles, then no electromagnetic waves were observed. However, after the passage of the compression, the pitch-angle anisotropy reversed. There were then larger fluxes of 90° pitch-angle particles, and ELF chorus emissions resonant with the energetic electrons occurred, as would be expected for Doppler-shifted cyclotron resonance.

Another means of stimulating emissions is to alter the wave-particle resonance by increasing the density of the plasma. Although it is difficult to raise the density of the magnetospheric plasma rapidly at any one location, isodensity contours are seldom parallel to the drift shells of energetic particles. Thus, the energetic particles
Figure 17. OGO-5 search-coil and electric-dipole measurements at ELF frequencies during a traversal of detached plasma regions as indicated by the ion density measurements in the lower panel [Kivelson & Russell, 1973].

drift into regions where the plasma wave speed and hence the resonant energies are different. Figure 17 illustrates such an occurrence in the outer magnetosphere [Kivelson & Russell, 1973]. The lower trace shows the ion density measured by the OGO-5 ion mass spectrometer. The upper traces show the wave amplitudes at frequencies from 10-1000 Hz. Initially the satellite is in a low-density region of 2-4 ion/cm³ with a high-frequency hiss present that is characteristic of the high-latitude dayside outer magnetosphere. Then, when enhanced plasma densities are encountered, new frequencies become unstable. Not all density enhancements cause plasma wave enhancements. Presumably this is due to the narrowness of these enhancements, resulting in an inability to duct the waves and lead to amplification or to the energetic particles fluxes being below the stably trapped limit. With the complement of wave, particle and plasma instrumentation on Mother-Daughter and GEOS we should be able to further investigate these regions in much finer detail.
Figure 18. Simultaneous occurrence of Pc1 and Pc5 micropulsations at synchronous orbit [Barfield & Coleman, 1972].

Figure 19. Simultaneous observations at synchronous orbit (ATS-1) and at the nominal conjugate point (Tungsten, NWT) during an IPDP or sweeper event [Bossen et al., 1975].
There is much to be learned about ULF waves too. Figure 18 shows Pc5 and Pc1 waves observed simultaneously with the ATS-1 magnetometer [Barfield & Coleman, 1970]. While ATS-1 can measure the magnetic component of the waves very well, there was no low-energy or thermal-plasma instrumentation with which to measure the plasma conditions during these events. Thus, the source of these waves must to some extent be left to speculation. We note that ATS-6 has a good complement of plasma diagnostics although it has no electric-field experiments. Thus some but certainly not all of these problems may have been attacked before the start of IMS.

A very strong aspect of the GEOS programme will be ground-satellite correlations. Figure 19 shows a simultaneous dynamic spectrum of an IPDP or sweeper seen at ATS-1 and its conjugate point [Bossen et al., 1975]. In the ATS-1 data at the top, no upward sweeping in frequency is observed. Furthermore, much less wave activity is seen over the entire period. This raises the question of whether the waves which are not seen at ATS-1 are generated at a different longitude or radial distance. Perhaps some of the fluctuations are generated in the ionosphere. The possibility of having several satellites in synchronous orbit, such as ATS-6 and GEOS, plus having radial cuts with Mother-Daughter when combined with a network of ground magnetometers should provide answers to these questions.

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**TUNGSTEN**

**ATS 1**

TOTAL POWER
HORIZONTAL PLANE
3.3 dB contours

TOTAL POWER
V-D PLANE
3.3 dB contours

$10^0 (\text{GAM/SEC})^2 / \text{HZ}$

Figure 20. Simultaneous observations at synchronous orbit and the nominal conjugate point during a Pi2 micropulsation.
Figure 20 shows a simultaneous ground-satellite Pi2 burst studied by Arthur & McPherron [1975]. Both show a high-frequency enhancement in the burst, but not at the same frequency. The tone just below 0.2 Hz in the ATS-1 record is spacecraft-generated. Again, at low frequencies there are emissions not seen in space. Here we have the problem of why the space signal was not seen on the ground. Where is the correct conjugate point of ATS-1? Apparently, not a single station, but a network of ground stations surrounding the expected conjugate point is required. The extensive ground network around the GEOS conjugate point should be very helpful in this regard.

![Graph showing diurnal variation of magnetic field at ATS-1](image)

**Figure 21.** Dependence of the diurnal variation of the magnetic field at ATS-1 in synchronous orbit on the level of geomagnetic activity during winter solstice. Median variation for AE index 0-60γ together with most depressed quartiles for 0-60γ, 60-120γ etc. [after McPherron & Coleman, 1975].

### 5.3. Monitoring the State of the Magnetosphere

In addition to providing detailed *in-situ* data on magnetospheric processes, the magnetospheric satellites can serve as monitors of the state of the magnetosphere. This role could be quite useful in the timing of rocket and balloon launches. Figure 21 shows the field as measured by ATS-1 at synchronous orbit during sum-
mer solstice as a function of geomagnetic activity [McPherron & Coleman, 1975]. $V$ is vertical away from the Earth, $D$ is azimuthal in the direction of the Earth’s rotation, and $H$ is horizontal northward. Examining the $H$-component, we see that the field becomes more and more depressed during the night as geomagnetic activity increases, as measured here by the AE index. Measurements by GEOS in the midnight sector will thus be a sensitive indicator of the state of the magnetosphere.

Figure 22. OGO-6 observations of dawn-dusk component of ionospheric electric field during transits of the polar cap in the dawn-dusk meridian [Heppner, 1972].
5.4. MAGNETOSPHERE - IONOSPHERE COUPLING

One of the most interesting, yet least understood, regions of the magnetosphere is its lower boundary, the ionosphere. In particular, we need to determine the mechanisms by which energy and momentum are transferred from the outer magnetosphere into the ionosphere and then to the neutral atmosphere. Many of these mechanisms have been identified but their role is only qualitatively understood. Precipitating particles, wave damping and Joule heating in current systems all can heat the ionosphere. We must determine which is more important in a given situation. Similarly, since the ionosphere acts as a drag on the magnetospheric plasma in most situations, stresses must be transmitted from the magnetosphere to the ionosphere if the ionosphere is moving with the magnetosphere as it appears to do. Field-aligned currents can transmit this stress. If, on the other hand, the ionospheric plasma is not flowing with the magnetospheric plasma, then the field lines cannot be equipotentials and there must be potential drops, i.e. parallel electric fields along these field lines. Since these processes are occurring in and just above the ionosphere, we must fly low-altitude satellites to observe them.

Figure 23. OGO-5 observations of field-aligned currents and VLF electrostatic noise in the polar cusp [Fredricks et al., 1973].
Figure 22 shows the ionospheric electric field measured on three passes of the OGO-6 satellite across the polar cap. The broad depression in the electric field in the centre of each pass corresponds to antisunward flow. The asymmetries in these flows have been shown by Heppner [1972] to be controlled by the direction of the dawn-dusk component of the interplanetary magnetic field. However, we do not yet have a quantitative correlation between the potential drop across the polar cap and interplanetary conditions, nor do we know how to relate the size of the asymmetry to the magnitude of the dawn-to-dusk interplanetary magnetic fields.

Figure 23 shows an example of field-aligned currents observed in the polar cusp [Fredricks et al., 1973]. Similar results apply to the night-time plasma sheet [Scarff et al., 1973]. These currents are often accompanied by VLF electrostatic waves which in turn can cause anomalous resistivity leading to potential drops which are able to accelerate particles to auroral energies. As mentioned above these field-aligned currents also provide the coupling of magnetospheric stresses to the ionosphere. For example, the role of the field-aligned currents in the auroral oval studied by Zmuda & Armstrong [1974 and refs. therein] seems to be to drag the ionosphere along with the magnetospheric plasma as it convects from the plasma sheet to the dayside magnetosphere. Unfortunately, to date no satellite has been launched with the comprehensive set of instrumentation required to effectively investigate other than the morphology of these currents. Perhaps if the EXOS-B orbit carries it over the auroral oval it will be able to investigate this problem. Perhaps one of the Russian spacecraft will cover this. If not, then we may have to wait until the launch of the Electrodynamic Explorers which have the study of these currents as one of their primary goals.

6. Concluding Remarks

In closing we note that this review of objectives of the IMS satellite programme is far from being a comprehensive or exhaustive list. Rather, we have seen only a sampling of the many possible problems to be attacked and that sample is strongly biased to the problems on which the author has worked prior to IMS. Each of the investigators associated with the programmes discussed at the beginning of this article certainly has his own list of objectives just as large as mine, and many of these objectives we have scarcely even mentioned. In the area of the magnetospheric plasma, the most noticeable absence from our discussion was the problem of the acceleration of magnetospheric plasma. Which is more important: acceleration by parallel electric fields or cross-equipotential curvature and gradient drift? Also, we skipped over the use of energetic particles such as solar protons as probes of magnetospheric structure. Much has been done in this regard [Morfill & Scholer, 1973], but much remains to be done. Finally, our brief discussion of wave-particle interactions does little justice to the myriad of plasma-wave phenomena observed in the magnetosphere, many of whose sources remain merely objects of speculation.

In short, there is much to be done during the International Magnetospheric Study. This fact should not be construed to mean that magnetospheric physicists have been lax in their efforts over the last decade. On the contrary, their efforts have been quite successful, and we have benefitted tremendously from them. Our large list of
objectives consists of problems which are well defined and which can be solved with the IMS programme. If it were not for the pioneering efforts of the Explorer, OGO, ATS, and similar programmes, we would not be in this position today.

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DISCUSSION

M. Dryer: Have there been any studies regarding the magnetopause thickness as a function of distance from the subsolar point?

C.T. Russell: At the present time there are two studies in progress, one by Formisano and co-workers using the HEOS-1 data, and one by Gringauz and co-workers using Prognoz data, but the results are not in yet.

G. Rostoker: You have spoken of most of the scientific community accepting an open magnetospheric model. However, there is strong evidence in the work of McDiarmid and Burrows that the plasma sheet (the site of auroral phenomena) lies on closed but distended field lines. Can we therefore talk in terms of a closed magnetosphere when we deal with auroral oval activity?

C.T. Russell: With the exception of the occasional observation of loops of field lines in the plasma sheet (X and O neutral point pairs), I think most advocates of the open magnetosphere propose that the plasma sheet is on closed field lines. Auroral arcs in this picture are associated
with processes occurring on closed field lines, such as field-aligned currents and associated parallel electric fields.

G. Rostoker: I think that there is little evidence for neutral points in the tail. The most compelling evidence is southward $B_z$. However that may well be caused by the end effects of Birkeland currents in the tail. How strong do you feel the evidence for neutral points is?

C.T. Russell: If the tail lobes are open, that is the field lines eventually connect with the interplanetary magnetic field, then there must somewhere be a neutral point between the tail lobes on simply topological grounds. The evidence for open tail lobes is very strong: solar-particle entry, and the many aspects of the response of the magnetosphere are most readily explained in terms of this model. The question of whether the observed southward fields in the plasma sheet are caused by the appearance of the neutral point close to the Earth is a separate question, which cannot be answered by examining the magnetic data alone. However, the simultaneous behaviour of the tail lobes, in which the flux decreases after the appearance of the southward fields, the behaviour of the plasma sheet, which thins and then thickens, and the observed flows away and then later towards the Earth, require that the neutral points approach the Earth at substorm onset and then move away.