14 October 1977, Volume 198, Number 4313 SCIENCE

International Sun-Earth Explorer: A Three-Spacecraft Program

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The magnetosphere of a planet with a permanent magnetic moment is the space from which the solar wind is excluded by the planetary magnetic field. We know of the existence of three such magnetospheres, those of the earth, Jupiter (*1*), and Mercury (*2*), and we know that some exotic astrophysical objects (*3*) seem to possess magnetospheres. Since the early 1960's a succession of earth-orbiting spacecraft (*4*) has enlarged our understanding of how the earth's magnetic field is confined and shaped by the solar wind. Nevertheless, our knowledge is not sufficiently quantitative for reliable predictions of the properties of the magnetosphere, and thus we cannot claim a complete understanding of its structure and behavior. The International Sun-Earth Explorer (ISEE) Program, undertaken jointly by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), will use a three-spacecraft system to make a comprehensive attack on most of the more obstinate problems of magnetospheric structure, and is designed to make a large contribution to the International Magnetospheric Study (*5*). The major parameters of the three spacecraft are set out in Table 1.

Two of the spacecraft, ISEE-A and ISEE-B (known as the mother and daughter spacecraft, respectively), will be separated by a relatively small, controllable distance; this will allow measurements of the complex structures and dynamical properties of the magnetosphere that are less ambiguous than previous determinations. In particular, it will break the spatial-temporal ambiguity that arises when measurements are made by one spacecraft on a thin boundary, which may be in motion. The two spacecraft will be launched together on 19 October 1977, into the same highly elliptical orbit, carrying carefully matched payloads so that their measurements can be easily compared. The third spacecraft, ISEE-C, will be placed in heliocentric orbit 234 earth radii upstream (*6*) of the earth in the solar wind. Its launch is scheduled for 23 July 1978. As well as measuring magnetic fields and particles in the interplanetary medium, it will measure solar-wind parameters about 1 hour before the corresponding material is convected past the earth. Thus, after ISEE-C is in orbit, ISEE-A and ISEE-B will be analyzing dynamical processes in the magnetosphere that have been influenced by interplanetary conditions previously monitored by ISEE-C.

That magnetospheric measurements with a pair of spacecraft would be superior and desirable has been recognized since the discovery of the magnetopause (*7*) by Explorer 10 (*8*). Three multiple spacecraft missions were among the recommendations in a report of the U.S. Space Science Board published in 1968 (*9*). Around this period ESA, then the European Space Research Organisation (ESRO), embarked on a series of studies of small spacecraft for magnetospheric research, which were successfully concluded but were not implemented for financial reasons. Finally, at the February 1971 NASA-ESRO Program Review, it was suggested that these NASA and ESRO projects could be combined so that NASA would build the mother and ESRO the daughter spacecraft. In September 1971 NASA and ESRO representatives agreed on a tentative orbit and program. Meanwhile, NASA had completed a short internal study of another of the recommendations of the Space Science Board, "that continuous observations be made of the interplanetary medium." At the suggestion of Farquhar and co-workers (*10*), an orbit about the sunward libration point was proposed (*11*); it became clear that this third, heliocentric spacecraft would form a valuable improvement to the mother-daughter mission; and it was added to the program.

In 1972, at an early stage or organization of the ISEE program, investigators whose experiments will be carried on the spacecraft were selected by a joint NASA-ESRO committee. They were immediately formed into a Science Working Team, whose meetings have produced a well-defined, cohesive program. The technical interchanges between NASA and ESA, interacting with the Science Working Team, resulted in spacecraft structures and subsystems that satisfy most of the experimental requirements. This close liaison between investigators and project groups at an early stage should produce a better organized payload, and reduced costs by identifying and solving problems.

Data distribution and provisions for cooperation with other spacecraft and ground-based investigations received special attention at these meetings. In the past, spacecraft data for each experimenter have become available about 2 months after they are taken, as a result of delays in the complicated decommuta-

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tion and orbit determination process. Operations in "real time" require a computer on line with the tracking system, which is very expensive. A compromise solution was adopted for the ISEE mission, in which each investigator will receive his own data in detail after a 5-week delay, and will also receive a "data pool tape" incorporating information from eight other experiments. Quantities on the pool tape will be averaged over time intervals of a few minutes, and this tape is intended for use as an index so that an investigator can easily determine whether data from other ISEE experiments may be correlated fruitfully with his own. If he so determines, he must contact the appropriate investigators to obtain the refined data. Copies of the data pool tapes and microfilm plots made from them will be available to other scientists on request from the National Space Science Data Center for use in a similar way (*12*).

Scientific Objectives and Experiment Complement

Since the topology and structure of the earth's magnetosphere are largely known (Fig. 1), the objectives of the ISEE program are more concerned with the quantitative mechanism of its response to external perturbations and the small-scale structure of its parts. Thus the highest priority is given to the nature, structure, motion, and stability of the boundaries inherent to the magnetosphere: the bow shock, magnetopause, plasmapause, and neutral sheet (*7*). As mentioned above, ISEE-A and ISEE-B will usually be able to break the space-time ambiguity, while ISEE-C will provide essential knowledge of the input conditions that perturb these structures. One disturbing parameter is the direction of the interplanetary magnetic field, which has been found to have a profound effect on the structure and stability of the magnetosphere (*13*) and changes in which precede the onset of geomagnetic substorms (*14*). Observations will be made by ISEE-A and ISEE-B for several years, during which the earth's motion will rotate the axis of the magnetosphere with respect to the orbits of the spacecraft so that the apogee occurs at all local times. The data set obtained, complemented by that from ISEE-C in the upstream solar wind, will assist in formulating accurate quantitative models of the magnetosphere, of the mechanism of the magnetic substorm (*13, 15*), and of natural disturbances in the geomagnetic field at various frequencies (*16*).

Table 1. Parameters of the ISEE spacecraft.

Parameter	ISEE-A	ISEE-B	ISEE-C
Structure	Modified IMP (*23*)	New	Modified IMP
Spin rate, rev/min	19.7	19.8	19.75
Mass, kg	340	166	469
Payload mass, kg	89.0	27.7	97 (including antennas)
Payload power, watts	76	27	57
Number of experiments	13	8	12
Data rate, information bits per second			
High	16,384	8,192	2,048
Low	4,096	2,048	1,024, 512, 64
Spin axis alignment	Perpendicular to the ecliptic plane		

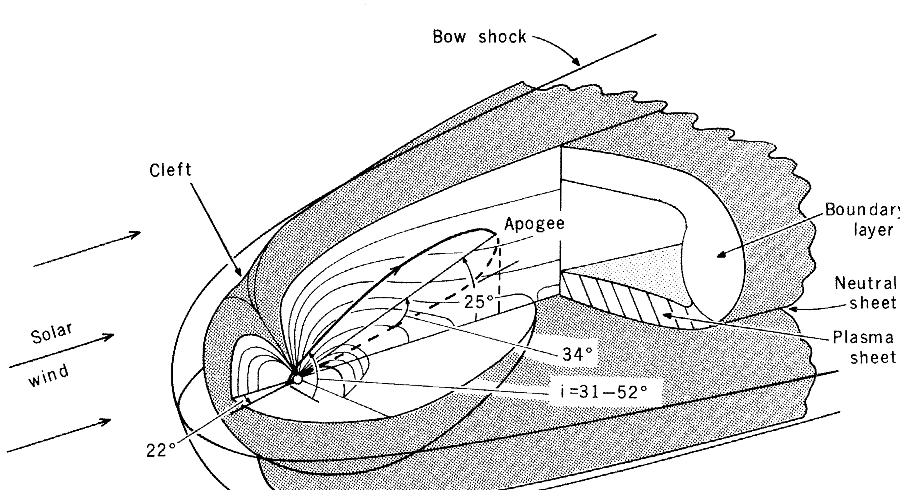


Fig. 1. Schematic view of the earth's magnetosphere, showing the trace of the bow shock and the magnetopause, and the orbit of ISEE-A and ISEE-B as it will be on 13 April 1978. The boundary layer is referred to as the mantle by some workers. The feature called the cleft constitutes a path by which plasma from the magnetosheath, the region between the shock and the magnetopause, may enter and find its way down to the ionosphere. The plasma sheet must, of course, merge with the boundary layer.

Plasma enters the magnetosphere at various points, and this process will be studied by ISEE-A and ISEE-C. For example, both spacecraft will carry plasma composition experiments that can identify the mass per unit charge of ions. Ions in the solar wind carry the charge they had in the solar corona whereas ions from the earth's ionosphere are predominately singly charged (He^{2+} and He^{+} are examples), so such experiments may provide a tracing technique to monitor the origin of plasma.

Since ISEE-A and ISEE-B can be situated at different distances down the earth's magnetospheric tail, and external conditions are known, quantitative measurements can be made of the flow of plasma and transport of energetic particles up and down the tail in response to changes in conditions in the interplanetary medium. This is of great current interest because there is evidence for particle acceleration in the tail, but the mechanism is not known (*17*).

These are the broad objectives for the mother-daughter pair, but with such heavily instrumented spacecraft as these (see Table 2) many other subsidiary aims will be formulated. A major individual objective of ISEE-C is to measure the isotopic compositions of both solar and galactic energetic particles. It will be possible, with newly developed position-sensitive detectors, to resolve individual isotopes of all nuclei with charge $Z = 1$ to 26, whereas previous studies have been limited at the very best to $Z \leq 8$. Such improvements will make it possible to investigate further the origin of cosmic rays and the processes of nucleosynthesis. Acceleration mechanisms for galactic and solar flare particles introduce specific charge-dependent distortions in the observed compositions. The relative abundances of isotopes of a particular charge should be rather insensitive to these distortions, so that the ISEE-C measurements should permit identification of acceleration mechanisms and of source isotopic composition.

Many interplanetary plasma phenomena will be studied, including plasma wave modes in the solar wind, interplanetary shocks, and the consequent acceleration of particles. These have general astrophysical applications. The mass composition and charge-state distributions of ions in the solar wind, and their variations, are poorly understood at present, and these will be determined over a wider range of conditions than has previously been possible. The charge-state distributions are directly related to coronal conditions at a few solar radii (*18*), where no other methods of measurement are applicable. Together, the relative abundances and charge-state distributions will be helpful in determining the mechanism of acceleration of ions into the solar wind, through the dependence of the mechanism on the charge-to-mass ratios of the ions. Large-scale flow patterns in the solar wind will be studied and related to coronal structure (*19*) around the maximum of the solar activity cycle in 1982. Recently developed radio direction-finding methods will be available on ISEE-C to track electrons emitted from solar events, even when their paths are out of the ecliptic plane (*20*).

Gamma-ray bursts will be studied by modifications of a few experiments, including one on ISEE-A. [The discovery of short, intense gamma-ray bursts was first announced by Klebesadel *et al.* (*21*) in June 1973 after the ISEE experiment selection took place.] The burst sources will be located with greater accuracy by time-of-flight triangulation in conjunction with experiments on other spacecraft.

Spacecraft and Orbits

Spacecraft ISEE-A and ISEE-B will be injected into the same orbit, of apogee 23 earth radii, as a stacked pair on a single Delta 2914 launch vehicle. As correlation is crucial, the instruments on the two spacecraft are similar (Table 2) and the measurement ranges have been chosen to take full advantage of the separation distances that can be arranged. A variable separation between these two spacecraft is required to fit in with the different scale sizes of magnetospheric features, and different instrument characteristics are required for measuring each scale size. It is evident that the separation strategy needs careful planning, but because the spacecraft are expected to last at least 3 years, three opportunities should be available. Since the orbit will remain approximately fixed in inertial space, the spacecraft will make a complete measurement cycle of the magnetosphere at least three times, and the scientific working team plan to adopt a different measurement program each time.

ISEE-A is larger and can carry more instruments than ISEE-B; its extra instruments are primarily to be used to investigate wave-particle interactions more thoroughly than can be done on the smaller craft. Figure 2 shows the mother and daughter spacecraft in orbital configuration—separated, with their booms and antennas deployed. ISEE-C is very similar in size and design to ISEE-A, but has different appendages and carries a hydrazine-powered maneuvering system to allow it to achieve and remain in its designated orbit.

The three ISEE's are the first spacecraft [other than the European GEOS (*22*)] whose exteriors are deliberately made equipotential in order to prevent differential charging across the surface. This is important to ensure accurate results from many of the experiments, particularly those designed to measure electric fields themselves, and those designed to measure particles whose energies, expressed in electron volts, are comparable to the probable potential of the spacecraft in volts. In addition, attempts will be made to control the potential difference between ISEE-A and the surrounding plasma by emitting streams of electrons from electron guns.

ISEE-A and ISEE-B will be spin-stabilized, with the spin vectors maintained perpendicular to the ecliptic plane within $\pm 1°$ and pointing north. To give some experiments all-around viewing, the spin rates will be slightly different (19.75 ± 0.05 revolutions per minute for ISEE-A and 19.8 ± 0.1 for ISEE-B) so that there will be a slow differential rotation. Care has been taken to prevent spacecraft appendages from casting shadows on the solar cell arrays which cover the surface, since this produces electrical interference as the shadows move on and off the arrays. The return of information will be normally at a rate of 4096 information bits per second from ISEE-A and 2048 from ISEE-B; both telemetry links will employ convolutional encoding to im-

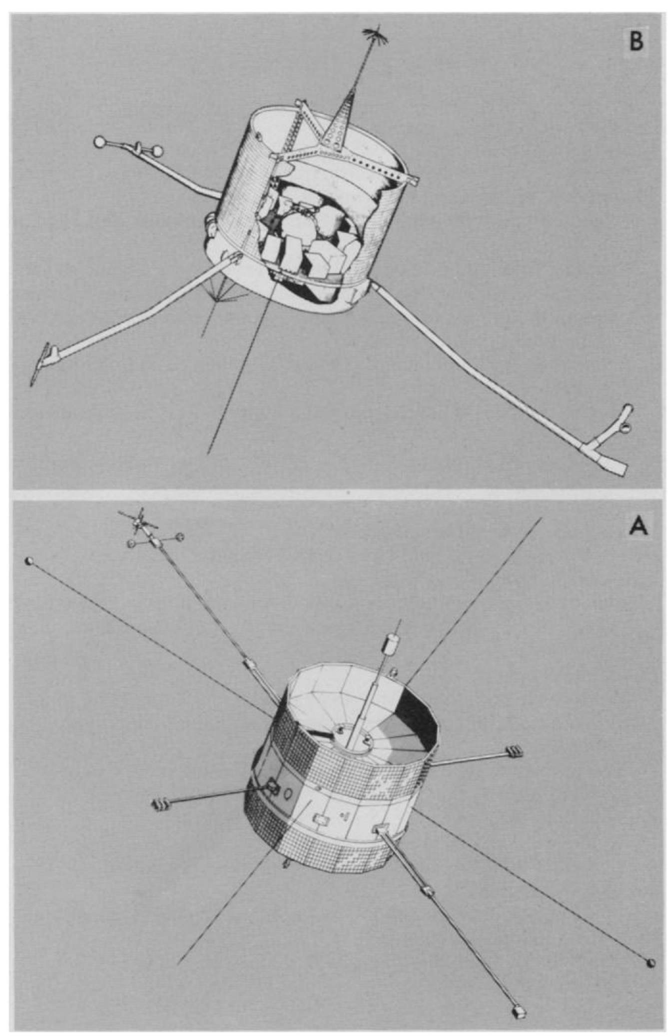


Fig. 2. The ISEE-B and ISEE-A spacecraft, shown separated and with the experiment booms and antennas erected.

prove the signal-to-noise ratio. The data transmission rates of both spacecraft can be increased by a factor of 4 on ground command for detailed examination of features of special interest. It is estimated that this higher rate will be used about 20 percent of the time—at first for one complete orbit in five, although a more complex procedure may be adopted later.

Each spacecraft will be eclipsed on each orbit as it passes behind the earth, but most of these eclipses will happen at low altitudes when the spacecraft are moving fast, so they will last only a few minutes each. However, when the apogee is in the antisunward direction, there will be longer eclipses, the longest lasting 5½ hours and occurring in the third year. ISEE-B is expected to survive this comfortably, but ISEE-A has a more open thermal design and will get colder. This may cause some problems, so the orbit was deliberately planned to place this eclipse as late as possible in the mission.

The orbit of ISEE-A and ISEE-B was chosen to satisfy several scientific and technical conditions.

1) The number of bow-shock crossings must be a maximum.

2) The initial line of apsides must be such that at least some bow-shock crossings are made early in the mission.

3) Crossings of the plasma sheet in the tail must be made.

4) The orbit must be stable enough for a mission lifetime of at least 3 years.

5) The maximum eclipse time must be less than 6 hours.

6) The solar-aspect angle at injection should be between 70° and 160°. (This is a technical requirement to reduce solar heating during launch.)

The number of bow-shock crossings depends on the apogee. With a higher apogee the orbit will intersect the bow shock for a longer period each year, but the orbital period will increase. The opposition of these two effects creates a slow variation of the total number of bow-shock crossings with apogee height, with a maximum at about 23 earth radii, the apogee chosen by the Science Working Team.

The original intention was to place the spacecraft into a transfer orbit with an

Table 2. Experiments, with principal investigators and institutions involved, for the ISEE program. Abbreviations: 1 $\gamma = 10^{-5}$ gauss; Z, atomic number; Q, charge; FWHM, full width at half-maximum; DES, differential energy spectrum; IES, integral energy spectrum; SPA, single parameter analysis; and MPA, multiple parameter analysis. Institutions are abbreviated as follows (with the affiliation of the principal investigator in italics): APL, Applied Physics Laboratory; Arizona, University of Arizona; Bern, University of Bern; BYU, Brigham Young University; CIT, California Institute of Technology; Chicago, University of Chicago; CNET, Centre National d'Etudes de Telecommunications; ESTEC, European Space Research and Technology Centre; GSFC, Goddard Space Flight Center; HAO, High Altitude Observatory; Imperial College, Imperial College of Science and Technology; Iowa, University of Iowa; JPL, Jet Propulsion Laboratory; Kiel, University of Kiel; LASL, Los Alamos Scientific Laboratory; Lockheed, Lockheed Research Laboratories; Maryland, University of Maryland; Max-Planck 1 and Max-Planck 2, Max-Planck-Institut at Garching and Lindau, respectively; MSFC, Marshall Space Flight Center; NASA Headquarters; NOAA, National Oceanographic and Atmospheric Administration; RIT, Royal Institute of Technology, Copenhagen; Rome, University of Rome; Stanford, Stanford University; Toulouse, University of Toulouse; TRW, TRW Systems, Inc.; UCB, University of California; Berkeley; UCLA, University of California, Los Angeles; and Washington, University of Washington.

Instrument title	Principal investigator	Institution
ISEE-A and ISEE-B		
Electrons and protons (A and B) Protons, 5 ev to 40 kev; electrons, 5 ev to 20 kev (high time resolution)	K. A. Anderson	*UCB*, Washington, UCLA, Toulouse
Low-energy protons and electrons (A and B) 1 ev to 50 kev in 63 bands with 16 percent resolution and large solid angle	L. A. Frank	*Iowa*, UCLA
Plasma waves (A and B) Magnetic field: 10 hertz to 100 khz (three axes, 16 channels; one axis only on B) Electric field: 10 hertz to 10 khz (three axes, 12 channels). Sweep frequency spectrum analysis of electric field signals: 10 khz to 200 khz (128 steps)	D. A. Gurnett	*Iowa*, TRW, JPL
Flux-gate magnetometer (A and B) ± 256 γ, ± 8192 (command); frequency response, 0 to 10 hertz	C. T. Russell	*UCLA*, Imperial College
Fast plasma (A) Protons; 5 ev to 40 kev; electrons: 5 ev to 20 kev (high time resolution)	S. J. Bame	*LASL*, Max-Planck 1
Plasma density (A) Resonance experiment on A, 0 to 350 khz. Phase-related waves at 683 khz and 272.5 Mhz	C. C. Harvey	*Paris Obs.*, ESTEC, CNET
Very-low-frequency wave propagation (A) Reception from Siple transmitter	R. A. Helliwell	*Stanford*
Direct-current electric field (A), 0.1 to 3200 hertz, nine steps	J. P. Heppner	*GSFC*, Iowa, NASA Hq.
Low-energy cosmic rays (A) Solar wind iron: suprathermal, multiply charged ions ($Z \leq Q \leq 26$): 5 to 50 kev/nucleon; 0.05 to 20 Mev/nucleon; 0.05 to 6 Mev/nucleon; 5 kev/Q to 20 Mev/nucleon	D. Hovestadt	*Max-Planck 1*, Arizona, Maryland GSFC
Energetic electrons (A) Protons, 25 kev to 2 Mev (8 channels); electrons, 25 kev to 1 Mev (8 channels) (B) Protons, 25 kev to 2 Mev (4 and 16 channels); electrons, 25 kev to 2 Mev (4 and 16 channels) Time-of-flight composition and angular scanning on A	D. J. Williams	*NOAA*, Max-Planck 2, Kiel, APL
Quasi-static electric fields (A), 0 to 5 mv/m; 0 to 12 hertz	F. S. Mozer	*UCB*, RIT, ESTEC
Fast electrons (A) 7 to 500 ev; 10 to 2000 ev; 105 to 7050 ev 7 percent FWHM resolution; 0.5-second time resolution	K. W. Ogilvie	*GSFC*
Ion composition (A) 0 to 40 kev/Q; 1 to 138 atomic mass units and plasma density	R. D. Sharp	*Lockheed*, Bern, Max-Planck 1, MSFC
Solar wind ion measurements (B) Ions, 50 ev/Q to 25 kev/Q; electrons, 35 ev to 7 kev	G. Moreno	*Rome*
Fast plasma (B) Ions, 50 ev to 40 kev; electrons, 5 ev to 20 kev	G. Paschmann	*Max-Planck 1*, LASL

apogee of 1390 km, which would have resulted in an initial mission orbit with an apogee of 23 earth radii and a perigee of 1390 km. This would have made extensive launch time available. However, since that was proposed the total mass to be launched has risen to an estimated 506 kg, and matching this with an apogee of 23 earth radii and the launcher performance gives a perigee height of 280 km, making the transfer orbit no longer possible. Calculations showed that the launch "windows" which satisfied the six conditions were extremely small—a series of 10-minute windows in late 1977 and another in the spring of 1978. These have been extended somewhat by relaxing the initial inclination requirement from 15° to 30°, incidentally increasing the difficulty of designing the telemetry antenna.

For the duration of each series of launch windows, there is a unique direction in space for the line of apsides if the orbit is to be stable; on whatever day the launch takes place, the line of apsides will have the same right ascension and declination. This means that the positions of the spacecraft at any time during their 3-year life can be predicted without knowing the precise day of launch. This is important because such things as the times of crossing of the tail current sheet and other regions of interest for correlative measurements can be accurately calculated in advance. In particular, the position of the orbit in the magnetosphere can be accurately predicted. The injection figures for ISEE-A and ISEE-B, not now expected to change before launch, are shown in Table 3 together with the orbital elements derived from them.

The sunward libration point, 234 earth radii from the earth, is the point on the earth-sun line where the gravitational attraction of the sun is equal to the sum of that of the earth and the centrifugal force. Equilibrium there is not stable, since uncompensated forces remain, but it is close enough to the earth for reasonable communications and far enough away for measurements made there to be unaffected by waves and particles reflected or generated at the magnetosphere or the bow-shock wave of the earth. Less hydrazine is required to keep a spacecraft near this point than near other points on the earth-sun line. In any case, ISEE-C cannot be held stationary there because, as viewed by receivers on the earth, the sun would then be right behind it and solar radiation would swamp the telemetry. This problem will be overcome by making the spacecraft oscillate around this "blind zone" in a "halo orbit" (*11*). An important parameter here is the width of the blind zone, and allowance has to be made for solar flares and side lobes of the responses of antennas on the earth. The halo orbit will have to be adjusted from time to time to keep its plane nearly normal to the earth-sun line.

ISEE-C is scheduled to be launched as soon after ISEE-A and ISEE-B as is practicable. It will be injected into a transfer orbit whose projection onto the ecliptic plane is shown in Fig. 3. The

Table 2 (continued).

Instrument title	Principal investigator	Institution
ISEE-C		
X-rays and electrons X-rays, 8 to 72 kev; electrons, 2 to 1000 kev	K. A. Anderson	*UCB*, HAO
Solar wind plasma Ions, 150 ev to 7 kev, 4.2 percent FWHM; electrons, 5 ev to 2.5 kev, 10 percent FWHM. Three-dimensional distribution function	S. J. Bame	*LASL*
High-energy cosmic rays Species H through Fe (resolution, 0.15 atomic mass unit, $1 < Z < 26$)	H. H. Heckman	*UCB*
Low-energy cosmic rays Particle composition; up to 20 Mev/nucleon	D. Hovestadt	*Max-Planck I*, Arizona, Maryland, GSFC
Energetic protons Protons, 30 kev to 1.4 Mev; alpha-particles, 1.4 to 6 Mev	R. J. Hynds	*Imperial College*, SRL, ESTEC
Cosmic-ray electrons and nuclei Electrons, 5 to 400 Mev (DES); protons, 36 to 13,000 Mev (DES); 13 Gev (IES) Elements separated: helium-sulfur, 60 to 13,000 Mev/nucleon (DES); > 13 Gev/nucleon (IES)	P. Meyer	*Chicago*
Plasma composition 470 ev/Q to 10.5 kev/Q; M/Q 1.4 to 6.5; 3 percent FWHM resolution	K. W. Ogilvie	*GSFC*, Maryland, Bern
Plasma waves Magnetic field: 8 channels, 60-db range, 20 hertz to 1 khz Electric field: 16 channels, 80-db range, 20 hertz to 100 khz (continuous, no switching)	F. L. Scarf	*TRW*, Iowa, JPL
Radio mapping Three-dimensional tracing of paths of type III bursts in band from 20 khz to 3 Mhz	J. L. Steinberg	*Paris Obs.*, GSFC
Helium vector magnetometer Eight ranges (± 4, ± 14, ± 42, ± 640, ± 4000, ± 22,000, and ± 140,000 γ); frequency response 0 to 3 hertz with three bands (0.1 to 1, 1 to 3, and 3 to 10 hertz) for measurements of fluctuations parallel to the spacecraft spin axis	E. J. Smith	*JPL*, CIT, BYU
High-energy cosmic rays Ranges: Z = 3 to 28 (Li to Ni); A = 6 to 64 (^{6}Li to ^{64}Ni); energy = 2 to 200 Mev/nucleon. Mass resolution: Li, 0.065 to 0.83 proton masses; Fe, 0.18 to 0.22 proton masses	E. C. Stone	*CIT*
Medium-energy cosmic rays Nuclei, Z = 1, 0.5 to 4 Mev/nucleon (SPA) and 4 to 500 Mev/nucleon (MPA); $2 \leq Z \leq 26$, 0.5 to 500 Mev/nucleon (MPA) Electrons, 0.7 to 0.2 and 0.3 to 12 Mev Isotopes, Z = 1 and 2, 4 to 80 Mev/nucleon; $3 \leq Z \leq 7$, 8 to 120 Mev/nucleon; $8 \leq Z \leq 16$, 10 to 200 Mev/nucleon	T. von Rosenvinge	*GSFC*
Ground base solar studies Solar spectral observations	J. M. Wilcox	*Stanford*

spacecraft will be near the halo orbit position about 30 days after launch, and injection into the final halo will take place 78 days later; the spacecraft will then be spin-stabilized with the spin vector perpendicular to the ecliptic plane and pointing north. The relative position of the moon is important, as its aspect as observed from the spacecraft is used to make the midcourse correction of the transfer orbit, and this requirement restricts the launch window to 2 or 3 days per month. ISEE-C will carry 95 kg of hydrazine for orbit injection and attitude control, representing a velocity increment of about 400 m/sec. It is estimated that about 105 m/sec of this will be needed for midcourse correction of the transfer orbit and 110 m/sec for deceleration at injection into the halo orbit. The remainder will be available for station-keeping adjustments of the orbit plane, attitude maneuvers, and so on, and is estimated to be sufficient to maintain the spacecraft in place for 5 years.

Separation Strategy

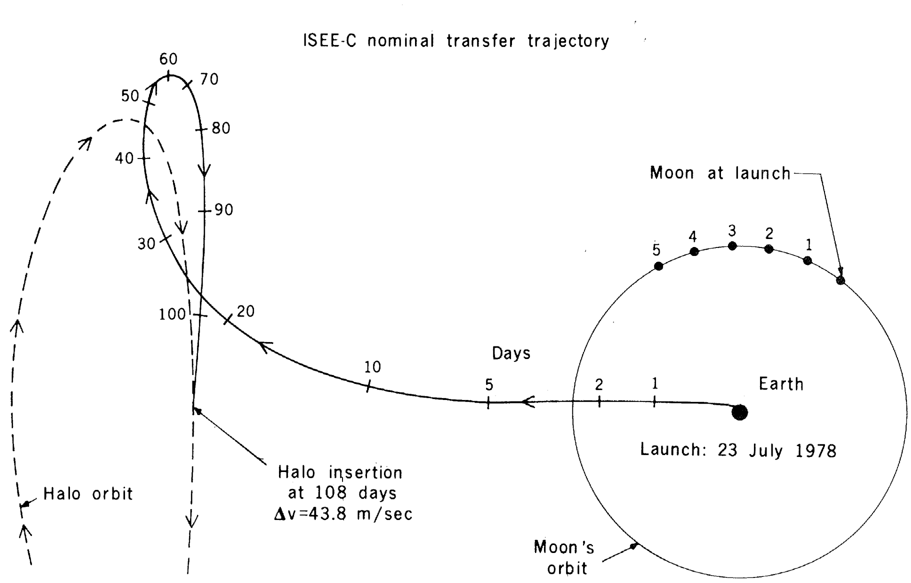
Because ISEE-B is the less massive of the two spacecraft, it was chosen to carry the gas-jet system by which the separation between it and ISEE-A will be altered, within the range 100 to 5000 km. In case of complete failure of the equipment on ISEE-B, ISEE-A will also carry a gas-jet system (chiefly for placing the spin vector normal to the ecliptic plane) and will be capable of limited separation control in case of complete failure of the experiment on ISEE-B.

At the beginning of the project it was quickly discovered that the only direction of separation which did not need enormous amounts of gas for stability and distance adjustment was along the path of the orbit. One of the limitations of the mission is the one-dimensional nature of the separation, and it is fortunate that true anomaly adjustment—that is, along the orbital direction—varies the line between the spacecraft perpendicular to most of the moving planes of the magnetosphere. The distance between the spacecraft will be altered by giving ISEE-B an impulse to start it drifting toward or away from ISEE-A. The impulses will alter the height of the ISEE-B apogee slightly, thus changing the orbital time period and the differential speed. It is interesting to note that giving ISEE-B an impulse toward ISEE-A will cause them to drift apart, and vice versa.

The most efficient point at which to make an adjustment is at perigee, and it will be made by a number of gas-jet impulses synchronized with the spacecraft rotation so that they are all in the same direction. The size of the adjustment will depend on the number of impulses; the maximum will be about 600 per orbit. This number is set by the decreasing efficiency as the spacecraft moves away from perigee, and the increasing amount of gas needed to correct orbit distortions as the adjustment is increased. In practice, more impulses can be used if a greater inefficiency of gas use is accepted. The 600 impulses will apply a velocity increment of 25 cm/sec, corresponding to a separation change of approximately 500 km per orbit at an altitude of 15 earth radii; a total increment of 16 m/sec will be available for separation maneuvers. Synchronism of the impulses with the rotation is organized by a sun sensor so these impulses cannot be given in the earth's shadow. As the spacecraft will not be in sight of a tracking station at most perigee positions, the gas impulses will be programmed by a start-and-stop timer, which can be set up to 9 hours in

Table 3. Launch parameters for ISEE-A and ISEE-B, taking as an example the launch date of 14 October. Abbreviation: R_e, earth radii.

Injection parameters	
Geocentric latitude	20.659238°
Geocentric longitude	121.694719°
Distance from the earth's center, km	6662.051395
Inertial velocity, km/sec	10.70058
Inertial elevation flight-path angle	1.3606°
Inertial azimuth flight-path angle	69.5270°
Derived initial orbital parameters	
Perigee distance from the earth's center, R_e	1.044
Apogee distance from the earth's center, R_e	23.17
Eccentricity	0.913787 rp
Inclination (equator)	28.766°
Launch date	14 October 1977



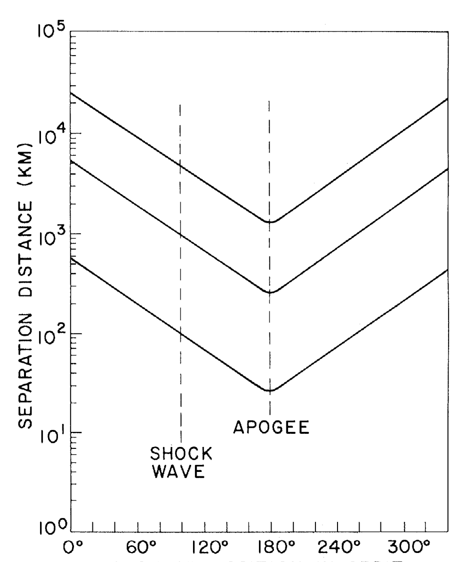


Fig 3 (left). Projection onto the ecliptic plane of the transfer orbit by which ISEE-C will go from the earth to its final halo orbit about the libration point between the sun and the earth. Abbreviation: Δ_v, velocity increment. Fig. 4 (right). Separation as a function of position in the orbit, for three valves of nominal separation, as defined at a distance of 15 R_e.

advance. It has been agreed that adjustments will not be made on consecutive orbits as the tracking system needs at least one complete orbit to redetermine the orbit after a maneuver. Because the speed of the spacecraft varies around the orbit, while the separation time remains constant if no drift is assumed, the separation distance varies a great deal. Figure 4 shows how the separation varies as the spacecraft go around their orbit: the nominal separation is defined to be that at a distance of $15R_e$, the height of the bow shock at the subsolar point.

Maneuvers of ISEE-A and ISEE-B will be controlled from the Multiple Satellite Operations Control Center at Goddard Space Flight Center (GSFC). ISEE-B will be operated by a team of engineers from the European Space Operations Centre, Darmstadt, Germany, who will base their maneuver calculations on tracking information supplied by the NASA network. To make changes in the separation drift speed, these engineers will have available a selection of preprogrammed adjustment packages. This will simplify operations, since calculations can be done in advance elsewhere. It is not expected that the packages will give exactly the right adjustment every time, and for most drifts a correction will be needed. The separation achieved will be measured to an accuracy of about ± 1 km.

A separation strategy has been planned for the period from launch to the end of 1978. The early orbits will be taken up with switch-on, calibration, and alignment maneuvers, but on the eighth orbit it is planned that the spacecraft will pass each other (a "flyby"); at this time the separation time will be effectively zero and the scientific work will begin. There are two recalibration periods, one in April and May and the other in August. A necessary condition for recalibration is that the spacecraft should be close together, so it is planned that they will again pass each other at these times. The second recalibration period is timed to coincide with the arrival of ISEE-C on station so that correspondence between the instruments on all three spacecraft can be checked.

Activities After Launch

Immediately after launch of ISEE-A and ISEE-B, the experimenters will come to GSFC to switch on and check their experiments. Those most concerned with the boom-mounted magnetic and electric field experiments will have special facilities to display and compare their data, which can be reduced on-line for short periods. They will then return to their home institutions to await the regular data and the pool data, to work on them in the usual way. A similar procedure will be followed after the launch of ISEE-C, when experimenters will again come to GSFC to turn on their experiments and make the first checks of them. This process will take a longer time than for ISEE-A and ISEE-B, since the spacecraft must be in the final halo orbit before the appendages can be fully erected.

The Science Working Team will remain active throughout the program. It will hold periodic meetings to discuss modifications to the separation strategy and topics related to the spacecraft and workshops at which data will be exhibited, discussed, and compared with those of other experimenters. These other experimenters may be part of the ISEE program or scientists working with ground-based, balloon- or rocket-borne, or other satellite experiments. Since the International Magnetospheric Study is an even larger program than ISEE, the possibilities for fruitful international cooperation are extensive, and everyone associated with ISEE is committed to realizing its maximum potential in this respect.

Summary

The International Sun-Earth Explorer is a three-spacecraft program of the National Aeronautics and Space Administration and the European Space Agency aimed at securing a more quantitative knowledge of the structure and stability of the magnetosphere. One spacecraft (ISEE-C) makes observations in the solar wind upstream of the earth, while the other two (ISEE-A and ISEE-B), in the same highly eccentric orbit but separated by a relatively small variable distance, observe inside the magnetosphere. This international program is concurrent with the International Magnetospheric Study, to which ISEE-A and ISEE-C form a large U.S. contribution. The scientific aims and technological methods are discussed.

References and Notes

1. For an account of Jupiter's magnetosphere, see *J. Geophys. Res.* **79**, 3489 (1974).
2. N. F. Ness, K. W. Behannon, R. P. Lepping, Y. C. Whang, K. H. Schattan, *Science* **185**, 150 (1974); *J. Geophys. Res.* **80**, 2708 (19→ K. W. Ogilvie, J. D. Scudder, V. M. Vasyliunas, R. E. Hartle, G. L. Siscoe, *ibid.* **82**, 1807 (1977).
3. According to one theory of pulsars, their pulsating character is the result of rapidly rotating magnetospheres.
4. Much of our information about the magnetosphere of the earth has been obtained through a series of orbiting geophysical observations [Eccentric Orbital Geophysical Observatories (EOGO's) and Polar Orbital Geophysical Observatories (POGO's)] operated by NASA during the 1960's and a series of ten Interplanetary Monitoring Probes (IMP's), which were put into various orbits from 1963 to the present. The former had probably the highest communication bit rate, and therefore the highest potential time resolution, of any spacecraft flown to date in the earth's magnetosphere, and were very complex and heavily instrumented. The latter have been placed in eccentric orbits, in orbit about the moon, and in large circular orbits of about 40 earth radii, and IMP-1, also called Explorer 18, was the first to delineate magnetic field topology. The European Space Agency has put in orbit two spacecraft of the HEOS series, HEOS-2 being especially useful because of its unique eccentric orbit, with a high inclination with respect to the ecliptic plane, and apogee approximately above the north pole of the earth.
5. The International Magnetospheric Study (IMS) is an international cooperative program. It began in January 1976 and will run through 1979; there will probably be 2 years of active follow-on experiments and data analysis. About 50 countries will participate; major spacecraft will be launched by the United States, ESA, the Soviet Union, and Japan. The key ingredients of the IMS are: (i) multinational spacecraft; (ii) new ground-based instruments arrays, some of which will greatly advance international data exchange standards by using simultaneous data collection, processing, and dissemination in real time at existing central data facilities; (iii) incoherent-scatter radars; and (iv) a variety of ground-based, balloon, rocket, and aircraft experiments. Although the IMS requires some new facilities and support, it is primarily based on effective use of planned programs. Several new facilities have been set up to provide information rapidly to IMS scientists. The IMS Central Information Exchange Office has been established in World Data Center-A in Boulder, Colorado, and regional offices have been set up in Paris, Moscow, and Tokyo; a monthly newsletter lists schedules and plans for spacecraft and ground-based measurements, and general IMS news. In addition, NASA has established the Satellite Situation Center to keep track of all spacecraft which contribute to the IMS. The U.S. federal program for the IMS is organized through the IMS Coordination Office, which is jointly sponsored by the National Oceanic and Atmospheric Administration and the National Science Foundation; scientific advice is provided by the National Academy of Sciences IMS Panel [J. G. Roederer, *Eos* **57**, 6 (1976); R. H. Manka, *ibid.*, p. 6].
6. One earth radius (R_e) = 6380 km; 234 R_e (1.49×10^6 km) is the distance from the center of the earth to the libration point between the earth and the sun.
7. Boundaries of the magnetosphere referred to in this article are the following: the magnetopause is the boundary between the earth's magnetic field and the interplanetary magnetic field; the bow shock, a collisionless standing shock wave caused by the interaction of the solar wind with the magnetosphere; the plasmapause, a boundary where the density of the plasma surrounding the earth, and mainly derived from the ionosphere, decreases rapidly; and the neutral sheet, a region near the ecliptic plane in the earth's magnetic tail surrounding the surface where the two lobes of the tail join. Experimental results on the bow shock are discussed by E. W. Greenstad [in *Magnetospheric Particles and Fields* (Reidel, Dordrecht, 1976), p. 13]; experimental results on the magnetopause and its association with the interplanetary magnetic field by M. P. Aubry, C. T. Russell, and M. G. Kivelson [*J. Geophys. Res.* **75**, 7018 (1970)] and M. G. Kivelson, C. T. Russell, M. Neugebauer, F. L. Scarf, R. W. Fredriks, *ibid.* **78**, 3761 (1973).
8. J. P. Heppner, N. F. Ness, C. S. Scearce, P. L. Skillman, *J. Geophys. Res.* **68**, 1 (1963); see also L. J. Cahill and P. G. Amazeen, *ibid.*, p. 1835. These are references to the first observations of the magnetopause; for a more recent overview, see S. I. Akasofu and S. Chapman, *Solar Terrestrial Physics* (Oxford Univ. Press, London, 1972), and reviews in the *Reviews of Geophysics and Space Physics*.
9. Space Science Board, *Physics of the Earth in Space 1968–1975* (National Academy of Sciences–National Research Council, Washington, D.C., 1968).
10. R. W. Farquhar, *NASA Tech. Rep. R-346* (1970); ——— and A. A. Kamel, *Celestial Mech.* **7** (No. 4), 458 (1973); R. W. Farquhar *et al.* *J. Spacecr. Rockets* **14** (No. 3), 170 (1977).

11. The sunward libration point is located on a line joining the sun and the earth and is approximately 1.5 × 10⁶ km from the earth. Because of the alignment with the sun, telemetry signals from a spacecraft located in the vicinity of this point will be degraded significantly by solar interference. This problem can be eliminated by placing the spacecraft into a halo orbit around the libration point. As viewed from the earth, such a spacecraft would appear to be in an elongated orbit around the sun. Although halo orbit is inherently unstable, fuel requirements to maintain it are modest.
12. Inquiries should be sent to Dr. J. I. Vette, National Space Science Data Center, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771.
13. The magnetosphere exhibits a phenomenon of instability called a "magnetic substorm," and these are presently the subject of considerable insterest and controversy. See, for example, S. I. Akasofu, *Physics of Magnetospheric Substorms* (Reidel, Dordrecht, 1977); R. L. McPherron, *J. Geophys. Res.* **75**, 5592 (1970); C. T. Russell and R. L. McPherron, *Space Sci. Rev.* **14**, 205 (1973).
14. Magnetospheric plasma is reviewed in L. A. Frank, *Rev. Geophys. Space Phys.* **13**, 974 (1975); magnetospheric magnetic fields are reviewed in C. T. Russell, *Rev. Geophys. Space Phys.* **13**, 952 (1975); V. M. Vasyliunas, in *Solar-Terrestrial Physics*, E. R. Dyer, Ed. (Reidel, Dordrecht, 1972), part 3, p. 192; R. A. Wolf, *Space Sci. Rev.* **17**, 537 (1975): S. I. Akasofu and S. Chapman, *Solar-Terrestrial Physics* (Oxford Univ. Press, London, 1972), p. 197.
15. G. L. Siscoe, in *Solar System Plasma Physics*, C. F. Kennel *et al.*, Eds. (North-Holland, Amsterdam, 1977).
16. An example of the extensive literature on pulsations is R. L. McPherron *et al.*, *Space Sci. Rev.* **13**, 411 (1972).
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22. GEOS is described in *ESA Bulletin No. 9* (European Space Agency, Paris, 1977).
23. This refers to the later members of the IMP series, which were open-ended multifaceted cylinders, spin-stabilized with the spin axis perpendicular to the ecliptic.
24. An international project of this magnitude involves many people and organizations and is built on the previous efforts of many others. It is not possible to acknowledge all participants by name but a glance at Table 2 indicates how many organizations are involved.

Ocean Surface Currents Mapped by Radar

Mobile coastal units can map variable surface currents in real time to 70 kilometers, using ocean wave scatter.

D. E. Barrick, M. W. Evans, B. L. Weber

Currents within 1 meter of the ocean surface are highly variable, being driven by geostrophic forces and tides, but are strongly influenced by the local surface wind and wave fields. These currents transport floating matter and thus are of great importance in coastal areas, where considerable damage can be done by surface-borne pollutants and oil. In the case of the large oil spill by the tanker *Argo Merchant* off New England in December 1976, for example, catastrophic environmental damage was averted because strong offshore winds counteracted the normal surface-current drift toward shore. In a positive vein, the upper portion of the sea carries the zooplankton and phytoplankton, which are the dominant components at the bottom of the food chain and are responsible for production of most of the world's oxygen. Many types of fish eggs are borne by surface currents, which are therefore of concern to the fisheries industry. The transport of water with anomalous temperature differences is now believed to be responsible for unusual weather patterns affecting entire continents.

Near-surface current patterns, and how they respond locally to the relevant prevailing forces, are a subject that is largely unknown. Yet the subject is a crucial ingredient for the effective management of operations in coastal waters, and an increasingly important input for global resource monitoring and weather predictions.

Current Measurements

In conventional methods of measuring currents moored meters are used; the most recent types are referred to as vector-averaging current meters and the Aanderaa meter (*1*). These devices must be moored at depths exceeding 10 m, and thus provide little indication of the current at the surface, which is often different. Furthermore, data must be either recorded aboard the buoy (to be picked up later for analysis) or telemetered to shore; the instrumentation for the latter often restricts the operating range from the receiver to tens of kilometers. Surface currents have been measured by tracking floating objects. Qualitative estimates can be obtained by photographing the dispersal of dye packages from an aircraft, or by analyzing satellite infrared and optical imagery of suspended sediment (to a coarser area scale) (*2*). Quantitative measurements are made by photographically recording the positions of time-released floats dropped from the air, as described by Richardson *et al.* (*3*), or by tracking a drifting drogue buoy from a ship (*1*). In the latter case, a high-precision navigation system is required on the ship to accurately establish the drift of the buoy. Operations with aircraft or ships are both expensive and time-consuming for the meager amount of current data obtained (one vector over a period of about 1/2 hour). The velocity accuracy of these float-locating techniques appears to be of the order of 10 to 15 centimeters per second in magnitude and 5° in angle (*2*). The location of such drogues by triangulation, using high-frequency (HF) surface-wave emissions from the buoy, is described in (*3*); although such drogues are inexpensive ($175), the positional accuracy deteriorates with distance from shore, making this an unacceptable alternative near the edge of the continental shelf.

We discuss here a coastally located HF radar system that can measure and map near-surface currents to ranges about 70 kilometers from shore. This instrument deduces current velocity from the echoes scattered continuously from the ocean waves; buoys and drifters are not required. The radar units were built to be transportable and quickly deployable on a beach. A minicomputer controls the radar and processes the signals, permitting a current-vector map to be plotted in the field after 1/2 hour of operation. Two spatially separated radar units are presently employed, simultaneously

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