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Nuclear and Ionic Charge Distribution Experiment on ISEE-1 and ISEE-3

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The experimental work carried out under this contract is a continuation of that originally performed under Contracts NAS5-20062 and NAS5-26739. The data analyzed are from the Max-Planck Institut/University of Maryland experiment on ISEE-1 and ISEE-3. Each spacecraft experiment consists of a nearly identical set of three sensors (designated the ULECA, ULEWAT and ULEZEQ sensors) designed to measure the energy spectra and composition of suprathermal and energetic ions over a broad energy range (<3 keV/e to >20 MeV/nucleon). Since the launch of ISEE-1 and -3, the MPE/University of Maryland experiments have generally performed as expected except for a partial failure of the ULEWAT sensor on ISEE-1 in August 1978. A number of scientific studies have either been completed, initiated, or are at various stages of completion.

A brief summary of Primary Results from our analysis is given below, followed by a more detailed summary of our major accomplishments at the University of Maryland.

- Determination of convective speed, effective temperature and spectral shape of thermal and suprathermal H^+, He^{++}, and $Q > 3$ ions in plasmoids in the distant magnetotail.
- First reported measurements of energetic (>100 keV) O^+ in the earth's plasma sheet.
- Discovery of He^+ ions in the earth's radiation belts.
- First comparison of simultaneous He/H abundance ratios in the solar wind and diffuse upstream events.
- First measurement of solar wind Fe charge states in coronal hole-associated high speed streams.
- First measurement of the CNO charge states in coronal hole-associated solar wind using heavy ion measurements in upstream events.
- First direct determination of the ionic charge state composition in ^{3}He-rich solar flares.

- Determination of the ionic charge state composition in He^+-rich solar flares.
- In situ observations of cometary pick-up ions at P/Giacobini-Zinner.

Magnetospheric Physics

Suprathermal Ion Composition in the Distant Geomagnetic Tail. The October 1982 to December 1983 excursion of the ISEE-3 spacecraft into the far geomagnetic tail has provided a unique opportunity for studying in some detail and over an extended time period the basic plasma dynamics in this heretofore relatively unexplored region of geospace. The UMD/MPE ULECA sensor is the only instrument on ISEE-3 that is capable of measuring the composition of the suprathermal plasma (~30 to 150 keV/e). We find that suprathermal H^+, He^{++}, and $Q > 3$ ions are a persistent feature of the distant tail. Differential intensities for 30 keV protons in the plasma sheet are essentially constant between the lunar distance and 220 R_E and about one order of magnitude smaller than in the near earth (<20 R_E) plasma sheet, as measured by our nearly identical sensor on ISEE-1.

Suprathermal ions are convected with the local plasma flow during fast moving particle structures (plasmoids) characterized by isotropic energetic electron distributions (measured by the MPE/UMD ULEWAT sensor) preceded by velocity dispersed ions and beaming electrons. We have been able to derive the convection velocity from the measured particle angular distributions in these plasmoids as well as the rest frame distribution functions for 3 to 150 keV/amu H^+, He^{++}, and $Q > 3$ ions. From a statistical survey of 20 plasmoid events, we showed that the different ion species in the distant tail (>80 R_E) are convected with a common convection velocity, with speeds ranging from ~200 to 1000 km sec^{-1} and a sample average of ~600 km sec^{-1}. The distribution functions in each event are well represented by exponentials in velocity of

the form $f(v) = f_o \exp(-v/v_o)$, with an average value of v_o for the 20 events equal to ~380 km sec^{-1} for protons and ~340 km sec^{-1} for alpha particles. The average values for proton number density, energy density, and effective temperature are 0.018 cm^{-3}, 160 eV/cm^3, and 6.1 keV, respectively, with an average He^{++}/H^{+} number density ratio of ~0.03 and effective temperature ratio of ~3.3 (roughly proportional to mass). These measurements, coupled with observations of the thermal plasma by the LANL experiment on ISEE-3, imply an efficient acceleration mechanism which is velocity dependent and indicate the importance of the solar wind as the seed plasma. In addition, we presented evidence that these plasmoids have lengths along the convective flow direction of ~80 R_E and have a cross-tail expansion of ~100 km sec^{-1} during their tailward propagation.

We also analyzed energetic electrons (75-115 keV) and suprathermal ($\gtrsim$30 keV) protons measured at the dawn side of the distant magnetosheath at ~50 R_E and ~180 R_E using the ULECA and ULEWAT sensors on ISEE-3. At ~50 R_E the electrons and protons are observed simultaneously in bursts of ~2 minutes duration. The absence of time dispersion indicates that the bursts are of a spatial rather than a temporal nature. The electrons at ~50 R_E are field-aligned and stream away from the magnetopause, while the protons exhibit a large parallel anisotropy that is symmetric with respect to the magnetic field in the plasma frame of reference. At ~180 R_E the energetic electrons, if any, are below our sensitivity level. However, suprathermal protons that are isotropic in the plasma frame have been observed. We interpreted our results in terms of magnetosheath flux tubes, perhaps the remnants of flux transfer events, which are connected to the tail magnetic field along the distant magnetopause. Up to ~100 R_E a coherent plasma sheet exists and particles can leak out along the connected field lines. After convection of these flux

tubes to ~200 R_E the suprathermal plasma sheet ions are coupled to the magnetosheath flow. Leakage of plasma sheet particles into the magnetosheath may be an important loss mechanism for the plasma sheet and may explain the exponential decay of energetic particle intensities observed following the plasma sheet recovery.

During the ISEE-3 Geotail Mission three events were identified from the magnetometer data which are consistent with a spacecraft crossing of a magnetotail flux rope. We analyzed energetic electron and proton observations during two of the possible flux rope events. During one event remote sensing of the flux rope with energetic protons revealed that the flux rope is crossed by the spacecraft from south to north. This allowed determination of the handedness of the magnetic field twist and of the flux rope velocity relative to the spacecraft. A minimal flux rope radius of 3 R_E was derived. Energetic proton intensity is highest just inside of the flux rope and decreases towards the core. Energetic electrons are streaming tailward near the outer boundary indicating openess of the field lines and are isotropic through the inner part of the flux rope.

Energetic O^+ Ions in the Earth's Magnetosphere. It has become increasing apparent that ionospheric ions, especially O^+ ions, constitute an important and sometimes dominant source for near-earth plasma regimes. However, previously the only reported measurements of O^+ ions in the earth's magnetosphere have been at energies below ~16 keV. We have reported the first measurements of very energetic (>100 keV) O^+ ions in the earth's plasma sheet using the ULECA sensor on ISEE-1. We found that substantial fluxes of energetic O^+ can occur in the recovery phase plasma sheet, with the intensity of O^+ ions (relative to H^+ ions) strongly correlated with geomagnetic activity. Our simultaneous observations of energetic H^+, He^{++} and O^+ ions

clearly indicated that both the solar wind and the ionosphere contribute to the production of suprathermal ions in the recovery phase plasma sheet. However, the acceleration mechanism for generating these energetic ions is not known.

We analyzed energetic (~130 keV) O^+ ions in the earth's magnetosphere at ~16 to 7 R_E during the two Coordinated Data Analysis Workshop 6 substorms on March 22, 1979. The behavior of thermal and suprathermal H^+ (10-130 keV) and suprathermal He^{++} (30-130 keV/e) ions was also studied. Approximately 15 min before the 1054 UT onset of the first substorm, energetic O^+ ions were observed streaming tailward. H^+ and He^{++} ions at all energies were generally streaming tailward from ~1059 to 1115 UT, consistent with the presence of a near-earth neutral line during this interval. From 1117 to 1124 UT the H^+ and He^{++} ions were observed flowing earthward, suggesting that at ~1117 UT the neutral line retreated tailward. A brief interval in the southern tail lobe, from ~1124 to 1126 UT, was highlighted by an intense O^+ beam streaming tailward; the O^+/H^+ ratio at 130 keV was 7 ± 2. This suggests that high energy O^+ ions may be accelerated directly out of the ionosphere. The recovery phase of the first substorm began a few minutes later and was characterized by large intensities of nearly isotropic suprathermal ions. The O^+/H^+ differential intensity ratio at 130 keV was quite large (~1) during the recovery phase of both substorms. This suggests that the O^+/H^+ ratio is relatively constant at equal energy per charge. If confirmed, this result would be of great importance in determining the operative acceleration mechanism.

Interplanetary Phenomena

Diffuse Ion Upstream Events. In a statistical study of 29 well-developed diffuse ion events observed upstream of the earth's bow shock, we compared the

He^{++}/H^{+} measured by the ULECA sensor at ~30 keV/e on ISEE-1 with the same ratio observed simultaneously in the solar wind by the LANL/MPE plasma instrument on the same spacecraft. This collaboration effort determined that a high correlation exists between the He^{++}/H^{+} ratio in upstream events and the same ratio in the solar wind, strongly suggesting that the solar wind is the dominant source for diffuse upstream ions. We also found that the ratio of He^{++} to H^{+} intensities at ~30 keV/e is on the average enhanced by a factor of 1.6 over the solar wind ratio. The enhancement is strongly correlated with Alfven Mach number (significant at the 98% confidence level); however, this correlation is dominated by three events that simultaneously have the lowest Alfven Mach numbers and the lowest enhancement factors (in fact, these three events are depleted in helium). Our results are consistent with the predictions of models for the Fermi acceleration of a seed particle population which is drawn from the solar wind with relatively little compositional bias and is then moderately enhanced in helium during the acceleration process. The identity of this seed population (e.g., the reflected component or shock-heated solar wind) has not been established; however our observations of a well-defined Alfven Mach number (~7) below which the diffusive He^{++} ions are depleted relative to the solar wind indicates that the microphysics of the bow shock plays an important role in determining the composition of the seed population.

We presented the first measurements of the charge state composition of heavy ($Q > 3$) ions in the diffuse component using the ULECA sensor on ISEE-1. We found that the relative charge state distributions for $Q > 3$ ions at ~33, 66, and 130 keV/e are consistent with an invariance of the charge state composition as a function of energy per charge, thus extending our previously reported energy-per-charge ordering for the He^{++}/H^{+} ratio in diffuse ion

events. Using the results of the previously mentioned survey (indicating a solar wind origin for these locally accelerated ions), we used the charge state composition of diffuse $Q > 3$ ions to estimate the charge state composition in the solar wind and hence to estimate the equilibrium coronal temperatures associated with a variety of solar wind flows. Of particular interest are the results we obtained for diffuse ion events occurring during coronal hole-associated high speed streams, since reported solar wind charge state measurements for high-speed streams are very limited. We found an average CNO ionization temperature of $(1.3\pm0.2) \times 10^6$ K for these events, which is consistent with predicted temperatures for coronal holes. Our results also indicated that the equilibrium temperature for coronal hole-associated solar wind is approximately constant over the range of solar wind speeds (420-680 km sec^{-1}) covered by the diffuse ion events in this survey.

Solar Energetic Particles. Using data from the ULEZEQ sensor on ISEE-3, we determined the ionic charge states of carbon, oxygen, and iron ions in He^+-rich solar energetic particle events for which the He^+/He^{++} ratio is greater than 0.3. The mean charge states of C, O, and Fe in these events are 6.0, 7.2, and 14, respectively. While the charge states of O and Fe are both consistent with an average coronal freezing-in temperature of $\sim 2.5 \times 10^6$ K, the presence of singly charged He indicates temperatures less than $\sim 8.5 \times 10^4$ K. The ionic charge states cannot be explained in terms of a model in which the coronal temperature determines a charge equilibrium which is subsequently frozen-in, nor can they be explained in terms of charge exchange during the passage through the outer corona after acceleration. It appears that either the acceleration and injection process is biased against particles with a high mass-to-charge ratio or that there exist pockets of low temperature plasma regions near the solar surface.

We also presented the first direct determination of the ionic charge state distributions of ^{3}He, ^{4}He, and Fe during ^{3}He-Fe-rich solar energetic particle events using the ULEZEQ sensor on ISEE-3. We found essentially all of the helium to be doubly ionized with $^3He^+/^3He^{++} < 0.02$ and $^4He^+/^4He^{++} < 0.03$. The mean charge state of Fe was 19 ± 2, which is significantly higher than the value found in solar energetic particle events with a normal composition. The high mean charge state of Fe suggests that high coronal temperatures are characteristic of the source plasma for ^{3}He-Fe-rich solar energetic particle events.

Cometary Physics

ICE Encounter with Comet Giacobini-Zinner. On 11 September 1985 the International Cometary Explorer spacecraft (formally named ISEE-3) traversed the tail of comet P/Giacobini-Zinner downstream of the nucleus at a closest-approach distance of 7800 km, thereby making the first in situ measurement at any comet. Using the UMD/MPE ULECA sensor on ICE, we have obtained conclusive evidence for the existence of energetic (~35 to 150 keV), singly charged heavy cometary ions within a distance of $\sim 1.5 \times 10^6$ km from the comet. These ions are most likely freshly ionized water molecules which have been "picked up" in the region upstream of the comet by the interplanetary electric $\vec{v}_{sw} \times \vec{B}$ field and the magnetic field frozen into the solar wind and then convected downstream to the spacecraft location.

The most direct evidence for establishing the mass of these ions was obtained from an analysis of the energy signals in one of the ULECA solid state detectors and is significant at the 3-sigma level. The analysis clearly indicates that the ions are singly charged and have a mass $\gtrsim 12$ amu. This mass identification is independently supported by analysis of particle directional

information. Transformation of the particle angular distributions observed at ~50,000 km from the comet during the inbound pass into a rest frame in which the distributions are nearly isotropic requires a transformation velocity which is consistent with the local solar wind velocity if one assumes that these particles are primarily singly ionized with a mass of 18 ± 6 amu. These results indicate that these ions are cometary ions principally from the water group (H_2O^+, O^+, H_3O^+, OH^+).

The existence of a frame of reference in which these water-group ions are isotropic implies that they have undergone strong pitch angle scattering, since their initial pitch angle distributions after ionization is highly anisotropic. Particle energies in the rest frame extend to substantially higher values than would be expected if these ions were locally accelerated or heated. Preliminary analysis indicates that the highest energy ions may have originated in the cometary upstream region (where the solar wind speed was higher by a factor of ~2 than at the observation location) and then accelerated adiabatically as they were convected downstream. Our derived ion density, ~0.1 cm^{-3} at 50,000 km, is consistent with a simple model for the production and transport of pickup ions. The variation of density with distance from the comet is also in reasonable agreement with this simple model.

Routine Data Processing

The University of Maryland Space Physics Group receives, on a regular basis, three types of ISEE data tapes from the IPD at GSFC: MCE tapes, data pool tapes; and telemetry data tapes (i.e., "decom tapes"). Since MPE/UMD has experiments on both the ISEE-1 and ISEE-3 satellites, there are actually two complete sets of tapes involved in the following procedures.

The MCE tapes are processed directly to obtain listings of satellite position and attitude parameters. Spacecraft positional information is especially important for interpreting ISEE-1 data, since the satellite follows a highly eccentric orbit that encompasses interplanetary space, the outer magnetosphere, the tail region, and the radiation belts. The routine processing of ISEE-3 MCE tapes was initiated after that spacecraft left the L1 halo orbit and began its excursion into the distant geomagnetotail and continued, for a time, with the flight of ICE/ISEE-3 to the comet Giacobini-Zinner.

The data pool tapes are routinely processed to obtain detailed listings of magnetic field, solar wind, and energetic particle data. Such information is extremely useful in correlative studies. As a further aid in interpreting our data, the magnetic field data from the ISEE-1 data pool tapes are routinely plotted and, for times the spacecraft is in projected interplanetary space, plots are also included of the calculated time-of-connection of the magnetic field with the bow shock.

The decom tapes received from IPD contain the complete telemetry data of the MPE/UMD experiments. In order to obtain an immediate and overall view of the available data, each decom tape is routinely processed upon receipt to obtain a file-by-file rate summary. A duplicate of each decom tape (as well as data pool and MCE tapes) is mailed to the experiments' co-investigators at the Max-Planck-Institut in Munich, West Germany. There the decoms are used to produce data summaries on microfiche and magnetic tape. The summary tapes produced by MPE are typically received by UMD ~10 months after real time. These tapes are sufficient for most types of analysis, although the original decom tapes are still required for fine temporal resolution. Selected ULECA rates are stripped from the ISEE-1 summary tapes in the generation of "super-

summary" tapes which are then used for the routine plotting of proton rates, Q > 3 ion rates, and He/H rate ratios.

The type of analysis performed on the ISEE tapes changes as different magnetospheric, solar, and interplanetary phenomena become the focus of interest. Therefore, the routine processing procedures and programs do not remain static, but continue to evolve along with the prevailing needs of the scientific staff.

Data Processing for Other Groups and the NSSDC

In addition to the exchange of data for collaborative studies, we make our data available (upon request) to other groups and individuals in the scientific community. In general these requests have involved non-routine data processing and analysis. We have also submitted ISEE data to several Coordinated Data Analysis Workshops.

Data has been submitted by our investigators at MPE, for our experiments, in a timely manner to the National Space Science Data Center, in accordance with "Guidelines for Submitting Data to the National Space Science Data Center".

Data Processing Tape Status

During the period of this contract the following numbers of tapes and microfilm were received from NASA/GSFC. The majority of the tapes received are still on site as processing and analysis continues on all data received to date. Some tapes have been returned to GSFC to clear contractual records.

	ISEE-1	ISEE-3
Decom	122 (thru 10/26/85)	85 (thru 10/19/85)
Data Pool	107 (thru 10/22/85)	53 (thru 10/26/85)
MCE	53 (thru 10/20/85)	0

Data Pool Microfilm	10 (thru 8/24/85)	9 (thru 9/14/85)

Tapes and microfiche from co-investigators at the Max-Planck-Institut in Garching, West Germany:

	ISEE-1	ISEE-3
Sum 1	9 (thru 9/22/84)	4 (thru 8/11/84)
Sum 2	8 (thru 9/22/84)	7 (thru 8/11/84)
Microfiche	97	45

Scientific Personnel

Researchers from the University of Maryland, Space Physics Group who participated in these studies include Dr. G. Gloeckler, Dr. F.M. Ipavich, Dr. A.B. Galvin, Dr. G.M. Mason and Dr. L.C. Tan.

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An ISEE-1/ISEE-3 chronological Bibliography is included in Appendix A.

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D. Colloquia, Seminars and Special Lectures

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E. Special Publications

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