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AN UPDATE ON THE ACTIVE MAGNETOSPHERIC PARTICLE TRACER EXPLORERS (AMPTE) PROGRAM

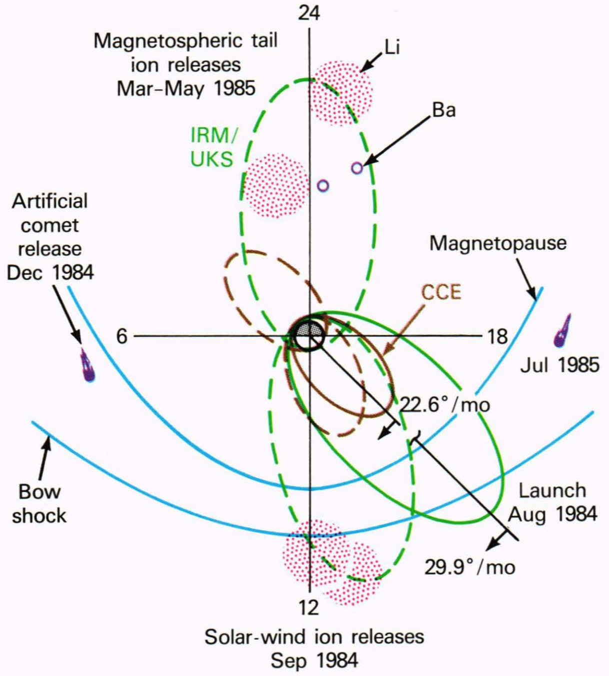
On August 16, 1984, the three spacecraft of the AMPTE mission were launched from Cape Canaveral into earth orbit atop a Delta rocket, culminating 13 years of planning and an intense three-year hardware effort. Each spacecraft was a complex, heavily instrumented, highly capable basic research tool, and each represented hundreds of man-years of effort. With the launch, a new phase of the program began, the large hardware teams moved on to other missions, and the AMPTE spacecraft began the mission in space for which they had been conceived. With both active experiments and a new and much more capable generation of instruments and data handling systems, AMPTE represents a significant advance in space plasma physics. The third anniversary of the launch seems a good time to reflect on the AMPTE mission and to review progress to date.

THE AMPTE MISSION

AMPTE stands for the Active Magnetospheric Particle Tracer Explorers program. It is a three-nation, three-spacecraft mission designed to study (a) the access of solar-wind plasma into the earth's magnetosphere (the volume of space around the earth dominated by the earth's magnetic field), (b) the transport and acceleration of plasmas inside the magnetosphere, and (c) the physics of the interaction between a cloud of cool, dense, artificially injected plasma and the hot, tenuous, magnetized, and rapidly flowing natural plasmas found in space. The three AMPTE spacecraft are the Ion Release Module (IRM), provided by the Federal Republic of Germany; the United Kingdom Subsatellite (UKS); and the Charge Composition Explorer (CCE), funded by NASA and designed and built by APL. Each carried extensive instrumentation from a number of scientific institutions to measure energetic particles (ions and electrons), magnetic fields, and electromagnetic waves in space. In addition, the IRM carried 16 ion-release canisters (eight filled with a barium-thermite mixture and eight with a lithium-thermite mixture) that could be released in pairs by command during the mission to create eight separate clouds of artificially injected ions, four each of barium ions and lithium ions. Previous *Technical Digest* articles have given a prelaunch overview of the mission[1] and accounts of the CCE preparation, the launch, and the first few months of the mission.[2,3] A special issue of *IEEE Transactions on Geoscience and Remote Sensing* describes each spacecraft, all flight instrumentation, and other aspects of the mission.[4]

There were two phases of the AMPTE mission: passive observations of the natural space environment by means of the spacecraft instruments, and active experiments that artificially injected ion clouds into space to create controlled perturbations observable locally from the spacecraft and remotely from the ground. The active experiments were a new and exciting technique: each would form an artificial, short-lived "comet" in space, and at the same time would inject ions rare in the natural environment that could be used as tracers of natural flows and acceleration processes. The passive observations were eagerly anticipated for several reasons. The IRM and the CCE contained a new generation of instruments, capable for the first time of measuring the elemental composition and ionic charge of the major energetic particle populations in space around the earth. The IRM and UKS spacecraft were designed to fly in close formation and make correlated measurements at known distances from each other. Their orbits covered the major outer magnetospheric regions and extended through the boundary of the earth's magnetic field (the "magnetopause") into interplanetary space and the hot, tenuous ionized gas flowing rapidly outward from the sun—the "solar wind." The CCE orbit covered the equatorial magnetosphere, including important regions poorly sampled by previous spacecraft, and carried instrumentation that could resolve long-standing questions about the composition and sources of the energetic magnetospheric particle populations.

The AMPTE mission profile and ion releases are schematically summarized in Fig. 1. The IRM was injected into an elliptical orbit with apogee of 18.7 R_E (earth radii from the center of the earth; one R_E is 6371 km) and an inclination of 28° from the equator. The UKS was injected into the identical orbit and used thrusters and an active ranging system to fly in close formation with the



	CCE	IRM	UKS
Apogee (R_E)	8.8	18.7	18.7
Period (h)	15.6	44.3	44.3
Inclination	<5°	28.8	28.8
Mass (kg)	242	705	77
Releases	–	8	–

Figure 1—Orbit configuration of the CCE and IRM/UKS at launch (solid lines) and near the times of solar-wind and magnetotail ion releases (dashed lines). After launch, the orbits precessed in the earth-sun frame as shown, allowing two separate lithium releases in the solar wind upstream from the bow shock. Three months later the orbits had precessed further, and the next release created an artificial barium-ion comet in the solar wind on the dawn flank. (The release location would normally be inside the bow shock, just beyond the magnetopause, as shown. At the time of the release, however, the solar-wind pressure was unusually high, and the bow shock was compressed earthward of the release.). Two barium and two lithium releases were carried out as the IRM precessed through the magnetotail; the final release was another barium ion comet in the dusk magnetosheath. The release markers are different sizes to indicate the much larger volume over which the expanding lithium atoms are photoionized.

IRM (tens to hundreds of kilometers apart). The CCE orbit is near-equatorial, with apogee of 8.8 R_E geocentric and perigee of 1100 km altitude. In addition to detailed studies of the natural environment, all eight active chemical-release experiments were carried out within the first year of the AMPTE mission.

ION RELEASES

As shown in Fig. 1, the apogees of all three spacecraft were in the early afternoon at launch. The orbital precession in the earth-sun frame is westward; about a month after launch, the IRM apogee was in the solar wind in front of the magnetosphere, directly between the earth and the sun. There, on September 11 and again on September 20, lithium releases from the IRM were commanded. For each release, $\sim 2 \times 10^{25}$ lithium atoms were vaporized from thermite canisters. Those atoms expanded away from the point of release at ~3 km/s and were photoionized with a time constant of about one hour, so that the ions were created over a volume of space greater than 3 R_E in diameter. The IRM and UKS, at the center of the expanding ball, detected major perturbations from each release. In each case the dense center portion of the ion cloud was conductive enough to create a diamagnetic cavity ~60 km in diameter within which the magnetic field strength essentially dropped to zero as the solar-wind magnetic field was temporarily excluded. The dense plasma cloud slowed and diverted the solar-wind flow,[5] producing strong plasma-wave activity.[6] As lithium ions were created outside of, or escaped from, the central region, they were accelerated by the convection electric field of the solar wind, and the energized ions were seen at the UKS and IRM.[7] All the ions were ultimately swept away from the point of release toward the magnetosphere, thus loading and marking that portion of the solar wind with lithium "tracer" ions. Inside the magnetosphere, the CCE particle instruments were in special modes searching for the impact of lithium ions, but unfortunately none were detected and only an upper limit could be placed on ion access from the solar wind to the CCE orbit.[8]

A unique aspect of the AMPTE release experiments is that they were real-time operations. Each spacecraft had its own Science Data Center (SDC), with dedicated computer facilities for data processing and display; centers were in England, in West Germany, and at APL. Each spacecraft's data were piped to its own SDC, where, during each release, the science teams assembled. Data on the interplanetary and magnetospheric environment from the three AMPTE spacecraft, from geosynchronous satellites, and from high-latitude surface magnetometer stations were displayed in real time and exchanged across the Atlantic. NASA, NOAA, DoD, and European spacecraft, receiving antennas, communication networks, and ground stations combined with large international scientific teams to carry out the release operations.

Released lithium atoms expand rapidly and photoionize slowly to inject ions over a huge volume of space. Vaporized barium atoms, on the other hand, expand more slowly (~1 km/s) and are photoionized much more quickly (~30 s) to form a very dense barium plasma cloud over a small region of space. These ions (unlike lithium ions) resonantly scatter sunlight in visible wavelengths (455.4 nm), so a sunlit release in deep space can be photographed by observers from the nightside of the earth. The third AMPTE active experiment, on December 27, 1984, injected $\sim 7 \times 10^{24}$ barium ions into the solar wind on the dusk flank of the magnetosphere. The experiment's goal was to simulate aspects of the interaction between the solar wind and a natural comet while having both remote optical observations and, for the first time, good in-situ (IRM and UKS) measurements of the interaction. This experiment and another similar artificial comet release on the opposite flank of the magnetosphere on July 18, 1985, were quite successful. The release created a barium ion cloud, or "coma," more than 500 km across, containing a core diamagnetic cavity ~ 100 km in diameter. Ions extracted from the core and coma formed a tail over 4000 km long in the antisunward direction (Fig. 2).

The most important aspect of the behavior of the artificial comets, however, may be that they differed significantly from predictions. The comet head and tail were expected to be visible to sensitive cameras for up to 30 min, but ions were extracted so rapidly that the comet lasted only 5 min—and in that time the comet head moved *sideways,* not antisunward (downwind). The comet releases have been discussed in detail in a special issue of *Nature*[9] and at several international meetings, including a recent conference at APL.[10] We have gained much theoretical insight into the complex and unexpected processes found to be operating, and into their applicability to real comets.

As the apogee of the IRM precessed through the antisunward tail of the magnetosphere, releases of barium (March 21 and May 13, 1985) and lithium (April 11 and 23, 1985) were commanded (Fig. 1). These releases inside the magnetosphere were designed to study both local interactions and the transport of the injected tracer ions toward the earth. The best model calculations indicated that some of the injected ions would be seen at the CCE,[11] but none were clearly detected. This was a surprise that seems to call into question the applicability of the available simplified steady-state models to the very dynamic magnetospheric environment. The local observations of all four releases with the IRM instrumentation again showed strong diamagnetic cavities and major perturbation of the local environment. (Unfortunately, because of on-board failure, contact with the UKS was permanently lost on January 16, 1985—before the magnetotail releases—so that only IRM measurements were available). Ion clouds injected into the slower plasma flows inside the magnetosphere lasted much longer than those outside the magnetopause. For example, ground and aircraft observations tracked the evolution of each magnetotail barium ion cloud for over 30 min.

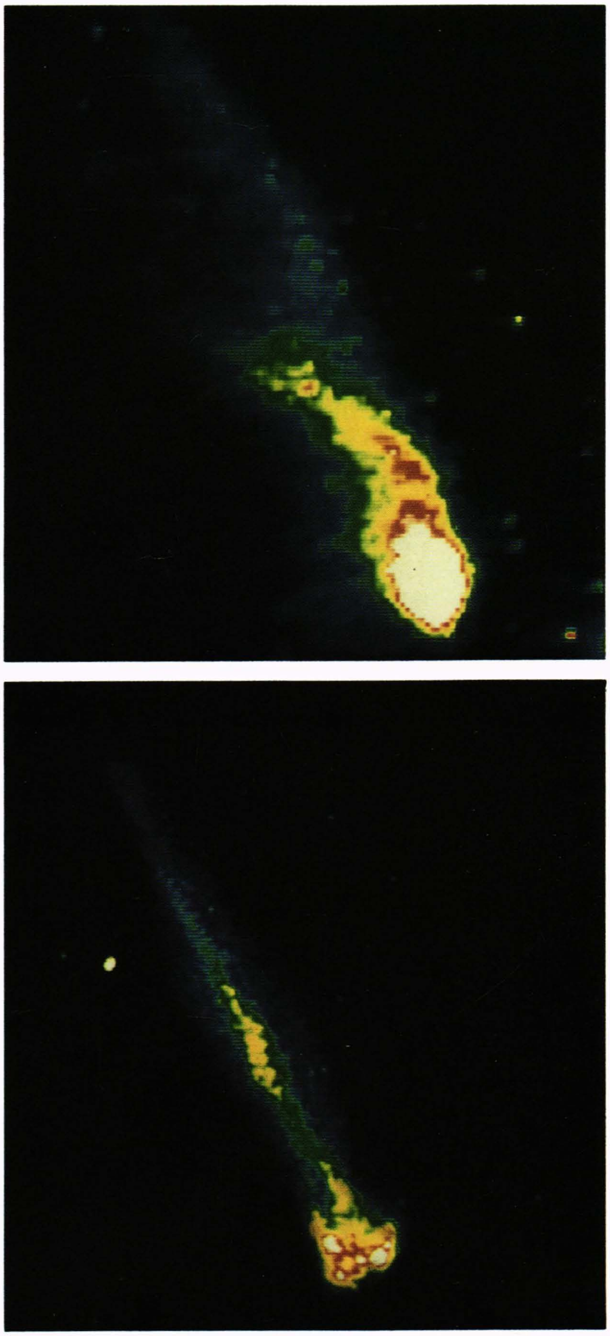
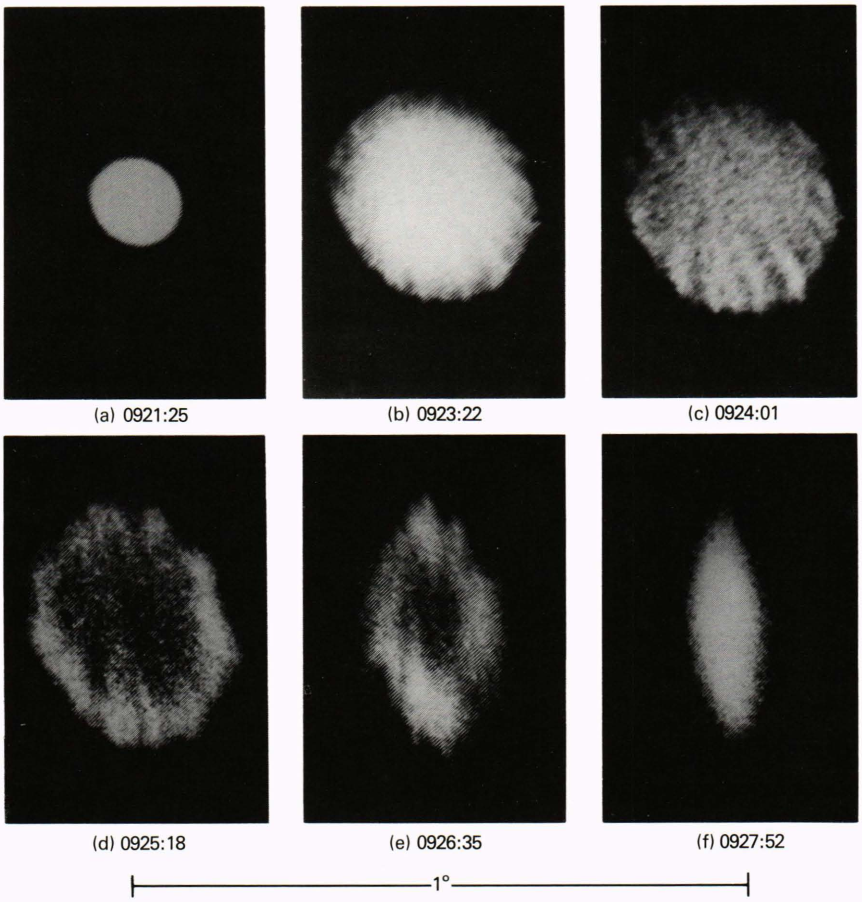


Figure 2—AMPTE barium releases in the solar wind (top) off the dawn flank of the magnetosphere (December 27, 1984) and (bottom) in the dusk magnetosheath (July 18, 1985) each created an artificial comet in deep space (103,000-km altitude). The released barium atoms rapidly photoionized to form a dense ion cloud, hundreds of kilometers across, which served as an obstacle to the solar wind flow. Currents flowing on the surface of the barium-ion cloud countered the solar-wind magnetic field and created a diamagnetic cavity (a zero-field region) within the cloud, while ions extracted from the cavity were swept "downwind"to form an ion comet tail. These false-color images of the comets were taken with a low-light-level television system aboard an Argentine Boeing 707 airborne observatory.[9]

Figure 3 shows the expansion and collapse of the magnetic cavity of the March 21 magnetotail barium release.[12] The release took place at 0920:38 UT, at a geocentric distance of 12 R_E in the equatorial plane near local midnight. The release cloud expanded radially at ~ 1.3 km/s and reached a maximum diameter $\gtrsim 420$ km about 3 min after the release, when the external magnetic pressure on the cavity's surface balanced the pressure of the expanding ions. The cloud then evolved into a hollow spherical shell of barium ions that developed instability-driven periodic surface irregularities[12] (most apparent in Fig. 3c). After that phase, the ion content of the shell declined as barium ions escaped, and the shell collapsed under the external magnetic pressure, forming an elongated structure (Figs. 3e and 3f) that was observed convecting in the magnetotail until about 1000 UT. Tracking the convection drift of the ion clouds gives an indication of the ambient electric fields in the magnetotail and suggests possible future active-release experi-



(a) 0921:25

(b) 0923:22

(c) 0924:01

(d) 0925:18

(e) 0926:35

(f) 0927:52

Figure 3—A sequence of 2-s exposures at 455.4 nm of the barium release at 12 R_E in the magnetotail on March 21, 1985 (0920:38 UT), from an intensified CCD camera at White Sands, N.M.[12] At that distance, 1° is about 1250 km. The expanding barium ions create a diamagnetic cavity with no internal magnetic field. The ions form a hollow shell that develops surface instabilities, and then, as the barium ion density decreases, collapses under the external magnetic pressure.

ments.[13] In addition, studies of the physical mechanisms that acted to extract ions from the release cavities have advanced our understanding of the theory and simulation of complex plasma interactions, including plasma instabilities and cometary ion-tail formation.[10]

STUDIES OF THE NATURAL ENVIRONMENT

The basic goal of the AMPTE mission was to study the origin of the energetic ions in the Van Allen radiation belts—that is, the access of solar-wind (and ionospheric) plasma to the magnetosphere, and the transport, acceleration, and loss of those particles inside the magnetosphere. The active-release experiments represent the newest and most visible approach to this goal; but to physicists, studies of the radiation belts with the new generation of instruments on the CCE and IRM were at least as promising and important.

The radiation belts around the earth were the first discovery of the space age, and we now believe that they are common in nature: among the planets we have visited in the solar system, every one that has a significant internal magnetic field (Earth, Jupiter, Saturn, and Uranus) is surrounded by intense fluxes of energetic particles. Much is now known about the earth's radiation belts and some of the processes that accelerate particles to high energies in space, but many questions remain. Before AMPTE, the elemental composition and the charge state of the radiation belt were very important unkowns. Only at low energies (below ~ 20 keV) and at very high energies (hundreds of thousands to many millions of electron-volts), had measurements been made, and they gave quite different answers. At the lower energies, the ion composition and charge state (significant percentages of singly charged helium and oxygen, almost no carbon) indicated an ionospheric source. (Ionospheric plasma is at a low charge state ($+1$ or $+2$). The solar wind plasma originated in the much hotter solar corona, and these ions are almost fully stripped of electrons (e.g., O^{+6} or O^{+7}).) At the high energies ($\gtrsim 2$ MeV), no charge-state measurements had been made, but the composition (carbon to oxygen ratio of ~ 0.5, for example) pointed to a solar wind source. Both the ionospheric plasma and the solar wind plasma were thus possible ultimate sources of the particles in the earth's radiation belts, and composition measurements were key to determining the relative importance of the two sources. In particular, a major problem in magnetospheric physics has been to determine the source and composition of the energetic particles that envelop the earth during geomagnetic storms. Each of these events, frequently triggered by solar activity, suddenly releases $\sim 10^{15}$ J of energy stored in the earth's magnetosphere, creating large new fluxes of particles trapped in the magnetosphere, with energies of 20 to ~ 500 keV, in a doughnut-shaped ring around the earth at altitudes ranging from about 2 to 5 R_E above the surface. The current associated with these particles measurably changes the surface magnetic field of the earth, and energy lost from currents and precipitating particles heats the upper atmosphere. Before AMPTE, many papers in the scientific literature had speculated on the sources and composition of these ions (hydrogen, helium, or oxygen were suggested). With existing instruments we could watch the particle fluxes appear and then decay with a time scale of hours and days, but we could not tell what types of ions they were and could only guess at their source.

AMPTE, however, used a new generation of particle sensors that measured a particle's time of flight (in the range of 2 to 300 × 10^{-9} s) between a very thin front foil (~ 30 to 160 nm thick, only a fraction of the wavelength of visible light) and a rear detector that measured total energy.[14-16] Since both the energy and the velocity of each ion were measured, thus determining the mass of all ions energetic enough to penetrate the very thin front foil, it became possible for the first time to make complete composition measurements in space. In some sensors the front foil was preceded by an electrostatic analyzer that preselected ions of a specific energy per charge (i.e., if set at 10 keV per charge, the analyzer would pass singly charged ions of ~ 10 keV energy, doubly charged ions of ~ 20 keV total energy, etc.). This enabled the sensor to determine simultaneously the energy, mass, and charge state of each incident ion. (For further discussion of the time-of-flight technique, see the *Johns Hopkins APL Technical Digest,* Vol. 6, No. 1 (1985).)

The promise of the new sensors was fulfilled almost immediately after launch. An intense magnetic storm occurred on September 4, 1984, and the ring current formed was monitored by the sensors on the CCE. A resulting series of coordinated papers by the CCE investigators, published in a special issue of *Geophysical Research Letters* (May 1985), settled, at least for that one storm, the decades-old question of particle composition. As shown in Fig. 4, hydrogen was the dominant ion, both prestorm and during the storm-time ring-current maximum. But the flux and energy density of singly charged oxygen (O^+) increased by factors of 1000 and more, so that O^+ became the second most important ion during the storm. That would indicate that a significant part of the plasma energized during a storm is of ionospheric origin. The study has now been extended to 20 storms, with similar results.[17] Hydrogen is the dominant ion injected during a geomagnetic storm, with 83% of the energy density. O^+ is next (12%), followed by N^+ (2%) and lesser ions (He^+, He^{++}, O^{++}). The hydrogen (H^+) probably comes from a combination of the solar wind and ionospheric sources, but the O^+ and N^+ are strong ionospheric indicators.

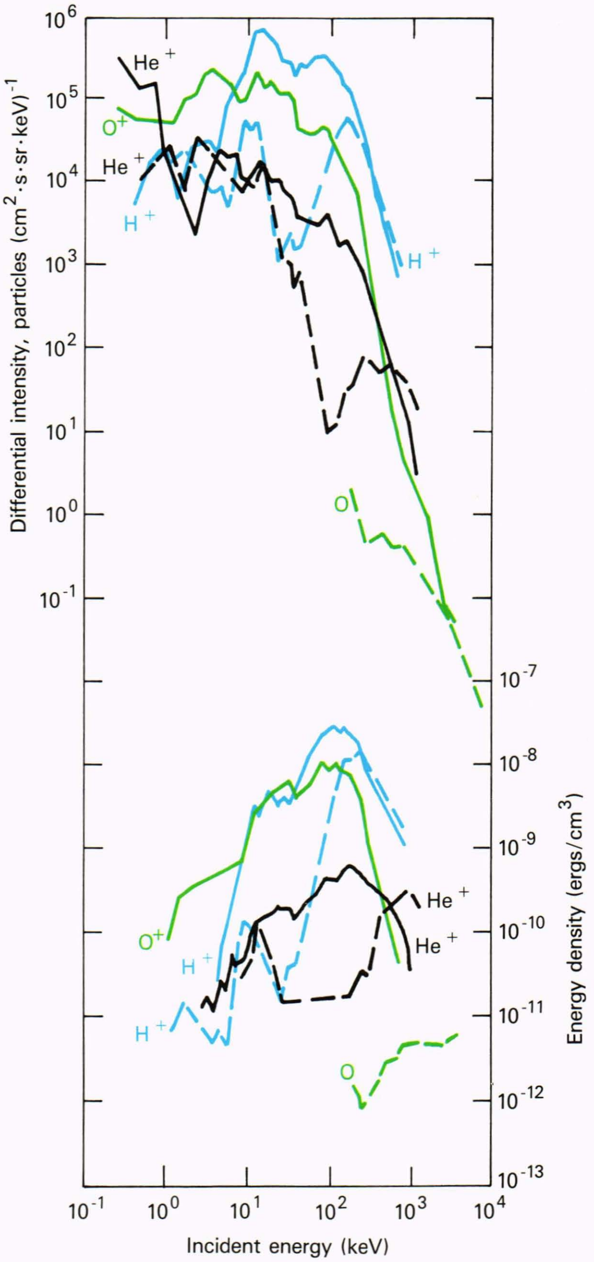


Figure 4—Differential energy spectra and energy densities for hydrogen (H^+), helium (He^+), and oxygen (O^+) ions at an equatorial geocentric distance of ~ 4 R_E, before (September 3, dashed lines) and during (September 5, solid lines) the peak of the geomagnetic storm of September 4-7, 1984. Oxygen intensities are the most enhanced of all species, but protons continue to dominate the storm-time fluxes.

More general studies of nonstorm-time magnetospheric energetic particle composition show that the solar wind and the ionospheric sources are about equally important.[18,19] Figure 5 is an example of composition seen on the CCE spacecraft with the University of Maryland/Max Planck Institute Charge Energy Mass Spectrometer (CHEM) experiment. Over a radial distance of about 5 to 9 R_E in the magnetotail, both high-charge-state oxygen and high-charge-state carbon (solar wind source) and O^+ and N^+ (ionospheric source) are clearly present. The intermediate charge states (O^{+2}, O^{+3}, N^{+2}, N^{+3},

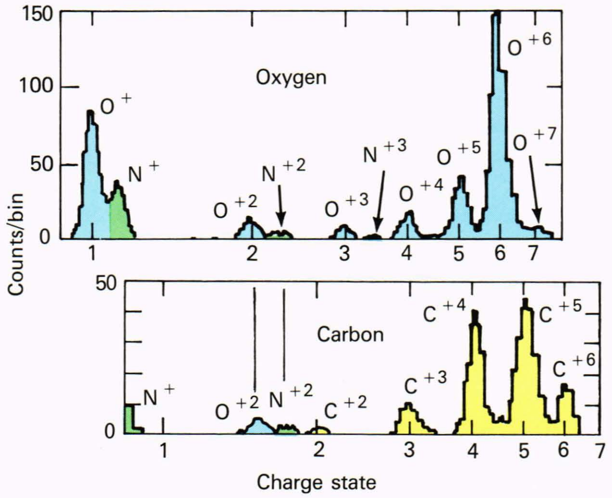


Figure 5—Data from the CCE CHEM instrument for a pass through the outer magnetosphere (radial distances of ~5 to 9 R_E, local time of 3 to 4 hours; February 28, 1985, 1020–2150 UT). The figure shows charge-state distributions for carbon, nitrogen, and oxygen ions in the ring-current and plasma-sheet particle populations over an energy range of 1.5 to 315 keV per charge. The relative abundances have not been corrected for sensor efficiency; the low charge states are more abundant than shown. (G. Gloeckler, private communication.)

C^{+2}, etc.) are created within the magnetosphere by charge exchange during collisions with local neutral hydrogen atoms. Note that carbon is common in the solar wind but very rare in the ionosphere, and only high charge states of carbon are seen (no C^+), whereas nitrogen is common in the ionosphere but rare in the solar wind, and only low charge states of nitrogen are seen. Thus, ions from both sources are present, intermixed, and accelerated to magnetospheric energies.

The composition of magnetospheric particles at higher energies presented CCE researchers with another major surprise. Figure 6, using data from the APL Medium Energy Particle Analyzer (MEPA) instrument, shows particle spectra for all major species in a representative pass through the outer magnetosphere. At energies up to several hundred thousand electronvolts, hydrogen ions dominate, as would be expected; hydrogen is by far the most abundant ion in the solar wind, in the outer ionosphere, and in the cosmos in general. At higher energies, however, a mixture of heavier elements becomes increasingly important; first helium, then oxygen, and finally, at energies above ~1 to 2 MeV, silicon and iron become the dominant elements in outer magnetospheric particle spectra.[20] Not only was this finding unexpected, but before the AMPTE/CCE there had been only fragmentary evidence of energetic magnetospheric ions heavier than oxygen, and iron had never been identified at all. These heavy ions undoubtedly originate in the solar wind, but are accelerated to millions of electronvolts of energy inside the magnetosphere.

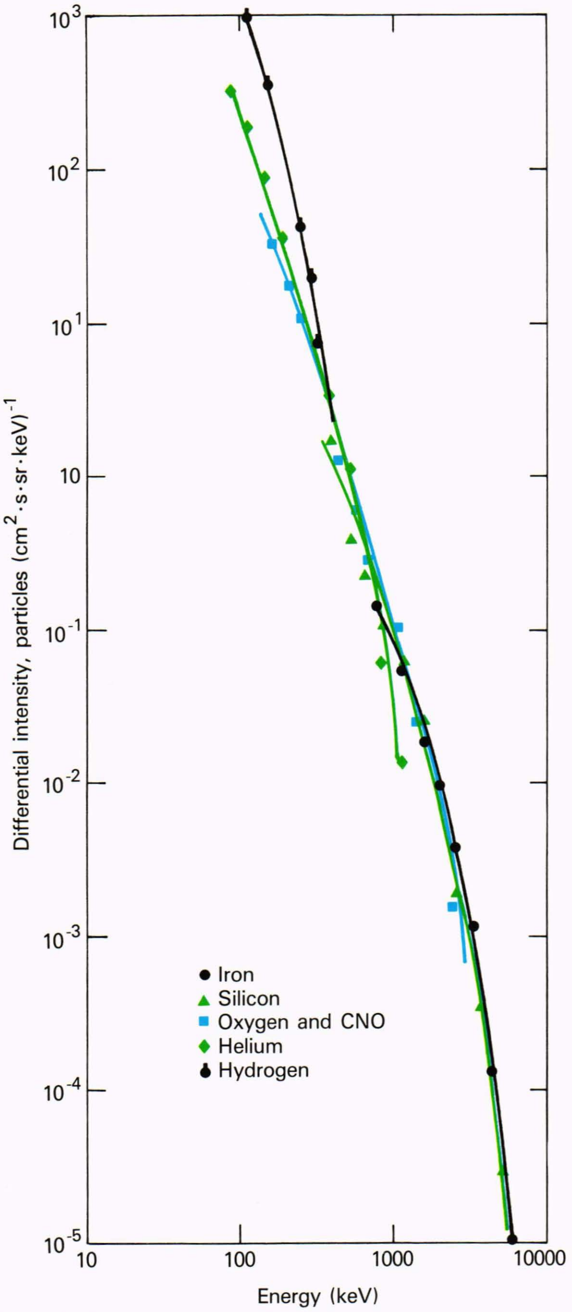


Figure 6—Ion species spectra in the outer magnetosphere (8 to 9 R_E) from the MEPA instrument on the CCE. Much closer to the earth, protons dominate the energetic trapped particle fluxes. It is thus surprising that in the outer magnetosphere spectra tend to be similar, with heavy ions dominating at the higher energies. (Data from September 25, 1984, 1515–2143 UT.)

I have touched here on CCE studies of the composition and origin of magnetospheric particles, but I could equally well have discussed any of a wide range of other topics that the AMPTE scientific team has reviewed in more than 200 presentations at scientific meetings and 150 publications. A short list of some of the other major discoveries and studies by AMPTE would include the discovery of energetic molecular ions (e.g., NO^+) in the magnetosphere;[21] the first determination of the solar-wind carbon abundance; accurate measurements of the solar-wind ion charge states (thus defining the temperature in the solar corona at which those charge states were "frozen-in");[22] observations of helium atoms of interstellar origin (not from the solar wind, but from beyond the solar system);[23] measurements of the radial profile of current distributions in the storm-time ring current;[24] and a wide range of studies on such topics as magnetospheric substorms, ion angular distributions, ion transport and loss, and electromagnetic waves in the magnetosphere. The uniqueness of the AMPTE measurements is worth stressing: the data shown in Figs. 4, 5, and 6, and those used in most of the studies mentioned above could not have been obtained with the instruments on any previous spacecraft. In the years preceding the AMPTE launch, many space scientists had come to feel that the energetic particle fluxes in the magnetosphere reflected a complex interplay of different source populations and acceleration, transport, and loss processes, and that measurements of ion composition and charge state were the key to further progress. AMPTE has fulfilled that expectation.

CODA

The original concept of the three-spacecraft, three-nation AMPTE mission[1] involved a separate Science Data Center in each nation, where the data from each respective spacecraft would be reduced to readily analyzable form (e.g., scientific units, plots) for the scientists to use. As mentioned earlier, that concept was fully carried out and has resulted in major contributions to the scientific productivity of AMPTE. The CCE SDC[25] is built around a dedicated VAX 11/785 computer at APL; since launch, it has been *the* essential interface between every scientist and engineer and the spacecraft. In addition to the monitoring at the CCE Control Center at the Jet Propulsion Laboratory, the SDC at APL has actively monitored spacecraft and instrument health in over 1000 real-time passes. At the SDC, all the CCE data are processed and stored (almost 100 gigabytes to date), more than 330,000 color data slides have been generated summarizing each instrument's data from each orbit, and all the scientific computing for all of the CCE science team is carried out. The SDC allows every CCE scientist to access quickly and use all the mission data from launch to date. The CCE SDC is unique in this capability, and it serves as a standard for future missions. Translation of the attractive concept of a central science data facility into the present highly productive working center is another AMPTE promise realized.

AMPTE has been one of those fortunate undertakings in which most of the early hopes *were* realized. The mission's cost was not high—in each nation the effort was sufficiently focused to be done by a small, dedicated team with high user involvement—but each spacecraft has been capable and innovative enough to make very significant contributions to space science. In the combination of its elements, the mission has yielded and continues to yield an extremely high scientific return. Two years into the mission (on August 13, 1986) the batteries on the IRM failed and contact with that spacecraft was lost. The CCE is now entering its fourth year of operation with all spacecraft systems and most experiments fully operational (a portion of one particle sensor has failed and another has experienced a gain shift); we hope it will have many more years of life. The data set for each spacecraft is now a permanent resource for the scientific community; the analytical effort on those data is at a peak and will continue for years to come.

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