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SPACE PLASMA PHYSICS AT THE APPLIED PHYSICS LABORATORY OVER THE PAST HALF–CENTURY

Exploration of our planet's space plasma environment began with the use of ground-based radio propagation experiments and with instruments carried to high altitudes by balloons and rockets. The Applied Physics Laboratory was intimately involved in these pioneering activities through the work of its first director, Merle A. Tuve, and one of its first staff members, James A. Van Allen. During the past half-century, the Laboratory's space plasma physics activities have evolved into a major and multifaceted effort involving the observation and study of phenomena from the Earth's atmosphere to the Sun and beyond to the outer planets and heliosphere. Space plasma physics has become a mature scientific discipline that now more than ever provides many challenges and promises of exciting discoveries for APL scientists in the future.

INTRODUCTION

Plasma physics is the study of the collective interactions of electrically charged particles with one another and with electric and magnetic fields. It has been estimated that 99% of the mass of the Universe exists as a plasma,[1] and the realization that plasma is the fourth physical state of matter is regarded as a major achievement of twentieth-century physics.[2] The Earth's environment is composed of complex plasmas, including the ionized layers of the atmosphere (the ionosphere) and the comet-like shape of the geomagnetic field (the magnetosphere), distorted by the continuous flow of plasma from the Sun (the solar wind).

The traditions of space plasma physics at the Applied Physics Laboratory are rooted in the background of its first director, Merle A. Tuve, who with Gregory Breit conducted radio reflection experiments from the Earth's ionosphere in the early 1920s.[3] They demonstrated the existence of the ionosphere and provided the "true beginnings of radar."[4] Merle Tuve helped to establish APL in 1942 and became its first director.

In 1945 James Van Allen was anxious to return to civilian employment at APL after serving as an ordnance and gunnery officer in the U.S. Navy since November 1942. He had worked at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington, helping to develop rugged vacuum tubes and photoelectric and radio proximity fuses for gun-fired projectiles. He was transferred to APL at the time of its creation. Van Allen had acquired an interest in cosmic-ray research from Scott Forbush at DTM and, with Tuve's support, organized a high-altitude research group at APL. This group developed experiments to be carried to high altitudes by V-2 rockets.[5] In a series of rocket flights beginning in 1946, Van Allen used Geiger counter telescopes to measure the total intensity of cosmic rays at altitudes of 161 km.[6,7] Figure 1 shows the altitude plot of the observed counting rate of a single Geiger counter flown on a V-2 rocket in July 1947.[8] It demonstrated for the first time the cosmic ray ceiling of the atmosphere, the altitude above which there is no appreciable effect of the atmosphere on the primary radiation. John J. Hopfield and Van Allen used a quartz spectrograph on an APL Aerobee rocket to measure the altitude profile of ozone at altitudes up to 60 km.[9] Hopfield and his colleagues measured the solar ultraviolet (UV) spectrum down to a 230-nm wavelength with a grating spectrograph flown on V-2 rockets at heights up to 155 km. Consequently, investigations in ionospheric, cosmic, atmospheric, and solar physics date back to the Laboratory's beginnings.

The excitement and inspiration associated with these early rocket investigations into space are apparent in Van Allen's narrative, published in the *Johns Hopkins APL Technical Digest* in 1983.[5]

> The small cadre of investigators was motivated by the exploratory nature of the opportunities and by the great freedom and flexibility of the circumstances, notably free of long-range planning, detailed accountability, and other bureaucratic constraints. It was a period in which the wartime spirit—that most individuals are honorable and that results are what count—carried over into peacetime pursuits. From the perspective of 1983 one may deplore the passing of such an epoch. Those of us who survived this early period of high-altitude rocket investigations were, with few exceptions, the ones who conceived and built the first instruments for satellite flight. Without this preparatory period we would have been ill prepared to conduct investigations with satellites.

Explorer I, the first satellite successfully launched by the United States on 31 January 1958, carried a radiation detector supplied by Van Allen (who had since moved from APL to the University of Iowa). At first this instrument seemed to malfunction, but Van Allen and colleagues discovered that regions of energetic particles were trapped in the Earth's magnetic field with fluxes so intense as to saturate their instrument (Fig. 2). This dis-

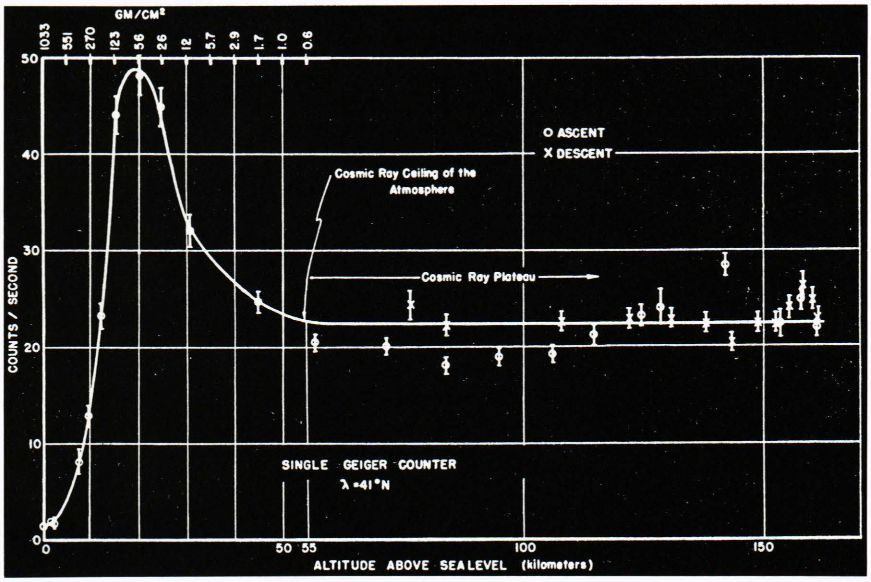

Figure 1. The counting rate of a single Geiger counter as a function of altitude from a V-2 rocket flight by Van Allen in July 1947. The first determination of the cosmic ray ceiling, at 55 km, resulted from this experiment. (Reprinted, with permission, from Ref. 8.)

covery revolutionized our view of the Earth's environment above rocket altitudes (about 200 km). Space was found to be occupied by complex plasmas that could have serious effects on instruments and humans.

The Applied Physics Laboratory intensified its space activities following the invention of the Doppler navigation technique in 1957 by Bill Guier and George Weiffenbach (Space Department Head between 1978 and 1985). In a letter to Milton S. Eisenhower, President of The Johns Hopkins University, dated 1 April 1958, R. E. Gibson, Director of the Applied Physics Laboratory, proposed the Doppler technique of using satellites for navigation purposes with the comment that "it appears that the simplicity of our scheme is unique."[10] Significant advances in space technology were made rapidly in these early Transit satellite years (see the article by Hoffman in this issue). The periods between satellite launches were measured in months instead of years or decades as they are now; and the realization that the space environment can have devastating effects on satellites inspired an active effort to study and understand plasmas and magnetic fields in space.

A small group was established within the newly formed Space Department to conduct studies of the space environment. George F. Pieper joined APL in September 1960 to head this new group, which included Carl O. Bostrom, who came at the same time. Donald J. Williams joined the group just a year later. Richard W. McEntire worked in this group as a summer student in 1962 and returned to APL in 1972 after receiving his Ph.D. in physics from the University of Minnesota. Bostrom later became supervisor of the Space Physics Group, then head of the Space Department, and ultimately Director, in 1980. S. M. (Tom) Krimigis succeeded Carl Bostrom as supervisor of this group in the 1970s and became head of the Space Department in 1991. Don Williams went on to be the Chairman of the Research Center in 1990. During the 1980s, when I became the group supervisor after Tom Krimigis, three new groups were created from

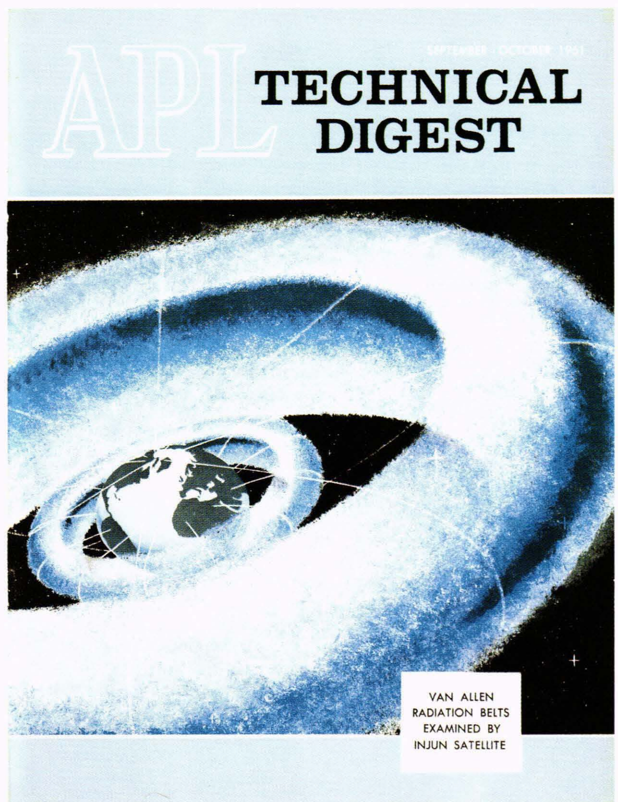

Figure 2. One of the first discoveries of the space age was featured on the cover of the September–October 1961 the *APL Technical Digest* : great radiation belts that surround the Earth, named after their discoverer, James A. Van Allen. The radiation belts were studied by APL scientists with the University of Iowa Injun satellite, launched piggyback with the APL-developed Transit 4A satellite.

the Space Physics Group. The Space Instrumentation Group, presently headed by Robert E. Gold, was formed in 1982 to develop advanced particle and optical instruments. The Geospace Remote Sensing Group was formed in 1988, originally headed by Ching–I. Meng, now supervisor of the Space Science Branch, and succeeded by Raymond A. Greenwald. This group conducts research of the upper atmosphere and ionosphere with optical, UV, and radar remote sensing techniques. The Computing and Networking Systems Group, led by Lora L. Suther, was organized from the Space Physics Group in 1991 to guide and operate the complex computing and display systems needed for space missions. From relatively modest beginnings during the early years of this Laboratory, the activities associated with the exploration and understanding of the plasma environment of the Earth and the solar system have evolved into a major and multifaceted effort at the Laboratory.

The purpose of this article is to describe some of the past, present, and future APL space physics activities and accomplishments, including the work on solar and magnetosphere particles and on the geomagnetic field using Transit satellites (especially 5E-1) and Triad, which operated for a solar cycle (11 years) and led to more than 100 scientific articles in distinguished journals. The APL particle instruments on the NASA Interplanetary Monitoring Platform IMP-7 and IMP-8 satellites (launched in 1972 and 1973, respectively) are still working today, after nearly two decades in space, producing significant advances in the understanding of the long-term behavior of solar plasmas. The APL Magsat satellite measured the geomagnetic field with unsurpassed accuracy (Fig. 3). Voyagers 1 and 2 carried APL particle experiments past all the major outer planets, and the Active Magnetospheric Particle Tracer Experiment (AMPTE) constellation of satellites produced an artificial comet in space and conducted particle and magnetic field measurements above the Earth's equator that had never been made before. The scientific articles resulting from these projects presently exceed a thousand. Recent investigations include imaging of the Earth's aurora from the Hilat and Polar Beacon Explorer and Auroral Research (Polar BEAR) satellites, which were restored from old Transit satellites (Polar BEAR was built from a Transit satellite "recovered" from the Smithsonian Institution's Air and Space Museum). The Tuve tradition of ground-based radio studies of the ionosphere is under way at APL, with networks of coherent radar systems in the north and south polar regions that are investigating complicated plasma characteristics in the auroral regions. The Laboratory has had its own solar observatory for many years, which has been investigating techniques for the high-resolution measurement of magnetic fields on the Sun's surface. Future areas of space research activity at APL include high-resolution magnetic-field measurements from the recently launched NASA Upper Atmosphere Research Satellite (UARS) and from the Swedish Freja satellite to be launched from China next year. Particle instruments are on their way to Jupiter on the Galileo spacecraft and over the Sun's pole on the Ulysses spacecraft. Techniques are being developed to "view" the plasma environment of the Earth (including the Van Allen belts) from space at special UV lines and with energetic neutral atoms.

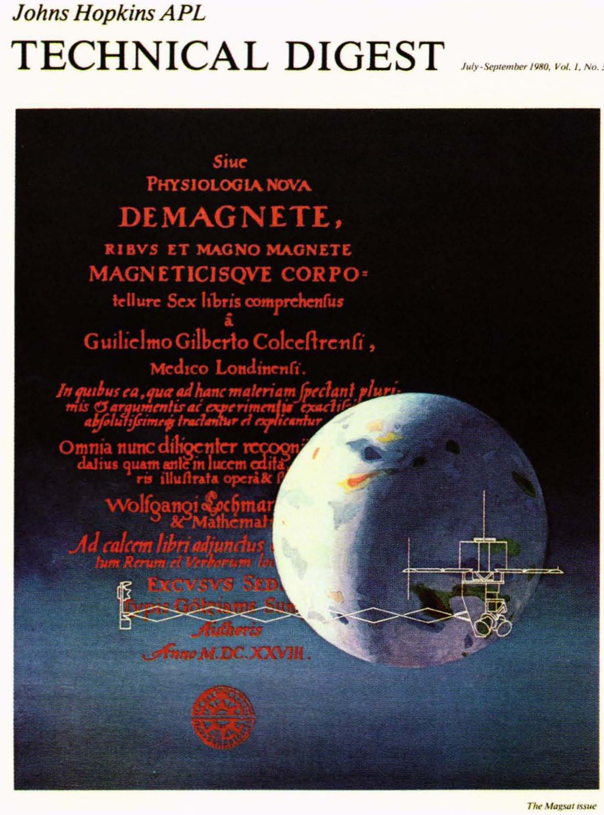

Figure 3. The cover of the July–September 1980 issue of the *Johns Hopkins APL Technical Digest* showed a line drawing of Magsat in the foreground and the Earth in the background, with the magnetic anomalies measured by Magsat and earlier satellite vehicles. This is silhouetted against the frontispiece of William Gilbert's seminal treatise on geomagnetism (*De Magnete*, second edition, 1628).

This article briefly describes the exciting space research activities that have been conducted over virtually the entire half-century history of the Laboratory. The Applied Physics Laboratory and the people responsible for its establishment and development have contributed to the most fundamental advances of space physics, ranging from the Earth's ionosphere, atmosphere, and magnetosphere, to the Sun, and out through the interplanetary medium.

THE TRANSIT DAYS

The program of research in particles and fields in space now under way began as part of the Transit navigation satellite program. In September 1960, George F. Pieper and Carl O. Bostrom joined APL to measure and study the radiation environment of the Transit satellites. Through collaboration with James A. Van Allen of the University of Iowa, arrangements were made to launch a research satellite, called the Injun 1, piggyback with the Transit 4A satellite. The Injun 1 satellite, built by the University of Iowa, included a set of solid-state proton detectors from APL, the first such detectors ever flown in space. These detectors made the first direct measurements of low-energy solar protons in the polar regions and contributed significantly to our understanding of the inner Van Allen radiation belt. The first article in the first issue of the *APL Technical Digest* (Fig. 2 shows the cover of this first issue) reported on Injun 1.[11] These two satellites also measured, for the first time, energetic protons from the Sun during a major solar flare. This activity began on 11 July 1961, just twelve days after Injun 1's launch. Figure 4 shows the flux of solar protons measured by Injun 1.[12] Coincidentally, the current head of APL's Space Department, S. M. Krimigis, did his master's thesis research at the University of Iowa using data obtained by the APL detectors on Injun 1.[13]

In July 1961 the U.S. Navy agreed to support a research and engineering satellite to be launched with Transit 4B in November 1961. In three and one-half months the TRAAC (Transit Research And Attitude Control) satellite was conceived, designed, built, and launched. It was during this time that Donald J. Williams (the present Chairman of the Research Center) joined the group of space scientists. The TRAAC satellite contained charged-particle detectors, including some from the Iowa group, and one of the few neutron detectors ever flown on a satellite.[14] The purpose of this instrument was to measure the albedo flux of neutrons that leaks out from the Earth's atmosphere, which is believed to be an important source of the inner radiation zone. At that time the absolute neutron leakage flux and its spatial distribution were known to a factor of no better than 5. A conference on the Earth's albedo neutron flux was organized and held at APL on 15–16 October 1963.[15]

THE 5E-1 SATELLITES

The 5E series of satellites were designed by APL from 1962 to 1964 to conduct scientific and engineering measurements on the space environment of the Transit navigation satellites. Four were launched piggyback on Transit type 5 satellites and three achieved orbit: 5E-1 (with the official NASA designation of 1963 38C) on 28 September 1963, 5E-3 (1963 49C) on 6 December 1963, and 5E-5 (1964 83C) on 12 December 1964. All three that achieved orbit met their primary objectives, and 5E-1 became one of the most scientifically productive satellites ever launched. Particle and magnetic field data were acquired routinely for more than six years, and the satellite remained functional for a period greater than an eleven-year solar cycle. An APL symposium was held on the eleventh anniversary of the 5E-1 Satellite on 27 September 1974 (just a day short of the eleventh year after launch). At that time, scientific results from 5E-1 had been published in forty-two articles in scientific journals.

The 5E-1 satellite attained a nearly circular polar orbit with an altitude of about 1100 km. The satellite carried a five-channel directional electron spectrometer, a proton spectrometer, three omnidirectional detectors, and a fluxgate magnetometer used in the attitude-determination system. The proton spectrometer consisted of two detectors oriented at 90° and 180° to the geomagnetic field lines. The omnidirectional detector was a 1.5-mm cubic lithium-drifted solid-state detector surrounded by hemispherical shields of different thicknesses. The electron spectrometer consisted of a row of five 1000-μm silicon surface-barrier detectors, all collimated to look in the same direction, nominally perpendicular to the magnetic field.

Starfish, the high-altitude nuclear explosion of 9 July 1962 (more than a year before 5E-1's launch), produced an intense region of trapped energetic electrons surrounding the Earth in much the same manner as the natural Van Allen radiation belts. The particle instruments on 5E-1 provided the first and only opportunity to study the time history of artificial radiation belts over a five-year period. Figure 5 shows the ten-day counting rates for electrons with energies of 1.2 MeV or greater, as observed by 5E-1 from October 1963 through December 1968 in various regions around the Earth[16] (denoted by the L value, measured in units of Earth radii, from $L = 1.3$ to 1.6). Bostrom and his colleagues concluded that the Starfish electrons had essentially disappeared by the end of 1968,

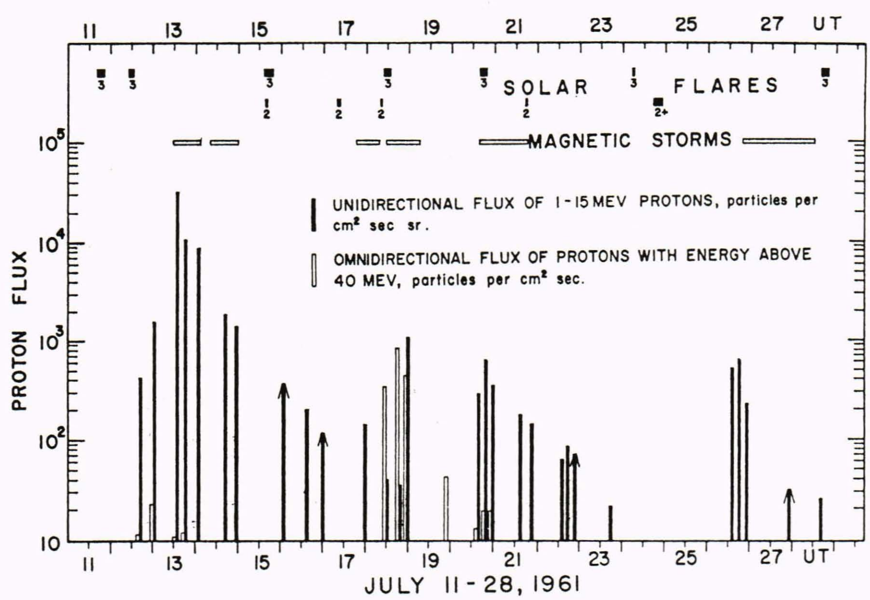

Figure 4. The flux of solar protons measured by the Injun 1 satellite during a major solar event, 11–28 July 1961. (Reprinted, with permission, from Ref. 12.)

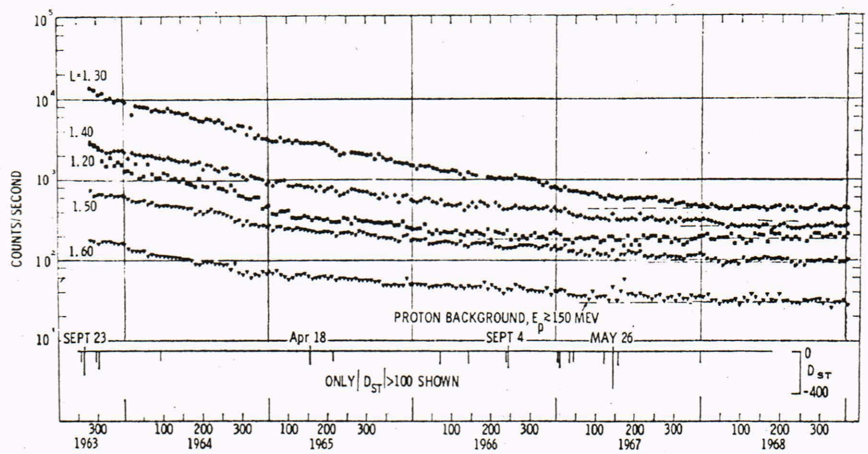

Figure 5. Ten-day average counting rates for electrons with energies greater than 1.2 MeV measured over a five-year period with the 5E-1 (1963 38C) satellite. (Reprinted, with permission, from Ref. 16.)

and that there was no natural source of electrons with energy of 1.2 MeV or greater.[16] They also found that the flux of lower-energy electrons (≥ 280 keV) had diminished to levels near enough the natural levels since 1966 to reveal the effect of natural events associated with magnetic storms.

The 5E-1 observations were used to study, for the first time, the characteristics of energetic protons in the Earth's magnetosphere emitted by the Sun after certain solar flares.[17–19] These observations of solar protons with energies between 1 and 100 MeV were used in combination with long-distance VLF (3–30 kHz) radio transmissions to develop ionization models in the Earth's atmosphere and ionosphere.[20]

Observations from 5E-1 were used to determine the diurnal variation of trapped electrons with energies of 280 keV or greater and of 1.2 MeV during magnetic quiet conditions. These characteristics were used to develop the first magnetic field model of the Earth's magnetosphere, which included a current sheet to account for the magnetospheric "tail."[21,22] Figure 6 shows this representation developed by D. J. Williams and his colleagues, and for many years regarded as the definitive model of the magnetosphere. The article describing this magnetospheric model became one of APL's most-cited articles.[23]

The 5E-1 satellite carried a three-axis magnetometer system as part of its attitude-determination system. The satellite was routinely tracked from APL, and magnetic disturbances were often observed by 5E-1 at northern high latitudes. Alfred J. Zmuda, who had joined APL in 1951 and was an internationally recognized expert on the geomagnetic field, was asked by satellite engineers for his advice on the nature of these disturbances. Zmuda, with the help of a young APL scientist, James Armstrong, ultimately attributed the magnetic disturbances to large-scale electric currents that flow continuously into and away from the auroral regions.[24,25] The existence of these currents (now referred to as Birkeland currents in honor of the Norwegian scientist who proposed their existence in 1908) was debated because it is not possible to identify them unambiguously from ground-based magnetic field measurements.[26] The magnetic observations from 5E-1 were used by Zmuda to provide the first diurnal pattern of Birkeland currents.[27] Figure 7 shows the diurnal vari-

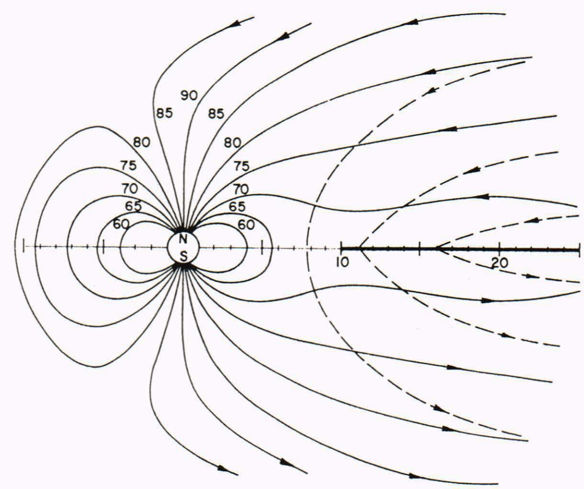

Figure 6. Representation of the geomagnetic field determined from particle characteristics measured with the 5E-1 satellite. The solid lines show the field lines in the noon–midnight plane obtained by adding a current sheet in the tail to an earlier model. The dashed lines are the field due to the current sheet alone. (Reprinted, with permission, from Ref. 22.)

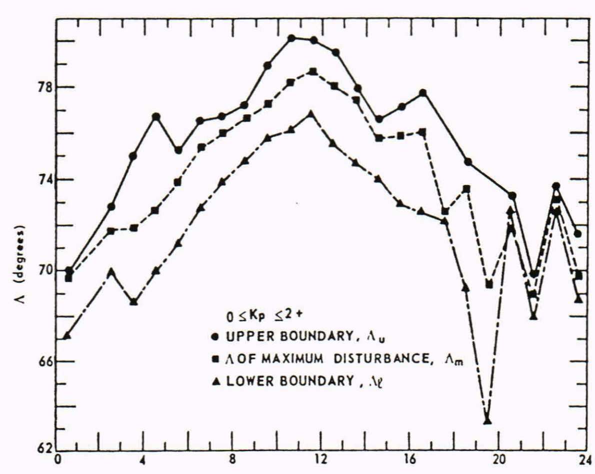

Figure 7. The location, in latitude against local time, of the magnetic disturbances measured by 5E-1. This was the first map of field-aligned currents in the auroral zone. (Reprinted, with permision, from Ref. 27.)

ation of the latitude magnetic disturbances determined in this way. This pattern was later refined with measurements from the APL Triad satellite. These observations confirmed earlier theories of Nobel Laureate Hannes Alfvén, who consequently became a close friend of APL. The results of the scientific studies of 5E-1 data were published in more than 40 articles in scientific journals, not a bad record for a U.S. Navy satellite whose primary objective was not necessarily space plasma research.

A follow-on to 5E-1 was attempted, but 5E-2 failed because of a problem in the launch vehicle, resulting in intense activity to reproduce 5E-2 experiments for launch in December 1964 on the 5E-5 satellite. The primary experiments on 5E-5 were a stellar ultraviolet photometer, designed by Andrew M. Smith,[28] and a rubidium-vapor precision magneter, both firsts in space; each was very successful. The stellar photometer conducted one of the first UV surveys of the celestial sphere,[28] and the rubidium magnetometer data provided one of the first opportunities to evaluate accurate models of the geomagnetic field.[29,30]

TRIAD

A. J. Zmuda's work with the 5E-1 magnetic field data led him to recognize the importance of the field-aligned currents to an understanding of auroral and space physics, and he requested that the Triad satellite, scheduled to be designed and built at APL, be equipped with an improved magnetometer system.[3] The term Triad is unusual in that it is a combination of acronyms: It stands for Transit-improved DISCOS (Disturbance Compensation System).[31] For attitude determination, Triad required a magnetometer system, but with far less resolution than the 12 nT proposed by Zmuda. A resolution of 700 nT is required to determine a satellite's attitude within 1° in a 40,000-nT total field, and Triad was to be the first APL/Navy navigation satellite with a programmable computer. Zmuda appealed to the Space Department Head, Richard Kershner, to include a special 13-bit analog-to-digital converter to provide the 12-nT resolution. Kershner agreed, but only with the proviso that the system have no effect on the satellite's major mission and that it be separate and independent from Triad's central computer. On 2 September 1972, Triad was launched on a Scout rocket from Vandenberg Air Force Base in California and was a complete success. Later, anomalies in the on-board central computer limited the amount of data that could be transmitted to the ground from the spacecraft; however, the separate data system for the magnetometer worked perfectly, and the telemetry system for the magnetometer was then available to transmit the magnetic field measurements on a continuous basis, which it did for more than eleven years!

The continuous high-resolution magnetic-field observations acquired by Triad allowed A. J. Zmuda and James Armstrong to determine the first statistical map of field-aligned currents and their flow directions in the auroral zone. The map shown in Figure 8 was published in the article "The Diurnal Flow Pattern of Field-Aligned Currents" by Zmuda and Armstrong, which appeared in the *Journal of Geophysical Research* on 1 November 1974.[32]

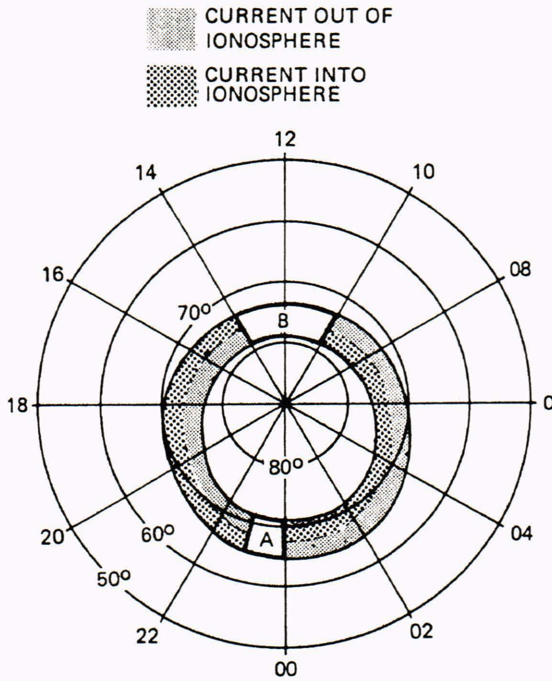

Figure 8. The spatial distribution of field-aligned currents and their flow direction determined from the analysis of Triad data by Zmuda and Armstrong. (Reprinted, with permission, from Ref. 32.)

Both Zmuda and Armstrong died during the summer of 1974, before they were able to see their article in print. The impact of this first map of field-aligned currents on the scientific community is demonstrated by the number of times it has been cited.[26,32] By 1983, when Triad was eleven years old, more than fifty scientific articles had been published on studies of the data, written by thirty-seven different authors throughout the world, including the United States, the Soviet Union, China, Japan, and Europe. Many of these scientists participated in a special American Geophysical Union Chapman Conference on magnetospheric currents held in April 1983, where Triad's birthday was celebrated and a selection of the papers published.[33]

Field-aligned Birkeland currents are important because they provide a link between the lower auroral ionosphere and the magnetosphere and interplanetary medium. They are also the source of a variety of interesting plasma phenomena in the Earth's neighborhood. The important role of field-aligned Birkeland currents in the flow of energy between the Sun and the Earth (as suggested by Karl F. Gauss and Kristian Birkeland, but refuted by Lord Kelvin and Sydney Chapman) becomes more evident with the improvement of satellite experiments and the advent of multisatellite observational programs. Five of the papers resulting from the Triad magnetic field analysis became some of APL's most frequently cited publications,[26] including papers by A. J. Zmuda and J. C. Armstrong in 1974,[32] T. Iijima (of the University of Tokyo) and T. A. Potemra twice in 1976,[34,35] M. Sugiura (of NASA Goddard Space Flight Center) and T. A. Potemra in 1976,[36] and T. Iijima and T. A. Potemra in 1978.[37]

NASA'S INTERPLANETARY MONITORING PLATFORMS

The Interplanetary Monitoring Platform (IMP) Program of NASA was the mainstream of the U.S. space research effort in fields and particles from the early 1960s to the early 1970s. Experiments designed and built at APL were flown on IMP-4, -5, -6, -7, and -8 (also referred to as Explorers 34, 41, 43, 47, and 50, respectively). The IMP-4 satellite (Explorer 34) was launched on 24 May 1967 in an orbit 34 Earth radii by 250 km, inclined nearly perpendicular to the ecliptic plane.[38] This satellite carried the APL Solar Proton Monitoring Experiment (SPME), which provided omnidirectional measurements (over the upper hemisphere) of protons with energies greater than 10 MeV, 30 MeV, 60 MeV, and in the range of 1 to 10 MeV. These instruments consisted of solid-state detectors in various configurations. Some technological firsts, such as in-flight calibration and monitoring of detector noise, were introduced with these instruments and have now become standard designs for follow-on experiments.

In 1968 S. M. Krimigis came to APL from the University of Iowa, where he had been conducting research with data from the Injun 5 and Mariner 4 and 5 spacecraft. He had just been selected as principal investigator for the charged particle measurements experiment for IMP-7 and -8. A separate and complementary instrument proposed by a Goddard/APL team of investigators, with D. J. Williams as principal investigator, had also been selected for IMP-7 and -8. Both instruments were designed and built at APL and launched in 1972 (IMP-7) and 1973 (IMP-8).

The IMP-7 and -8 experiments had an expanded scope and collectively cover energy ranges from 50 keV to 500 MeV for protons and heavier nuclei.[39] Electrons are measured over the range of 15 to 2.5 MeV, and solar and galactic X rays from 1.5 to 18 Å. The sensitivities of the instruments are such that studies have been carried out from quiet-time galactic intensities to intense solar flare events, to detection of electrons originating in the magnetosphere of Jupiter. The data represent a huge reservoir of physical measurements.

Figure 9 shows the ten-day average count rate of protons with energies between 0.5 and 0.96 MeV measured with IMP-8 over the eighteen-year period of 1973 to 1991 (private communication, R. B. Decker, 1991). These data, by themselves, represent a unique accomplishment, providing a very important contribution to the understanding of solar-cycle variations of solar energetic particles and the energization and transport processes associated with them. For example, a long-term variation in the particle counts is evident in Figure 9, with minima in 1977 and 1987, close to the periods of minimum eleven-year solar activity.

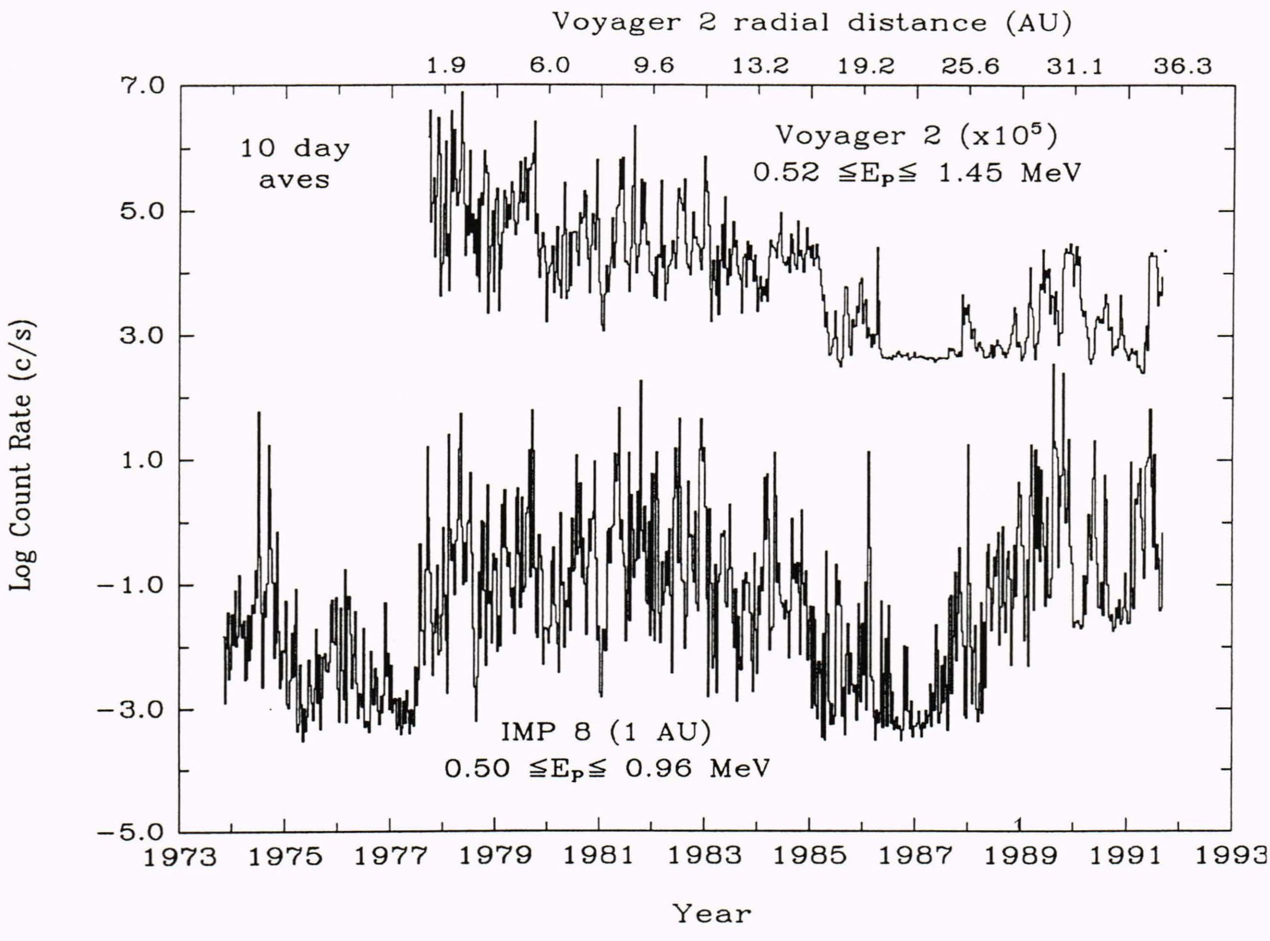

Figure 9. An almost two-decade plot of particle measurements from IMP-8 and Voyager 2 (private communication from R. B. Decker, 1991.)

INTERNATIONAL ULTRAVIOLET EXPLORER (PARTICLE FLUX MONITOR)

This unique program began on 28 December 1977 with a phone call from Goddard Space Flight Center (GSFC) requesting a particle radiation detector for the International Ultraviolet Explorer (IUE) spacecraft, which was to be launched 25 January 1978 from the Kennedy Space Center in Florida. An instrument to measure radiation belt particles was required to protect sensitive cameras from damage. A team headed by C. O. Bostrom (then Chief Scientist of the Space Department) went into action to build such an instrument. By 29 December 1977 a system had been breadboarded using spare parts from Voyager and Itos. On 30 December 1977 GSFC was notified that, depending on the time schedule, delivery of such an instrument was possible. A management decision of GSFC was needed to continue the program, and it was not until 3 January 1978 that permission was given to proceed. Designing the instrument and power supply was accomplished on 3–4 January 1978, and on 5–6 January the electronic assembly was built and inspected. By 7 January 1978, the unit was intact and testing began. It was learned on 8 January 1978 that delivery of the instrument had been moved up to 9 January to allow for integration with the spacecraft; on 9 January 1978 Steve Gary and Ted Mueller left Baltimore–Washington International airport in a snowstorm with the completed package, named the Particle Flux Monitor (PFM).

The successful launch of the IUE took place on 26 January 1978 at 12:36 EST. The PFM has continued to work perfectly since then and, as stated by GSFC, "is an invaluable instrument in mission operations." This unbelievable project lasted only six days from design to delivery.

ATMOSPHERE EXPLORER C, D, AND E

The Atmosphere Explorer (AE) mission was NASA's main satellite aeronomy program in the 1970s. The AE payloads consisted of particle detectors, mass spectrometers, Langmuir probes, airglow photometers, and other instruments devoted exclusively to aeronomy. The Photoelectron Spectrometer (PES) experiment was a joint experiment led by John P. Doering of The Johns Hopkins University Department of Chemistry and by Carl O. Bostrom and James C. Armstrong of APL.[40,41] The PES experiment consisted of high-resolution energy measurements of electrons with energies between 1 and 500 eV (over an energy bandpass, $\Delta E/E$, of 2.5%). The principal objective of this experiment was to measure the spectra of electrons produced in the thermosphere by photoionization processes, which was accomplished with great success,[42,43] and the experiment also provided detailed information on precipitating electrons associated with magnetospheric processes.[44] The PES experiment was flown on the AE-C, AE-D, and AE-E satellites launched on 13 December 1973, 6 October 1975, and 20 November 1975, respectively.

THE AMPTE PROGRAM

The three spacecraft of the AMPTE mission were launched on 16 August 1984 from Cape Canaveral into Earth orbit atop a Delta rocket, culminating thirteen years of planning and development by a large group led at APL by S. M. Krimigis, John Dassoulas, and R. W. McEntire.[45,46] The AMPTE program was a three-nation, three-spacecraft mission designed to identify the sources of the Van Allen radiation belts and to study the complicated plasma processes that occur in comets. The three AMPTE spacecraft were 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 satellite 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 sixteen 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 provide a description of the mission and accounts of the CCE preparation, the launch, the first few months of the mission, and some of the principal scientific results.[47,48] The cover of the January–March 1983 issue of the *Technical Digest* (Fig. 10) shows a drawing of the APL CCE satellite. A special issue of *IEEE Transactions on Geoscience and Remote Sensing* in 1985[49] describes each spacecraft, all flight instrumentation, and other aspects of the mission.

The AMPTE mission had two phases: 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 that would be 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 that are rare in the natural environment and that could be used as tracers of natural flows and acceleration processes. The IRM and the CCE contained a new generation of instruments, capable for the first time of measuring the elemental composition and ionic charge over a broad energy range of the major energetic particle populations in space around the Earth. The IRM and UKS spacecraft were designed to fly in close formation and to 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, including a ring-like current flowing around the Earth.

A unique aspect of the AMPTE program is the Science Data Center assembled at APL with the help of Bruce Holland, Lora Suther, and Stu Nylund.[50] The Science

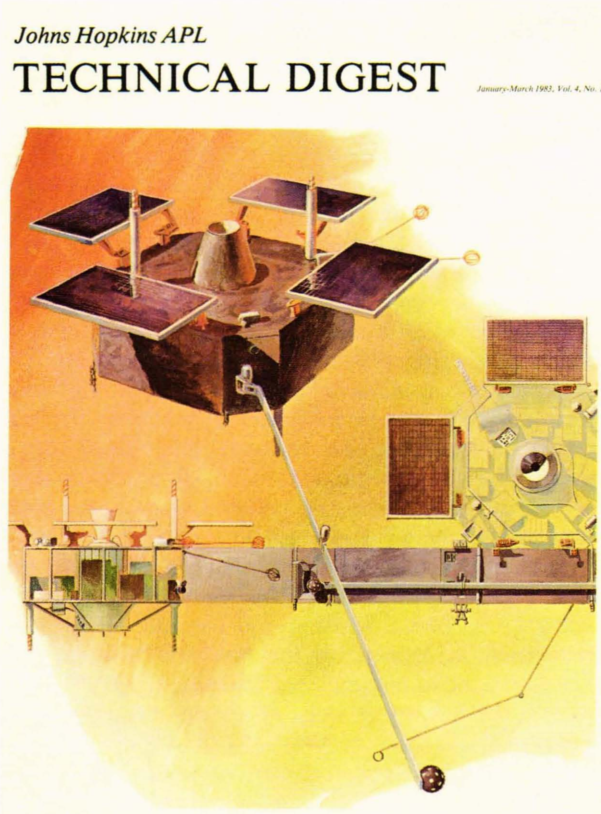

Figure 10. A special issue of the *Johns Hopkins APL Technical Digest* was devoted to the Active Magnetic Particle Tracer Explorers (AMPTE) mission (January–March 1983). Its cover featured an artist's conception of the APL Charge Composition Explorer (CCE) satellite, which was one of the three international satellites.

Data Center received and displayed data from CCE in real time, that is, as events in space occurred. It was the focal point for all CCE data and also received data from a variety of other satellites and ground-based observatories. The APL Center, in combination with similar centers for IRM in Germany and for UKS in England, became a command center for the ion releases. Science teams supporting each satellite would assemble in the three data centers and communicate by telephone and data link. All the observations and inputs made it possible to evaluate the complicated conditions in space and in the magnetosphere as these unfolded. The conditions of the solar wind, the interplanetary magnetic field, and the geomagnetic field were watched intensively. Not until this international group of scientists was satisfied with the conditions was the command for an ion release sent to the IRM satellite. As luck would have it, the best conditions were predicted to occur during the early morning hours in Germany and England, which meant that the CCE team had to begin its watch at APL just after midnight. These watches were characterized by initial excitement, followed by long tension-filled periods of waiting for just the right conditions, often concluding in disappointment as the best conditions faded away. Occasionally everything fell into place, and the release button was pressed. A cheer would rise on both sides of the Atlantic when the UKS and IRM satellites first detected the effects of the ion release. These activities raised space research to a new level of excitement.[51]

On 11 September and again on 20 September 1984, lithium releases from the IRM were made. Inside the magnetosphere, the CCE particle instruments were in special modes searching for the impact of lithium ions; unfortunately, none were detected, but an upper limit could be placed on ion access from the solar wind to the CCE orbit.[52] Perturbations of the geomagnetic field caused by the lithium cloud released on 11 September 1984 were detected by CCE and on the ground.[53,54] We believe that the lithium cloud triggered oscillations in the geomagnetic field when it struck the nose of the magnetosphere. Consequently, a distinct effect of the artificial ion release made outside the Earth's magnetosphere was detected inside the magnetosphere.

The third AMPTE active experiment, on 27 December 1984, injected barium ions into the solar wind on the dusk flank of the magnetosphere. This experiment produced an artificial comet that was observed from the ground by many people in the western United States and was referred to by the press as the Christmas comet.[53] This and another similar artificial comet release on the opposite flank of the magnetosphere on 18 July 1985 were quite successful. The release created a barium ion cloud, or coma, that measured greater than 500 km across and contained a core diamagnetic cavity about 100 km in diameter. Ions extracted from the core and coma formed a tail more than 4000 km long in the antisunward direction. The cover of the January–March 1985 issue of the *Technical Digest* (Fig. 11) shows a false-color image of one of the artificial AMPTE comets taken with a low-light-level television camera on board the airborne observatory of the Argentine Air Force. The comet releases were discussed in detail in a special issue of *Nature* (1986).[55] We have gained much insight into the complex and unexpected processes found in comets.

The CCE satellite has provided the first comprehensive measurement of the composition of the ring current, a doughnut-shaped ring around the earth at altitudes ranging from about 2 to 5 Earth radii 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 articles in the scientific literature had speculated on the sources and composition of these ions (hydrogen, helium, and oxygen were suggested). Existing instruments made it possible to watch the particle fluxes first appear and then decay with a time scale of hours and days, but not to determine what types of ions they were or their source.

The AMPTE program 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 (about 30 to 160 nm thick, only a fraction of the wavelength of visible light) and a rear detector that measured total energy.[56] The promise of the new sensors was fulfilled almost immediately after launch. An intense magnetic storm occurred on 4 September 1984, and the ring current formed was monitored by the sensors on the CCE.

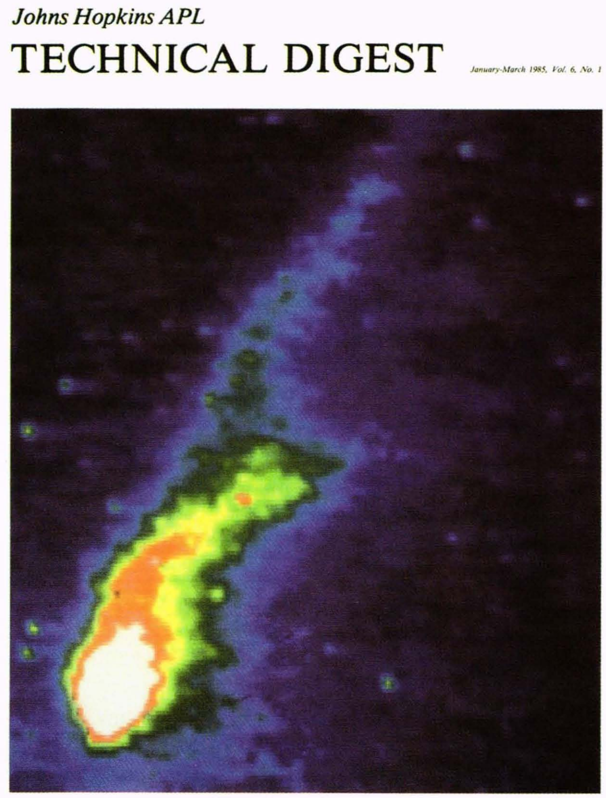

Figure 11. The January–March 1985 issue of the *Johns Hopkins APL Technical Digest* featured an artificial Active Magnetic Particle Tracer Explorers (AMPTE) comet of barium ions that was created by the release of 6.6 lb of barium metal from the German AMPTE Ion Release Module (IRM) Spacecraft, 71,000 miles from the Earth. The comet head was 310 miles across, and its tail stretched more than 2800 miles.

A resulting series of coordinated papers by the CCE investigators, published in a special issue of *Geophysical Research Letters* (May 1985),[57] settled, at least for that one storm, the decades-old question of particle composition. 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, which would indicate that a significant part of the plasma energized during a storm is of ionospheric origin. The study has now been extended to twenty storms, with similar results. Hydrogen, with 83% of the energy density, is the dominant ion injected during a geomagnetic storm.

The composition of magnetospheric particles at higher energies presented CCE researchers with another major surprise. At energies up to several hundred thousand electron volts, 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 about 1 to 2 MeV, silicon and iron become the dominant elements in outer magnetospheric particle spectra. Not only was this finding unexpected, but before the AMPTE/CCE only fragmentary evidence had been found of the existence 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 electron volts of energy inside the magnetosphere. The results of these studies have been published in more than 400 scientific articles; they were featured on the covers of *Nature*,[58] *EOS (twice)*,[59,60] *Geophysical Research Letters*,[57] and *IEEE Transactions*;[49] and they received extensive coverage in the press and on television.

Contact with the UK satellite was lost on 16 January 1985, and IRM's batteries failed on 13 August 1986. The Earth's radiation belts, the subject of all the intense study, induced damage to CCE's command system, preventing normal operations after June 1989. The CCE provided more than four and one-half years of continuous data on energetic particles and fields near the Earth that will be studied for years.

VOYAGER

The encounter of Neptune by the Voyager 2 spacecraft in August 1989 was a dramatic climax to the historic Grand Tour of the Solar System's giant outer planets. The Voyager program, one of the most successful and exciting space projects to date, has revealed numerous surprises at each of its targeted planets. The APL group, led by Tom Krimigis, Carl Bostrom, Ed Keath, Dan Peletier, Steve Gary, and Dennis Fort, designed and fabricated the low-energy charged-particle (LECP) instrument used in this program.[61]

The two spacecraft were launched in late 1977. Each had a close encounter with Jupiter in 1979, followed by encounters with Saturn in late 1980 and 1981 for Voyagers 1 and 2, respectively. After its Saturn encounter, Voyager 1 left the ecliptic plane and had no further close encounters with other planets of the solar system. Voyager 2 encountered Uranus and Neptune in 1986 and 1989, respectively. The Voyager spacecraft, and the LECP instrument in particular, will continue to make measurements of the interplanetary environment until about the year 2015, when the anticipated decay of the power supply from the radioisotope thermoelectric generator might require that mission operations cease, as power will be insufficient to operate vital spacecraft subsystems.

The LECP experiment was designed at APL to measure the intensity, energy spectra, composition, angular distributions, and spatial and temporal characteristics of ions and electrons encountered by the spacecraft. Particles with energies greater than about 20 keV are so characterized. Such particles are fundamental components of the interplanetary environment (through solar, galactic, and local acceleration processes) and the space environments that surround the planets.

Many of the scientific findings of the LECP experiment have been summarized in some detail in the *Technical Digest*,[62] generally following the occurrences of the individual planetary encounters with Jupiter, Saturn, Uranus, and Neptune. These sources, in turn, cite more detailed studies available in the scientific literature. To date, studies with LECP have resulted in more than 150 publications. One of the most important aspects of the Voyager mission is that multiple planetary magnetospheric environments have been visited by identical instrumentation.

An appreciation for the breadth and scope of the results returned by the LECP instrument can be gained from Figures 12 and 13, which show energy–time spectrograms that summarize the LECP results at each planet.[62] Figure 12 shows the results of the ion measurements, and Figure 13 shows electron results. For each panel of Figures 12 and 13, the vertical scale shows particle energy of 30 keV to 4 MeV for ions and 20 keV to 1 MeV for electrons. The horizontal scale shows both time in days (day of year) and radial distance to the center of the planet (expressed in planetary radii), and the color is coded according to the intensity of the particles at each particular time and energy. The blacks and reds represent the most intense fluxes, and the blues and whites represent the least-intense fluxes. (See the color scale to the right of each figure; the units are particles/cm^2·s·sr·keV.) For comparison, the top panel of each figure shows results from the Earth's magnetosphere as sampled by the medium-energy particle instrument (MEPI) experiment (Donald J. Williams, principal investigator) on NASA's International Sun–Earth Explorer (ISEE-1) spacecraft.

One crucial theme of magnetospheric physics that has developed with the Voyager program is the importance of the interactions that occur between magnetospheric particles and the planetary satellites and rings.[63] At Earth, the Moon is so far away (≈60 Earth radii) that its interactions with the magnetospheric environment are minimal. A surprise at Jupiter was that the major source of plasmas within the magnetosphere was the volcanoes of the satellite Io. For example, the LECP data revealed that a major constituent of the magnetospheric ions is sulfur, known to be a key component of Io. At Earth, the source of magnetospheric particles was thought to be the solar wind (principally hydrogen and helium), but the upper atmosphere (hydrogen, helium, oxygen) may well be the dominant contributor. All the magnetospheres visited by Voyager have well-developed Van Allen or radiation belt populations. Consequently, all of these magnetospheres are prodigious accelerators of charged particles. The charged particle intensities do vary (by up to 3 orders of magnitude, according to Figs. 12 and 13), but not dramatically, given the widely varying conditions that exist from planet to planet. Curiously, the Earth and Jupiter, planets that would appear to be most different, not only in size and makeup, but also in the source of power for driving magnetospheric processes (solar wind versus rotational dynamo), seem to be closest in peak radiation belt intensities achieved.

The next great encounter anticipated by the Voyager teams is that of leaving the plasma environment of the Sun, the heliosphere, and entering the plasma environment of the interstellar regions of our galaxy. A workshop was hosted by APL this year (22–23 January 1992) for both Voyager and Pioneer projects to prepare for this last encounter. The heliosphere within the interstellar environment is quite analogous to the planetary magnetospheres within the solar wind environment. An interstellar wind blows with respect to the Sun, and it is anticipated that a bullet-shaped heliospheric cavity will form within that wind. We also expect to encounter structures analogous to the magnetospheric bow shock and magnetopause, an interstellar shock wave beyond a heliopause.

The Voyager 1 and 2 spacecraft have joined the older Pioneer 10 and 11 spacecraft (launched in 1972 and 1973, respectively) in the search for these plasma structures. Because of the nature of the planetary gravitational assists received by the Voyager spacecraft, they are traveling faster than the Pioneer spacecraft. For example, Voyager 1 overtook the solar radial distance of Pioneer 11 in 1988, and it will overtake Pioneer 10 in 1998. Because the Voyager spacecraft are directed toward the "nose" of the heliospheric structure, Voyager 1 will likely be the first spacecraft to encounter the heliopause.[64] The Voyager spacecraft have already revealed much more about our solar system than anyone could have confidently anticipated.

THE HILAT SATELLITE

Satellites have provided images of the aurora in visible wavelengths (4000–8000 Å) that have confirmed previous theories that it is indeed a global phenomenon and that it can occur in a continuous band encircling the geomagnetic pole; however, these images could be acquired only in the night sky because of the high background of reflected sunlight during the daytime. Although it is impossible to view auroras with the unaided eye in the sunlit sky, satellite, rocket, and surface measurements of energetic particles, ionospheric disturbances, and geomagnetic disturbances have confirmed that they must be there. The high-latitude (Hilat) satellite provided, by means of the Auroral Ionospheric Mapper instrument, the first images of the aurora under full daylight conditions. This instrument was developed at APL by a team led by Ching-I. Meng and Fred Schenkel.[65,66] The imager could be operated in a predetermined fixed number of spectral wavelengths in the range from about 1100 to 2000 Å. This range was selected because the albedo from the scattering of incident solar radiation is negligible at wavelengths shorter than about 2000 Å and auroral images could be obtained in the sunlit atmosphere. The sunlit image of the aurora acquired by Hilat, shown on the cover of the April–June 1984 issue of the *Technical Digest* (Fig. 14), shows a complicated and beautiful form that cannot be seen by any observer on the ground because the ultraviolet wavelength (1493 Å) of the image is absorbed by the atmosphere below the altitude of the emission.

As spectacular as these images are, they represent only a portion of the objectives of the Hilat program. The auroral regions are the focal points of an important type of solar–terrestrial interaction. A considerable amount of energy from interplanetary space (approaching 10^{12} W) is funneled into the auroral regions, producing light, ionization, heat, X rays, and low-frequency sound waves. The primary mission of Hilat was to explore the complicated plasma processes that occur in these regions. The unique complement of radio propagation *in situ* and re-

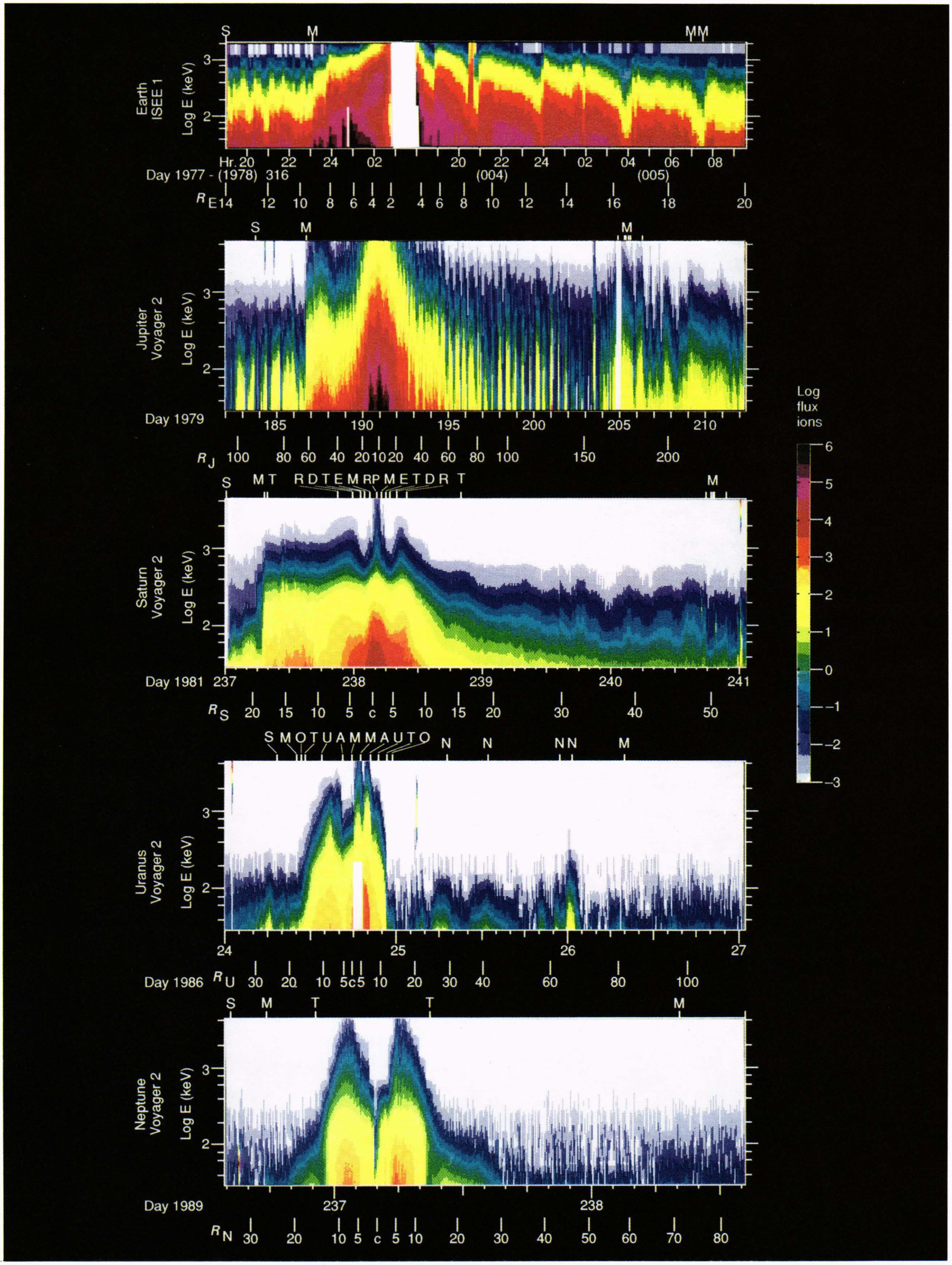

Figure 12. Energy–time intensity spectrograms (computer generated) that summarize low-energy charged-particle (LECP) ion measurements at (from bottom to top) Neptune, Uranus, Saturn, and Jupiter. For comparison, the top panel shows results for Earth as sampled by the MEPI (medium-energy particle instrument) experiment on NASA's ISEE-1 (International Sun–Earth Explorer) spacecraft. (Reprinted, with permission, from Ref. 62.)

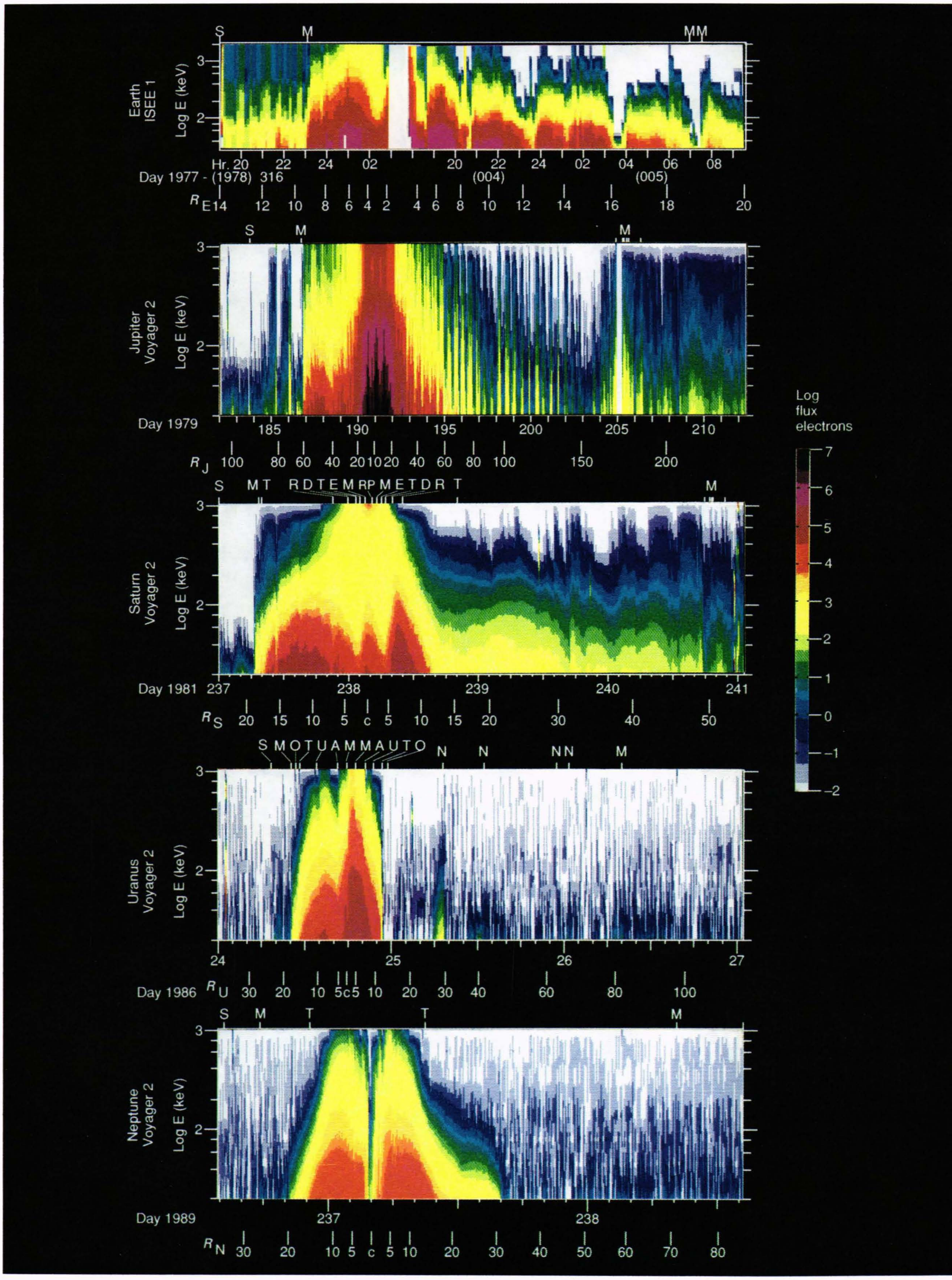

Figure 13. Same as Figure 12, but for electrons rather than ions. (Reprinted, with permission, from Ref. 62.)

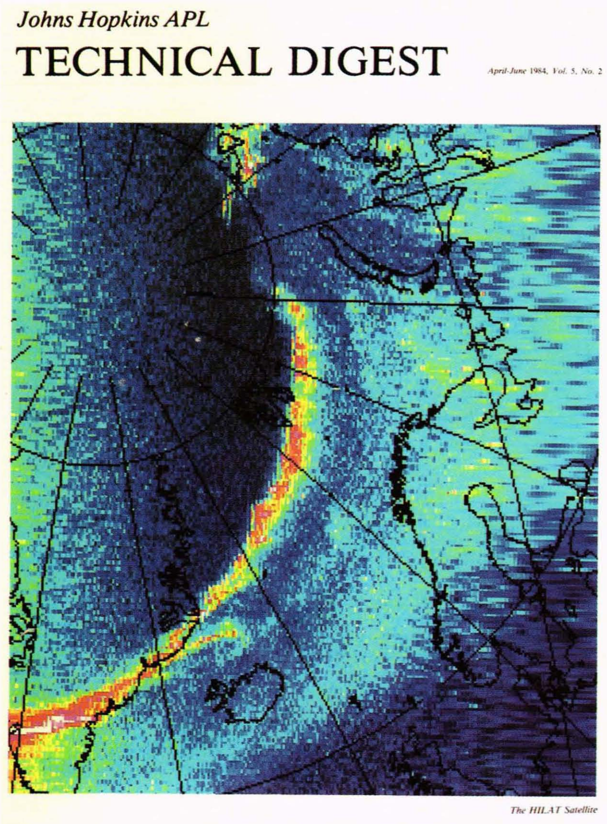

Figure 14. The April–June 1984 issue of the *Johns Hopkins APL Technical Digest* showed a false color presentation of the aurora borealis, or northern lights. The image was taken by the ultraviolet imaging system on board the Hilat satellite on 23 July 1983, when the north polar region was illuminated by the Sun. The auroral form stretches in an arc across the southern tip of Greenland to the north of Iceland, Scandinavia, and Siberia.

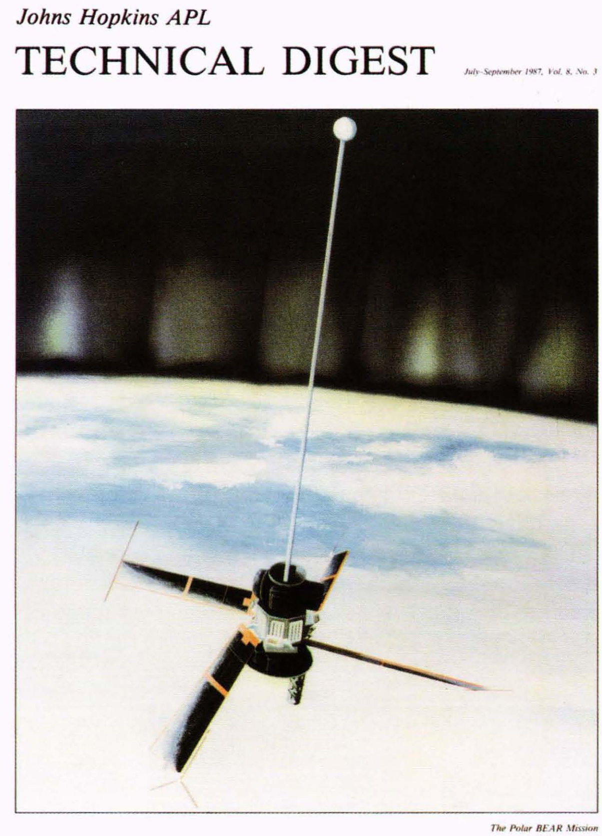

Figure 15. An artist's conception of the Polar BEAR satellite was shown on the cover of the July–September 1987 *Johns Hopkins APL Technical Digest*. The Polar BEAR satellite is shown in orbit with the aurora borealis in the background.

mote-sensing instruments on board Hilat were used to measure auroral phenomena and their effects on radio wave propagation through the auroral zone. The satellite, sponsored by the Defense Nuclear Agency and the U.S. Air Force, was a rebuilt Navy Transit navigation satellite, similar to the 5E-1 satellite described earlier. It was launched on 27 June 1983 and operated successfully for more than six years.

THE POLAR BEAR SATELLITE

The great success of Hilat led to a request for a follow-on satellite, eventually to be called Polar BEAR. The plan was to convert another APL-built Navy navigation satellite for Polar BEAR, but none was immediately available. When the Smithsonian Air and Space Museum opened in 1976, APL had donated a fully equipped Oscar-17 satellite for display. In July 1984, the satellite was reclaimed to become Polar BEAR (Fig. 15).[67]

Polar BEAR carried an advanced-design, multichannel UV auroral imaging system called Auroral Ionospheric Remote Sensor (AIRS), a high-resolution magnetic field experiment and a multifrequency radio beacon. Polar BEAR was launched on 13 November 1986 and acquired data at the same time as Hilat. Routine collection of data from Polar BEAR was discontinued in 1990.

RADAR STUDIES OF SPACE PLASMAS

In 1983 a group of APL scientists and engineers, including Raymond Greenwald and Kile B. Baker, traveled to Goose Bay, Labrador, to install a high-frequency radar designed to look at density irregularities in the high-latitude ionosphere.[68] The radar, which operates at frequencies from 8 to 20 MHz, detects the coherent backscattered signal produced by ionospheric density irregularities that have a spatial periodicity equal to half the radar wavelength. By observing the motion of these ionospheric irregularities, it is possible to derive information about the electric field that drives the motion of plasma in the magnetosphere.[69] In addition to observing the bulk motion of the plasma, the radar can also determine the Doppler power spectrum. The width of the spectrum is related to the level of turbulence in the electric field. This radar system has provided a wealth of new information on the ionosphere and space plasmas. Merle Tuve would have been very interested in these results.

An interesting aspect of high-latitude studies is the phenomenon referred to as conjugacy. Charged particles and magnetohydrodynamic waves are channeled along the magnetic field lines within the Earth's magnetosphere. One would therefore expect similar physical processes to occur at the two ionospheric endpoints of a closed magnetic field line. On the other hand, magnetic field lines that originate in one hemisphere and connect to the solar wind (i.e., open field lines) would not be expected to show a conjugate relationship in the other hemisphere. Studies of conjugacy could help trace magnetic field lines and determine the boundary between the open and closed regions; they could also be used to examine the roles of solar illumination and ionospheric conductivities in the formation of ionospheric irregularities and electric field turbulence.

In conjunction with the British Antarctic Survey (BAS), APL embarked on a joint research project to install a radar system near the magnetic conjugate point of Goose Bay in the Antarctic. Kile Baker of APL was part of this expedition. The location is near Halley Station, an Antarctic research base operated by BAS on the Brunt Ice Shelf in the Weddell Sea. Figure 16 shows the location of Halley Station in Antarctica.[70] Also shown are the conjugate location of Goose Bay and the fields of view of both radar systems.

Data from the Halley radar have been correlated with observations obtained with the Defense Meteorological Satellite Program (DMSP) as it passed over the radar's field of view. The study was directed toward examining the ionospheric image of the magnetospheric cusp, and it showed a clear correlation between the features seen by the satellite and those observed by the radar. The cusp was found to be a region where ionospheric irregularities on a scale of 10 m were generated, and the irregularities moved under the influence of a highly turbulent electric field. The convection pattern observed by the radar showed a flow reversal typical of the pattern predicted in the Southern Hemisphere for a particular orientation of the interplanetary magnetic field. That flow reversal, embedded within the cusp, was consistent with a change in sign of the horizontal plasma drift observed by the satellite. Studies with DMSP and the radar are now under way to examine the correlations under different interplanetary monitoring platform conditions.

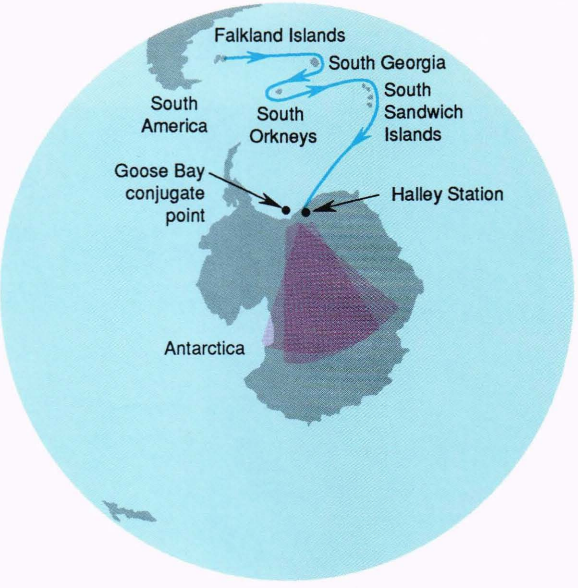

Figure 16. A map of Antarctica showing the field of view of the Halley high-frequency radar, the conjugate mapping of the Goose Bay high-frequency radar, and the path of the USS *Bransfield* (blue line) on the trip from the Falkland Islands to Halley. (Reprinted, with permission, from Ref. 70.)

SOLAR PHYSICS

The Applied Physics Laboratory has a long and distinguished record of research on energetic protons and other particles emitted by the Sun. To understand better the physical processes that can lead to the emission of energetic particles, solar physics research was expanded in early 1980s, after the launch of NASA's Solar Maximum Mission (Solar Max), and the new emphasis was on the Sun itself. Solar Max images of the X-ray–emitting loops and arches in solar flares revealed the rapidly moving thermal conduction fronts that distribute heated flare plasma in the solar atmosphere. When illuminated by this plasma, the loops and arches outline the magnetic fields where the energetic flare particles are accelerated.

A solar observatory was established by David M. Rust in the mid-1980s to serve as a laboratory for testing prototype components of new instruments for research on solar activity and internal structure.[71] A Sun-tracking telescope provides a stable beam of sunlight for instruments mounted on the telescope itself or on two fixed benches. One of the first devices tested at the observatory was a helioseismograph, an instrument that measures solar surface vibrations. Later observations with the helioseismograph at the National Solar Observatory in New Mexico gauged the rate of rotation in the layers just below the Sun's surface.

Because solar vibrations are best detected by the Doppler shifts they induce, successful helioseismology requires the use of an optical filter with a very narrow and very stable passband. Working with the Australian National Measurement Laboratory, APL scientists developed tunable Fabry-Perot filters made of lithium niobate, a transparent electro-optic crystal. The position of the band passed by one of these filters can be maintained to one part in ten billion by an electric feedback loop keyed to a stabilized laser. These filters are now gaining acceptance at solar observatories elsewhere. At APL development is continuing with the aim of perfecting a compact telescope/filtergraph for monitoring solar activity from a space observatory.

In 1986 the Solar Group received a University Research Initiative grant to start a Center for Applied Solar Physics. Since then, the Center has sponsored the design of an instrument to measure ejections of solar electrons into interplanetary space, and Center scientists designed and built a solar vector magnetograph that is now in daily operation at the National Solar Observatory.[72] This instrument shows the position and orientation of the magnetic fields in sunspot regions and is used to detect the development of electric-current–carrying structures that can become unstable and provide the energy for solar flares.

At the heart of the vector magnetograph is one of the APL lithium niobate filters, with which the polarization state of the sunlight in a very narrow spectral band can be measured. By application of the Zeeman theory of the splitting and polarization of light emitted by atoms in the presence of a magnetic field, APL scientists can infer the field direction and strength from solar filtergrams.

THE FUTURE

The traditions of space research begun by Tuve and Van Allen continue at APL with increased involvement in a variety of activities. On 12 September 1991, NASA's Upper Atmosphere Research Satellite (UARS) was launched carrying another APL magnetic field experiment. The Swedish Freja satellite is scheduled for launch in the autumn of 1992 with one of the most sophisticated magnetic field experiments ever carried into space.

The Galileo spacecraft was launched by a space shuttle on 13 October 1989 on a trip to Jupiter carrying the APL Energetic Particles Detector (EPD), an instrument designed to measure the characteristics of the energetic particle populations in the Jovian magnetosphere.[73] Galileo used two gravity-assist flybys of Venus in February 1990 and of the Earth in December 1990, and it will use a second Earth flyby in December 1992 to gain enough energy to reach Jupiter in December 1995.

The Ulysses spacecraft was launched in October 1990 on its way over the poles of the Sun with a low-energy charged-particle experiment built at APL in collaboration with scientists at AT&T Bell Laboratories, the Universities of Kansas and Thrace, and other institutions. This instrument will obtain measurements of interplanetary ions at energies greater than 50 keV and electrons above 30 keV with five separate solid-state detector telescopes.[74] Ulysses is expected to arrive at Jupiter in February 1992, where the Jovian gravitational field will deflect the probe south of the ecliptic plane.

The Japanese Geotail satellite is scheduled for launch in July 1992 as part of the International Solar Terrestrial Physics Program (ISTP). This program will consist of a constellation of satellites supplied by the United States, Europe, the Soviet Union, and Japan. Geotail will carry APL's Energetic Particle and Ion Composition Instrument (EPIC). This instrument will measure the composition and charge state of 10 keV/q to greater than 3 MeV/nucleon ions throughout the Earth's magnetic tail.[75] The spacecraft will execute remarkable maneuvers, with a nightside double-lunar swingby to distances of 220 Earth radii in the geomagnetic tail and a low-inclination orbit at geocentric distances of 8 to 30 Earth radii.

Plans are under way to fly a large balloon-borne telescope in the Antarctic at 30 km above the surface. The telescope will supply light to a solar vector magnetograph similar to APL's ground-based one and will provide images with 10 times the spatial resolution. The plan is for it to fly for two weeks in constant sunlight above the turbulent layers of the Earth's atmosphere, which have always limited the resolution of even the largest ground-based telescopes. A series of successful balloon flights at the rate of one per year will provide magnetograms with unprecedented stability and sensitivity through all phases of the solar cycle. This research is expected to provide the basis for a Sun-monitoring observatory in space to improve forecasts of impending flares for the benefit of astronauts and many sensitive ground-based activities.

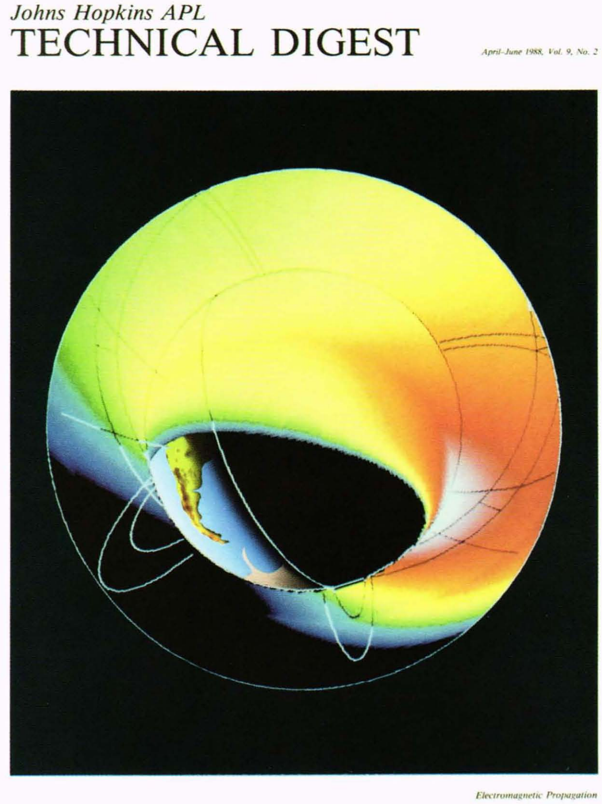

Figure 17. The cover of the April–June 1988 issue of the *Johns Hopkins APL Technical Digest* featured a computer simulation of an image of the Earth's trapped radiation expressed in energetic neutral atoms. The view is from 1400 km above a point 18 degrees from the south magnetic pole. The image was based on an actual energetic neutral atom image acquired from the ISEE-1 spacecraft during an intense geomagnetic storm.

A new instrument for viewing the magnetosphere was recently developed, based on the technique of energetic-neutral-atom (ENA) imaging.[76] This technique is based upon a charge-exchange process involving an energetic ion trapped in the geomagnetic field and neutral hydrogen atoms in the geocorona. In a charge-exchange process, the energetic ion becomes an energetic neutral particle and flies off in a straight line, unrestrained by the geomagnetic field. In this manner, the ENA can be detected with satellite instruments, and an image can be produced of the charged-particle environment of the Earth. The *Technical Digest* cover for April–June 1988 (Fig. 17) shows an image of the Earth's ring current computer-simulated by Edmond Roelof. An APL instrument that combines charged-particle measurements with the ENA imaging technique has been selected for flight by NASA on the Cassini spacecraft. This mission will investigate the vicinity of Saturn and send a probe into the atmosphere of Titan.

SUMMARY

Several possible references to the aurora may be found in the records of the ancient Greeks, and Chinese writings before 2,000 B.C. describe the magnetic compass. The

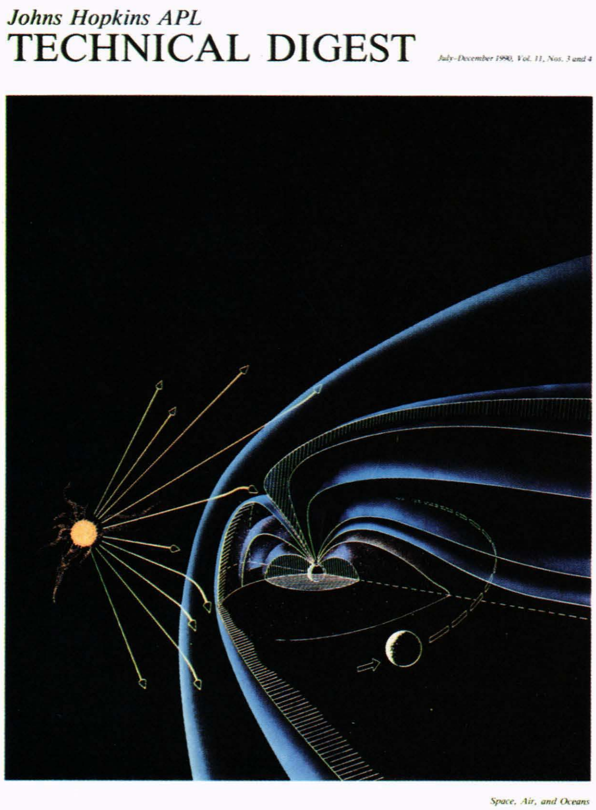

Figure 18. The Earth's magnetosphere and its interaction with the solar wind were shown on the cover of the July–December 1990 *Johns Hopkins APL Technical Digest*. The cover shows the progress that has been made in understanding the plasma environment of the Earth over the past thirty years when it is compared with the cover of the first *APL Technical Digest*, shown in Figure 2.

observation of sunspots by Galileo in 1610 led to the eighteenth-century discovery of the eleven-year sunspot cycle and recognition of the connection between solar activity and aurora. Preliminary probing of our planet's environment began in modest ways with radio waves and with experiments carried to high altitude by balloons and rockets. Space physics as an identifiable discipline began with the launch of the first Earth satellites in the late 1950s and the discovery of the Van Allen radiation belts. Discoveries made with satellite missions have revolutionized our view of the Earth and its environment. We have discovered that space is not a vacuum, but is a hostile environment that can damage satellites and kill humans. We know that the flow of plasma from the Sun severely distorts the Earth's magnetic field into a comet-like shape called the magnetosphere (Fig. 18), that most of the other planets also have magnetospheres, and that even the Solar System may have a similar configuration called the heliosphere.

The Applied Physics Laboratory has been intimately involved in many of the discoveries of space plasma physics, dating back to the pioneering work of Merle Tuve and James Van Allen. The APL space plasma physics activities have grown from a small group of scientists conducting research on energetic particles and magnetic fields in space, to an effort involving dozens of scientists and engineers investigating regions from the Earth's atmosphere, to the Sun and beyond, to the outer planets, and to the heliosphere. Space plasma physics has become a mature subject, but new observations continue to reveal phenomena not previously understood, and new techniques are being developed to provide new and unique perspectives on our environment. Continued progress will require development of complex space missions that will be technologically challenging. If the record is any indication, APL will remain an active and enthusiastic supporter and contributor to the goals of the U.S. space program and to space plasma physics.

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