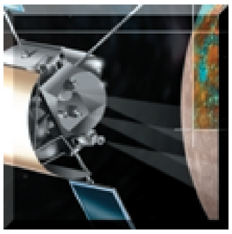


Radiation Belts and Beyond

Donald J. Williams, Barry H. Mauk, Donald G. Mitchell, Edmond C. Roelof, and Lawrence J. Zanetti

We present the beginnings and evolution of APL research into energetic charged particles and magnetic fields in space. Examples are provided of the many discoveries and surprises stemming from this research program as it progressed from a small, in-house effort in the early 1960s to today's extensive program in which the Laboratory closely interacts with the national and international space research communities. We describe a future for APL space research that promises to provide a continuing rich harvest of breakthroughs and new perspectives. These new perspectives should lead to an understanding of solar energetic particles and planetary radiation belts that will allow greatly improved predictions of space weather and its effects on systems operating in space as well as on Earth's surface. (Keywords: Particles and fields, Space Department, Space research.)

INTRODUCTION

The genesis of space research at APL occurred at the very beginning of the Transit Program, the world's first satellite navigation system. That system, a constellation of satellites in low-altitude Earth orbit, provided routine, accurate navigation fixes for 32 years before being retired from service in 1996 (see the *Johns Hopkins APL Tech. Dig.* **19**(1), 1998, for a history and description of the Transit Program). Since the early 1960s, Space Department scientists have built and launched some 67 instruments to measure energetic particles and magnetic fields in space. Of these, 37 have been flown on 28 satellites built by the Space Department, and 30 have been flown on non-APL satellites.

How did such a focused operational program spawn a basic research effort in space? As we shall see, the answer is relatively straightforward; less straightforward is the continued nurturing of that effort and the subsequent evolution of the Space Department into one of the top space research institutions in the world.

Why the need for a basic research effort in space? The answer is contained in the title of this article—radiation belts! Nearly concurrent with the inception of the Transit Program, Prof. James Van Allen of the University of Iowa (and a former APL staff member) announced the discovery of the Earth's radiation belts, intense populations of energetic (tens to thousands of kiloelectronvolts) charged particles trapped in the Earth's magnetic field. Because the intensities were sufficient to cause concern about the operations and the operating lifetimes of Earth-orbiting satellites, the Space Department began a program to characterize this newly discovered hazard at Transit satellite altitudes and assess its potential impact on the program. Consequently, the initial thrust of the Laboratory's space research effort was to measure the particles and fields in the low-Earth-orbit environment. This initial effort evolved into a research program ranging from the near-Earth environment to the far corners of the solar system.

THE EARLY DAYS

APL's entry into space research began with the launch of the University of Iowa satellite Injun I with Transit 4A on 29 June 1961. An APL designed and built solid-state proton detector was included in the Injun instrument payload. After Injun I, the Space Department built and launched a series of satellites and instruments to measure the electron and proton environment that would be encountered in Transit's near-polar, several-hundred-kilometer-altitude orbit. Highlights from this early effort included

- New knowledge about high-energy protons emitted from the Sun (solar protons) and their entry into the Earth's magnetic field
- Measurements of the injection and decay of electrons from the 1962 Starfish nuclear detonation in space (see the article by Ebert and Hoffman, this issue)
- First satellite flight of a neutron detector to search for the source of radiation belts
- First simultaneous measurements of energetic electron intensity time variations at low and high altitudes, thereby showing the global behavior of the radiation belts over extended time periods
- A direct measure of the long-term behavior of the inner radiation belt
- The first realistic, analytical model of the region in space around the Earth dominated by its magnetic field, the magnetosphere, derived in 1965 from the latitude and longitude variations of energetic electron intensities at Transit 5E-1 altitudes
- The first measurement and mapping of the electric currents flowing along magnetic field lines that play a major role in defining the high-latitude magnetosphere

As an example of these results, we show in Fig. 1a this early model of the Earth's magnetosphere. The diagram displays the noon-midnight meridional plane and clearly illustrates the finite extension of the Earth's magnetic field in the sunward direction as well as the stretched, extended field lines in the antisunward direction. This model was used successfully by APL researchers to track variations in the latitudinal structure

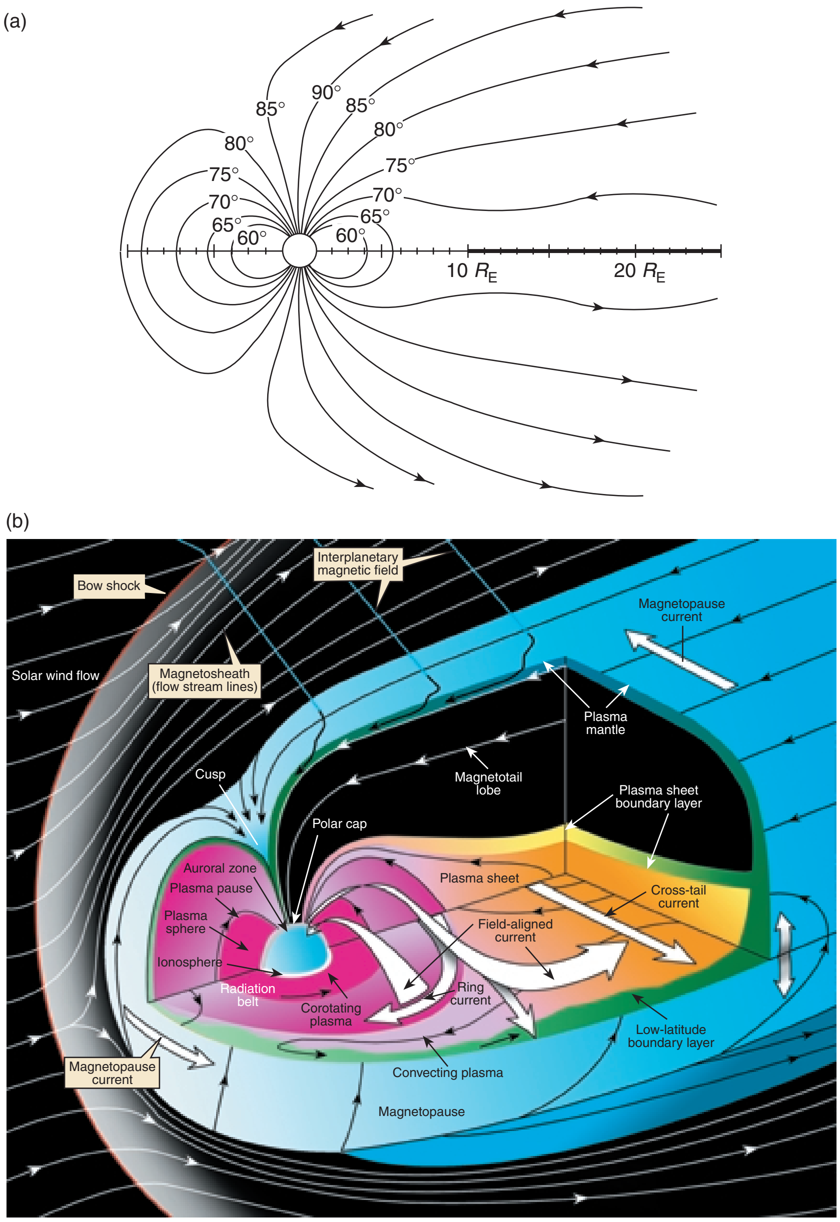


Figure 1. APL's many contributions to space research include investigation of the Earth's magnetosphere. (a) Magnetic field configuration inferred from energetic electron measurements obtained from the APL satellite Transit 5E-1 (international designation, 1963-38C). The Sun is to the left. Magnetic field lines are labeled by the latitude at which they intersect Earth's surface. The heavy solid line beginning at 10 R_E (Earth radii) in the midnight equator represents a sheet of current flowing out of the plane of the figure. (b) Schematic of the three-dimensional magnetosphere based on nearly 40 years of observations.

of electrons at Transit altitudes during geomagnetic storms. The extensive work performed by the space research community over the past four decades has resulted in greatly improved three-dimensional models of the Earth's extended magnetic field configuration. Figure 1b schematically illustrates the presently accepted view of the Earth's magnetosphere and some of its resident particle populations and current systems.

Along with their studies of solar particle intensities and radiation belt structure and dynamics, APL researchers investigated magnetic field variations measured at Transit altitudes. First reported as "transverse magnetic disturbances," these variations were soon recognized as the signatures of electric currents flowing along geomagnetic field lines. From this discovery and the subsequent mapping of the field-aligned current signatures as observed from a number of low-altitude APL satellites, researchers at the Laboratory provided the first measure of the global current systems linking the low- and high-altitude regions of the magnetosphere. A schematic of these currents, called Birkeland currents (after the Norwegian scientist, Kristian Birkeland, who postulated their existence in the early 1900s), is shown in Fig. 2.

This result was fundamental in resolving ambiguities that had existed for several decades about the nature of the low-altitude current system. From ground-based observations, early researchers had long recognized the existence of such a system. However, these observations alone were not able to determine uniquely the geometry of the currents. APL satellite observations resolved this difficulty and showed that the low-altitude currents flow out of and into the ionosphere from the high-altitude reaches of the magnetosphere, thus providing a global linkage between the ionosphere and the magnetosphere. The statistical distributions and magnitudes of these currents are used as benchmarks for a variety of magnetospheric modeling, simulation, and theoretical studies.

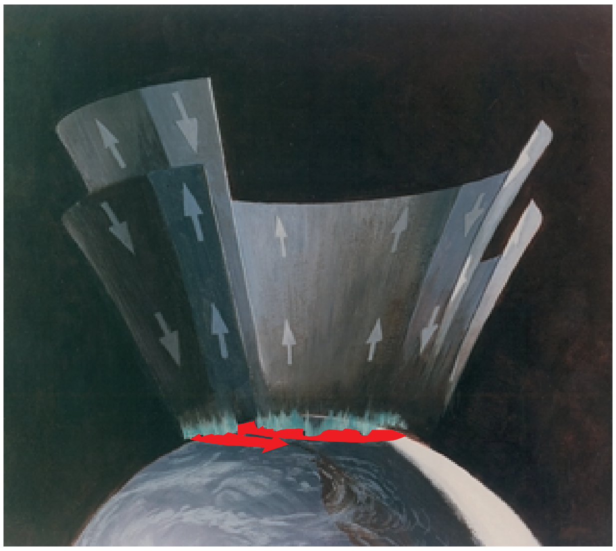


Figure 2. Artist's conception of the magnetic field-aligned current system in the ionospheric auroral zone. This system links the ionosphere to the high-altitude regions of the magnetosphere. The red arrows indicate the accompanying horizontal ionospheric current, at times carrying more than 1 million A at a 120-km altitude.

The success of APL's internal space research effort paved the way naturally to direct participation in the nation's broader space research program. Results from our early solar proton measurements led to the provision of APL designed and built solar proton monitors on three NASA Interplanetary Monitoring Platform (IMP) satellites and six NOAA weather satellites in the late 1960s and early 1970s. These APL instruments were the first to routinely monitor the intensity of solar protons in the vicinity of Earth and directly over Earth's polar caps. They produced a continuous measure of solar proton intensities in near-Earth space. In addition to these first "space weather" instruments, more sophisticated APL research instruments also were selected for inclusion in the IMP Program.

With the launch of the IMP satellites, APL's space research endeavors extended well beyond the radiation belts into the heliosphere, that volume in the interstellar medium dominated by the Sun's expanding atmosphere. And so began another phase of the Laboratory's space environment research program—studies of solar and heliospheric processes occurring outside the Earth's magnetosphere that produce the energetic particles seen during periods of solar activity.

INTO THE HELIOSPHERE

A key element of solar activity and the impact of solar particles on the Earth's environment is the propagation of these particles through the heliosphere. Which solar-active regions connect to the Earth? Do solar particles propagate unabated, or are they altered in intensity, energy, and spectral shape in their travels to the Earth? Answers to questions such as these had to be pursued to assess the effects of solar activity at Transit altitudes.

APL studies in solar and heliospheric physics in the early 1970s demonstrated the possibility of tracing the path of energetic particles observed in the near-Earth environment back along interplanetary magnetic field lines to their solar origins. These studies took into account that, in the absence of scattering, energetic charged particles simply would follow magnetic field lines as they flowed outward from the Sun. Although controversial and subject to much skepticism at the time, this finding has become a standard research factor in heliospheric studies and an important key in determining which solar regions will impact the Earth as activity develops.

We now know that energetic heliospheric particles are produced not only in active regions at the Sun but also in shock structures propagating through the heliosphere. APL research instruments on the NASA IMP satellites enabled the first detailed study of energetic ion and electron acceleration by shock waves generated at the Sun and passing the Earth. These long-lived instruments continue to return a steady stream of reliable data from locations throughout the solar system, providing researchers the database required to continue their heliospheric studies. The APL detectors on the IMP 8 satellite, still functioning some 25 years after launch, provide a dramatic example of the reliability achieved by APL instrument engineers!

Moving toward the edge of the heliosphere (Fig. 3), the NASA Voyager 1 and 2 spacecraft have carried APL instruments to the farthest corners of the solar system yet explored, some 65 AU (1 AU is the Earth-Sun distance) from the Sun. While the Voyagers are racing out of the solar system at 2.5 AU/year, APL experiments continue to measure the same species of energetic particles at 1 AU on IMP 8 and the Advanced Composition Explorer (ACE), as well as on the Ulysses spacecraft. Ulysses orbits the Sun every 5.5 years along a 1.3 × 5.3 AU ellipse whose plane is almost exactly perpendicular to the ecliptic plane containing the orbit of the Earth.

By comparing the data obtained from IMP, Voyager 1 and 2, ACE, and Ulysses, APL scientists have established that structures familiar in the 1 AU environment extend not only well out of the ecliptic plane, but also out as far as the Voyagers have reached within the ecliptic plane. The plasma ejecta from eruptions on the Sun show up many months later in the outer heliosphere. Also, periodic variations in energetic ion intensities caused by disturbances in the interplanetary plasmas and corotating interaction regions (fields that rotate with the Sun as swirling spiral streamers) can be identified by their clock-like occurrence at the positions of the distant Voyagers every 26-day solar rotation period.

This intimate coupling between the Sun's activity and the disturbances that propagate outward to at least 100 AU justifies the concept of a "heliosphere" as the dynamic cavity in the interstellar medium carved out by the Sun's expanding atmosphere. The transition region from the solar system plasma environment to that of interstellar space, the heliopause, is thought to be at a distance of many tens to over 100 AU. With the anticipation of obtaining the first measurements to be made in the interstellar medium, APL scientists are continually searching the Voyager data for signs of the approaching edge of the solar system.

During their extensive journeys, APL experiments have sampled the planetary magnetospheres of the outer solar system and have thereby enabled a program of research into outer planet magnetospheres and their

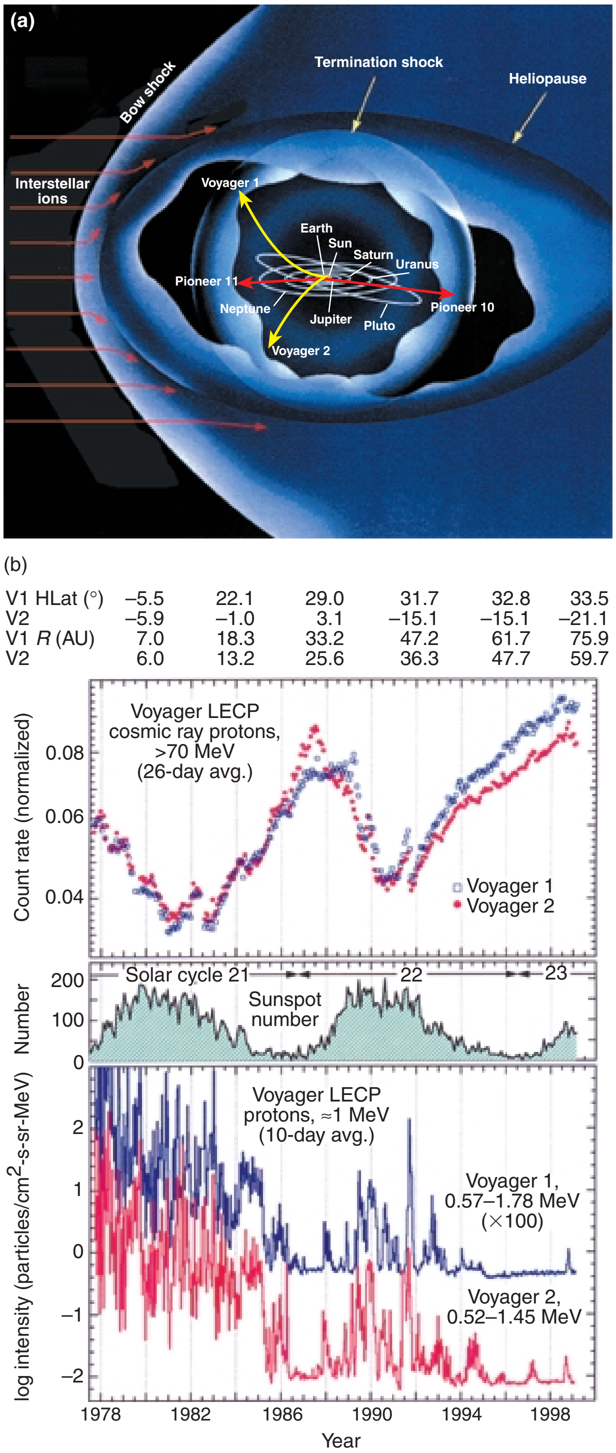


Figure 3. APL has contributed to an understanding of heliospheric physics. (a) A schematic of the heliosphere, the volume defined in the local interstellar medium by the outflowing solar wind, showing the termination shock (distance at which the supersonic solar wind becomes subsonic), heliopause (distance at which the interstellar medium is encountered), and bow shock (distance at which interstellar ions begin to be deflected around the heliopause). The positions in 1995 of active heliospheric spacecraft carrying APL instruments are shown. None of the boundaries depicted have yet been observed. (b) A 20+ year time history of proton intensities as measured on the Voyager spacecraft by the onboard APL instruments as they travel toward the edge of the heliosphere and first contact with interplanetary space. (H = heliosphere, *R* = radial distance, LECP = Low-Energy Charged Particle instrument.)

energetic particle populations. We briefly describe this program in the following section.

TO THE OUTER PLANETS

As discussed earlier, APL began a study of space environments to assess their impact on the operational space systems being designed and implemented by the Laboratory. The active role Space Department researchers have played in transforming the study of space environments into a mature scientific discipline has resulted in an in-house emphasis on basic research as well as pragmatic application. This emphasis has led, through competitive selection, to involvement with NASA's Solar System Outer Planets Exploration Program. It began with NASA's selection of APL instrumentation for inclusion onboard the Voyager 1 and 2 spacecraft, launched in 1977, and came to fruition with the Voyagers' subsequent encounters of the outer planets' magnetospheres: Jupiter's in 1979, Saturn's in 1980 and 1981, Uranus' in 1986, and Neptune's in 1989 (see the Space Science and Technology section of *Tech. Dig.* **11**(1 and 2), 1990). It has continued with the Ulysses encounter of Jupiter in 1992, the Galileo spacecraft now orbiting Jupiter (since December 1995; see "Jupiter—At Last!" in *Tech. Dig.* **17**(4), 1996), and Cassini, currently on its way to an orbiting encounter with Saturn to begin in 2004. On all of these missions, APL has provided (with vital contributions from its many collaborators worldwide) state-of-the-art instrumentation designed to study the energetic charged particle environments of the outer (nonterrestrial) planets.

The results obtained from these instruments have been nothing less than spectacular. They have demonstrated, along with previous results at Jupiter and Saturn provided by the Pioneer 10 and 11 spacecraft, a common and fundamental characteristic of magnetized planets: They are prodigious accelerators of charged particles. In certain specific cases we know the cause of the acceleration (e.g., magnetic field-aligned electric fields in Earth's auroral regions); in many other cases, the causes remain a mystery (e.g., the acceleration of electrons at Earth and Jupiter up to energies of tens of MeV, the heating of ions at Jupiter to tens of millions of degrees).

Some appreciation for the breadth and scope of these results may be gained by an examination of Fig. 4. Radiation belts are shown in energy-time ion "spectrograms" for the planets visited by Voyager 2 and for Earth (obtained from the Energetic Particle Sensor on the Earth-orbiting International Sun-Earth Explorer satellite, ISEE 1). The vertical scales show ion energies from ≈30 keV to ≈4 MeV. The horizontal scales show time in days (day of year) and radial distance *R* to the center of the respective planets (expressed in planetary radii). The time/distance axes have been scaled for each planet to show the crossings of the major boundaries determined by that planet's interaction with the solar wind. The first and last M indicate crossings of the planetary magnetopause (within which the planet's magnetic field is confined), and S indicates crossings of the bow shock (established upstream of the magnetopause in the supersonic solar wind). The colors are coded (scale to the right) according to particle intensity, i.e., particles/(cm^2 s sr keV), and the same color scale is used for all of the planets.

The intense populations of energetic charged particles residing in these planetary magnetic fields stand out clearly in Fig. 4. As the distance in each panel is scaled according to the planet's radius, a sense of the absolute scales is obtained by noting that the entire panel for the Earth would fit easily between ±2 planetary radii at Jupiter. Differences between these snapshots of planetary charged particle populations are generally related to the relative importance of solar wind control and internally driven processes. For example, many of the sudden changes seen at the Earth in Fig. 4 are reconfigurations of the Earth's distant magnetic field related to magnetic substorms and are thought to be driven by the solar wind interaction with the magnetosphere. The solar wind also is believed to be responsible for some of the structure apparent in the Uranian magnetosphere. The strong periodic modulations at Jupiter and the more subtle periodic modulations at Saturn are evidence for the dominance of internal processes.

Other planetary findings from the Voyager Low Energy Charged Particle instrument include

- Evidence that Io, through its volcanoes, is a dominant source of energetic particles within Jupiter's magnetosphere
- The observation of unexpected longitudinal differences in Saturn's energetic particle populations
- The observation that the magnetosphere of Uranus responds to solar wind variations
- Evidence that the moon Tritan is the dominant source of energetic particles in Neptune's magnetosphere

The more recent missions, Ulysses and Galileo, have added dramatically to our knowledge of the behaviors of planetary magnetospheres. The Galileo Energetic Particle Detector (EPD) has revealed vivid signatures of the strong interaction between the satellite Io and Jupiter's space environment in the form of electron beams that mimic those at Earth that produce the beautiful northern and southern lights (see *Tech. Dig.* **18**(2), 182–187, 1997). EPD data were used to discover dynamic energetic particle signatures that mimic magnetic storm signatures at Earth, a remarkable result since it indicates that the solar wind may have measurable effects deep within Jupiter's magnetosphere, despite the

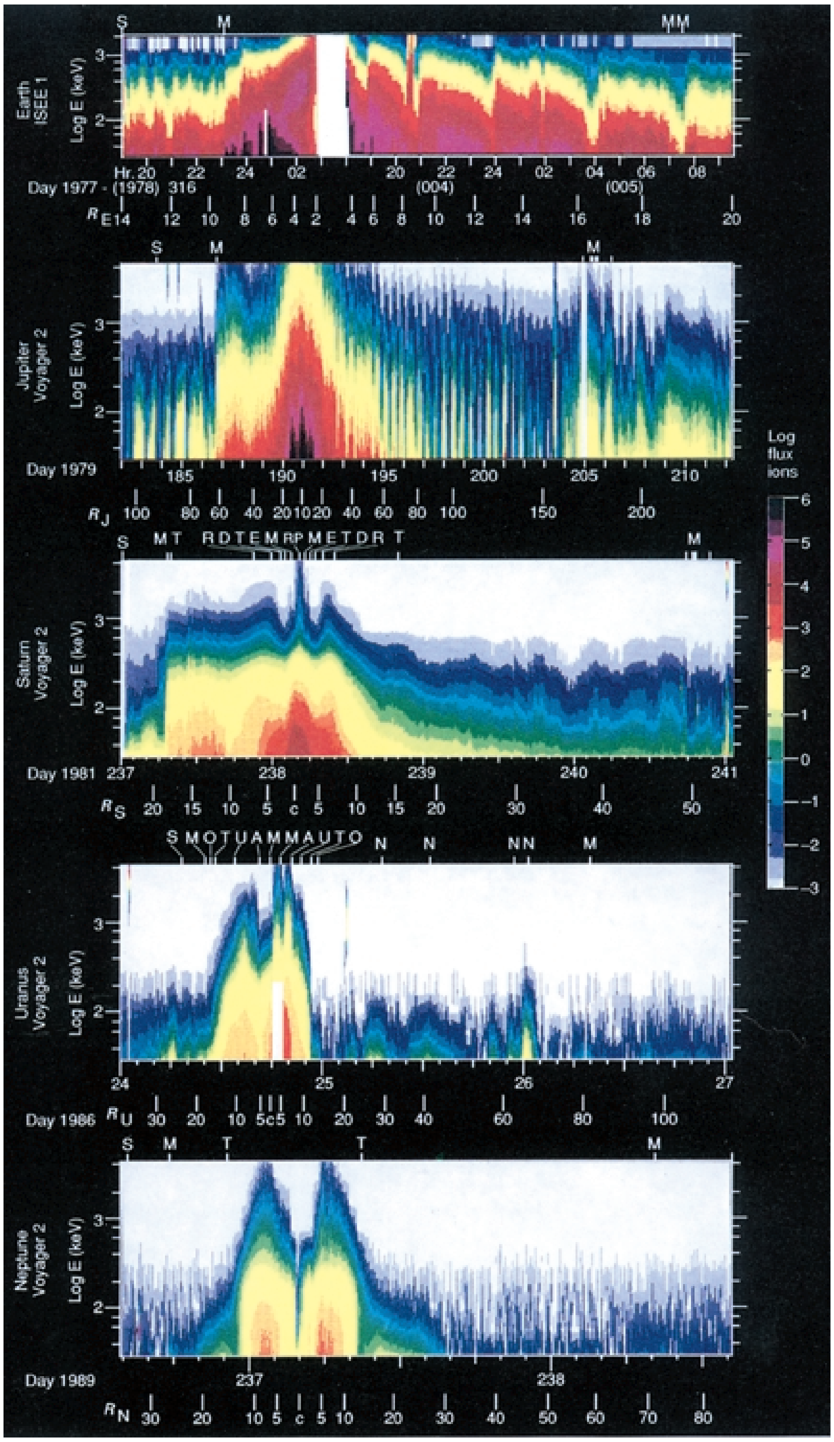


Figure 4. Computer-generated energy-time spectrograms summarizing APL energetic ion observations at Earth, Jupiter, Saturn, Uranus, and Neptune. The intensity scale on the right is common to all panels. (A more detailed discussion of the figure can be found in *Tech. Dig.* **11**(1 and 2), 63–71, 1990.)

apparent predominance of internal processes at Jupiter. Data from the EPD have also led to the discovery and exploration of a "magnetosphere within a magnetosphere," established by the magnetized moon Ganymede residing deep within the interior of Jupiter's magnetosphere. Ganymede not only possesses an intrinsic magnetic field but, as data from EPD have demonstrated, also has its own trapped particle population and therefore is a "member in good standing" of the solar system family of magnetospheres—in fact, its magnetosphere is larger than that of Mercury (Fig. 5).

THE NEXT STEP: IMAGING THE RADIATION BELTS

Continuous advances in state-of-the-art instrumentation are required to maintain the steady pace of discoveries and new knowledge that have characterized the APL space research effort over the past four decades (see the Appendix). Space Department engineers have provided this essential function in exemplary fashion. The family of energetic particle instruments developed at the Laboratory has yielded an excellent and continually improved measure of the energy spectrum, angular distribution, and composition of the charged particle populations encountered in space with energies ≥15 keV. Being insensitive to the charge state of the energetic ions, these instruments will also measure any energetic neutral atoms (ENAs) that happen to enter the detector aperture. Recognizing this, APL scientists began in the early 1980s a systematic program of demonstrating, designing, constructing, and proposing instrumentation that would provide the next major step in the study of charged particle populations in space—obtaining global images of their spatial distributions and their variations with time using the new technique of imaging ENA emissions from magnetospheric environments (see *Tech. Dig.* **9**(2), 144–163, 1988, and **11**(1 and 2), 72–76, 1990).

How do such ENA emissions arise? Often, the space environment within which energetic charged particles are observed is also permeated with a tenuous neutral particle population. Earth, for example, has a neutral hydrogen exosphere, the hydrogen geocorona that extends to many Earth radii in altitude; similar neutral

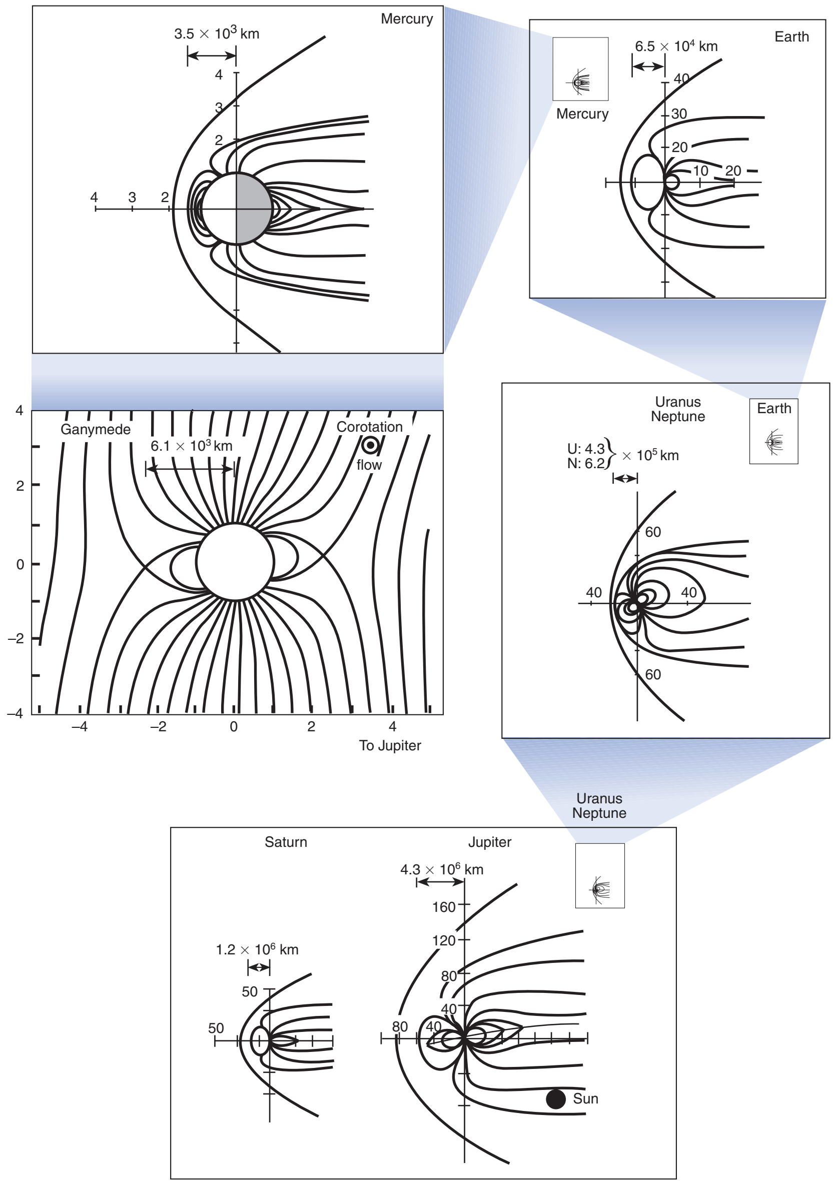


Figure 5. Schematic depicting the relative sizes of the known solar system magnetospheres. The axes are scaled in units of the radius of the body in kilometers: R_M = 2,436, R_G = 2,631, R_E = 6,378, R_U = 26,150, R_N = 24,874, R_S = 60,272, R_J = 71,434.

atmospheres, though with different composition, exist at Jupiter and Saturn.

Even the heliosphere possesses a neutral atmosphere composed of the interstellar hydrogen atoms that flow in from the local interstellar medium. With a small but non-zero probability, the resident energetic ions undergo charge exchange with these neutral atoms, resulting in the creation of a distribution of cold ions (the former neutral atmospheric atoms) and a population of ENAs that travel in straight-line paths with essentially the same speed and direction as the original energetic ions. Thus, many space environments "glow" with ENAs, much like a hot oven glows with photons. Therefore, regions in space within which the energetic ions and neutral atoms interact radiate a population of ENAs, which, when detected at a remote location, can provide an image of the interacting volume. Modeling techniques then allow us to extract a global image of the energetic ion population responsible for the ENA image.

Figure 6 illustrates what could be expected from an ideal ENA imaging instrument in Earth orbit (bottom right panel). The figure shows computer-simulated ENA images obtained from various orbital vantage points. The images, shown every 15° in latitude from 45°N to 60°S, are computed from a model ion population derived from a measured ENA image. Beginning with a view of the strong midnight-noon asymmetry of the emitting region, the views evolve through side-on views of the illuminated magnetic field lines at midnight to a view of the complex emitting structure as seen from below. In practice, an image of the energetic ion population would be extracted from each of the ENA images obtained, thereby providing a global view of the spatial structure and its time variations.

APL scientists have pioneered the ENA approach to global visualizations of the magnetosphere for more than a decade—an effort that has included developing advanced ENA measurement techniques, creating innovative modeling approaches to extract the sought-after images of the ion populations, and convincing skeptics of the feasibility of such an approach. This effort has been rewarded through the selection of APL ENA imaging instruments on two NASA research missions, the Cassini spacecraft now en route to Saturn, and the Image mission scheduled for launch into Earth orbit in early 2000. As the two instruments are essentially the same, we show in Fig. 7 a schematic and picture of the Ion and Neutral Camera (INCA), a portion of the Cassini Magnetospheric Imaging Instrument (MIMI). The size of the aperture is determined by the sensitivity required

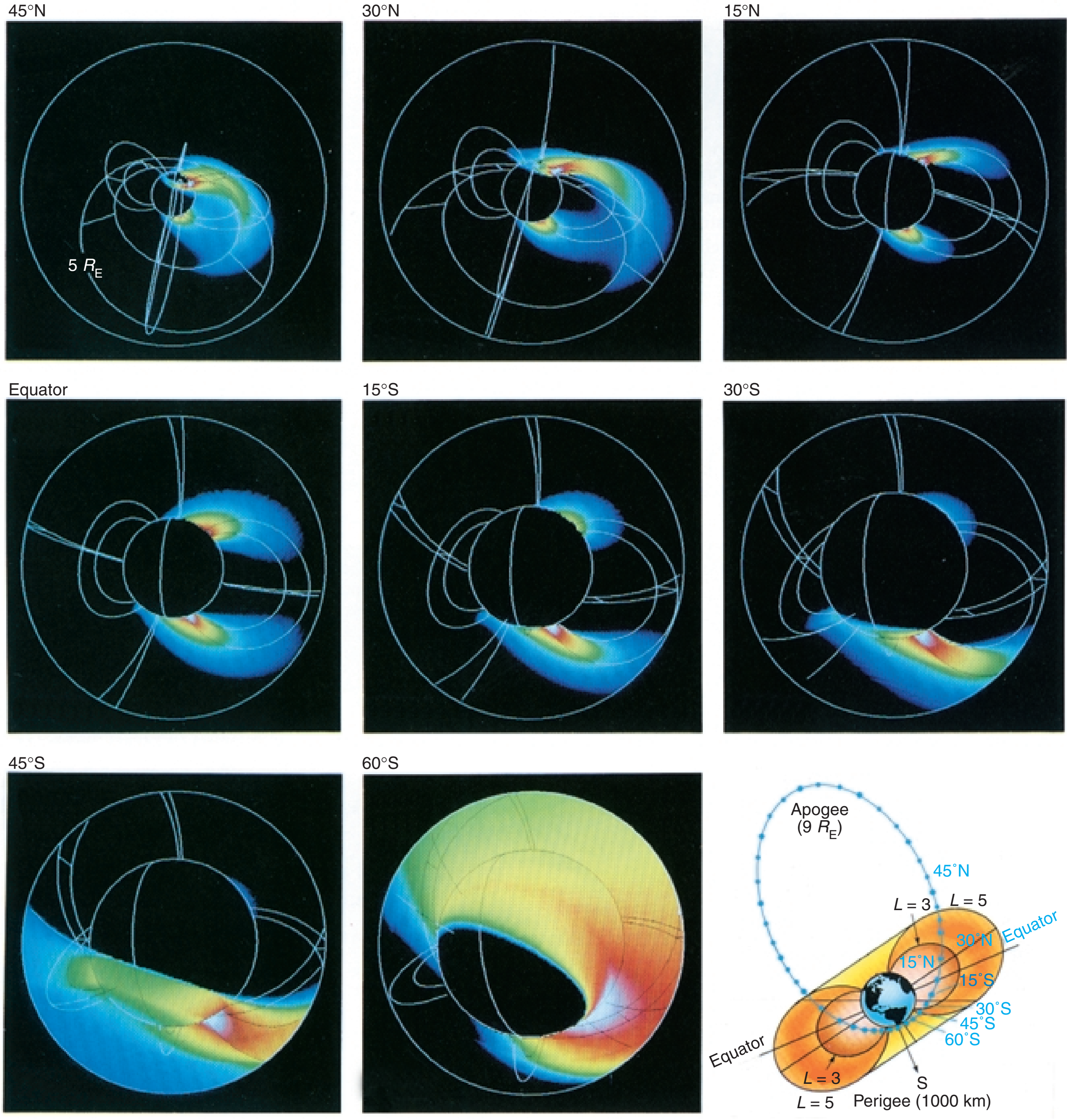


Figure 6. Computer simulation of energetic neutral atom (ENA) images generated by Earth's energetic ion population during a geomagnetic storm. The images, labeled by the latitude of observation, are shown from the corresponding perspectives in the orbit depicted in the lower right panel. Contours against the sky are as follows: circles in the magnetic equator at 3 and 5 R_E; equatorial lines of constant magnetic longitude every 45° (beginning with noon to the left); and magnetic field lines L intersecting the equator at 3 and 5 R_E in the dawn, noon, dusk, and midnight meridians. The Earth terminator is indicated; the Sun is to the left.

for obtaining statistically significant images in a physically meaningful time frame.

INCA is designed as a two-dimensional imaging instrument with a field of view of 90° × 120°. Energetic ions are deflected away from the detectors by an electric field applied across the aperture plates. To form images, INCA measures the arrival directions, velocities, and mass species of the entering ENAs. The technique involves sensing the position of the ENA, first as it penetrates an entrance foil and then at the backplane microchannel plate, thereby establishing the ENA's trajectory and time of flight within the instrument. The sensor produces images of the region within which the hot plasma interacts with the cold ambient neutral

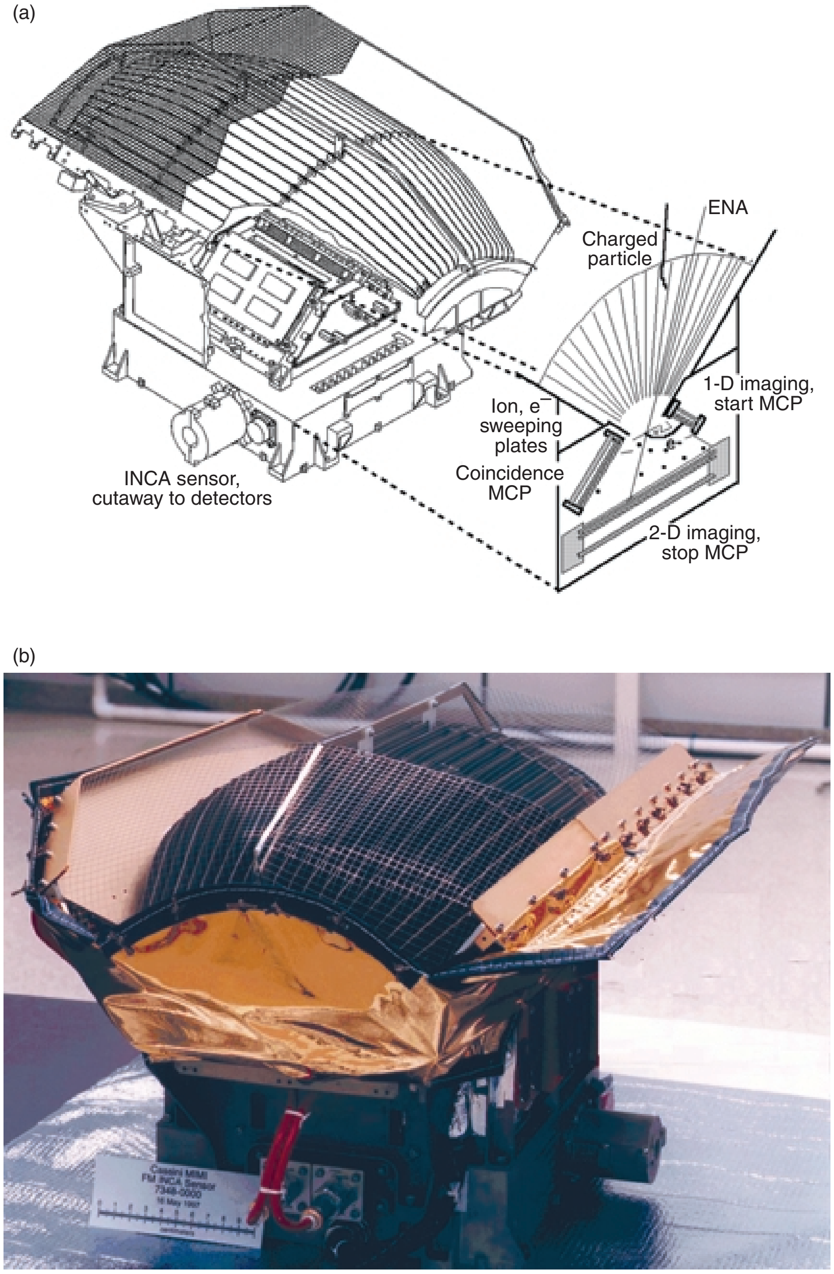


Figure 7. The Ion and Neutral Camera (INCA) sensor (a) cutaway diagram and (b) Cassini Magnetospheric Imaging INCA (flight model). ENAs pass through a collimator region with high voltages (to sweep charged particles away) and then pass through a very thin foil. Secondary electrons generated in the entrance foil are steered to a one-dimensional imaging microchannel plate (start MCP), where the position of the ENA along the entrance slot is determined, as is the start time for a time-of-flight (TOF) measurement. The ENA moves to the back of the sensor where it passes through another thin foil and then encounters a two-dimensional imaging MCP (stop MCP) where its (x, y) position is determined along with the stop time for the TOF measurement. A third, coincidence MCP is used to substantially reduce the background of the measurement. The final measurement products for the sensor are ENA arrival direction, energy, and mass species (hydrogen and oxygen).

gas sorted as a function of neutral species (O and H) and velocity (or energy) from ≈20 keV to several MeV. A large geometric factor (≈2.4 cm^2-sr) allows sufficient sensitivity to obtain statistically significant images in ≈1 to 30 min, depending on conditions and location. By turning off the deflection voltage across the aperture plates, INCA also will be configured to obtain very high sensitivity ion measurements, providing the angular, energy, and species distributions of *in situ* ions.

MIMI/INCA will provide the first global images of the energetic particle populations within Saturn's magnetosphere, beginning in 2004. When Cassini obtains a gravity assist from a flyby of Jupiter in December 2000, MIMI will capture the first global magnetospheric images of Jupiter's energetic charged particle environments. In addition, MIMI will accumulate the first images of energetic protons in the heliosphere by detecting the ENAs produced by charge-exchange collisions between shock-accelerated energetic protons and the interstellar hydrogen atoms flowing in from the local interstellar medium. Because MIMI registers these ENAs from the entire sky, the resulting data will generate an image of the energetic protons populating the interplanetary shocks and provide a global heliospheric visualization of the shock structures themselves.

Within the Saturnian magnetosphere, MIMI will yield ENA images depicting the energetic ion population's interaction with both Saturn's atmosphere and the atmosphere of its moon Titan (Fig. 8). From the global models of Saturn's ion populations as extracted from these ENA images, it will be possible to invert the convolution process and use the Titan ENA images to estimate the structure and makeup of its atmosphere. This offers the Cassini mission the unique possibility of remotely monitoring the usually invisible high-altitude regions of Titan's atmosphere, even from considerable distances.

The APL ENA imager to be launched on the Image satellite will be the first designed for high-altitude observations in the Earth's magnetosphere. It has the sensitivity to gather images similar to those shown in Fig. 6. However, the main expectations for this new, precedent-setting technique are discoveries that will give a new perspective on the global structures and dynamics of magnetospheric energetic ion populations. This shift in perspective could prove to be every bit as dramatic as the initial discovery of the Van Allen radiation belts. This next step will open a new era in the study of charged particles in space, leading to better understanding and hence to improved predictive capabilities concerning their creation and behavior. And that, after all, is why APL got into space research in the first place!

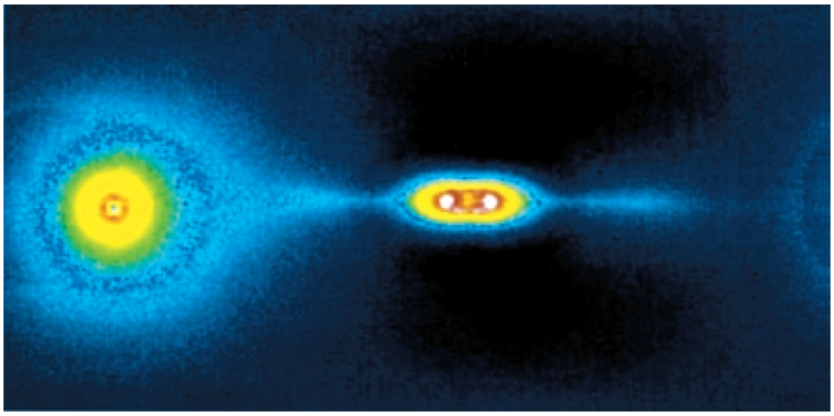


Figure 8. Simulated image of the ENA emission from the Saturnian magnetosphere, with locally enhanced emission surrounding the large moon, Titan. This enhancement is the result of the elevated cold neutral gas associated with Titan's exosphere. The image simulates an INCA image taken 3 hours from closest approach to Titan during a typical Cassini encounter.

APPENDIX: EVOLUTION OF ENERGETIC CHARGED PARTICLE DETECTORS AT APL

The schematics shown here trace the evolution of the energetic charged particle detector at APL from a simple omnidirectional configuration, which was indiscriminately sensitive to all charged particles, to the sophisticated directional species-identifying instruments of today. Figure A shows a cubical solid-state detector surrounded by a hemispherical shield. The thickness of the shield determines the energy sensitivity for electrons (represented in blue) and ions (red). The additional shielding provided below the detector by the instrument and the spacecraft generally restricts the main response of the detector to particles arriving through the hemispherical shield.

To narrow the directional response of the detector, shielding is used in Fig. B to establish an aperture defining its angular response. The use of foils over the aperture defines the electron and ion sensitivity of the instrument. Several such detectors are required on nonspinning satellites to obtain the particles' angular distribution. This arrangement often was used in conjunction with that shown in Fig. A. To improve the measurement of the angular distribution, the detector was mounted on a spin-stabilized satellite as indicated in Fig. C. Full angular distributions in the satellite spin plane could then be measured by simply sampling the detector many times during one spin period.

The configurations shown in Figs. A–C do not discriminate between species, i.e., electrons and ions are measured together. The judicious use of foils can adjust the energy response of the detector so that in specific regions in space it most likely responds to either electrons or ions. However, the ambiguity remains, and other techniques must be used to separate and identify the particles being measured. Adding a detector as in Fig. D as well as coincidence logic based on the response of both detectors partially solves this problem. A careful choice of detector thicknesses and coincidence logic allows identification of electron and ion responses. In addition, ion species can be identified for those ions penetrating the front detector.

Because electron scattering within the front detector may contaminate the ion measurement, an improved electron-ion separation technique is needed. To accomplish this, a magnetic field perpendicular to the plane is added to the configuration in Fig. E. Electrons are deflected into the side-mounted detector while ions pass through the field and impact the detector stack viewing the aperture. The addition of a third detector in the stack denotes that the energy range over which ion species are resolved is determined by the number and thickness of the detectors and foils used. The configuration in Fig. E represents an effective, efficient method of identifying and measuring electron and ion composition.

Because of the inherently three-dimensional nature of charged particle distributions in space, the two-dimensional distributions obtained in the satellite spin plane provide an incomplete and at times misleading picture of the true distributions.

Fig. A

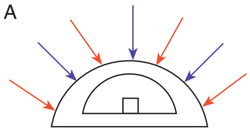


Fig. B

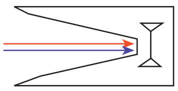


Fig. C

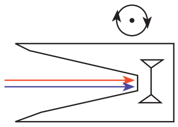


Fig. D

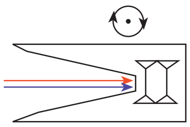


Fig. E

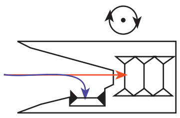


Fig. F

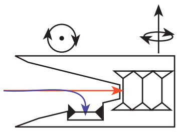
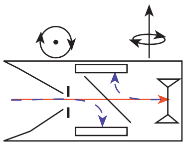


Fig. G

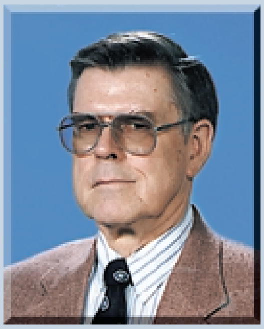


To correct this deficiency, a stepping motor has been added to the configuration shown in Fig. F. The combination of satellite spin and the stepping motor provides a complete scan of the sky so that a full three-dimensional distribution function is measured. This configuration is the basic workhorse for APL energetic charged particle measurements.

One major improvement has been the extension of the composition measurements to much lower energies through the use of time-of-flight techniques. Figure G shows such an arrangement. Ions pass through a very thin foil and impact the solid-state detector, where their energy is measured. Electrons knocked out of the foil and the detector by the ions are accelerated to the electrostatic mirror where they are deflected into the respective channel plate detectors, thereby providing start and stop pulses measuring each ion's transit time through the system. The ion's mass is then obtained from knowing its energy and transit time. This configuration often is used with that shown in Fig. F to provide as complete a description as possible of the energetic particle populations encountered in space.

None of these configurations would be possible were it not for the concomitant and dramatic improvements in the electronics required to process the detector outputs. The major improvements in speed, noise levels, power consumption, size, logic complexity, computational power, and reliability have been necessary ingredients in this evolution.

THE AUTHORS



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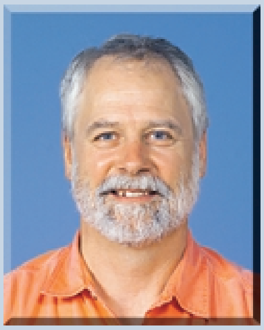

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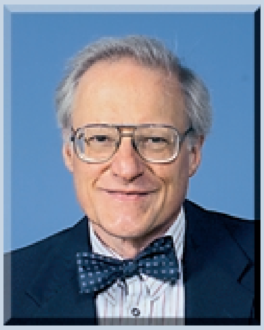

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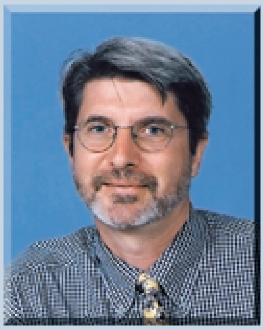

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