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THE VOYAGER PROGRAM AT APL

The Applied Physics Laboratory has designed and fabricated the low-energy charged particle instrument used in NASA's Voyager Program. In addition, APL participates in other Voyager activities through encounters of Jupiter, Saturn, Uranus, and Neptune. An overview is presented of the Laboratory's involvement with the instrument, emphasizing results achieved at Neptune.

INTRODUCTION

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. Figure 1 shows the trajectories of the Voyager 1 and 2 spacecraft projected onto the ecliptic plane and summarizes the major events of the Voyager Program.

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. The trajectory of Voyager 1 was constrained by one of its principal scientific missions: closely studying Saturn's large satellite, Titan, one of only two planetary satellites with a significant atmosphere. Had that mission been only a partial success, Voyager 2 would have served as backup, and its trajectory would have been similarly constrained. The outstanding success of Voyager 1 at Saturn and Titan allowed Voyager 2 to be targeted toward Uranus and Neptune. These close encounters occurred in early 1986 and late 1989, respectively.

Throughout all of the dramatic Voyager events, APL, with Stamatios M. Krimigis as principal investigator, has shared in the excitement through one of ten scientific instruments (eleven, if one counts the radiotelemetry system, which serves a dual purpose) that was launched with each Voyager spacecraft. Specifically, the Laboratory, with support from colleagues at the University of Maryland, the University of Kansas, and Bell Laboratories in New Jersey, designed and fabricated the low-energy charged particle (LECP) instrument. Throughout the Voyager mission, APL has also participated in mission planning, data reduction and archiving, and the scientific interpretation of the LECP and other instrument data. Over 140 articles containing LECP data have been published in refereed scientific journals; APL participation has been

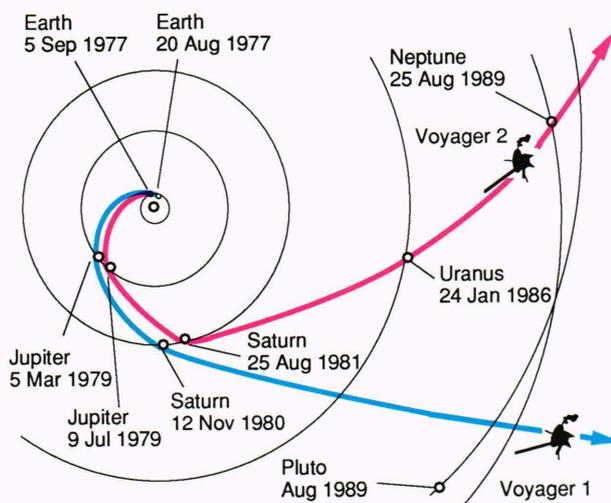


Figure 1. Voyager 1 and 2 trajectories projected onto the ecliptic or planetary orbit plane. Pluto's position at the time of the encounter of Neptune is shown for perspective; it was not encountered by Voyager.

fundamental to all results achieved. The publication rate of such articles will continue for years to come. The Voyager spacecraft (1 and 2), in general, 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 (RTG) may require that mission operations cease, since power will be insufficient to operate vital spacecraft subsystems.

THE LECP INSTRUMENT AND FUNCTION

The Laboratory designed the LECP experiment to measure the intensity, energy spectra, composition, angular distributions, and spatial and temporal characteristics of ions and electrons that are 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.

The space environment that surrounds the giant planets, as well as that around Earth, is controlled largely by the magnetic fields generated within the interiors of the planets. This magnetic field carves out a bullet-shaped cavity within the solar wind, a supersonic ionized gas that blows away from the Sun at a speed of about 400 km/s. The cavity, called a planetary magnetosphere, extends in the solar direction to a distance of about 12 planetary radii for Earth and to distances of 50 to 100 planetary radii for Jupiter. In the anti-solar direction, the "magneto-tail" portions of the cavities have been observed (for Jupiter) to extend to distances of many AU (astronomical units; 1 AU = the distance between the Sun and Earth, or 1.5×10^8 km).

An apparently fundamental characteristic of planetary magnetospheres is that they are prodigious accelerators of charged particles. Within the Earth's magnetosphere, the most well-known consequences of this process are the beautiful optical displays of the polar region called auroras (northern lights) and the Van Allen radiation belts that surround the Earth, posing radiation hazards to both astronauts and sensitive equipment. Because of the acceleration properties of magnetospheres, the ions and electrons measured by the LECP instrument are always significant, and often dominant, components of the particle populations and plasmas (ionized gases controlled by electromagnetic forces) that fill planetary magnetospheres. The characterization of the processes that generate auroras and the Van Allen belts near the giant outer planets is among the many objectives of the LECP instrument.

Figure 2 shows one flight unit of the LECP instrument. The main particle sensors are located within the dark, conical collimators on the figure. The LECP instrument consists of two major subsystems, the low-energy magnetospheric particle analyzer (LEMPA), which is attached to the upper collimator on the figure, and the low-energy particle telescope (LEPT), which is attached to the lower collimator. The LEMPA is optimized for high-particle-flux environments, while the LEPT, which performs the mass discrimination function, is optimized for low-flux environments. Both subsystems have many solid-state detectors that can be used in various coincidence/anti-coincidence configurations; resolving times are as little as 50 ns. Such fast timing provides substantial control of spurious signals in harsh radiation environments. The subsystems are both mounted within a cylindrical structure that rotates 360° with respect to the electronics box, which constitutes the lower part of the instrument. This function enables the measurement of angular variations in the particle fluxes. The hemispherical structure at the top of Figure 2 contains additional sensors that allow directional fluxes to be measured in the third dimension, perpendicular to the main rotation plane. Details of the LECP design can be found elsewhere.^{1,2}

Figure 3 shows the mounting position of the LECP instrument with respect to the rest of the Voyager spacecraft. The remote sensing instruments are all located at

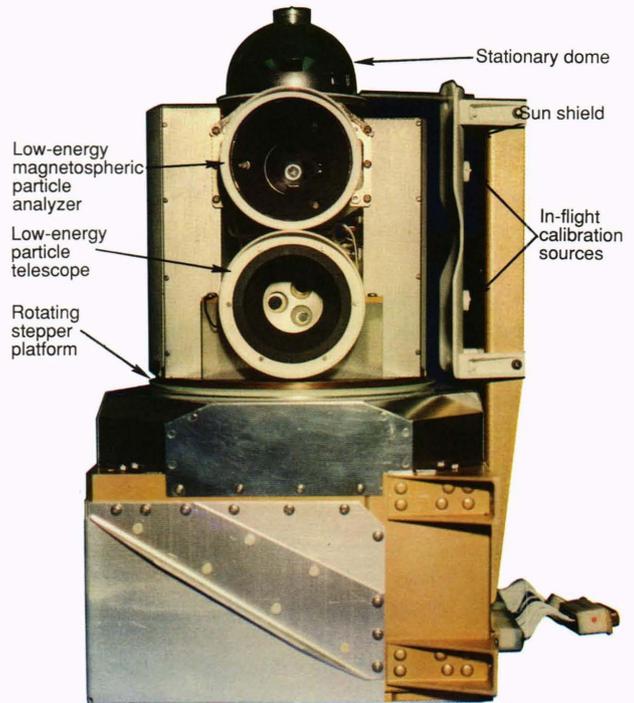


Figure 2. A flight unit of the Laboratory's LECP instrument, which flew with the Voyager 1 and 2 spacecraft.

the end of the "science boom," at the very top of the figure. The LECP instrument is located at the midway point of the boom and is one of a complement of instruments that return information about the "fields-and-particles" environment of the planetary and interplanetary regions. Supporting the LECP instrument in this effort are the Plasma Experiment, which characterizes charged particles at energies below those characterized by the LECP instrument, the Cosmic Ray Experiment, consisting of particle analyzers optimized for cosmic ray energies and fluxes, the Magnetometer Experiment, with sensors mounted on the boom at the lower left of Figure 3, the Planetary Radio Astronomy Experiment (PRA), which uses the "rabbit ears" antenna shown just below the main body of the spacecraft, and the Plasma Wave Experiment, which uses the same antenna as the PRA. Additional features shown in Figure 3 are the large, 3.7-m-dia. umbrella-shaped high-gain antenna, which almost always faces Earth to support telemetry and command functions, and the RTG, which supplies power to the spacecraft via the intermediary of heat generated by a radioactive decay process.

SCIENTIFIC FINDINGS

Many of the scientific findings of the LECP experiment have been presented in detail within the *Johns Hopkins APL Technical Digest*, generally following the occurrences of the individual planetary encounters with Jupiter,³ Saturn,^{4,5} and Uranus.^{6,7} These sources, in

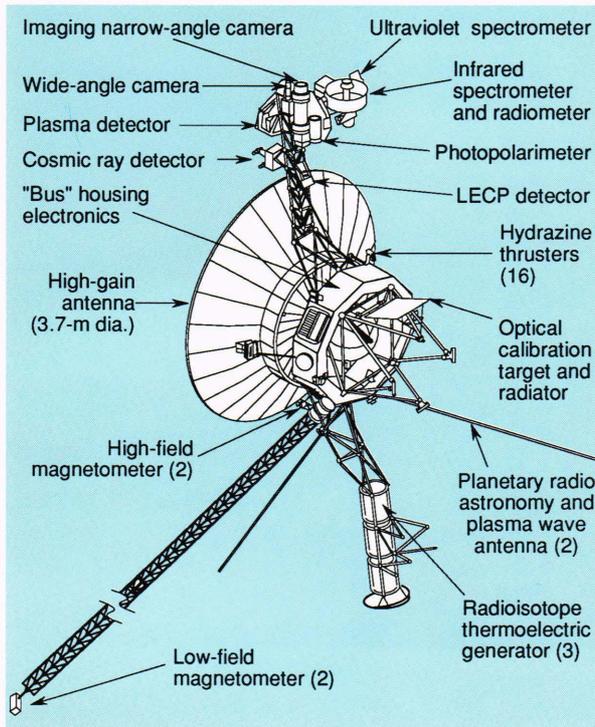


Figure 3. A drawing of the Voyager spacecraft, indicating the positions of the scientific instruments and some spacecraft subsystems. (Spacecraft shown without thermal blankets for clarity. Break in low-field magnetometer boom indicates that the boom is much longer than shown.)

turn, cite more detailed studies available in the scientific literature. One of the most important aspects of the Voyager mission is that multiple planetary magnetospheric environments have been visited by identical instrumentation. Thus, we have made substantial progress with the comparative aspects of magnetospheric studies. With systems that are too complex to understand from first principles when the information is limited, comparative studies become particularly crucial. The comparative aspects of Voyager magnetospheric studies are addressed in Refs. 6 and 7.

An appreciation for the breadth and scope of the results returned by the LECP instrument can be gained by examining Figures 4 and 5, which show energy-time "spectrograms" that summarize the LECP results at each planet. Figure 4 shows the results for the ion measurements, and Figure 5 shows electron results. For each panel, 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/cm²·s·sr·keV.) For comparison, the top panel of each figure shows results from the Earth's magnetosphere as sampled by the MEPI

(medium-energy particle instrument) experiment (Donald J. Williams of APL, principal investigator) on NASA's International Sun-Earth Explorer (ISEE-1) spacecraft.

Each Voyager planetary encounter was a "flyby," and the ISEE data were selected from different orbits to simulate an Earth flyby trajectory. In general, the spacecraft first encountered each magnetosphere from the subsolar direction, flew to within 1 to 10 planetary radii from the planet's center, and then exited the magnetosphere along the flanks of the extended magnetotail. Figure 6 shows ecliptic plane projections of the Voyager trajectories near Jupiter, Saturn, and Uranus. In each panel the Sun is to the left, and the trajectories are placed in the context of the "bow shocks" and "magnetopauses." The bow shocks appear because the solar wind blows from the Sun at supersonic speeds with respect to the planets. The magnetopauses demarcate the extent of the direct influence of the planet-generated magnetic fields. The boundaries are established by a pressure balance condition between the dynamic and thermal pressures of the solar wind on one side and the internal-magnetic plus trapped-particle thermal pressures on the other side. The trajectory of Voyager 2 at Neptune was somewhat peculiar and will be discussed later.

Returning to Figures 4 and 5, tick marks above each color spectrogram panel indicate the occurrence of specific events. The first "S" always indicates the encounter of the inbound bow shock, as previously discussed. In general (with the exception of Neptune), a shock-associated signature is observed within the LECP data (ions in particular), since plasma shock waves are sources of particle energization. The first and last "M" above each panel indicate the positions of the inbound and outbound magnetopause. For the inbound trajectories, the magnetopauses constitute a major event for the LECP data characteristics (with Neptune again being somewhat peculiar).

All of the panels of Figures 4 and 5 have been scaled to include the inbound shock and magnetopause, through the closest approach positions, and out to beyond the outbound magnetopause positions. Thus, these figures offer snapshot views of the global magnetospheric characteristics. For example, by reading the planetary radii associated with the inbound magnetopauses, one senses the relative scale sizes of the different magnetospheres. Since Jupiter's radius itself is much larger than those of the other planets ($R_J : R_S : R_U : R_N : R_E \approx 11:8:4:4:1$), its magnetosphere is clearly the giant, while Earth's is the midget.

In comparing the panels of Figures 4 and 5, we can attribute some of the differences to the characteristics of the trajectory. For example, at Uranus the trajectory left the spacecraft within the magnetosphere's magnetotail for an extended period. Thus, relative to the other panels it appears, misleadingly, that the radiation belts of Uranus (the most intense and colorful portions of the displays) are much more tightly constrained relative to the overall scale of the magnetosphere. Other differences, however, truly reflect the relative natures of the respective magnetospheres. The sharp discontinuities in the right-hand sides of the Earth's spectrograms relative, say,

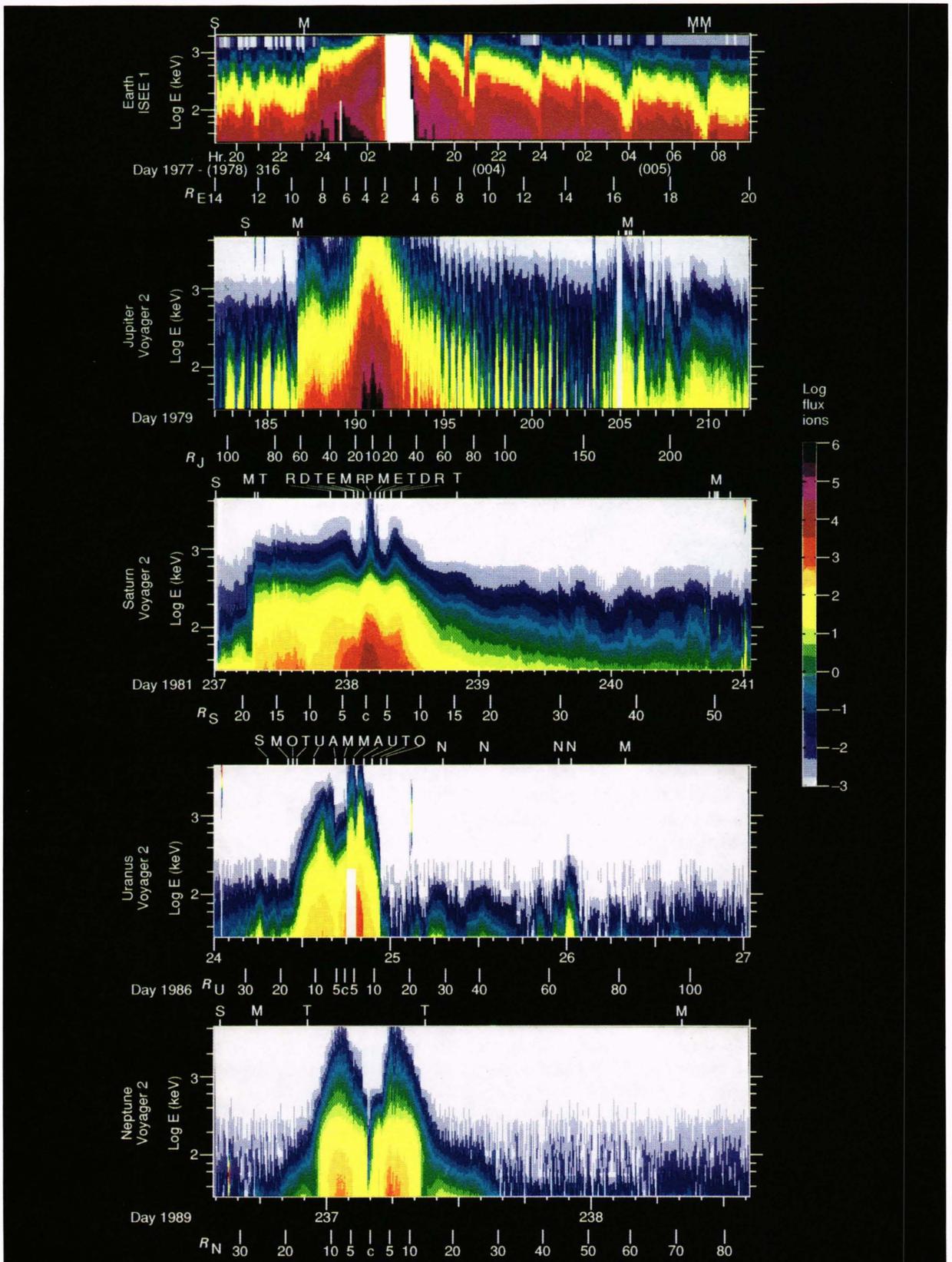


Figure 4. Energy-time intensity spectrograms (computer generated) that summarize LECP ion measurements at (from bottom to top) Neptune, Uranus, Saturn, and Jupiter. For comparison, the top panel shows results for Earth as sampled by the MEPI (medium-energy particle instrument) experiment on NASA's ISEE-1 (International Sun-Earth Explorer) spacecraft (figure generated by Donald J. Williams of APL). (A fuller discussion of Figs. 4 and 5 can be found under "Scientific Findings.")

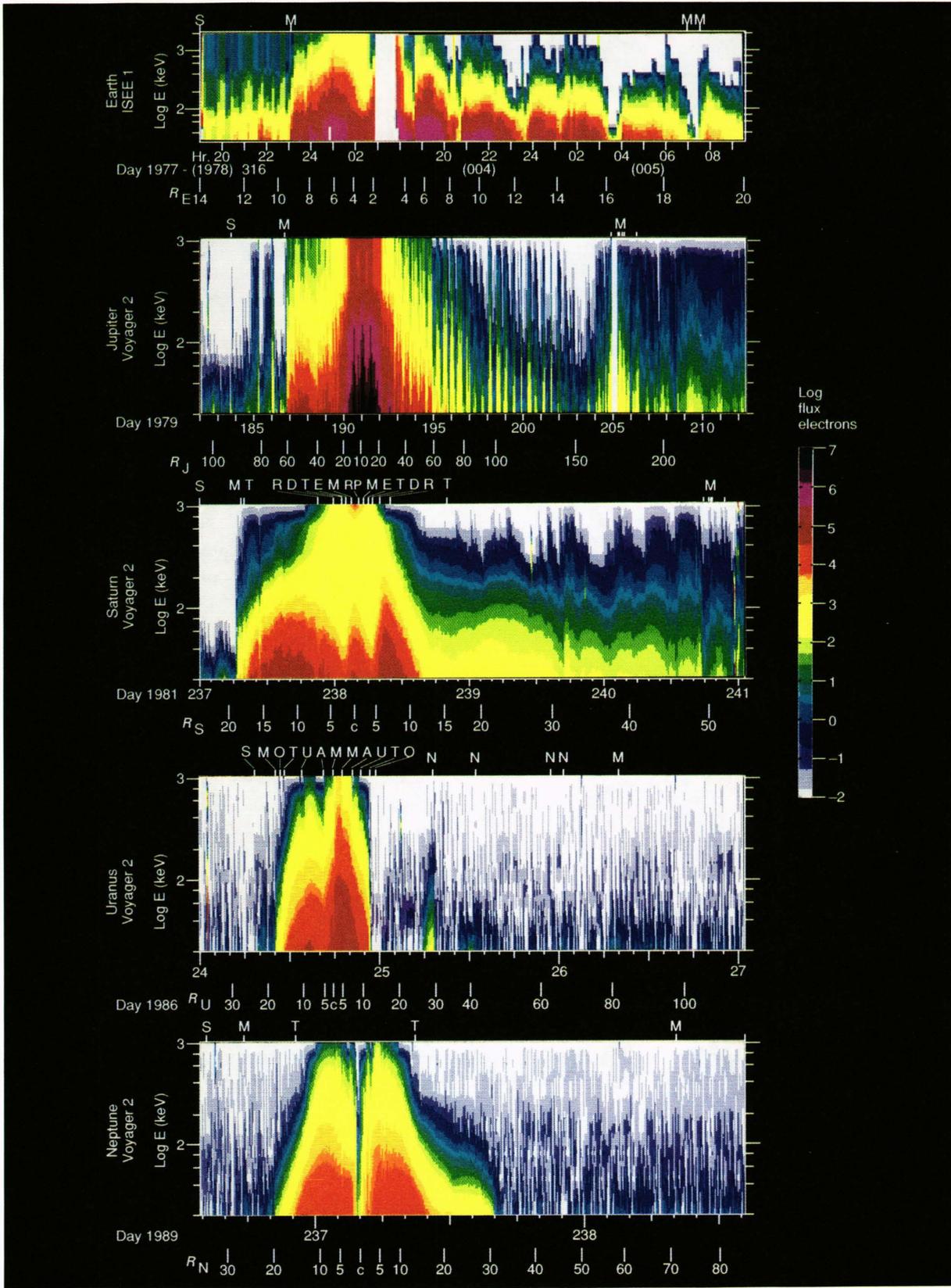


Figure 5. Same as Figure 4, but for electrons rather than ions.

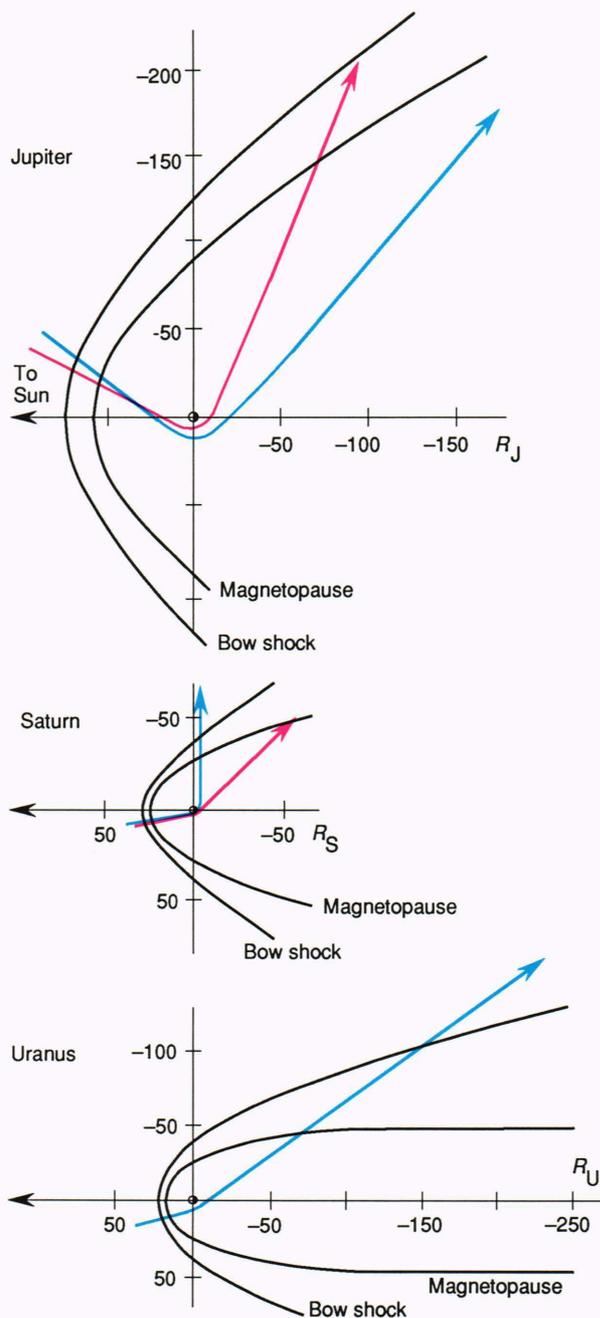


Figure 6. Ecliptic plane projections of the Voyager 1 (red) and 2 (blue) spacecraft trajectories near Jupiter, Saturn, and Uranus. The Sun is to the left for all three planets. (Sizes were scaled according to the relevant planetary radii and cannot be used to discern relative sizes of the different magnetospheres.)

to those of Saturn indicate that the Earth's magnetosphere is dynamically a much more active environment. Conventional wisdom says that the Earth's magnetosphere is powered by its highly variable interaction with the solar wind, while Saturn's magnetosphere is much more insulated from such effects, since it is powered to a greater extent by the dynamo effects associated with its rotation. Jupiter, which is another rotationally domi-

nated magnetosphere, shows dramatic, periodic modulations keyed to its rotation period (10 h). The periodicities occur because the internal magnetic axis is misaligned to the planet's spin axis by about 10° . Such effects are almost absent at Saturn due to the absence of such misalignment. The subtle spin modulations that do occur at Saturn (discovered with LECF data—see the right-hand sides of the Saturn panels) are not well understood.

The comparison between the magnetospheres of Uranus and Neptune is intriguing in that intrinsically the magnetospheric parameters are very similar. Because the spin axis of Uranus pointed almost exactly antiparallel to the solar wind velocity, however, the rotational shielding of the magnetosphere from solar wind influences was weak. Thus, some dynamical features were observed at Uranus analogous to those observed at Earth (e.g., the "spike" of activity located at the beginning of day 26 in the Uranus panel of Fig. 4). Such effects have not been identified at Neptune.

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.⁷ At Earth, the Moon is so far away ($\approx 60 R_E$) that its interactions with the magnetospheric environment are minimal. A surprise at Jupiter was that the major source of plasmas within the magnetosphere are the volcanoes of the satellite Io. For example, the LECF 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 is thought to be the solar wind (principally hydrogen and helium) and the upper atmosphere (hydrogen, helium, oxygen).

At Saturn, Uranus, and Neptune, the relative role of planetary satellites as a source of plasma particles is less clear, but the importance of magnetosphere/satellite interactions is obvious. Above the Saturn, Uranus, and Neptune panels of Figures 4 and 5 are tick marks (in addition to those labeled "S" and "M" described earlier), which indicate the times when Voyager crossed the orbital path of some of the major satellites of the respective planets. At Uranus and Neptune we see clear signatures within the LECF data associated with many of these crossings, and a general depression at Saturn near the many crossings (more detailed studies show some precise correlations). The satellites clearly have a role in controlling the intensities of the radiation belt particles. At Uranus and Neptune, the interactions are reciprocal. In particular, radiation damage to the methane ice surfaces of some of the satellites and rings, caused by the particles measured by the LECF instrument, is apparently responsible for the extremely darkened appearance of some of those surfaces.⁷

Although we have concentrated on differences apparent in Figures 4 and 5, we have ignored the obvious observation that in certain respects the magnetospheres have substantial similarities. All of the magnetospheres shown have well-developed Van Allen or radiation belt populations. Thus, as indicated previously, all of these magnetospheres are prodigious accelerators of charged

particles. This condition apparently exists irrespective of the different configurations (e.g., the degree of rotational shielding from solar wind influences) that are represented. The intensities do vary (by up to 3 orders of magnitude, according to Figs. 4 and 5), 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)—would appear to be closest in the peak radiation belt intensities that are achieved.

NEPTUNE RESULTS

The encounter by Voyager 2 of Neptune has not previously been described in the *Technical Digest*. We will provide here some details, which are summarized from Ref. 8. One exciting aspect of this encounter was the characteristics of the trajectory that was used. Figure 7 shows a sketch of the encounter geometry. A prime target of the mission was the satellite Triton, which, like Titan at Saturn, has a significant atmosphere. Other peculiarities of Triton are its retrograde orbital motion (with respect to the spin direction of Neptune) and the substantial deviation of its orbital plane away from Neptune's equatorial plane. In order for Voyager 2 to achieve a close rendezvous with Triton, the spacecraft had to travel very closely to the cloud tops of Neptune's atmosphere (≈ 5000 km) to receive a substantial gravitational trajectory assist. Also, because of the configuration of the encounter, the spacecraft flew right over Neptune's polar cap. Never before had Voyager traveled so closely to a planet, and never had it explored a planet's polar regions.

For the fields-and-particles experiments on the spacecraft, this trajectory presented an exciting possibility: processes analogous to those generating the auroras or northern lights at Earth might be directly observed within an extraterrestrial environment. The LECP team was, in fact, rewarded with observations of particle structures that are markedly similar to those observed by low-altitude Earth-orbiting satellites when they fly over optical auroral features. These structures were observed within the deep V-shaped particle dropout apparent in the bottom panels of Figures 4 and 5 when the spacecraft was near its closest approach. We do not yet understand these structures, since the environment within which they were observed is quite different from the Earth's auroral environment.

Figure 8, a schematic of Neptune's magnetosphere, summarizes other results from the Voyager encounter. The two outer boundaries are the bow shock and the magnetopause described earlier. Also, the dipolar-shaped planetary magnetic fields are shown with black lines. An important finding of several of the fields-and-particles experiments on Voyager was that the magnetic axis (\mathbf{M}) and the spin axis ($\mathbf{\Omega}$) are substantially tilted with respect to each other (by $\approx 47^\circ$, Ref. 9). Results from the Uranus encounter (where the tilt was $\approx 60^\circ$) were similar. Thus, the orientation of the magnetosphere with respect to the spacecraft trajectory depends on the spin phase

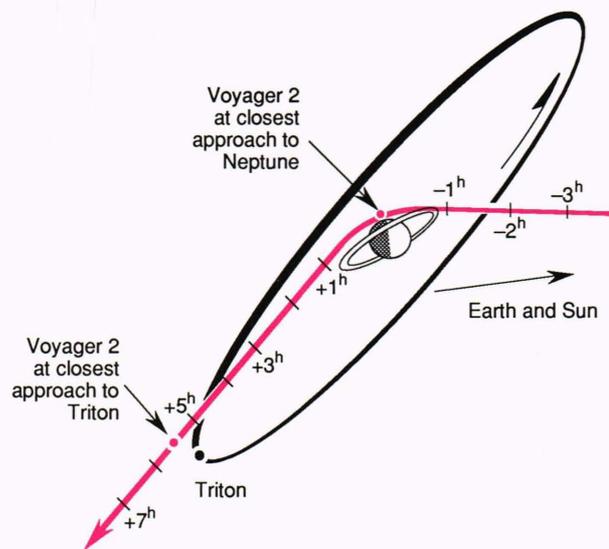


Figure 7. A schematic of the trajectory of the Voyager 2 spacecraft in the vicinity of the Neptune/Triton system. Tick marks indicate times from closest approach.

of the planet. In fact, the spacecraft crossed Neptune's magnetopause on its inbound trajectory just as the "cusp" of the internal magnetic field configuration (the funnel-shaped region where the magnetic field lines converge on their way to the planet) was pointing toward the spacecraft position. Therefore, unlike the previous encounters, a strong radiation particle signature was not observed at the magnetopause of Neptune, as mentioned earlier. Radiation belt particles tend to be confined to the vicinity of the "magnetic equators."

The most intense radiation belt particles tend to form a torus-shaped structure that surrounds the planet; its symmetry axis is dictated by the direction of the magnetic axis \mathbf{M} . A cutaway version of such a torus is shown in Figure 8. Significantly, the outer boundaries of the torus coincide approximately with the orbit of Triton, also shown on the figure. The bottom panel of Figure 4 shows that Triton (whose orbital positions are indicated with tick marks labeled "T" on the top of the panel) exerts a major controlling influence on the radiation belt particles, as alluded to earlier. Beyond Triton's orbit, the intensity of particles is dramatically reduced.

Other LECP instrument findings at Neptune include:

1. Composition measurements suggestive of an atmospheric source (including the detection of the ionized molecules, H_2).
2. Measurement of particles near Triton sufficiently intense to explain by direct particle bombardment the ultraviolet emissions observed by Voyager's ultraviolet spectrometer to be emanating from the atmosphere of Triton.
3. Measurement of particles near the newly discovered satellite 1989N1 sufficiently intense to explain by particle radiation processing the extreme darkening of the methane ice surfaces of the satellite.
4. Observation of several features within the time profiles of the LECP data that probably resulted from par-

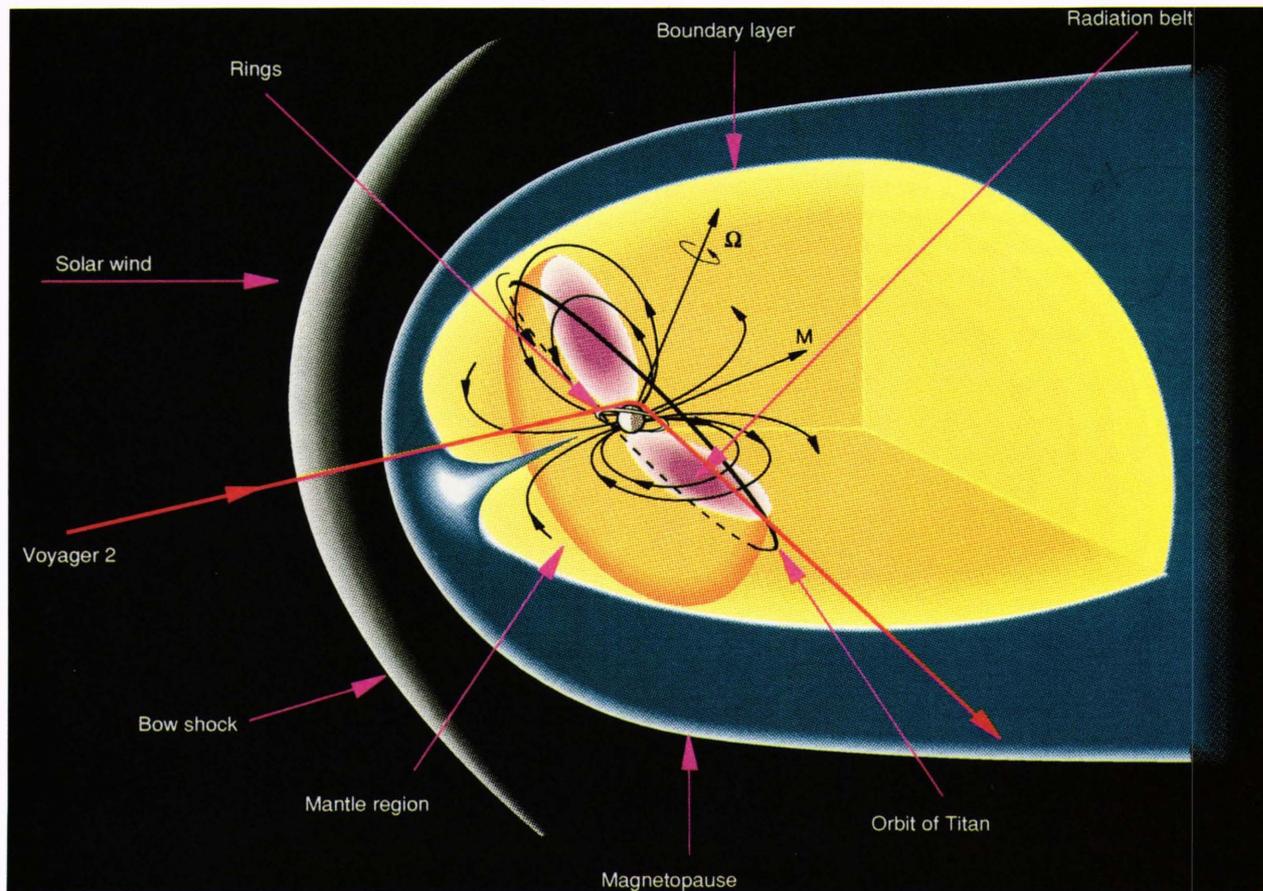


Figure 8. Schematic of Neptune's magnetosphere derived from measurements made by Voyager 2 (Ω = spin axis, M = magnetic axis).

ticle absorptions associated with some of the newly discovered satellites 1989N1 through 1989N6.

THE FUTURE

The Voyager spacecraft, both 1 and 2, continue to operate and generate valuable data about the interplanetary fields-and-particles environment.

The next great encounter anticipated by the Voyager teams is that of the plasma boundary structures separating the plasma environment of the Sun, the "heliosphere," and the plasma environment of the interstellar regions of our galaxy. 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 one anticipates 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." Within the heliopause we should find a shock wave structure (the so-called termination shock) within the solar wind that would transform the wind from supersonic to subsonic.¹⁰

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 radial position 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.

Much uncertainty exists about the positions of the heliospheric plasma boundaries, nominally placed at about 100 AU, and indications are that the positions can be quite variable. At times the termination shock could be as close in as about 50 AU.¹¹ If so, this structure could be encountered as soon as 1993 by Voyager 1. But the mission could end by around 2015 without encountering these boundaries, when Voyager 1 will be at a solar distance of about 130 AU.

In the absence of the encounter with the heliospheric boundaries, the Voyager spacecraft will continue to reveal much about the structure of the outer regions of the heliosphere. They have already revealed much more about our Solar System than anyone could have confidently anticipated.

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THE AUTHORS



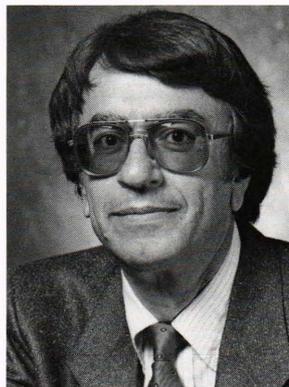
BARRY H. MAUK was born in Long Beach, California, in 1950, and received undergraduate and graduate education at the University of California at San Diego (Ph.D. in physics, 1978). Before joining APL in 1982, he was co-investigator and project scientist for an Auroral X-Ray Imaging Balloon Program at the University of Washington in Seattle. He is now a member of APL's Principal Professional Staff, co-investigator with NASA's Voyager Program, and principal investigator on a program to supply an Energetic Neutral Atom Camera to fly with NASA's Earth Observing

System platforms. Dr. Mauk's research interests focus principally on the physics of the aurora and of planetary magnetospheres. He has published about 50 papers on these topics, is associate editor of the *Journal of Geophysical Research (JGR-Space Physics)*, and has received NASA's Group Achievement Award for Voyager Science Investigations and the *JGR* Editor's Citation for excellence in refereeing.



EDWIN P. KEATH was born in Boyd, Texas, in 1937 and received a Ph.D. in physics from the North Texas State University in 1972. Before joining APL in 1974, he was a research fellow at the University of Texas at Dallas, where he carried out a study of high-energy gamma rays using a balloon-borne detector system, and was also a co-investigator on the Pioneer 8 and 9 Cosmic Ray Detector Instruments. Since coming to APL, Dr. Keath's primary research interests have been the development of spacecraft instrumentation and the study of planetary magnetospheres. He is a

co-investigator on several spacecraft programs, including the low-energy charged particle instrument on the Voyager spacecraft, the medium-energy particle analyzer on the NASA-Active Magnetospheric Particle Tracer Explorers spacecraft, and the Energetic Neutral Atom Camera for the Earth Observing System.



STAMATIOS M. KRIMIGIS is the Chief Scientist of APL's Space Department. He received degrees in physics from the University of Minnesota (bachelor's, 1961) and the University of Iowa (M.S., 1963; Ph.D., 1965, both under the direction of James A. Van Allen). He remained at Iowa as Research Associate (1965-66) and Assistant Professor of Physics (1966-68) before joining APL in 1968. Dr. Krimigis's research interests include the Earth's magnetosphere, the Sun, the interplanetary medium, and the magnetospheres of the planets. He has been the principal investigator or co-

investigator on several NASA spacecraft, including the low-energy charged particle experiment on Voyagers 1 and 2, and was principal U.S. investigator for the Active Magnetospheric Particle Tracer Explorers program. Dr. Krimigis has published over 235 papers, has been awarded the NASA Medal for Exceptional Scientific Achievement twice, and has served as Chairman of the National Academy of Sciences Committee on Solar and Space Physics. He is a Fellow of the American Geophysical Union and the American Physical Society, a member of the Citizens' Advisory Committee for the Congressional Caucus on Science and Technology, and a member of the NASA Advisory Committee on Space Science and Applications.