ionospheric plasma convection patterns, and electric fields. By 1983, when TRIAD was 11 years old, over 50 scientific articles had been published on studies of the data, written by 37 different authors throughout the world, including the U.S., U.S.S.R., the People's Republic of China, Japan, and Europe. Many of these scientists participated in a special American Geophysical Union Chapman Conference on "Magnetospheric Currents" held in April 1983. TRIAD's birthday was celebrated at that conference and a selection of the papers was published.[15]

Field-aligned currents (now often referred to as 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 that field-aligned Birkeland currents have in the flow of energy between the sun and the earth (as suggested by Gauss and Birkeland, but refuted by Kelvin and Chapman) becomes more evident with the improvement of satellite experiments and the advent of multisatellite observational programs.

## REFERENCES

[1] T. A. Potemra, "Magnetospheric Currents," *Johns Hopkins APL Tech. Dig.* **4**, 276-284 (1983).

[2] K. Birkeland, *The Norwegian Aurora Polaris Expedition 1902-3, Vol. 1, On the Cause of Magnetic Storms and the Origin of Terrestrial Magnetisms,* H. Aschehoug and Co., Christiania (Oslo), Norway (1908).

[3] S. Chapman, "On Certain Average Characteristics of World Wide Magnetic Disturbance," *Proc. R. Soc. A* **115**, 242-267 (1927).

[4] A. Dessler, "The Evolution of Arguments Regarding the Existence of Field-Aligned Currents," in *Magnetospheric Currents,* T. A. Potemra, ed., *Geophys. Monogr. Am. Geophys. Union* **28**, pp. 22-28 (1984).

[5] E. H. Vestine and S. Chapman, "The Electric Current-System of Geomagnetic Disturbances," *Terr. Magn. Atmos. Electr.* **43**, 351-382 (1938).

[6] H. Alfvén, "A Theory of Magnetic Storms and of the Aurorae," *Proc. R. Swedish Acad. Sci.* **18**, No. 3 (1939); also *Eos* **51**, 180-194 (1970) with comments by A. J. Dessler and J. M. Wilcox.

[7] S. Chapman, *Ann. de Geophys.* **24**, 497 (1968).

[8] A. J. Zmuda, "Dispersion of Velocity and Anomalous Absorption of Ultrasonics in Nitrogen," *J. Acoust. Soc. Ameri.* **23**, 472-477 (1951).

[9] A. J. Zmuda and L. N. McClung, "Vertical Extrapolation of Geometric Field Components," *Trans. Am. Geophys. Union* **36**, 939-942 (1955).

[10] E. H. Vestine, *The Rocket Technique Applied to Exploration of the Geomagnetic Field to Great Heights within the Atmosphere,* JHU/APL CM-480 (1948).

[11] A. J. Zmuda, J. H. Martin, and F. T. Heuring, "Transverse Magnetic Disturbances at 1100 km in the Auroral Region," *J. Geophys. Res.* **71**, 5033-5045 (1966).

[12] W. D. Cummings and A. J. Dessler, "Field-Aligned Currents in the Magnetosphere," *J. Geophys. Res.* **72**, 1007-1013 (1967).

[13] C. O. Bostrom, D. S. Beall, and J. C. Armstrong, "Time History of the Inner Radiation Zone, October 1963 to December 1968," *J. Geophys. Res.* **75**, 1246-1256 (1970).

[14] J. Dassoulas, "The TRIAD Spacecraft," *APL Tech. Dig.* **12**, 2-13 (1973).

[15] T. A. Potemra, ed., *Magnetospheric Currents, Geophys. Monogr. Am. Geophys. Union* **28** (1984).

ACKNOWLEDGMENTS—These studies would not have been possible without the vision and dedication of Alfred J. Zmuda and James C. Armstrong, the cooperation and support of Richard B. Kershner, the Space Department, APL, the Navy Navigation Satellite Program, and the continued support of the National Science Foundation and the Office of Naval Research. The dedication and assistance of the members of the Space Department, whose outstanding efforts contributed to the success of the 5E-1 (1963-38C) and TRIAD programs, are gratefully acknowledged.

# HOT PLASMA AND UNUSUAL COMPOSITION IN JUPITER'S MAGNETOSPHERE

STAMATIOS M. KRIMIGIS

**S. M. Krimigis, T. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, G. Gloeckler, L. J. Lanzerotti, E. P. Keath, R. D. Zwickl, J. F. Carbary, and D. C. Hamilton,** "Low Energy Charged Particle Environment at Jupiter: A First Look," *Science* **204**, 998-1003 (1979).

**S. M. Krimigis, T. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, G. Gloeckler, L. J. Lanzerotti, E. P. Keath, R. D. Zwickl, J. F. Carbary, and D. C. Hamilton,** "Hot Plasma Environment at Jupiter-Voyager 2 Results," *Science* **206**, 977-984 (1979).

The genesis of the two papers by Krimigis et al., published in 1979, that detailed the Voyager observations at Jupiter actually came eight years earlier when several of the co-authors joined a team to propose participation in the then recently announced opportunity for an "Outer Planets Grand Tour" program that envisioned sending two spacecraft to successively encounter Jupiter, Saturn, and Pluto and Jupiter, Uranus, and Neptune. Traditionally, the opportunities for such prestige missions in particle measurements had been preempted by the "Big Three" of space science at that time, namely, James Van Allen of the University of Iowa, John Simpson of the University of Chicago, and Frank McDonald, then at NASA's Goddard Space Flight Center. Our proposal represented an attempt by their former students and our contemporaries to introduce a new generation of state-of-the-art instrumentation into the study of magnetospheres.

Following evaluation of the proposals, our team was selected to participate in the definition phase of the Outer Planets mission with Robbie Vogt of Cal Tech (who proposed with McDonald) as the team leader and, in a gesture by NASA toward the younger generation, my-

## Hot Plasma Environment at Jupiter: Voyager 2 Results

Abstract. *Measurements of the hot (electron and ion energies* $\geq 20$ *and* $\geq 28$ *kiloelectron volts, respectively) plasma environment at Jupiter by the low-energy charged particle (LECP) instrument on Voyager 2 have revealed several new and unusual aspects of the Jovian magnetosphere. The magnetosphere is populated from its outer edge into a distance of at least* ~ *30 Jupiter radii* ($R_J$) *by a hot* ($3 \times 10^8$ *to* $5 \times 10^8$ *K) multicomponent plasma consisting primarily of hydrogen, oxygen, and sulfur ions. Outside* ~ *30* $R_J$ *the hot plasma exhibits ion densities from* ~ $10^{-1}$ *to* ~ $10^{-6}$ *per cubic centimeter and energy densities from* ~ $10^{-8}$ *to* $10^{-13}$ *erg per cubic centimeter, suggesting a high* $\beta$ *plasma throughout the region. The plasma is flowing in the corotation direction to the edge of the magnetosphere on the dayside, where it is confined by solar wind pressure, and to a distance of* ~ *140 to 160* $R_J$ *on the nightside at* ~ *0300 local time. Beyond* ~ *150* $R_J$ *the hot plasma flow changes into a "magnetospheric wind" blowing away from Jupiter at an angle of* ~ *20° west of the sun-Jupiter line, characterized by a temperature of* ~ $3 \times 10^8$ *K (26 kiloelectron volts), velocities ranging from* ~ *300 to* > *1000 kilometers per second, and composition similar to that observed in the inner magnetosphere. The radial profiles of the ratios of oxygen to helium and sulfur to helium* ($\leq$ *1 million electron volts per nucleon) monotonically increase toward periapsis, while the carbon to helium ratio stays relatively constant; a significant amount of sodium (Na/O* ~ *0.05) has also been identified. The hydrogen to helium ratio ranges from* ~ *20 just outside the magnetosphere to values up to* ~ *300 inside; the modulation of this ratio suggests a discontinuity in the particle population at* ~ *50 to 60* $R_J$. *Large fluctuations in energetic particle intensities were observed on the inbound trajectory as the spacecraft approached Ganymede, some of which suggest the presence of a "wake." Five- and 10-hour periodicities were observed in the magnetosphere. Calculations of plasma flow velocities with the use of Compton-Getting formalism imply that plasma is mostly corotating to large radial distances from the planet. Thus the Jovian magnetosphere is confined by a plasma boundary (as was implied by the model of Brice and Ioannidis) rather than a conventional magnetopause. Inside the plasma boundary there exists a discontinuity at* ~ *50 to 60* $R_J$; *we have named the region inside this discontinuity the "inner plasmasphere."*

We report here preliminary results from measurements made with the low-energy charged particle (LECP) instrument on Voyager 2 as it approached and traversed the magnetosphere of Jupiter. The primary objectives of the LECP instrument (*1*) are to make measurements of the hot plasma ($\geq 20$ keV and $\geq 28$ keV for electrons and ions, respectively), to characterize the composition of the hot plasma and energetic particle population, and to determine the particle flows and spatial distributions. In addition, we discuss the effects associated with the possible wake of Ganymede.

The LECP instrument consists of two basic sensors. The low-energy particle telescope (LEPT) is primarily a composition instrument capable of identifying the major ion species; the low-energy magnetosphere particle analyzer (LEMPA) performs basic hot plasma (ion-electron) measurements at low and medium energies with good electron-ion separation over a large (~ 1 to $10^{11}$ $cm^{-2}$ $sec^{-1}$ $sr^{-1}$) dynamic range. To obtain a measure of particle anisotropies on a nonspinning spacecraft, both the sensors are mounted on a stepping motor that rotates in eight steps through 360° in time intervals of 48, 192, or 384 seconds. The LECP instrument was described in (*2*).

*Inbound pass.* The LECP instrument first observed evidence of Jupiter's magnetosphere when sunward-moving ions ($E \geq 28$ keV) were observed at ~ 800 Jupiter radii ($R_J$) in front of the planet. This distance, more than one-third of an astronomical unit (AU), is substantially farther sunward than the first ion fluxes detected by LECP on Voyager 1 (~ 600 $R_J$ sunward). As on Voyager 1, the frequency of occurrence of the appearance of such ions increased as Voyager 2 approached the planet.

Figure 1a shows selected electron and ion channel count rates for the inbound traversal of the magnetosphere, which began on day 184 with the first encounter of the planet's bow shock at ~ 98 $R_J$; these bow shocks are identified primarily by the change in particle flow direction. Subsequent bow shock crossings are noted, as are the Jovian plasma boundary (rather than magnetopause) crossings, which we will explain later. Also shown are the $\alpha$ particle to proton ($p$) flux ratios and the exponent $\gamma$ of the electron and ion energy spectrum expressed as a power law in energy ($E^{-\gamma}$). A very brief excursion into the magnetosphere occurred at ~ 71 $R_J$; final entry into the magnetosphere occurred at a distance of ~ 63 $R_J$ on day 186 (identified from the low-energy electron fluxes).

The $p/\alpha$ ratio exhibits variations over a factor of 40 with the first two maxima coinciding with the two plasma boundary crossings. However, subsequent peaks in the ratio generally correspond to relative minima in particle intensities, that is, there appear to be more protons relative to helium off the equator. Generally the $p/\alpha$ ratio is much larger inside the magnetosphere than either the solar wind value (~ 20 to 50) or the Jovian atmosphere value of ~ 9 (*3*). The electron spectra became softer while the ion spectra became harder during the two plasma boundary crossings.

Prior to closest approach, the LECP experiment was commanded into a fixed, nonstep mode wherein the low-energy ends of the LEMPA and LEPT telescopes were oriented to be almost entirely covered by the sunshade. This reduced the geometrical factors of these telescopes by up to ~ 95 percent and provided the opportunity to continue composition measurements by LEPT through spacecraft periapsis. Selected ion and electron data obtained through periapsis are plotted in Fig. 1b. Unlike the Voyager 1 inbound observations, evidence of an approximate 5-hour periodicity began to appear in the particle fluxes beginning at ~ 33 $R_J$; the periodicities persisted until ~ 16 $R_J$. Jovian particle flux periodicities were previously observed by instruments on the inbound Pioneer 10 spacecraft (*4*, *5*). After the last dayside plasma boundary crossing (Fig. 1a) and prior to the onset of the periodicities, the fluxes, although variable, did not increase significantly with decreasing distance to the planet. At about the time of onset of the 5-hour periodicities, however, the fluxes began to increase toward their peak values reached near periapsis (Fig. 1b).

*Ganymede encounter.* Large fluctuations, some periodic, in the electron and ion intensities began at ~ 0400 on day 190 and terminated at ~ 1200 (all times are in SCET, spacecraft event time). The closest approach to Ganymede occurred at ~ 0714 SCET. Passage through the nominal ($O_4$ model) particle drift shell corresponding to the Ganymede orbit began at ~ 0741 and terminated at ~ 0821. The spacecraft trajectory was expected to cross the Ganymede wake region ~ 1 hour after closest approach. In Fig. 2b are shown 24-second average counting rates of several electron, proton, and ion channels at a pitch angle of ~ 90° during self as the deputy team leader. Members of the Definition Group included John Simpson and Peter Meyer from the University of Chicago, James Van Allen from the University of Iowa, and Ian Axford, then at the University of California at San Diego. Needless to say, in defining the instrument complement, each member of the definition team was constantly on alert to make sure that their own interests and aspirations were represented in the final document. Just before the completion of the Mission Definition report, however, the Nixon Administration decided that it could not afford the price tag on the Outer Planets mission, and the program, through some last-minute maneuvering, was reduced to the so-called Mariner-Jupiter-Saturn mission, which was to consist of two much less capable spacecraft that would each have only a four-year lifetime and encounter just Jupiter and Saturn.

Each of the teams represented on the Definition Group wrote new proposals, and our team was selected; neither Iowa nor Chicago made the final selection. We were notified in December 1972 that the first meeting was to take place that month at JPL to begin the process of planning the exciting mission. It should be noted that even though our proposal had been judged by the peer review selection committee as outstanding, there was quite a bit of maneuvering within NASA on how to proceed because of the difficulty in turning down the proposals of the Chicago and Iowa groups. Instrumental in arguing for participation by our team in the mission was the NASA program scientist, Mike Mitz (deceased), and the deputy director of planetary programs, Ichthiaque Rasool (now in private business in Paris). Our team consisted of Carl Bostrom and myself of APL, T. P. Armstrong of the University of Kansas (a close associate of mine from our Iowa days), George Gloeckler of the University of Maryland (a former student of Simpson and a close associate of his), C. Y. Fan, then at the University of Arizona, and W. I. Axford who served as the theorist on our team; L. J. Lanzerotti of Bell Laboratories joined the team in the second phase of the proposal for the Mariner-Jupiter-Saturn program.

The proposed instrument[1] included sensors with an energy threshold down to the 20 kiloelectronvolt range, building on the experience of the Energetic Particle Detector of Williams and Bostrom (built at APL) and the Charged Particle Measurements Experiment built by Krimigis and Armstrong (also at APL) that had just been launched on the IMP-7 spacecraft. Another sensor complement proposed to measure individual ion species down to energies of 100 to 200 kiloelectronvolts per nucleon, using very thin (2 to 5 micron) silicon detectors that had been used earlier by Krimigis and Armstrong in gross composition studies of the Earth's magnetosphere. The capability of the University of Maryland group under Gloeckler in making large rectangular detectors, not available commercially, and their experience in composition studies contributed to making the composition "telescope" very elegant, somewhat beyond the state of the art for its time.

We should recall that nothing was known about the magnetosphere of Jupiter at the time the experiment was designed. The Pioneer 10 and 11 spacecraft were launched in 1972 and 1973, respectively, and were to encounter Jupiter for the first time in 1973 and 1974. The Pioneer instrumentation consisted of detectors that had an energy threshold an order of magnitude higher ($\sim 500$ kiloelectronvolts compared to our $\sim 20$ kiloelectronvolts) for ions, and their dynamic range was substantially less than our team's design. It was precisely these instrumental differences that enabled our measurements in the Jovian magnetospheric system in 1979 to provide fundamental new information regarding the plasmas and trapped radiation, even though the two Pioneer spacecraft had already encountered the planet five years earlier.

A major discovery of the Pioneer missions had been the unexpectedly large size of Jupiter's magnetosphere, previously estimated to extend to about 50 Jovian radii (a Jupiter radius is 71,400 kilometers) upstream of the planet on the sunward side but actually observed to extend as far as about 140 Jovian radii. The agent for this tremendous inflation of Jupiter's magnetosphere was suspected to be some low-energy particle population, but the Pioneer instrumentation was unable to provide the measurements necessary to answer that essential question. As it turned out, our experiment measured the "hot plasma" component in the magnetosphere of Jupiter that provided the principal source for the inflation of the magnetosphere to such large distances from the planet. The temperatures of the plasma ranged from about 20 kiloelectronvolts to as high as 45 kiloelectronvolts ($200 \times 10^6$ to $500 \times 10^6$ K), and the density was about $10^{-3}$ per cubic centimeter; this was the hottest plasma yet observed in our investigations of the solar system up to that time. In addition, the composition telescope obtained measurements showing that the elemental abundances in the hot plasma contained heavy ions such as oxygen and sulfur in numbers that were comparable to those of protons. The source of the plasma, as became evident a few days after closest approach to the planet by Voyager 1, was elemental sulfur and sulfur dioxide injected into the magnetosphere by the volcanoes on Jupiter's satellite Io (see the front cover). Thus, an essential aspect of the basic physics of the magnetosphere of Jupiter was discovered only because the instrumentation that our team had put together was able to make measurements in a regime of energy and composition that was not previously observed. If the Pioneer 10 and 11 instruments had had that same capability, they would have discovered both the hot plasma and the unusual composition, which might have led to an inference of Ionic volcanoes back in 1973-74 prior to the observations of Voyager.

It is interesting to note that we had several discussions among members of the team on the relevance of interpreting the low-energy ion data in terms of a Maxwellian hot gas with a high energy, non-Maxwellian tail. This approach was initially agreed upon in a long conversation I had with George Gloeckler concerning an analysis that he performed on the angular distributions of ion measurements in the outer magnetosphere, where corotation velocities of the plasma are large (600 to 1000 kilometers per second). During the encounter, the team had already recognized that the angular distribution of the ions was far too anisotropic to be explained by the mere heating of protons, and that it must have had a very strong component of heavier ions, as subsequent composition measurements made clear. The validity of our interpretation in terms of a hot plasma model was clinched when we were able to confirm from Fred Scarf, principal investigator of the plasma wave instrument, that the cut-off frequencies of continuum radiation in the outer magnetosphere were consistent with densities of about $10^{-3}$ per cubic centimeter, i.e., similar to those deduced from our analysis of the charged particle data. This astounding result implied that there was no low-energy (less than 20 kiloelectronvolts) plasma in the outer magnetosphere of Jupiter, and none was measured by the MIT plasma probe on Voyager. Extensive analysis of the Voyager 2 data firmly established the inferences from Voyager 1 that the hot plasma in Jupiter's magnetosphere determines the dynamics of the interaction between the Jovian magnetic field and the solar wind.

The second and most important discovery of the Voyager encounters with the magnetosphere was the observation of plasma outflow from the nightside, which, although present in the Voyager 1 data, was not clearly identified until the Voyager 2 encounter in July 1979. It became evident that there was substantial outflow of this hot plasma from the nightside of the magnetosphere and that it most likely constituted the principal energy loss process at a rate of about $10^{20}$ ergs per second (about $10^{13}$ watts). The characteristics of that plasma outflow were examined by us in great detail, and we decided that it presented a new phenomenon that we labeled the "magnetospheric wind." In the Voyager 2 paper, we provided a conceptual sketch of what we believed to be the basic plasma physics of Jupiter's magnetosphere; the model has remained essentially unchanged to this day, despite considerable discussion within the scientific community on the details of the model.

In summary, the popularity of citations for the two papers is principally due to the novelty of the observations, which would not have been there were it not for the daring (foolishness?) of the experiments and engineers in pushing the instrument design significantly beyond what prudent, state-of-the-art instrumentation concepts would have dictated at that time. Contributing to the frequency of citations is undoubtedly the novelty of the interpretation of the observations and the significant level of discussion introduced in the theoretical community on the details of the concepts expounded in the two papers.

## REFERENCE

[1] S. M. Krimigis, T. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, G. Gloeckler, and L. J. Lanzerotti, "The Low Energy Charged Particle (LECP) Experiment on the Voyager Spacecraft," *Space Sci. Rev.* **21**, 329-354 (1977).