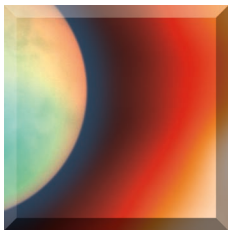

Recent Research Highlights from Planetary Magnetospheres and the Heliosphere

Christopher P. Paranicas, Robert B. Decker, Donald J. Williams, Donald G. Mitchell, Pontus C. Brandt, and Barry H. Mauk

This article briefly describes planetary magnetospheres and the heliosphere, including their structure and dynamics. Principally, we focus on the topology of these regions and their boundaries, as well as magnetospheric content and the loss of charged and neutral particles to planets, satellites, and surrounding space. Signatures of particle loss processes, such as energetic neutral atoms and auroral emissions, are considered, as is the subject of charged particle weathering of icy surfaces. In each section, consideration is given to measurement to show how data collection parallels questions about underlying physics. Recent research highlights and controversies are included throughout.

INTRODUCTION

Many solar system objects such as the Sun, Mercury, Earth, and Ganymede (the largest moon of Jupiter) possess intrinsic global magnetic fields. By contrast, some bodies such as Mars and Earth's Moon do not, but do display local magnetizations of their surfaces. In a plasma environment, globally magnetized bodies are surrounded by structures called "magnetospheres" if the magnetic field of the central body can deflect any external magnetized plasma that impinges on it. To understand this requirement for a magnetosphere to exist, it is helpful to consider the example of Earth's magnetosphere, which deflects the solar wind well before it reaches the surface. A thin layer called a "magnetopause" is formed which separates the population of the Sun's plasma (the outwardly flowing solar wind) from the terrestrial plasma. This boundary is influenced by the surrounding medium and tends to represent the balance between the "pressure" of Earth's magnetic field and the pressure of the solar wind. As conditions vary at the Sun, the pressure associated with the solar wind can change, causing planetary magnetopauses to push outward or contract until new equilibrium positions are reached.

In this article, we report on some recent work on magnetospheres in the solar system and on the heliosphere. We focus on the structure of magnetospheres first, including their magnetic topology, boundaries, and plasma and neutral content. We then shift to the subject of magnetospheric emissions, describing some older methods of studying these structures, such as auroral imaging, and some newer ones, such as energetic neutral atom (ENA) imaging. We also consider the interactions of magnetospheres with solar system objects. To

conclude, the section on weathering gives an example of how magnetospheric physics shares some common research questions with the field of planetary geology.

MAGNETOSPHERIC STRUCTURE

Topography

In Fig. 1, we have reproduced a figure from Williams et al.[1] showing the relative scale sizes of the solar system magnetospheres currently known to exist. These schematics depict the central body, some magnetic lines of force, and in several cases the magnetospheric "bow shocks." A bow shock is a standing wave upstream of the magnetopause. As ionized gas flows from the Sun (i.e., the solar wind), the bow shock represents the first boundary in space that communicates the planet's electromagnetic presence. The solar wind plasma is transformed as it passes through the bow shock where, for instance, it is slowed and heated. Higher-energy ions and electrons that are accelerated, for example, by solar flares can be further accelerated at the bow shock and deflected around it.

Each of these globally magnetized objects carves out a region of space whose shape and size depend on local conditions and the strength of the object's own magnetic field (see Ref. 2 for a more technical discussion). Mercury's magnetic moment is about one thousandth that of Earth's; it is in the strongest solar field among the planets and is continuously impacted by the highest-density solar wind among the planets. (The solar wind density decreases as the inverse square of radial distance R from the Sun, i.e., $1/R^2$, and the solar wind magnetic field strength decreases as $1/R^2$ out to roughly 3 AU and beyond that decreases as $1/R$.) Thus, Mercury's magnetosphere (R = 0.39 AU) occupies a fairly confined region of space around the planet (see Ref. 3 for a more complete discussion).

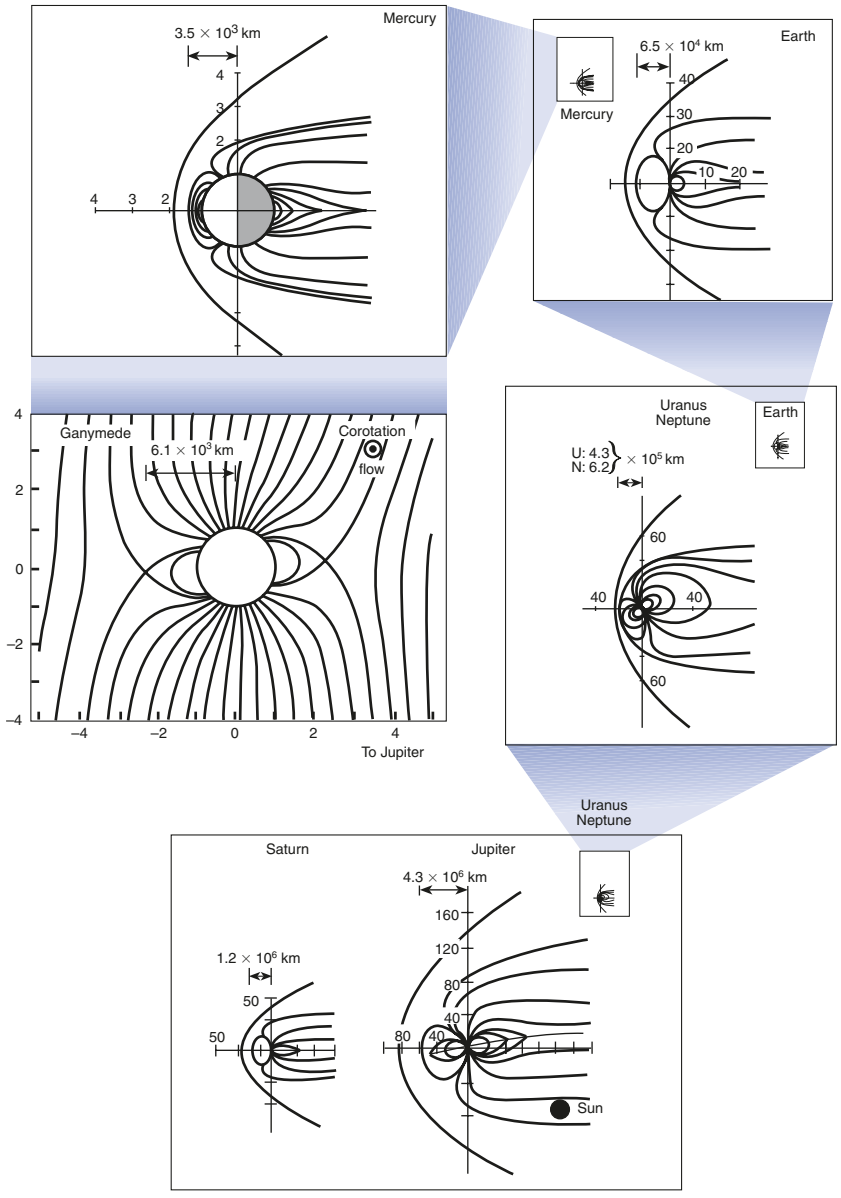

Figure 1. Planetary magnetosphere scales. This figure shows the relative scale sizes of the solar system magnetospheres. Indicated are magnetic field lines and bow shocks.

Jupiter's magnetosphere (R = 5.2 AU) is the largest among the planetary magnetospheres. It has been noted that if it were visible, Jupiter would be the largest object in the sky. The size of the Sun is drawn in Fig. 1 for comparison. Embedded within this extended structure is the satellite Ganymede's own magnetosphere, an unanticipated finding before the arrival of the Galileo spacecraft in 1995. Ganymede's intrinsic magnetic field was discovered by the magnetometer[4] and plasma wave instrument[5] on Galileo. APL's Energetic Particles Detector provided the evidence of closed magnetic field lines near Ganymede, which helped establish that this satellite's surroundings had the topology of a magnetosphere.[6]

The solar wind carries the Sun's magnetic field and creates a very large magnetic object encompassing the entire solar system and its planets. It is known from remote measurements of backscattered solar Lyman-α that an interstellar wind (speed, $\approx$25 km s^{-1}) exists outside our solar

system. Therefore, our solar system forms its own magnetosphere called the "heliosphere." It is believed that the heliospheric termination shock is formed when the much faster solar wind (speed, ≈450 km s^{-1}) meets the slower interstellar medium. Beyond the termination shock is a thick region of the slowed solar wind whose outer boundary, called the "heliopause," separates this shocked solar wind from the interstellar plasma. So, in some sense, the region bounded by the heliopause (i.e., the heliosphere) forms a magnetosphere that is turned inside out. The interstellar plasma beyond the heliopause is deflected around the heliosphere, most likely by passing through a weak bow shock.

In Fig. 2, we show a 3-D example of the magnetic field topology near the planet Mercury to illustrate a less idealized case of the fields associated with a magnetosphere. This figure, from the work of Kabin et al.,[7] shows the results of a magnetohydrodynamic simulation that explicitly takes into account the effects of the plasma on the field.

To better understand this figure, it is helpful to know that the designation of magnetic field lines as "closed" is used when both ends connect to the same magnet. Such field lines allow the trapping of energetic charged particles, which move nearly freely along field lines. As these particles move along field lines to regions of higher field strength they get reflected, and therefore are considered magnetically trapped. The Van Allen radiation belts at Earth are an example of trapped charged particles. Figure 2 shows that the relatively confined closed field line region of Mercury's magnetosphere would not sustain the kinds of radiation belts found at Earth or Jupiter (see below). Also shown are "open" magnetic field lines. These have a single footpoint on the central body and connect to the magnetic field of the surrounding medium. The open field lines shown in Fig. 1 are swept back in the anti-sunward direction because flowing plasma moving away from the Sun at speeds of 300–700 km s^{-1} drags the field lines with it. The open field lines in Fig. 2 represent a numerical solution that includes the surrounding fields and plasma.

Boundary Structures

Magnetospheric boundaries represent transition regions, which, for instance, can separate nearly equal magnetic fields that originate from different sources. Numerous spacecraft have, taken together, made measurements at the boundaries of all six known planetary magnetospheres and the one known moon magnetosphere, Ganymede. Only the heliosphere's boundary regions have not been characterized by *in situ* measurements. This appears to be changing as the two Voyager spacecraft approach the edges of the solar system. As of mid-2005, Voyager 1 was at about 96 AU and Voyager 2 was at 77 AU. It is worthwhile to consider the heliospheric case in more detail because it shows how quickly the search for these predicted structures can become very complicated.

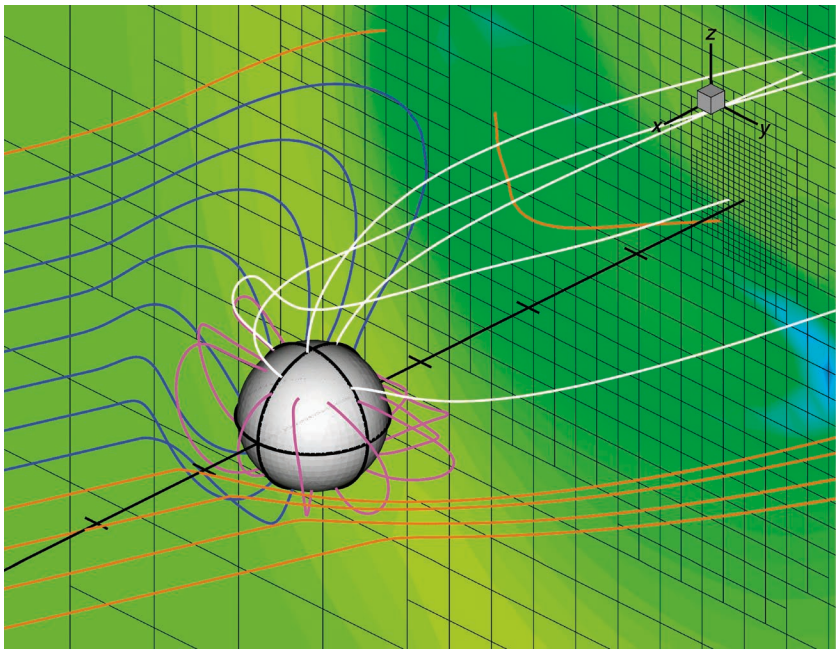

Figure 2. Magnetic field lines near Mercury created in a magnetohydrodynamic simulation. Open (white and purple) and closed (magenta) Mercury field lines are shown as well as the solar wind field (orange) not connected to the planet. The purple and white field lines connect, respectively, to the northern and southern hemisphere of the planet. The *x* axis is in the direction of the solar wind flow. (Reproduced from Ref. 7 with permission from Elsevier, © 2000.)

The global structure of the heliosphere itself can be modeled by numerically solving a complex set of coupled differential equations that include various quantities of observational interest. Figure 3 shows color-coded plasma proton temperatures (see the color bar) and streamlines of thermal proton flow velocities (curves with arrows).[8] The shortest distance from the Sun to the heliospheric bow shock is several thousand times greater than the shortest distance from Jupiter to its bow shock (see Fig. 1). By analogy with the planetary magnetospheres, several other boundaries are also anticipated. Cool interstellar plasma flows in from the right (see streamlines), is slightly heated and deflected across a possible weak bow shock, and is further deflected as it is forced to flow around the heliopause. Meanwhile, the supersonic solar wind plasma (streamlines) flows radially outward from the Sun (at the origin in this meridional view of the heliosphere),

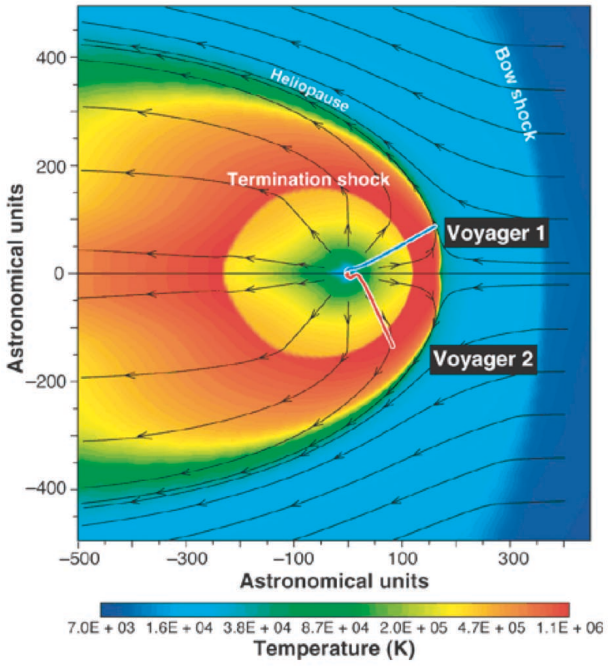

Figure 3. Trajectories of Voyager 1 (blue) and 2 (red) superimposed on the heliosphere. Like the planetary magnetospheres, a bow shock is formed as well as a heliopause. The detection of these boundaries relies on measurements of subtle changes in the local particles and fields. (Reproduced from Ref. 8 with permission from AAAS, © 2001. See also www.sciencemag.org.)

is gradually heated by interactions with interstellar neutral ions, and is then decelerated to subsonic speeds, deflected, compressed, and further heated as it crosses the termination shock. This shocked solar wind plasma in the heliosheath (the region between the termination shock and the heliopause) is redirected to flow from right to left down the enormous volume known as the "heliotail." It is the heliopause that separates the heliosphere proper (the region containing material mainly of solar origin) from the interstellar medium.

Also shown in Fig. 3 are the trajectories of the Voyager 1 and 2 spacecraft, as projected forward in time so that Voyager 1 crosses the heliopause at about 175 AU (in the year 2027); this is about 400 times the distance from Earth to our Moon.

Recently, instruments on Voyager 1 reported evidence that the spacecraft had come close to the termination shock. Beginning in mid-2002, the two instruments that detect energetic ions and electrons observed abrupt intensity increases that could not be explained as populations of energetic particles originating from solar activity. These intensity increases include short-scale bursts (lasting a few hours or days) that are superposed on medium-term plateaus (lasting several months) that are, in turn, superposed on an overall long-term (at least 2.5 years) increase.

Had Voyager 1 crossed the termination shock? In principle, this question should be readily answered by examining data from the plasma instrument; unfortunately, the plasma instrument on Voyager 1 has been inoperable since 1980. However, based on analyses of the arrival directions of low-energy ions into the Low Energy Charged Particle (LECP) instrument, Krimigis et al.[9] claimed that Voyager 1 had indeed entered a region of subsonic solar wind flow (i.e., the heliosheath) in mid-2000 at 85 AU, remained there for about 6 months, and then re-entered the supersonic solar wind in early 2003 at 87 AU (the termination shock is expected to move in and out in response to variations in solar wind dynamic pressure). This claim has been disputed by members of the Voyager 1 cosmic ray subsystem team[10] and magnetic field team.[11] The latter agree that Voyager 1 is monitoring energetic particles from the termination shock, but contend that Voyager 1 has remained in the near-upstream (i.e., sunward) vicinity of the shock. Although this debate continues, we expect to set more reliable limits on flow speeds based on more refined analyses of 2.5 years' worth of termination shock–associated data, now in hand.

Magnetospheric Populations

All the known magnetospheres (and the heliosphere) contain plasma, often coexisting with neutral gas and other material (dust, ring particles, satellites, etc). In this section, we give a few examples of how the contents of the heliosphere and planetary magnetospheres are used to understand how matter and energy flow through these structures.

Magnetospheric plasmas have very low densities; e.g., near Jupiter's satellite Europa, plasma pressures are about 10^{-13} bar, compared with about 1 bar at the Earth's surface. Still, these particles are responsible for many aspects of magnetospheric dynamics and for much of the magnetosphere's emission to surrounding space. For example, electrons in Jupiter's inner magnetosphere are responsible for synchrotron radiation, which was detected as a radio signal at Earth in the 1950s.[12] Charged particles are also responsible for various kinds of global emissions such as the planetary aurorae and the flux of ENAs, both of which are imaged remotely. Finally, despite their small number, magnetospheric and heliospheric particles weather surfaces in space, literally chipping away at icy surfaces and chemically modifying them (see the next section).

Much attention is paid to the composition of charged and neutral particles. Composition is a signature of each particle's source and is used to study how matter flows through these systems, how it becomes transformed and energized, and how it is ultimately lost to the planet's atmosphere, rings and satellites, or surrounding space. Analyses of the ions in Earth's magnetosphere, for instance, suggest that some ions are of ionospheric origin while others can be traced to the solar wind. Jupiter's

magnetosphere is heavily populated by the dissociation and ionization products of SO_2, which is continuously supplied by the volcanic satellite Io. Saturn's magnetosphere has an abundance of neutral OH gas, which was detected by the Hubble Space Telescope (HST) because it emits at 350 nm. Composition studies are critical at the magnetized outer planets (Jupiter, Saturn, Uranus, and Neptune) because ring and satellite surfaces and atmospheres continuously exchange material with magnetospheres.

The heliosphere provides an interesting example that reveals how charged particle population studies can be connected to details of the particles' source. As expected, ions in the solar wind tend to reflect the solar composition ratio (90–95% protons, 5% He^{++}, with trace ions of O, C, Si, and others). Most of the He in the solar wind is doubly ionized; the singly ionized He component constitutes only about 10^{-4} of the solar wind composition (G. Ho, APL, personal communication, 2005). Non-negligible fluxes of He^{+}, or "pickup helium," begin to appear at energies of a few times the solar wind speed. This is because pickup helium originates from interstellar neutrals that enter the solar system and become ionized. As ions, these particles are then carried away from the Sun, i.e., they are picked up by the outwardly flowing solar wind. Many interstellar neutrals continuously enter our solar system and, depending on their ionization potentials or interactions with the solar wind plasma, get picked up at different radial distances from the Sun and are carried back outward. These freshly created ions can become highly energized near the Sun's termination shock described above, providing the source of so-called anomalous cosmic rays that are detected throughout the solar system.

Another interesting example is the upper atmosphere of Mars and the loss of its atmospheric population. The interior of Mars was once thought to contain a dynamo-generated magnetic field that could withstand the impacting solar wind. Some evidence suggests that when the Martian magnetosphere was formed, oceans or lakes existed on that planet. The Martian dynamo likely died early, during Mars' Noachian Epoch,[13] leaving the planet with no magnetic field and an upper atmosphere directly exposed to the solar wind.

Whether a body has a magnetosphere or not, some surface molecules can be photo-dissociated and the dissociation products can be photo-ionized. Without a magnetosphere, ions created in this manner can be carried off by the action of the solar wind near the surface. On Mars, some water remains frozen in the shallow subsurface and in the polar caps; even today, the Martian atmosphere apparently continually loses mass. APL is participating in the Aspera 3 plasma experiment onboard the European Mars Express mission. This experiment is collecting ions of different composition to study these processes and the origins of various ions.

MAGNETOSPHERIC EMISSIONS

As noted earlier, features of Jupiter's magnetosphere were detected from Earth as early as the 1950s, when so-called decametric emissions were measured coming from that planet. Likewise, Shemansky et al.[14] detected OH densities at Saturn using HST measurements, illustrating the power of investigating distant bodies from Earth orbit. Some of the most striking emissions from planetary magnetospheres are auroral. Taken together, these various kinds of emissions are used to study the properties of magnetospheres remotely, and they reveal critical details about both the structure (e.g., boundaries and content) and dynamics (e.g., how particles are injected, lost, and radiate) of magnetospheres. In this section, we discuss some types of emissions and how they are used to study magnetospheres.

In Fig. 4, we show a UV image from the HST of Jupiter's aurora in the northern hemisphere of the planet. Indicated on the figure are the footprints of three of the Galilean satellites—Io, Europa, and Ganymede—whose radial distances from Jupiter are 5.9, 9.4, and 15 R_J, respectively (1 R_J = 71,398 km). As these satellite locations are known, it was determined that Jupiter's main auroral oval must correspond (following magnetic field lines) to regions in the magnetosphere beyond 15 R_J. The means by which these icy bodies transmit a signal to the distant auroral region of Jupiter contains a lot of

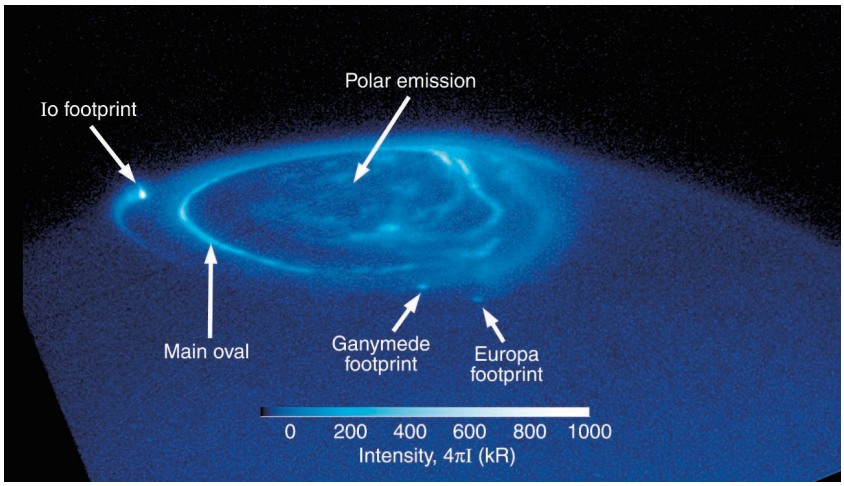

Figure 4. The Jovian aurora in UV as measured by the HST imaging spectrograph. The footprint of Io and its small tail as well as the footprints of other satellites are illustrated. Note the asymmetries in the main oval and the activity contained by it.

interesting physics. A recent discussion of these emissions can be found in Ref. 15.

Another type of emission entirely is that in ENAs (Brandt et al., this issue, give a complete description of the history of ENA imaging and its current applications). ENAs are created when singly charged energetic ions undergo charge exchange with ambient neutral gas. No longer ions and magnetically trapped, ENAs exit magnetospheres in nearly straight-line paths and survive to great distances in surrounding space. ENA imaging of the outer planets is a new endeavor. APL's magnetospheric imaging instrument on the Cassini spacecraft has enabled us to make global images of ENA fluxes from the magnetospheres of Jupiter and Saturn as well as the atmosphere of the satellite Titan. ENA images of Jupiter were obtained near the end of 2000, when Cassini flew by that planet. Mauk and colleagues[16] used ENA images from Jupiter to confirm the presence of a neutral gas torus associated with the satellite Europa (originally predicted by Lagg et al.[17]). Before this discovery, only the satellite Io was thought to produce enough neutrals to sustain what amounts to an extended atmosphere reaching around Jupiter.

Figure 5 is an ENA image of Saturn's magnetosphere obtained by Cassini. This figure[18] shows high fluxes of ENAs originating predominately from within about 10 R_S of the planet. Peak ENA brightnesses occur when injected and/or inwardly diffusing ions encounter clouds of OH, O, H, and other neutral gases. Other detections of neutral gas, such as the OH cloud inferred from the HST or more recent UV analyses,[14] can be used in conjunction with these images to detect material that is illusive at optical wavelengths. Furthermore, by using successive ENA images, we can, for instance, track populations of ions that are injected deep within magnetospheres and corotate with the planet. These investigations help us to study not only ion and neutral populations but also their dynamics.

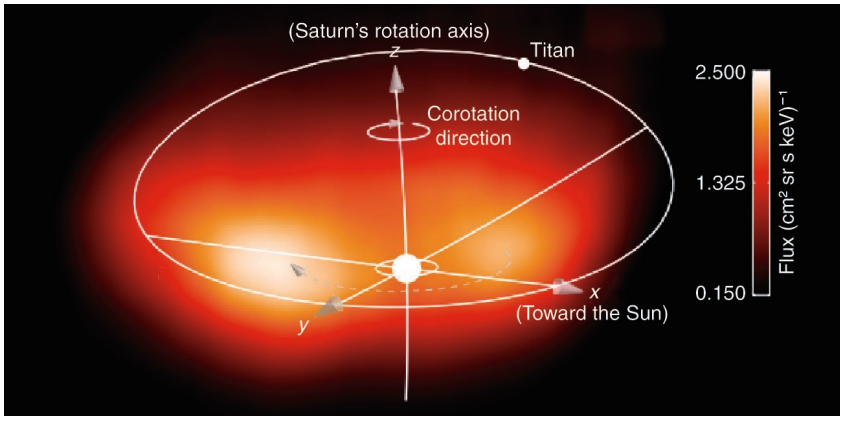

Figure 5. Saturn's magnetosphere as imaged in ENAs. Cassini was south of the planet's spin plane. The orbit of the satellite Titan is approximately 20 R_S (1 R_S = 60,268 km). This figure gives a sense of the global extent of ENA emissions. (Reproduced from Ref.18 with permission from AAAS, © 2005. See also www.sciencemag.org.)

WEATHERING

In this final section, we discuss the role of magnetospheric populations in weathering satellites. Satellite surfaces and other surfaces in the solar system evolve through a number of processes. In magnetospheres, these surfaces receive a constant flux of photons, charged and neutral particles, and micrometeoroids. Such weathering alters the surfaces in a number of ways, for instance, by ejecting and redistributing ice molecules and implanting ion species that become chemically incorporated into the ice. It is therefore not well understood how much of the optical surface is due to materials originating outside the body and how much is due to intrinsic materials that have been weathered at the surface. This question is critical to understanding how surface composition studies, for example, can be used to understand satellite interiors, such as a hypothetical ocean below the surface.[19]

We have used data from the Galileo spacecraft to simulate the surface weathering of Europa by energetic electrons. Energetic electrons carry the largest dose of radiation into the optical layer and therefore control the energetics of the surface. In Fig. 6, we present a simulation of the dose rate into Europa's surface. This figure shows an outline of the satellite longitude and latitude with an overlay of approximate dose rate contours based on data. The bull's eye of the dose occurs at the point where Jupiter's corotating magnetospheric plasma overtakes the satellite in its orbit. As Jupiter's magnetosphere sweeps over Europa, the trapped energetic ions and electrons impact the satellite surface and are lost, depositing their energy into the top layer of ice. The distribution of the radiation dose shown in the figure was compared with the distribution of frozen, hydrated sulfuric acid on Europa's surface.[20] The latter was created by images from the Galileo Near-Infrared Mapping Spectrometer. The strong longitudinal and latitudinal correlations between the electron dose distribution and the hydrate concentration supported the idea that the hydrate is produced in a weathering process, i.e., it is not a material intrinsic to Europa.

SUMMARY

In this article, we have attempted to describe some of the elements of magnetospheres: their magnetic field topologies and the content and dynamics of their particle populations. We then turned our attention to different kinds of magnetospheric emissions, which reveal details of these structures, even when detections of these emissions are made remotely. Finally, we talked about how trapped plasmas

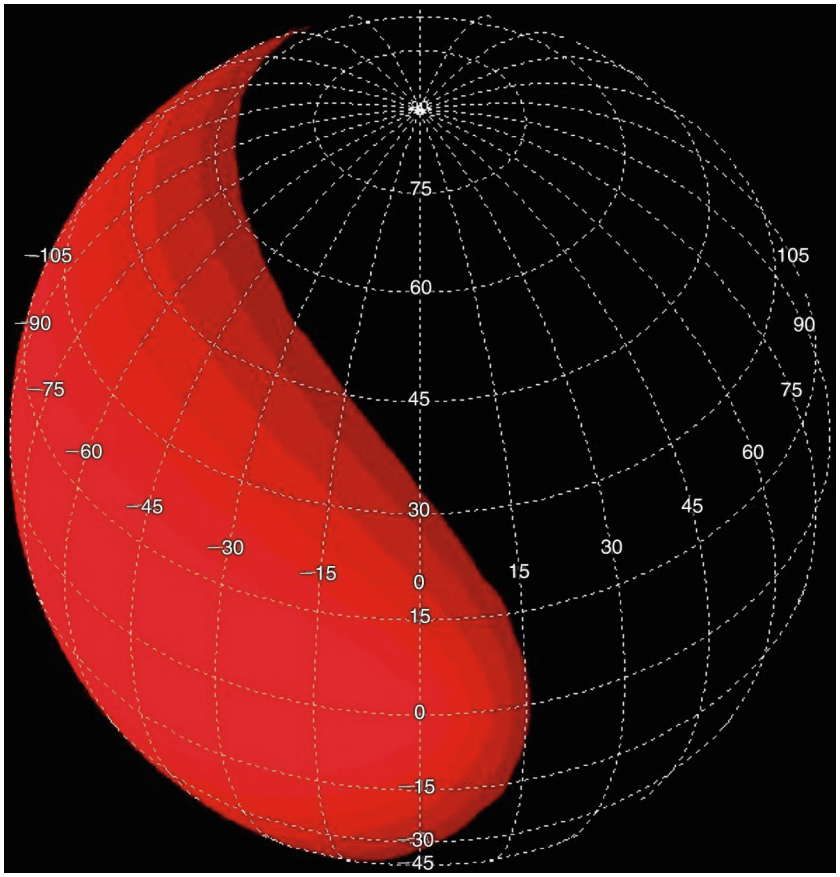

Figure 6. Satellite weathering. The outline of Europa is shown in longitude and latitude, with the radiation dose distribution qualitatively superimposed as contours. Dose decreases away from the bull's eye on Europa's trailing hemisphere. The dose pattern was based on actual data and a simple model of how trapped particles are lost to a satellite surface.

weather satellites, a process which both alters the optical surface and acts as a source of new material to the magnetosphere. In each section we have attempted to bring out some of the details using examples and controversies from recent research. Data returned from current (e.g., Cassini, ACE, Voyager 1 and 2, Ulysses, and Earth-orbiting spacecraft) and future (e.g., Juno) missions will continue to shape our understanding of magnetized bodies throughout the universe.

ACKNOWLEDGMENTS: We wish to thank J. T. Clarke, L. Prockter, A. Dombard, and C. Monaco and to acknowledge support from research grants between JHU and NASA.

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CORRIGENDA (see p. 296, Volume 26, Number 3)

P. 157, col. 1, line 5: "*Topography*" should read "*Topology*"
P. 157, col. 2, line 31: "*Jupiter*" should read "*Jupiter's magnetosphere*"

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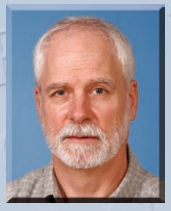

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Christopher P. Paranicas has done research on Earth's magnetosphere and the planetary magnetospheres for about 20 years. Dr. Paranicas is working on the Galileo Jupiter and Cassini Jupiter and Saturn charged and neutral particle data sets. His main area of interest is the weathering of satellite surfaces in planetary magnetospheres. **Robert B. Decker** is an expert on the heliosphere who has published extensively on the Voyager 1 and 2 spacecraft data. Dr. Decker is the PI on the IMP-8 CPME and a Co-I on the Voyager LECP. Before he retired from APL, **Donald J. Williams** was Director of the Research Center. Dr. Williams has worked on NASA, NOAA, DoD, and foreign satellite programs and was the PI on the Galileo EPD. **Donald G. Mitchell** is the Lead Scientist for the HENA instrument on the IMAGE MidEx mission. Dr. Mitchell is also the Instrument Scientist for the Magnetospheric Imaging Instrument on the Cassini mission. **Pontus C. Brandt** received his Ph.D. in the ENA imaging of planetary magnetospheres. Dr. Brandt is currently involved with Venus Express and TWINS as well as the analysis of ENA images from IMAGE, Cassini, Mars Express, and Double Star. **Barry H. Mauk** is the Supervisor of the Particles and Fields Section of the Space Physics Group at APL. Dr. Mauk is a Co-I on the upcoming Juno mission to Jupiter and on the Voyager LECP and Cassini MIMI instruments. All authors, except Donald Williams, are permanent members of the APL staff. For further information contact the lead author at chris.paranicas@jhuapl.edu.