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PERSPECTIVE

New Surprises in the Largest Magnetosphere of Our Solar System

Norbert Krupp

En route to its ultimate rendezvous with Pluto, the New Horizons spacecraft passed through the magnetic and plasma environment of Jupiter in February 2007. Onboard instruments collected high-resolution images, spectroscopic data, and information about charged particles. The results have revealed unusual structure and variation in Jupiter's plasma and large plasmoids that travel down the magnetotail. Data on Jupiter's aurora provide details of the interaction with the solar wind, and a major volcanic eruption from the moon Io was observed during the encounter.

A planet with a magnetic field deflects the solar wind (a stream of ionized particles continuously leaving the Sun), forming a cavity that protects the planet against this harsh environment by excluding particle radiation. This outermost region where the internal magnetic field of a planet dominates is called the magnetosphere. Besides Earth and Mercury, each of the four gas giants (Jupiter, Saturn, Uranus, and Neptune) have magnetospheres. The only moon known to have its own magnetosphere is Ganymede, one of the four so called Galilean moons of Jupiter. Although the magnetosphere of a planet is compressed on the side facing the sun, it is enormously stretched on the opposite side (Fig. 1), forming a region called the magnetotail. Jupiter's magnetosphere is the largest in our solar system (with a diameter ~200 times that of Jupiter itself), and its magnetotail is at least 10,000 jovian radii R_J (1 R_J = 71,400 km).

This immense magnetospheric system has now given up some of its secrets. The previously unexplored deep magnetotail of Jupiter was traversed for the first time by the New Horizons spacecraft in February 2007 on its way toward Pluto. Before that encounter, Jupiter had been visited by seven other spacecraft, including the first jovian orbiter mission, Galileo, and six flyby missions (Pioneer 10 and 11, Voyager 1 and 2, Ulysses, and Cassini). The trajectories of each of the previous missions covered only regions of the magnetosphere near the planet, or the spacecraft departed the magnetosphere along the dawn, dusk, or noon flanks. These previous measurements, especially in the magnetotail, penetrated only about 150 R_J.

Data from all of the previous missions have shown that Jupiter's moon Io is the most important player in the configuration and dynamics of the jovian magnetosphere. Io is the most volcanically active body in our solar system, and its volcanoes produce about 1 metric ton of SO_2 per second . This huge amount of material is partly being ionized and partly being transported into the magnetosphere of Jupiter. As a result, the magnetic field lines are loaded with heavy ions (S and O) and are even further stretched, forming a so-called plasma disk around Jupiter's equatorial plane. This "pancake" is filled with charged particles and wobbles during each rotation of the planet. As the mass loading and the stretching of the field lines reach a limit, the plasma is released into the magnetotail in the form of a magnetic bubble called a plasmoid. The mass released in plasmoids is a large part of the mass of the entire system. Analysis of the data from the particles and field instruments onboard the spacecraft can be used as a tool to observe plasmoid structures in magnetospheres.

New Horizons, with its unique trajectory through the jovian magnetotail, yielded a series of surprises. McComas *et al.* (*1*) report low-energy ion measurements at distances between 200 and 2500 R_J. They point out that the observations show a tremendous amount of structure, including sharp discontinuities and variations of several days. The surprise is that, even at those distances, the plasma has imprinted the rapid rotation of the jovian system, which is "visible" in a 10-hour modulation of particle parameters. Another key result is the identification of large-scale plasmoids filled with O and S ions from the moon Io and H_3^+ and H^+ from the jovian ionosphere. The surprise here is that the plasmoids seem to reoccur every 3 to 4 days, even at those distances. This observation confirms the earlier Galileo observations at ~100 R_J and can help to address the remaining question of mass-loading rates and mass release down the tail.

The results of McNutt *et al.* (*2*) also address the plasmoid observations in terms of velocity dispersions, directional anisotropies, and ion-composition variations. It seems plausible that the observed reconnection events (collisions between magnetic field lines that are followed by a plasmoid release) seen in Galileo data at 100 R_J expanded and survived down the tail and were observed by the New Horizons instrumentation. Evidence for that scenario is the S:O ratio, which is only comparable inside the events in the Galileo data and inside the plasmoids in the New Horizons data.

The investigation of auroral emissions (Fig. 2) is also a useful tool to "see" the dynamics of the invisible magnetosphere and to understand the influence of the solar wind at Jupiter. Gladstone *et al.* (*3*) discuss the jovian aurora measurements in the ultraviolet wavelength range during the New Horizons flyby. They also found surprises in their data implying a major change in the night-glow emissions since the Voyager era, as well as an unusual local-time dependence of precipitating-electron fluxes that is consistent with a possible source region in the dusk side of the magnetosphere. Those results can be used to gain a better understanding of the influence of

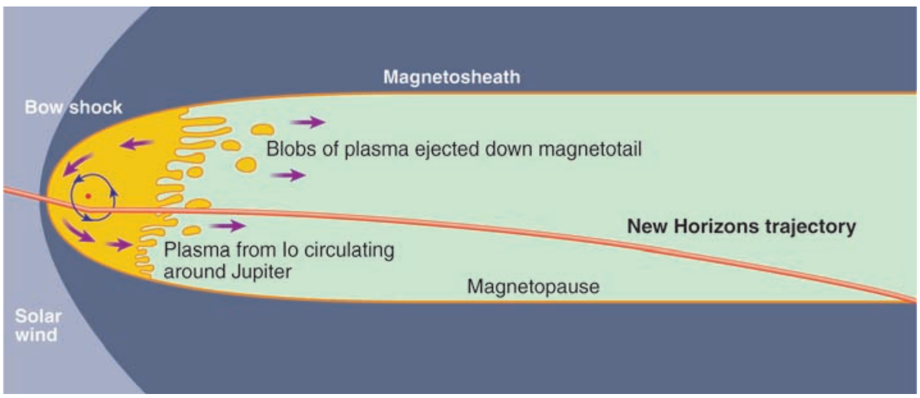

Fig. 1. Schematic diagram of Jupiter's plasma environment and the trajectory of the New Horizons spacecraft. The solar wind hits the magnetic field of Jupiter (red dot) to create a bow shock and flows around the planet in a magnetosheath and an extended magnetotail. Plasma from the moon Io (orbit shown as purple arrows) and from other sources is ejected down the magnetotail. The magnetic boundary between the planet's magnetic field and the solar wind is called the magnetopause. [Adapted by K. Sutliff from a NASA image]

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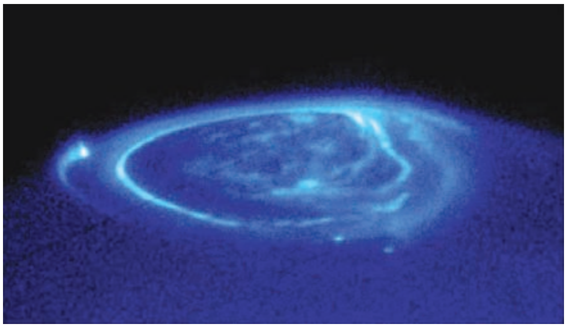

Fig. 2. Hubble Space Telescope image of Jupiter's aurora taken at ultraviolet wavelengths in November 1998. The planetary magnetic field funnels charged particles onto the atmosphere, causing the molecules to glow. Besides the main auroral oval, additional glowing lines with a bright spot on one end result from the magnetic flux tubes that connect Jupiter with its moons Io, Ganymede, and Europa. [Photo credit: NASA/ESA/University of Michigan]

energetic electrons on the brightness of the various regions of jovian aurora. They may also provide evidence for dynamic changes in the auroral emissions with the solar cycle. In addition, the extended and structured auroral emissions associated with the interaction between Jupiter and its satellite Io seen in the New Horizons data will help to shed light on the magnetosphere/moon coupling system.

New Horizons has also observed a major volcano eruption during the flyby. Spencer *et al.* (*4*) report details of a very large volcanic plume (320 to 360 km in height) above the surface where the material condenses in the plume rather then being ejected from the source. By analyzing this material and modeling the eruption, another question could be tackled: How variable is the mass provided by Io and how does this affect the mass loading of the magnetosphere with all its implications? The New Horizons measurements will provide crucial data for resolving that puzzle.

The investigation and knowledge of the jovian system is important for understanding the origin and formation of our planetary system. As the largest and most massive planet, Jupiter played a critical role in that process. The data from New Horizons will also help to focus future missions to the jovian system, several of which are being discussed among the international science community for the next decade. Additionally, if we understand "our" Jupiter better, we will be able to further understand the extrasolar "hot Jupiters" of other stars. Those massive gas giants with 10s of Jupiter masses most probably have strong internal magnetic fields with huge and powerful magnetospheres. Our understanding of the jovian magnetosphere will also help us to comprehend our own terrestrial magnetosphere; this shield protects us and all terrestrial life against the harsh interplanetary environment.

References

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REPORT

Diverse Plasma Populations and Structures in Jupiter's Magnetotail

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Jupiter's magnetotail is the largest cohesive structure in the solar system and marks the loss of vast numbers of heavy ions from the Jupiter system. The New Horizons spacecraft traversed the magnetotail to distances exceeding 2500 jovian radii (R_J) and revealed a remarkable diversity of plasma populations and structures throughout its length. Ions evolve from a hot plasma disk distribution at ~100 R_J to slower, persistent flows down the tail that become increasingly variable in flux and mean energy. The plasma is highly structured—exhibiting sharp breaks, smooth variations, and apparent plasmoids—and contains ions from both Io and Jupiter's ionosphere with intense bursts of H^+ and H_3^+. Quasi-periodic changes were seen in flux at ~450 and ~1500 R_J with a 10-hour period. Other variations in flow speed at ~600 to 1000 R_J with a 3- to 4-day period may be attributable to plasmoids moving down the tail.

The jovian magnetotail is created by the interaction of the supersonic solar wind with Jupiter's magnetic field and plasmas. This structure stretches at least 500 million km antisunward from Jupiter, as evidenced by several transient encounters 5000 to 9000 R_J behind the planet when Voyager 2 was approaching Saturn (*1*).

Jupiter's moon Io spews out volcanic gases, roughly 1000 kg s^{-1} of which (mostly S and O) become ionized and are trapped in the planet's strong magnetic field, forming the Io torus (*2*). Roughly half of the torus ions are lost via charge exchange; the other half are transported radially outward and ultimately escape down the tail (*3*). In addition, Jupiter's ionosphere provides a roughly comparable number of light ions, primarily H^+ and H_3^+, to the magnetosphere (*4*–*6*). This mixture of ions, along with Jupiter's fast rotation rate (~10 hours), creates a dense rotating plasma disk that dominates the inner magnetosphere (*7*). A key issue for the jovian magnetosphere is how more than 500 kg s^{-1} of heavy ions from Io and a comparable number of light ionospheric ions are lost from the system down the magnetotail (*7*).

Jupiter's magnetosphere and near tail were previously explored by seven spacecraft, including extensive observations from Galileo, which was in orbit there from 1995 to 2003 (*8*, *9*). However, other than the brief Voyager 2 intervals at very great distances, no previous spacecraft had made observations more than ~200 R_J from Jupiter. Then, on 28 February 2007 the New Horizons (NH) spacecraft flew past Jupiter en route to its primary mission at Pluto, following nearly an ideal trajectory for magnetotail observations. The observations reported here sample the low-energy plasma ions and their properties from ~200 to ~2500 R_J deep in the magnetotail (Fig. 1).

NH's Solar Wind Around Pluto (SWAP) instrument makes coincidence measurements of ions with energy per charge (E/q) ranging from 35 eV/q to 7.5 keV/q within a 276° × 10° field of view (FOV) centered on NH's high-gain antenna pointing direction. Other than a few data gaps, SWAP observed the magnetotail continuously back to >1700 R_J. From there back to >2500 R_J when observations were terminated, NH repeatedly crossed back and forth between the deep magnetotail and the surrounding magnetosheath.

Near closest approach, we observed narrow energy distributions of low-energy ions (tens of eV/q). These ions are almost certainly an even lower-energy population (few eV) that was subsequently accelerated into SWAP by spacecraft charging, as is sometimes observed in the terrestrial magnetosphere [e.g., (*10*)]. Inside of ~130 R_J, SWAP observed the low-energy tail of the hot plasma disk ion population (*9*, *11*). These

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