Galileo's Probe Sends a Weather Report from Jupiter

Analyzing data from the Galileo spacecraft, which has been orbiting Jupiter since 7 December 1995, is not a job for those who require instant gratification. Delayed for three years after the Challenger disaster, the spacecraft then spent six years in its 3-billion-kilometer journey to the Solar System's largest planet. Moreover, because Galileo's high-gain antenna never fully unfurled, the spacecraft must instead transmit data using its low-gain antenna—at the glacially slow rate of a few tens of bits per second. When one knows as little about a system as we do about Jupiter, however, a trickle of data can unleash a flood of new results. The most recent results,[1–11] based on *in situ* measurements of Jupiter's atmosphere and innermost magnetosphere by Galileo's probe, have raised questions about the giant planet's composition, even as they have resolved some fundamental questions about the driving force of the zonal, or east–west, winds that give rise to the planet's banded appearance. Because of Jupiter's large size, and because it is thought to have a near-protosolar composition, these results may have important implications not just for our understanding of Jupiter and similar planets, but also for our ideas on the formation and evolution of the Solar System.

The first-ever *in situ* measurements of Jupiter's atmosphere reveal conditions to be dry and windy; but is this true globally or just the result of local weather?

Planning a probe

Perhaps the most amazing aspect of the Jupiter-probe mission is that it was possible at all. Calculations showed that inserting the probe into the Jovian atmosphere near the equator, with a velocity component parallel to Jupiter's rotation, would reduce its entry velocity relative to the atmosphere sufficiently for it to survive the resulting accelerations (over 2200 m/s^2) and temperatures (about 14 000 K). Nevertheless, the probe designers faced some difficult trade-offs.

One trade-off involved the number of probes: A single probe could provide detailed information from a single site about temperatures, wind velocities, energetic particles, atmospheric composition, lightning activity, cloud characteristics and radiative fluxes. Multiple probes could provide less information about any one site, but might return information more representative of the planet (or at least its equatorial region) as a whole. The designers ultimately selected the single probe, because it maximized flexibility—an important consideration given our limited knowledge of Jupiter's atmosphere—while minimizing cost. As it turned out, the entry-site weather, which developed after the release of the probe on 13 July 1995, exacerbated the problems inherent in generalizing measurements of a single probe to the planet as a whole.

Earth-based observations[2] of the probe entry site showed it to be a relatively dry, cloud-free region of downwelling gas. Although such regions typically cover only 1% of Jupiter's surface, it is probably safe to make some important generalizations based on the probe's measurements.

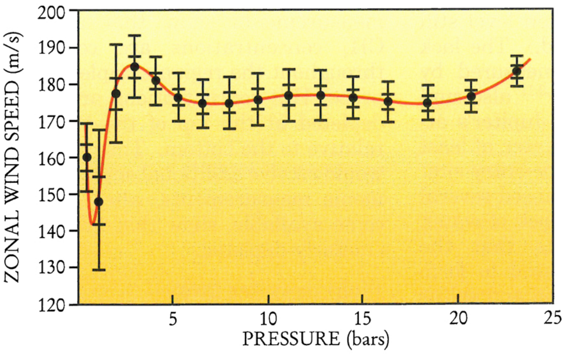
Hot gas and deep winds

Because they are essentially independent of local weather phenomena at the probe entry site, the probe's measurements of Jupiter's radiation belts and exosphere (or extreme outer atmosphere) are likely to be typical of the planet as a whole. Jupiter's radiation belts exhibited a shell-like structure,[10] with peaks in the particle fluxes outside and inside the planet's bright ring—at about 2.2 and 1.5 Jupiter radii (about 157 000 and 107 000 km), respectively. At 1.35 radii, the particle flux fell rapidly to zero, indicating the curvature of the planet's magnetic field lines.

Inside the radiation belts, the temperature, pressure and density of Jupiter's exosphere were all higher than predicted down to 500 km above the 1-bar pressure level, but agreed fairly well with predictions at lower altitudes.[5] Given the feebleness of sunlight at Jupiter, the high exospheric temperatures seem to imply that some other energy source is important in the outer exosphere.

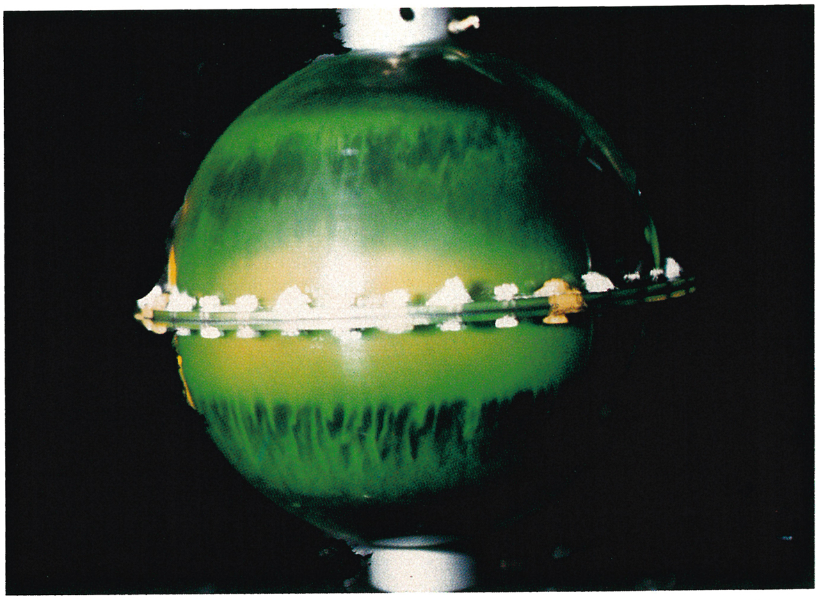
Even some of the measurements made deep in Jupiter's atmosphere clearly have important general implications. Researchers have long argued about whether Jupiter's zonal winds are merely a surface phenomenon, driven primarily by solar radiation, or whether they are powered by energy from Jupiter's interior and hence extend deep into the Jovian atmosphere. The Doppler shifts of the probe's radio signal recorded by the Galileo orbiter showed that Jupiter's zonal winds persist steadily at around 180 m/s down at least to the 20-bar pressure level.[3,4] (See the figure below.) Because little sunlight can penetrate to such depths, the winds must almost certainly be driven primarily by convective energy from within Jupiter rather than from outside it.

In the 1970s, Friedrich Busse (University of Bayreuth) constructed a model in which Jupiter's rapid rotation rate, coupled with the spherical boundaries of the planet's atmosphere organized its atmospheric convection into a series of cylindrical shells, each shell containing long, thin convective columns aligned with the rotation axis. The intersection of the shells with the planet's roughly spherical outer cloud layers gave rise to its banded pattern of zonal winds. These general ideas have since received support from computer simulations[12] and laboratory experiments.[13] In 1993, Zi-Ping Sun and Gerald Schubert (University of Califor-



JUPITER'S ZONAL WINDS extend deep into its atmosphere, indicating that they are driven by energy from the interior rather than by sunlight. Wind speeds in this revised profile are about 10% lower than those published in reference 4. (Courtesy of David Atkinson, University of Idaho.)

nia, Los Angeles) and Gary Glatzmaier (Los Alamos National Laboratory) conducted preliminary supercomputer simulations of fluid flow in a rapidly rotating spherical shell, heated from below. Although highly simplified, these simulations did generate a stable, banded pattern of zonal winds similar to that of Jupiter. Recent laboratory experiments on rapidly rotating, convecting fluids confined in spherical shells, conducted by Peter Olson (Johns Hopkins University) and Jean-Baptiste Manneville (Curie Institute in Paris), found that thin spherical shells generate more zonal bands than do thick shells. (See the figure at right.)



FLUIDS CONVECTING in rapidly rotating spherical shells organize into a series of cylindrical shells, concentric with the rotation axis. In this flash photo of a laboratory experiment with a shell, with the presumed geometry of Jupiter's atmosphere, entrained green fluorescein outlines instantaneous convection patterns. (Courtesy of Peter Olson, The Johns Hopkins University.)

Forecast: dryer than normal?

The greatest difficulties in extrapolating from local measurements to global conclusions concern the concentrations of condensable volatile compounds in Jupiter's atmosphere. In general, the abundances and ratios of most elements and isotopes measured by the probe's mass spectrometer were consistent with the prevailing hypothesis for Jupiter's origin—namely, that it condensed from the protosolar dust cloud.[6] However, there are some significant and suggestive exceptions to this general rule. The Jovian atmosphere contains about 18% less helium[6,7] and 90% less neon[6] than expected. This observation led Caltech's David Stevenson and Mark Roulston to suggest that such depletion could result from neon dissolved in helium condensing in Jupiter's metallic-hydrogen core and settling into its deep interior. Operating on a grander scale, this process could account for the greater helium depletion observed on neighboring Saturn, as suggested by Stevenson and Cornell University's Edwin Salpeter 20 years ago.

The lack of oxygen (as H_2O) measured by the probe—only 20% of the solar abundance—is harder to explain, particularly because carbon (as CH_4) and sulfur (as H_2S), which are expected to behave similarly to oxygen, were present at a few times their solar abundances, as expected. (Nitrogen—as NH_3—is also expected to behave similarly to oxygen, but because of calibration problems, the nitrogen level still remains to be determined.) The lack of clouds or lightning measured by other probe instruments[8,9,11] also support the conclusion that Jupiter's atmosphere contains little water, at least in the vicinity of the probe-entry site.

Researchers have advanced several scenarios to explain the lack of water. One possibility suggests that the planetesimals that coalesced to form Jupiter were rich in carbon and sulfur (and, perhaps, nitrogen), but poor in oxygen. Alternatively, some processes may preferentially segregate water from the other volatile compounds, either during or after the formation of the planet. The third alternative blames the dearth of water on local conditions prevailing at the probe entry site. Indeed, terrestrial experience shows that downwelling gas, like that believed to be present at the probe entry site, is generally drier than the atmosphere as a whole. However, for the dryness to persist over the entire 180 km trajectory of the probe, the downdraft at the probe entry site would have to be—in the words of Tobias Owen (University of Hawaii at Manoa)—"the mother of all downdrafts." Many researchers would like some independent support for this hypothesis before accepting that weather phenomena can assume such giant dimensions. Sushil Atreya (University of Michigan) and Owen think that such support could be forthcoming from probe mass-spectrometer measurements. These measurements show that although CH_4 concentrations are consistent throughout the region sampled by the probe, H_2S concentrations are highly depleted at the top of the trajectory relative to the bottom. This viewpoint would receive additional support if ammonia measurements, when they become available, show that nitrogen is similarly depleted.

Help from far away

In 1991, William Folkner and Robert Preston of the Jet Propulsion Laboratory in Pasadena, California realized that they might be able to use radio telescope arrays, such as the Very Large Array in Socorro, New Mexico, to track the radio signal of Galileo's probe as it sent data to be recorded by the Galileo orbiter. The technical challenges of this undertaking were indeed formidable: The probe antenna's signal was over 2 billion times weaker on Earth than at the Galileo orbiter. Nonetheless, the VLA and the Australia Telescope Compact Array at the Paul Wild Observatory near Narrabri, New South Wales, were able to pick up and track the probe's signal down at least to the 7-bar pressure level. Because ammonia and water absorb radio waves, the very fact that the VLA was able to track the probe to this level suggests that the clouds of water–ammonia ice expected to exist at the 4–5-bar level may not be present within 1500 km of the probe entry site.

Extracting more information than this is a difficult process. Because the probe's signal is so weak, researchers trying to determine the probe's Doppler shift must compare the VLA and ATCA readings with the actual bit stream the probe sent to the orbiter. So far, they have reconstructed only the first 17 minutes of data from the VLA, down to about the 4-bar level. Their preliminary wind profile agrees within experimental errors with that determined by the Galileo orbiter.

Ultimately, the researchers hope to combine information from the orbiter, the VLA and ATCA to derive a detailed three-dimensional trajectory for the probe through Jupiter's atmosphere. Such a trajectory would allow them to better understand energy and momentum transfer in Jupiter's atmosphere. It also may be possible to extract more quantitative information on nitrogen abundances from the attenuation of the probe's signal caused by ammonia.

RAY LADBURY

References

1. R. E. Young, M. A. Smith, C. K. Sobeck, Science **272**, 837 (1996).
2. G. Orton *et al.*, Science **272**, 839 (1996).
3. R. F. Beebe, A. A. Simon, L. F. Huber, Science **272**, 841 (1996).
4. D. H. Atkinson, J. B. Pollack, A. Seiff, Science **272**, 842 (1996).
5. A. Seiff *et al.*, Science **272**, 844 (1996).
6. H. Niemann *et al.*, Science **272**, 846 (1996).
7. U. von Zahn, D. M. Hunten, Science **272**, 849 (1996).
8. L. A. Sromovsky *et al.*, Science **272**, 851 (1996).
9. B. Ragent, D. S Colburn, P. Avrin, K. A. Rages, Science **272**, 854 (1996).
10. H. M. Fischer, E. Pehlke, G. Wibberenz, L. J. Lanzerotti, J. D Mihalov, Science **272**, 856 (1996).
11. L. J. Lanzerotti *et al.*, Science **272**, 858 (1996).
12. Z.-P. Sun, G. Schubert, G. A. Glatzmaier, Science **260**, 661 (1993).
13. P. Olson, J.-B. Manneville, Icarus **122**, 1 (1996).

. . . And Io Yields Still More Surprises

Almost four centuries after Galileo's telescope revealed moons orbiting Jupiter, those same moons are revealing their secrets to the Galileo spacecraft—starting with Io's differentiated structure and magnetic properties.

Researchers have come to expect spectacular surprises from Io, the innermost of Jupiter's Galilean satellites. The Voyager missions revealed Io to be the most volcanically active object in the Solar System. Voyager also revealed the importance of Io's interactions with Jupiter's magnetosphere, which generate a potential of 400 kV across the moon's diameter and currents of over a million amperes between Io and Jupiter's ionosphere. As a result of this past performance, researchers eagerly waited for Galileo to pass within 900 km of Io, a factor of 20 closer than any of Voyager's flyby's. Initial analysis of the data indicates that, once again, Io has not disappointed.

Probing Io to the core

Problems with Galileo's tape recorder limited the amount of information researchers could gather about Io. In part because Voyager's images had already revealed a great deal of information about Io's surface, the highest priority was given to measurements that might reveal something about the moon's internal structure and dynamics, specifically its gravitational and magnetic fields.

The mass within a body determines its gravitational field; thus, the precise shape of the field, especially very near the body, reveals information about the distribution of mass therein. Using the Doppler shift of Galileo's 2.3 GHz signal to determine the gravitational acceleration experienced by the spacecraft, John Anderson and W. Sjogren of Jet Propulsion Laboratory in Pasadena, California, and Gerald Schubert of University of California, Los Angeles, were able to measure the precise shape of Io's gravitational field, from which they calculated the moon's moment of inertia.[1]

Because Io's moment of inertia was substantially smaller than would be expected for an equivalent uniform mass distribution, Anderson, Sjogren and Schubert concluded that Io has a heavy core—probably a mixture of iron and iron sulfide—surrounded by a mostly silicate mantle. The core would have a radius of 651 ± 79 km, (about 36% of Io's radius of 1821.3 km) if it were composed of pure iron, or 942 ± 118 km (52% of Io's radius) if it were composed of a eutectic (minimum-melting-point) mixture of iron and iron sulfide. Given the preponderance of sulfur involved in Io's volcanism, the second number is probably a better guess.

The existence of a heavy Fe–FeS core within Io, surrounded by a lighter predominantly silicate mantle would explain why magmas on Io tend to be silica rich and iron poor. It also indicates that, at some point in its history, the moon was sufficiently hot and molten that differentiation could occur between its heavy and light components. In this respect, Io's history may be similar to that of the terrestrial planets. Measurements of Jupiter's magnetic field in the vicinity of Io indicate that there may be other similarities that are even more profound.

A magnetic moon?

Although Galileo has only recently returned all of the data it took during the Io flyby on particle fluxes and electromagnetic fields, the spacecraft previously returned one-minute averages of its magnetometer readings. These data indicate that near Io, Jupiter's magnetic field drops about 38% from its unperturbed value of 1860 nanotesla. At the Spring meeting of the American Geophysical Union in May, Margaret Kivelson of UCLA[2] suggested that this large drop could arise from the acceleration of large numbers of ions from Io in the vicinity of the spacecraft or from a magnetic field generated by Io itself. After showing that even generous upper limits on the contributions of ion fluxes cannot account for the magnitude of the field perturbation at Io, Kivelson argued that an intrinsic field of Io—probably generated by a dynamo mechanism similar to that of Earth and Mercury—is necessary to explain the results. If this explanation stands up when the detailed analyses of particle fluxes and fields become available, Io would be the first moon found to generate its own magnetic field. However, given the importance of tidal heating in Io's energetics and the possibility that the moon's core might remain liquid right to the center, "the resulting fluid flow structure and dynamo generation would both be quite different from what we think is happening in Earth's core," says Gary Glatzmaier (Los Alamos National Laboratory). (See PHYSICS TODAY January, page 17.)

Other Galilean moons

Although Io's opening act will be tough to follow, Galileo is poised to answer many of the questions raised by the Voyager missions about the other Galilean satellites—Europa, Ganymede and Callisto. In sharp contrast to Io's young, rocky and volcanically sculpted surface, Callisto, the farthest of the Galilean satellites from Jupiter, has a largely static, ancient and icy surface, marked by some of the largest and oldest impact structures in the solar system. Europa and Ganymede seem to be transitional between these two extremes. Researchers hope Galileo will help them to better understand the compositions of these moons and to quantify the importance of tidal forces, volcanism, tectonic activity and cratering on each of the moons.

By the nominal end of its mission in December 1997, Galileo will have returned images of Europa, Ganymede and Callisto with resolutions as fine as 12 m/pixel, 10 m/pixel and 29 m/pixel, respectively, as well as data on their spectroscopy, and gravitational and magnetic fields. All of this will surely keep researchers busy, but many will also be hoping for another trip to Io in 1998.

RAY LADBURY

References

1. J. D. Anderson, W. L. Sjogren, G. Schubert, Science **272**, 709 (1996).
2. M. G. Kivelson *et al.*, submitted to Science. ■