PLANETARY SCIENCE

Galileo Suggests Deep Roots To Jupiter's Fierce Winds

Earthly weather forecasters may not know for sure what tomorrow will bring, but at least they know what drives the winds: the heat of the sun warming Earth's atmosphere. But their brethren in planetary meteorology have not been so lucky when it comes to understanding weather patterns on the four gas giant planets of Jupiter, Saturn, Uranus, and Neptune. Is it the sun's warmth that drives the howling winds of these planets, or is it their own internal reserves of heat, which have been seeping outward for billions of years?

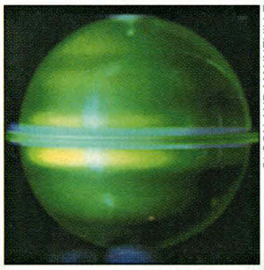
The four spacecraft that have flitted past Jupiter in the past 20 years couldn't answer this question because they could not pierce the clouds shrouding the planet. But last December, the Galileo probe took a suicidal plunge into Jupiter's racing clouds. Continuing analysis of that data, presented at last month's American Geophysical Union (AGU) meeting, clearly establishes that Jupiter's 650-kilometer-per-hour winds extend unabated at least to a depth of 130 kilometers, well below the last glimmerings of the sun. What's more, Earth-based receivers almost miraculously picked up the probe's faint signal from deep in the atmosphere, providing confirmation of the deep, high-speed winds.

"Galileo is telling us that the winds have deep roots," says planetary meteorologist Andrew Ingersoll of the California Institute of Technology, and this "tilts the evidence pretty heavily in favor of a deep source for the winds"—most likely the planet's internal heat. "This helps explain Jupiter's very stable weather; it's like a giant flywheel spinning forever," says Ingersoll. The probe's findings also dovetail with new results from a laboratory model suggesting that a deep heat source could explain Jupiter's alternating bands of winds.

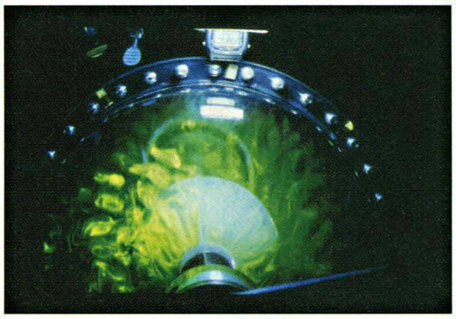
Planetary meteorologists have had a long wait for the lowdown on Jovian winds. "Back in the early 1970s," says Ingersoll, "I just assumed the [Jovian] weather was like Earth's—confined to a shallow layer, driven by sunlight, and not much deeper than the sunlight went. But Fritz Busse [a planetary scientist now at the University of Bayreuth] kept pointing out that it was a fluid planet, and there was nothing to stop the winds and weather from continuing on down." There seemed to be plenty of energy available from below to drive such winds. Observations from the Voyager spacecraft in 1979 confirmed that, like a star, Jupiter has an internal source of heat, emitting almost twice as much energy as it absorbs from the sun. The source isn't the nuclear fusion that fuels a star, but heat lingering from the planet's formation, plus heat generated by a continual drizzle of helium "raindrops" falling into the deep interior (*Science*, 2 February, p. 593).

The stability of Jupiter's winds also seemed to favor a deep, steady driver, notes Conway Leovy of the University of Washington. For example, Jupiter's pattern of banded clouds has not changed substantially during a century of ground-based observation, and the wind speeds remained rock-steady during the 4 months between the flybys of the two Voyagers. Earth's atmosphere rarely exhibits such poise. And the sheer magnitude of the winds seemed difficult to sustain in only a shallow layer of the atmosphere, says Leovy.

On the other hand, models run in the 1980s suggested that Jupiter's trademark cloud bands are the signature of a sun-driven system similar to Earth's. Gareth Williams of the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, started with a computer model used to simulate terrestrial weather, then altered the parameters to match Jupiter's 71,000-kilometer radius and rapid spin rate of one rotation per 12 hours. These changes intensified the Coriolis effect and transformed the few, meandering jet streams of Earth into a bevy of straight jets running in alternating directions, like those on Jupiter. And these strong, narrow jets were generated in a thin atmospheric layer that was independent of anything below.



OLSON AND MANNEVILLE



All stirred up. In a model of Jupiter, temperature differences between core and surface drive convection *(above)* that coalesces into bands as the model is spun *(top)*.

To get to the bottom of whether Jupiter's atmosphere is Earth-like or star-like, the Galileo team sent its probe plunging beneath Jupiter's clouds. At the AGU meeting, David Atkinson of the University of Idaho and his colleagues reported that they had clocked the winds driving the falling probe across the planet by monitoring the frequency of the radio signal that was beaming data back up to the Galileo orbiter. The Doppler effect shifted the frequency as orbiter and probe moved relative to each other, so that Atkinson could derive the motion of the probe.

That analysis was initially complicated by higher-than-expected temperatures in the probe, but Atkinson and his colleagues reported that the most thorough analysis yet shows that down to a depth of 130 kilometers beneath the cloud tops, the probe was swept along at 650 kilometers per hour, even though sunlight faded to darkness about 80 kilometers down. And in a startling announcement at the meeting, William Folkner of the Jet Propulsion Laboratory in Pasadena, California, and his colleagues independently confirmed the probe's movements nearly down to the bottom of the illuminated region—by monitoring the Doppler shift of the 25-watt probe signal from almost a billion kilometers away, using Earth-based radio telescopes.

These results make for "a very strong case" for winds driven from deep within Jupiter, says Gerald Schubert of the University of California, Los Angeles, a probe team meteorologist. He adds that other probe results reveal a layer of stable atmosphere—which would resist vertical movements—between the altitudes where sunlight is absorbed and the deepest high-speed winds. This barrier, he says, makes top-down solar heating an even less promising driver for the deep winds.

While most planetary meteorologists are impressed with the probe results, not everyone is convinced that the winds are deep-driven. "There are limitations to the observations," notes Williams. "They are strictly local, but people are assuming they have global applicability. They're taken from probably the most complex part of the planet. And it's an instant snapshot." Still, one global indicator that seemed to favor sun-driven weather may actually point to deep heating: the cloud bands. In a paper in a forthcoming issue of *Icarus*, Peter Olson and Jean-Baptiste Manneville of The Johns Hopkins University describe experiments with a model Jupiter consisting not of mathematical equations in a computer but of a spinning, fluid-filled plastic sphere 30 centimeters in diameter—a scheme for modeling Jupiter conceived by Busse 25 years ago. The centrifugal force due to the spinning simulates the pull of gravity—except that it pulls "up," not down. If "gravity" is going the wrong way in the model Jupiter, Busse reasoned, then the heat should flow the wrong way too. So, instead of heating the interior, he cooled it, setting up convection of the model's fluid layers.

Busse originally found that Jupiter's rapid rotation organizes spinning vortices like Earth's highs and lows into a ring at a single latitude. But Jupiter's fluid "atmosphere" is so much deeper than Earth's that the vortices can extend deep into the planet or even through it to appear in the other hemisphere.

Olson and Manneville took Busse's "reverse" model Jupiter another step toward the real planet. They cooled the core more intensely, until the model's convection was more vigorous than Busse's had been or than computers can yet simulate mathematically. The columnar vortices persisted, stabilized by the planet's rotation the way spinning steadies a gyroscope, but they broke from their circular pattern to wander chaotically. Theoreticians have long wondered whether these vortices would feed energy into globe-girdling jets, as regions of high and low pressure do on Earth. That's just what happened in Olson and Manneville's model, and the jets formed the familiar Jovian banding.

Such experiments and the Galileo data support the contention that Jupiter's banded wind pattern is linked to the deep interior, but they don't explain the connection in detail. Understanding exactly how deep heat spawns the winds will be a focus of the 2-year mission of the Galileo orbiter, which will be returning its first images of Jupiter's cloud tops next month. Now that they have gotten under Jupiter's skin, scientists hope to divine the inner workings of the planet by stepping back and watching.

–Richard A. Kerr

DISTANT UNIVERSE

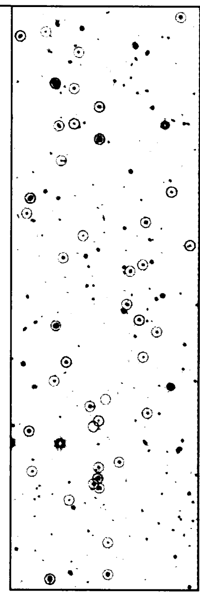
Precocious Structures Found

To astronomers, the story of how structures formed in the universe is like a movie with most of the frames missing. They can view at least some of the first scene, 15 billion years ago, in the cosmic microwave background, which retains an imprint of the universe's primordial fluctuations in density. And they know the denouement in today's universe: great clusters, filaments, and walls of galaxies. Because of the difficulty of surveying galaxies billions of light-years away, however, the period in between is largely a blank. Now their best look yet at the missing footage has left them more puzzled than ever.

What is confusing them is the timing of the tale. New observations made by a Caltech team with the Keck 10-meter telescope in Hawaii suggest that walls and voids may have already been common in the universe billions of years ago, when the conventional accounts of structure formation say the process was just getting started. The team, Judith Cohen, David Hogg, Michael Pahre, and Roger Blandford, reported in *Astrophysical Journal Letters* last month that 60% of the galaxies they charted in a deep, narrow sky survey fell within five wall-like structures spaced at irregular intervals over roughly 5 billion light-years. If that conclusion stands up—and new, unpublished data suggest it will—it "extends the formation of these structures way back in time," says Cohen.

It may also conflict with the kind of universe favored by many theorists: one that contains enough mass to bring its expansion to a halt, given infinite time. In more tenuous universes, cosmic expansion quickly weakens the long-range gravitational interactions by which structures coalesce, so they have to form early. But a heavier cosmos can be more patient in pulling together the filaments and walls seen today. "If you've got large-scale structure early on," says Margaret Geller of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts, "you've got a problem" with a heavy cosmos.

Sky surveys use "redshifts"—the increasing displacement of galaxies' light toward the red end of the spectrum as they get farther away—to add depth to the two-dimensional pattern of galaxies dotting the heavens. Ten years ago, Geller and her CfA colleague John Huchra used a redshift survey to discover the Great Wall, a sheetlike collection of galaxies stretching over hundreds of millions of light-years in the nearby universe. More recent surveys (*Science*, 7 June, p. 1436) have shown that somewhat smaller walls, filaments, and voids—vast regions nearly empty of galaxies—are common in our cosmic neighborhood.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Long view. Colors indicate galaxies belonging to three distant structures.

Such nearby surveys say nothing about how the structures got there. Several years ago a team including David Koo at the University of California, Santa Cruz; Alexander Szalay at Johns Hopkins University; Thomas Broadhurst of the University of California, Berkeley; and Richard Ellis at the University of Cambridge began looking for clues by making "pencil beam" surveys that measured the redshifts of galaxies out to more than a billion light-years away. They found clumpy structure as far as they could see, far enough to make theorists uncomfortable.

The discomfort abated, however, with the larger and deeper Canada-France Redshift Survey (CFRS), a multi-institutional effort in five different parts of the sky, which surveyed 600 galaxies out to distances roughly three times farther than those in the survey by Koo and colleagues. Although CFRS found at least one coherent structure in deep space, says team member Simon Lilly at the University of Toronto, "the [distant] clustering was quite weak." That implied that the pronounced clumping seen today must have developed relatively quickly since then—in general accord with theorists' expectations.

The Caltech results, however, turn up the discomfort level again. The group relied on a so-called "multislit spectrograph" built by Cohen and Beverley Oke, which can make 30 of the time-consuming redshift measurements at once, to chart 106 galaxies out to slightly greater distances than those of the CFRS. Instead of choosing their galaxies from images made in visible light, they used infrared images. In the nearby universe, the cooler, older galaxies seen in such images tend to be more clustered, perhaps because gravity has had longer to draw them together, and the group wondered whether this tendency would persist at greater distances.

It did. "By just looking at [the data] in a very cursory way, you can immediately see what we are calling large-scale structures," says Pahre: five peaks in the density of galaxies along the line of sight.

The team argues that the peaks are likely to indicate structures the size and shape of the Great Wall, but dozens of times farther away.

Early clustering is also turning up in several other patches of the sky, where members of the Caltech team along with Lennox Cowie, Antoinette Songaila, and Esther Hu at the University of Hawaii are using the Keck to collect redshifts. The results have yet to be published, but the clustering is even emerging in one patch, mapped by the Hubble Space Telescope, that includes the faintest and most distant galaxies ever observed (*Science*, 26 January, p. 450). For Szalay, the conclusion is clear: "On very large scales, there is much more structure than anybody thought."

Whether the red galaxies that show this distant clustering really are the best tracers of the rest of the universe's matter, most of which is unseen, or "dark," is still an open question. But if they have revealed the basic cosmic architecture, it may be an emptier universe than theorists would like.

–James Glanz