with high spin–orbit coupling, and so on. Each of them could, conceivably, be brought into the strong-coupling regime by finding the right twist angle, and there's no telling what surprising properties they could show. Says Jarillo-Herrero, "It may take a while before we can make high-quality devices"—graphene is exceptional in its propensity to form large, defect-free crystals—"but this might be a whole new field of magic-angle superlattices."

Johanna Miller

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Jupiter's wind bands have deep roots

Gravity measurements by NASA's *Juno* spacecraft resolve a long-standing debate about the structure of gas giants.

NASA/JPL-CALTECH/SWRI/MSSS/GERALD EICHSTÄDT/SEÁN DORAN

FIGURE 1. JUPITER'S ACTIVE ATMOSPHERE, in an enhanced-color image from NASA's *Juno* spacecraft. The planet's bands of dark and light clouds support powerful zonal winds and long-lived storms like those in the so-called String of Pearls (white ovals).

All four of our solar system's gas giants sport stripes. Jupiter's bands, the most prominent, offer even amateur astronomers a stunning view of the planet's complex atmospheric dynamics. Planetary scientists are especially intrigued by the areas between the stripes, where east–west winds whip clouds around the planet at up to 150 m/s.

For decades researchers have debated the depth of Jupiter's jet streams, or zonal jets. Some argued that the winds persist only tens or hundreds of kilometers beneath the visible cloud layer. In their view, Jupiter was a giant, uniformly rotating body topped with a razor-thin tier of atmospheric action. Others maintained that the jets stretch much deeper as part of a rich, complex atmosphere, perhaps sustained by heat from the Jovian interior.

Now, a year and a half after settling into orbit around Jupiter, NASA's *Juno* spacecraft has resolved the debate.[1] Precise gravimetry measurements reveal that Jupiter's winds stretch relatively deep into the planet, plunging up to 3000 km beneath the colorful cloud tops.[2] Beyond that depth, Jupiter's magnetic field takes over and forces the pressurized, conductive hydrogen in the interior to rotate uniformly.[3] The results solve an important puzzle about Jupiter's structure and could provide a blueprint for profiling other gas worlds in and beyond the solar system.

Odds and evens

The air in Jupiter's light-colored stripes is at relatively high pressure; the dark stripes are regions of low pressure. Those pressure differences, combined with Jupiter's rotation, cause the roughly two dozen zonal jets to alternate easterly and westerly directions. The jets are not just mirror images of each other. Jets in the northern hemisphere tend to be stronger, particularly in the vicinity of 24° N latitude, where the planet's fiercest cloud-top winds have been recorded. The southern hemisphere is a bit calmer, perhaps contributing to the presence of most of the famous long-lived Jovian storms, including the String of Pearls cluster shown in figure 1 and the Great Red Spot.

For theorists trying to determine the mechanism that drives the zonal jets, the hemispheric asymmetry rules out the simplest models, which makes the question of depth all the more important to answer. Fortunately, the north–south differences also open up a means of determining the jet streams' vertical reach. Winds that stretch deep into the planet would presumably transport a significant amount of mass. And because the winds blow differently in the north than in the south, the density profiles of the two hemispheres should be distinct.

To probe Jupiter's mass profile, mission scientists led by Luciano Iess at the Sapienza University of Rome used *Juno* as a free-falling test particle in the planet's gravitational field. During close approaches in December 2016 and May 2017, the spacecraft received radio signals from an antenna on Earth and retransmitted them. Subtle tugs on the probe over the course of its polar orbit were detected via Doppler shifts in the signals received at Earth.

The researchers calculated a series of harmonic functions to describe how the Jovian gravitational field deviates from that of a perfectly spherical mass distribution (see the article by Tristan Guillot, PHYSICS TODAY, April 2004, page 63). The even harmonics capture deviations that are symmetrical with respect to the equatorial plane. They are dominated by Jupiter's bulge at the equator.

If Jupiter wore only a thin outer layer of atmospheric turbulence, then the even harmonics would tell nearly the whole story. But *Juno*'s drifting revealed more at play. Mission scientists measured substantial odd harmonics, which reflect asymmetry in mass distribution between Jupiter's northern and southern hemispheres. As shown in figure 2, the largest gravitational anomalies correspond to the regions with the greatest wind gradients—with a peak measured at the blustery belt at 24° N. The researchers found that the odd harmonics are consistent with a relatively simple model in which the zonal winds extend downward several hundred kilometers near the poles and about 3000 km at the equator.

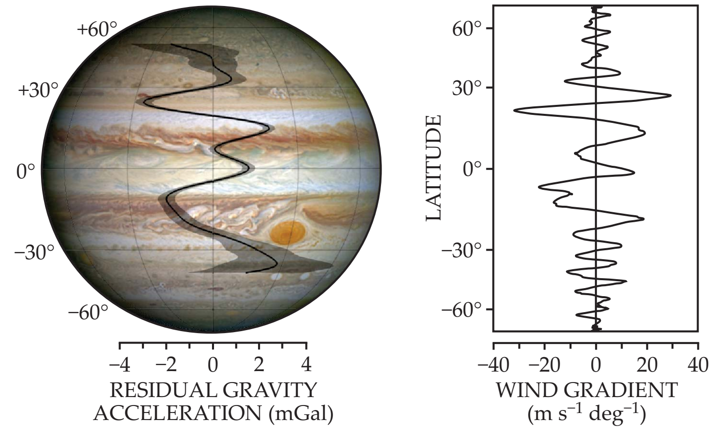

FIGURE 2. GRAVITATIONAL-FIELD ANOMALIES due to mass redistribution by Jupiter's atmospheric winds, in milligals (0.01 mm/s^2). The graph on the left, which is superimposed on a *Hubble Space Telescope* image of the planet, depicts the gravitational deviations from spherical symmetry, by latitude, that are unrelated to Jupiter's flattened shape. As shown in the graph on the right, those deviations are the result of mass redistribution by the planet's powerful zonal winds; the wind gradient is measured as the change in easterly wind velocity per degree latitude. (Adapted from ref. 1.)

At 4% of the planet's mean radius, 3000 km may not seem all that impressive. Yet at that depth, the pressure approaches 10^5 atmospheres. As pressure increases, so does the electrical conductivity of hydrogen and thus its susceptibility to Jupiter's potent magnetic field. In theory, that should cause Jupiter's innards to rotate as if they were a single rigid body. The mass distribution implied by the even harmonics, which are largely unaffected by atmospheric dynamics, supports that picture.

Comparative planetology

Planetary scientists expect to uncover more complexities in Jupiter's wind profile as *Juno* continues collecting data. For example, the researchers assumed in their model fitting that the speeds of the jet streams decay exponentially with depth. But data from telescopes and NASA's *Galileo* mission in the 1990s suggest that winds can strengthen, weaken, and even shift directions as a function of altitude beneath the cloud tops.

Still, the successful resolution of the deep-versus-shallow debate is a key step toward deciphering Jupiter's overall structure. The finding suggests that convection powered by Jupiter's internal heating is central to the winds observed at the cloud tops. Fluid dynamicists can refocus their laboratory simulation and numerical work on devising new models or refining enduring ones, including a 1976 proposal that posits a series of nested rotating cylinders within Jupiter that manifest as jets on the planet's exterior.[4] The findings that emerge could aid researchers

studying not only Jupiter but also Saturn, Uranus, Neptune, hot Jupiter–like exoplanets, and even brown dwarfs, which are intermediate in mass between the heaviest gas giants and the lightest stars.

Preliminary gravity measurements of Saturn, however, suggest that the lessons of Jupiter are not universal. In mid 2017 the *Cassini* spacecraft executed 22 tight orbits around the ringed giant before taking a final plunge; six of those "grand finale" passes were dedicated to gravimetry.

In a set of papers accepted by *Science* but not yet published, Iess and other *Cassini* mission scientists report that Saturn's jet streams stretch deeper than Jupiter's. That makes sense, since the pressure of Saturn's atmosphere builds up more slowly with depth than Jupiter's. But the odd harmonics of Saturn's gravitational field seem to defy the exponential decay model of the zonal winds, and the even harmonics don't jibe with the idea of a uniformly rotating interior. "Some people thought that once you know Jupiter, you know Saturn," Iess says. "That's proving not to be the case. Now we have a unique chance to do comparative planetology."

Andrew Grant

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A leap in precision for diamond-defect NMR

The technique's spectral resolution is now sharp enough to reveal a molecule's unique chemical fingerprint.

Known for its noninvasiveness, NMR has long been a fixture in medicine, structural biology, and many other arenas. In conventional implementations, induction coils are used to detect magnetic signals generated when a sample's nuclei, polarized by an external magnetic field, are manipulated with RF pulses. (See the article by Clare Grey and Robert Tycko, Physics Today, September 2009, page 44.) But because nuclear spins polarize weakly—at room temperature, even a state-of-the-art magnet pulls only about 1 extra spin per 10 000 into alignment with its field—NMR doesn't work well on tiny samples. A microliter (1 mm^3) or more of material is typically required to produce a detectable signal.

Researchers have long sought to perform NMR spectroscopy at far smaller scales—on single biological cells, single proteins, even single atoms. To do so, they've proposed swapping out induction coils for more sensitive instruments: atomic-scale diamond defects known as nitrogen–vacancy (NV) centers.

In an NV center, two adjacent carbon atoms are replaced with a nitrogen atom and a vacancy. Isolated in the diamond lattice, the defect's spin-1 electronic state is highly sensitive to external magnetic fields. NV centers can therefore serve as exquisite magnetometers, able to sense nanotesla fields generated by a sample at the crystal's surface. (See the article by Lilian Childress, Ronald Walsworth, and Mikhail Lukin, Physics Today, October 2014, page 38.) Conveniently, the defects fluoresce with a probability that depends on the spin state, so the magnetometer can be read out optically.

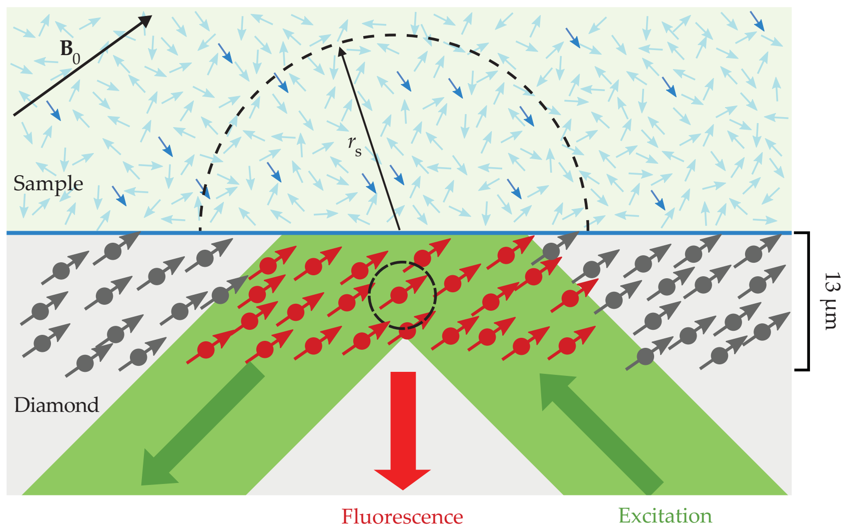

FIGURE 1. AN NMR SCHEME exploits point defects in diamond known as nitrogen–vacancy (NV) centers to generate spectra from a 10-picoliter volume of a sample at the surface. When the sample's nuclear spins are placed in a magnetic field $\mathbf{B}_0$ and subjected to a resonant RF pulse, the polarized fraction (darker blue arrows) precesses about the field axis and produces its own oscillating magnetic signal. That signal is recorded in the spin states of NV centers embedded near the diamond's surface. Those spin states can be inferred from the fluorescence generated with a green light pulse. An NV center, such as the one circled here, detects signals predominantly from within a radius r_s proportional to its depth. (Adapted from ref. 1.)

Over the past 10 years, researchers have made steady progress toward NV-center NMR spectroscopy. But they've struggled to achieve the spectral resolution necessary to tease out subtle frequency shifts in molecules' NMR signals caused by nuclear interactions and shielding effects of electrons. Those shifts, known respectively as scalar couplings and chemical shifts, give a molecule its unique spectral fingerprint; if they're unresolved, you can, for example, detect a hydrogen nucleus, but you can't identify its host molecule.

Now a Harvard University team led by Ronald Walsworth, Mikhail Lukin, and Hongkun Park has demonstrated that with a clever measurement scheme and an appropriate sensor design, NV-center NMR can indeed resolve scalar couplings and chemical shifts.[1] The sample volume need only be a few picoliters—about the size of a biological cell.

The lifetime problem

The Harvard team's scheme is illustrated in figure 1. The sensor, a diamond implanted with a thin subsurface layer of