mixing. His result neither strongly dismissed nor supported the idea, but for decades afterwards conventional wisdom held that fish could be ignored in ocean mixing. It often happens in science that a flurry of unconnected activities on a common topic emerge almost simultaneously, however, and such has been the case for biogenic ocean mixing.

In 2004, Huntley and Zhou[3] pointed out that the expected levels of turbulence in schools of fish are comparable to those associated with storms. In a subsequent paper, my colleagues and I argued[4] that the kinetic energy expended by the biosphere is sizeable compared with global mixing requirements; we further suggested that the true swimmers (fish), when all lumped together, provide about half of the biosphere input, with the balance coming from zooplankton. Exciting, direct confirmation of hugely elevated turbulence levels in vertically migrating shrimp-like animals followed from Kunze and colleagues[5].

A major question is how efficiently biogenic turbulence actually mixes the ocean. The answer hinges on length scales. Very small whorls introduced into a fluid will be quickly damped by friction, and thus will not mix the fluid. To illustrate, consider a tall coffee cup with a slight gradient in creaminess from top to bottom; small whorls at the bottom would have little effect on the cream at the top before dying a frictional death. Guidance on the size at which turbulence changes from unimportant to important in mixing is provided by the Ozmidov scale, which takes into account how stratified a fluid is and how strong the turbulence is. Given that many zooplankton are comparable to or smaller than oceanic Ozmidov scales, one view is that biogenic mixing is negligible[6]. The story is not yet complete, however. It could be that zooplankton schooling introduces larger scales and increases mixing efficiency[7]. Although an attempt[8] to observe such an effect failed to do so, the search continues.

Into this mix comes the paper by Katija and Dabiri[1]. The authors emphasize that the mere act of swimming implies that some water travels with the swimmer. Whereas viscosity lessens the effect of turbulent mixing, here it is found to increase the total transport. In remarkable videos obtained by scuba divers in shoals of jellyfish (Fig. 1), dye releases clearly show the process (see Supplementary Information[1]). One wonders what the jellyfish made of all this, but that would be another story.

The relevance to mixing, however, can be simply described. Suppose a jellyfish is in cold water, and swims vertically to warmer zones. Some amount of cold water will follow (the videos suggest a surprisingly large amount). Once there, mixing of the local fluid properties ensues. From energetics estimates based on the dye's behaviour, the effect seems to be sizeable. This mechanism is implicit in previous energetics estimates, but it has escaped explicit notice until now and lessens doubts, based on Ozmidov scales, about the possible strength of biogenic mixing.

Translation of Katija and Dabiri's results from anecdotes to assessments of possible global impacts remains to be carried out. Should the overall idea of significant biogenic mixing survive detailed scrutiny, climate science will have experienced a paradigm shift. To quote Carl Wunsch[9], modellers will "need to start thinking about the fluid dynamics of biology", to which he added, "that's a tough one" — as, indeed, it is. ■

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PLANETARY SCIENCE

Windy clues to Saturn's spin

Adam P. Showman

Saturn's rotation period has been a mystery. An estimate based on its meteorology comes with implications for our understanding of the planet's atmospheric jet streams and interior structure.

The rate at which a planet rotates is a fundamental property that informs our understanding of its formation, evolution, internal dynamics and meteorology. For planets with solid surfaces, the spin rate can simply be determined by tracking the motion of landforms as they rotate across the surface. But for the gas giants Jupiter, Saturn, Uranus and Neptune, which lack any solid surfaces, determining the rotation rates of their interiors is more difficult. Saturn has proved the most enigmatic, and in recent years our imprecise understanding of its rotation rate has become obvious[1]. On page 608 of this issue, Read and colleagues[2] use clues from Saturn's dynamic meteorology to derive a new estimate for its rotation rate.

Tracking cloud motions over time shows that Saturn's atmosphere, like all atmospheres, does not rotate as a solid body but contains several east–west jet streams. Air at the equator circles the planet once every 10 hours 12 minutes, whereas air at higher latitudes can take up to 30 minutes longer to do so[3]. These cloud-tracked wind measurements imply that Saturn's atmosphere contains a broad equatorial jet — extending from 30° N to 30° S latitude — that flows eastward at speeds that are up to 450 m s^{-1} faster than air at higher latitudes. High-latitude atmospheric regions (outside the equatorial jet) are further subdivided into differentially rotating latitude bands whose relative speeds typically differ by 100 m s^{-1}.

But what is the rotation rate of Saturn's interior? Despite the planet's fluid nature, electromagnetic forces in the electrically conducting interior should keep the interior rotation at nearly a single value. But is this interior rotation rate faster, slower or intermediate between the wide range of atmospheric

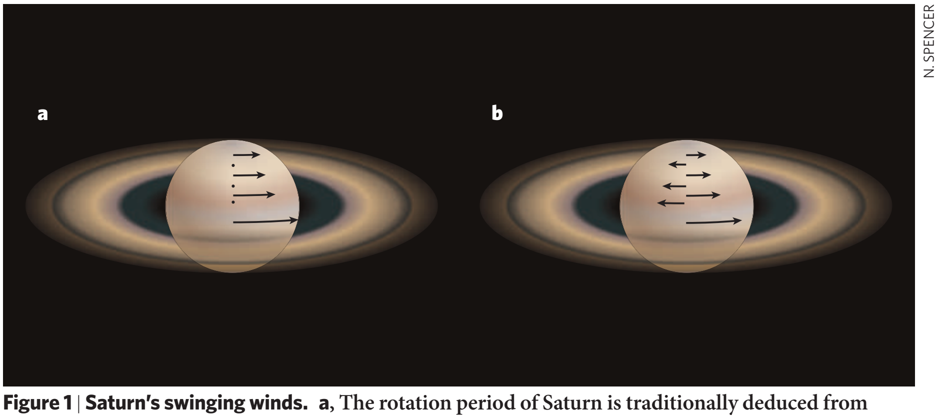

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Figure 1 | Saturn's swinging winds. a, The rotation period of Saturn is traditionally deduced from periodicities in the planet's radio emission. These measurements have long suggested that the planet's atmospheric winds move solely in an eastward direction (right-pointing arrows), varying in strength with latitude and interspersed with nulls in speed (dots). **b,** Read and colleagues' new estimate[2] of Saturn's rotation period, which is based instead on the planet's dynamical meteorology, implies that the winds alternate between eastward and westward (left-pointing arrows) with latitude.

rotation rates determined by cloud tracking? Answering this question has broad implications not only for the planet's interior structure[4], but also for our understanding of whether the jet streams are primarily eastward or westward relative to the interior — and hence for the degree of angular-momentum exchange between the atmosphere and the interior, for the thermal structure below the clouds, and for the formation mechanisms of the jet streams.

For Jupiter, Uranus and Neptune, the key to unlocking this puzzle lies in the radio emission from sources in the planets' magnetospheres (the region of space near the planet where the planetary magnetic field dominates over that of the solar wind). Because the magnetic dipoles of these planets are tilted relative to their axes of rotation, magnetospheric emissions exhibit a periodicity that allows the rotation period of the magnetic field — and therefore of the planetary interior where the field is generated — to be determined. Saturn's magnetic dipole does not seem to exhibit such a tilt, however. Although Saturn does emit radio waves whose periodic modulations were long assumed to define the rotation rate[5], recent measurements[1] show that this period varies by about 1% over intervals of months and so cannot represent the interior rotation.

Read *et al.*[2] adopt a radically different approach. They propose that Saturn's rotation rate can be determined by considering the dynamical stability of the planet's jet streams. Using observational estimates of winds and temperatures at and above the clouds, they expand on previous work[6] in which they showed that, at many latitudes, the pattern of the jet streams is almost neutrally stable — lying very near the boundary between stability and instability — according to a stability theorem developed by Vladimir Arnol'd. In the neutral configuration, this theorem relates a flow's east–west wind speed to the latitudinal gradient of a quantity called the potential vorticity — essentially, the rate at which individual air columns spin, divided by a measure of the vertical thickness of the columns. Because the potential vorticity is independent of the reference frame, but the east–west wind speed is not, knowledge of the potential vorticity can be used to determine the reference frame in which the east–west wind speed must be evaluated for the neutrality condition to be valid. This allows an estimate of the interior rotation rate.

Read and colleagues' analysis[2] builds on previous theoretical and observational work suggesting that such a near-neutral configuration is plausible for both Jupiter and Saturn[7–10]. But why would a flow adopt a state that is neutrally stable? Under appropriate conditions, Saturn's loss of heat to space, and the turbulent transports of momentum that help to pump the jet streams, may force the jets to become unstable. But because Saturn's radiated heat flux is meagre, the timescales for radiative cooling and jet pumping — and hence for the jets to gradually become unstable — are probably years to decades. By contrast, the natural timescale for a strongly unstable jet to naturally develop eddies that rob the jet of energy — thereby making it less unstable — is typically days to weeks. Because of this mismatch in timescales, these competing processes could drive the flow into a configuration that is almost neutrally stable. Analogous arguments have been put forward to explain the configuration of the large-scale air flow in Earth's mid-latitudes, but in that case the instability timescales are not well separated from the radiative timescales, weakening the argument for such a neutral configuration.

Interestingly, the planet's interior rotation rate of 10 hours 34 minutes proposed by Read *et al.*[2] — like that suggested in another recent attempt to estimate the rotation rate[11] — is intermediate between the fastest and slowest atmospheric rotation rates determined from cloud tracking. Such a value suggests that Saturn's winds exhibit an alternating pattern, with eastward-flowing jets at some latitudes and westward-flowing jets at others (Fig. 1). This is significantly different from the original estimate from Saturn's radio emission[5], which implied a slower interior rotation period of 10 hours 39 minutes for which all the observed winds would be eastward. Because of the dynamical linkage between winds and temperatures, the new rotation rate has additional implications for the latitudinal gradient of temperatures below the clouds, as well as for the mass of Saturn's putative rocky core.

Because Jupiter's jet streams also alternate between eastward and westward, the revised rotation period gives Saturn a more Jupiter-like countenance than previously appreciated. Nevertheless, Saturn's winds are stronger than Jupiter's, its banded cloud patterns and populations of hurricane-like vortices differ considerably, and its magnetic field, which is almost symmetrical about its axis — a puzzle in its own right — contrasts with Jupiter's tilted dipole. These contrasts indicate that the planets are cousins rather than twins, whose intriguing mix of similarities as well as differences will keep planetary scientists engaged for years to come. ■

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EARTH SCIENCE

Trickle-down geodynamics

Nicholas Arndt

Analysis of the platinum-group elements in a particular type of ancient volcanic rock provides clues about Earth's early history as well as a fresh approach to understanding mantle dynamics.

In a paper on page 620 of this issue[1], Maier *et al.* provide a provocative hypothesis for those engaged in the study of Earth's evolution. Their evidence comes from measurements of the concentrations of platinum-group elements (PGE) in ancient volcanic rocks known as komatiites, which originated from deep within the mantle.

Maier *et al.* find that the contents of these elements in 3.5-billion- to 3.2-billion-year-old komatiites from Barberton in South Africa and Pilbara in Western Australia are lower than those in younger komatiites. To explain the difference, they propose that the deep-mantle source of the older komatiites was deficient in PGE. According to a widely accepted hypothesis, the mantle acquired these elements as a surface layer of meteoritic material, the 'late veneer', whose deposition terminated with the 'late heavy bombardment' 3.8 billion years ago. Maier *et al.* propose that alloys of iron and the PGE trickled slowly down through the mantle and — so their thinking goes — older komatiites did not receive their full dose whereas younger ones did.

For Earth scientists, the value of the PGE is that they provide unique information about the composition and evolution of the mantle. Three of these elements, osmium (Os), iridium (Ir) and ruthenium (Ru), normally behave compatibly — that is, they tend to be retained in the solid phase during partial melting of the mantle or crystallization of rock. The other three, platinum (Pt), palladium (Pd) and rhodium (Rh), as well as the geochemically similar element rhenium (Re), are incompatible — they partition preferentially into the melt. This contrasting behaviour leads to changes in the