

NEWS & VIEWS

PLANETARY SCIENCE

Music of the stratospheres

Timothy E. Dowling

Fifteen-year oscillations in Saturn's equatorial stratosphere bear a striking resemblance to the shorter-term oscillations seen on Earth and Jupiter — akin to notes played on a cello, a violin and a viola.

Planetary lower atmospheres — the tropospheres — are clamorous. If, in addition to sound waves, one could hear buoyancy waves, which have periods measured in minutes, and vorticity waves, which have periods measured in days, the effect would be a deafening cacophony of enormous range. Time series of atmospheric data reveal a surprising response to this tropospheric din: the overlying stratospheres are answering back, and playing the deepest notes of all.

Studies by Orton *et al.*¹ and Fouchet *et al.*² (pages 196 and 200 of this issue) reveal that Saturn's equatorial stratosphere exhibits a 15-year oscillation in wind direction and temperature that is remarkably similar in structure to 2-year and 4-year oscillations in the stratospheres of Earth and Jupiter, respectively. Considering that a stratosphere is like a complicated sound box attached to the elaborate musical instrument that is the troposphere, this discovery is like listening to notes played on three random orchestral instruments and finding that they all are from the string section — and perhaps all from the same instrument.

Stratospheres are so named because they resist convective forces and so are comparatively

stable. They form because the transmission of thermal infrared radiation to space by participating molecules (greenhouse gases) becomes efficient for pressures of 200–100 hectopascals and lower (1 hPa = 1 millibar; pressure, of course, decreases with height). Each of the seven stratospheres in the Solar System — those of Venus, Earth, Jupiter, Saturn, Titan, Uranus and Neptune — has its bottom, the boundary with the troposphere known as the tropopause, at approximately 100 hPa. (The other four atmospheres, those of Mars, Io, Triton and Pluto, have surface pressures significantly less than 100 hPa.) In terms of waves, the tropopause plays much the same part as the bridge on a violin or cello (Fig. 1), and its consistent placement near 100 hPa marks a pivot point for comparative planetology.

Orton *et al.*¹ analysed more than two decades' worth of observations from NASA's ground-based Infrared Telescope Facility (IRTF), focusing on wavelengths that are sensitive to methane and ethane emissions, which are diagnostic of stratospheric temperatures. A 14.8 ± 1.2 -year oscillation stands out clearly in their time series. Fouchet *et al.*² used the Cassini spacecraft's Composite Infrared Spectrometer

(CIRS) to obtain thermal spectra from Saturn's limb — the edge of the planet where the line of sight passes through the most atmospheric mass, yielding high vertical resolution for the upper stratosphere. Their observations reveal the vertical structure of this oscillation, showing alternate bands of eastward and westward winds from an altitude of 0.2 hPa down to 5 hPa.

There are two terrestrial candidates as analogues to Saturn's 15-year signal, the quasi-biennial oscillation³ (QBO) and the semiannual oscillation⁴. The QBO has a mean period of 28 months, during which time the direction of the jet stream at a given altitude in Earth's equatorial stratosphere switches from eastward to westward and back again, alternating with time, just as is now seen on Saturn.

The mechanism driving the QBO is more complicated than the ratcheting friction between bow and violin string, but it is not more complicated than the trials and tribulations of everyday life. Imagine a father trying to retrieve two (or more) rambunctious toddlers from a tall climbing frame. He clambers up the west side to coax down tot no. 1, blocking all the other kids' access on that side in the



Figure 1 | An atmosphere as an upside-down violin. The strings are the troposphere, vibrating with many eastward- and westward-propagating waves. The bridge is the tropopause, transmitting the waves up into the soundbox, the stratosphere. The primary difference is that, unlike a typical string instrument, a stratosphere responds by dropping the input frequencies down by two or more orders of magnitude — from periods of minutes and days down to years.

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process. Meanwhile, tot no. 2 scrambles up the east side. Dad plants tot no. 1 on the ground, and heads up the east side to retrieve tot no. 2, while tot no. 1 breezes back up the west side. When dad and tot no. 2 return to the bottom, one full cycle is complete. Of course, no self-respecting parent would put up with this nonsense, but what jet streams lack in intelligence, they make up in perseverance.

In fact, the troposphere is a playground for a large array of westward- and eastward-propagating waves that are constantly clambering up into the stratosphere. Forty years ago, this was recognized⁵ as being key to the QBO mechanism. Each type of wave has a different personality. Buoyancy waves (internal gravity waves) travel in all directions; they are just like the waves on the ocean, but internal to the atmosphere. Near the equator, the vorticity waves (Rossby waves) travel slowly westward. In addition, there is a class of 'half waves' (equatorial Kelvin waves) that lean against each other across the equator; they travel rapidly eastward.

When any of these waves drifts upwards and encounters a stratospheric jet going in the same direction, it deposits its momentum just shy of the jet maximum, which has the effect of coaxing the jet downwards in a slow but continuous manner; this led to the first complete description⁶ of the QBO mechanism. Meanwhile, waves that travel in the opposite direction are not blocked but can scramble all the way to the top of the climbing frame, thereby starting a new jet in their direction, which then slowly descends. The upshot is that the roughly 2-year period of the QBO on Earth is governed more by the strength of the wave flux, and the size and shape of the stratosphere, than by the rate of rotation or revolution of the planet.

Significantly, Jupiter also exhibits a QBO-like oscillation, with a period of 4.5 (Earth) years, appropriately called the QJO (quasi-quadrennial oscillation)⁷. As described by Fouchet *et al.*², similarities between Saturn's 15-year oscillations and the QBO/QJO include strong equatorial confinement of temperature extremes; asymmetry between the eastward and westward wind shears, with stronger eastward shears; and out-of-phase temperature changes between the equator and 15–20° latitude.

My guess is that the lengthening of the period from Earth to Jupiter to Saturn relates to their decreasing proximity to the Sun, which reduces the total energy budget available to their waves. But watch out: in addition to the QBO, Earth's stratosphere exhibits a strong signal with a 0.5-year period; this is the semiannual oscillation (SAO) mentioned earlier (Mars also seems to show an SAO⁸). The Saturn year is 29.5 Earth years, meaning that the Saturn wave is, at least descriptively, an SAO (for comparison, the corresponding time ratio for Jupiter's QJO is 4.5/11.9 = 0.38, which is not semiannual). Whereas Earth's SAO is driven by the different response to surface heating between the ice of Antarctica and the surrounding ocean,

it is not obvious what the analogy is on Saturn (although its large ring shadow probably has a role).

The influence of the QBO and SAO on Earth's weather cannot be overstated. They modulate seasonal activity, the behaviour of the Hadley cell (the overturning circulation that predominates in the tropics), the strength of the polar vortex, the mixing of atmospheric trace species, and even the predictability of regional patterns such as the Indian monsoon in August and September⁹. Because the portfolio of eastward waves is distinct from that of westward waves, the eastward and westward phases of the QBO are different. The big news is that this asymmetrical, long-period response has now been observed in the stratospheres of three planets. The question for modellers is whether these stratospheres are like three

different string instruments, or are more like three of the same instruments being played differently.

Timothy E. Dowling is at the Comparative Planetology Laboratory, University of Louisville, Louisville, Kentucky 40292, USA.
e-mail: dowling@louisville.edu

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COMPUTATIONAL BIOCHEMISTRY

Old enzymes, new tricks

Giovanna Ghirlanda

Although enzymes are superb catalysts, their range of reactions is limited to those that support life. Their repertoire could be expanded by a method that allows artificial enzymes to be made from scratch.

Enzymes are astoundingly good catalysts: they allow reactions to occur billions of times faster than would be possible without them, at temperatures much lower than those required by typical synthetic catalysts. But enzymes have evolved to accelerate only biological reactions, under the narrow set of conditions that are compatible with life. Two papers from the same group, one in this issue (Röthlisberger *et al.*¹, page 190) and another in *Science* (Jiang *et al.*²), show how these limitations can be overcome. They describe a method for designing enzymes that catalyse unnatural reactions, and demonstrate its use for two different chemical transformations.

Enzymes work by lowering the activation energy of reactions, specifically by confining substrates in binding sites that stabilize the highest-energy arrangement of atoms in the reaction pathway (known as the transition state). They also shield the reactants, thus preventing possible side reactions. The idea behind the latest work^{1,2} is simple — model the transition state for a reaction, stabilize it by surrounding it with carefully placed chemical groups, graft the resulting active site into an existing protein and then alter the amino-acid sequence of the protein to accommodate the changes. In practice, this is a complicated procedure. For starters, building an accurate model of a transition state requires a detailed understanding of the reaction's mechanism, which isn't always available. Furthermore, transition states are modelled using quantum-mechanical calculations, but

currently available methods can handle only a limited number of atoms, and are often inadequate for modelling enzyme reactions.

Designing a protein that folds into a given structure is equally challenging. For a protein made of 100 amino acids, there are about 10¹³⁰ possible sequences, each of which can adopt many different conformations. The thermodynamic stability of every sequence and conformation must therefore be calculated to find the lowest-energy structure (that is, the one most likely to form). Some simplifications can be made using advanced computational methods to quickly eliminate unfavourable combinations. This has resulted in several notable accomplishments, such as the complete redesign of a protein consisting of 28 amino acids³, the design of an amino-acid sequence that forms a structure not found in nature⁴, and the engineering of naturally occurring proteins into biosensors for trinitrotoluene (TNT) and other small molecules⁵.

With these precedents, you might think that designing catalytic proteins should be straightforward, but success has been limited. Catalytically inactive proteins have been converted into modestly catalytic ones for two different reactions, but the observed enhancements of rate^{6,7} were only about a millionth of those produced by naturally occurring enzymes. It is also sometimes difficult to prove that designer enzymes are truly catalytic on the basis of biochemical observations, and some exciting claims have been found to be flawed.