seen in many terrestrial systems, in which the greatest diversity of consumers occurs in association with the greatest diversity of primary producers. The lack of connection between phytoplankton and zooplankton diversity might result because the unicellular nature of the phytoplankton eliminates a major source of diversity for consumers. Unlike the spatial and structural complexity produced by, say, a canopy of tropical trees, the phytoplankton contribute little structure to their environment. Theory predicts that the morphological complexity of large terrestrial plants provides niches for the smaller organisms that exploit them, and the diversity of these organisms increases fractally as their own size declines[10]. By increasing the uncertainty of species associations in time and space, small size and hydrodynamic complexity might also reduce the frequency of co-evolved feeding relations that foster the correlated diversity of terrestrial plants and arthropods (herbivorous insects, pollinators and so on). In this sense, differences in the relative sizes of primary producers and their consumers in aquatic and terrestrial environments might contribute to fundamental differences in the ways in which these communities are organized[11].

What, then, determines zooplankton diversity? Irigoien *et al.*[3] suggest that, as with phytoplankton, it stems from a shifting balance between competition for food and resistance to predators. But there are other possible explanations. Ecological theory has yet to thoroughly consider the mechanisms that might couple or decouple predator and prey diversity along productivity gradients, and this remains a promising area for research. As this paper[3] shows, broad, cross-system comparisons, interpreted in the light of general theories, can reveal surprising commonalities in the diversity of life. ■

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Planetary science

How Mercury got its spin

Stanley F. Dermott

The orbital period of Mercury and its period of rotation are known to be in a 3/2 ratio, but the chances of the planet reaching this state seemed so small as to be unfeasible — until now.

Like most of the large satellites in the Solar System, the Moon's orbital period and its period of rotation are the same: the Moon completes both an orbit of the Earth and a rotation about its own axis in 27.3 days, and hence always keeps the same face towards the Earth. But, in 1965, observations[1] of Mercury turned up a great surprise: the rotational period of that planet is only two-thirds of its orbital period (59 days compared with 88 days). Quite how Mercury entered this '3/2 spin–orbit resonance' has been a puzzle — although now Correia and Laskar[2] (on page 848 of this issue) propose a solution.

The initial spin rate of our own satellite might have been as short as 10 hours, but it has been braked over time by the action of the tides raised on the Moon by Earth. Because the orbit of the Moon is eccentric, its rotational period should have ended up about 3% lower than the orbital period — with the result that, over a period of about three years, we would be permitted to see both sides of our satellite[3,4]. But the synchronous state of matching spin and orbital rates — a 1/1 spin–orbit resonance — has been reached because the Moon has a small, permanent deformation. The gravitational interaction between the Earth and the quadrupole moment of the Moon accounts for the stability of the 1/1 spin–orbit resonance[5].

That other spin–orbit resonances were possible was not realized before the 1965 radar observations of Mercury, made at the Arecibo Observatory in Puerto Rico. But the stability of these spin–orbit resonances was quickly explained[6–8]. The dynamical stability of Mercury's spin state is best understood by plotting the path of the Sun in a reference frame centred on, and rotating with, the solid body of the planet (Fig. 1). Because the ratio of the rotational and orbital periods is the ratio of two integers, the path in the rotating frame is closed. Analysis shows that the oscillation of the angle between the long axis of the planet and the direction of pericentre (the point in the orbit at which the Sun is closest; Fig. 1b), follows the same equation as describes the damped oscillations of a pendulum[4].

So how did Mercury enter this resonance? There are two terms in the equation of motion for the planet. One term describes the strength of the resonance (the depth of the potential well), which in this case depends on the eccentricity of Mercury's orbit and the resonant integers — basically, the shape of the looped path in Fig. 1b. The second term depends on the tidal torque exerted by the Sun that drives the spin towards the resonant encounter. The problem is that if these two terms remain constant, the pendulum equation is reversible

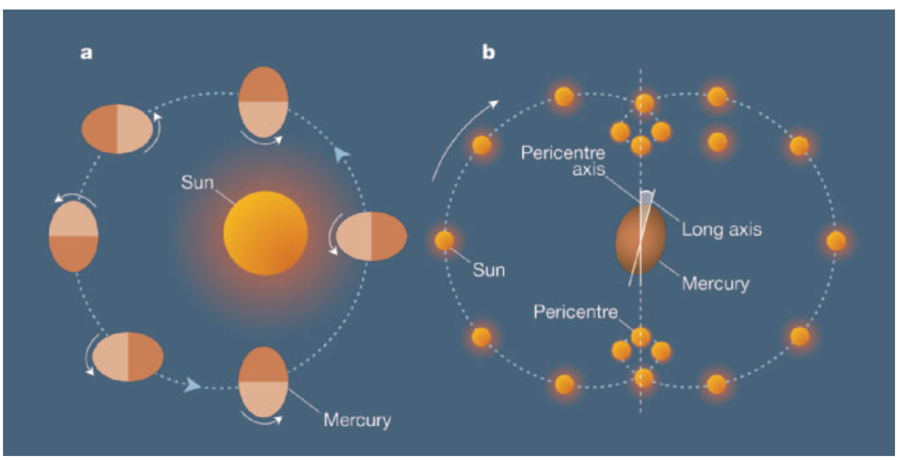

Figure 1 **Mercury's 3/2 spin–orbit resonance.** a, **The rotational period of the planet Mercury is exactly two-thirds of its orbital period. Hence, on every second passage of the planet through the pericentre (the point in the elliptical orbit closest to the Sun), Mercury presents the same face to the Sun.** b, **The dynamical stability of this unusual resonant lock, or spin–orbit coupling, can be understood by plotting, at equal intervals of time, the position of the Sun in a reference frame that is centred on Mercury and rotates with the solid body of the planet. The angle described by the long axis of the planet and the direction of pericentre oscillates like a pendulum and follows the damped-pendulum equation[4].**

and the system passes through the resonance without capture[8]. Previous attempts to understand Mercury's capture into its spin–orbit resonance invoked changes in the tidal torque that broke the symmetry of the system; capture was possible, but the probability of its happening was on the low side[8], at only 7%.

Correia and Laskar[2] have achieved new insight into the problem of the capture of Mercury through their investigation of the long-term dynamical evolution of the planet's orbital eccentricity (that is, how much it deviates from a perfect circle). Periodic oscillations of planetary orbital eccentricities and of their inclinations to the plane of Earth's orbit around the Sun were first analysed by Joseph Louis Lagrange, in terms of coupled linear oscillators[9]. More recent analyses of these regular oscillations suggest that the orbital eccentricity of Mercury should vary between 0.11 and 0.25 (eccentricity is zero for a circle). If that variation is included in the capture model, the probability of capture decreases — making the problem of resonant capture even worse[4].

However, Laskar has shown in earlier work[10] that the variations in the orbital eccentricities and inclinations of the inner, terrestrial planets cannot be completely described by a sum of the normal modes of coupled oscillators. In fact, the motions of these orbital elements are chaotic on timescales of millions of years; Mercury's eccentricity shows the greatest chaotic variation, from near zero to as high as 0.45 or more[10]. When this larger variation is factored into the capture, as Correia and Laskar have now done[2], it at last becomes clear how Mercury could have arrived in its 3/2 spin–orbit resonant state. Because the eccentricity can decrease to near zero, the strength of the resonant coupling can similarly drop to near zero (the looped path in Fig. 1b would be a uniform circle); all resonances except the 1/1 resonance could become unstable, allowing the planet to escape from resonance. In contrast, the excursions of the eccentricity to high values is tracked by corresponding changes in Mercury's spin rate, driven by the tidal torque. The result is that some resonant states — including the 3/2 spin–orbit resonance — are passed through many times and the probability of eventual capture is greatly increased.

Correia and Laskar's calculations[2] suggest that, over a four-billion-year period, the most likely state for Mercury to be captured in is, in fact, the 3/2 spin–orbit resonance. The chaotic variation of the planet's eccentricity means that this was no improbable accident after all. ■

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Condensed-matter physics

Plasmas put in order

Thomas C. Killian

Plasmas are usually a hot soup of dissociated electrons and ions. There are, however, techniques for cooling plasmas, and simulations show that an ultracold plasma could be made to crystallize.

In a typical plasma, energetic collisions tear neutral atoms apart to produce ions and electrons, which then attract or repel each other through the Coulomb force. Plasmas must be hot — as in a flame, or on the surface of the Sun — for this process to occur. At such high temperatures, the random thermal motion of the particles dominates; the positions of individual particles show no correlation or order, despite their Coulomb interactions. In *Physical Review Letters*, Pohl *et al.*[1] show, through computer simulations, how this situation might be reversed: by laser-cooling a neutral plasma, a system could be created in which the Coulomb interactions dominate and the particles arrange themselves into ordered shells or lattices.

Plasmas in which the Coulomb interaction is larger than the thermal energy are described as being strongly coupled. In nature, such plasmas are expected to exist in exotic environments, such as the crusts of neutron stars and the interiors of gas-giant planets. A few examples of strongly coupled plasmas have been created in the laboratory, such as laser-cooled ions, in Penning traps[2] or storage rings[3], that freeze at millikelvin temperatures to form lattices called Wigner crystals. Dusty plasmas[4] of highly charged, micrometre-size spheres suspended in a discharge plasma show similar ordering.

Laser cooling has not been used on a neutral plasma because the high energies involved would overwhelm the cooling force, or the plasma would expand into the surrounding vacuum before the lasers could do their job. Recent experiments, however, have created ultracold neutral plasmas[5] that are cold enough to make laser cooling of the plasma feasible. To create an ultracold neutral plasma, atoms are first laser-cooled to about 1 mK and then excited by a laser pulse to an energy just above the ionization potential. The temperature of the electrons freed by ionization is roughly equal to the difference between the ionizing photon's energy and the ionization potential, and can easily be tuned from 1 to 1,000 K. The initial kinetic energy of the ions, because of their large mass, is close to that of the original neutral atoms, although

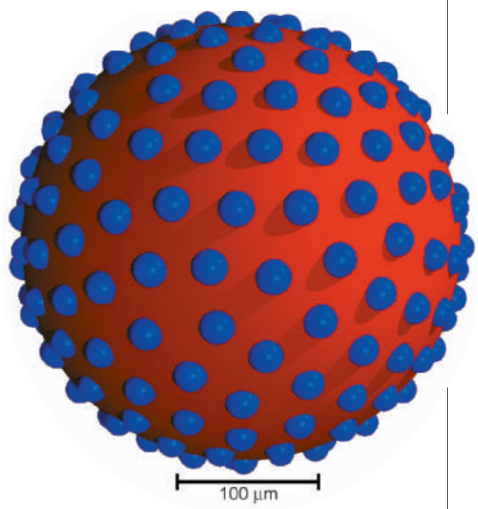

Figure 1 **Crystallization in a laser-cooled neutral plasma. Simulations by Pohl *et al.*[1] indicate that the ions in a neutral plasma could take on ordered structures when subjected to laser cooling. This image shows the typical arrangement of ions in one of several concentric ion shells.**

equilibration in the first few hundred nanoseconds following ionization raises the ion temperature to about 1 K. Subsequent laser cooling of the ions should push the plasma deep into the strongly coupled regime[6,7].

To model ultracold neutral plasmas, Pohl *et al.*[1] used a molecular-dynamics calculation to track the positions and velocities of the constituent particles as they expand into the surrounding vacuum. This would be an undergraduate physics problem if the system consisted of only one electron and one ion. But the number of interactions that must be calculated during each time-step of the simulation scales as the square of the number of particles involved. This makes it a herculean task to track the 100,000 particles necessary to capture the dynamics of an ultracold neutral plasma. Fortunately, some simplifications are possible. If the electrons are hot enough (at about 30 K), they move quickly and follow the potential-energy surface created by the positive ions. The electrons can then be treated as a background fluid whose equilibrium properties are easily calculated