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

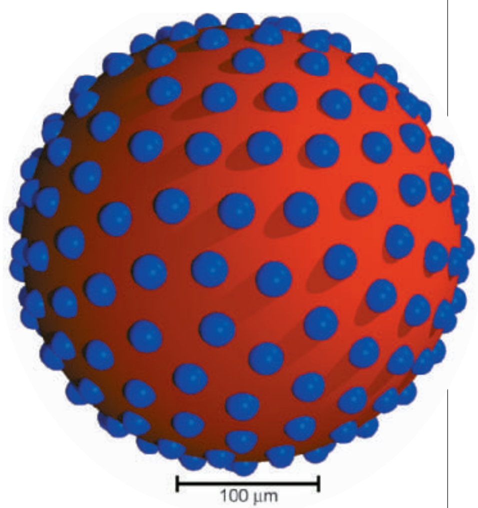

Figure 1 **Crystallization in a laser-cooled neutral plasma. Simulations by Pohl *et al.*[1] indicate that the ions in a neutral plasma could take on ordered structures when subjected to laser cooling. This image shows the typical arrangement of ions in one of several concentric ion shells.**

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

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at each step. This reduces the number of particles by half, but more importantly, it means that the massive, sluggish ions, not the speedy electrons, determine the minimum time-step, so a few days' calculation can cover the microsecond timescale on which ordering of the ions would occur.

Pohl and colleagues' simulations of a spherically symmetric plasma, with an initial ion density of around 10^8 cm^{-3} and a diameter of 20 μm, show that the ions first crystallize into a lattice structure as the plasma is cooled. If the cooling is rapid relative to the timescale of the plasma's expansion, the ions relax further into concentric shells, in each of which there is two-dimensional hexagonal ordering of the ions (Fig. 1).

The first step towards achieving such crystallization has already been taken, with the demonstration of a laser spectroscopic probe[5] of ions in the plasma. Here, the temperature of the ions and the expansion of the plasma are monitored through the Doppler shifts in the spectrum of laser radiation absorbed by the ions. Further studies along these lines will reveal the forces at work during the expansion, and the laser–ion interaction that allows spectroscopy is the same as that required for laser cooling. Pohl *et al.*[1] have developed a powerful tool with which to model crystallization in laser-cooled neutral plasmas. Now it's up to the experimenters to make it happen. ■

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Cell biology

A channel for protein waste

Randy Schekman

Cells destroy misshapen proteins; viruses use the same methods to destroy healthy cellular proteins that are involved in antiviral defences. A long-sought intermediary in the process has now been uncovered.

Cells go to great lengths to ensure that protein molecules fold properly and function in the correct cellular compartment. Mistakes are dealt with harshly: the offending proteins are destroyed. On pages 834 and 841 of this issue, Lilley and Ploegh[1] and Ye *et al.*[2] describe how they identified a molecule that helps redirect proteins out of one compartment, the endoplasmic reticulum, to the waste-disposal machinery.

At first glance, the process of weeding out unwanted proteins seems straightforward enough. An elaborate cellular machine, the proteasome, attacks misfolded proteins that have become tagged with a small polypeptide marker, called ubiquitin. This machine is driven by the cellular energy store, ATP.

For many years, this editing function was thought to target only proteins that are found in the body of the cell — the cytoplasm — and it was assumed that other degrading enzymes would deal with proteins in distinct compartments. But around a decade ago, converging lines of investigation highlighted a role for the proteasome in the degradation of proteins that misfold in the endoplasmic reticulum (ER)[3–5], a major site of protein synthesis and the first port of call for proteins that are destined for the cell surface or to be secreted. Thus, mutant glycoproteins are somehow regurgitated to the cytoplasm, where ubiquitin tagging promotes the recruitment of the proteasome to the surface of the ER. ATP then drives the ubiquitin-tagged protein into the clutches of the proteasome through the intervention of another protein, called p97 in mammals[6]. The net outcome is that damaged goods are reduced to peptides and glycans.

Certain viruses that seek to subvert the capacity of an immunologically competent cell to mount an antiviral defence have exploited this editing pathway. Proteins known as class I major histocompatibility complex (MHC) molecules are essential in alerting the immune system to the presence of viruses, but cytomegalovirus has evolved a devious means of diverting newly synthesized MHC molecules from this task. Two viral glycoproteins, US2 and US11, insert themselves into the ER membrane and interrupt the flow of class I molecules to the cell surface, redirecting them to an enzyme that is responsible for ubiquitination and thus into the jaws of the proteasome[7].

On their way out of the ER, redirected MHC class I molecules are assumed to pass through the same portal that is used for the regurgitation of misfolded cellular proteins. But no such connection has been firmly established, nor is the identity of this portal known. One candidate for such a channel is Sec61, a protein that creates the pore through

100 YEARS AGO

It is eighteen months or more since Mr. Marconi succeeded in establishing wireless communication across the Atlantic. On that occasion a few congratulatory messages were exchanged, a great deal was written on the subject in the Press, and the more timorous of cable shareholders were reported to be much troubled. A little later the attempt was made to demonstrate that this achievement was not merely a firework display, but was capable of direct commercial application; the Marconi Co. entered into a contract to supply the *Times* with news from America by wireless telegraphy, and for a day or so there appeared items of news in that paper under the heading "By Marconigraph." But after a few messages something went wrong, and the public were given to understand that a piece of auxiliary machinery had broken down. It is to be presumed that this piece of machinery has at length been repaired, for Mr. Marconi has once again come very much to the front with long-distance transmission work. The announcement, which we published last week, that he had been successful in maintaining a supply of news to the *Campania* on her voyage across the Atlantic with a regularity sufficient to allow of the publication of a daily paper on board that vessel affords evidence that he is still steadily pushing forward the practical development of wireless telegraphy. We have repeatedly urged in these columns that the real work of wireless telegraphy lay in communication with ships, and it is therefore a greater pleasure to record this latest development than it would be to announce the reopening of Transatlantic communication.
From *Nature* 23 June 1904.

50 YEARS AGO

In the House of Commons on June 15, Mr. Geoffrey de Freitas asked the Under-Secretary for Air whether the physical sub-committee of the Meteorological Research Committee had yet considered the problem of weather modification; and what conclusions it reached… Mr. George Ward, in a written reply, stated that the committee had recently considered this subject and come to the conclusion that there is no reliable evidence that rainfall has ever been artificially increased on an economically useful scale, and that there is no scientific basis for believing that any method yet proposed would be successful in achieving such a result.
From *Nature* 26 June 1954.

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