system' — necessary for *P. aeruginosa* to cause a short-term infection — was reduced by as much as 25 times. The expression of other genes associated with virulence was also reduced; these genes include those that produce surface appendages called pili, as well as those that encode toxins such as LipA and ToxA.

These data imply that RetS is normally required for the full expression of the factors required to produce an acute infection, and are consistent with the decreased ability of RetS-deficient *P. aeruginosa* to cause disease. In contrast, *P. aeruginosa* genes that are involved in the formation of the sugar-rich matrix that encloses a biofilm — the *psl* and *pel* genes[3–6] — were markedly upregulated in the mutant bacteria. This suggests that RetS usually turns off the genes needed to make a biofilm.

We make choices every day on the basis of the information at hand. Bacteria must do so too, and the outcomes of their decisions can have life-or-death consequences, both to the bacteria and to the host. For bacteria, these choices — such as whether or not to form a persistent biofilm — are based in large part on local environmental cues, and are effected through altered gene expression. For instance, *P. aeruginosa* decides to form biofilms on abiotic surfaces, such as catheters or contact lenses, only when an energy source (such as sugars) and other nutrients (such as iron) are readily available[7,8]. Otherwise, it remains free-living. Goodman and colleagues' findings suggest that *P. aeruginosa* also has a decision to make when in the context of a mammalian host: does it cause a short-term infection or does it persist in a biofilm state? An acute infection provides a means of bacterial propagation, whereas in a biofilm the organism is lying low and is thus less likely to be recognized and attacked by the immune system.

The very existence of a regulatory system that mediates this decision suggests that the choice is a crucial one for microbes, and one that they must constantly re-evaluate. Studies of *Bordetella bronchiseptica* — an organism related to the microbe that causes whooping cough — provided one of the first molecular illustrations of this decision[9]. Thus, *B. bronchiseptica* forms biofilms best when the genes required for acute infection are turned off. However, expression of a toxin required for acute infection can block biofilm formation, hinting that the functions required to cause disease and those required to make a biofilm might actually be incompatible. Similarly, my own group has found that expression of the type III secretion system, required for acute infection in *P. aeruginosa*, also inhibits biofilm formation[10].

We would do well to continue learning about how bacteria can switch from disease to persistence and back again. A better understanding of this decision could lead to new strategies for dealing with bacterial infections. ■

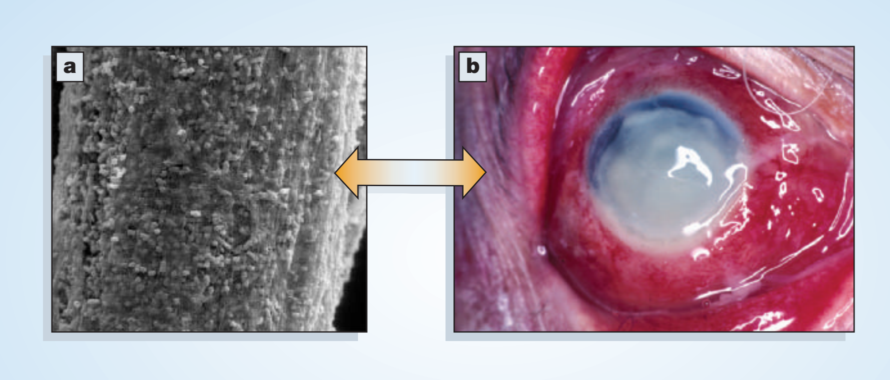

Figure 1 **Persistence versus infection. Goodman *et al.*[1] have discovered a regulatory system in the bacterium *Pseudomonas aeruginosa* that might enable it to choose between two lifestyles in a mammalian host: growing as a surface-attached, persistent community (a biofilm), or causing a short-term infection.** a, **An electron micrograph of a *P. aeruginosa* biofilm on a suture. Individual cells can be seen, surrounded by a sugar-rich matrix. (Courtesy Jon Budzik and the Ripple EM facility, Dartmouth College, New Hampshire.)** b, **An inflamed eye — the effect of an acute *P. aeruginosa* infection of the cornea. (Courtesy Patrick Saine and Michael E. Zegans, Dartmouth Medical School, New Hampshire.)**

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Planetary science

Volcanoes on Quaoar?

David J. Stevenson

Quaoar, a large body in the Kuiper belt, has crystalline water ice on its surface, yet conditions there should favour amorphous ice. Does this mean that resurfacing has taken place — perhaps even volcanism?

Our planetary system does not end at Pluto. Hundreds of bodies exist in the Kuiper belt, which extends outwards from Pluto, sharing the same plane as the planetary orbits. The largest known bodies in the Kuiper belt are not much smaller than Pluto, and some have similar dynamics to that planet. Although the existence of the Kuiper belt had long been hypothesized, the first Kuiper-belt body was discovered only in 1992, by Jewitt and Luu[1]. These same authors now propose[2] that Quaoar, the largest known of these bodies, has crystalline water ice on its surface and possibly also ammonia (see page 731 of this issue). The presence of crystalline ice is surprising, because it is widely believed that its formation requires a temperature of around 100 K or more — substantially higher than the surface temperature of these bodies. The precise temperature required, however, is not known and may not be the same in laboratory experiments as it is in space. Yet it might be that we are seeing evidence for 'planetary' processes such as volcanism within these bodies.

The discovery and characterization of the Kuiper belt is among the most important developments in planetary science in the past decade[3]. As is usual with the discovery of new bodies (inside or outside the Solar System), the initial excitement focused on the dynamical implications: why do they occupy these orbits and how did they form? Some orbital migration may occur, but it is likely that these bodies never experienced much higher surface temperatures than the ambient conditions provided by the Sun (temperatures of about 50 K or less). Quaoar, discovered in 2002 by Trujillo and Brown, is the largest body to be found in our system since the discovery of Pluto in 1930. It has a radius of about 650 km, roughly half that of Pluto. The composition and nature of the surfaces of these bodies are difficult to determine, yet such characteristics may be important for understanding their history. Colour and brightness (albedo) can be informative, but spectroscopy at near-infrared wavelengths is the preferred technique of investigation.

Water is the most abundant condensed material in the Universe, and it should form the 'bedrock' for solid bodies in the outer Solar System. This does not necessarily mean that the water would be readily observed; it could be hidden beneath a mantle of other material. Still, it is not surprising that Jewitt and Luu[2] observed the distinctive spectroscopic feature of water ice. But water ice that forms and remains at very low temperatures would be expected to be amorphous — that is, lacking the periodic structure of crystalline water ice. This is because the highly coordinated architecture of a crystal lattice is difficult to establish when molecules are added to a substrate at very low energy (temperature). At higher temperature, amorphous ice rearranges to crystallize into the ordered, thermodynamic ground state (and releases latent heat as it does so).

More controversially, Jewitt and Luu claim evidence for ammonia ice. The slight dip they see in the spectrum of reflected light around a wavelength of 2.22 micrometres is a subtle characteristic, and seems to be part of a broader spectral feature that is imperfectly understood. Brown and Trujillo have observed the crystalline water-ice feature independently (personal communication), and they also report a putative feature at 2.22 micrometres — but they favour methane or some other explanation for the shape of the spectrum in this region. Irrespective of whether one believes the evidence for ammonia — and it would indeed survive for only a limited time on the surface — it is likely that this molecule is present to some extent in the internal make-up of Quaoar: ammonia is present in interstellar space and is a natural (although possibly minor) carrier of nitrogen in the Universe. This raises the intriguing possibility of water–ammonia volcanism.

For any Kuiper-belt object with a radius greater than about 200 km, the time taken for heat to diffuse through the body is longer than the lifetime of long-lived radioactive elements — the same elements that provide most of Earth's geothermal heat flow. These bodies are expected to contain sufficient rocky material, half or more by mass, for their temperature to easily exceed 200 K deep down during their evolution. An ice mixture that contains both water and ammonia would begin to melt at a temperature of about 175 K. The melt produced would be one-third ammonia and two-thirds water, and it would be much less dense than the surrounding ice–rock mixture. It could percolate upwards and perhaps segregate to form a fluid-filled crack. Even in the low gravity of Quaoar, a crack of a few kilometres in length would create a hydrostatic 'head' exceeding several atmospheres of pressure, probably sufficient to enable the crack to propagate to the surface, or near to it. All of these processes are directly analogous to basaltic volcanism on Earth and other terrestrial planets. The cooling lava would contain crystalline water ice and crystalline ammonium hydrate, which could become exposed by infrequent impacts on the surface of Quaoar.

This is speculative and might be unnecessary. There may be non-thermal processes that make crystalline ice and do not depend on the presence of a massive body with a warm subsurface. Crystalline ice has been observed in the disks around newly forming stars[4] (but we do not know the thermal history of this dust). Evidently, more observations are needed, both of our Solar System and of more distant targets. Data from the infrared space observatory Spitzer[5], currently in orbit, are expected to help. More laboratory data are also in order. But we should not exclude the possibility that planetary processes such as volcanism could occur in volatile-rich bodies at these outer reaches of the Solar System. ■

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Behavioural biology

Name that tune

Daniel Margoliash

Understanding how early auditory memories are laid down could help to explain their role in vocal development. Some ingenious experiments in birds provide fresh ideas about how such memories are represented.

A central discovery that emerged from the early studies of Konrad Lorenz and Nikolaas Tinbergen was that animals have innate predispositions that guide the learning of species-appropriate signals. Birdsongs are a good example of such signals. Young songbirds must learn their specific songs by listening to adults, and research has provided insight into how auditory memories are formed under species-specific constraints, and how those memories help to guide song development. Yet the organization of the 'acquired template' for song learning that is formed from the early experience of hearing other birds sing remains a mystery, at both the neurobiological and (more surprisingly) the behavioural levels. Elsewhere in this issue (page 753), Rose *et al.*[1] describe certain features of that template: they show how white-crowned sparrows (*Zonotrichia leucophrys*, Fig. 1), birds that have long been used in this line of research, can assemble a complete song in proper sequence when exposed early in life only to fragments of that song.


FRANK LANE PICTURE AGENCY/CORBIS

Figure 1 **Model singer — the white-crowned sparrow.**

Song in birds (and speech in humans) is the culmination of the interplay between innate physiological constraints and environmental cues, including social interactions, song models and auditory feedback. The process is further shaped by developmental constraints such as the limited 'sensitive periods' when song models can be memorized. Researchers investigating song learning must therefore assess the degree to which a bird's success or failure to acquire a song results from interactions among these many influences. For example, when presented with tape-recorded songs of their