NEWS & VIEWS

PHOTONICS

A cooling light breeze

Khaled Karrai

Mirrors confine light, and light exerts pressure on mirrors. The combination of these effects can be exploited to cool tiny, flexible mirrors to low temperatures purely through the influence of incident light.

Looking at how a poppy oscillates back and forth in a gentle breeze tells us something about the rigidity of the flower's stem and the strength of the prevailing wind. Observing the movement of a tiny mirror attached to a stem-like post in a 'photon breeze' might be similarly illuminating. Such displacements could reveal the spooky quantum-mechanical behaviour of the mirror itself and maybe even gravity's role in quantum mechanics[1] — no mean feat. The problem is that under normal, room-temperature conditions such effects are masked: the mirror contains an exceedingly large number of thermally excited atoms, so it is in a state of permanent random agitation around its average position on its stalk. And cooling by traditional cryogenic means does not go far enough to remove these 'non-coherent' thermal effects.

In this issue, three papers[2–4] show two ways of using the pressure of incident photons to damp down thermal agitations. Gigan *et al.* (page 67)[2] and Arcizet *et al.* (page 71)[3] both build on an earlier method[5,6] for mirror cooling, and for the first time succeed in using radiation pressure to cool miniature mirrors down from room temperature to effective temperatures of just 10–20 kelvin. And Kleckner and Bouwmeester (page 75)[4] reach a record low temperature of 0.135 K by using a variant of radiation-pressure cooling that uses two lasers in a method known as cold damping[7]. Although spotting intriguing quantum-mechanical effects is probably still some distance away, the research marks a promising step in that direction.

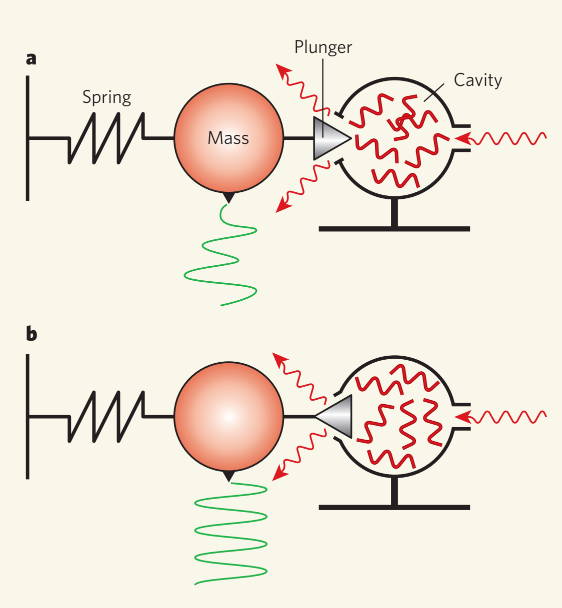

Figure 1 | Calming light. In the radiation-pressure experiments[2–4], a conical mirror-like plunger controls light leakage from an optical cavity, and is mounted rigidly on a thermally vibrating mass on a spring. These vibrations move the plunger, and so change the photon density in the cavity and the radiation pressure on the mirror. Owing to light's finite speed, these changes do not occur instantaneously, resulting in 'back-action' in the system. **a**, When the mirror is mounted with its tip pointing into the cavity, the back-action always acts to counter the original thermal fluctuation, resulting in optical cooling of the mirror. **b**, If, instead, the mirror is mounted with its tip pointing out from the cavity, the delayed changes in radiation pressure amplify the fluctuation so that the system enters into a sustained, optically pumped mechanical self-oscillation.

To understand how these experiments work, imagine a conical plunger that is rigidly attached to a mass on a spring (Fig. 1). If such a system is in thermal equilibrium with its environment, it will normally be animated by permanent random (brownian) vibrations around its average position. These vibrations peak at a frequency corresponding to the natural frequency of oscillation of the mass and spring, and can be used to regulate the leakage of light from a cavity that is continuously filled with photons from a separate light source.

The photons exert pressure not just on the walls of the cavity, but also on the plunger, acting to force it outwards. The strength of the pressure depends on the number of photons stored in the cavity at any one time. This is in turn determined by the leakage rate, and so by the position of the plunger. At each sudden random fluctuation of the plunger's position, the cavity fills or empties to a new photon density, and so a new radiation pressure. This readjustment cannot happen instantaneously, as light travels at a finite velocity. While it takes place, a temporary 'back-action' force results that is crucial to the optical cooling, or quiescence, scheme.

Assume, in the first instance, that the tip of the plunger cone is pointing into the cavity (Fig. 1a). With this geometry, if the initial fluctuation drives the plunger outwards, more photons leak out, and the pressure inside the cavity is reduced. The result is a suction force that acts to pull the plunger back in again. Conversely, when the initial fluctuation acts to drive the plunger inwards, an excess pressure is created in the cavity, resulting in a back-action that pushes the plunger out again. The net result is that the plunger and the attached mass experience a viscous drag that dampens the system's random fluctuations, whatever their initial direction. In other words, the system cools down.

A regular damping mechanism, such as a hydraulic shock absorber or immersing the oscillating body in oil, cannot bring about cooling in this way: the damping fluid would simply heat under the effect of the thermal fluctuations and thus reheat the mass. The beauty of the optical scheme is that, despite the high energy density of photons in the cavity, the light acts as an 'ultracold' damping fluid that does not restore heat to the body. The excess energy gained from the damping will escape irreversibly into the surrounding vacuum, taking away some of the thermal energy that drives the random vibrational motion.

Incidentally, the converse heating effect can be obtained by using a plunger with its conical tip oriented outwards instead (Fig. 1b). In this case, an initial thermal fluctuation outwards will limit the number of photons escaping, increasing the pressure in the cavity, and a fluctuation inwards will lead to a greater leakage of photons, reducing the internal pressure. Thus, whichever way it goes, the thermal fluctuation is amplified.

The experimental challenge facing the authors of these papers[2–4] is keeping the photons in the cavity over a timescale similar to the natural oscillation time of the mass–spring system. One can then ensure that the photons impinge on the mirror at just the right time in the system's cycle to achieve a maximum damping (or amplification) effect — rather as a hand on a child's swing at the right time in the cycle increases or decreases its amplitude of oscillation.

With tiny mirrors, this kind of control is far from trivial. Gigan *et al.*[2] and Arcizet *et al.*[3] achieve it by constructing a mirror that forms one end of a very high-quality optical cavity and functions as plunger, mass and spring all in one. Kleckner and Bouwmeester[4], by contrast, use the cavity only for 'reading out' the position of the fluctuating flexible mirror through precise measurements of the transmitted and reflected light-intensity profiles. The position parameter is then fed with a delay into an electronic feedback loop that controls the intensity of a second laser beam separate from the source of the cavity photons. This beam impinges directly on the mirror[7]. Such a configuration mimics the function of the plunger, but the precise timing of the second beam that thus becomes possible provides a tremendous amplification to the damping, and hence a record optical quiescence effect.

In all these experiments[2–4], the degree of cooling achieved so far is limited by the heating that results from vibrations of the mirror's flexible attachments, and most probably from residual optical absorption by the mirror. To observe the promised quantum-mechanical effects, cooling to just a few millikelvin is needed. That could require the use of microfabrication techniques to produce mechanical oscillators of lower mass that are more easily damped, and cavities of increased optical quality.

Among the prizes for such endeavours could be the chance to study quantum superpositions of a photon and a macroscopic mechanical oscillator. That in turn might find practical use in ultra-precise methods for displacement sensing and for measuring the mass of single atoms and molecules. The road to that destination is a long one; but it is at least now well signposted. ■

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EVOLUTIONARY BIOLOGY

To work or not to work

David C. Queller

Coercion, not kinship, often determines who acts altruistically in an insect colony. But underlying affinities for kin emerge when coercion is removed: kin selection is what turns suppressed individuals into altruists.

When Shakespeare's Prince Hamlet remarked that his uncle Claudius was "A little more than kin…" he was referring to the added relationship of stepfather that came after Claudius killed Hamlet's father and married his mother. "A little more than kin" could also describe a feature of many social insects. Owing to their odd genetic system, called haplodiploidy, full sisters in ants, bees and wasps are related by 3/4, more than a little above the standard value of 1/2. Historically, this extra kinship figured prominently in the acceptance of W. D. Hamilton's theory of kin selection[1], which holds that workers evolved to altruistically forgo reproduction because they can pass on more of their genes by raising siblings. But a series of papers[2–5], including one on page 50 of this issue[3], shows that the other half of Hamlet's description — "…and less than kind" — may be more apt. Workers are less than kind both because they must be coerced into their 'altruistic' roles and because workers are often also the ones doing the coercing.

Of course, kin selection is not just about relatedness; a little more or less kinship can matter less than larger differences in the costs and benefits of altruism[6,7]. A study of a Malaysian hover wasp by Field *et al.*[2] provides an elegant demonstration of this point. Some workers work harder than others, and relatedness to the queen does not explain the difference. In this species, rank comes with age. The second-oldest female is the heir apparent, and she reduces her risky foraging. Field and colleagues' experiments showed that this is causal. Removing the second-ranked female causes the third-ranked female to reduce her foraging in line with her improved prospects. Similarly, the amount of prospective gain also mattered; experimentally reducing colony size (adults and brood) caused second-ranked females to increase altruistic foraging, consistent with the diminished value of inheriting the queenship.

Thus, workers slacken off when they may become queens and work hard when that path is blocked. In social insects that, like the hover wasp, have small colonies and morphologically similar queens and workers, it is usually the queen that does the blocking by her dominance behaviour. For social insects with larger colonies, queen dominance is often replaced by other forms of control. First, there is nutritional coercion. Poorly fed females become small workers and well-fed ones become large queens. This limits the ability of workers to reproduce, but in most species it does not eliminate it fully. Given an opportunity, workers often will lay eggs. In a large colony, the queen could not successfully police all such behaviour and often ignores it. Instead, other workers do the policing, destroying the eggs of their co-workers[8].

A comparative study of ten policing species by Wenseleers and Ratnieks[3] again shows that altruism is modulated more by constraints on worker reproduction than by relatedness. The species with the highest fraction of fully committed altruistic workers — those that do not lay eggs — tend to be those with lower relatedness, contrary to simple expectation. Instead, more workers are fully committed when policing is most effective, as measured by the fraction of worker-laid eggs eaten by either queens or other workers. Workers are not leaping at every opportunity to be altruistic; they are coerced into that role, often by their fellow workers.

Does this mean that Hamilton's kin-selection theory is dead? The answer is no. One could invoke the efforts social insects make to exclude non-relatives from colonies, or the astonishing sex ratios that reflect kin-selected preferences for sisters over brothers[7]. But let us stick with the issue of direct reproduction. For

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Figure 1 | Queen control. A comb of the stingless bee *Melipona* with the cell caps removed to show female larvae. Each female receives the same food, and therefore can choose whether to develop as a worker (identifiable here as those with a large head and eyes) or as a queen (small head and eyes). So many females opt to become queens that the workers kill off the surplus[3], a form of control that in this species replaces queen selection through nutrition.