MATERIALS SCIENCE

Evolutionary Photonics with a Twist

The iridescent appearance of the hard forewings of scarab beetles can be caused by complex helical nanostructures.

Pete Vukusic

The visual appearance of many animals is determined not by pigments but by structural processes that allow the animals to manipulate electromagnetic radiation—mostly visible light and color—in courtship, to find prey, or to escape predators. Studies of fish scales (*1*), insect coatings (*2*), and bird feathers (*3*) have revealed a wealth of complex biological structural designs and optical effects that mirror many technological photonic system designs. These photonic technologies are beginning to draw inspiration from the natural world for new generations of devices and products (*4*). On page 449 of this issue, Sharma *et al*. (*5*) add knowledge to this area by elucidating the processes through which the scarab beetle, *Plusiotis gloriosa*, reflects structural color from its external surfaces (elytra) in the form of left-handed circularly polarized light.

Iridescence with a difference. What appears to human eyes as green iridescence from certain scarab beetles, such as *Plusiotis alphabarrerai* shown here, mostly constitutes circularly polarized color.

Left-handed circularly polarized reflection means that from the perspective of the observer, the electric field vector of the light reflected from the beetle describes a left-handed corkscrew, or helix, along its direction of propagation. Circularly polarized reflection from specific beetles was first observed nearly a century ago (*6*). *P. gloriosa*'s tendency to do this is thus not an isolated example, but the attribute is nonetheless rare. It requires a distinct azimuthally twisted—or helical—character in the nanostructure that forms the first few micrometers of its elytra. In these beetles, the spatial pitch of this helix creates the intrinsic periodicity that, to human vision, produces bright iridescent color (an example of this is shown in the figure).

Synthetic systems that exhibit strongly circularly polarized color reflections include certain layered mesophases, specifically those associated with cholesteric liquid crystals (also known as chiral nematic liquid crystals). Their circularly polarized optical properties arise because their constituent molecules lack inversion symmetry. This produces intermolecular forces that favor a specific small azimuthal twist through the whole system. In this way, an intrinsic physical helicity is generated that is right-handed or left-handed depending on molecule geometry, yielding right- or left-handed circularly polarized reflection, respectively (*7*).

Previous studies of circularly polarized colored reflections from beetle elytra revealed the presence of helicity and described the strong analogy with cholesteric liquid crystals (*8*). Electron micrographs of sections through these beetle elytra revealed "Bouligand structures" (*9*)—the characteristic series of curves within periodically contrasted layers that indicate the presence of helical symmetry in the constituent material.

In *P. gloriosa* and several other Rutelinae (*10*), however, the structural complexity goes beyond mere helically ordered layering. The elytral surfaces of these beetles consist of arrangements of mostly hexagonal micrometer-scale multicolored cells. The different colors are a result of nested close-packed surface concavities that shape the underlying structure, creating a set of color properties that depend on the nature of the illumination.

Using confocal microcopy, Sharma *et al*. now infer that in cross section, the form and geometry of these surface structures and subsurface features are analogous to the focal conic domains that spontaneously form at the free surface of a cholesteric liquid crystal (*11*). Given that the dynamics and formation processes of liquid crystals are generally well understood, this association provides new insight, beyond that of earlier cholesteric liquid crystal analogies (*8*), for the set of variables that may advance our understanding of the self-assembly pathways of this structurally colored insect cuticle. With a few noteworthy exceptions (*12*), the formation processes of these insect systems are not as well understood as are their photonics.

Helical nanostructure may have different biological functions. Where such helicity is present without accompanying circularly polarized reflection—for example, in some plant epidermi (*13*)—it may serve to add mechanical strength. This is mimicked effectively at the millimeter scale by processed plywood. However, the beetle helical ultrastructure is arguably too complex and too costly to produce without the benefit of a suitable optical selection advantage, such as effective signaling. The strong circularly polarized reflection observed in the beetles may, for example, play a role in intraspecific communication. This is especially the case for another scarab, *Plusiotis resplendens*. It exhibits strong broadband reflection of both left- and right-handed circularly polarized light due to the presence of two chirped helical layered regions separated by a half-wave plate (*14*).

Despite some initial behavioral studies, it remains unknown whether the circularly polarized reflection from these special beetles provides a channel of communication. However, Chiou *et al*. recently showed that such communication is possible for a marine

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crustacean: the stomatopod *Odontodactylus* sp. Not only does this species signal brightly using circularly polarized colored light reflected from two posterior abdominal appendages, but it also responds behaviorally to circularly polarized stimuli (*15*). Its method for doing so is elegant. Chiou *et al.* revealed that incident circularly polarized light is converted to linearly polarized light when it is transmitted through a quarter-wave plate in specific cells of the eyes' midband region. Upon conversion to linearly polarized light, alignments of conventional microvilli (the basic elements that construct the photoreceptive region of the eye) are used for its photoreception.

This apparently adapted coupling between a circularly polarized light source and a circularly polarized light detection system in stomatopods is unlikely to be the only one in biological systems. Whether circularly polarized reflection in beetles such as *P. gloriosa* also has such an intraspecific communication purpose remains to be seen.

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ASTRONOMY

A Flare for Acceleration

Radio and gamma-ray observations show that particles are accelerated to extremely high energies very close to a black hole.

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As black holes swallow matter, they often expel jets of plasma that can reach speeds very close to the speed of light. In the giant elliptical galaxy M87, 50 million light-years away, radio observations have traced such jets down to the immediate surroundings of the black hole, to less than 100 event horizon radii (*1*, *2*). However, radio observations alone cannot provide a complete picture of the power carried by these jets, their speed, or their composition. Gamma-rays, first detected from jets more than a decade ago, provide crucial evidence that particles are being accelerated to very high energies. But the relatively poor angular resolution of gamma-ray telescopes has prevented direct determination of where these particles are coming from. That uncertainty has now been resolved, at least for M87. On page 444 of this issue, Acciari *et al*. (*3*) report the first radio imaging of the site of a gamma-ray flare—and it is very close to the black hole.

Acciari *et al*. tracked changes in the jet's brightness and structure at radio, x-ray, and gamma-ray wavelengths. Jets are unsteady, with relatively quiet periods punctuated by sharp upswings in luminosity, called "flares." Over a period of a few days in early 2008, three independent arrays of very-high-energy (VHE) gamma-ray detectors noticed a sudden increase in radiation from M87. The VHE band, corresponding to photon energies of around a teraelectron volt (TeV), is readily observed from the ground by detecting the streak of blue Cherenkov radiation emitted as the photon passes through the atmosphere. At the same time, the Very Long Baseline Array (VLBA) mapped an increase in the radio emission near the black hole, in the form of a bright patch that moved outward during the ensuing months. The coincidence of the gamma-ray flare and the sudden appearance of a new patch of radio emission is strong evidence that the two phenomena are connected.

The detection of gamma-rays from so close to the black hole is slightly surprising. VHE gamma-rays can be absorbed by infrared and visible-light photons to create electron-positron pairs. If the intensity of long-wavelength radiation is high enough, the gamma-rays will be completely extinguished. This is thought to be the situation close to the black holes in luminous objects such as quasars. When some quasars were first shown to be gamma-ray emitters in the early 1990s (*4*), most theorists concluded that the radiation had to be produced far from the black hole—hundreds or thousands of event horizon radii—where the long-wavelength radiation background is weaker (*5*–*7*). Compared to other gamma-ray sources,

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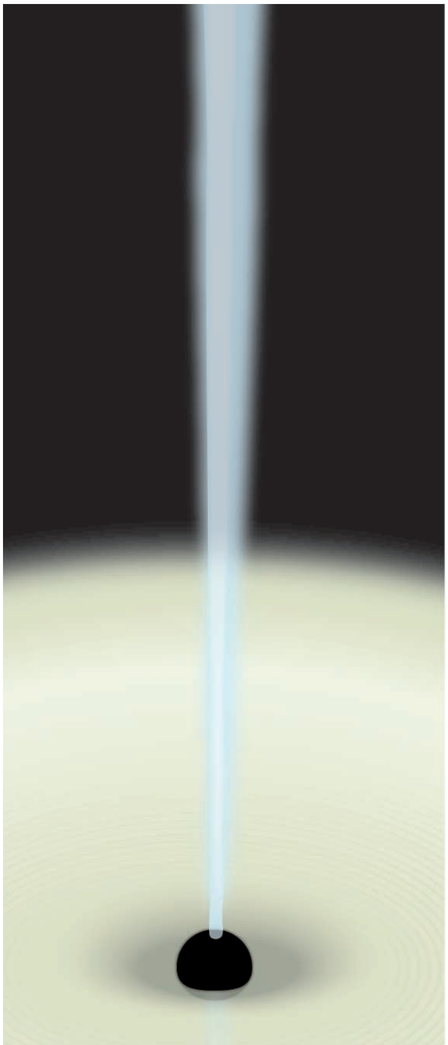

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Flares and jets. M87's jets are thought to form just outside the region where a swirling disk of gas makes its final plunge into the black hole, as shown in this artist's conception. Gamma-rays from jets have long been regarded as evidence of particle acceleration to very high energies, but it was not known whether this acceleration occurs far from the black hole or close in. The new results by Acciari *et al*. show that this acceleration occurs right at the base of the jet.