

however, the luminosity of M87 is low, making it plausible that we can see gamma-rays coming from close in (see the figure).

Another curious feature of the M87 detection is that it comes from a jet that is not pointing at us—the jet is at an angle of $\sim 15^\circ$ to 30° relative to our line of sight. For most other gamma-ray-emitting jets, we appear to be looking straight “down the barrel.” For observers with such a vantage point, effects predicted by the special theory of relativity would conspire to aid the escape of gamma-rays, increase their apparent luminosity, and make the onset of flares appear more sudden. We have no such advantage in our view of M87—that is, unless the flaring material is somehow moving toward us, rather than following the general track of the jet (8).

Jets produce radiation not only at radio and gamma-ray wavelengths, but at all wavelengths in between. In sources where gamma-rays are detected, they seem to dominate the total output, but there is usually a second broad peak of radiation at longer wavelengths. How that radiation is produced remains unclear. The longer wavelengths may arise from the

gyration of electrons in the jet’s magnetic field (synchrotron radiation), whereas the shorter wavelengths probably result from the scattering of radiation by energetic electrons (Compton scattering). But it is not known whether the supply of photons for the scattering process comes from the synchrotron radiation or from some other source (for example, an accretion disk) external to the jet (5, 6). By correlating the time dependence of flares at different wavelengths, astronomers hope not only to pin down the details of the emission process, but also to answer broader questions about how jets are powered, accelerated, and focused into narrow streams.

With the region for acceleration now identified by Acciari *et al.* as being closer than expected to the black hole, other questions regarding the source of power for the jets can be addressed: Is it the energy contained in the swirling gas about to be swallowed, or is it rotational energy stored in the black hole itself (9)? We also do not know whether the jets are made of ordinary plasma consisting of protons and electrons, or of an exotic mix of electrons and positrons. And the importance

of magnetic fields in jet dynamics and energetics, though strongly suspected, has yet to be proven. Gamma-ray astronomy will likely play a key role in resolving these questions, not only via the ground-based TeV arrays but also through the Fermi Gamma-Ray Space Telescope, launched in 2008 and expected to release its first data later this year.

References and Notes

1. W. Junor, J. A. Biretta, M. Livio, *Nature* **401**, 891 (1999).
2. With a mass estimated at between 3 and 6 billion solar masses, the black hole in M87 has an event horizon (the Schwarzschild radius) of 60 to 120 times the radius of the Earth’s orbit, or 8 to 16 light-hours. The radio observations resolve the jet down to scales of several light-weeks.
3. V. A. Acciari *et al.*, *Science* **325**, 444 (2009); published online 2 July 2009 (10.1126/science.1175406).
4. R. C. Hartman *et al.*, *Astrophys. J.* **385**, L1 (1992).
5. C. D. Dermer, R. Schlickeiser, *Astrophys. J.* **416**, 458 (1993).
6. M. Sikora, M. C. Begelman, M. J. Rees, *Astrophys. J.* **421**, 153 (1994).
7. A. P. Marscher *et al.*, *Nature* **452**, 966 (2008).
8. D. Giannios, D. A. Uzdensky, M. C. Begelman, *Mon. Not. R. Astron. Soc.* **395**, L29 (2009).
9. R. D. Blandford, R. L. Znajek, *Mon. Not. R. Astron. Soc.* **179**, 433 (1977).

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MICROBIOLOGY

Tumbling for Stealth?

Roman Stocker and William M. Durham

One of the most remarkable and pervasive feats in the microscopic world is the coordination of flagella, the slender, whiplike structures that protrude from many types of cells. The collective motion of

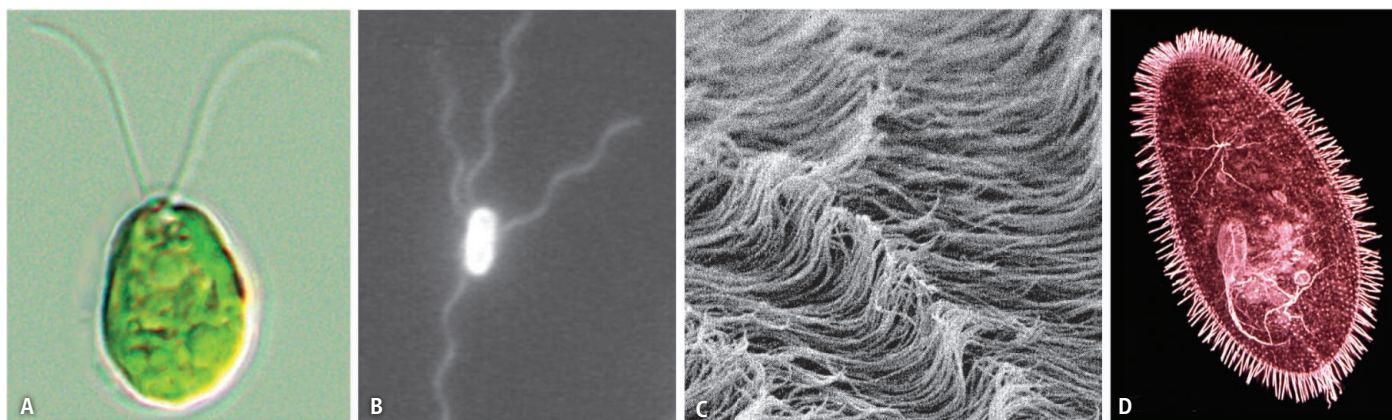
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flagella (also known as cilia when they occur in large numbers in eukaryotes) drives fluid transport (1), and permits individuals to save energy through cooperation (2). Because the internal structure of cilia is highly conserved among eukaryotes from algae to humans, free-swimming organisms like *Chlamydomonas* (see the first figure, panel A) have long been powerful

A green alga changes its flagellar beating patterns to create a run-and-tumble motion that may help it escape predation.

model systems (3). On page 487 of this issue, Polin *et al.* (4) show how synchronization of the flagella in *Chlamydomonas reinhardtii* governs the movement of this green alga through water, a key determinant of its ecological fitness.

Polin *et al.* found that *C. reinhardtii* actively switches between synchronized and asynchronous flagellar beating. When the



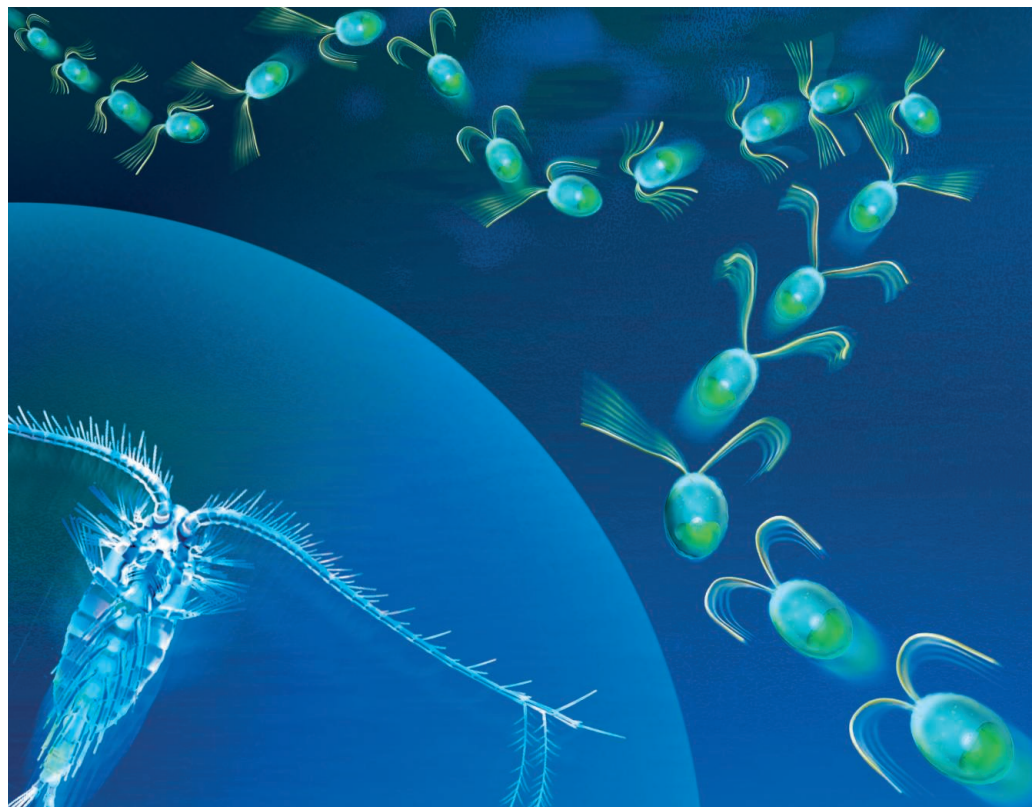
Cilia and flagella. The alga *Chlamydomonas reinhardtii* (body size 7 μm by 10 μm) (A) swims with two flagella. The bacterium *E. coli* (body size 1 μm by 2 μm) (B) swims by coordinating several helical flagella (12). The coordinated

motion of thousands of cilia produces metachronal waves (wavelength 5 μm) (13) (C); these waves propel microorganisms like *Paramecium* (body size 50 μm by 100 μm) (D).

flagella beat in synchrony, they perform a “breaststroke” that propels the cell forward. Every 11 s on average, the cell desynchronizes its flagella, triggering a sharp change in direction. This behavior resembles the run-and-tumble motion of the bacterium *Escherichia coli* (see the first figure, panel B). When *E. coli* bundles its 4 to 10 flagella, rotation of the flagella within a bundle provides propulsion in a nearly straight path (the “run”). When one or more of the motors driving the flagella reverse direction, those flagella leave the bundle, causing a change in direction (the “tumble”) (5). Polin *et al.* find that *C. reinhardtii* switches between the synchronous and asynchronous states by modulating the difference in the beat frequencies of its two flagella. When the frequency difference is small, the flagella synchronize, whereas when it is large, disarray prevails and the motion of the flagella decouples, causing the cell to turn sharply.

Synchronization arises in many biophysical processes, including cardiac pacemakers, clapping crowds, flashing fireflies, croaking frogs, and firing neurons. The classic example dates back to Huygens (6), who observed that the pendula of two clocks suspended from the same beam slowly vary in frequency until their swings are perfectly out of phase. This synchrony is achieved via forces transmitted through the beam. The results of Polin *et al.* indicate that, in a similar fashion, the two flagella of *C. reinhardtii* synchronize via forces transmitted through the fluid. Fluid forces have been known to synchronize the motion of microorganisms swimming near each other, including spirochetes and spermatozoa (2), and to induce the bundling of *E. coli*'s flagella during a run (7).

Passive synchronization through hydrodynamic coupling is also widely believed to be responsible for metachronal waves (8), (see the first figure, panel C), in which thousands of cilia undulate like “the wave” performed by crowds at stadiums. These patterns are responsible for a wide range of functions, from the flushing of the human respiratory system to the propulsion of microorganisms (see the first figure, panel D). The passive synchronization liberates a ciliated organism from the need to control each cilium with high accuracy.



Run-and-tumble swimming. The swimming pattern of *Chlamydomonas* discovered by Polin *et al.* could be a stealthy tactic to avoid encounters with predators such as copepods. Straight runs occur when the alga's two flagella beat in unison, whereas tumbles are triggered when their motion is not synchronized. To minimize predation risk, the run length must be smaller than the predator's capture radius, represented by the spherical surface (9, 11).

Polin *et al.* show that the hydrodynamic coupling of *C. reinhardtii*'s flagella is periodically interrupted. By comparing the flagellar beating statistics of tethered cells with the statistics of turning events of free-swimming cells, they conclude that flagellar desynchronization results in a sharp, random change in direction. Their results suggest that the increase in the frequency difference between the flagella, and the ensuing tumble, are under the control of the cell.

The best strategy to explore new space is to swim straight, because a tumbling cell partially retraces its path (9). So why would *Chlamydomonas* choose to tumble? *E. coli* tumbles to perform chemotaxis: Each tumble is a random reorientation, but by selectively delaying tumbles, the cell can move to more favorable conditions in a chemical gradient. The mean time between tumbles (1 s) is dictated by Brownian rotational diffusion, which prevents *E. coli* from swimming straight for more than a second. But *Chlamydomonas* is 10 times as large and thus 1000 times less susceptible to rotational diffusion: It could swim straight to its target, but chooses not to.

The explanation may lie in a trade-off between the quest for resources and the

avoidance of predators. Tumbling reduces predator encounters when the run length is smaller than the predator's capture radius (9). The resulting diffusive swimming can confer an evolutionary advantage over straight swimming (10) and is common among microorganisms (9). The tumbles reported by Polin *et al.* could thus be a stealthy strategy to avoid predators (see the second figure). Consistent with this idea, the capture radius of small predatory copepods, 4 to 8 mm (11), is larger than the mean run length of ~1 mm reported by Polin *et al.*

The global importance of the microscopic world often stems from its huge number of inhabitants: A myriad of tiny algae like *Chlamydomonas* produce a substantial fraction of the world's oxygen, and millions of microscopic cilia help us breathe it. Yet, as Polin *et al.* show, a fundamental understanding of their collective effects hinges on a thorough characterization of microscopic processes on the level of an individual.

References and Notes

1. G. L. Baum, Z. Priel, Y. Roth, N. Liron, E. J. Ostfeld, Eds., *Cilia, Mucus, and Mucociliary Interactions* (Dekker, New York, 1998).
2. G. I. Taylor, *Proc. R. Soc. London A* **209**, 447 (1951).
3. G. Vogel, *Science* **310**, 216 (2005).
4. M. Polin, I. Tuval, K. Drescher, J. P. Gollub, R. E. Gold-

- stein, *Science* **325**, 487 (2009).
- H. C. Berg, *E. coli in Motion* (Springer, New York, 2004).
 - C. Huygens, *Horologium Oscillatorium* (Apud F. Muguet, Parisiis, France, 1673); English transl., *The Pendulum Clock* (Iowa State Univ. Press, Ames, 1986).
 - H. Flores, E. Lobaton, S. Mendez-Diez, S. Tlupova, R. Cortez, *Bull. Math. Biol.* **67**, 137 (2005).
 - S. L. Tamm, *J. Exp. Biol.* **113**, 401 (1984).
 - A. W. Visser, T. Kiørboe, *Oecologia* **148**, 538 (2006).
 - A. W. Visser, *J. Plankt. Res.* **29**, 447 (2007).

- The feeding current, u , produced by a hovering predator of radius a , can be modeled in the far field by a Stokeslet, which yields $u \approx Ualr$ to leading order, where U is the near field feeding velocity and r is the distance from the predator. The capture radius is the distance r at which u is equal to the prey swimming speed (100 $\mu\text{m/s}$). For small copepods, $a \approx 100 \mu\text{m}$ and $U = 4$ to 8 mm/s, yielding $r = 4$ to 8 mm.
- L. Turner, W. S. Ryu, H. C. Berg, *J. Bacteriol.* **182**, 2793 (2000).

- S. L. Tamm, G. A. Horridge, *Proc. R. Soc. London B Biol. Sci.* **175**, 219 (1970).
- We thank H. Berg, K. Foster, T. Kiørboe, T. Powers, and S. Tamm for insightful comments. R.S. acknowledges support from NSF (OCE CAREER 0744641) and W.M.D. acknowledges a National Defense Science and Engineering Graduate Fellowship.

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CHEMISTRY

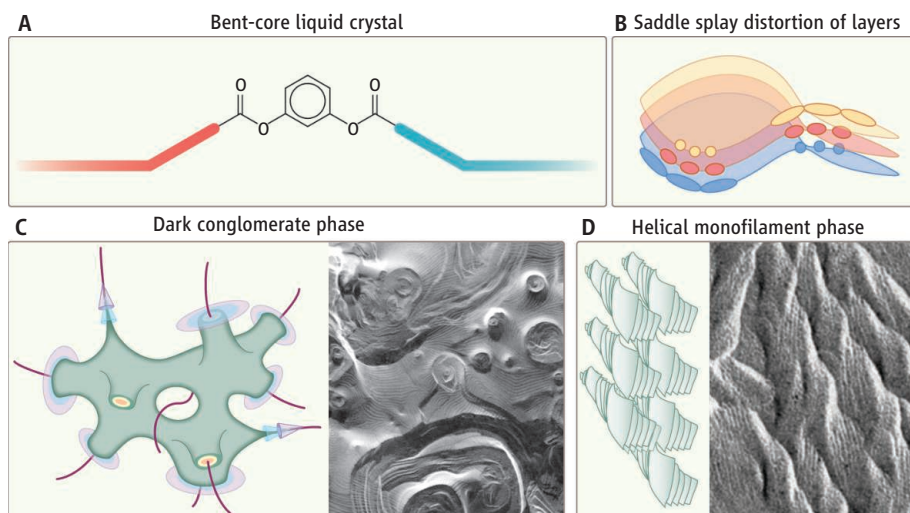
How Deformation Can Lend a Hand to Molecular Ordering

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The spontaneous separation of mirror-image molecules—enantiomers—into distinct crystals, first seen by Louis Pasteur (1), played a key role in the development of the basic principles of stereochemistry and is widely used to separate chiral compounds (2). Such “spontaneous resolution” has since been observed in many different molecular systems, such as monolayers and clusters (3), but it seemed highly unlikely to occur in an isotropic fluid phase, given the random motions that take place in the liquid state. Yet Hough *et al.* report on page 452 of this issue (4) that achiral molecules with a “boomerang” shape spontaneously resolve into right- and left-handed domains in an isotropic liquid. In related work on page 456, Hough *et al.* (5) show that members of this class of molecules can assemble into helical nanofilaments that lead to a new type of supramolecular ordering.

The fluids in question are liquid crystals based on so-called bent-core (boomerang-shaped core) molecules (see the figure, panel A). Liquid crystal molecules commonly organize themselves so that the cores of the molecules are aligned to some extent; in smectic liquid crystals, the molecules move within well-defined layers. The cores bear flexible side chains that disrupt crystal-packing interactions and promote formation of fluid phases. Typically, a liquid crystal phase is a mosaic of relatively large domains. Within each domain, the cores are ordered along one direction, but this direction varies between domains, so the material is anisotropic. This anisotropy causes the materials to be birefringent, exhibiting light and dark domains when viewed with crossed polarizing filters.

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How chiral phases shape up. (A) Bent-core molecules consist of an aromatic center, linked (in the case shown) with ester groups, to other rigid aromatic groups (red and blue). These groups bear flexible side chains at their extremes. (B) The layers of the smectic liquid crystal phase undergo splay distortions, which cause right- and left-handed chiral domains to form. Here, the colors represent different layers. Depending on the particular molecules used, this process can create (C) a chiral isotropic liquid in a sponge-like “dark conglomerate” phase, or (D) helical nanofilaments, which are shown both schematically and as freeze-fracture micrographs.

In most cases, achiral molecules create a material with achiral domains. However, the bent-core liquid crystals can undergo spontaneous resolution (6, 7) in their fluid form, resulting in chiral domains. The core of these molecules does not stay flat but twists along the bonds between the aromatic ring and the adjoining ester or imine groups (see the figure, panel A). The twisting creates either left- or right-handed helices, which undergo further packing to create chiral superstructures that are also polar in terms of the directionality of the cores.

Up to now, the phases formed by the bent-core molecules were like other liquid crystals in that they displayed anisotropy over large areas: The chirality of the different domains leads to light and dark regions when viewed with a polarizing optical microscope. How-

ever, the system described by Hough *et al.* (4) is different. The authors find that the phase that forms upon cooling the ordinary isotropic liquid, where the molecules move freely, still appears to be isotropic, at least at the macroscopic level. This “dark conglomerate” (DC) phase displays no long-range order and appears very dark when viewed with crossed polarizing filters. It is termed a conglomerate because the sample resolves spontaneously into domains (8–10)—in this case, homochiral domains up to hundreds of micrometers in width. The chirality of these domains manifests itself in remarkable optical activity: the ability to rotate plane-polarized light.

How can a liquid of achiral molecules that is isotropic at the macroscopic level exhibit signatures of chirality? In the layered DC phase, the molecules have short-range order (over