PLANETARY SCIENCE

# New Views of Asteroids

Erik Asphaug

Imagine exploring the surface of a near-Earth asteroid. You must be delicate in your traversal of this warped and mountainous world, an irregular agglomeration several kilometers across that pulls with a mere ten-thousandth the gravity of Earth (*1*)—a body so small you might jump off, never to return. The asteroid spins beneath a brilliant sun, sweeping out constellations and cycling the landscape into night and day more rapidly than you are used to (*2*). Promontories loom at improbable angles, and a stark horizon drops abruptly a hundred meters from your feet. In this precipitous world, your progress is further hindered by microgravity and the extraordinarily loose soil: Each gentle step raises volumes of dust and sends you floating for minutes. Global voyages may in principle be achieved with measured steps, but it takes an hour or more to complete the slow, all-but-unpredictable trajectories governed by the weird gravity and Coriolis forces (*3*). For the most part you just relax and enjoy the view of your home planet, appearing the size of a marble at arm's length, into which this asteroid may someday collide if left alone.

This microgravity fantasy is rooted in spacecraft and radar imaging of several near-Earth asteroids and other minor planets, and some application of routine physics. We can hope to witness this scenario in our lifetimes. More detailed speculation remains imprudent until we find out whether asteroids are intact, or fractured and cavernous; whether they sequester volatile ices in their not-so-deep interiors; and whether they harbor rich deposits of metals, exotic minerals, or prebiotic compounds. Almost certainly asteroids are stranger than we assume, and the enchantment of their discovery—spurred on by wide public access to recent images and reflected in the popularity of comets and asteroids in contemporary doomsday cinema—is spreading to a wide forum as we begin to learn the answers to these questions.

Near Earth Asteroid Rendezvous (NEAR), the first-launched NASA Discovery spacecraft, is a spearhead for asteroid science. NEAR will maneuver in early 1999 into the first orbit about a low-gravity planet, the ~14 km × 40 km Earth-approaching asteroid 433 Eros, to circle some 30 to 100 km above the surface, revolving at a stately ~5 m s$^{-1}$ for a year or more. Multispectral mineralogy, altimetry, magnetometry, orbital gravimetry, and unprecedented color images (with a resolution of 3 m per pixel) will transform little-known Eros into one of the most exhaustively explored members of our solar system, and the first body in that size range to be (we hope) approximately understood.

**The view from asteroid 4179 Toutatis on 29 September 2004**, when it comes within 0.1 astronomical unit of Earth. The view is from an observer in close orbit; the stars and the appearance of Earth are exact, with Earth about the size of a full moon. [Composite image created by E. De Jong and S. Suzuki of DIAL/JPL]

Last June, as an en route preview to that encounter, NEAR flew by the main-belt asteroid 233 Mathilde for the first look at a primitive C-type object (*4*), as reported by Veverka *et al.* and Yeomans *et al.* in this issue on pages 2106 and 2109 (*5*). Although the resolution was 50 times as coarse as expected at Eros, the images of Mathilde reveal some surprises and provoke an overdue reevaluation of asteroid geophysics. Mathilde has survived blow upon blow with almost farcical impunity, accommodating five great craters with diameters from 3/4 to 5/4 the asteroid's mean radius, and none leaving any hint of global devastation. Given that one of these great craters was the last to form, preexisting craters ought to bear major scars of seismic degradation, which they do not. Furthermore, asteroids Gaspra and Ida (encountered by Galileo en route to Jupiter) and the small martian satellite Phobos all exhibit fracture grooves related to impact, yet fracture grooves are absent on the larger, more-battered Mathilde. Perhaps fractures are hidden beneath deep regolith, or are so pervasive that Mathilde is nothing but regolith: a "rubble pile." In any event, Mathilde demonstrates that the formation of large craters can be quite local, and locally energetic: Ejecta was accelerated to escaping speeds (~20 m s$^{-1}$) without greatly disturbing the remainder of the asteroid. Interstitial voids greatly limit an impact shock wave's propagation but also enhance particle speeds within a smaller shocked region; porosity may thus explain Mathilde's strange craters, given its very low (~1.3 g cm$^{-3}$) density.

Until NEAR succeeds at Eros, the most detailed information about Earth-approachers derives from radar echo experiments. Powerful polarized signals are beamed from (and echoes received at) either of two antennas—one in Arecibo, Puerto Rico, and the other in Goldstone, California. Unlike optical imaging, this technique additionally constrains surface roughness, electrical properties, density, position, velocity, rotation, and shape (*6*). Less than 2 weeks after the discovery of Earth-crossing asteroid 1989PB, radar echo experiments revealed the first detailed images (*7*) of an asteroid—a probable contact binary later named 4769 Castalia. A more favorable apparition was provided by 4179 Toutatis, yielding the reconstructed view (*8*) shown in the figure. Extensive upgrades to the Arecibo antenna will be completed this spring, providing dozens of Toutatis-quality detections per year, spacecraft-quality images of the closest approachers, and hundred-pixel images of dozens of main-belt asteroids (*9*).

These irregular bodies (~1 to ~50 km in diameter) may hardly seem like planets in their own right, yet the distinction is becoming vague. Consider the third largest asteroid, 4 Vesta, a basalt-covered volcanic body 530 km in diameter that resembles the moon as much as it does Mathilde or Toutatis. Recent views (36 km per pixel) by the Hubble Space Telescope (*10*) show a 460-km crater, with raised rim and central peak, covering the entire southern hemisphere—an impact scar surpassing (in relative diameter, but not relative depth) the great chasms of Mathilde. Such craters greatly challenge our understanding of impact processes on asteroids, and on planets in general; evidently, our sci-

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ence must adapt. The study of asteroids is therefore particularly exciting, as small planets provide the fulcrum for the growth of planetology, and for an evolution of geophysics in general. Complex and poorly understood solar system processes—such as impact cratering, accretion and catastrophic disruption, the evolution of volcanic structures, and the triggering of differentiation—may reveal themselves only in a study across the gamut of planets, from the least significant house-sized rock to the most stately terrestrial world. Like clockwork miniatures, asteroids demonstrate primary principles governing planetary evolution at an accessible scale, and thousands await discovery and exploration in near-Earth space alone.

**References and Notes**


1. For a typical asteroid with density $1.5 < \rho < 2.5$ g cm$^{-3}$, escape velocity (in meters per second) is about equal to asteroidal radius (in kilometers). If you can jump half a meter on Earth, you could leap off of an asteroid 5 km in diameter.
2. Rotational periods vary tremendously. Speedy Castalia revolves every 4 hours, Mathilde every 17 days. Non-principal-axis rotator Toutatis (see figure) has nothing that can be called a "day," forever showing different horizons. For further insights, see Scott Hudson's Web page, http://www.eecs.wsu.edu/~hudson/asteroids.html.
3. This "human ICBM" mode of transportation is ill-advised; D. J. Scheeres *et al.*, *Icarus* **121**, 67 (1996) demonstrated the complexity of trajectories proximal to Castalia.
4. For a video view of the Mathilde encounter, see http://hurlbut.jhuapl.edu/NEAR/Mathilde/images.html#ani.
5. J. Veverka *et al.*, *Science* **278**, 2109 (1997); D. K. Yeomans *et al.*, *ibid.*, p. 2106.
6. S. J. Ostro *et al.*, *Astron. J.* **102**, 1490 (1991). Visit the asteroid radar research home page at http://echo.jpl.nasa.gov.
7. R. S. Hudson and S. J. Ostro, *Science* **263**, 940 (1994).
8. ———, *ibid.* **270**, 84 (1995).
9. The upgraded Arecibo antenna will also be used to image the "back side" of Mathilde, which was not seen during the NEAR flyby.
10. P. C. Thomas *et al.*, *Science* **277**, 1492 (1997).


MATERIALS SCIENCE

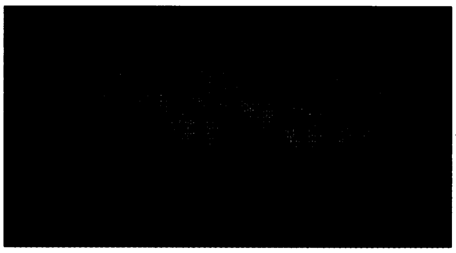
# Conducting Polymers: From Novel Science to New Technology


J. Campbell Scott


On page 2103 of this issue, Lonergan describes a hybrid device in which an inorganic semiconductor and a conducting polymer are combined to create a diode, one of the fundamental building blocks of electronics (*1*). Polymers of the sort used by Lonergan, which become electrically conductive after being doped with electron donors or acceptors, have occupied an increasingly prominent place in physics, chemistry, and materials science since Shirakawa first reported his method for the polymerization of acetylene (*2*). Much research has since been motivated (and many grants funded) by the conviction that there is a huge potential for technological and commercial exploitation, yet the record reveals only a few truly successful products (*3*). What can we learn by examining the history of conducting polymers?

In addition to the technological possibilities, interest in polyacetylene was driven by scientific curiosity into the effect of broken symmetry in the *trans*-isomer form, which gives rise to highly nonlinear phenomena such as solitons (*4*). Experimental data in the early 1980s were eagerly scrutinized by theorists in search of tests of their calculations in nonlinear dynamics. Identification of polarons (single electronic charges, self-trapped by a structural distortion) and bipolarons (doubly charged) followed in short order (*5*). At the same time, synthetic chemists were exploring new materials and synthetic procedures to yield higher conductivity and environmental stability. The "holy grail" became an air-stable polymer with the conductivity of copper. In retrospect, it is hard to believe that serious consideration was given to the use of plastics to replace wiring, circuit board connections, motor windings, or solenoid coils.

Nevertheless this period was an extremely productive time, owing to the synergy of scientists with backgrounds as diverse as field theory, solid-state physics, and physical and synthetic chemistry. A milestone was reached in the development of conducting polymers when it was recognized that they could be synthesized by electrochemical polymerization, then subsequently dedoped and redoped by electrochemical methods (*6*). Thus, properties such as electrical conductivity and optical absorption could be manipulated in ways that are not possible with conventional semiconductors and metals. This distinction has led to the introduction, or at least the trial, of conjugated polymers in new technological niches, and it is this feature that Lonergan exploits (*1*).



**Conjugated conductor.** Space-filling model of a polypyrrole chain. Carbon atoms are white; nitrogen atoms are blue.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One of the earliest commercialization attempts was in batteries (*3*), on the basis of electrochemical energy storage characteristics combined with a perceived weight advantage. However, because of breakthroughs in other battery materials such as lithium ion and metal hydride, and because volumetric capacity turned out to be more important than weight, conducting polymer batteries were not successful and have been withdrawn from the market. Electrolytic capacitors, introduced in 1992, have been more successful. Here, conducting polymers permit an all-solid-state device and obviate the problem of containing a liquid electrolyte by gelation or encapsulation.

Another unique and advantageous property of conjugated polymers lies in the processing and compatibility that one associates with plastics. The earliest examples—polyacetylene, polyphenylene, polythiophene, and polypyrrole (see figure)—were not very tractable, but considerable synthetic effort to add side-chain substituents has resulted in materials that are quite soluble in common organic solvents, and even (as with derivatives of polythiophene and polyaniline) in water. Thus, the materials engineer has at hand processes for casting thin conducting layers on a wide variety of substrates, or for blending the conducting polymer with structural polymers in films and fibers.

The resulting range of applications accounts for the majority of today's production of conducting polymers. Antistatic blends of conducting polyaniline or polypyrrole in textile fibers prevent the buildup of charge and the resultant damaging discharge. Camouflage fabrics can be treated to prevent radar reflection. A major manufacturer of photographic film coats the base layer with a transparent conductive layer of polyethylenedioxythiophene in order to make the sheet easier to handle during deposition of the optically active dyes, and to alleviate some of