Asteroids have become notorious as celestial menaces but are best appreciated in a positive light, as surreal worlds bearing testimony to the origin of the planets

The Small Planets

by Erik Asphaug

Growing up in the Space Age, my friends and I would sometimes play the gravity game. One of us would shout, "Pretend you're on the moon!" and we'd all take the exaggerated slow strides we'd seen on television. "Pretend you're on Jupiter!" another would say, and we'd crawl on our hands and knees. But no one ever shouted, "Pretend you're on an asteroid!" In that pre-*Armageddon* era, who knew what "asteroid" meant? Now a grown-up who studies asteroids for a living, I still don't know how to respond.

Although we haven't seen any of the largest asteroids up close, they probably resemble shrunken, battered versions of the moon. In their weaker gravity, visiting astronauts would simply take longer strides. But below a few dozen kilometers in diameter, gravity is too feeble to press these so-called minor planets into even an approximately round shape. The smallest worlds instead take on a carnival of forms, resembling lizard heads, kidney beans, molars, peanuts and skulls. Because of their irregularity, gravity often tugs away from the center of mass; when added to the centrifugal forces induced by rotation, the result can seem absurd. Down might not be down. You could fall up a mountain. You could jump too high, never to return, or launch yourself into a chaotic (though majestically slow) orbit for days before landing at an unpredictable location. A pebble thrown forward might strike you on the head. A gentle vertical hop might land you 100 meters to your left or even shift the structure of the asteroid underfoot. Even the most catlike visitor would leave dust floating everywhere, a debris "atmosphere" remaining aloft for days or weeks.

These aspects of asteroid physics are no longer only theoretical curiosities or a game for children. Space missions such as the Near Earth Asteroid Rendezvous (NEAR), the first probe to go into orbit around a minor planet, are dramatically modernizing our perception of these baffling objects. But in spite of careful observations and the occasional proximity of these bodies to Earth, we know less about asteroids (and their relatives, the comets) than we knew about the moon at the dawn of space exploration. Minor planets exhibit a delicate interplay of minor forces, none of which can be readily ignored and none of which can be easily simulated in a laboratory on Earth. Are they solid inside, or aggregate assemblages? What minerals are they composed of? How do they survive collisions with other small bodies? Could a lander or astronaut negotiate an asteroid's weird surface?

Half-Baked Planets

My graduate studies began during the Bush administration, when asteroids were mere dots—a thousand points of light known to orbit primarily in a belt between Mars and Jupiter. A few lesser populations were known to swoop closer to Earth, and then there were comets in the Great Beyond. From periodic variations in color and brightness, asteroids were inferred to be irregular bodies ranging in size from a house to a country, rotating every several hours or days. More detailed properties were largely the stuff of scientific imagination.

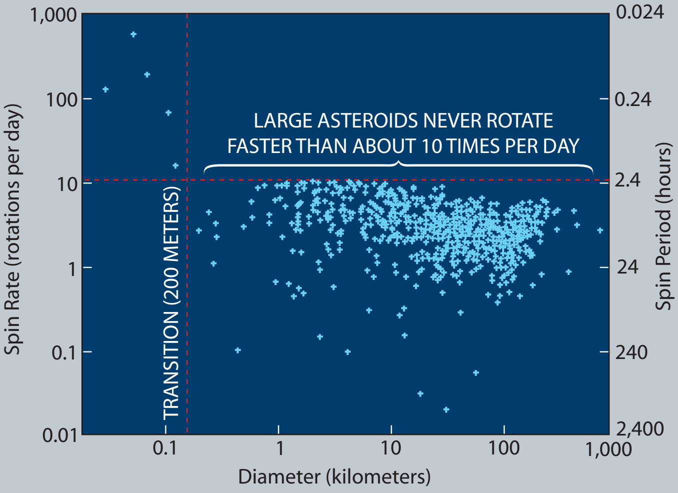
Asteroids residing closer to Mars and Earth commonly have the spectra of rocky minerals mixed with iron, whereas asteroids on the Jupiter side are generally dark and red, suggesting a primitive composition only coarsely differentiated from that of the primordial nebula out of which the planets began to coalesce 4.56 billion years ago [*see illustration on page 48*]. This timing is precisely determined from analysis of lead isotopes—the products of the radioactive decay of uranium—in the oldest grains of the most primitive meteorites. In fact, meteorites have long been suspected to derive from asteroids. The spectra of certain meteorites nearly match the spectra of certain class-

JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND NASA

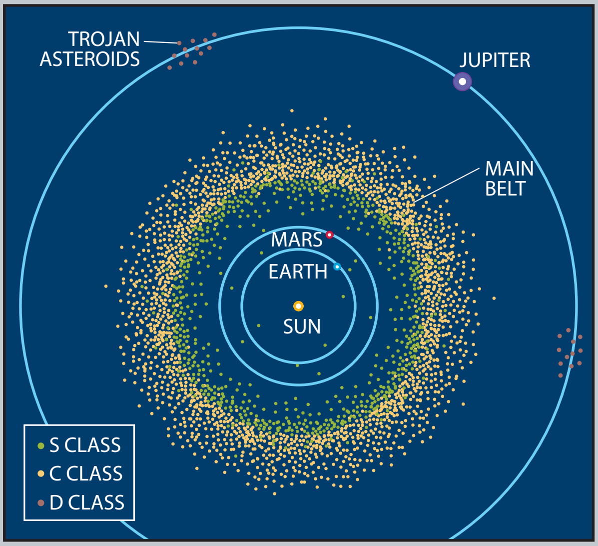
GIANT PAW PRINT is a strange crater on the asteroid Eros, so dubbed by scientists now studying this 33-kilometer-long space rock with the NEAR space probe (*center of lower image*). On the other side of the body is a youthful, saddle-shaped gouge (*left of upper image*) full of unexplained markings. Through images such as these, asteroids are now turning from astronomical objects—mere points of light—into geologic objects—whole worlds whose exploration has only begun.

Types of Asteroids

Where They Roam



TWO GROUPS OF ASTEROIDS emerge on a plot of their rotation rates (*vertical axis*) versus size (*horizontal axis*). No known asteroid larger than 200 meters across rotates faster than once every 2.2 hours. The cutoff is easy to explain if these asteroids are piles of rubble that fly apart if spun too fast. Smaller asteroids, which can turn once every few minutes, must be solid rocks. The transition probably arose because of collisions.



MAIN ASTEROID BELT lies between the orbits of Mars and Jupiter, but stragglers cross Earth's orbit (and sometimes collide with Earth) or revolve in sync with Jupiter (in two groups known as the Trojan asteroids). The inner main belt consists mainly of stony or stony-iron asteroids (S class); farther out the asteroids are darker, redder and richer in carbon (C class and D class).

LAURIE GRACE; SOURCE: PETR PRAVEC *Academy of Sciences of the Czech Republic (from sunkl.asu.cas.cz/~asteroid/3FRAs)*

es of asteroids. We therefore have pieces of asteroids in our possession.

Many astronomers used to think that telescope observations, combined with meteorite analysis, could substitute for spacecraft exploration of asteroids. Although the puzzles proved more stubborn than expected, researchers have been able to piece together a tentative outline of solar system history. For the planets to have accreted from a nebula of dust and gas, there had to be an initial stage in which the first tiny grains coagulated into growing bodies known as planetesimals. These became the building blocks of planets. But in the zone beyond Mars, gravitational resonances with massive Jupiter stirred the cauldron and prevented any body from growing larger than 1,000 kilometers across—leaving unaccreted remnants to become the present asteroids.

The largest of these would-be planets nonetheless accumulated enough internal heat to differentiate: their dense metals percolated inward, pooling and perhaps forming cores, leaving behind lighter rocky residues in their outer layers. Igneous activity further metamorphosed their rock types, and volcanoes erupted on some. Although none grew large enough to hold on to an atmosphere, hydrated minerals found in some meteorites reveal that liquid water was often present.

Encounters among the planetesimals became increasingly violent as Jupiter randomized the orientation and ellipticity of their orbits. Instead of continuing to grow, the would-be planets were chiseled or blasted apart by mutual collisions. Their pieces often continued to orbit the sun in families with common orbital characteristics and related spectra. Many asteroids and meteorites are the rock- or metal-rich debris of these differentiated protoplanets. Other asteroids (and most comets) are more primitive bodies that for various reasons never differentiated. They are relics from the ur-time before planets existed.

The Sky Is Falling

A decade ago no asteroid had been imaged in any useful detail, and many astronomers had trouble taking them seriously. The first asteroids, discovered in the early 1800s, were named in the grand mythological manner. But with the tenth, the hundredth and the thousandth, asteroids began taking on the names of their discoverers, and then of discoverers' spouses, benefactors, colleagues and dogs. Now, after a century of near-neglect, serious interest in asteroids is waxing as new observations transform them from dim twinkles in the sky into mind-boggling landforms. For this, asteroid scientists can thank National Aeronautics and Space Administration administrator Daniel S. Goldin and the dinosaurs.

Goldin's "faster, better, cheaper" mantra has been a boon to asteroid science, because a visit to a tiny neighbor is both faster and cheaper than a mission to a major planet. The specter of fiery death from above has also focused minds. The discovery of the Chicxulub crater in the Yucatán vindicated the idea that the impact of an asteroid or comet 65 million years ago extinguished well over half the species on Earth [see "An Extraterrestrial Impact," by Walter Alvarez and Frank Asaro; Scientific American, October 1990; "Collisions with Comets and Asteroids," by Tom Gehrels; Scientific American, March 1996].

A repeat is only a matter of time, but when? Until we completely catalogue all significant near-Earth asteroids—a job we have just begun—poker analogies must suffice. (We will never completely catalogue the comet hazard, because each comet visits the inner solar system so rarely.) The chance of a global calamity in any year is about the same as drawing a royal flush; your annual chance of dying by other means is about the same as drawing three of a kind. None of us is remotely likely to die by asteroid impact, yet even scientists are drawn to the excitement of apocalypse, perhaps too often characterizing asteroids by their potential explosive yield in megatons instead of by diameter. Our professional dilemma is akin to notoriety in art: we want asteroids to be appreciated for higher reasons, but notoriety pays the bills.

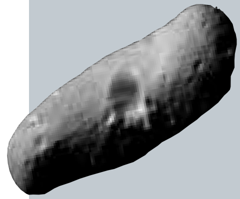
Egged on by this nervous curiosity, we are entering the golden age of comet and asteroid exploration. Over a dozen have been imaged [*see box on next page*], and each new member of the menagerie is welcomed with delight and perplexity. They are not what we expected, to say the least. Small asteroids were predicted to be hard and rocky, as any loose surface material (called regolith) generated by impacts was expected to escape their weak gravity. Aggregate small bodies were not thought to exist, because the slightest sustained relative motion would cause them to separate.

Reduced to Rubble

But observations and modeling are proving otherwise. Most asteroids larger than a kilometer are now believed to be composites of smaller pieces. Those imaged at high resolution show evidence for copious regolith despite the weak gravity. Most of them have one or more extraordinarily large craters, some of which are wider than the mean radius of the whole body. Such colossal impacts would not just gouge out a crater—they would break any monolithic body into pieces. Evidence of fragmentation also comes from the available measurements for asteroid bulk density. The values are improbably low, indicating that these bodies are threaded with voids of unknown size.

In short, asteroids larger than a kilometer across may look like nuggets of hard rock but are more likely to be aggregate assemblages—or even piles of loose rubble so pervasively fragmented that no solid bedrock is left. This rubble-pile hypothesis was first proposed two decades ago by Don Davis and Clark Chapman, both then at the Planetary Science Institute in Tucson, but they did not suspect that it would apply to such small diameters.

Shortly after the NEAR spacecraft flew by asteroid Mathilde three years ago on its way to Eros, the late planetologist



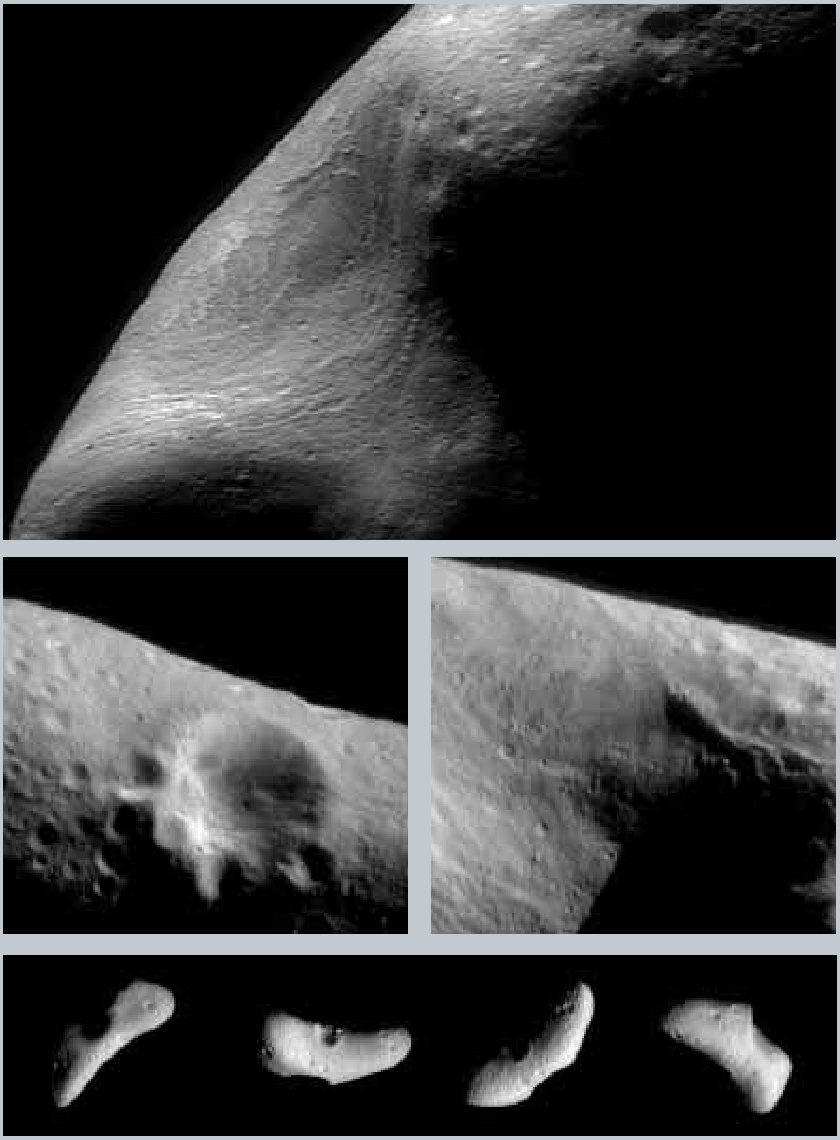
NEAR's Courtship with Eros

A Lovely Rock

Eros, currently orbited by the NEAR spacecraft, resembles a boat with a narrow bow, a wide stern and a prominent crater on the concave deck. Copious mounded and blocky debris around this crater show the influence of gravity during its formation. A boulder is inside, stopped halfway; it can't seem to figure out which way is down. Another prominent divot, on the opposite side, is so big that it is part of Eros' overall shape. If it is of impact origin, as is probable, its formation must have cracked Eros into a few great pieces mantled in lesser fragments and debris.

The name "Eros" befits a coy flirtation with Earth. Unfortunately, this love affair may end in sorrow. Paolo Farinella of the University of Trieste and Patrick Michel of Nice Observatory have calculated that Eros has a 5 percent chance of colliding with Earth in the next one billion years, with an intensity exceeding that which extinguished the dinosaurs.

NEITHER SOLID ROCK NOR DUST BUNNY, Eros is a conglomerate of several major pieces crosscut by faults, scarps and ridges. The largest structure is a smooth, striated gouge that is nearly devoid of craters (*below*). The most prominent crater—the "paw print" six kilometers across—has massive deposits on its rim, which indicate that gravity dictated its formation (*center left*). A steep ridge, which runs parallel to the linear markings, suggests faulting in a coherent material (*center right*). The asteroid rotates once every five and a half hours (*bottom*).

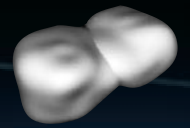


JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND NASA

Asteroid Visitations

The Rock Concert

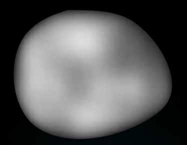
CASTALIA



Official catalogue number: 4769 **Dimensions:** 1.8 x 0.8 kilometers
Density: 2.1 grams per cubic centimeter (surface) **Orbit type:** Earth crossing
Spectral class: S **Rotation:** 4 hours

Castalia was the first asteroid ever to be imaged. In August 1989 it flew within 11 lunar distances of Earth—still too far for optical telescopes but close enough for radar. Steven J. Ostro and his group at the Jet Propulsion Laboratory targeted the body with powerful and precise beams from the world's largest radio telescope, in Arecibo, Puerto Rico. Castalia's peanut shape suggests two 800-meter pieces resting together despite the very weak gravity. Radar echoes from other Earth-crossing asteroids now tell us that contact-binary configurations are common.

VESTA



Official catalogue number: 4 **Dimensions:** 525 kilometers in diameter
Density: 3.3 grams per cubic centimeter **Orbit type:** Main belt
Spectral class: V **Rotation:** 5.34 hours

Only Vesta among the large asteroids has a surface of basaltic rock from ancient lava flows. In the distant past, it evidently differentiated into layers and underwent many of the same geologic processes as early Mars or Earth. Dozens of Vesta-like bodies presumably existed at one time but were broken apart into families of smaller asteroids. Iron meteorites are thought to come from the cores of these shattered worlds and igneous meteorites from their crusts and mantles. In 1996 the Hubble Space Telescope obtained this image of Vesta, showing a huge crater 430 kilometers across. Perhaps a billion years old, this crater might be the source of the small V-type asteroids observed today.

EROS

Official catalogue number: 433
Dimensions: 33 x 13 x 13 kilometers
Density: 2.7 grams per cubic centimeter
Orbit type: Near Earth
Spectral class: S
Rotation: 5.27 hours

GASPRA

Official catalogue number: 951 **Dimensions:** 19 x 12 x 11 kilometers
Density: Not known **Orbit type:** Main belt (Flora family)
Spectral class: S **Rotation:** 7.04 hours

Gaspra was the first asteroid visited by a spacecraft: Galileo flew by in 1991 on its way to Jupiter. Some have argued that its half-dozen large concavities are not craters but facets formed when Gaspra broke off from its parent asteroid. On the other hand, in the weak, irregular gravity of Gaspra, the largest impact craters would naturally take on such a flat, lopsided shape.

MATHILDE

Official catalogue number: 253 **Dimensions:** 66 x 48 x 46 kilometers
Density: 1.3 grams per cubic centimeter **Orbit type:** Main belt
Spectral class: C **Rotation:** 17.4 days

On its way to Eros, NEAR made the first spacecraft encounter with a primitive C-type asteroid. This blacker-than-coal spheroid, the largest asteroid yet visited and one of the slowest rotators, follows an eccentric orbit extending to the outer reaches of the main belt. The spacecraft's trajectory was slightly deflected by Mathilde, telling us its mass. The implied density is less than half that of the closest matching meteorites, carbonaceous chondrites, so if Mathilde is made of the same material, it must be very loosely packed. The same is true of another C-type asteroid, Eugenia, recently studied using a ground-based telescope equipped with sophisticated adaptive optics.

The giant craters are amazing. Several are wider than Mathilde's average radius, yet none have rims or ejecta deposits, which are associated with large craters on other worlds. Also, none of the craters have been degraded by subsequent cratering; we can't even tell which impact happened first or last. It is as though some deity has come and taken tidy bites from a cosmic apple.

TOUTATIS

Official catalogue number: 4179 **Dimensions:** 4.5 by 2.4 by 1.9 kilometers
Density: 2.1 grams per cubic centimeter (surface) **Orbit type:** Earth crossing
Spectral class: S **Rotation:** Two separate periods (5.41 and 7.35 days)

Since the first observations of Castalia, better opportunities for radar detection of asteroids have presented themselves, most notably for asteroid Toutatis. Strongly influenced by Earth's gravity, its orbit is chaotic. Also, it wobbles with two types of motion that combine to create nonperiodic rotation. A visitor would never see the same horizon twice. On September 29, 2004, Toutatis will come within four lunar distances, whereupon it will be visible with binoculars.

IDA & DACTYL

Official catalogue number: 243
Dimensions: 56 x 24 x 21 kilometers **Density:** About 2.5 grams per cubic centimeter
Orbit type: Main belt (Koronis family) **Spectral class:** S **Rotation:** 4.63 hours

Two years after visiting Gaspra, Galileo flew by this main-belt asteroid. An unexpected gem from this encounter was the discovery of Dactyl—the first known asteroid satellite, a mere 1.4 kilometers in diameter. The Galileo team used Dactyl's orbit to calculate Ida's mass. The implied density is much lower than that of the most closely related type of meteorite, ordinary chondrites, so Ida must be of different composition or else porous. Some believe that Dactyl agglomerated out of slow ejecta from one of Ida's largest craters, although this would have been very difficult to achieve dynamically. Daniel Durda of the Southwest Research Institute in Boulder, Colo., showed that Dactyl and Ida could have formed as a pair a billion or more years ago, when Ida's parent body was disrupted. But it is hard to explain how Dactyl could have survived for so long without being destroyed.

SCOTT HUDSON *Washington State University* (*Castalia*); BEN H. ZELLNER *Georgia Southern University* AND NASA (*Vesta*); JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY AND NASA (*Eros* and *Mathilde*); NASA/JET PROPULSION LABORATORY (*Gaspra*); NASA/JPL (*Ida*)

Flintstone or Rubble?

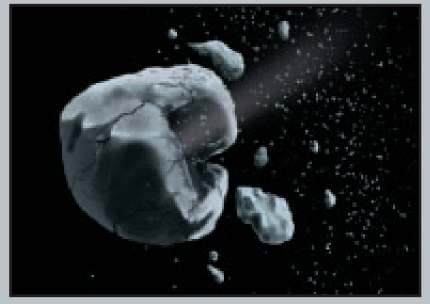
Really Deep Impacts

RUBBLE-PILE ASTEROID, whose fragmented structure bears the scars of all its past collisions, is struck again by a smaller asteroid at high speed. Such bang-ups are fairly common.

In the aggregate body the blast remains confined to the local area. Within a few minutes, the smallest, fastest debris has escaped. The larger fragments drift slowly outward.

Some large pieces escape; some return. A few days later things have settled down. Over time the wound will be covered in debris thrown out by bombardment and other processes.

SOLID ASTEROID, a monolithic chunk of rock, responds very differently to a collision than the rubble pile does—just as a log responds differently to the blow of an ax than a mound of wood chips does.



The shock wave propagates deep into the interior, blasting apart the whole body. The fastest ejecta are soon gone, leaving larger fragments to undergo a gentle gravitational dance for hours.

Many of these pieces come to rest in a pile of rubble. Because it is so easy to turn a solid rock into a rubble pile, few asteroids larger than a few hundred meters across are still solid.

BRYAN CHRISTIE

Eugene M. Shoemaker (for whom NEAR has been renamed) realized that the huge craters on this asteroid and its very low density could only make sense together: a porous body such as a rubble pile can withstand a battering much better than an integral object. It will absorb and dissipate a large fraction of the energy of an impact; the far side might hardly feel a thing. A fair analogy is a bullet hitting a sandbag, as opposed to a crystal vase.

What about the jagged shapes of most asteroids? Intuition tells us that dramatic topography implies solidity. But first glances can deceive. When measured relative to the fun-house gravity, no regional slope on any imaged asteroid or comet exceeds a typical angle of repose (about 45 degrees), the incline at which loose debris tumbles down. In the steepest regions, we do see debris slides. In other words, small bodies could as well be made of boulders or even sand and still hold their shape. Dunes, after all, have distinct ridges yet are hardly monolithic. Rapid rotation would contribute to an elongated, lumpy appearance for a rubble pile.

Direct support for the rubble-pile hypothesis emerged in 1992, when comet Shoemaker-Levy 9 strayed too close to Jupiter and was torn into two dozen pieces. Two years later this "string of pearls" collided with the giant planet [see "Comet Shoemaker-Levy 9 Meets Jupiter," by David H. Levy, Eugene M. Shoemaker and Carolyn S. Shoemaker; Scientific American, August 1995]. According to a model I developed with Willy Benz of the University of Bern, the comet could have disassembled as it did only if it consisted of hundreds of loose grains in a slow cosmic landslide. As the comet was stretched by Jupiter's tides, the grains gravitated into clumps much like water beading in a fountain. From this breakup we proposed that comets are likely to be granular structures with a density around two thirds that of water ice. What applies to comets might apply to asteroids as well.

When Nothing Matters, Everything Matters

Yet the rubble-pile hypothesis is conceptually troublesome. The material strength of an asteroid is nearly zero, and gravity is so low you are tempted to neglect that, too. What's left? The truth is that neither strength nor gravity can be ignored. Paltry though it may be, gravity binds a rubble pile together. And anyone who builds sand castles knows that even loose debris can cohere. Oft-ignored details of motion begin to matter: sliding friction, chemical bonding, damping of kinetic energy, electrostatic attraction and so on. (In fact, charged particles from the sun can cause dust at the surface to levitate.) We are just beginning to fathom the subtle interplay of these minuscule forces.

The size of an asteroid should determine which force dominates. One indication is the observed pattern of asteroidal rotation rates. Some collisions cause an asteroid to spin faster; others slow it down. If asteroids are monolithic rocks undergoing random collisions, a graph of their rotation rates should show a bell-shaped distribution with a statistical "tail" of very fast rotators. If nearly all asteroids are rubble piles, however, this tail would be missing, because any rubble pile spinning faster than once every two or three hours (depending on its bulk density) would fly apart. Alan Harris of the Jet Propulsion Laboratory in Pasadena, Calif., Petr Pravec of the Academy of Sciences of the Czech Republic in Prague and their colleagues have discovered that all but five observed asteroids obey a strict rotation limit [*see illustration on page 48*]. The exceptions are all smaller than about 150 meters in diameter, with an abrupt cutoff for asteroids larger than about 200 meters.

The evident conclusion—that asteroids larger than 200 meters across are multicomponent structures or rubble piles—agrees with recent computer modeling of collisions, which also finds a transition at that diameter. A collision can blast a large asteroid to bits, but those bits will usually be moving slower than their mutual escape velocity (which, as a rule of thumb, is about one meter per second, per kilometer of radius). Over several hours, gravity will reassemble all but the fastest pieces into a rubble pile [*see illustration above*]. Because collisions among asteroids are relatively frequent, most large bodies have already suffered this fate. Conversely, most small asteroids should be monolithic, because impact fragments easily escape their feeble gravity.

Qualitatively, a "small" asteroid sustains dramatic topography, and its impact craters do not retain the debris they eject. It looks like a battered bunker in a war movie. A "large" asteroid is an assemblage of smaller pieces that gravity and random collisions might nudge into a rounded or, if spinning, an elongated shape. Its craters will have raised rims and ejecta deposits, and its surface will be covered in regolith. But this size distinction is not straightforward. Asteroid Mathilde could be considered small, as it has no visible rims or ejecta deposited around its enormous craters, or large, as it is approximately spheroidal. Tiny Dactyl could seem large, also being spheroidal and sustaining such well-developed craters. The ambiguity is a sign that the underlying science is uncertain.

Shock Value

Given that geophysicists are still figuring out how sand behaves on Earth and how landslides flow, we must be humble in trying to understand conglomerate asteroids. Two approaches are making inroads into one of their key attributes: how they respond to collisions.

Derek Richardson and his colleagues at the University of Washington simulate asteroids as piles of discrete spheres. Like cosmic billiards on a warped pool table—the warp being gravity—these spheres can hit one another, rebound and slow down because of friction and other forms of energy dissipation. If balls have enough collisional energy, they disperse; more commonly, some or all pile back together. Richardson's model is particularly useful for studying the gentle accretionary encounters in the early solar system, before relative velocities started to increase under the gravitational influence of nascent Jupiter. It turns out to be surprisingly difficult for planetesimals to accrete mass during even the most gentle collisions.

High-speed collisions, more typical of the past four billion years, are more complicated because they involve the minutiae of material characteristics such as strength, brittle fracture, phase transformations, and the generation and propagation of shock waves. Benz and I have developed new computational techniques to deal with this case. Rather than divide a target asteroid into discrete spheres, we treat it as a continuous body, albeit with layers, cracks, or networks of voids.

In one sample simulation, we watch a 6,000-ton impactor hit billion-ton Castalia at five kilometers per second. This collision releases 17 kilotons of energy, the equivalent of the Hiroshima explosion—and enough to break up Castalia. We simulate Castalia as a two-piece object held together by gravity. The projectile and an equal mass of Castalia are vaporized in milliseconds, and a powerful stress wave is spawned. Because the shock wave cannot propagate through vacuum, it rebounds off surfaces, including the fracture between the two pieces of the asteroid. Consequently, the far piece avoids damage. The near piece cracks into dozens of major fragments, which take hours to disperse; the largest ones eventually reassemble. This outcome is very sensitive to what we start with. Other initial configurations and material parameters (which are largely unknown) lead to vastly different outcomes. Asteroids that start off as rubble piles, for example, are hard to blast apart.

Rendezvous with Eros

We can also work backward, inferring the rock properties of an asteroid by trying out different initial guesses and comparing the simulations with observations. As an example, I have worked with Peter Thomas of Cornell University to re-create the largest crater on Mathilde as precisely as possible: its diameter and shape (easy enough), its lack of fracture grooves or damage to existing craters (somewhat harder) and the absence of crater ejecta deposits (very hard).

If we assume that Mathilde was originally solid and monolithic, our model can reproduce the crater but predicts that the asteroid would have cracked into dozens of pieces, contrary to observations. If we assume that Mathilde was originally a rubble pile, as Shoemaker suggested, then our impact model easily matches the observations. Kevin Housen of the Boeing Shock Physics Lab and his colleagues have also argued that Mathilde is a rubble pile, although they regard the craters as compaction pits—like dents in a beanbag—rather than excavated features.

Understanding asteroid structure will be crucial for future missions. A rubble pile will not respond like a chunk of rock if we hope to gather material for a sample return to Earth or, in the more distant future, construct remote telescopes, conduct mining operations or attempt to divert a doomsday asteroid headed for Earth. The irregular gravity is also a problem; spacecraft orbits around comets and asteroids can be chaotic, making it difficult to avoid crashing into the surface, let alone point cameras and instruments. NEAR is therefore conducting most of its science a hundred kilometers or more away from Eros. At this distance the irregular, rapidly rotating potato exerts almost the same gravity that a sphere would. The spacecraft's deviation from a standard elliptical orbit will enable NEAR scientists to measure the density distribution within Eros.

Orbiting Eros at the speed of a casual bicyclist (corresponding to the low gravity), NEAR is beaming a torrent of data toward Earth. The primary objective is to clarify the link between asteroids and meteorites. Cameras are mapping the body to a few meters' resolution, spectrometers are analyzing the mineral composition, and a magnetometer is searching for a native magnetic field and for interactions with the solar field. Upcoming missions will probe asteroids and comets in ever greater detail, using a broader range of instruments such as landers, penetrators and sample returns [*see box at right*].

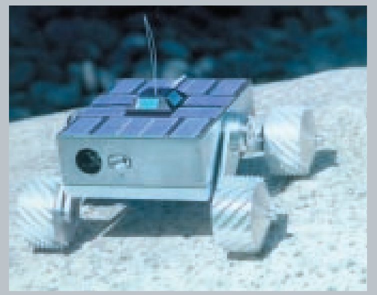
These discoveries will help plug a vast conceptual hole in astronomy. We simply don't understand small planetary bodies, where gravity and strength compete on sometimes equal footing. Asteroids are a balancing act, as serene as the moon yet of cataclysmic potential, large enough to hang onto their pieces yet too small to lose their exotic shape. Neither rocks nor planets, they are something of Earth and Heaven.

Upcoming Missions

The NEAR Future

Before any of us can set foot on an asteroid, minor planets must be poked and prodded just as the moon was before *Apollo 11* could land. To this end, several new missions will follow up the ongoing success of the Near Earth Asteroid Rendezvous.

Two will collect samples and bring them back to Earth. NASA's Stardust spacecraft was launched in February 1999 toward Comet Wild 2 and is expected to return in 2006 with a piece of the tail (some grains of precious dust). The Japanese space agency plans to launch the MUSES-C space probe in 2002 to collect material from the asteroid Nereus, where it will also release a NASA-built "hopper" that will jump across the surface like a flea [*see illustration below*]. Although it has wheels, it is anyone's guess whether the hopper will be able to obtain enough friction to drive.



NANOROVER will hop across the surface of the asteroid Nereus. (For plans to build your own model, see spaceplace.jpl.nasa.gov/muses3.htm on the World Wide Web.)

NASA/JET PROPULSION LABORATORY

The Comet Nucleus Tour, or Contour, has recently been selected for a 2002 launch and is scheduled to closely inspect two distinct cometary nuclei in 2003 and 2006 and perhaps a third in 2008. Another comet probe, the European Space Agency's Rosetta, should set out in 2003 and rendezvous in 2011 with Comet Wirtanen (a distant comet nudged toward the inner solar system by an encounter with Jupiter). It will also visit two small asteroids en route. Rosetta and its lander will watch as Wirtanen, moving from the outer solar system toward its closest approach to the sun, changes from a cold, quiet ice world into an eruptive, gas-shrouded spectacle.

The first mission to perform a geomechanical experiment on an asteroid will be Deep Impact, which, if all goes well, will blow a large crater in Comet Tempel 1 using a 500-kilogram copper projectile. How large? That depends on the cometary properties, which we hope to learn. A similar, though perhaps less dramatic, mission could perform seismic imaging of an asteroid's interior by firing a stream of "smart" bullets—shielded projectiles that each encapsulate an accelerometer and a radio transmitter. Each accelerometer would record not only its own brutal deceleration into the asteroidal surface, telling whether it struck fine powder or gravel or rock, but also the seismic signal from other bullets as they come slamming in over the course of one asteroid rotation. Together they would reveal the structure of the asteroid's interior, just as geologists have learned the internal structure of Earth by listening to earthquakes.

—E.A.

The Author

ERIK ASPHAUG recalls his quarter-dropping days playing the video game Asteroids: "You get two big chunks and maybe two smaller chunks whenever you kill an asteroid. In truth you'll get hundreds of tiny, fast pieces and some larger pieces filling your screen with pesky debris." Besides his gaming ambitions, Asphaug gardens and plays guitar to his one-year-old son, Henry, and simulates asteroid collisions on a Cray T3E supercomputer. He is a researcher at the University of California, Santa Cruz. In recognition of his work, Asphaug was awarded the 1998 Urey Prize of the American Astronomical Society.

Further Information

Hazards Due to Comets and Asteroids. Edited by Tom Gehrels. University of Arizona Press, 1994.

Mining the Sky. John Lewis. Addison-Wesley, 1996.

Disruption of Kilometre-Sized Asteroids by Energetic Collisions. Erik Asphaug, Steven J. Ostro, R. S. Hudson, D. J. Scheeres and Willy Benz in *Nature,* Vol. 393, pages 437–440; June 4, 1998.

Meteorites and Their Parent Planets. Second edition. Harry McSween. Cambridge University Press, 1999.

Asteroid Fragmentation and Evolution of Asteroids. Eileen Ryan and William Bottke. *Annual Reviews of Earth and Planetary Science,* Vol. 28, pages 367–389. Annual Reviews, 2000.

For updates on the Near Earth Asteroid Rendezvous mission, visit http://near.jhuapl.edu

For general information on near-Earth objects, go to http://neo.jpl.nasa.gov

The author's Web site is at http://planet.ucsc.edu