

A night sky filled with numerous shooting stars of various colors (white, yellow, red) streaking across the dark blue background. In the foreground, a dark, silhouetted mountain range is visible against the starry sky. The overall scene is dramatic and captures the beauty of a meteor shower.

# NATURAL HISTORY

9/03

SECRETS OF  
SHOOTING STARS



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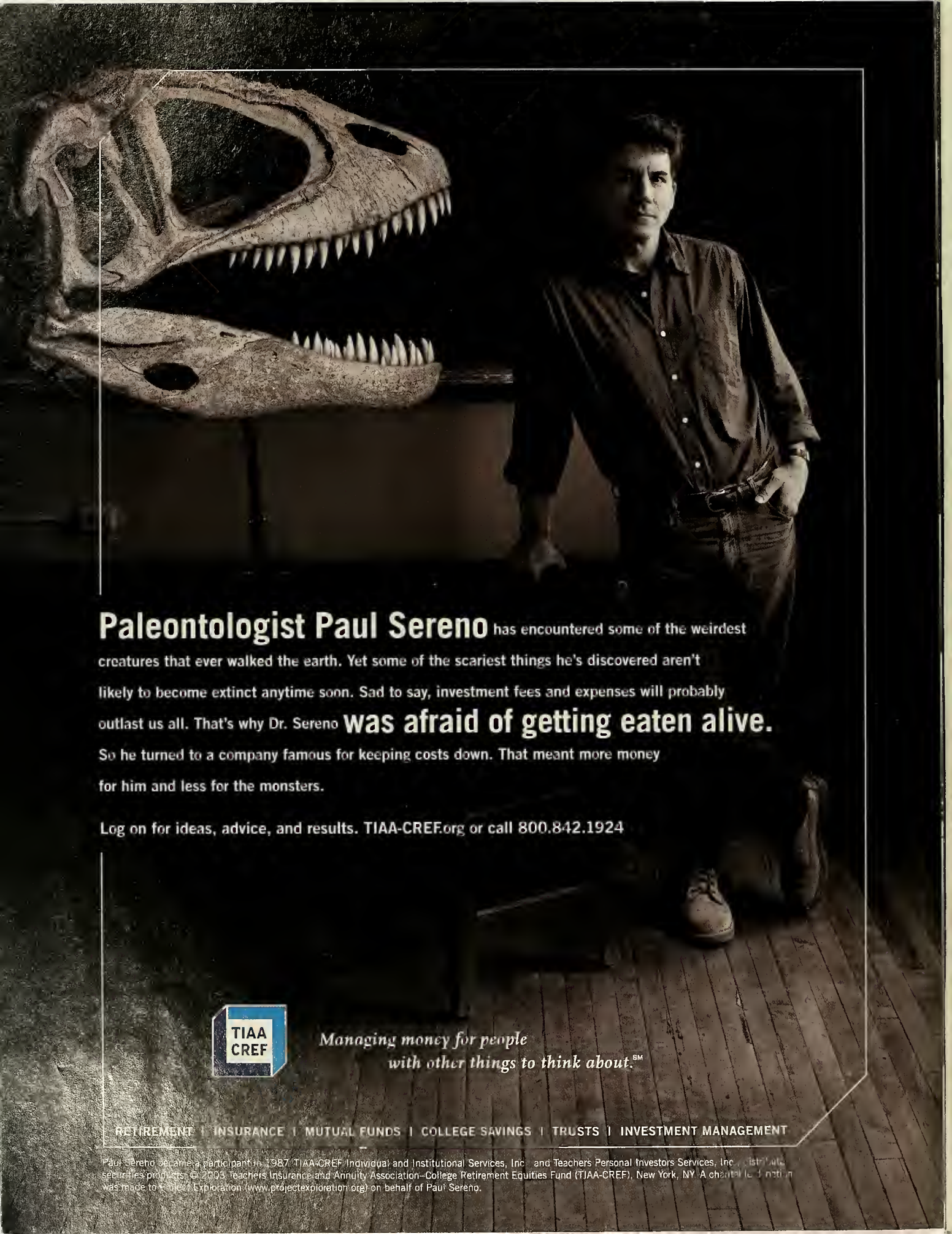
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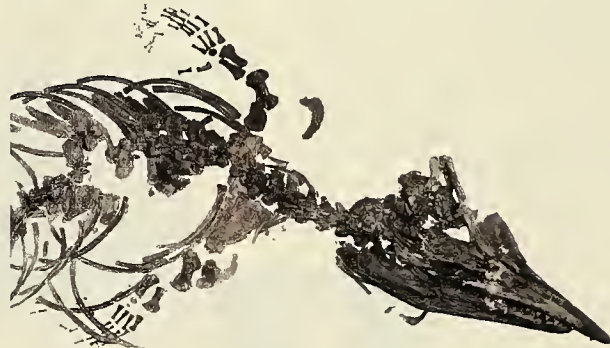
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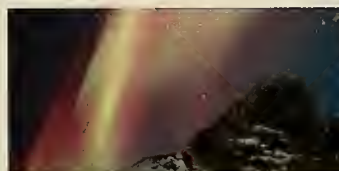
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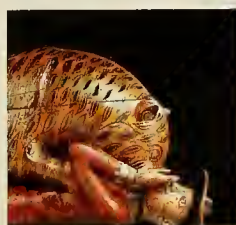
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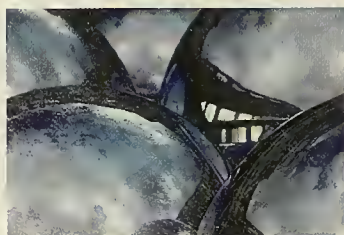
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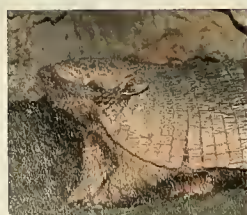
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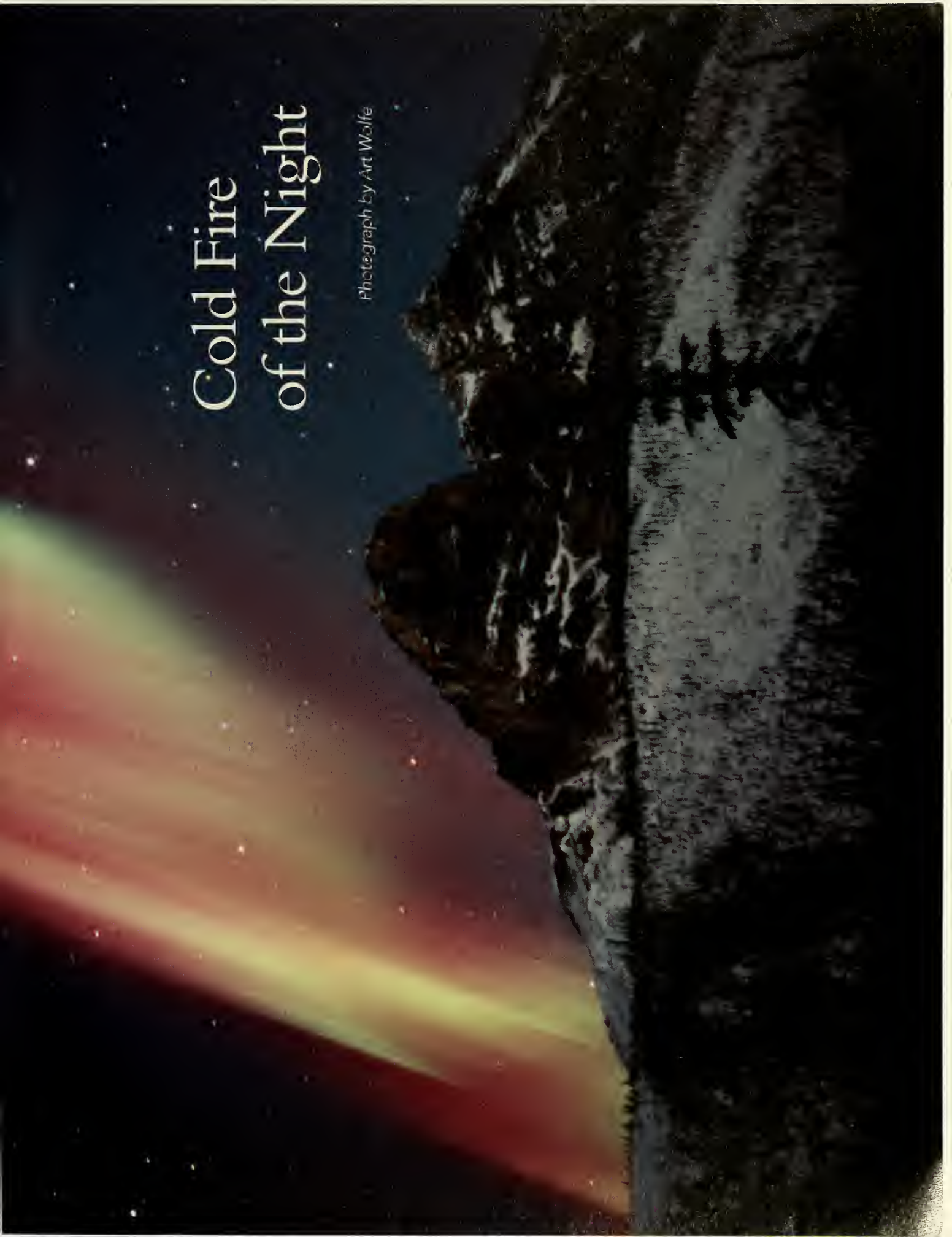
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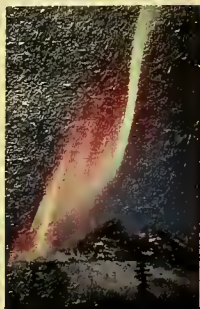


# Cold Fire of the Night

Photograph by Art Wolfe



◀ See preceding pages



Aurora was the radiant Roman goddess of dawn, a charioteer who could light up the night sky. Her namesakes, the aurora borealis and aurora australis, are similarly un-Earthly: electrons and protons pour out of the Sun and speed through space until they hit a region rich in gases—the atmospheres of most planets and of a few moons do nicely. As the particles collide with different gases, they trigger colored light—works: red or green from oxygen, for instance, or blue or violet from nitrogen.

If Earth had no magnetism, like Venus, the light show would be erratic. If Earth were magnetized closer to its equator, as Neptune is, Mexico City would be prime for viewing. As it is, auroras on Earth follow magnetic lines of force that converge at the north and south magnetic poles. They can be seen year-round; check the Internet for readily available aurora “weather” forecasts.

Eager to capture the lights, photographer Art Wolfe took the frozen Dalton Highway, which stretches 414 miles from Fairbanks to Prudhoe Bay, Alaska. He watched the aurora reel and dance in pale greens for two hours above the Brooks Range. What he found most mystical was that “when the film was developed, there were lovely reds that had been there, but just couldn’t be picked up by the naked eye.”

—Erin M. Espelie

## Hard Rain

Every year about this time, when the night skies are clear, and when standing still under the stars for half an hour doesn’t call for a parka, I like to go outside and take in the show. It’s pretty simple astronomy: orient to a few constellations, vaguely familiar from the same splendid viewing last year; check out Joe Rao’s latest almanac of the Moon and planets (see “The Sky in September,” page 65); and, with any luck, “catch a falling star.”

Most meteors are nothing fancy: a fleeting streak, often not very bright. A friend to say, “Hey, look!” is nice, because if you glance in the wrong direction, it’s gone. But if rocks from the sky seem a small thing, no more consequential than the fireflies of July and August, take a look at the Moon. Turn to page 46 for the gallery of lunar photographs that accompany G. Jeffrey Taylor’s article, “Moonstruck.” Make a mental note of the chaotic surface. And the next time you’re looking at the real Moon, imagine that you’re a time traveler, gazing at the Earth as it appeared, say, four billion years ago.

It’s easy to forget that the Moon records the history of our own cosmic neighborhood. The Earth, too, was once subjected to an inconceivably violent rain of rock—and without water or an atmosphere, our planet, too, might still look like the wasted battlefield of an epic war. The story of meteorites, as Donald Goldsmith tells it in his “Bolts from Beyond” (page 28), is a tumultuous one, but it is also a story with great scientific promise: a few dozen meteorites have been identified from the Moon, Mars, and the asteroid Vesta, serendipitous gifts from the cosmos that carry vital clues about our planetary origins.

To most people, though, the most noteworthy meteorite of the Earth’s past was the one that killed the dinosaurs. That, too, was probably a lucky accident—for us. It’s hard to imagine how we mammals could have so thoroughly covered the Earth had the killer asteroid not knocked off some big reptiles and opened up some turf. In his article “Terrible Lizards of the Sea” (page 36), Richard Ellis describes one of the more successful families of prehistoric creatures with large teeth that ever roamed—or at least swam—the Earth: the mosasaurs. Mosasaurs had flourished for a long time, 25 million years, and there is no reason to think they were on their way out when they were abruptly extinguished. We may owe our very existence to a big, fast-moving rock.

This month the newly renovated Arthur Ross Hall of Meteorites reopens at the American Museum of Natural History. Anyone fortunate enough to visit will find plenty more reasons there, as our columnist Neil deGrasse Tyson (“Universe,” page 18) puts it, to “keep looking up.”

—PETER BROWN

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# We found our best watch in a history book

In 1923 a small watchmaker in Europe built the first watch to display the day and date while using an automatic movement. Only 7 of these watches were ever made and we've only actually seen one of these masterpieces in a watch history book. Antique experts say these watches are so rare that they could fetch more than \$500,000 at auction today.

As we researched early chronographs from the Schaffhausen region, we found that they were among the most complex and stylish works of art to be made during the Roaring 20's. And yet no one has attempted to replicate the vintage design and function of these early watches until now. The watch design that you see here has been painstakingly crafted with the inspiration of the earliest chronographs right down to the screw down crown. It is built with a classic 21 jewel automatic movement, the kind sought after by fine watch collectors.

From the sweeping second hand to the roman numerals on the unique ivory colored face, every detail has been carefully

engineered to replicate the look and feel of the earliest chronographs. This six-hand movement includes two smaller dials that display the day and month. The third interior dial is a 24 hour military time clock in which the sun and the stars graphically depict AM and PM.

This watch's mechanical movement utilizes a self-winding mechanism inspired by John Harwood, who received the patent on the first automatic movement in 1923. Thus this watch never needs batteries and never needs to be manually wound. The watch comes in a beautiful case and interchangeable black and brown bands included.

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## CONTRIBUTORS



In his twenty-five-year career Seattle-based photographer **ART WOLFE** ("The Natural Moment," page 6) estimates he has taken a million photographs (see his Web site at [www.artwolfe.com](http://www.artwolfe.com)). His latest book, *Edge of the Earth, Corner of the Sky*, showcases Wolfe's landscape photography, with essays by Art Davidson. Wolfe made his photograph of the northern lights in Alaska under the midnight light of a half moon in March.

Trained as both a research astronomer and an attorney, **DONALD GOLDSMITH** ("Bolts from Beyond," page 28) devoted himself to popularizing astronomy thirty years ago. Since then he has written more than twenty books and collaborated on many PBS television programs on astronomy, including the 1991 series *The Astronomers*. In 1995 he was awarded the American Astronomical Society's Annenberg Foundation Prize for outstanding contributions to science education through astronomy. He lives in Berkeley, California.



"I've always been interested in life in the sea—past, present, and future," says naturalist, author, and artist **RICHARD ELLIS** ("Terrible Lizards of the Sea," page 36). His story in this issue on mosasaurs, a formidable group of extinct marine lizards, is adapted from his new book, *Sea Dragons: Predators of the Prehistoric Oceans* (University Press of Kansas). His other recent books include *The Empty Ocean* and *Aquagenesis: The Origin and Evolution of Life in the Sea*. Ellis is a research associate in paleontology at the American Museum of Natural History in New York.

Photographer and botanist **DICCON ALEXANDER** ("Splendid Isolation," page 42) is a scientific associate in the botany department of the Natural History Museum in London. Since 1994 he has done extensive work with a team from the Royal Botanic Garden in Edinburgh, Scotland, documenting the unique flora of the Socotra archipelago.



**G. JEFFREY TAYLOR** ("Moonstruck," page 46) is a research professor in the Hawai'i Institute of Geophysics and Planetology at the University of Hawai'i in Honolulu. His primary interest is planetary evolution, focusing on the role of magmatism and impacts in the history of the Moon, Mars, Mercury, and the asteroids, as well as on the role of aqueous alteration processes on Mars. He is the author of more than 140 refereed articles. He and Linda Martel, an associate at the institute, also publish an online popular science magazine, *Planetary Science Research Discoveries* ([www.psrdr.hawaii.edu](http://www.psrdr.hawaii.edu)).



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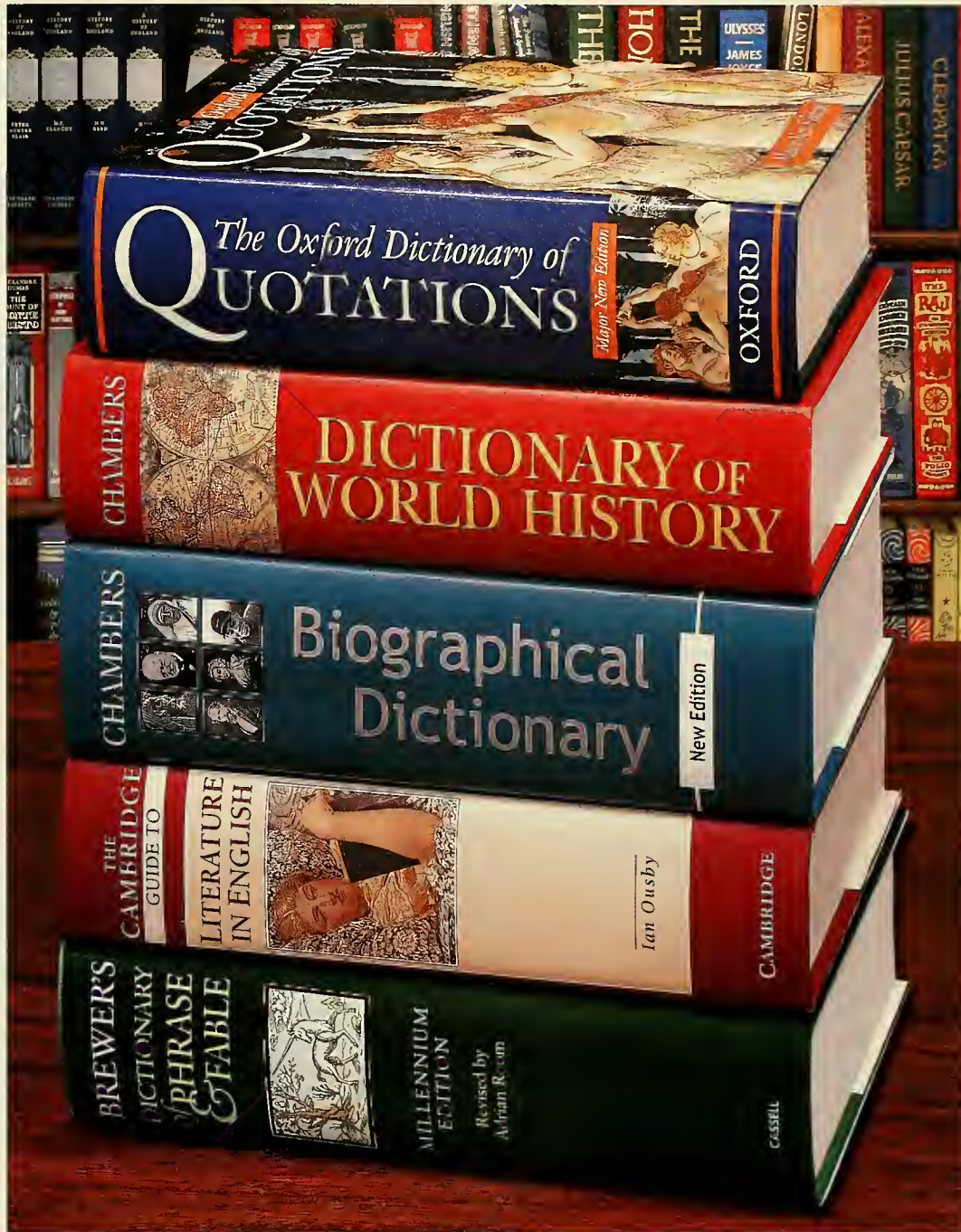
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## LETTERS

### Who Minds the Store?

The two discussions of the looting and destruction of Iraq's precious ancient artifacts—"Lost Time," by John Malcolm Russell, and "Aftershocks," by David Keys [6/03]—are a wake-up call about the folly of retaining world-class antiquities in their third-world countries of origin. Only in the great museums and universities of the first world can irreplaceable

Iraqi lives it would have been worth losing to safeguard the museums and their artifacts.

If we had used our limited resources to protect the cultural assets of Iraq, what else might have been destroyed? Certainly the destruction was a tragedy, but to blame the military for the results of civil disorder is unreasonable.

Much of the looting seems to have been well

and is prohibited by the 1954 Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict. Art is not necessarily safer in first-world countries: major paintings in Germany were destroyed during the Second World War, and several hundred works by the sculptor Auguste Rodin were lost when the offices of Cantor Fitzgerald were destroyed during the 9/11 attack.

As an alternative to expropriation, the former Ottoman practice of dividing excavated finds between the host country and the foreign institution sponsoring the excavations reduces the risks associated with having all your eggs in one basket. Host countries might consider reinstating such a practice—with the understanding that divisions could be negotiated as open-ended loans rather than as gifts—but only if collectors and certain museums in the first world stop financing the plunder of archaeological sites.

Mr. Everhart correctly blames the looting on the looters, but it is unrealistic to eliminate a police force and then hope that criminals will no longer commit crimes. No one argues that anybody should have been placed in mortal jeopardy to protect the museum, but would guarding it have been that dangerous? Major armed resistance around the museum ended on April 9, the museum was looted on April 10–11, the staff began returning on April 12, and the United States posted guards at the building on

April 16. Did the military consider protection of the museum to be a high priority it could not safely fulfill prior to April 16? Or was it unconcerned about the museum until the media and Secretary of State Colin Powell compelled it to take action? Only an independent investigation can provide answers to such questions.

### Strategic Waters

I found the review by Sandra Postel ["Hydro Dynamics," 5/03] of Robert Kandel's and Diana Raines Ward's books on the nature and scarcity of freshwater to be extremely poignant. At the moment I am sitting beside the Shatt al Hillah, a river within just miles of the Euphrates. The importance of freshwater in this region is impossible to miss.

Today's decisions on the distribution and use of water will ripple through decades, if not centuries, of human interaction. The availability of water in the Middle East is a particularly thorny problem. Constructing one or two state-of-the-art desalination plants on the Mediterranean along the Gaza Strip would lessen the Palestinians' reliance on Israeli-controlled water. Large plants might even provide the Palestinians with a marketable product. For the Palestinians to have the capacity to sell water in excess of their needs, particularly to Israel, would establish a commodity exchange far more valuable than the cheap labor that now daily crosses the borders.

Given the political will,



*"I can't understand why he has to go ashore to look for bugs."*

antiquities be properly conserved and studied.

Expropriation of antiquities from a place like Iraq, where the population has been subjected to despotism and has no connection with the ancient culture under its feet, is the most suitable solution.

*John B. Bute  
El Lago, Texas*

David Keys seems to blame the damage done to Iraq's archaeological heritage on the lack of military intervention. As both a veteran and a scientist, I'd like to ask how many American or

planned and executed. Why didn't the Iraqis do more to protect their treasures? And shouldn't they take at least some responsibility for the lawlessness?  
*Michael J. Everhart  
Derby, Kansas*

**JOHN MALCOLM RUSSELL**  
REPLIES: Both letters raise issues that have been the subject of much debate.

Although the tradition of the victor expropriating the art of the vanquished—a tradition Mr. Bute seems to advocate—goes back to Mesopotamia, this practice is no longer fashionable,

the U. S. could negotiate donations from the many Arab countries that bemoan the plight of the Palestinian people yet offer little in the way of long-term economic solutions. Helping to build a viable Palestinian economy through the manufacture of this “artificial” natural resource would do positive things for everyone concerned.

*Lt. Col. Mark L. Kimmey  
U.S. Army Reserve  
Humanitarian Assistance  
Coordination Center  
Al Hillah, Iraq*

### Ode to the Earth

Gabrielle Walker’s article on the geological epoch known as “snowball Earth” [“The Longest Winter,” 4/03] shows not only her

impressive knowledge of the subject but also her masterful writing style—referring to Earth’s earliest organisms as “cottage industries,” for instance, or describing volcanoes as being “perfectly happy to erupt under ice.”

Perhaps Princeton should ask her to teach in the English department rather than the geosciences department.

*Robert M. Martin Jr.  
Dallas, Texas*

### The Joys of Fieldwork

Robert Dunn’s story about army ants and their beetle “guests” [“Impostor in the Nest,” 6/03] brought forth personal waves of nostalgia. As a field entomologist, I have vivid memories of pursuing butterflies in

southern Mexico while dining on those same basic jelly sandwiches Mr. Dunn was eating in Costa Rica (mine, however, were made with peanut butter as well).

I was moved by his description of his fieldwork, as well as by the sense of adventure that he portrayed so well. Our techno-savvy, dot-com culture, with its “reality-based” nightly television offerings, makes many people forget that the vast majority of living things on our planet still reside in remote places, awaiting our discovery and study.

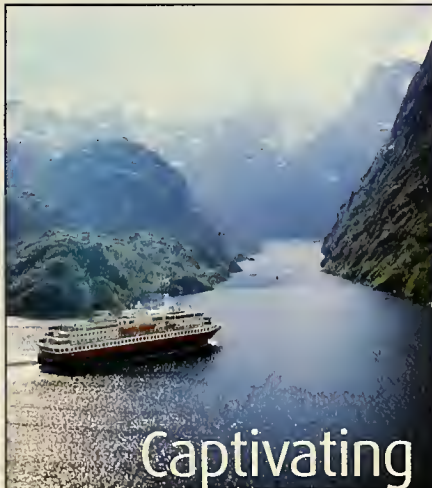
The same passion for discovery and adventure that inspired the early icons of natural history (Captain James Cook, Charles Darwin, Alfred Russel Wallace, and so on)

can still be integrated into a respectable professional career by any youngster living today.

*Gary Noel Ross  
Baton Rouge, Louisiana*

AMENDMENT: The first paragraph of Martha Hurley’s reply to an enquiry concerning a photograph of the golden Vietnamese cypress [“Letters,” 6/03] was intended to refer to cypresses in general. Preferable wording would have been: “The caption should have specified that for a mature cypress to bear both needles and scaly leaves on the same branch is highly unusual.”

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## Blowin' in the Wind

Imagine finding marine plankton drifting through thin air at 30,000 feet. That's the surprise that greeted Kenneth Sassen of the University of Alaska, Fairbanks, and his colleagues when they examined ice crystals collected by a research aircraft that had flown through cirrus clouds over Oklahoma in September 1997. A recent paper by Sassen and his co-authors shows numerous images of variously shaped crystals with cell-like structures embedded in them.

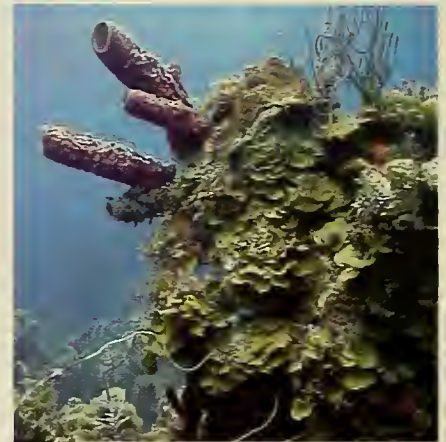
The clouds were remnants of Hurricane Nora, which had originated in the Pacific Ocean, swept up Mexico's Baja Peninsula, and slowed to a tropical storm over the U.S. Southwest. The investigators think Nora's high winds whipped up droplets of seawater and then lofted the droplets, along with their resident plankton, to the top of the troposphere. From there the plankton blew far overland to the east, all the while serving as nucleation points for some of the ice crystals that formed in the clouds. ("Midlatitude cirrus clouds derived from Hurricane Nora: A case study with implications for ice crystal nucleation and shape," *Journal of the Atmospheric Sciences* 60:873-91, April 1, 2003)

## Drugs from Seaweed?

Plants have no immune systems. Chemical warfare is their way of fighting pathogens and parasites: they manufacture compounds that prevent the growth of specific disease-causing microorganisms. And sometimes those compounds are effective against human pathogens as well—the basis for much pharmacological research as well as traditional medicine, and many exhortations to preserve biodiversity.

Julia Kubanek, a biochemist at the Georgia Institute of Technology in Atlanta, and her colleagues at the Scripps Institution of Oceanography in La Jolla, California, suggest that seaweed could be similarly tapped for future drugs. Marine plants literally live in a sea of bacteria, archaea, viruses, and fungi—some of which are bound to be pathogenic—yet they seldom get sick. Surprisingly little is known about seaweed's chemical defenses, but Kubanek and her team have begun to remedy that deficiency.

From the brown alga *Lobophora variegata*—a tropical seaweed especially dominant in the Caribbean—the investigators have isolated a potent new compound they call lobophorolide. In laboratory tests, small quantities of it stunted the



The alga *Lobophora variegata* (greenish ruffles): apothecary of the sea?

growth of two marine fungi that cause disease in marine plants.

Nevertheless, lobophorolide had no effect on a pathogenic bacterium, and did not repel herbivorous fishes. Kubanek and her team think other compounds may pick up where this one leaves off. Algae may turn out to be underwater pharmacies, deploying a variety of medicines, each aimed at a different affliction. ("Seaweed resistance to microbial attack: A targeted chemical defense against marine fungi," *Proceedings of the National Academy of Sciences* 100:6916-21, June 10, 2003)



New Guinea's gift to the world

## The Fruits of Prehistory

Agriculture began in Mesopotamia, the "cradle of civilization," right? True, but it also seems to have arisen independently in several other places as well, including China and Mesoamerica. In the 1970s some archaeologists asserted that New Guinea was one of those places. Their evidence at the time was equivocal, but now Tim Denham of Flinders University in Adelaide, Australia, and his colleagues have collected enough strong evidence to show that bananas were first farmed in the highlands of New Guinea at least 7,000 years ago.

What did they find? Numerous fossilized remains—plant crystals (of taro as well as bananas) and pollen—that complement the well-dated remains of ancient cultivation mounds and ditches. Nowadays there are hundreds of varieties of bananas; collectively they've become one of the world's most important food crops. Strange to relate, however, fruit lovers in the United States have been munching on bananas only since the nineteenth century. ("Origins of agriculture at Kuk Swamp in the highlands of New Guinea," *Science* 301:189-93, July 11, 2003)





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## Experiment of the Month

It isn't easy being an archaeologist. The ancient artifacts you work with are often battered and fragmentary, and you have to base a lot of your interpretations on the stratum where you find the artifacts. Given the many species of burrowing animals—which seem pretty cavalier about the effects of their excavations on scientific evidence—it seems perilous indeed to put much stock in the discovery stratum. Animals might have displaced your crucial artifacts many times before you unearthed them.

Knowing what a burrower the armadillo is—and how little attention had been paid to it—the Brazilian archaeologists Astolfo G. Mello Araujo of the University of São Paulo and José Carlos Marcelino of São Paulo's Department of Historical Patrimony decided to study the animal's effects on an experimental "dig" at the São Paulo Zoo. They spray-painted four groups of ersatz artifacts (actually ceramic shards and stone flakes) in four distinct colors and sprinkled them into four separate layers in the ground. The result was a two-foot-deep "layer cake," whose top layer of artifacts was open to the air and whose other layers were separated from one another by eight inches of earth.

Then a lone female armadillo was turned loose at the site for almost two months, after which the archaeologists surveyed the



Six-banded armadillo (*Euphractus sexcinctus*), the archaeologist's helper?

thoroughly mucked-up earth. The effects were easy to see: blue objects pushed many inches up to the yellow ones, yellows pushed down among the blues, big and small items both dislodged. Fortunately, though, the concentration of objects from a given stratum still peaked near their original level.

One possible benefit of this kind of "noise" in the archaeological signal is that by bringing artifacts to the surface, armadillos can help archaeologists locate promising sites for their own, more systematic digging. ("The role of armadillos in the movement of archaeological materials: An experimental approach," *Geoarchaeology* 18:433–60, 2003)

## Love and Death

In North America, if you see a classic spiderweb with a dense, zigzag thread through its center, the web could well have been spun by *Argiope aurantia*. Even more striking than the web, though, is the species' sexual politics: for the male, copulation is suicide.

Other male spiders die during mating, but that's because the females kill and eat them. Evolutionary biologists Matthias W. Foellmer of Concordia University in Montreal and Daphne J. Fairbairn of the University of California, Riverside, have now determined that in *A. aurantia* the males themselves are programmed to undergo sudden death—attacked or not.

Whether his partner is a defenseless, molting juvenile or a consenting though potentially aggressive adult, the male goes into his death throes within moments of inserting the second of his two pedipalps (mating appendages) inside the second of the female's two genital apertures. Once that pedipalp inflates, it's curtains for the guy. Within fifteen minutes—and

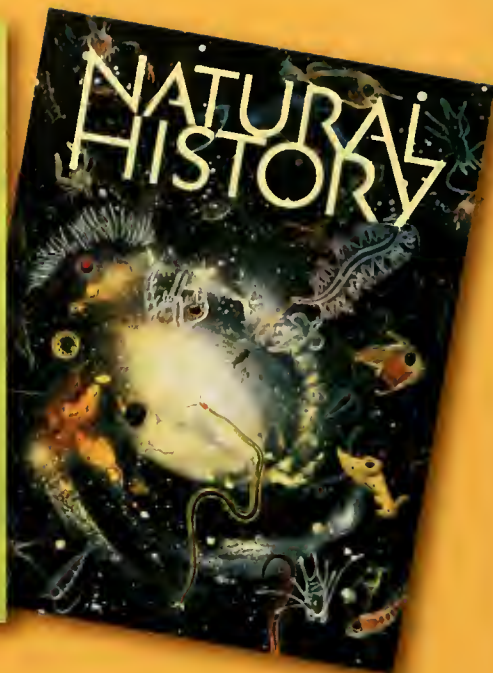
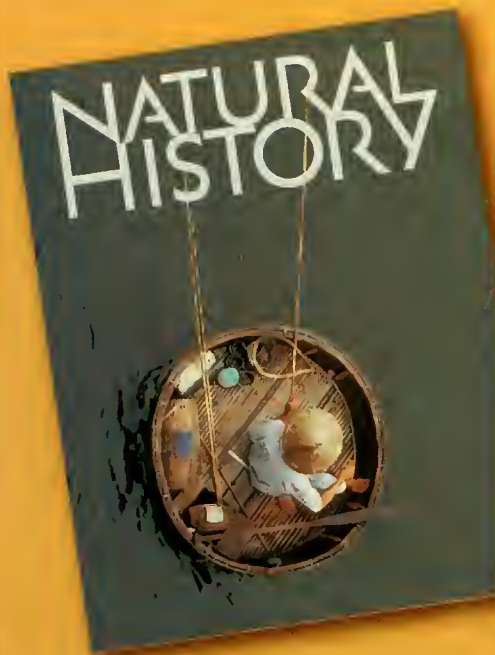


Object of desire: A female yellow garden spider (*Argiope aurantia*)

usually sooner—his heart stops, even when the female is prevented (by experimenters) from molesting him. A further bit of proof that death occurs without female complicity: one male, after inserting his first pedipalp in the normal place, moved elsewhere on the female's web and inexplicably inserted his second pedipalp into a nearby dead mealworm. He died instantly—and not of shame at his mistake.

What could be the evolutionary advantage of dying just after mating? Foellmer and Fairbairn speculate that, because most mating is opportunistically imposed on defenseless juvenile females, the dead male may act as a "mating plug"—a kind of temporary, organic chastity belt—to prevent other males from having their turn. ("Spontaneous male death during copulation in an orb-weaving spider," *Proceedings of the Royal Society of London B (Suppl.)*, DOI 10.1098/rsbl.2003.0042, 2003)

*Stéphan Reeb* is a professor of biology at the University of Moncton in New Brunswick, Canada, and the author of *Fish Behavior in the Aquarium and in the Wild* (Cornell University Press).



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# NATURAL HISTORY

THE WONDERS OF NATURE AT YOUR FINGERTIPS

# In the Beginning

*Back in the olden days—the first trillionth of a second after the big bang—energy was matter, matter was energy, and  $E=mc^2$  ruled.*

By Neil deGrasse Tyson

Physics describes the behavior of matter, energy, space, and time, and how the forces of nature enable their interplay. From what scientists have been able to determine, all biological, chemical, and physical phenomena emerge from how four, and only four, forces push and pull the contents of the universe. But is that all there is?

In almost any area of scientific inquiry—but particularly in physics—the frontiers of discovery live at the extremes of measurement. At the extremes of matter, such as the neighborhood of a black hole, you find gravity (one of the four forces) badly warping the surrounding fabric of space-time. At the extremes of energy, you sustain thermonuclear fusion in the ten-million-degree cores of stars (where the attraction of the strong nuclear force overwhelms the repulsion of the electromagnetic force). And at every extreme imaginable, you get the outrageously hot, outrageously dense conditions that prevailed during the first few moments of the universe.

Daily life, I'm happy to report, is entirely devoid of extreme physics. On a normal morning, you get out of bed, wander around the house, eat something, dash out the front door. And by day's end, your loved ones fully expect you to look no different than you did when you left, and to return home in one piece. But imag-

ine arriving at the office, walking into an overheated conference room for an important 10 A.M. meeting—and suddenly losing all your electrons. Or worse yet, having every atom of your body fly apart. Or suppose you're sitting in your office trying to get some work done by the light of your desk lamp, and somebody flicks on the overhead light, causing your body to ricochet from wall to wall until you're jack-in-the-boxed out the window. Or what if you go to a sumo wrestling match after work and see the two spherical gentlemen collide, disappear, then spontaneously become two beams of light?

If that kind of scene played itself out daily, modern physics wouldn't look so bizarre, knowledge of its foundations would flow naturally from life experience, and our loved ones probably would never let us go to work. But back in the early minutes of the universe, those antics happened all the time. To envision that era, and understand it, one has no choice but to establish a new form of common sense, an altered intuition about how physical laws apply at the extremes of temperature, density, and pressure.

Enter the world of  $E=mc^2$ .

Einstein first published a version of his famous equation in 1905, in a seminal research paper titled "On the Electrodynamics of Moving Bodies." Better known as the special theory of



relativity, the concepts advanced in that paper forever changed the understanding of space and time. Einstein, then just twenty-six years old, offered further details about his tidy equation in a separate, remarkably short paper published later that year: "Does the Inertia of a Body Depend on Its Energy-Content?" To save you the effort of digging up the original article, designing an experiment, and testing the theory, the answer is "Yes." As Einstein wrote,

If a body gives off the energy  $E$  in the form of radiation, its mass diminishes by  $E/c^2$ . . . . The mass of a body is a measure of its energy-content; if the energy changes by  $E$ , the mass changes in the same sense. . . .

Sensibly cautious about the truth of his statement (it was a theoretical prediction, after all), he then suggested:



Gregory Gioiosa, *Tri-Composition of Existential Time*, 1995

It is not impossible that with bodies whose energy-content is variable to a high degree (e.g. with radium salts) the theory may be successfully put to the test.

There it is: the algebraic recipe for all occasions when you want to convert matter into energy or energy into matter. In those simple sentences Einstein unwittingly gave astrophysicists a computational tool,  $E=mc^2$ , that extends their reach from the universe as it now is, all the way back to infinitesimal fractions of a second after its birth.

The most familiar form of energy is the photon, a massless, irreducible particle of light. You are forever bathed in photons: from the Sun, the Moon, and the stars, to your stove, your chandelier, and your night light. So why don't you experience

$E=mc^2$  every day? The energy of visible-light photons is far less than the amount of energy that is equivalent to the mass of the least massive subatomic particles. There is nothing else those photons can become, and so they live happy, though boring, lives.

Want a little action? Start hanging around gamma-ray photons that have some real energy—at least 200,000 times more than that of visible photons. You'll quickly get sick and die of cancer, but before that happens, you'll see something truly weird. Matter-antimatter pairs of electrons—one of the many dynamic duos in the particle universe—pop into existence where photons once roamed. Yes, energy turns into matter. Then, as you watch, you'll see some of the matter-antimatter pairs of electrons collide, annihilating each other and creating gamma-ray pho-

tons once again. And yes, matter turns back into energy. It all happens according to  $E=mc^2$ .

Increase the gamma rays' energy by a factor of another 2,000, and you still have gamma rays—but now with enough energy to turn susceptible people into the Hulk. Furthermore, pairs of these potent photons now have enough energy to spontaneously create much more massive particles: neutrons, protons, and their antimatter partners.

The cosmological significance of particles and photons transmuting into each other is staggering. The background temperature of our expanding universe, calculated from measurements of the microwave bath of light that pervades all of space, is a very chilly 2.73 degrees Kelvin—455 degrees below zero Fahrenheit. Yesterday, though, the universe was a little bit hotter, and a little bit smaller, than it is today. The day before, it was hotter and smaller still. Roll the clocks backward some more—say, 13.7 billion years—and you land squarely in the primordial soup of the big bang.

The way space, time, matter, and energy interacted as the universe expanded and cooled from the beginning is one of the greatest stories ever told. But to explain what went on in that cosmic crucible, you must find a way to merge the four forces of nature into one. That challenge includes finding a way to reconcile two incompatible branches of physics: quantum mechanics (the science of the small) and general relativity (the science of the large).

Although physics hasn't yet reached that finish line, physicists know exactly where the stumbling blocks are: they all pile up during the "Planck era"—so named for the German physicist Max Planck, who fathered quantum mechanics in 1900. The Planck era began with the big bang and ended  $10^{-43}$  second later (that's one ten-million-trillion-trillion-trillionth of a second): in that unimaginably short time the universe grew to

$10^{-35}$  meter (one hundred-billion-trillion-trillionth of a meter) across.

Not to worry, though. The clash between gravity and quantum mechanics poses no practical problem for the contemporary universe. Astrophysicists apply the tenets and tools of general relativity to problems very different from the ones normally encountered in quantum mechanics. But in the beginning, during the Planck era, the known universe was a lot smaller than an atomic nucleus, and so there must have been a kind of shotgun wedding between the large

and the small. Alas, the vows exchanged during that ceremony continue to elude us all; no known laws of physics describe the universe with any confidence during what was surely the briefest marriage in history.

At the end of the Planck era, gravity wriggled loose from the other, still-unified forces of nature, taking on its familiar independent identity. As the universe aged by a factor of a hundred million to the venerable age of  $10^{-35}$  second, it continued to expand and cool. What remained of the unified forces split into the electroweak and the strong nuclear forces. Later still, the electroweak force split into the electromagnetic and the weak nuclear forces, laying bare the four distinct forces we have come to know and love. Today the weak force controls some kinds of radioactive decay, the strong force holds the nucleus together, the electromagnetic force binds molecules, and gravity operates on bulk matter. And all those forces had established their independence by the time the universe was a mere trillionth ( $10^{-12}$ ) of a second old.

All the while, the interplay of matter and energy was incessant. Shortly before, during, and after the strong and electroweak forces parted company, the material universe was a seething ocean of quarks, leptons, their antimatter siblings, and bosons, which are particles that con-

vey the various forces. None of the particles belonging to these families is thought to be divisible into anything smaller or more basic.

Fundamental though they are, each family of particles comprises several species. The boson family includes the ordinary visible-light photon. The most familiar leptons (to the

*Galaxies, planets, and people owe their existence to a trifling primordial imbalance of matter and antimatter.*

nonphysicist, anyway) are the electron and perhaps the neutrino. And the most familiar quarks are . . . well, there are no familiar quarks. Each species has been given an abstract name that serves no real philological, philosophical, or pedagogical purpose except to distinguish it from the others: up and down, strange and charm, and top and bottom.

Quarks are quirky beasts. Unlike the more familiar proton, which has an electric charge of plus-one, or the electron, which has a charge of minus-one, quarks have fractional electric charges that come in thirds. And you'll never catch a quark all by itself; it will always be clutching on to other quarks nearby. In fact, the force that keeps two or more of them together actually grows stronger the more you try to pull them apart—as if they were connected by some kind of subatomic rubber band. If you pull a couple of quarks far enough apart, the rubber band snaps and the stored energy summons  $E=mc^2$  to create a new quark on each end of the break, leaving you with quark pairs once again.

But during the era of seething quarks and leptons the universe was so dense, and the average separation between quarks was so small, that it doesn't make any sense to say whether quark pairs were attached or not. Under those conditions, an allegiance between adjacent quarks could not be unambiguously established. In spite of

being collectively bound, they moved freely among themselves, like ingredients in a quark soup.

Strong theoretical evidence suggests that an episode in the very early universe, perhaps during one of the force splits, endowed the universe with a slight but remarkable asymmetry: for every billion and one particles of matter, there were a billion particles of antimatter. That small difference hardly got noticed amid the continuous creation, annihilation, and re-creation of quarks and antiquarks, electrons and antielectrons (better known as positrons), and neutrinos and antineutrinos. The odd man out always had plenty of chances to find someone to annihilate with.

But not for much longer.

As the cosmos continued to expand and cool, it grew to the size of the solar system, and its temperature dropped below a trillion degrees Kelvin. A millionth of a second had passed since the beginning.

That "tepid" universe was no longer hot enough or dense enough to cook quark soup, and so the quarks all grabbed dance partners, creating a permanent new family of heavy particles called hadrons. Among the hadrons were protons and neutrons as well as other, less familiar heavy particles, all made up of various combinations of quarks. The slight matter-antimatter asymmetry afflicting quarks and leptons now got passed to the hadrons, but with extraordinary consequences.

As the universe continued to cool, ambient photons could no longer invoke  $E=mc^2$  to manufacture hadron-antihadron pairs. Not only that, when hadrons and antihadrons met and annihilated, the energy of the resulting photons diminished in the ever-expanding universe, dropping below the threshold required to create new hadron-antihadron pairs. For every billion annihilations—leaving a billion photons in their wake—a single hadron survived. Those loners would

ultimately get to have all the fun: serving as the building blocks of galaxies, stars, planets, and people.

Without the billion-and-one-to-a billion imbalance between matter and antimatter, all mass in the universe would have annihilated, leaving a cosmos made of photons and nothing else—giving fresh meaning to the phrase “Let there be light.”

**B**y now, one second has passed since the beginning of time.

The universe has grown to a few light-years across. At a billion degrees, it's still plenty hot—and still able to cook up electrons and positrons, which continue to pop in and out of existence. But in the expanding, cooling universe, their days (seconds, really) are numbered. What was true for hadrons is true for electrons: the expansion makes annihilation a one-way trip, and eventually only one electron in a billion survives.

When the cosmic temperature drops below a hundred million degrees, protons and neutrons fuse to form atomic nuclei, of which 90 percent are hydrogen, and 10 percent are helium and trace amounts of deuterium, tritium, and lithium.

Two minutes have passed since the beginning.

Not for another 380,000 years does much happen to the primordial soup. Throughout those millennia the temperature remains hot enough for electrons to roam free among the atomic nuclei, batting them to and fro. But all this freedom comes to an abrupt end when the temperature of the universe falls below 3,000 degrees Kelvin (about half the temperature of the Sun's surface). Right about then, the electrons combine with all the free nuclei, leaving behind a ubiquitous bath of visible-light photons, and completing the formation of particles and atoms in the infant universe.

As the universe continues to expand, its bath of photons continues to lose energy, dropping from visible light to infrared to microwaves. And today, everywhere astrophysicists look, they

find an indelible fingerprint of 2.73-degree microwave photons, whose pattern on the sky retains the memory of the distribution of matter just before atoms formed. From that, cosmologists can deduce many things, including the age and shape of the universe.

**B**ut what happened before all this? What happened before the beginning?

Astrophysicists have no idea. Or, rather, our most creative ideas have little or no grounding in experimental science. Yet I have found that many religious people tend to assert, with a tinge of smugness, that something must have started it all: a force greater than all others, a prime mover. In the mind of such a person, that something is, of course, God.

But what if the universe was always there, in a state or condition we have yet to identify—a multiverse, for instance? Or what if the universe, like its particles, just popped into existence?

I'll grant that such replies satisfy nobody. Nevertheless, they remind us that ignorance is the natural state of mind for a research scientist on the ever-advancing frontier. People who believe they are ignorant of nothing have neither looked for, nor stumbled upon, the boundary between what is known and unknown in the cosmos. And therein lies a fascinating dichotomy. “The universe always was” seldom gets recognized as a legitimate answer to “What was around before the beginning?”—even though for many religious people, the statement “God always was” is the obvious and pleasing answer to “What was around before God?”

*Astrophysicist Neil deGrasse Tyson is the Frederick P. Rose Director of the Hayden Planetarium in New York City. Videotapes of a dozen of his lectures, under the title “My Favorite Universe,” were recently released by the Teaching Company ([www.techco.com](http://www.techco.com)). All twelve are based on essays that have appeared in Natural History.*

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# The Pleasure (and Pain) of “Maybe”

*Both tease and terrorist exert control by fostering uncertainty in their targets.*

By Robert M. Sapolsky

Then there was the summer Jonathan spent unsuccessfully wooing Rebecca. Both were savanna baboons living in the Serengeti Plains in East Africa, part of a troop I've been studying intermittently for twenty-five years. Jonathan was a gangly juvenile that had recently joined the troop; Rebecca was the confident young daughter of one of the highest-ranking matriarchs. Jonathan had taken one look at Rebecca

mate. What he was willing to settle for was a chance to groom her. But Rebecca was having none of it; she hardly acknowledged his existence. Whenever she'd sit down in the shade, or hang out with some friends, there was Jonathan, eager to groom her—and almost invariably getting the cold, fur-covered shoulder.

By all logic, such spectacular lack of success should have made Jonathan give up, or, as a psychologist might

her. Once she even groomed him back for a few distracted seconds, leaving him in baboonish ecstasy.

And that was all it took. Aglow from these crumbs of attention, poor Jonathan would redouble his efforts for the next few days.

The whole soap opera frustrated me enormously. I was working alone out in the middle of nowhere, probably badly in need of some “social grooming” myself, and clearly identifying with Jonathan. I sublimated Jonathan's predicament into grand orations in my head: “Here are the primate roots of our magnificent human capacity for gratification postponement. Here, in this pathetic dork of a baboon and his willingness to keep trying again and again despite a pitiful success rate, is the key to human greatness. Here is the suitor who keeps up a fifty-year courtship, the obsessive who spends a decade constructing a life-size replica of Elvis out of bottle caps. Here's all of us who forwent immediate pleasure in order to get good grades in order to get into a good college in order to get a good job in order to get into the nursing home of our choice.”

What is it that gives us the power to do the harder thing, to be disciplined and opt for delayed gratification? And why is the rare, intermittent reward, the hint that you might win the lottery, so compelling? Two recent studies—one published in the journal *Nature*, the other in the journal *Science*—go a long way toward explaining



Olivia Parker, *Wheel of Uncertainty*, 1995

and developed a god-awful male baboon crush that had him loping around after her wherever she went.

What he was probably after was to get her to groom him, or maybe even to coax her into something more inti-

put it, should have caused “the behavior to extinguish.” But eventually Rebecca became a little less resistant, and then, every so often, perhaps once a week, she gave in to his dogged devotion and let him groom





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these mysteries. But before considering those reports, it's worth taking a brief tour through some parts of the brain that play a key role in the story.

The starting point of the tour is the frontal cortex, a region that takes up a much larger proportion of the primate brain than it does in other animals. The frontal cortex plays a big role in executive control, delayed gratification, and long-term planning. It does so by keeping the limbic system in check, primarily through neural projections that can release an inhibitory neurotransmitter into that deeper, more ancient brain system that specializes in emotion and impulsivity. Furthermore, the frontal cortex excels at resisting stimulating inputs from the limbic system: "Screw studying for the exam; run amok instead."

People with tight, regimented, "repressive" personalities have elevated metabolic rates in the frontal cortex, whereas sociopaths have lower-than-normal ones. If a person's frontal cortex is accidentally destroyed, he or she becomes a "frontal" patient—sexually disinhibited, hyperaggressive, socially inappropriate.

With all that going for it, the frontal cortex is the closest thing we have to a neural basis for the superego.

But just what is it that gives the frontal cortex the backbone to ignore the siren call of the limbic system? There has long been evidence that a projection or conduit into the frontal cortex from a brain region called the ventral tegmentum plays a major role. This conduit serves as a Doctor Feelgood, dispensing doses of dopamine, a neurotransmitter closely associated with pleasure. Drugs such as cocaine increase the dopamine signal along this pathway, which is one reason they are so popular. Animals rigged up to get an electrical charge through the ventral tegmentum will work like maniacs, pressing levers, forgoing every earthly pleasure offered to them, in order to get the stimulus.

So when is dopamine released? For a long time the answer seemed obvious: right after getting something highly desirable, a reward. Suppose you've implanted electrodes in a monkey's brain that enable you to monitor when the dopamine pathway gets activated. Sure enough, if you give the monkey some great reward from out of nowhere, you'll see a burst of activity: dopamine bathing the monkey's frontal cortex.

But in a series of studies in the mid-1990s, Wolfram Schultz, a neuroscientist then at the University of Fribourg in Switzerland, did some critical studies that threw that simple picture into disarray. Schultz trained monkeys to perform simple tasks to gain a reward. For example, if an animal pressed the correct lever, after a few seconds' delay it would get a bit of some desirable food. There was one special condition: a light would come

*"A relationship," a cynical friend used to say, "is the price you pay for the anticipation of it."*

on, signaling to the monkey that it could now begin its task. One might predict that the dopaminergic pathway would be activated after that food reward was received. But that's not what happened. The activity peaked right after the light came on, before the monkey performed its task.

In this context, the pleasurable dopamine isn't about reward. It's about anticipating the reward. It's about mastery and expectation and confidence. ("I know what that light means; I know the rules: *if* I press the lever, *then* I'm going to get some food. Hey, I'm all over this. This is going to be great.")

Psychologists refer to the period of anticipation, of expectation, of working for reward as the "appetitive" stage; the stage afterward, which commences with reward, they call the consummatory stage. Schultz's findings

show that if you know your appetites are eventually going to be sated, pleasure is more about the appetite than about the sating. I am reminded of the cynical observation of a classmate in college, a person with a long string of disastrous relationships. "A relationship," he used to say, "is the price you pay for the anticipation of it."

Well, how about that? We've just sorted out the neurochemistry of putting up with thirty-year mortgages. All you need to do is train for longer and longer intervals between light and reward, and those anticipatory bursts of dopamine will fuel increasing amounts of lever pressing, or monthly payments.

One of the two recent studies I alluded to earlier fills in a critical gap in this story. Writing in the 10 April 2003 issue of *Nature*, Paul E. M. Phillips and his colleagues from the University of North Carolina, Chapel Hill, tell how they have measured bursts of dopamine in rats down to the millisecond. They have shown that the burst comes just before the behavior. And here's the clincher: when they artificially stimulated the dopamine release (rather than letting the light cue trigger it), the rat suddenly started pressing the lever. The dopamine fuels the behavior.

How might these findings apply to the savanna soap opera of Jonathan and Rebecca? There he sits, dozing in the equatorial sun. Rebecca appears in the distance (dramatic entrance at the other end of the field, wind-swept fur, the whole deal). Jonathan's appetitive light goes on, and his ventral tegmentum gets all hyperactive and releases dopamine like mad. This gives his frontal cortex the impetus to do the harder thing, to resist the easy out of just sitting there in his midday torpor. Instead, he gets up and walks across that endless field, powered by the anticipatory certainty (Wagner now in the background) that she is going to let him groom her.

But logically, Jonathan should react this way only if there's a tightly coupled *if-then* clause guiding his relationship with Rebecca. (If I show certain behavior, then I will get a reward.) But there isn't any such certainty. There's an *if-maybe*. Jonathan pursues Rebecca, but it only works some of the time. And yet that is enough to keep him re-inforced, or motivated. Why does Rebecca's coyness work? Why does "intermittent reinforcement" seem so much more enticing than a sure thing?

In the second paper, published in the 21 March 2003 issue of *Science*, the neuroscientist Christopher D. Fiorillo of the University of Cambridge and his colleagues (one of whom is Schultz) addressed that question with a brilliant experiment, once again with monkeys. Back to the laboratory setup: Light comes on, press lever, get the reward a few seconds later. Now add the Jonathan-Rebecca component, *maybe*: Light comes on, press lever, get the reward—but only, on average, 50 percent of the time. Right on the fulcrum of uncertainty, maybe yes, maybe no. Now what happens to the dopamine activity?

Remarkably, it increases. And even more remarkable is the way it does so: Light comes on, and there's the usual dopamine rise, fueling the lever pressing. Then, lever pressing completed, a second phase of dopamine release begins, gradually increasing until it peaks right around the time the reward would normally occur.

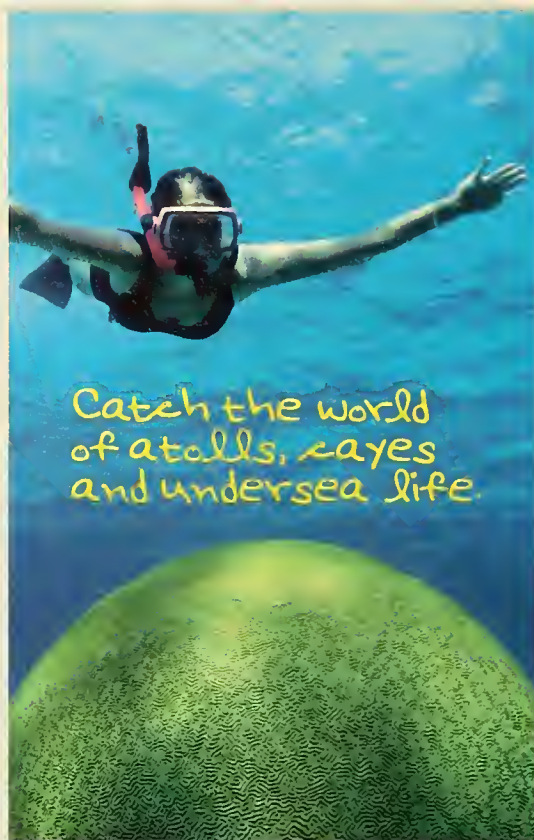
Suppose the experimenters decrease the degree of uncertainty, of unpredictability: Light comes on, lever is pressed, but now there's only a 25 percent chance of reward. Or make it 75 percent. Of course, 25 percent and 75 percent are opposite trends in the chances of reward, but they do have one thing in common: they carry less of a *maybe* than the 50 percent scenario. What happens? The secondary rise in dopaminergic activity takes place, but to a smaller extent. The most dopamine is released when the uncertainty is greatest.

This finding explains why intermittent rewards can be so profoundly reinforcing. And the experimental findings dovetail nicely with the literature in the physiology of stress, which reveals the dark side of *maybe*: a punishment with a fair chance of occurring can be vastly more stressful than a predictable one. When the inflection of punishment is unpredictable, stress-hormone levels and blood pressure are likely to rise, and the risk of stress-related disease rises, too. Joan Silk, a primatologist at the University of California, Los Angeles, has presented evidence that one of the skills honed by alpha-male baboons to keep the competition off kilter is to be brutally aggressive at times in utterly random, unpredictable ways. The corrosive core of terrorism, too, is the orange-alert world of never knowing where or when.

The research by Fiorillo and his colleagues may also help explain why the chance of a huge reward, even the most ludicrously remote *maybe* of a chance, can be so addictive, spiraling wild-eyed gamblers into squandering the kids' food money at the casino. That gleaming calculator of a cortex sits there marinating in all sorts of frothy, hormonal, affective influences, which can make so-called rational assessments end up as pretty irrational. That's why, if the lottery payoff is big enough, we become convinced—no matter what the odds against it—that we've got the lucky number and that we're soon going to be in social-grooming heaven.

And Jonathan and Rebecca? Well, she remained more interested in the high-ranking, prime-age guys, and he eventually got over his crush. A few years later, though, they had one wild twenty-four-hour fling, on a day that she was at the peak of her ovulatory cycle. But that's another story.

Robert M. Sapolsky is a professor of biological sciences and neurology at Stanford University. His most recent book is *A Primate's Memoir: A Neuroscientist's Unconventional Life among the Baboons*.



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# Squeeze Play

*Brodingnagian earthmoving “worms” dig their tunnels with a hydraulic ram.*

By Adam Summers ~ Illustration by Roberto Osti

When I first saw a live caecilian, I was convinced that I was looking at an earthworm large enough to strike fear in the heart of an Alabama large-mouth bass. The animal squirming through the sphagnum moss was *Dermophis mexicanus*, a Central American species of amphibian that reaches two feet in length and is as fat around as the most decadent Cuban cigar. Like common earthworms, caecilians’ brown-gray bodies sport closely spaced, circumferential grooves; the animals’ blunt heads bear a striking resemblance to their tails, their eyes are quite small, and they lack arms and legs. If you were to grasp one in your hand, it would squirm like a healthy night crawler trying to escape the hook.

But such a scene is about as likely as latching onto a fifty-pound bass. Caecilians so seldom have contact with people that most species have no common name. Although they are amphibians, caecilians are denizens of the terrestrial underworld. (One odd species, the atypically aquatic *Typhlonectes natans*, can be bought in pet stores, albeit under the misleading name “rubber eel.”) Anyone hoping to find one should bring a shovel to the world’s humid tropics.

As you dig, however, you’ll quickly be reminded that burrowing is tough. The short, stout arm bones of moles and armadillos reflect the extreme demands of tunnel excavation, as do the thick, reinforced skulls

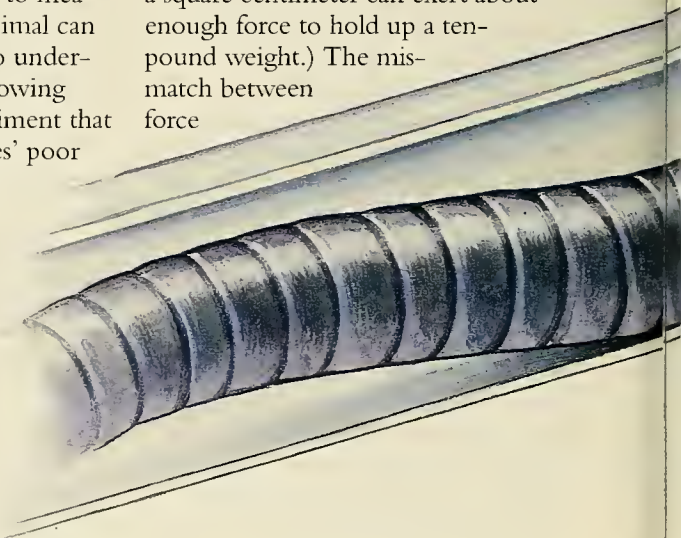
of other burrowing vertebrates, such as the caecilians. Those animals have abandoned limbs altogether in favor of slicing through the earth with their narrow bodies.

Like digging, studying the mechanics of burrowing is also tough, because, well, it happens underground. Nevertheless, James C. O’Reilly, a biomechanist at the University of Miami in Florida, has managed the task, and in the process has discovered that caecilians such as *D. mexicanus* not only look like worms, they move like them.

A caecilian faces one primary constraint as it burrows through the ground: the hardness of the soil. So if you want to understand how fast and through what kinds of soil a caecilian can move, the critical factor to measure is how forcefully the animal can manage to ram the earth. To understand the mechanics of burrowing O’Reilly designed an experiment that took advantage of the species’ poor eyesight. Laboratory animals were fooled into “burrowing” into a clear acrylic tube with a ninety-degree bend. Beyond the bend, a second tube, filled with soil and connected to a sensitive force gauge, was set inside the first. When a caecilian encountered the soil-filled tube, the animal

would push against the soil as hard as it could, seeking to escape the alien environment of the artificial burrow. And as hard as it could push, it turns out, was much harder than what O’Reilly had expected.

*D. mexicanus* burrows by straightening its vertebral column and ramming its head into the dirt. (The action is not unlike pushing a tent peg into the ground.) Large bundles of muscle that can move the vertebral column line both sides of the caecilian’s spine. The muscles obviously contribute to burrowing, but their cross-sectional area can account for only about a quarter of the pushing force. (As regular readers of this column may recall, the potential force a muscle can generate depends directly on its cross-sectional area. A muscle with a cross section of a square centimeter can exert about enough force to hold up a ten-pound weight.) The mismatch between force



and cross-sectional area implied either that caecilians possess a different kind of muscle tissue than do other vertebrates, or that the animals possess another source of pushing power.

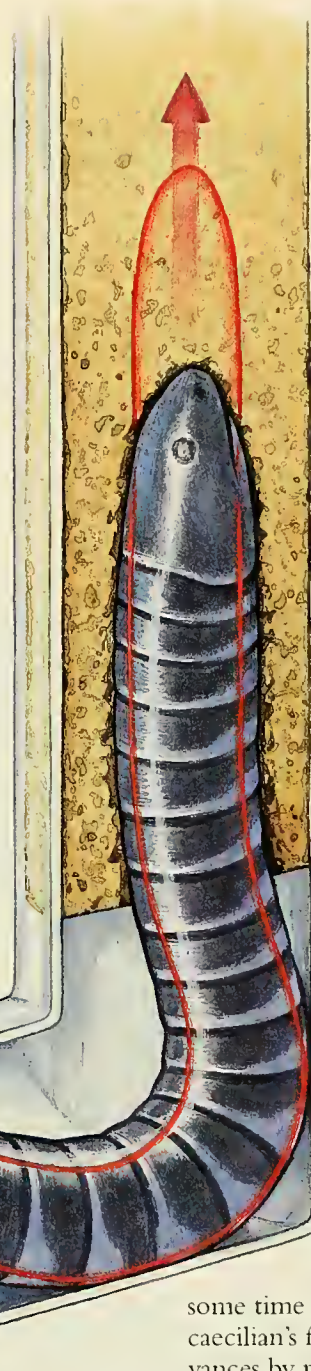
It turns out that caecilian muscle is much like yours and mine. The extra power comes, somewhat obliquely, from another group of muscles. Just under its skin lies a coiled layer of connective tissue that wraps its insides from head to tail. That tissue in turn surrounds and joins to several thin layers of muscle, laterally lining the animal's body. When these muscles contract, they don't directly push the head forward. But the contraction does increase the pressure in the caecilian's body, which, now thinner, must become longer if its volume is to remain constant.

By anchoring the rear half of its body against the inner walls of the burrow, the animal can direct virtually all the force of the muscular compression toward the head, much like a hydraulic ram. The head shoots forward with the extra force measured during O'Reilly's experiment [see illustration at right]. The mechanism is known as hydrostatic motion. Once extended, the animal, kinking its body near its head against the burrow

wall to provide friction, can then draw its tail forward by relaxing the same muscles and bringing up its spine.

The sequence is just like a worm's squirm. But worms don't have spinal cords, and caecilians do; the spine has to go somewhere when the animal is short, plump, and at rest. Unlike most vertebrates, caecilians can kink their vertebral column up inside their body, for which they possess a very lax set of connections between the skin and the spine. The spinal nerves, for instance, are set in S-bends at rest, leaving plenty of slack for the short-and-fat, then long-and-thin sequence during locomotion.

Borrowing technology from heart



In this recreation of the work of James O'Reilly and his colleagues, a two-foot-long burrowing amphibian known as a caecilian (*Dermaphys mexicanus*, here shown approximately 75 percent actual size) has moved along a clear plastic tube and encountered soil. To move underground, the caecilian relies on two complementary groups of muscles, in three different ways. One group controls the simple battering action of its vertebral column. The second group is connected to spirals of tendons just under the skin. When the latter muscles contract, the animal becomes thinner; because the caecilian's volume is constant, the now-squeezed animal must become longer. By anchoring itself with S-shaped kinks, the animal can apply this lengthening force in a forward direction. At the same time, the tendons (not shown), which are arranged much like the material in a "Chinese" finger trap, push on the skull, providing a third source of force. A burrowing caecilian can thereby generate more than twenty pounds of forward force. (The contracted, elongated state of the animal is outlined in red; its diameter, but not its length, is exaggerated here for clarity.)

surgeons, O'Reilly and his colleagues, David Carrier of the University of Utah in Salt Lake City and Dale Ritter at Brown University in Providence, Rhode Island, implanted miniature pressure gauges, smaller than a grain of rice, into the body cavities of several caecilians. The pressure peaked, they discovered, at the same time as the forward force did, confirming their hydrostatic-motion hypothesis. Thus what a caecilian does while burrowing is more like driving a steam piston into the ground than pounding a tent stake. Furthermore, when the animal was prevented from sealing its single lung—thus preventing the pressure of the muscles from being transmitted throughout the rest of the body—the caecilian's burrowing force dropped considerably.

Biomechanists have known for some time that the earthworm (a caecilian's favorite meal) also advances by pressurizing its body and squeezing its head forward. So there is a certain symmetry to this story: the only known vertebrate to move by hydrostatic locomotion happens to prey on an invertebrate that relies on the same mechanism. What would it feel like to bait a hook with one of these animals, and reel in a fifty-pound largemouth?

Adam Summers (asummers@uci.edu) is an assistant professor of ecology and evolutionary biology at the University of California, Irvine.

# Bolts from Beyond

*Some “shooting stars” come to Earth bearing secrets from other planets, as well as clues about the makeup of the solar system before the planets formed.*

By Donald Goldsmith



*A bolide, or particularly bright meteor, hurtles across the sky, leaving a trail that lasts for a few seconds. This lithograph appeared in 1868, in Amédée Guillemin's book *The Heavens*.*

For two centuries, astronomers and geologists have recognized that the Earth is continually bombarded by small extraterrestrial objects called meteoroids. Each piece of this cosmic debris has its own orbit around the Sun. Because some of those orbits cross the Earth's, our planet and certain bits of the debris inevitably reach the same point at the same time and collide.

Every day, in fact, about a hundred tons of extraterrestrial material rain onto our planet, most in the form of grains of dust that float gently downward and land undetected. Some of that dust has been captured by collectors mounted on high-flying aircraft, but the great hope for obtaining significant amounts of it resides with the spacecraft *Stardust*, launched in 1999 and now on the other side of the Sun from Earth. Early in 2006 *Stardust* will return to Earth with samples of the interplanetary medium.

It is probably natural to think of meteorites—as the meteoroids that fall to Earth are called—as threatening, even dangerous, phenomena. The best-known meteorites, not surprisingly, are the ones that strike something important, perhaps one of us. Despite the impression left by Hollywood movies, however, people have been hit by meteorites only once or twice in recorded history, and those impacts led to only minor injuries. The only verified mammalian fatality from a meteorite impact in the past century was a dog unlucky enough to occupy the exact spot near Alexandria, Egypt, where a meteorite from Mars struck on a June day in 1911. Closer to home (and more typical), on October 9, 1992, a large meteorite that passed over the eastern United States in a mere forty seconds reached its ground zero in Peekskill, New York, where it demolished the rear end of an aged Chevrolet [see “nature.net,” by Robert Anderson, page 63].

Truly large meteorites, such as the thirty-four-ton iron monster that the Arctic explorer Robert Edwin Peary brought from Cape York, Greenland, to New York's American Museum of Natural History in 1897, rank among the scarcest, and scariest, objects on Earth. Fifty thousand years ago, a meteorite the size of a house and the weight of a destroyer struck near what is now the town of Winslow, Arizona, excavating a

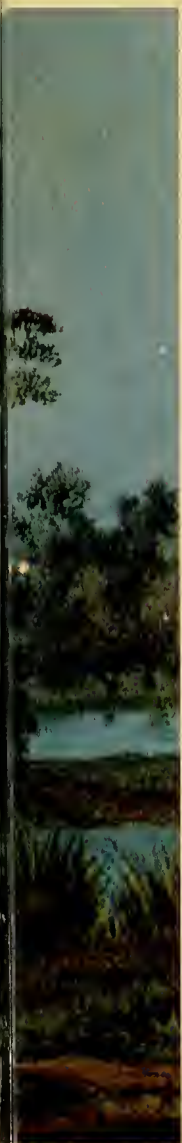
mile-wide hole known as the Barringer Meteorite Crater. Several much larger, though highly eroded, terrestrial impact craters have also been discovered, stark reminders that an object many miles in diameter strikes the Earth every 50 million to 100 million years.

Sixty-five million years ago the best-known of those supermassive impactors blasted a crater more than a hundred miles across, centered near what is now the town of Chicxulub on the northwest coast of Mexico's Yucatán Peninsula. The incoming object raised an immense cloud of grit and dust that rose high above the atmosphere, spread around the globe like syrup on ice cream, and took months to settle back down. Because the geologic record shows that the Chicxulub impact coincided with the extinction of the dinosaurs (as well as with that of many other earthly species), most paleontologists regard it as the cause of the dinosaurs' demise. Their extinction made room for the subsequent radiation of mammals into newly vacant ecological niches.

Yet meteorites also play a much less sinister role. Sizable meteorites offer astronomers and geologists extraterrestrial fragments, free for the finding—“the poor man's space probes.” In spite of the extensive alteration of their exteriors by their passage through Earth's atmosphere, those fragments nonetheless provide highly valuable samples of the early matter in the solar system.

In recent years it has also become clear that the incoming rain of meteoroids has a flip side: the much smaller, but potentially immensely significant, outflow of debris kicked into space by large impacts. A monster meteorite that strikes the Earth can shoot fragments of itself, along with terrestrial matter loosened by the impact, far out into space, adding to the swarm of meteoritic grit that already orbits the Sun. Even more important, the same process takes place on other worlds as well: the Moon, Mars, and the asteroid Vesta have all lost identifiable chunks that have made their way to Earth. Although the mass of that debris is an insignificant part of the total mass of incoming meteoroids, the recognition that matter can, and does, travel from planet to planet raises the stunning possibility that life itself, encapsulated within those bits of rock, might also pass between worlds.

Long before their nature was understood, meteoroids no larger than a small pebble continually attracted attention. Earth's atmosphere protects us well, however, so we have nothing to fear from colliding with a pebble. But the fact that each colliding meteoroid has an enormous velocity with respect to the Earth, typically between ten and forty miles per



second, has noteworthy consequences. Unable to move out of the way as the meteoroid plunges toward Earth, atmospheric gases pile up ahead of it, just as they do at the front of the space shuttle as it re-enters our atmosphere. The pressure exerted by the swiftly accumulating head of atmospheric gas heats the meteoroid (and the shuttle) to 3,000 degrees Fahrenheit or higher. Even a pebble-size meteoroid heats enough of the surrounding gas, as well as itself, to create a bright "shooting star"—the transitory visible object astronomers call a meteor.

Although a typical shooting star may appear to land over the next hill, it actually flames out be-

are classified into three main groups: stony, stony-iron, and iron. Each group embodies, in the details of its chemical composition, the history of its formation far from the Earth. The oldest meteorites are the stony ones, and within that group the oldest of all are the chondrites, so named for their rounded, glassy inclusions called chondrules.

Henry Clifton Sorby, a nineteenth-century meteorite enthusiast, described chondrules as "droplets of fiery rain." Dating of the chondrules, based primarily on the radioactive uranium they contain, has identified chondrites as old as 4.6 billion years, far older than any other rocks on the

Earth or the Moon. This age dates the oldest chondrites to the epoch when the Sun and its planets began to form within a diffuse cloud of gas and dust. Within a few million years, many of those pieces had joined together to form the large objects that now orbit the Sun: the four inner, rocky planets; the Earth's moon; and the solid cores and large moons of the four gas-giant planets.



The Willamette Meteorite, which weighs almost sixteen tons, was discovered near Oregon City, Oregon, on November 9, 1906. It is now in the collection of the American Museum of Natural History in New York City.

tween twenty-five and eighty miles above the observer. During the meteoroid's roaring trip through the atmosphere, most of its mass sloughs off as tiny shards of matter. To survive such a violent passage, and thus to reach Earth's surface as even a small remnant meteorite, the original meteoroid must be larger than a chair. Most meteors never end up as meteorites. When they do, they can be identified soon after their fall by their still-warm surfaces. Identifying older meteorites on the ground usually takes a practiced eye and a good deal of luck. On rare occasions a fall of hundreds of meteorites spreads over a few square miles.

On the basis of their composition, meteorites

Some material from the primordial solar system, however, never became part of a planet or a large moon. Instead, that debris continued to orbit the Sun, most of it between the orbits of Mars and Jupiter, a region known as the asteroid belt. Asteroids are just meteoroids large enough to be identified with a telescope as individual objects: the asteroid belt comprises not only thousands of asteroids but also millions of smaller objects.

Today, more than four and a half billion years after the Sun and its planets formed, most of the leftover debris continues to orbit outside the orbit of Mars. But gravitational forces from the other planets continually divert some of the debris into smaller orbits that cross the Earth's. When our planet encounters a region particularly rich in debris, most notably in mid-August and in mid-November, everyone in the world gets the chance to see a "meteor shower." On every clear night of the year, though, dozens of meteors can be seen by anyone with decent vision (or a good pair of glasses) and the patience to gaze steadily at the sky.



And of all the meteoroids that reach the Earth's surface, the vast majority are, in effect, minute asteroids.

But what of the meteoroids that come from other large objects in the solar system? To escape from Venus or the Earth, matter must be ejected at a velocity of at least seven miles a second; on Mars, three miles a second will suffice. No modest impact can ping matter off a surface at such speeds; the impactor must be more than 300 feet across, substantially larger than the one that excavated the Barringer crater.

Once blasted into space, a typical fragment traces an elongated trajectory around the Sun. On every orbit, it makes a close approach to the planet it came from, and the gravity of that planet either recaptures it or deflects it into a new orbit. If the new orbit becomes so elongated that it crosses the orbit of another planet, the second planet's gravitational field may pull the fragment into its embrace. In some cases that second planet is Jupiter—by far the most massive planet, whose gravitational force can either capture the fragment or launch it entirely out of the solar system. But a sizable fraction of the material ejected from either Mars, Venus, or the Earth—more than one-third—actually ends up on the surface of one of the other two planets.

Of course, finding such interplanetary messengers depends a great deal on where they fall. Most of them, given the ratio of water to land on the Earth's surface, plunge unseen into the oceans. But on the slowly flowing ice fields of Antarctica, where other rocks are scarce, meteorites are ripe for the plucking. Of the several-score meteorites that have been securely identified as hailing from the Moon or from Mars, two dozen or so have been antarctic finds.

The chemical composition of every meteorite identified as lunar or Martian differs, subtly but surely, from the composition



Leonid meteor shower of November 12, 1799, as seen off the southeast coast of Florida

of every terrestrial rock. The chemical profiles of the meteorites match those of rocks sampled on Mars and on the Moon several decades ago [see "Moonstruck," by G. Jeffrey Taylor, page 46]. Strangely, no meteorites from Venus have yet been identified, though some of them should have reached the Earth, and a chemical analysis of the Venusian surface has been available for a quarter century. The luck of the cosmic draw may have led to that negative result; better meteorite searches may soon change it.

By examining Martian meteorites for the effects of impacts from cosmic rays—fast-moving, highly energetic atomic nuclei that permeate space—physicists have determined that they spent between 12 million and 17 million years in interplanetary transit before colliding with the Earth. All but one of those meteorites are less than 1.3 billion years old. The lone exception is a meteorite designated ALH 84001, so named because it was the first meteorite discovered in the Allan Hills of Antarctica in 1984.

In 1996, however, ALH 84001 became the most famous meteorite on the planet. An interdisciplinary team of scientists announced that this rock from Mars bore intriguing clues that life had once flourished on another planet. Moreover, the radioactive decay of minerals within the meteorite showed that the rock had formed 4.5 billion years ago, a time early in the history of the solar system. In that distant epoch the surface of Mars apparently had abundant running water, and thus a far greater potential than it does today for harboring life on its surface.

What were the signs of life within ALH 84001? First, it contained compounds that often occur in organisms on Earth. Second, it included tiny, magnetized grains of iron oxide and iron sulfide much like the ones that certain bacteria pro-



A dazzling bolide streaked across midwestern skies on February 12, 1875.

duce to orient themselves in the Earth's magnetic field (Mars, too, must once have had a substantial magnetic field). Finally, it held within it a number of submicroscopic ovoid shapes, similar in form to various tiny fossils on Earth but much smaller than any of them.

For a few months many investigators hoped ALH 84001 would demonstrate that ancient life on Mars had been brought to Earth by two cosmic collisions: one that blasted the rock loose from Mars in the first place, and a second, 15 million years later, that slammed it into our planet. Alas, the verdict has largely gone against the believers (though there are still holdouts). Some earthbound organisms may have contaminated the meteorite.

The resemblance between its mineral inclusions and the magnetic grains made by bacteria is apparently just happenstance. And the ovoids, too small to hold the molecules needed to carry out the chemical reactions of life, are just chance deposits with interesting shapes.

Nevertheless, ALH 84001 is a striking reminder that whenever a giant impact dislodges a life-bearing fragment from an inhabited world, life from that world could travel to another. In principle, since Jupiter's gravity expels some meandering meteoroids from the solar system, life might even be able to cross interstellar

distances millions of times greater than the distance between Earth and Mars, eventually to find its way onto worlds that belong to other planetary systems.

**P**anspermia, the concept that all life in the universe had a common origin and has been carried from planet to planet with the passage of time, sprang from the mind of the Swedish chemist Svante Arrhenius at the beginning of the twentieth century. The demonstrated fact that material does travel from one planet to another lends credence to the hypothesis. But could any life-forms have survived the shock of the blastoff, the long, harsh cold and exposure to radiation in space, and the final trauma of passing through a planet's atmosphere and colliding with its surface?

Apparently they could have. Calculations of the blast-off process, together with experiments on such hardy bacteria as *Bacillus subtilis* and *Deinococcus radiodurans* (the latter notable for surviving doses of radiation a few thousand times the lethal dose for a human being), imply that microorganisms can survive not only the shock of impacts like the ones required to eject matter into interplanetary space, but also millions of subsequent years of orbiting in the cold. Microorganisms in space can be protected against interplanetary ultraviolet radiation by a few microns of shielding, which even a small rock can provide. (Protection against cosmic-ray particles might require several feet of solid material, implying that only relatively large ejected rocks could ferry life safely through space.) Some forms of life can remain dormant for many centuries, and possibly even for the thousands of millennia it takes for a meteoroid to travel from planet to planet.

Passing through a planet's atmosphere, even one as thin as the veil surrounding Mars, substantially slows down a meteoroid before it lands. During that ten- or twenty-second passage, as its surface becomes red-hot, much of the meteoroid breaks apart or flakes off. But the passage happens so quickly that the interior of any sizable meteoroid fragment, including any microorganisms along for the ride, could remain cool. H. Jay Melosh of the University of Arizona in Tucson, the leading expert on the exchange of matter between planets, puts it this way: "Earth's atmosphere—and Mars's to some extent—couldn't have been better designed to let organisms down gently."

How can one estimate the probability that life-forms do travel from world to world, as Arrhenius envisioned? One conclusion seems rock-solid: The distances between the planets within our solar system (or within other planetary systems) make such a transfer billions of times more likely *within* a single planetary system than *between* planetary systems. Thirty years ago Carl Sagan concluded that probably not a single meteorite from another planetary system could ever reach the surface of the Earth. Earlier this year Melosh undertook detailed calculations to demonstrate systematically that Sagan's assertion remains valid. The vast distances between the stars make the interstellar-panspermia hypothesis—that life has been transferred not only within a planetary system but also between systems—mathematically almost impossible, no matter how well a life-form could survive an interstellar voyage.

But for travel between the planets within a particular system, panspermia seems entirely possible. The Martian meteorites demonstrate that much already. Life on Earth may yet prove to be descended



Meteor storms are rare, but this portrayal of a spectacular storm on the night of November 12–13, 1833, is not fanciful. Witnesses in eastern North America reported sighting tens of thousands of meteors, and a succession of brilliant fireballs.



*A bright shooting star blazes a trail of hot gases as it burns up in the topmost reaches of the atmosphere, between twenty-five and eighty miles above the ground. If you're in the right place at the right time, you may witness such an event any clear night of the year. The U.S. astronomer Edwin Emerson Barnard captured this meteor in a wide-field photograph in December 1916.*

from ancient life on Mars—and any ancient life on Mars may in turn have come from Earth.

**E**ven if meteorites turn out not to have brought life to Earth from other planets (or vice versa), they still arrive here loaded with useful information. Geologists have noted, for instance, that every meteorite from Mars contains carbon-oxygen compounds, sulfur-oxygen compounds, and minerals common in terrestrial clay—all of which signal that water was present at the time they were formed.

Perhaps even more amazing is what geologists have deduced about the geologic history of Mars from what might seem meager evidence in eight Martian meteorites. The key to the deduction lies in what can be inferred from the measured ratios of various isotopes in various rocks. (A chemical element can occur in nature in several varieties called isotopes. The isotopes of any one element are iden-

hafnium tends to end up in rocks outside the core. The ratio of tungsten-182 (which came from hafnium) to total tungsten in the Martian meteorites turned out to be relatively high, signaling that the region from which they originated had been part of the early crust.

Furthermore, Lee and Halliday concluded, Mars must have differentiated itself into core, mantle, and crust within a few tens of millions of years after it formed. Thereafter it has remained geologically quiet, its crust relatively intact for almost the entire history of the planet. If, during the past four billion years, Mars had instead undergone plate-tectonic activity similar to that on Earth, more material from the core would have found its way into the crust. In that case, the ratio of tungsten-182 to tungsten-184 would have been lower, because much more tungsten-184 from the original core would have been mixed into the crust.

*Even if meteorites turn out not to have ferried life to Earth, they still arrive here loaded with information.*

tical in their chemical properties, but they differ in mass as well as in stability against radioactive decay.)

Geologists Der-Chuen Lee of the Academia Sinica in Taiwan and Alexander N. Halliday of the Swiss Federal Institute of Technology in Zurich measured the proportions of various isotopes of tungsten in the eight meteorites from Mars. Tungsten-182, a rare isotope, arises from the radioactive decay of hafnium-182. The measured quantity of tungsten-182 in a meteorite therefore shows how much hafnium-182 was present in the rock when it formed. From that measurement, it was straightforward to calculate how much hafnium of all isotopes was present in the original rock.

Lee and Halliday then measured the total amount of tungsten in the meteorites, almost all of which is tungsten-184. All tungsten combines readily with iron-rich material, which, because of its high density, tends to concentrate in the core of a planet. Hence tungsten, too, became concentrated in the core. As a consequence, the rocks that did not contain much iron became relatively depleted in tungsten. Those rocks were the ones that came to form the Martian crust and mantle.

In contrast with tungsten, hafnium does not interact readily with iron-rich material, but it does combine readily with the elements in rocks lacking in iron. Hence when a planet differentiates into an iron-rich core and an iron-poor crust and mantle,

**T**his December the European Space Agency's Mars Express lander *Beagle 2* is scheduled to touch down on the Martian surface. The following month NASA's Mars Exploration Rover Mission will put two robot rovers on opposite sides of the red planet to scrutinize the surface for signs of water and provocative rocks. Someday within the next decade or two, Martian materials may be brought to Earth for analysis. A detailed examination of them should yield geologic conclusions even more startling and fine-grained than the ones derived from the tungsten isotopes. For example, if sedimentary rocks exist on Mars, they may contain fossil evidence of life from the era when liquid water flowed on the planet's surface.

Someday, too, well before this century ends, geologists will walk on Mars; one of their number has already walked on the Moon. Their explorations will enhance the findings of the robot investigators that preceded them. Perhaps they will find rocks containing evidence of life—or possibly life itself—hidden beneath the Martian surface. Until then, we earthlings can continue to look for microscopic visitors, or their fossil remnants, that might reside in meteorites from Mars or from other worlds. The full implications of those interplanetary transfers, which depend on a more complete knowledge of what those visitors from other worlds have carried to Earth, will be intriguing to sort out. □

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# TERRIBLE LIZARDS OF THE SEA

*When dinosaurs ruled the land, other giant reptiles stalked the deep. Some may have borne more than a passing resemblance to sea serpents.*

By Richard Ellis

In 1780 in Maastricht, Netherlands, workers in a limestone mine ninety feet deep discovered the huge jaws and part of the skull of an unknown fossil creature. An army surgeon named C. K. Hoffmann directed the quarrymen to bring the entire rock containing the find to the surface, but soon lost possession of it. The prize was claimed by the landowner, a clergyman named Goddin, who in turn had to watch helplessly as it was carried off by Napoleon's army in 1795. It is now on view at the National Museum of Natural History in Paris.

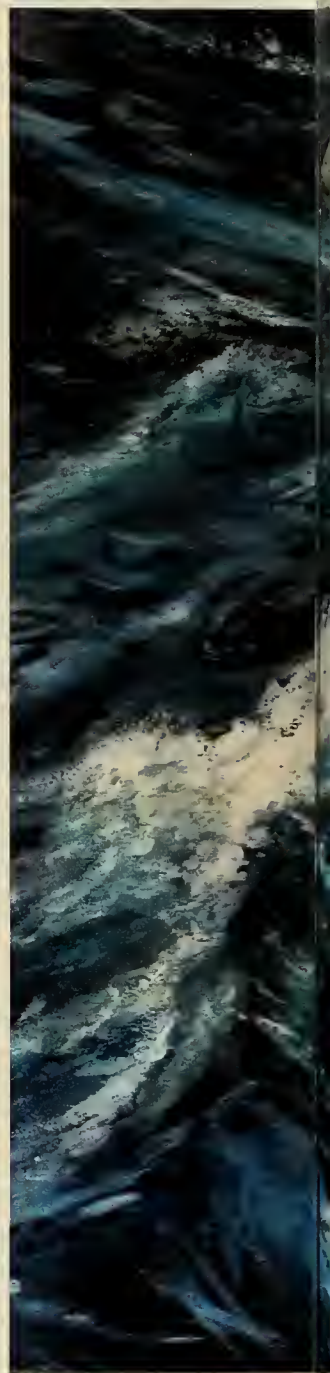
What was this rockbound monster? Pieter Camper, a renowned Dutch anatomist of the day, believed the jaw, which measured more than five feet long, belonged to a toothed whale. One of Camper's contemporaries, the French naturalist Barthélemy Faujas de Saint-Fond, likened it to a crocodile. Unswayed by the creature's size, Camper's son Adriaan Gilles Camper correctly pointed out its resemblance to lizards of the family Varanidae, such as the monitor lizard. In 1822 the animal was accorded a genus name, when the English geologist and clergyman William Daniel Conybeare called it *Mosasaurus*, from *Mosa*, the Latin name of the Maas (Meuse) River near Maastricht, and *saurus*, for "lizard." Later, the hapless surgeon Hoffmann was honored in the species name, *hoffmanni*.

That first specimen gave its name, in more general form, to all its relatives that followed it into the limelight of paleontology. A diverse group of aquatic reptiles, the mosasaurs arose about 90 million years ago, in the middle of the Cretaceous Period, and flourished for 25 million years. All were

lizards, and thus only distantly related to their terrestrial counterparts, the dinosaurs [see illustration at the top of page 39]. Although almost certainly descended from terrestrial forebears, mosasaurs adapted well to the open seas, and some species reached enormous size. In the ocean they achieved a commanding position as predators that would not be matched until whales and dolphins appeared on the scene 30 million years later.

The proliferation of the mosasaurs followed a dramatic rise in worldwide sea levels, when shallow seas covered much of Europe and North America. Sea levels eventually fell once again, rendering the remains of the mosasaurs accessible, and the discovery of gigantic sea lizards in the badlands of the American West captured the public's imagination in a way exceeded only by the unearthing of the dinosaurs themselves. In a chapter titled "Wonder of the Kansas Plains," in his 1887 book *Sea and Land: An Illustrated History of the Wonderful and Curious Things of Nature Existing before and since the Deluge*, James W. Buel expressed the public's amazement:

The fabulous monsters that were believed in in the





Mosasaur, a diverse group of aquatic reptiles, arose about 90 million years ago and coexisted with the terrestrial dinosaurs until both groups were wiped out when the Earth collided with an asteroid, 65 million years ago. *Tylosaurus proriger*, the mosasaur envisioned in this 1899 painting by Charles R. Knight, preyed on fish, shellfish, and probably certain large aquatic birds, as well as on other small mosasaurs and plesiosaurs. The species could grow as long as fifty feet and weigh as much as eleven tons.

olden times, the dragons, serpents, etc., are thrown in the shade by these truly ancient monsters that once swam in the ocean that finally became land-locked, and the bottom of which is now raised high above the water level. The shore line of that old ocean is distinctly marked. Imagine the water between New York and London a dry plain, its whales and fishes stranded in the mud, on the sides of the great hills, and on the plateaus that we know exist, and an idea can be formed of the *mauvaise terres*. [Yale paleontologist O. C.] Marsh says that in one place he counted from his horse the remains of five huge monsters spread upon the plain.

Coincidentally, *M. hoffmanni*, the first mosasaur species to be recognized, still holds the record for size: Theagarten Lingham-Soliar, a paleontologist at the University of Durban-Westville in Kwazulu-Natal, South Africa, estimates that in life the Maastricht specimen was fifty-eight feet long and weighed between twenty and twenty-two tons. He thinks the creature may have lived in nearshore waters that were perhaps between 130 and 165 feet deep. Other species took to the open ocean, and may have dived deeply for prey. Still others lurked

in the shallows, ready to ambush anything that happened by, or developed heavy, rounded teeth that enabled them to crush the thick shells of bivalves. All of them vanished, however, around the same time the last of the terrestrial dinosaurs and air-borne pterosaurs met their doom.

Or did they? According to one theory, the snakes—a group whose origins remain shrouded in mystery—share such a close kinship with the extinct mosasaurs that they almost could be considered the surviving branch of the lineage.

**T**he immediate ancestors of mosasaurs have not been identified, but they probably looked a lot like aigialosaurs, usually considered shore-living, semiaquatic lizards. Aigialosaurs were three or more feet long, with a tail as long as the head and

or warm-blooded. In any case, mosasaurs were active predators. The lower jaws, which were only loosely connected at the front, each had a hinge joint in the middle, enabling the animals to swallow large prey. A system of continual tooth replacement ensured an ever-sharp battery of teeth. In addition, in most species the pterygoid bones that made up the hard palate on the roof of the mouth were equipped with teeth that kept slippery fish, squid, or other prey from wriggling free after they had been grabbed by the jaw teeth.

Mosasaurs were not the only reptilian predators in the seas; others were well established by the time they appeared, notably the plesiosaurs (with four flippers and, often, elongated necks), the crocodilians, some gigantic sea turtles, and the ichthyosaurs (which were shaped somewhat like dolphins but

had a sharklike, vertical tail fin). By the time of the mosasaurs, however, the ichthyosaurs were heading toward extinction, though they had been around for nearly 150 million years. As a group they had started out as ambush predators, but they had evolved into species that caught their prey by pursuit. Unfortunately for the ichthyosaurs, fish were getting harder to catch. As Lingham-Soliar has observed, the fast, highly evasive bony fishes were thriving at the time and spreading around the globe, and so the energy costs of catching prey by pursuit were becoming increasingly untenable for marine reptiles.

**M**osasaurs excelled instead as ambush predators. Judy A. Massare, a paleontologist at the State University of New York College at Brockport, has

analyzed their swimming capabilities, and she concludes that mosasaurs could accelerate rapidly to capture prey. The long, thin shape of the animal, she notes, enabled it to cut through the water with minimal resistance while using its large body surface for propulsion. Moreover, she explains, the end of the creature's long tail would have generated extra thrust, particularly in species that had an expanded end to the tail.

In many of the earliest descriptions of swimming mosasaurs, scholars speculated that the reptiles undulated their entire bodies, like snakes or eels. In 1991, however, Lingham-Soliar concluded from a study of mosasaur vertebrae that only the rear two-thirds of the animal's body undulated when it swam; the forward third was stiffened. The motion, he said, was similar to that of a swimming



Fossilized jaws and partial skull of *Mosasaurus hoffmanni* are removed from the limestone mine in the Netherlands where they were discovered in 1780. The fossil was the first, and remains the largest, mosasaur ever found.

body combined, not unlike today's monitor lizards. Anatomically, they could well pass for mosasaur ancestors. But no fossils of them have been found that are older than those of the mosasaurs themselves, so it is safer to regard them as a sister group. Once mosasaurs began to evolve in the sea, however, they quickly traded their feet for flippers, and their tails lengthened and became vertically flattened, like those of eels and crocodiles. Whereas their ancestors had laid eggs on land, mosasaurs developed the ability to deliver young alive in the water.

Mosasaurs may have been ectothermic, or cold-blooded, as are all living reptiles; the shallow seas and coastal waters where many species lived would have been relatively warm. But some species appear to have dived deeply or frequented cooler depths, so perhaps they were partly endothermic,



cod, an American alligator, or a Galápagos marine iguana. Then, just a year later, Lingham-Soliar proposed that one large mosasaur, *Plioplatecarpus marshi*, essentially “flew” underwater, like a penguin or a California sea lion, using its flippers in up-and-down movements instead of a forward-and-back rowing motion.

The idea of underwater flight in mosasaurs has sparked spirited debate among paleontologists. Elizabeth L. Nicholls of the University of Calgary in Alberta, Canada, and Stephen J. Godfrey of the Calvert Marine Museum in Solomons, Maryland, note that in penguins and similar underwater fliers, the tail is much smaller than it is in nonfliers. But, they maintain, there is no reason to think that the tail was unusually short in this species. They also contend that the animal’s huge flippers would not have been particularly effective as “wings,” and that the species’ powerful pectoral girdle—the skeletal arch that supported its forward fins—could have served other functions. Certain sharks, for instance, shake their prey violently to dismember it into edible chunks, and they have similarly well-developed pectoral girdles that support the “sharp movements of [their] pectoral fins.”

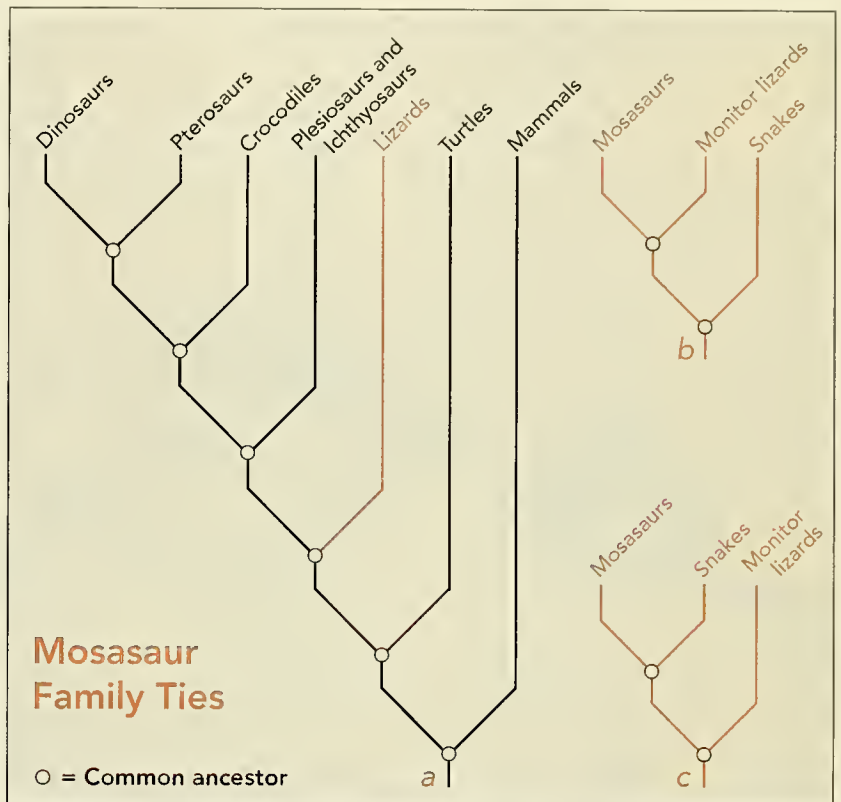
One of the most formidable of the mosasaurs was *Tylosaurus proriger*, a species that could grow as long as fifty feet and weigh as much as eleven tons. It had a slim body, huge jaws, and heavy, sharp, cone-like teeth. Its trademark feature, though, was the elongated tip of its muzzle, which projected eight inches beyond the frontmost teeth in the upper jaw. The protuberance may have acted as a ram that could stun prey, defend against sharks and other predators, or battle rivals of its own species.

*Tylosaurus* inhabited the shallow Niobrara Sea, which once covered what is now the Great Plains of North America. The animal preyed on fish, shellfish, and probably certain large aquatic birds, as well as on small mosasaurs and plesiosaurs. That description of its diet is not just guesswork. In 1987 James E. Martin and Philip R. Bjork, both of the Museum of Geology at the South Dakota School of Mines and Technology in Rapid City, described the stomach contents of a South Dakota fossil of *Tylosaurus*. The stomach included the remnants of the diving bird *Hesperornis*, a bony fish, a shark, and a small mosasaur.

Not all mosasaurs ambushed or chased down

fast-moving prey. The genus *Globidens* had rounded teeth instead of the more typical conical spikes. Those teeth were adapted not for gripping prey, but for crushing shellfish, probably ammonites. Such round-toothed species were also the only mosasaurs that did not have palatal teeth: crushed shellfish did not have to be “walked” to the throat the way struggling vertebrates did.

Specimens of mosasaurs that have been excavated are about ten times as plentiful as dinosaur fossils are. Yet despite the large body of evidence, some questions about them have been difficult to answer. For a long time, for instance, no one knew how they were born. Mosasaurs seem ill equipped to have laid eggs on land, as sea turtles do. But if they gave birth to live young, one would ex-



Geneological family tree of reptiles and mammals (a) shows that lizards—including mosasaurs—are no more closely related to dinosaurs than they are to several other major reptile groups. Within the lizard group, both mosasaurs and snakes are considered closely related to lizards of the family Varanidae, whose living representatives include the monitor lizards. A common view (b) is that snakes and mosasaurs are fairly distant relatives, but according to a more recent suggestion (c), snakes and mosasaurs share a close common ancestor.



pect to find embryonic bones preserved with some of the adult skeletons.

It was not until the 1990s that Gorden L. Bell of the Museum of Geology at the South Dakota School of Mines and Technology discovered the bones of two prenatal mosasaur embryos, along with the fragmentary remains of the mosasaur *Plioplatecarpus primaevus*. The bones were disarticulated, but that seemed to have been caused by scavenging dogfish sharks, whose teeth were abundantly preserved in the immediate vicinity. Further support for a live-birth life cycle came in 2001, when Michael W. Caldwell of the University of Alberta in Edmonton, Canada, and Michael S. Y. Lee of the University of Adelaide in Australia published a description of a fossilized aigialosaur with at least four well-developed embryos. The orientation of the embryos suggested birth was tail first, which would have reduced the possibility of drowning.

**A**nother matter of contention has been whether any mosasaurs were deep divers. Bruce M. Rothschild and Larry D. Martin, both from the University of Kansas Natural History Museum in Lawrence, examined the fossilized vertebrae of some North American mosasaurs for evidence of a bone disease called avascular necrosis. The disease was present in nearly every skeleton they examined of *Tylosaurus* and *Platecarpus*, two of the most common mosasaur genera. Avascular necrosis occurs when the blood supply to the bones is cut off. It is the telltale sign of an episode of decompression sickness, commonly known as “the bends,” which is caused by the formation of nitrogen bubbles in the bloodstream as an animal ascends after a deep dive.

Rothschild and Martin conclude that the mosasaurs

belonging to those two genera were deep-water specialists that may have dived too often and gone too deep. The episodes of the bends, the investigators speculate, may have resulted from crises such as the need to escape predators, or the reckless pursuit of prey. They also report that in South Dakota, skeletons of large mosasaurs occur in the same area as the remains of giant extinct squids. “It is possible,” they write, “that *Tylosaurus* may have dived to great depths to capture squid, as the modern sperm whale does now.”

For some paleontologists, however, the jury is still out on deep diving. Amy Sheldon of Oklahoma Panhandle State University in Goodwell, for instance, disagrees about the deep-diving ability of *Platecarpus*. The animal had relatively dense, heavy bones, she notes, which would have tended to keep it submerged. Present-day sea cows, she continues, have dense bones, and they inhabit only shallow waters. In contrast, dolphins, some whales, ichthyosaurs, and some turtles have porous, light bones, and many dive (or dove) deeply.

**P**erhaps the greatest mystery about the mosasaurs is their disappearance. For at least 25 million years they prospered, spreading throughout the major oceans of the world. It seems unlikely that they had reached anything like their evolutionary potential at the time they vanished. Yet vanish they did, 65 million years ago.

Few would doubt that their demise was linked to the same asteroid impact and disruption of the food chain that wiped out the pterosaurs and the terrestrial dinosaurs. The plesiosaurs also disappeared at the same time (unless one insists on the existence of the fabled Loch Ness monster). Of the large marine reptiles, only crocodiles and sea turtles somehow survived.

But did all mosasaurs really disappear? In recent years many paleontologists have embraced the view that birds are descended from one group of dinosaurs, and so birds must be considered dinosaurs, too. If so, the familiar claim that dinosaurs became extinct is no longer tenable. No one yet is demanding quite such a radical shift in paleontological thinking about mosasaurs. But Caldwell,



*Pachyophis woodwardi*, dating from about 95 million years ago, is one of the earliest known snakes. To some investigators its relatively heavy ribs suggest it was a marine species, and perhaps a close relative of the mosasaurs.

Lee, and others are now ruffling some paleontological feathers, so to speak, by maintaining that snakes and mosasaurs are more closely related to each other than either group is to any other group of lizards. In support of that view, they point out, for instance, that snakes, like mosasaurs, possess

ered in a limestone quarry some twelve miles north of Jerusalem, it is nearly four feet long. It had small hind legs—including femur, tibia, fibula, and tarsals—as well as other characteristics that, they argued, support the idea that snakes are closely related to mosasaurs.



Fossilized skeleton of a thirty-foot-long *Tylosaurus proriger* shows that the animal was a formidable predator. The flattened tail provided strong propulsion for ambushing prey. The projecting tip of its skull, a trademark feature of this and similar species of mosasaurs, may have acted as a ram for stunning prey, defending against sharks, or battling rivals.

palatal teeth as well as flexible lower jaws that enable them to swallow large prey.

It has generally been thought that the first snakes were terrestrial, and that their ancestors were terrestrial lizards similar to the ones belonging to the family Varanidae—the same family that is regarded as close to the mosasaurs. But in the newly proposed scenario, the mosasaurs, together with the earliest snakes and certain lizards such as the aigialosaurs—all of them aquatic—evolved from a common aquatic or semiaquatic ancestor [see illustration at top of page 39]. The earliest terrestrial snakes then descended from their aquatic forebears, and, as herpetologists have long maintained, the aquatic snakes that exist today descended even later from the terrestrial snakes.

Where, however, is the fossil evidence that marine snakes preceded terrestrial ones? Terrestrial snakes were indisputably present about 100 million years ago, and perhaps somewhat earlier. That date sets the bar for finding early marine snakes. One early candidate, *Pachyophis woodwardi*, dating from about 95 million years ago, was originally described as a snake in 1923 [see photograph on opposite page]. Lee and his colleagues have reevaluated that fossil; its relatively heavy ribs suggest to them that the species was marine, but the evidence is equivocal. Another fossil snake of about the same antiquity, *Pachylachis problematicus*, was described by Caldwell and Lee in 1997. Discov-

The same limestone quarry from which *P. problematicus* was excavated has yielded another 95-million-year-old fossil snake species, *Haasiophis terrasanctus*. But as often happens in paleontology, a newly unearthed fossil can confuse more than it clarifies. Analysis of the specimen by the late paleontologist Eitan Tchernov and his colleagues led to another interpretation. *H. terrasanctus* was about three feet long and also had legs, but its jaw structure appears more closely related to the larger, living snakes of today than the jaw of *P. problematicus* does. Hence it could be, as Tchernov and his coworkers suggested, that both *P. problematicus* and *H. terrasanctus* were advanced snakes that had re-evolved legs from vestigial structures.

The descent of snakes is a contentious topic in vertebrate biology and is not likely to be settled without more hard evidence. Unfortunately, the bones of small snakes are delicate and their fossils are hard to come by. Nevertheless, Caldwell and Lee have stimulated some new thinking. In their 1998 book *The Evolution Revolution*, Kenneth J. McNamara and John Long, both of the Western Australian Museum in Perth, welcomed the mosasaur connection, giving it a down-under perspective:

When you are next out snorkeling and are startled by a sea snake, it may not only be some highly derived snake that you are frantically paddling away from, but all that remains of a great radiation of aquatic reptiles that once dominated the seas. □

This article was adapted from Richard Ellis's forthcoming book, *Sea Dragons: Predators of the Prehistoric Oceans*, which is being published by the University Press of Kansas in October.



The dragon's blood tree (*Dracaena cinnabari*; seen close up, above, and in its habitat at right) grows by sending out branches that bifurcate in a predictable, simple, self-similar manner. According to Friedrich E. Beyhl, a botanist in Kelkheim, Germany, the branching can be modeled as a fractal, a mathematical object that branches repeatedly according to a simple rule.

Of more interest to the people of Socotra (and beyond) is the tree's resin. Pliny, the Roman natural historian, called it *cinnabaris* for its red color, and reported that the red liquid was pressed from a dragon's body by a dying elephant. Gladiators would smear the resin on their bodies before combat, both for its ferocious, intimidating red color and for its disinfectant properties in treating wounds. Dragon's blood appears in the Nordic saga of Sigurd in the same role. The Arabic word for the resin is *dam al-akhawein*, "the blood of the two brethren," which alludes to the legendary twins Castor and Pollux. (The Greek name for the islands, *Dioscorida*, alludes to those twins, too.) It was a common ingredient in varnishes of the past; Socotrans today decorate pottery with the dark resin.

One of the closest relatives to *D. cinnabari* today grows on the Canary Islands in the Atlantic; evidence from fossil pollen suggests that some 20 million years ago the tree and its relatives spanned the length of the arid southern shore of the Tethys Sea, the remnant of which we know today as the Mediterranean.



# Splendid Isolation

*With several hundred endemic plant species, the lonely Socotra archipelago is a refuge to the old and a birthplace for the new.*

*Photographs by Diccon Alexander*

In the Indian Ocean, south of Yemen and east of the Horn of Africa, lies the Socotra archipelago—an ark of endemism comparable to the Galápagos Islands in the Pacific, or to Lake Malawi on the mainland of Africa. But it is the flora, not the fauna, of these islands that strikes the mind and dazzles the eye—no finches are here, to set the biologist's mind to wondering.

Roughly a third of the 900 plant species on the archipelago's islands live nowhere else. The dry climate has turned members of familiar groups, such as the cucumbers, into desert-adapted oddities no one would recognize in a vegetable garden. The islands, which became isolated from the African-Arabian plate some ten million years ago, give refuge to an array of living fossils as well as to so-called disjunct taxa: species whose closest relatives occur thousands of miles away.

This unique ecosystem seemed threatened by modern development as the twentieth century drew to a close. Although the islands have long been inhabited (some 50,000 people live on them today) and have long been known to the outside world (2,000 years ago a Greek or Roman sailor would have called the main island Dioscorida, considering it part of frankincense country), the United Nations and the government of a reunified Yemen (which controls most of the archipelago) became concerned that the inevitable encroachment of industrialized society would destroy Socotra's unique flora. The first step in preservation was to identify and study the species, so an international team of botanists and other biologists headed to the islands: the first time such research had been initiated in a hundred years. One of the investigators, Diccon Alexander of the Royal Botanic Garden in Edinburgh, Scotland, captured some of the plants on film. A sampling of his photographs is shown on these four pages.

—THE EDITORS





In 1887, when Western naturalists first described *Dendrosicyos socotrana*, the cucumber tree, it grew in Djibouti (then known as French Somaliland) as well as on the islands of the Socotra archipelago. Today the tree, which stores water in its succulent trunk, occurs only on Socotra's dry, limestone plateaus and plains. The cucumber tree is the only arborescent member of the family Cucurbitaceae (the gourds), which also includes lianas and other vines.

The cucumber tree is an extreme example of island gigantism; until 10 million years ago, when the Socotra islands were still part of the African mainland, no broad-trunked trees could have flourished side by side with such large herbivores as elephants and rhinoceroses. When the islands broke away from continental Africa, the absence of such herbivores left a new ecological niche into which the trees could grow . . . and grow.

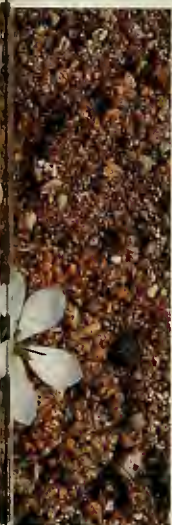


According to the *Periplus of the Erythraean Sea*, a travelogue written roughly 2,000 years ago by an unknown Greek mariner, Socotra came under the domain of the king of the frankincense country. It was an appropriate addition: the species pictured here, *Boswellia elongata*, is one of seven frankincense species endemic to the island. Precisely what led to such a diversity of *Boswellia* is not known.





*Euphorbia abdelkuri* occupies, along with some other members of its genus, a niche similar to the cacti of the Americas; it has a succulent stem in which to store water. These cactus-like plants grow in the region known as Macaronesia (principally, the Azores, Madeira, the Canary Islands, and the Cape Verde Islands) as well as in southern and eastern Africa and on the islands of the Socotra archipelago. *E. abdelkuri* grows on the chain's island of Abd al-Kuri. Unlike many of its relatives, it lacks defensive spines and protects itself instead with a sap that irritates the eyes and skin, no doubt to discourage herbivores seeking a succulent feast on such a desert island.



Taxonomists place *Dirachma socotrana* in a family, *Dirachmaceae*, with only one other species (the latter occurs in Somalia). The plant is no herb; the flowers seen here are precursors of the ones that will adorn a sweet-smelling tree. On the basis of molecular data and seed morphology, *Dirachmaceae* belongs to the order *Rosales* (best known for the roses).



The Socotran desert rose (*Adenium obesum sokotranum*), a barrel-shaped succulent, belongs to a species that occurs throughout southern Arabia; probably little more than geographical isolation separates these plants from the main species, *A. obesum*. Socotran fishermen use its poisonous bark to kill small fish for bait, and pastoralists tie strips of the bark around the necks of their grazing livestock to keep wild cats—the island's only significant carnivores—at bay.

# Moonstruck

*Giant impacts, cataclysmic bombardments, oceans of magma hundreds of miles deep: no wonder the lunar landscape inspires such fascination.*

By G. Jeffrey Taylor

**T**he lunar surface is gray, powdery, and lifeless. There, no grassy meadows or forests grow; there, no microorganisms abide to break down the nonexistent traces of any former life. No brooks babble or rivers rage, no lakes or oceans are swayed by the Earth's tidal pull. There is no atmosphere (and so no wind). No volcanoes erupt; no tectonic plates move. So little happens on the Moon that the Apollo astronauts' footprints will last for millions of years. Only a constant rain of meteoroids slowly reshapes the surface.

The lunar landscape might sound boring, but its lack of geologic action makes the Moon an exciting place to those of us who want to understand the early history of the solar system. The Moon's cratered surface records an ancient chapter in the evolution of our own planet, one largely erased on Earth. We share a history of bombardment by ancient meteoroids, but information preserved on the Moon about the size, frequency, and duration of that early bombardment is long lost on Earth. When we lunar scientists analyze moon rocks from the Apollo collection, returned to Earth by the astronauts, or when we map the distribution of minerals and elements on the Moon, we become time travelers. We can still find on the Moon remnants of the process that separated a once-molten orb into crust, mantle, and metallic core. From the evidence found on the Moon, geophysicists can extrapolate a picture of the early history of the four terrestrial planets.


Yet when President John F. Kennedy proclaimed in 1961 that Americans would reach the Moon by the end of the 1960s, he was far more interested in outdoing the Soviet Union than he was in science. But the Cold War game of "gotcha" did yield groundbreaking scientific dividends. The won-

drous Apollo missions returned to Earth with nearly 840 pounds of rock and dirt between July 1969 and December 1972. Those samples were supplemented with a few ounces of soil brought to Earth between 1970 and 1976 by the Soviet Union's Luna missions. Because the provenance of each rock and each bag of soil was carefully documented, the lunar samples have provided the "ground truth" against which to measure and calibrate the data gathered through remote sensing.

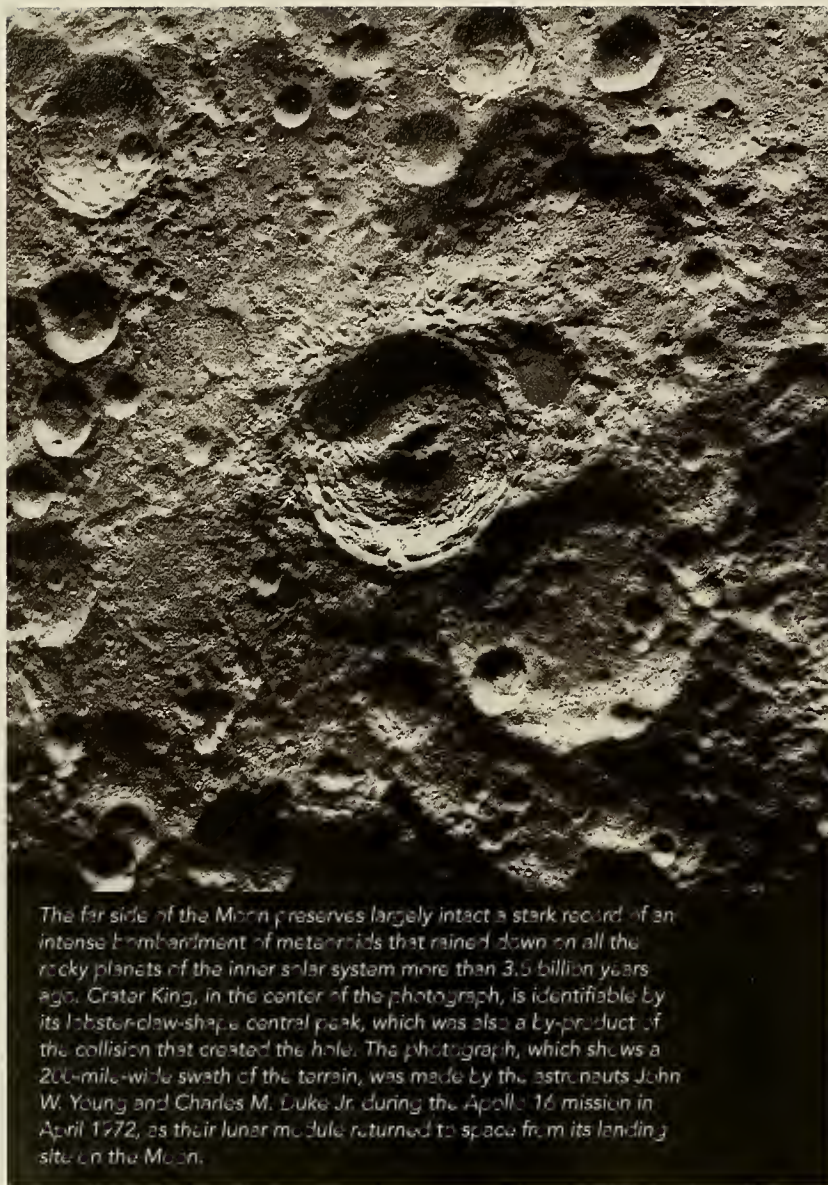
Perhaps the greatest irony of going all the way to the Moon to collect samples of its rock is that, after the fact, it became obvious that lunar rock was present here on Earth all along. It had come in the form of meteorites, blasted off the Moon by the shattering force of other, incoming meteoroids and preserved in the ice fields of Antarctica or on the hot deserts of northern Africa. The chemical compositions of those rocks, the relative abundances of the oxygen isotopes locked up in their molecules, their mineralogy, and their textures all betrayed their lunar heritage. About twenty-five separate lunar meteorite falls have been identified. Although no one knows exactly where they came from on the Moon, the lunar meteorites have provided valuable data about the composition of the lunar crust.

In 1976, after the Apollo and Luna programs had ended, attention shifted away from the Moon, and spacecraft were sent to places in the solar system where no robot had gone before. Lunar exploration remained on hold until 1990. In that year the *Galileo* spacecraft zipped past the Earth and the Moon on its way to Jupiter. Along the way, it collected lunar data. Four years later the *Clementine* spacecraft orbited the Moon, and NASA's Lunar Prospector mission followed in 1998. Those three missions carried a battery of re-





The blue planet rises over the lunar highlands, the remnants of the Moon's original crust. Anorthosite, a rock made up primarily of the mineral plagioclase feldspar, is the main constituent of the highlands. Fairly light in weight, anorthosite, precipitating from the slowly cooling ocean of magma that covered the early Moon to depths of hundreds of miles, floated to the top. The anorthosite rock then cooled to form a solid crust above the hot, liquid mantle. The crusts of the solar system's inner, rocky planets, including Earth, may have formed in a similar way. The photograph was made by the astronaut Alfred Worden during the Apollo 15 mission in the summer of 1971.



The far side of the Moon preserves largely intact a stark record of an intense bombardment of meteoroids that rained down on all the rocky planets of the inner solar system more than 3.5 billion years ago. Crater King, in the center of the photograph, is identifiable by its lobster-claw-shaped central peak, which was also a by-product of the collision that created the hole. The photograph, which shows a 200-mile-wide swath of the terrain, was made by the astronauts John W. Young and Charles M. Duke Jr. during the Apollo 16 mission in April 1972, as their lunar module returned to space from its landing site on the Moon.

mote-sensing instruments that made it possible to map the chemical composition, magnetic field, mineralogy, and topography of the Moon—in short, to portray the Moon in an entirely new and far more detailed perspective.

The first astronomer to observe the Moon through a telescope was Galileo, and it was he who divided the lunar surface into two major terrains. These are generally referred to as the terrae, or “continents,” and the maria, or “seas.” The terrae, usually called highlands, are more heavily cratered, lighter in color, and higher than the maria; the heavier cratering of the highlands also implies that they are older than the maria. Although the maria are not seas, and the terrae are not continents, as they are known on Earth, Galileo’s initial classifi-

cation served lunar scientists well for a long time. He asserted that the highlands and maria are made up of different kinds of rock, and the Apollo samples seemed to confirm that. Anorthosite, a rock made almost entirely (more than 90 percent) of one mineral, plagioclase feldspar, seemed abundant in the highlands, whereas dark, solidified flows of basalt lava were the bedrock of the “seas.”

But studies by Bradley L. Jolliff and his colleagues at Washington University in St. Louis, which integrate the latest data from orbiting sensors with the data from lunar samples, reveal a far more complicated Moon. Morphology and color do not tell the entire story of the surface composition. The concentrations of iron and thorium, for instance, have proved useful in distinguishing rock types from one another and in monitoring geochemical processes.

Those and other chemical data partition the Moon into several distinctive chemical provinces. The basalt making up the maria is rich in iron. A large swath of the near side of the Moon incorporates high concentrations of thorium. Most of the Moon’s iron-rich basalt maria occur on the near side as well, where they alternate with highlands having only moderate concentrations of iron. But a large region of rugged highlands on the far side, as well as heavily cratered patches on the near side, are poor in both iron and thorium. Those regions are battered portions of the ancient lunar crust, and they have been a key focus of the most recent efforts to understand the early history of the Moon.

One striking area is a huge impact crater on the far side, the South Pole–Aitken basin (SPA). It measures some 1,550 miles across, and its floor is eight miles lower than the surrounding highlands. SPA has a markedly different composition from the rest of the far side of the Moon. It is particularly rich in iron and thorium, which, because SPA is so deep, might reflect the composition of the Moon’s interior.

The new data from space probes and lunar meteorites have helped planetary scientists refine their understanding of the Moon’s origin and geologic history. A successful theory of lunar origin must explain two key facts. One is all the spinning of the Earth and the Moon. The Earth rotates on its axis, and the Moon traces a circular path around the Earth, rotating once with each orbit.

The second fact to explain is the puny size of

the metallic iron core of the Moon. The Earth's core takes up about an eighth of our planet's volume. In contrast, as Lon L. Hood of the University of Arizona in Tucson and his colleagues have shown with magnetic data from the Lunar Prospector mission, the core of the Moon accounts for less than 1 percent of the Moon's volume.

None of the traditional theories of how the Moon formed can explain those two observations in a straightforward way. According to the fission hypothesis, the primitive Earth was once spinning so fast (a day would have lasted just five hours) that a blob of it spun off, forming the Moon. But it takes extreme assumptions to get the Earth spinning that fast, and then to slow the Earth-Moon system down. No reasonable explanation has been forthcoming.

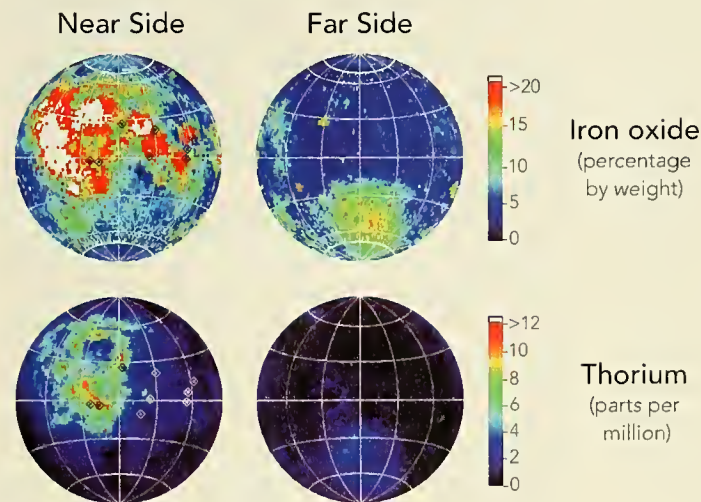
Other hypotheses are similarly flawed. According to the capture hypothesis, the Earth's gravity simply caught the Moon as it drifted too near. But planetary scientists have always viewed such a capture as implausible because it's so tricky to do dynamically. And, in any event, it does not readily explain why the captured Moon has such a small metallic core. In yet another scenario, the so-called binary planet, or co-accretion, hypothesis, the Earth and the Moon all formed at the same time by the accretion of small bodies. But that scenario, too, requires a particular and somewhat unlikely balancing of forces to make it happen, and it, too, does not explain why metallic iron is so much less abundant in the Moon than it is in the Earth.

The flaws in the traditional hypotheses led planetary scientists to seek other explanations for the Moon's origin. A new idea blossomed in 1984, at a scientific conference held in Kailua

Kona, Hawai'i. The seeds of the idea had been planted a decade earlier by William K. Hartmann and Donald R. Davis of the Planetary Science Institute in Tucson, and independently by Alastair G. W. Cameron of the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, and William Ward of the Jet Propulsion Laboratory in Pasadena, California. The bold, new idea imagines a dramatic and violent birth for the Moon during a collision between Earth and an object about the size of Mars.

That so-called giant-impact hypothesis does explain the two key observations about the Earth-Moon system. To get the right amount of angular momentum into the system you need a big, off-center whack. The giant impact could have provided that whack. The hypothesis also explains why the Moon has such a small core. Computer simulations of the giant impact, made both by Cameron and independently by H. Jay Melosh of the University of Arizona and his colleagues, show that both bodies would melt in the impact and the dense core of the impactor would fall as blobs of melt into the similarly liquefied iron core of the Earth. The ejected material—the proto-Moon—would be nearly (though not quite completely) devoid of metallic iron, and so it would form primarily out of the rocky mantle materials surrounding the cores of the impactor and the budding Earth.

The giant-impact hypothesis has become the reigning favorite among planetary scientists. Computer models by John E. Chambers, now at the NASA Ames Research Center in Moffett Field, California, suggest that the Earth formed from smaller objects in a relatively narrow, ring-shaped zone centered at the present Earth-Sun distance.



Concentrations of the elements iron (in the form of iron oxide) and thorium are useful indicators of the geochemical "provinces" of the Moon. Both elements are far more common in the maria—the lunar "seas" that represent the outflow of the magma onto the satellite's surface—than they are in the rocky, mountainous regions known as terrae. The maria are readily visible in the two false-color maps of the near side of the Moon. The maps of the far side have far less of both of those elements; the highlands there are made up chiefly of a calcium-rich feldspar. One glaring exception to that general rule appears around the south pole on the Moon's far side: the South Pole-Aitken basin. The high levels of iron and thorium there suggest to geologists that the deep interior of the Moon is rich in both elements.

The giant impactor would have formed in the same region, giving it a similar chemical composition. Any further differences between the Earth and the Moon can be accounted for by the giant impact. For example, chemical reactions would have created new lunar compounds during the event, and the hot blob of molten matter would have evaporated the Earth's most volatile elements into space.

**I**n spite of the success of the giant-impact theory and the insights it gives about what the Moon is made of, the bulk composition of the Moon remains uncertain. The thickness of the lunar crust, the composition of the lower crust, and the composition of the mantle beneath it are all blanks.

Most of the rock fragments in the first soil samples returned from the Moon by Apollo 11 in 1969 were pieces of basalt from the lava flows underlying Mare Tranquillitatis (the Sea of Tranquility). The dark soil included some small, whitish fragments of anorthosite. Studying those samples John A. Wood of the Smithsonian Astrophysical Observatory made three bold and imaginative inferences from the white bits of rock. First, he decided they had nothing to do with the underlying basalt; instead, he maintained, they came from the highlands, which, he guessed, were dominated by anorthosite's main mineral component, plagioclase feldspar. (The Apollo missions had not yet ventured to the highlands.)

Wood's second audacious—and completely unsubstantiated—claim was that all the lunar highlands were made of the rock anorthosite. How, he wondered, could that have happened? He thought about how magma slowly cools beneath the Earth's surface, about how the minerals in the magma can separate from each other according to their densities, just as oil floats on vinegar in salad dressing. That line of thinking led Wood to the third of his suggestions: that plagioclase feldspar floated to the surface of a Moon-encircling ocean of magma to form the initial rocks of the lunar crust.

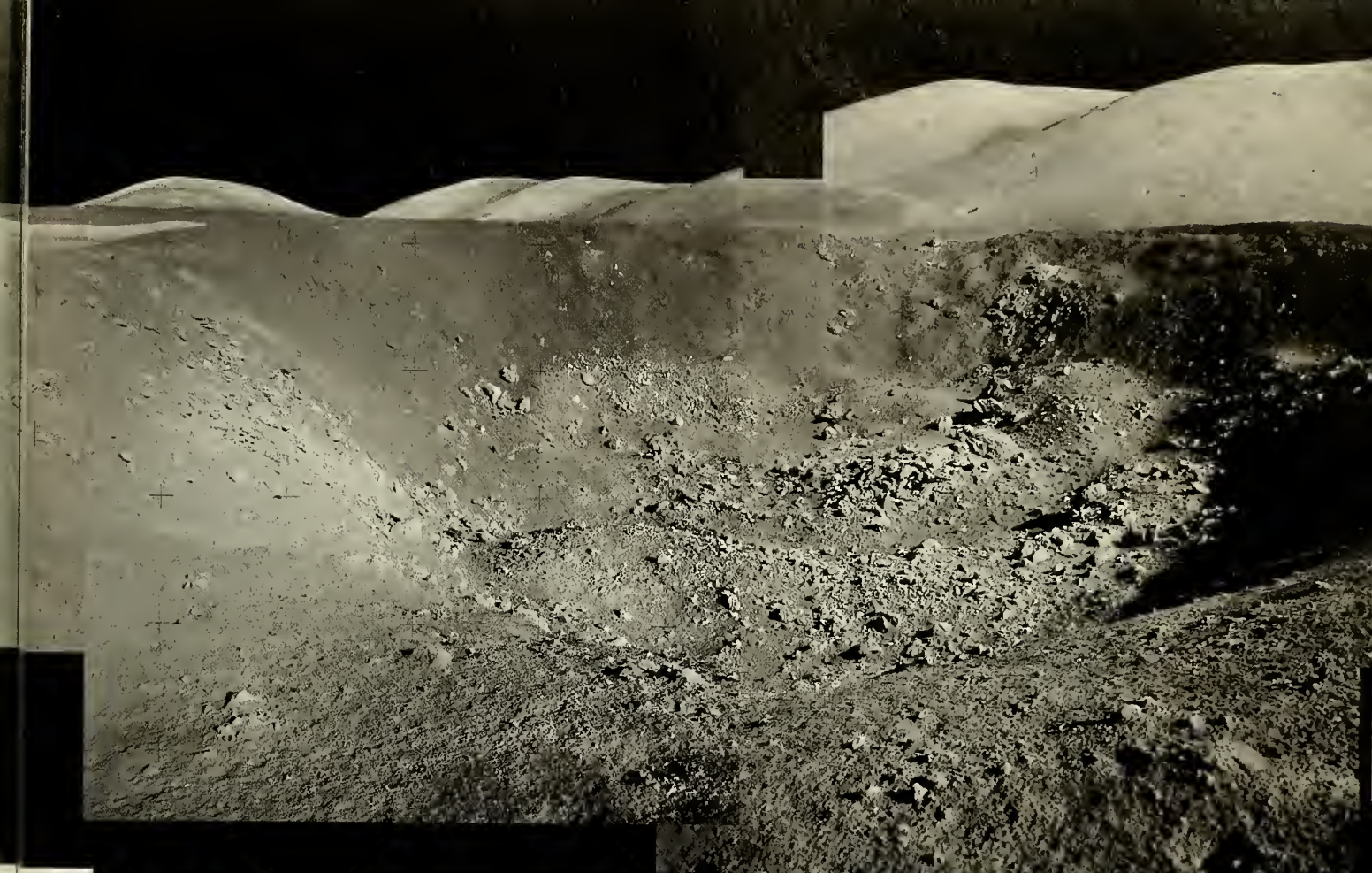
Evidence in favor of Wood's speculations soon began to accumulate. Anorthosite rocks were found in abundance in 1972 at the Apollo 16 landing site, in the lunar highlands. Geochemists noted that some chemical characteristics of mare basalt lavas were complementary to the chemistry of highland anorthosites. For example, the mare basalts were depleted in aluminum and europium, whereas the anorthosites were loaded with aluminum and enriched in europium. Those findings suggested that the magma in the deep interior regions of the Moon, where the basalt lavas formed, were part of the same magma in which plagioclase



feldspar floated to give rise to the anorthosites. The complementary chemistry then arose as the magma differentiated according to the density of its crystalline components. Taken together, this line of thinking had an astonishing implication: because the mare basalts formed at depths of hundreds of miles, the magma ocean must have been hundreds of miles deep.

The most basic piece of confirming evidence for Wood's theory, however, was still lacking: proof that the ancient highlands are made of anorthosite rock. In 1994 the Clementine mission and Paul G. Lucey, my colleague at the University of Hawai'i, solved that problem. The orbiting *Clementine* spacecraft photographed the entire lunar surface. Lucey then calibrated the photographs against the "ground truth" from the Apollo landing sites and the returned soils, and so figured out how to convert the intensity of light reflected by a particular patch of ground into a measure of the concentration of iron present there.

But what could measuring iron concentrations have to do with finding anorthosite in the lunar highlands? None of the minerals known as feldspars contain iron. But when plagioclase feldspar accumulated in the initial melt to form anorthosite rock, small concentrations of iron-bearing minerals could also be frozen into the



The astronaut and geologist Harrison Schmitt (standing next to the lunar rover at the left) photographs the 34-foot-wide Shanty Crater, as he and the crater are in turn photographed by his crewmate Eugene Cernan. The crater and the mission's landing site both lie on the eastern edge of the Sea of Serenity, which appears on the upper-right face of the Moon when seen from the northern hemisphere of Earth. At the Shanty Crater the two astronauts discovered orange soil, colored by beads of glass created during volcanic activity some 3.7 billion years ago. Cernan made the photograph during the Apollo 17 mission in December 1972, the final Apollo mission to the Moon.

rock. Hence anorthosite could contain a few percent iron by weight. The maps derived from the Clementine data show huge regions of the highlands, particularly on the far side, that are between 1 and 4 percent iron by weight, with an average of about 3 percent. The finding confirmed a central tenet of the magma-ocean hypothesis: the original crust of the Moon was anorthosite rock formed out of plagioclase feldspar floating in a dense global magma.

**T**he lunar highlands are a cratered mess; piles of rubble are heaped around thousands of craters, as wide as hundreds of miles across, that lie one right next to another in silent testimony to an ancient bombardment of the Moon. About forty-five craters are huge circular basins at least 200 miles across, the low centers surrounded by concentric mountain ranges. These mountain ranges attest to the violence of meteoroids; almost all the samples brought back from them are either greatly

deformed or are part of complex fragmental mixtures of rock called breccias.

When did that massive pummeling take place? It must have happened before the visible maria formed, because they are not covered or scoured by the materials ejected from the huge craters. Samples indicate that the oldest maria are slightly less than 3.8 billion years old, so the bombardment occurred between 4.5 billion years ago (about the age of the Earth and Moon) and 3.8 billion years ago. Before the Apollo samples became available, many planetary scientists had favored an early, intense bombardment associated with the late stages in the accretion of the planets. The bombardment would have decreased rapidly after the Moon formed, as Earth, the Moon, and the rocky planets swept up the smaller chunks of material still orbiting the Sun. By 3.9 billion years ago a relatively clement period would have prevailed.

But studies of the lunar samples pointed toward an alternative scenario, first put forward in 1975.

Fouad Tera and Gerald Wasserburg of Caltech radiometrically dated rocks from the lunar highlands. The data led them to suggest that the impact rate declined rapidly soon after the Moon formed, but then returned to spectacularly high levels around 3.9 billion years ago. Such a deluge would have affected the Moon and perhaps the rest of the solar system, or at least its inner region, between Mercury and Mars. The dramatic increase in impact rate 3.9 billion years ago became known as the cataclysm. There was a brief flurry of interest in the idea, but then it was essentially dropped until 1990, when the late Graham Ryder of the Lunar and Planetary Institute (LPI) in Houston revived it.

Impact craters or basins can be dated only by examining the materials melted during the impact. (The resulting rocks are known as impact-melt breccias, or impact melts for short.) Ryder and others identified groups of impact melts by their chemical compositions and showed that different groups had different ages. By associating specific groups of

### *A rock collected from one lunar basin could test the cataclysm hypothesis.*

impact melts with specific basins and applying the principles of stratigraphy, lunar scientists determined that several basins were formed later than 3.9 billion years ago, in the ensuing 100 million years. In short, the newly analyzed data showed that these basins could have been formed in the cataclysm.

There has been no lack of imagination in devising models that might explain the cataclysm. Perhaps a large asteroid, say the size of the asteroid Ceres, 600 miles across, was blown apart in a collision, and its fragments showered the inner solar system. Or perhaps a passing star perturbed the orbits of comets in the Oort cloud (a swarm of trillions of comets that surrounds our solar system), and several comets came crashing into the inner solar system. Or perhaps objects from the Kuiper belt were the culprits, the rocky bodies—of which Pluto is an example—that circle the sun outside the orbit of Neptune. Uranus and Neptune might have formed at about the time of the suspected cataclysm, and maybe they dragged Kuiper belt objects into collision courses with the other members of the solar system.

The cataclysm has clearly become an important concept. The rub is that not everyone agrees with the idea that several huge basins formed in one relatively narrow, 100-million-year interval. Some geochemists argue that the sites of the Apollo land-

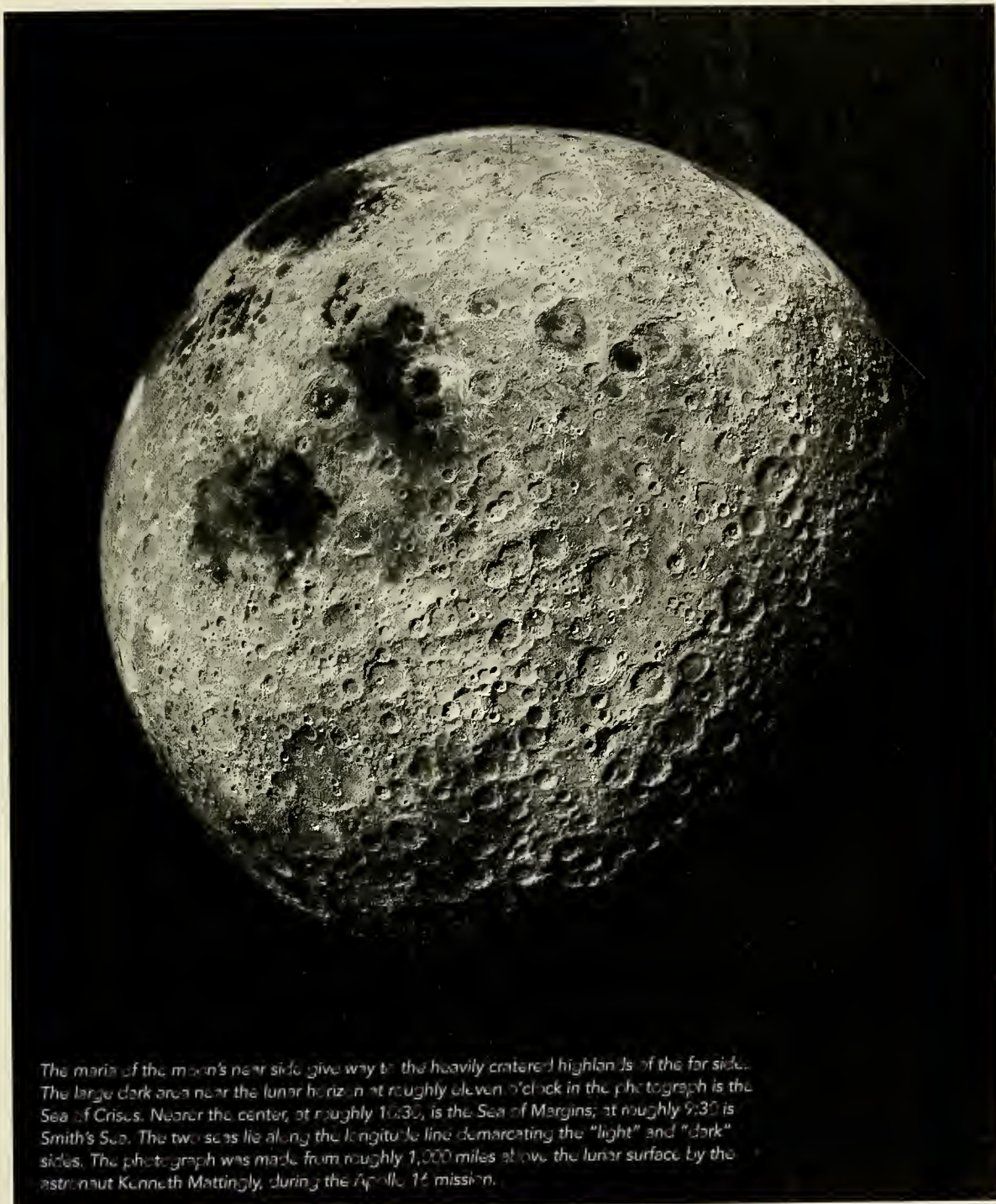
ings were all reworked by the immense impact that created the Imbrium basin. Mare Imbrium, which makes up the right eye of the man-in-the-Moon, is 725 miles across. Its formation would have drastically altered the lunar surface. Thus, people skeptical about the cataclysm argue that the age measurements of basins that cluster close to the same time period actually reflect that one event: the formation of one relatively young basin stopped and reset the geological clocks that record the ages of the other basins allegedly created in the cataclysm.

One difficulty with the skeptical argument is that there are subtle, but significant, compositional and age differences among impact melts. To be certain, geochemists need samples from basins that were clearly not affected by the Imbrium event.

One possible source of such untainted data are Earth's lunar meteorites. The ones originating in the lunar highlands could be identified by their chemical makeup. Barbara A. Cohen (now at the University of New Mexico in Albuquerque) and her colleagues at the University of Arizona extracted pieces of impact melt from several lunar meteorites and measured their ages. These meteorites most likely come from regions of the far-side highlands far from Imbrium, and so are untainted by Imbrium debris. None of the samples was older than 3.9 billion years, a result consistent with a spike in the impact rate 3.9 billion years ago.

Still, it is scientifically preferable to collect samples of the melt that formed during the creation of a specific lunar impact basin. A prime candidate for a collection site is the South Pole–Aitken basin, which lies virtually opposite Mare Imbrium—hence as far from Imbrium's contaminating influence as possible. SPA is the oldest basin on the Moon, and determining the ages of impact melts from SPA could test the cataclysm hypothesis. If SPA is much older than 3.9 billion years—say, 4.3 billion years old—the cataclysm hypothesis becomes less compelling. Basins would have formed between 4.3 billion and 3.8 billion years ago, not in the relatively short time hypothesized for the cataclysm. In contrast, if SPA is 3.9 billion or perhaps even 4 billion years old, the cataclysm hypothesis gains favor.

We time travelers have pieced together an intriguing story about the Moon, a story with great implications for our understanding of the formation and geologic histories of the rocky planets—what happened to the Moon most likely happened to all the rest. But planetary scientists also tell many variations on the story. To settle on one version, people will have to return to the Moon.



The maria of the moon's near side give way to the heavily cratered highlands of the far side. The large dark area near the lunar horizon at roughly eleven o'clock in the photograph is the Sea of Crises. Nearer the center, at roughly 10:30, is the Sea of Margins; at roughly 9:30 is Smith's Sea. The two seas lie along the longitude line demarcating the "light" and "dark" sides. The photograph was made from roughly 1,000 miles above the lunar surface by the astronaut Kenneth Mattingly, during the Apollo 16 mission.

The world's space agencies are not unaware of the opportunities: China, Europe, India, and Japan all have plans to send robotic scientific missions to the Moon. An extensive study by the U.S. National Academy of Sciences placed the highest priority on bringing samples back from the South Pole–Aitken basin. Analyses of these samples would help determine the bulk chemical composition of the Moon; test ideas for planet formation

and lunar origin; provide more details of how impacts excavate huge holes on planetary surfaces; and shed light on the bombardment history of the solar system. In short, it would help answer the question: How did the universe give rise to us? □

*The lunar photographs accompanying this article were taken during the NASA Apollo missions and were reproduced by photographer Michael Light. They are on permanent exhibit at the Rose Center of the American Museum of Natural History in New York City.*



The quipu served as a kind of database among the Incas. The knots, colors, and lengths of the cords encoded information about people, land, and crops. This quipu is from the Chancay culture, which flourished in a coastal valley of Peru from the thirteenth until the fifteenth centuries.

## The Varieties of Mathematical Experience

*Ethnomathematics is a powerful tool for understanding other cultures.*

By James V. Rauff

**T**he Incan *quipu* is an unusual object, an assemblage of slender, knotted cords tied along a thicker, main cord. The cords are dyed a variety of colors: when it's bundled up, a quipu looks like a multicolored mop; when it's spread out, it resembles a long rope necklace or a grass skirt. The quipus of the ancient Incas of Peru encoded a wide range of data about people, land, and crops for the government bureaucracy. The code was efficient and compact: the color, number, and relative spacing of

the cords, and the number and type of knots tied into each cord, all held significance. A quipu might include as many as 2,000 cords, in some fifty or sixty different colors. I won't venture to estimate the storage capacity of a quipu in bits or bytes, but the system was, in its unique way, a pre-Columbian database for the Andes—an artifact of a mathematical tradition that developed entirely outside Western models.

Marcia Ascher, emerita professor of mathematics at Ithaca College in

New York, and her husband Robert Ascher were instrumental in deciphering the code of the quipu (their book *Code of the Quipu: A Study in Media, Mathematics, and Culture* was published in 1981). Since then Marcia Ascher has focused her considerable analytic skills on a whole range of similar mathematical artifacts and concepts outside mainstream Western culture. Her latest offering, *Mathematics Elsewhere: An Exploration of Ideas across Cultures*, is a collection of essays on mathematical concepts in use by



small-scale, traditional societies: a series of reports from an explorer "in the field." Ascher both examines the nature of the mathematics put into practice by individual societies and considers how those non-Western mathematical concepts fit into and express the ethos of the cultures that gave rise to them.

Ascher's book is at once a scholarly progress report and an introduction for the curious general reader to a relatively new area of study known as ethnomathematics. The field, which has emerged in the past two decades, lies at the intersection of anthropology, education, and mathematics. For the ethnomathematician, all signs of counting, measuring, designing, patterning, modeling, sorting, or reasoning are evidence for the existence of mathematical ideas. Such ideas, whether implicit or explicit, past or present, and no matter what the cultural setting, are grist for the ethnomathematician.

Among the Iqwaye people of Papua New Guinea, for instance, fingers, toes, and the spaces between toes are tools for counting to numbers much higher than 10 or 20 or 28; instead, they form the basis of a sophisticated numbering system that can count to numbers of indefinitely large size. Among the Cayuga of New York state, the rules of a game of chance called *dish*, which were documented in the late nineteenth century, clearly demonstrate that the players understood the laws of probability. The assigned point values for each possible outcome of the game closely corresponded to their associated probabilities—at least as clearly as the rule in poker that four-of-a-kind beats a full house.

In the brief history of ethnomathematics, two international conferences on the topic have already been convened, the first in Granada, Spain, in 1998, and the second one last year, in Ouro Preto, Brazil. The International Study Group on Ethnomathematics claims membership from

around the world. The Brazilian mathematician Ubiratan D'Ambrosio, emeritus professor of mathematics at Brazil's State University of Campinas, who is generally credited with defining the field, has called it a "research program in the historical and epistemological foundations of mathematics with pedagogical implications." That entails, in part, charting the diversity among groups of people in the realm of mathematics: the ways numbers are understood and conceived, the methods of reasoning, and the systems people adopt

*Mathematics Elsewhere:  
An Exploration of Ideas  
across Cultures*  
by Marcia Ascher  
Princeton University Press, 2002;  
\$24.95

to model and find patterns in their own social and natural environments. D'Ambrosio's program aims at compiling a universal history of mathematics that includes contributions from every culture on the planet.

**M**athematics Elsewhere fits squarely into D'Ambrosio's program, and she organizes the bounty of cases she cites around the themes of divination, time, maps, relationships, and art. From Madagascar, for instance, she describes a divination practice that has endured for four centuries, in essentially the same form, among members of the island's diverse ethnic and sociopolitical groupings. Madagascans seeking advice and guidance consult an expert, known as an *ombiasy*, in a divination system called *sikidy*. The diviner grabs a fistful of the seeds from a local tree out of a bag and makes a column of four random piles. He then removes the seeds from the piles two at a time, until each pile is reduced to either one or two seeds. He then repeats the process three more times, each time placing the new column of piles to the left of the preceding column. In the end he has sixteen piles of

seeds before him, each containing either one or two seeds, arranged in four columns.

The diviner then applies a single rule to selected pairs of the sixteen piles. If both piles in a pair are the same size, he makes a new two-seed pile. If the two piles have different sizes, the diviner makes a new one-seed pile. He then applies the same rule to certain pairs among the new piles he has just created. In the end, he constructs what Ascher calls a tableau of sixteen columns, with four piles of seeds in each one. The tableau is then "read" by the diviner—"where the logical algebra leaves off and the attribution of meaning begins," as Ascher notes.

The rule for combining pairs of piles, as Ascher points out, is identical with the XOR ("exclusive or") operation familiar to computer scientists. (The name comes from the logical operation of combining two statements into one with a prescribed meaning of the word "or"; by convention, the resulting combined statement is said to be true if one and only one of the original statements is true. If both statements are true, or both are false, the combined statement is considered false.) Ascher also explains in great detail that by combining the pairs in the particular order he follows, the diviner incorporates the procedure known in Western mathematics as even-parity checking, which helps ensure that no calculating mistakes are made along the way.

Ascher's approach to the *sikidy* system is typical of many ethnomathematical studies. A particular cultural artifact is shown to have mathematical properties related to mathematical systems in the West (in this case, to some of the ideas associated with computers and cryptography). But her purpose is not to compare the diviner to a computer scientist; rather, her aim is to demonstrate that the mathematical techniques we in the West think of as modern and advanced can arise independently of Western influence, and in unexpected places. Such a demon-

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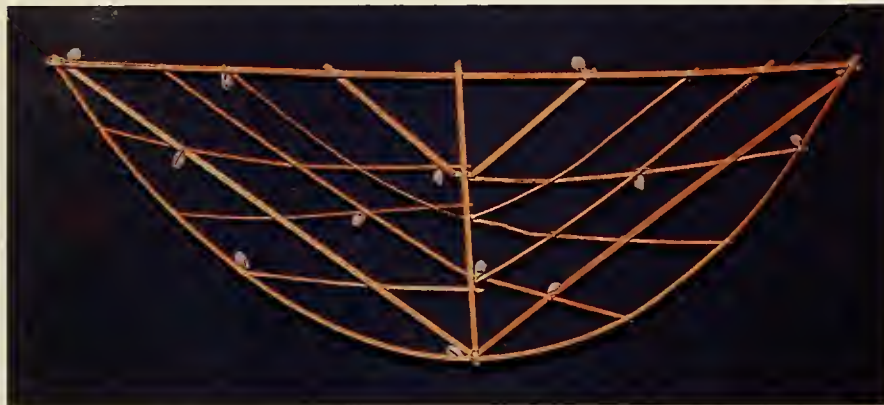
stration is of obvious interest and relevance to historians of mathematics, but its scope has a much wider appeal. Ascher offers a new way of understanding the customs and traditions of non-Western people, adding the lens of mathematics to those of literature, anthropology, and sociology. When one views cultural practices from a mathematical perspective, understanding is deepened, vague descriptions are clarified, and the sophisticated conceptual underpinnings of those practices are revealed.

ethnomathematics in their own work. One study group, for instance, which calls itself the Ciulistet, invites elders from the Yup'ik people of western Alaska to collaborate with native teachers and University of Alaska professors on, among other things, the design of educational materials for Yup'ik children. One outcome of their work has been to present counting to the children in accord with the way Yup'ik culture itself visualizes the operation. Another educational innovation spurred by ethnomathematics

her tour de force on "the logic of divination," Ascher turns her attention to some of the fascinating ways people have developed of keeping track of time. Calendars have long been a staple of ethnomathematical research, but *Mathematics Elsewhere* offers some fresh twists. Most appealing is the case of the Rato Nale ("priest of the sea worms"), the highest-ranking priest of the Kodi people, who live on the island of Sumba in Indonesia. The sea worm in question is a marine annelid (*Leodice viridis*) that spawns only once a year. The Rato Nale is charged with predicting the event, which marks the beginning of a series of local festivals whose observance must also correspond to a lunar-solar calendar. Ascher explains how the priest, who is responsible for the yearly calendar arrangements, draws both on astronomy and seasonal environmental clues to mark time in a way that is also faithful to the cycles of the Sun and the Moon. Her description provides an intriguing case study in how traditional customs select, define, and reinforce the interactions between nature, culture, and time.

On the Indonesian island of Bali, Ascher focuses on the so-called Javanese-Balinese ritual calendar (also known as the Pakuwon) and its magical and dizzying sequences. Numerous cultures use calendars that mark off multiple cycles, she notes, but the Pakuwon calendar, with its ten concurrent cycles, is uniquely intricate. Somewhat confusingly (to Western ears) the cycles are known as "weeks." The Pakuwon calendar assigns each day of the year to "weeks" made up of ten days, nine days, eight days, and so on, all the way down to a one-day "week." In other words, every day has ten names in the Pakuwon calendar, one for its position in each of the ten "weeks."

One reason for all this cycling is that many important Balinese events fall on particular days of certain kinds of "weeks": for example, the three-day week determines the market schedule. Spiritual matters are also re-



Latticework "stick charts," such as the one pictured above, represented ocean movements and, sometimes, the position of islands. They were used as navigational aids by Marshall Islanders and others throughout Micronesia.

It is worth emphasizing that in traditional systems such as the ones Ascher describes, there is no distinction between pure and applied mathematics. Ethnomathematicians therefore find it useful to contrast "global," or Western, mathematics with the "local" mathematical knowledge of individual cultures. Local mathematics can be detected, for instance, in the work of artisans and craftsmen, as well as in the lives of farmers, fishermen, healers, storytellers, and street merchants. It manifests itself in beadwork, games, hairstyles, maps, painted designs, songs, and woven goods. Local mathematics cannot be separated from its social setting; it functions as a part of the total cultural picture.

That emphasis on the total cultural perspective has led mathematics educators working in non-Western settings to recognize the importance of

is the "dancing numbers" project, led by James Barta, an associate professor of early childhood education at Utah State University in Logan, Utah. Among other projects, Barta is working with elders of the Ute people in Colorado and Utah on methods of teaching symmetry and basic arithmetic through beadwork patterns.

Numerous similar projects for teaching Western mathematics in traditional settings are under way from Papua New Guinea to the inner cities of the United States. All recognize that an understanding of local mathematical knowledge can both validate a child's native culture and provide a bridge to modern Western mathematics.

Ascher proves adept at illuminating the connections between local and global mathematics. After

flected in the calendar; a son or daughter's date of birth within the eight-day week, for instance, suggests the child's identity in a previous incarnation. A year in this calendar—a "full supercycle" of all the weeks, as Ascher explains—is 210 days long. The period is a kind of mathematical compromise: it is the shortest period that includes an integral, or whole, number of weeks of one, two, three, five, six, seven, and ten days. (In terms familiar to Western high school students, the least common multiple of 1, 2, 3, 5, 7, and 10 is 210.)

But of course "weeks" of four, eight, or nine days do not fit evenly into such a "full supercycle"; that would require a supercycle twelve times as long as 210 days, or nearly seven "solar" years—an unwieldy length of time for a calendar. Instead, to ensure that even the weeks of four, eight, and nine days are all complete cycles, special adjustments are made. For example, two additional "seventh" days are added to the twenty-six complete eight-day cycles to enable them to fit evenly into the year.

This wonderfully complex calendar can be pictorially represented on a seven-row, thirty-column *tika*, a colorful calendric object that can be either painted or carved on wood or printed on paper. Ascher explains how visualizing their calendar as a *tika* enables the Balinese to solve, in their heads, complicated questions about the occurrence of specific calendar days. One point she emphasizes is particularly useful: the Pakuwon's cycles of weeks neither measure elapsed time nor coordinate with solar or lunar cycles. Rather, they represent the myriad cyclic forces in Balinese cosmology, since each calendar day is literally marked by a multiplicity of intersections among concurrent cycles. Divorced from physical cycles, Ascher notes, the calendar "becomes a creative expression of abstract mathematical ideas," yet it also functions as an expression of the "logic of interlinked cycles" pervasive in the Balinese culture.

Ascher's next stop is the Marshall Islands, in the western Pacific Ocean, where she explores the map-making genius of its seafaring people. Western navigators are accustomed to finding landmasses by their shapes and positions on maps overlaid with a grid system: latitude and longitude. We read maps of the sea that incorporate symbols for prevailing winds, currents, and depths—characteristics we regard as essential to navigation. But the Marshall islanders take little interest in those factors—what count instead are the shapes and orientations of the ocean swells that break around islands.

Ascher begins her account of Marshallese "wave piloting" by describing the use of the *mattang*, a stick-chart training device for prospective navigators that represents the general pattern of how ocean swells break around an atoll. She then explains the kinds of stick-chart maps that show real ocean-swell patterns: *rebbeliths*, which chart either the entire archi-

pelago or particular atolls within it; and *meddos*, which are maps of smaller regions. Both kinds of maps highlight the culturally salient features of the Marshallese seascape—which, from a Western perspective, represent a truly unique way of modeling the world.

Another example of an unusual way of modeling the world—in this case, the interactions within a community—emerges among Basque villagers of the Sainte-Engrâce region, in the French Pyrenees. Here, on Ascher's account, social relations are conceptualized according to a circular model known as *bardin-bardina*, or "equal-equal." One might think the concept of equality, one of the most basic of mathematical relations, would be impervious to cultural variation, but Ascher soon puts that notion to rest.

Among the villagers, a community is understood as, literally, a circle of households. From the center of that conceptual circle, each household has a "left" neighbor and a "right" neigh-



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bor. The concept of equality is realized concretely, in a system of tasks that rotate among the households, and accomplish the community's sheep-herding and cheese-making work. The sheep-herding tasks, for instance, are explicitly ranked according to their prestige and authority. The rotation then ensures that no status hierarchy is permanent, and that every household undertakes every task, from highest to lowest in status, at some point in the process. Equality in this system, Asher argues, is "a dynamic process of interaction involving rotation, serial replacement, and alternation."

**M**athematics Elsewhere is a challenging book for nonspecialists, with a high proportion of its content devoted to traditional mathematics. Part of what makes the volume accessible to the general reader, though, is Ascher's evident love for her subject. The mathematics she includes clearly serves a larger purpose: to enhance and illuminate the anecdotes that are the foundation of genuine cultural understanding. Ascher never loses sight of the people who have created the artifacts and ideas she explores. And, as she frequently reminds the reader, she is bound by her own culture and her own audience to use Western mathematical terminology to describe the mathematics of others. She is at pains to remain as true as possible both to the mathematics and to the anthropology.

The great value and contribution of ethnomathematics is that it shows mathematics as a human endeavor, arising from peoples' needs and desires to understand and find patterns in their physical, social, and spiritual worlds. Ethnomathematics asks all of us to recognize the diversity in those patterns, and in the ways people understand their world. In short, ethnomathematics asks us to see the mathematics elsewhere.

*James V. Raiff is a professor of mathematics at Millikin University in Decatur, Illinois.*

*Monster of God:  
The Man-Eating Predator in  
the Jungles of History and the Mind*  
by David Quammen  
W.W. Norton & Company, 2003;  
\$25.95

**D**avid Quammen likes to visit places on the wave crests of ecological change. One of his previous books on natural history, *The Song of the Dodo*, dealt with island biogeography and endangered species. *Monster of God*, his latest environmental travelogue, is filled with place names that few readers will recognize: Garrangali, a swampy expanse in Arnhem Land, on the remote northern coast of Australia, where a complex network of channels and underground tunnels provides a unique breeding ground for



Tiger mauling a British officer; wooden sculpture, India, c. 1790

saltwater crocodiles; the Gir forest in India's Gujarat state, northwest of Bombay, whose cattle-herding inhabitants, the Maldharis, maintain an uneasy truce with the last remaining lions on the Indian subcontinent; Braşov, in the rugged Carpathian Mountains of southeastern Romania, where *Ursos arctos*, the European equivalent of a grizzly, is one of two major predators (the other is the human sports hunter); and the Bikin Valley, in the foothills of the snowy Sikhote-Alin Mountains of far eastern Russia, where the Amur tiger considers trappers' dogs a sublime delicacy.

Quammen's stated purpose is to

By Laurence A. Marschall

give his readers some feeling for what it means to be part of the food chain, an "awareness of being meat." Most people nowadays are city dwellers, to whom meat is a substance between two halves of a sesame-seed bun, and for whom predatory animals are just curiosities to be exhibited or pests to be exterminated. But to the residents of Arnhem Land, Gir, Braşov, and Bikin, predators are animals that hunt people—and sometimes eat them. Life for such folks, one imagines, is not the predictable routine of a nine-to-five commuter, but rather a regimen of vigilance punctuated with moments of sheer terror, like a continuous rerun of *Jaws* with real blood and no popcorn.

Needless to say, Quammen has dug up some teeth-clenching stories and met some memorable characters. A few, such as Val Plumwood, an Australian philosophy professor, know firsthand what it's like to be prey. In 1985 a crocodile "somewhere between eight and twelve feet" snatched her from her canoe and flung her about in a series of the frenzied "death rolls" with which crocs try to drown and dismember their prey before swallowing the

pieces. Plumwood managed to disengage from the jaws of the croc, drag herself to shore, hike several hours to reach civilization and rescue, and eventually convey her experience in several academic articles, in one of which she relates the "total terror, total helplessness, total certainty, experienced with undivided mind and body, of a terrible death," which many less fortunate victims must have faced.

Most of Quammen's informants, however, are naturalists, hunters, farmers, and herders, who can offer more evenhanded opinions on predators and their possible peaceful co-existence with humankind.

Both the bear and the crocodile populations seem to be hanging on for now, in part, ironically, because some balance has been reached between protecting them and cultivating them for sport, meat, and leather. Romania's one-time dictator, Nicolae Ceaușescu, for instance, ordered bears to be protected so that he could shoot them himself, which he did by the dozen. There's some evidence, Quammen notes, that predators thrive under despotic social regimes, though not because tyrants are environmentally aware.

The most endangered predators Quammen meets are Indian lions, which were once protected by Indian nabobs but now threaten local livestock and compete with the populace for scarce resources. Yet residents of the Gir forest respect the creatures that endanger but also enrich their lives: "I've spent so many hours of my life thinking about lions," Quammen describes one villager telling him. "Slowly I came to realize . . . that this landscape belongs to the lions if it belongs to anyone. 'And if they can't stay here, where will they go?'" One hopes—for all these lions, tigers, bears, and crocs—not the way of the dodo.

**Meteorites, Ice, and Antarctica:**

**A Personal Account**

by William A. Cassidy


Cambridge University Press, 2003;  
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roids that collide daily with the Earth, only a minuscule fraction are large enough to make it to the ground before they burn up entirely. And of those, most fall unseen into the oceans or bury themselves in the ground, where they rapidly weather and become indistinguishable from terrestrial rocks.

Meteorites that happen to fall on the Antarctic ice sheet, however, meet a different fate. Buried by annual snowfalls after impact, they eventually become embedded in the two-mile-thick frozen mantle that overlies the continent. The ice both protects them from weathering and concentrates them in certain areas. As the ice flows at, let's say, glacial speeds downhill to the sea, meteorites are carried along with the flow. When the ice meets barriers such as mountain ranges along the way, the meteorite flotsam it carries is cast on the foothills like so many piles of driftwood on a beach, readily distinguished against the background of windswept snow. In such places, geologists have discovered, you can stretch out your hand in almost any direction and pick up a rock from another world.

William Cassidy, emeritus professor of geology and planetary science at the University of Pittsburgh, was the founder, in 1976, of the U.S. Antarctic Search for Meteorites (ANSMET), a pioneering effort to mine Antarctica's extraterrestrial bonanza. In nearly three decades of bone-chilling expeditions, Cassidy's team, along with similar groups from Japan and Europe, have collected more than 30,000 meteorites from the ice fields of Antarctica, more than fifteen times the number that had turned up elsewhere in the preceding two centuries.

For the casual reader, Cassidy provides an exciting picture of what it's like to be a meteorite hunter on the world's cruelest continent—from tales about surviving in hurricane-force winds that tear tents to shreds, to wry ruminations about answering the call of nature when the outside tempera-

tures are cold enough to freeze your spit before it hits the ground.

But Cassidy's book is also full of authoritative science. Nearly all Antarctic meteorites, he notes, are splinters ejected from collisions between asteroids—those miniature worlds that have accumulated mostly between the orbits of Mars and Jupiter. Because asteroids are thought to be remnants of the material that formed the planets some 4.6 billion years ago, Antarctic specimens may carry important clues about how the solar system formed. The new wealth of data, however, has raised as many questions as it answers: the great variety of rock types among meteorites, for instance, indicates that the early solar system was not as uniform as astronomers once thought, ei-



Piece of the ALH 84001 meteorite from Mars, discovered in Antarctica.

ther in temperature or in chemical composition.

The most remarkable finds on the ice sheet are a handful of meteorites that appear to be chunks from other large bodies in the solar system. In most cases they are rocks chipped off the Moon. Amazingly, though, some of them come from Mars [see "Bolts from Beyond," by Donald Goldsmith, page 28]. Cassidy describes in convincing detail how geologists can infer the planetary origins of such specimens (and, in some cases, even the lunar or Martian crater from which they were once ejected). And he gives a brief account of the most famous, and most controversial, meteorite of all, ALH 84001. According to some geologists, ALH 84001 con-



tains evidence of fossil life on Mars.

The controversy comes as no surprise: the study of meteorites preserved in ice fields is still a young science. So many specimens have accumulated so rapidly that analysis has yet to catch up with the available evidence. Yet Cassidy makes an excellent case for continuing the hunt for evidence. If a research enterprise can be measured by the excitement and beauty of its fieldwork, by the unique value of its data, and by the insights it yields into “big questions”—What are we made of? Where did we come from?—the study of Antarctic meteorites will remain a hot topic for many decades to come.

***The Land of Naked People:  
Encounters with Stone Age  
Islanders***

*by Madhusree Mukerjee*  
Houghton Mifflin Company, 2003;  
\$24.00

Global technology, for better or for worse, has made it possible for Lapland caribou herders and Amazon hunter-gatherers to watch reruns of *The Simpsons* with the cultural savoir faire of Los Angeles suburbanites. So it comes as a bit of a shock to read about the near-total isolation of the inhabitants of North Sentinel Island, a smallish member of the Andaman Islands chain, which lies some 750 miles south of Calcutta in the Bay of Bengal. The island's hundred or so inhabitants—the only remaining group of Andamanese still untouched by modern civilization—may still, like their fellow islanders a century ago, live as hunter-gatherers who wear no clothes, do not plant crops, and have only minimal use of fire (they cannot make it, but preserve hot embers to transport from place to place). They may even still be oblivious to the connection between intercourse and conception—just as they were in the nineteenth century, when travelers found that the Andamanese

*(Continued on page 66)*

**nature.net**

## Hit Parade

By Robert Anderson

Meteorites are no longer the rare objects I once imagined them to be. The realization came to me soon after I began searching the Internet for information about them, and found Bill Arnett's “The Nine Planets” ([www.nineplanets.org](http://www.nineplanets.org)). Under the heading “Small Bodies,” click on “Meteors, Meteorites and Impacts” for a quick run-down on the subject and a great list of links. At the link [www.solarviews.com/eng/edu/micromet.htm](http://www.solarviews.com/eng/edu/micromet.htm), I was surprised to learn how easy it is to collect these extraterrestrial visitors by the hundreds.

I immediately went outside my home with a ladder and scooped up some of the fine silt that accumulates in my roof's rain gutters. My son helped me extract the iron bits from the dirt with a magnet, and voilà! We soon had a tiny pile of metallic particles to examine under a microscope lens. We discovered a number of good candidates for micrometeorites—primordial space dust that literally rains down on our roof. Another site, “Micrometeorite Webquest” ([staff.harrisonburg.k12.va.us/~gorder/mm\\_main.html](http://staff.harrisonburg.k12.va.us/~gorder/mm_main.html)), explains how to collect the celestial specimens directly from rainwater. Click on the hypertext “images” to get some idea of the size and shape of the objects my son and I were looking for.

Not surprisingly, meteoroids that create fireballs as they plunge through the atmosphere are more exciting to most people. Scroll all the way down the meteor page at “The Nine Planets,” cited above, and under the heading “Impacts,” click on “The Peekskill Fireball” ([starchild.gsfc.nasa.gov/docs/StarChild/](http://starchild.gsfc.nasa.gov/docs/StarChild/)

[shadow/solar\\_system\\_level2/peekskill.html](http://shadow/solar_system_level2/peekskill.html)) to see a movie of one of the more spectacular events of its kind. Recorded in 1992, the fireball first appeared over West Virginia and broke up as it traveled. A sizable chunk of it crashed into a parked red Chevrolet Malibu coupe in the town of Peekskill, New York. You can see a piece of the famous specimen at “The R.A. Langheinrich Museum of Meteorites” ([nyrockman.com/museum.htm](http://nyrockman.com/museum.htm)). A link there will even take you to several photographs of the impacted Malibu.

You'll find an impressive list of links to sites that highlight comets and the asteroid belt—the source of most of the meteoroids that enter Earth's atmosphere—at NASA's “National Space Science Data Center” (go to [nssdc.gsfc.nasa.gov/planetary/planets/](http://nssdc.gsfc.nasa.gov/planetary/planets/) and click on “Asteroids and Comets”). Such giant asteroids as Vesta—the only asteroid from which terrestrial meteorites have been identified to date—are featured there.

In spite of Hollywood's disaster-movie infatuation five years ago with colossal comet and asteroid impacts, public interest in the theme has waned. Unfortunately, the danger hasn't. But at another NASA Web site (go to [impact.arc.nasa.gov/](http://impact.arc.nasa.gov/) and click on “OECD Report on NEO Hazard”), you'll find a report noting that an impact might be averted, given early enough warning. A complete guide for close-encounter paranoids can be found at NASA's “Near-Earth Object Program” ([neo.jpl.nasa.gov](http://neo.jpl.nasa.gov/)), an excellent fount of NEO information of all kinds. Click on “Close Approaches” in the list on the left to see exactly how near the Earth some NEOs will approach in the future, and how close some have come in the recent past—a sobering experience.

*Robert Anderson is a freelance science writer living in Los Angeles.*

# The Quest for the Golden Lens

*A perfect alignment of massive objects would offer clues to the rate of cosmic expansion.*

By Charles Liu



Pol Bury, *Fountain*, 1985

Long ago, Greek bards sang of Jason, a prince denied his throne unless he could provide his usurper with the Golden Fleece. Accompanied by a crew of young heroes, Jason set off on the great ship *Argo* to find this mysterious treasure, known to be in the land of Colchis, at the far eastern end of the Black Sea. The ancient Greeks immortalized their heroes in the stars, and many of the names that still designate stars and constellations today bring to mind Jason's mythical voyage: Carina, Puppis, and Vela represent the keel, stern, and sail of the *Argo*; Castor and Pollux, who accompanied Jason, became Gemini; and Hercules was one of Jason's mates.

Few, if any, modern astronomers lead the adventurous lives of Jason and his Argonauts, yet many of us are on a

quest for something golden. The object we seek, of course, is no fanciful animal skin, but the rarest of cosmic coincidences: a "golden lens." Such a lens, created by the interaction of a quasar and a galaxy perfectly aligned with Earth, would enable astronomers to deduce one of the holy grails of astronomy: the Hubble constant, or the expansion rate of the universe.

Among the cosmic mariners seeking that prize is Somak Raychaudhuri, an astronomer at the University of Birmingham in England. Observing in the X-ray part of the spectrum, he and his collaborators have been studying one promising celestial candidate, known as B1422+231. Despite its unglamorous name, the object would surely be elevated to the stuff of legend if, indeed, its lens were golden.

Einstein's general theory of relativity—the unification of space, time, and gravity—predicts the existence of gravitational lenses, including golden ones. Massive objects bend space-time around them, creating a dimple in space-time akin to the depression made by a bowling ball on a trampoline. Any light passing through such a dimple follows a curved path.

Now imagine a massive object that lies between a shining beacon and an observer. The massive object bends the light streaming at it from the beacon; if the alignment is right, the bent light can focus or magnify the original image of the beacon for the observer, perhaps to many times its original brightness. Hence the intervening object acts as a lens—not because it's made of glass or plastic, but because its gravity bends light.

Astronomers love gravitational lenses. They are sheer cosmic serendipity, but they provide us, free of charge, with a powerful telescope. Of course, you get what you pay for. First, they're quite rare; the Earth, the lens, and the light source have to line up just about exactly to give rise to a measurable lensing effect. If they deviate from a straight line by less than a thousandth of a degree of arc—about the width of a penny 3,000 feet away—the lens splits the magnified image into two or more irregularly spaced patches of differing brightness.

A second, and worse, problem with gravitational lenses is their blotchiness—they aren't created by smooth, regular massive objects, but rather by

complex, asymmetric ones such as galaxies and clusters, with scattered dense and sparse spots. Such a lens distorts as well as magnifies the light that comes through, sometimes creating multiple, twisted images of the objects behind it. It's more like looking through the thick glass bottom of a bottle of lemon soda than through a good magnifying lens.

From such lemon bottles, though, astronomers have mixed excellent lemonade. The distortions themselves carry information about the universe. Imagine what happens if the light source changes its appearance—if, say, a quasar suddenly brightens with a new burst of energy. Each distorted multiple image of the quasar represents a different path taken by light through the dimpled space-time surrounding the lens, and some of those paths are longer than others. So first one image brightens—the one with the shortest path—then the one with the next-shortest path, and so on. The time between brightenings, it turns out, depends on two factors: the structure of the lens and the expansion rate of the universe—the Hubble constant. So all we need for a solid measurement of the Hubble constant, independent of the usual redshift of receding galaxies, is to identify a gravitationally lensed image of a flickering source with a near-perfect alignment, a readily measurable time delay, and a smooth, uncomplicated intervening mass. That's what gilds a gravitational lens.

With such stringent requirements, it's little wonder that Raychaudhury and his colleagues could have embarked on a quest that others had envisioned many years before their time but left still unfulfilled. Within a few years of looking, though, they thought they'd found a good candidate golden lens. The light from quasar B1422+231, which lies some 11 billion light-years from Earth, passes through a lens created by an intervening mass about three billion light-years from Earth. The lens gives rise to four detectable images of the

quasar [see photograph on next page]. Furthermore, other astronomers had recently reported measuring a time delay in the brightening of two of those images.

With the orbiting Chandra X-ray Observatory, Raychaudhury and his colleagues found that the lensing ob-

ject wasn't a single galaxy, but rather an entire group of galaxies, whose distribution of mass was relatively smooth and uncomplicated—one key requirement for a golden lens. Raychaudhury created 300 possible models of the shape of the lens, and simulated the lensing properties of each model.

## THE SKY IN SEPTEMBER

By Joe Rao



Often elusive, fleet Mercury appears low in the eastern sky at dawn beginning around September 20. Rising about ninety minutes

before sunup, it reaches its greatest elongation, or angular separation from the Sun (18 degrees west of our star), on the morning of the 27th. By early October the innermost planet returns to the obscurity of the Sun's glow. On the morning of the 24th, look low toward the east for a broad triangle outlined by Mercury, Jupiter, and the Moon; Mercury is below and to the right of the Moon.

By month's end Venus graces the evening, appearing just above the western horizon. Use binoculars to look for it between fifteen and twenty minutes after sunset.

Mars, just past its opposition of August 28, dominates the night sky. The orange-tinged planet is departing Earth's vicinity as rapidly as it arrived last month. As the distance between our home and Mars increases from 35 to 42 million miles this month, the planet fades from magnitude  $-2.9$  to  $-2.1$ . Yet at the same time, viewing Mars becomes more convenient. The planet culminates at 12:55 A.M. local daylight time on the 1st, and at around 10:30 P.M. on the 30th. At those times the planet is about 33 degrees above the horizon

(as seen from midnorthern latitudes), where its apparition is sharpest. Mars seems to follow the nearly full Moon across the sky during the night of September 8–9.

Jupiter emerges from the Sun's glare during the second week of September. At magnitude  $-1.7$ , the planet shines low in the east about an hour before sunup at midmonth. By the end of the month it's already up by 4:30 A.M. local daylight time. On the morning of the 24th, Jupiter rises above and to the right of a slender crescent Moon, and about 7.5 degrees above Mercury.

Saturn rises progressively earlier this month, appearing after 1:30 A.M. local daylight time on the 1st and coming up before midnight by the 27th. It shines in the constellation Gemini. The rings of the yellowish zero-magnitude planet tip about 25 degrees toward Earth.

The Moon waxes to first quarter on September 3 at 8:34 A.M. and to full on the 10th at 12:36 P.M. Because this full moon is the one nearest to the autumnal equinox, it is designated the harvest moon. The Moon wanes to last quarter on September 18 at 3:03 P.M., and it becomes new on the 25th at 11:09 P.M.

The autumnal equinox occurs at 6:47 A.M. on September 23.

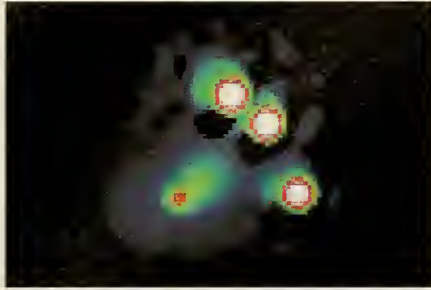
*Unless otherwise noted all times are given in Eastern Daylight Time.*

## BOOKSHELF

(Continued from page 63)

From the simulations he calculated the time delays that would result.

Unfortunately, the simulations showed that only two of the four images would yield measurable time delays. Moreover, one of those two im-



False-color image of the gravitational lens system B1422+231. Each of the four brightest points of light represents a single quasar some 11 billion light-years from Earth; the multiple images are caused by the bending of the quasar's light as it passes near an intervening system of galaxies some 3 billion light-years from Earth.

ages is too faint for its brightening to be feasibly measured with current technology. The conclusion: B1422+231 is indeed a fascinating gravitational lens system, but it's not quite golden.

As with most quests, Jason's journey was much more interesting than the reward at its end. "What became of the fleece afterwards," wrote the nineteenth-century American writer Thomas Bulfinch, in his classic *Mythology*, "we do not know, but perhaps it was found after all, like many other golden prizes, not worth the trouble it had cost to procure it."

Rest assured, though, that if a golden lens is found, it will retain its value. We astronomers will monitor its flickering year after year until it yields a firm, independent measurement of the Hubble constant. And we won't stop at one such lens; we'll study every golden lens we can find, to cross-check our results. The Argonauts' odyssey ended long ago, but this cosmological golden quest has only just begun.

Charles Liu is an astrophysicist at the Hayden Planetarium and a research scientist at Barnard College in New York City.

all believed that women get pregnant through certain spirit-laden foods.

Geopolitically, the Andamans seem an unlikely place for such an aboriginal stronghold. They lie smack in the middle of major trade routes that connect India, Singapore, and the Far East; native islanders must have long been accustomed to seeing sailing ships from the great mercantile empires pass within hailing distance.

Yet for centuries hailing was about all that happened—the islanders had a reputation for being fiercely hostile people who resembled African pygmies. Indeed, for two centuries the natives (the name "Andaman" has been linked with a Sanskrit word for "naked man") met most approaches by foreigners with arrows and stones. (That attitude was perhaps warranted by the fact that when ships did enter the island's precincts, they had a habit of abducting stray natives and selling them as slaves or curiosities.) With their dense jungles and fearsome population, the islands held little attraction for permanent settlements until 1858, when British colonists from India established a penal colony at a harbor on South Andaman, calling it Port Blair.

The arrival of Westerners led to the dissolution and demoralization that has befallen so many other groups of indigenous peoples: a once impenetrable society began to slowly come apart. The British brought unfamiliar diseases that drove one native tribe of Andamanese nearly to extinction by the end of the nineteenth century. Japanese invaders in the 1940s cleared swaths of island land for airstrips and military installations. An Indian government replaced the British after the war, and the islands became a prime target for development to accommodate the subcontinent's refugee population. By the 1970s the remaining members of the Onge tribespeople, living on the southernmost island, Little Andaman, had been forced into settlements after seeing their forests bulldozed so that authorities could

resettle a flood of refugees from Bangladesh.

Madhusree Mukerjee, a former editor at *Scientific American*, has been coming to the islands since the mid-1990s to document the condition of the native population that remains: about 500 individuals of various tribes and dispositions. Many of them occupy a strange limbo between traditional and modern, living part-time in government housing but carrying on old ways whenever they can. Most Jarawa tribespeople still dwell in forested areas of the largest island, where they are openly hostile to settlement and to settlers. And then there are the Sentinelese, protected from any contact with the outside by government edict and by their isolated location, to the west of the island chain.

The story is a distressing one, and ironic in that the Indians, once British subjects, are now colonizers themselves. "We have to teach them some morals," the local secretary of tribal welfare tells Mukerjee, in a voice that echoes Queen Victoria's provincial governors. But the forces at work here are too impersonal and too relentless for either blame or hope. To be sure, the North Sentinelese are still more or less untouched, but one senses that they, too, will not remain that way for long. At the end of her tale, Mukerjee comes close enough to their island to see them, then retreats at the last minute as if she were carrying a contagion—as, in a way, she is. There's little she can do for the Andamanese, other than give us a glimpse of indigenous people still reeling from their first encounters with global civilization, seen through the eyes of one who wonders what it all means, both for them and for us.

Laurence A. Marschall, author of *The Supernova Story*, is the W.K.T. Sahn professor of physics at Gettysburg College in Pennsylvania, and director of Project CLEA, which produces widely used simulation software for education in astronomy.

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# AT THE MUSEUM

AMERICAN MUSEUM OF NATURAL HISTORY 

## Arthur Ross Hall of Meteorites Reopens September 20

### Interview with Curator Denton Ebel

*Denton Ebel is curator of meteorites in the Museum's Division of Physical Sciences and curator of the reconceptualization and rebuilding of the Arthur Ross Hall of Meteorites, which reopens September 20, 2003. He spoke with us about meteorites, the new hall, and the likelihood of a meteorite falling near you.*



R. MICKENS/AMNH

Denton Ebel holds the Johnstown meteorite which fell in Colorado in 1924. It is thought to be a piece of Vesta, one of the largest of the asteroids which orbit the Sun beyond Mars.

**Q: What is a meteorite?**

It's a rock from space. It's a piece of a shooting star that falls to Earth. It's a meteor when it's in the sky; when it hits the Earth it's a meteorite. Most meteorites are pieces of asteroids. A very few are comets.

**Q: What do meteorites tell us?**

Meteorites record the history of our solar system. When we look at disks where young stars are being formed today, the same processes are taking place that we think occurred when our Sun was born, 4½ billion years ago. But here we have the actual leftovers of that process so we can deduce how our solar system originated. If you could cool the Sun into a rock you could hold it in your hand, it would have the same chemical composition as some meteorites. Because it's a universal process, we are by extension learning about all the other solar systems out there and how they might

form and, in particular, why is the Earth here, how do the elements necessary for life get distributed in a solar system among the planets, and then, of course, what makes some zones of the solar system habitable. Where might there be life? This is something that humans are interested in.

**Q: What will be new in the Ross Hall of Meteorites?**

Well, the architecture, for one thing, will be new. The ceiling will be raised to its full height, which

gives you a sense of space since these are rocks from space. When you go into the halls of Gems and Minerals next door, you enter a cave-like kind of room, which is reminiscent of where those rocks come from.

When you enter the hall, you will be invited to ascend a 16-inch platform, which will exhibit the basic concepts. This is the introductory section. The raised platform will surround the central object, which is Ahnighito, the largest meteorite "in captivity," part of the Cape York meteorite. There is only one larger meteorite—in Africa, which is where it fell in Namibia—the Hoba meteorite. Two other pieces of the Cape York meteorite are also displayed in our new hall.

The hall surrounding Ahnighito has three sections addressing what me-

eteorites tell us about the origins of our solar system, about the formation of the planets and planetary processes, and finally about how meteorites and the dynamic solar system interact with planets, particularly through impacts.

The Meteor Crater of Arizona will be highly featured in the hall with a scale model in a diorama. This is the best-preserved meteorite impact crater on the surface of the Earth, and it's 50,000 years old. It's in the Arizona desert so it's really very accessible, and we're collaborating with the people at the Meteor Crater Visitor's Center to create a really first-class model of it. It will have a cutaway section so you can see how the crater was originally shaped because it's got a lot of silt and infill in it—50,000 years is a long time.

**Q: Can you describe how the hall will tie to some of the other Museum halls?**

In the Museum there are several halls that deal with the physical sciences: the Cullman Hall of the Universe and the Gottesman Hall of Planet Earth in the Rose Center and the Morgan Memorial Hall of Gems and the Guggenheim Hall of Minerals. And the Ross Hall of Meteorites really fits between the Hall of the Universe and the Hall of Planet Earth. The universe is the setting in which our solar system formed. In the Hall of Meteorites, we focus on the origin of our solar system, the formation of planets, and the chemistry that underlies all of this, all through the meteorite specimens. This, in turn, provides the setting to explore the mysteries of planet Earth.



DAVID J. HODDY AND J.D. ZELLENUS

Meteor Crater, Arizona

Our hall is very different from an older school of meteorites display, which would look at meteorites with a classification or nomenclature kind of approach as simply rocks that have different properties. The new hall will be much more focused on the processes and what they tell us about the larger scenario. So it's more like a hall of meteorites and planetary origins, much in the same way that a hall of vertebrate evolution differs from a hall of fossils.

**Q: Can you say a little about your own research?**

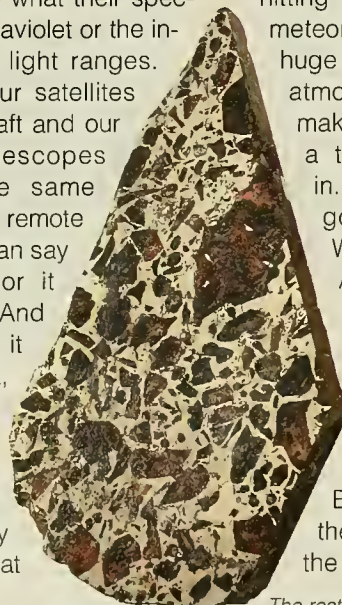
My research has largely been in the chemistry of how the particular components of chondrites, very primitive meteorites, actually formed in the solar nebula. Chondrites are really sedimentary rocks made up of dust and then chondrules, these round droplets that were once molten and now are little beads, many containing glass, which were present in the early solar system.

I'm also working in collaboration with other scientists in looking at meteorites to see how they reflect and

absorb light, like sunlight. Because one of the ways we understand the chemistry of, say, an asteroid is to look at all the wavelengths of light that it reflects from the Sun and then compare that to what we can measure in the laboratory on a known specimen. So if you have meteorites A, B, and C, you can measure what their spectra look like in ultraviolet or the infrared or visible light ranges.

And then with our satellites and our spacecraft and our Earth-based telescopes we can do the same measurements of remote objects and we can say it looks like A or it looks like B or C. And in that way, if it looks like a duck, and it quacks like a duck...we can say to some degree what asteroids far away look like and what they might be.

Another cool thing that I've



Huckitta meteorite

been doing is some work on tomography. This is CAT-scanning, three-dimensional imaging of meteorites, and is very new. We're just beginning to learn how to extract information this way. We intend to include a "fly-through" of a meteorite sample in a new production for the theater in the new hall.

**Q: What are the real chances of a large-scale meteorite impact?**

Well, we're not going to have a meteorite the size of Texas. First of all, anything that big we already have seen, we already know about. There's never in human history been an impact anywhere near the kind that wiped out so many of the dinosaurs. But here it's important to learn about the composition of asteroids that pass near Earth. If you have an object that is made of lots of smaller objects, like a pile of dust and stones, do you want to break it up or do you want to try to push it away?

If you jump into a swimming pool, it's no problem. If you jump off the George Washington Bridge, it's like hitting a brick wall. Same thing for meteorites flying through space at huge speeds. They hit the Earth's atmosphere and at first it just makes a lot of friction, but there's a thicker layer which we live in. We need to have oxygen to go to the top of Mt. Everest. Well, that's very high up. Around that height, a little higher actually, most meteorites hit this wall of air and they shatter or even vaporize. There are meteorites the size of your fist landing daily somewhere on Earth. But most meteorites land in the ocean, because it's by far the largest target.

*The restoration of the Arthur Ross Hall of Meteorites is made possible through the generosity of the Arthur Ross Foundation.*

# MUSEUM EVENTS

## EXHIBITIONS



Porcelain statues of the spirit mandarins of the Mother Goddess religion

### **Vietnam: Journeys of Body, Mind & Spirit**

Through January 4, 2004  
Gallery 77, first floor  
This comprehensive exhibition presents Vietnamese culture in the early 21st century. The visitor is invited to "walk in Vietnamese shoes" and explore daily life among Vietnam's more than 50 ethnic groups.

*Organized by the American Museum of Natural History, New York, and the Vietnam Museum of Ethnology, Hanoi. This exhibition and related programs are made possible by the*

Experience the sights  
and sounds of a bustling

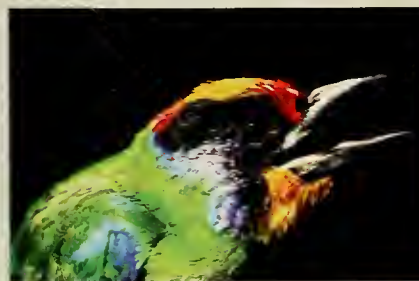
## Vietnamese Marketplace

and sample traditional  
foods at Café Pho.

Through January 4, 2004

77TH STREET LOBBY, FIRST FLOOR

*philanthropic leadership of the Freeman Foundation. Additional generous funding provided by the Ford Foundation for the collaboration between the American Museum of Natural History and the Vietnam Museum of Ethnology. Also supported by the Asian Cultural Council. Planning grant provided by the National Endowment for the Humanities.*



Golden-throated barbet, Ngoc Linh, Vietnam

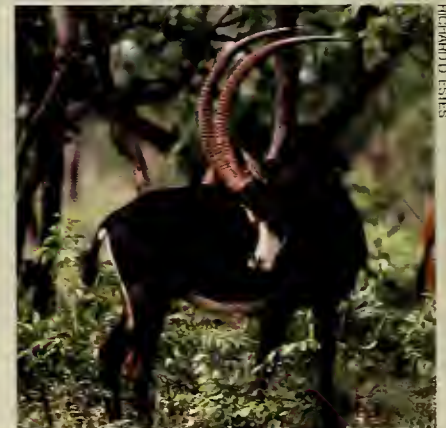
**Discovering Vietnam's Biodiversity**  
Through September 28  
Akeley Gallery, second floor  
This exhibition of photographs highlights Vietnam's remarkable diversity of plants and animals.

*This exhibition is made possible by the Arthur Ross Foundation and by the National Science Foundation.*

## LECTURES

### **A Certain Curve of Horn**

Tuesday, 9/16, 7:00 p.m.  
John Frederick Walker weaves the fascinating story of the survival of the giant sable antelope, found only in Angola, with politics, colonialism, and revolution.



Sable antelope bull in the Luando Reserve, Angola

### **Prehistoric Art: The Symbolic Journey**

Thursday, 9/25, 7:00 p.m.  
Anthropologist Randall White surveys the history of creative expression.

## FIELD TRIPS

### **Fall Bird Walks in Central Park**

Eight-week sessions start  
on September 2, 3 & 4.

## CHILDREN'S ASTRONOMY PROGRAMS

**Stories of the Sky**  
Saturday, 9/20, 12:30–2:00 p.m.  
(Ages 4–6, each child with one adult)

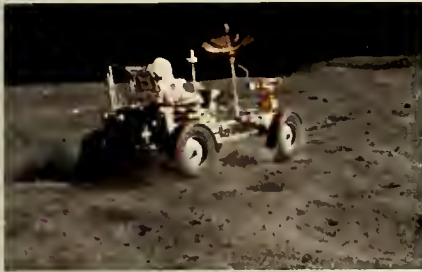
**Einstein for Everyone:  
Adventures in Light!**  
Sunday, 9/21, 12:30–2:00 p.m.  
(Ages 4–6, each child with one adult)

**I Want to Be an Astronaut**  
Tuesday, 9/23, 4:00–5:30 p.m.  
(Ages 4–6, each child with one adult)



### Fly Me to the Moon

Thursday, 9/25, 4:00–5:30 p.m.  
(Ages 4–6, each child with one adult)



Lunar Roving Vehicle

CHARLES M. DUKE, JR./NASA

### Space Explorers: The Planets (and Meteorites) of Our Solar System

Tuesday, 9/9, 4:30–5:45 p.m.  
(Ages 10 and up) In the Hayden Planetarium Space Theater

### HAYDEN PLANETARIUM PROGRAMS

#### Virtual Universe:

#### Stellar Dynamics

Tuesday, 9/2, 6:30–7:30 p.m.  
Redefine your sense of “home” on this monthly tour through charted space.

#### Celestial Highlights:

#### Stars of Autumn

Tuesday, 9/30, 6:30–7:30 p.m.  
Find out what’s up in the October sky.

#### Motion and Matter

14 Wednesdays, 9/3–12/10  
College-level introduction to space science.



NASA

### Choosing a Telescope

Three Mondays, 9/15–29  
A practical introduction to the seemingly endless choice of telescopes available to the amateur astronomer.

### Photons to Photos: Spying on Stars with Spectroscopy

Four Tuesdays, 9/23–10/14  
This course addresses the methods astronomers use to deduce the history of stars and galaxies from the colors of the light they emit.

### SPACE SHOWS

#### The Search for Life: Are We Alone?

Narrated by Harrison Ford

#### Passport to the Universe

Narrated by Tom Hanks

#### Look Up!

Saturday and Sunday, 10:15 a.m.  
(Recommended for children ages 5 and under)

### LARGE-FORMAT FILMS

In the Samuel J. and Ethel LeFrak IMAX® Theater

#### Coral Reef Adventure

A fantastic underwater journey to document some of the world’s largest and most beautiful—and most threatened—reefs.

#### Pulse: a STOMP Odyssey

Take a rhythmic voyage of discovery around the world of percussion and movement.

### INFORMATION

Call 212-769-5100 or visit [www.amnh.org](http://www.amnh.org).

### TICKETS AND REGISTRATION

Call 212-769-5200, Monday–Friday, 9:00 a.m.–5:00 p.m., or visit [www.amnh.org](http://www.amnh.org). A service charge may apply.

All programs are subject to change.



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### Starry Nights: Live Jazz

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Rose Center for Earth and Space

#### Ray Baretto and His Band

*Starry Nights is made possible by Lead Sponsor Verizon and Associate Sponsors CenterCare Health Plan and WNBC-TV.*

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For further information, call 212-769-5606 or visit [www.amnh.org](http://www.amnh.org).

# Private Choices

By Dru Clarke

The kick screen was weighed down with a slime of wet, fallen leaves and hairy algae. The children hauled it from the creek bed onto a level place along the bank. There they eagerly knelt beside it and, with forceps, began to grasp anything that moved, transferring their finds to white plastic ice-cube trays filled with creek water. The fourth-graders, from the town of Saint George in northeastern Kansas, were taking part in a project called Streamshot, and our purpose was to measure the environmental health of Blackjack Creek. Our assessment would be simply an index of its macroinvertebrates, a sampling of small but not microscopic animals widely used as indicators of freshwater quality.

The children's trays began to fill with mayfly nymphs, aquatic sow bugs, and the larvae of blackflies, caddisflies, and bloodred midges. And clinging to the slippery underside of the very last leaf was a leech. Teased from its tenuous hold, the leech slid into one of the tray's compartments and immediately sensed a change in its surroundings. Suctioning itself to the bottom of the tray, it accorded its way around the confines of the strange white room, then reared up like a rising periscope to take a look around.

The kids shrieked with joy, awe, and horror. "Watch out! It'll suck your blood!"

I assured them that this was a vegetarian leech.

"How do you know?"

"Well, it was on a leaf, wasn't it?"

Finally they calmed down to watch its sinuous movements with fascination.

I usually released our captured "macros" at the end of our surveys, but on that day I had agreed to

preserve them as specimens for the school's reference collection. Sometimes we have to make tough choices. I dumped the contents of the ice-cube trays into a jar and screwed on the lid.

Later that afternoon I deposited the jar in the refrigerator of the education department office. But the fridge wasn't working properly, and when I returned to retrieve the jar several days later, the water—and everything in it—was frozen solid. I thrust it quickly into a nearby microwave oven, then began delicately separating the lifeless invertebrates and tweezing them into individual specimen jars filled with alcohol and water.

Suddenly a gliding movement in the bottom of the collection jar caught my eye. The leech was alive! Somehow the creature had survived the freezing and thawing unscathed. I dumped the contents of the jar into a pie pan, and there the leech continued its exploratory behavior, alternately squeeze-boxing its

finely segmented body into a tight ball and expanding to a full inch and a half.

I was amazed and humbled by its grit. I put the animal in my palm and felt a slightly pleasant sensation as it crept along my "life line." Its personal specimen jar was labeled and waiting. I hesitated, then dumped the alcohol mixture from the specimen jar, rinsed it, and filled it with the thawed creek water. I tweezed the now frantically squirming leech into the container, put it into a shoebox with the

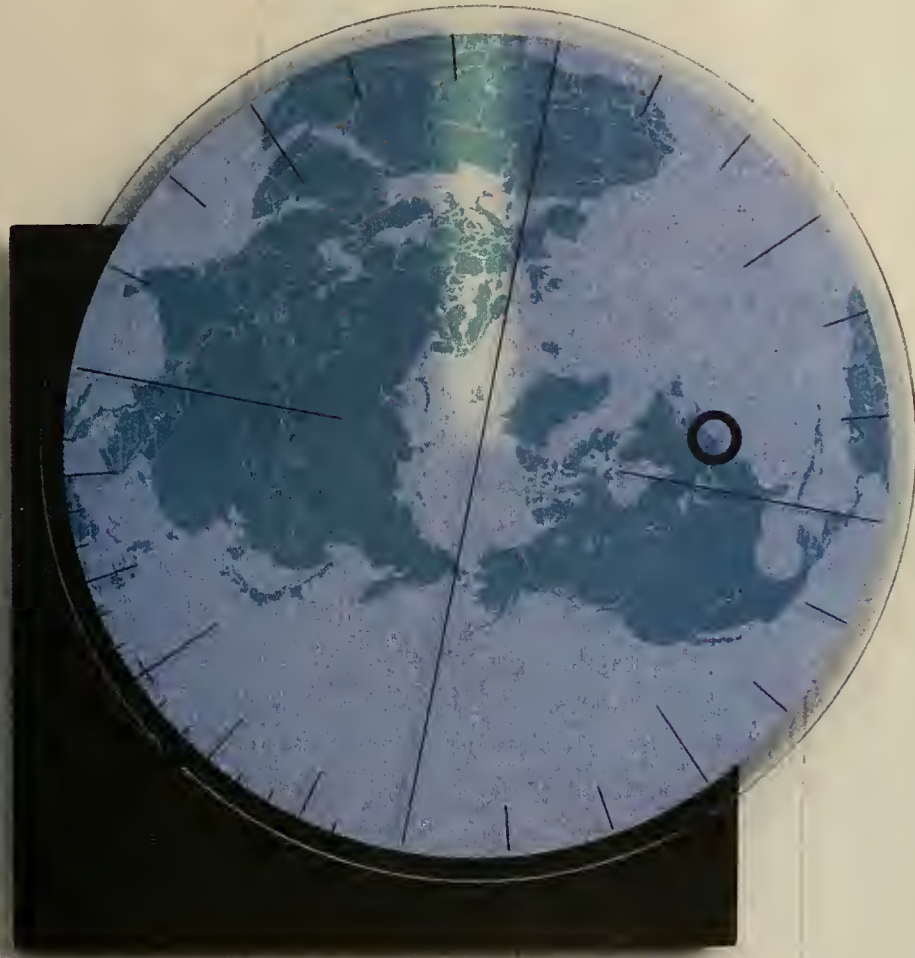
rest of the collection, and headed for home.

After dinner I peeked into the shoebox: the leech had climbed to the top of its jar and was huddled inside the lid. "Enough of this," I thought. Shoving the jar into my coat pocket, I rummaged for my car keys and drove to the banks of Blackjack Creek, parking at the spot where we had collected our samples. After tossing the jar's contents into the dark water, I watched the flowing creek in the beams of my headlights for a few more minutes. Nothing stirred on the surface. The leech was home free. Sometimes our choices become epiphanies.



*Dru Clarke taught marine science and ecology in secondary school for thirty-one years. She lives in the Flint Hills of northeastern Kansas.*

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