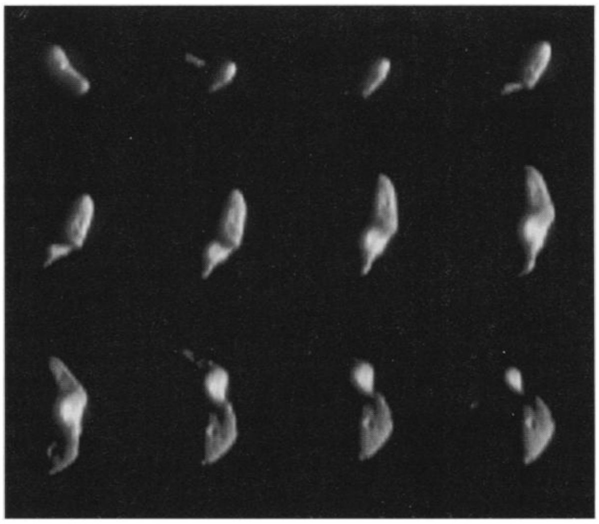
PLANETARY SCIENCE

Small Asteroids Point to a Source for Meteorites

New observations of the commonest asteroids suggest that, beneath a reddish cloak, they are made of the same stuff as ordinary meteorites

Rocks by the ton fall to Earth every year, and yet no one knows where most of them come from. The asteroids that swarm between Mars and Jupiter have long been the prime suspects, but 95% of meteorites don't match any particular asteroid or even any general asteroid type. Last week's flyby of asteroid Braille highlighted a rare exception (see p. 993), but efforts to link the most common meteorites—so-called ordinary chondrites, thought to be made of primordial solar system material—to the most common type of asteroid, the S-type, have come up dry (*Science*, 6 September 1996, p. 1337). At last month's Asteroids, Comets, and Meteors meeting in Ithaca, New York, however, astronomers presented the best evidence yet that S-type asteroids are just big chunks of ordinary chondrite after all, cloaked in some way that hides their true nature.

Seen in the telescope, the subtle reddish cast of S-types looks nothing like the gray of chondrites. But at the meeting, astronomers Michael Hicks and David Rabinowitz of the Jet Propulsion Laboratory in Pasadena, California, reported that the smaller the S asteroid, the more its color resembles that of ordinary chondrites. Because smaller asteroids are also thought to be the youngest, the relation could mean that some kind of weathering process reddens the surface of larger, older asteroids.



Stealth asteroid? Weathering of the 33-kilometer-long asteroid Eros may hide its true identity as primordial rock.

"The question now is not whether there is a connection between S asteroids and ordinary chondrites," says astronomer Richard Binzel of the Massachusetts Institute of Technology. "There is a relation. The problem now is unraveling the process" that disguises ordinary chondrite asteroids. Not everyone is so sure, and no one has duplicated the cloaking process in the lab. Still, the S-type source is gaining support as it heads toward a major test early next year, when the Near Earth Asteroid Rendezvous (NEAR) probe will orbit and inspect an S-type asteroid.

Asteroid specialists have long suspected that some kind of weathering process might be giving S asteroids a deceptive reddish tint. So they have aimed their telescopes at the smallest S-types, reasoning that because smaller asteroids are more likely to be blasted to smithereens in a collision with another asteroid, their life-spans should be shorter, giving the rigors of space little time to alter their surfaces.

Last fall, Binzel reported evidence that these youngest asteroids also look the most chondrite-like. His ongoing survey of more than 1000 asteroids showed a whole range of colors. At one extreme was the reddish cast most common in larger bodies; at the other were neutral, ordinary chondrite–like colors. They were seen in up to 10% of the smallest bodies in his survey, roughly a kilometer across.

Since 1996, Hicks and Rabinowitz have been focusing on even smaller asteroids, ranging from 10 kilometers down to 100 meters in size. The colors of such small objects are difficult or impossible to measure in the main asteroid belt, but they can be recorded among the so-called near-Earth asteroids, which have somehow escaped from the main belt (see sidebar). Of the more than 140 near-Earth asteroids Hicks and Rabinowitz have studied, those above a diameter of a kilometer or so mostly resemble S-types, while "a large number" (about 25%) of those smaller than a kilometer resemble ordinary chondrites in color.

Escaping From the Asteroid Belt

Recent observations may have fingered the type of asteroid responsible for most meteorites (see main text). And thanks to progress in orbital dynamics, another mystery may also be yielding: how asteroid debris is slung toward Earth in the first place.

Planetary scientist Clark Chapman of the Southwest Research Institute in Boulder, Colorado, explains that, unperturbed by external forces, an asteroid or any debris it sheds would never leave the main belt, beyond the orbit of Mars. In recent decades, however, dynamicists found two narrow zones in the main belt, so-called "escape hatches," where Jupiter's powerful gravity can stir up orbital chaos and send rock careening toward Earth. But that meant only the handful of asteroids close to an escape hatch could conceivably contribute to meteorite falls on Earth.

Computer simulations are now revealing other routes out of the asteroid belt. Last year, the late Fabio Migliorini of the Astronomical Observatory of Torino in Italy and his colleagues found that the gravity of Mars creates unexpectedly large amounts of orbital chaos in many zones of the asteroid belt. The chaos is powerful enough to nudge rocks out of the belt and toward the orbit of Mars, where martian gravity could hurl some of them toward Earth.

And this spring, dynamicists Paolo Farinella of the University of Trieste in Italy and David Vokrouhlicky of Charles University in Prague resurrected the century-old Yarkovsky effect to shake things up further in the main belt. The Russian engineer I. O. Yarkovsky had recognized that the "afternoon" quadrant of a solar system body—the side that has been exposed to the sun for the longest—would be the hottest, generating the strongest thermal radiation. The resulting radiation pressure, he said, would slowly alter the body's orbit. Farinella and Vokrouhlicky showed that the Yarkovsky effect is strong enough to move small asteroids into chaotic zones for transport to Earth. Taken together, the two effects mean "we can get meteorites from a broader distribution of locations," says astronomer Richard Binzel of the Massachusetts Institute of Technology—enough to keep Earth well supplied with falling rock. –R.A.K.

CREDIT: JHU APL/NASA

To planetary scientist Clark Chapman of the Southwest Research Institute in Boulder, Colorado, the findings clinch the case that S-type asteroids are the source of most meteorites. "It looks to me like the story is finished," he says. But Chapman notes, "You do need a step between the observation of a continuum [of color] and making an interpretation of what's doing it."

What may be doing it, say Binzel, Chapman, and others, is a process called space weathering. Just as exposure to the elements alters rocks on Earth, the space elements—such as the solar wind and the impacts of micrometeorites—can alter the surface of freshly exposed asteroidal rock by vaporizing part of a mineral and redepositing it elsewhere on the surface. Just how it works is a mystery, though, says meteoriticist Harry McSween of the University of Tennessee, Knoxville. "I believe in space weathering," he says, "but we don't really understand it."

As a result, some researchers hesitate to accept that S asteroids are chondrites in disguise. "I'm still skeptical, because space weathering [of asteroids] hasn't been proven," says astronomer Lucy-Ann McFadden of the University of Maryland, College Park. "It's easy to invoke space weathering but difficult to prove" that it's behind the differing appearance of S-types and ordinary chondrites. Planetary scientist Carlé Pieters of Brown University agrees, but notes that, in the lab, simulated space conditions can give ordinary chondrites at least some resemblance to S-types. And she says that space scientists are also learning how the solar wind and micrometeorite impacts alter soils on the moon—a model for what may happen to S-type asteroids.

Space weathering may not be the only process altering the look of larger S-types, Binzel adds. Because of their weak gravity, small asteroids may retain little of the finest debris generated by impacts, resulting in a coarser surface coating than is found on more massive asteroids. Particles of different sizes scatter light differently, which could contribute to the differences in color. With plenty of possible explanations at hand, Chapman and others aren't discouraged by the mystery of what reddens S-types. "There's been a major shift of opinion," says Chapman. "It's just the details that remain to be cleaned up."

Some of the details could be cleaned up starting this Valentine's Day, when the NEAR spacecraft goes into orbit around the 33-kilometer-long S-type asteroid Eros. X-ray and gamma ray instruments on NEAR will for the first time determine the elemental composition of an asteroid's surface, something that no amount of space weathering should alter. NEAR's close look could prove crucial in understanding cloaking and pinning down the link between S-types and chondrites. But if not, the frustrations could persist until a future mission to an S-type—as yet unplanned—actually scoops a sample from an asteroid and brings it back to Earth.

–RICHARD A. KERR

DEVELOPMENTAL BIOLOGY

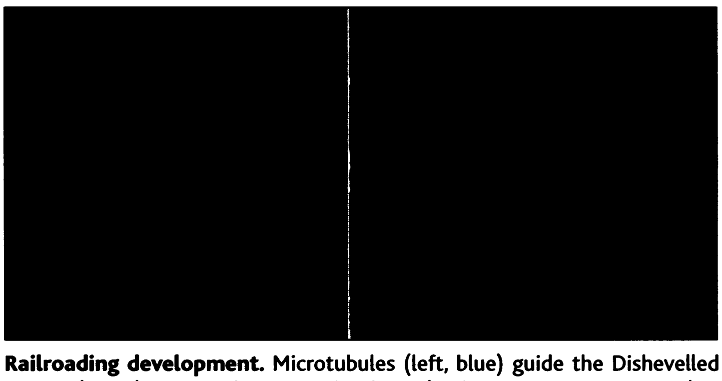
Many Modes of Transport For an Embryo's Signals

Developing embryos may actively ship key signaling molecules from place to place, instead of relying on diffusion to carry the messages

The developing embryo is a complex and ever-changing world, where landmarks quickly form and disappear and the entire geography shifts over time. Orchestrating these changes are protein messengers that constantly flow within and between cells, directing the next stage of shape change and cell division. But how do these messengers travel to their appointed destinations?

The classic paradigm is that a developmental signaling molecule diffuses freely from its source, so that nearby cells get the biggest dose and feel the strongest effects. "People have been talking about gradients since the beginning of embryology," says developmental geneticist Thomas Kornberg of the University of California, San Francisco (UCSF). But he notes that researchers have been unable to find these concentration gradients for a few key signaling molecules. And simple gradients can't explain the physical changes that accompany some crucial developmental events.

Now, thanks to an increasingly popular method of tracking proteins in space—hooking a glow-in-the-dark marker to the protein of interest—researchers can watch signals traverse cells in real time. Experiments with such methods are beginning to suggest that cells may actively ship some proteins around rather than relying on diffusion to carry the message. For example, 2 weeks ago researchers reported that frog eggs apparently haul a key signaling protein across the egg on a sort of intracellular railroad. Once at its destination, the protein helps trigger a cascade of messages that transform that side of the egg into the back of the embryo. And Kornberg's recent work on developing fly wings has sparked a bold new theory of transport: Rather than waiting for instructions to reach them, target cells may themselves send out long, skinny extensions to pick up messages from the source cells. "It's a way-out unexpected wrinkle," Kornberg says.



Railroading development. Microtubules (left, blue) guide the Dishevelled protein (green) to one side of a fertilized egg. (Each region is 35 μm across.)

CREDIT: LARABELL AND ROWNING

These and other studies offer a first glimpse into what may be a complex transportation system within the developing embryo, says developmental biologist Sergei Sokol of Harvard Medical School in Boston. "We used to have this simplistic view that different proteins diffuse readily in the cytoplasm. Now, more and more people think of it as a compartmentalized process," he says.

Still, the work is preliminary, cautions developmental geneticist Clifford Tabin of Harvard Medical School, and few papers have sewn up the details of these new modes of transport. For example, although Tabin agrees that the cell extensions Kornberg has spotted "are in a great place to be transmitting all sorts of signals," so far no one has proved that they actually do so. All the same, says developmental geneticist Andrew McMahon of Harvard University, these and other transport findings are giving development researchers "new food for thought."

Riding the egg's railroad

One of the key tasks in the life of a just-