Seeing Stars in a Handful of Dust

Interstellar material brought to Earth in meteorites is yielding clues to the nuclear furnaces that forged it 5 billion years ago and more, in the interiors of giant stars

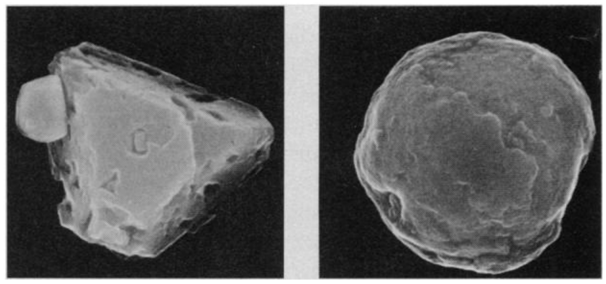
UNTIL VERY RECENTLY, THE STUFF THAT makes up the stars and is scattered through the voids between them lay far beyond the reach of astronomers. It could be admired and studied only from a distance. Earth and everything on it coalesced from such material, but during the birth of the solar system the former interstellar gas and dust was torn apart atom by atom and thoroughly rearranged. As a result, the atoms that make up rock and ocean and air retain no more memory of the stars that forged them than the carbon atoms in a person's body retain of the plant or animal that held them before.

But 3 years ago, University of Chicago planetary scientist Edward Anders changed all that when he found specks of ancient stardust on the surface of the earth. The material—snowy silicon carbide crystals, black specks of graphite, and diamonds just thousands of atoms across—had survived the birth of the solar system and now, 4 billion years later, was being delivered to Earth in meteorites. "This is material formed outside of the solar system," says University of Washington astronomer Donald Brownlee. "We actually have pieces of other stars in hand."

As fast as Anders has separated these grains from meteorites, Ernst Zinner of Washington University in St. Louis has been analyzing them, using a microanalytic instrument called an ion microprobe to measure the proportions of specific isotopes—the fingerprints of the star that formed each grain. And now a few scientists are reading those fingerprints. Some are using them to probe deep into the nuclear furnaces of stars. Others are tracing the long-dead stars that contributed material to the infant solar system. "This is a whole new field of astronomy," says astrophysicist Donald Clayton of Clemson University, "and the ion microprobes are the new telescopes."

So far, only a handful of other astronomers share Clayton's awareness of the importance of these grains, he says, but he expects that to change. "I think we are going to see the field grow in the next decade as more disciplines find that meteoritics has the key to a lot of the things they are interested in."

Few astronomers had thought that solid grains from the interstellar medium could emerge unchanged from the tumult and searing heat that accompanied the birth of the sun and the planets. Anders points out that many probably did vaporize, but a few hung on in the cooler, gentler outer reaches of the solar system. As the tenuous solar nebula collapsed to form solid bodies, he says, many of the grains were captured and preserved in the rocky asteroids that orbit between Mars and Jupiter. Many more probably lie locked in comets (see box). The asteroid belt is the prime source of meteorites, which carry the former starstuff to Earth.



Stardust memories. *Grains of silicon carbide* (left) *and graphite* (right) *remember their past.*

When Anders discovered the grains, he was combing meteorites in search of something else: exotic nuclei resulting from the fission of super-heavy elements. As part of his search, he dissolved his samples in strong acids and noticed that the process left a residue of fine powders. First, he saw tiny diamonds a few angstroms wide, then micron-sized flecks of graphite and silicon carbide. But it wasn't until Anders analyzed their isotopic makeup that he realized he had his hands on something truly unique.

By mass spectrometry, Anders examined the ratios of different isotopes of both the bulk elements in the grains—silicon and carbon—and trace components such as argon, neon, and xenon. He checked certain key ratios, including one of xenon isotopes that is known to clearly mark everything in the solar system. Such isotopic "signatures" branded most of the solar system during its formation, when material from different stars, carrying different isotopic ratios, all vaporized and blended the isotopes into a homogenous mix. Anders' grains, however, bore a foreign xenon signature. He realized that he was holding pristine interstellar dust. "It was explosive to realize this isn't just some solar system dust junk," comments Clayton.

The dust must have acquired its distinctive isotopic fingerprints in the complex interplay of nuclear reactions—element-building processes as well as radioactive decays—within a specific class of stars. When the grains condensed in stellar "winds" or supernova explosions, they carried with them the isotopic ratios of their parents.

What kind of stars were these? The presence of carbon—the common denominator in silicon carbide, graphite, and diamond—suggested the progenitor stars had to be carbon-rich. They also had to have vast atmospheres in which material expanding from the star could condense. The likeliest birthplace for the grains, Anders and his colleagues concluded, was the bloated, tenuous red giant stars known as Asymptotic Giant Branch, or AGB stars. Convection processes presumably dragged carbon-rich material up to the surface of the stars, says Anders. The grains solidified as some of this material blew outward into the star's atmosphere.

Anders based his conclusions about the stellar source of the grains on bulk analyses. But since different grains come from different stars, his work with large samples limited him to studying average properties of the stellar sources. When Zinner learned to tease out isotopic abundances from individual grains with an ion microprobe, which can perform mass spectrometry on a mere speck of material, he opened the way to a far more detailed reading of the grains. Each grain has its own story to tell about the element-forming processes of its parent star.

Together, the work of Anders and Zinner has given astronomers a new tool of vast potential. For the first time, says Clayton, they have the luxury of concrete laboratory data (something almost unheard-of in astronomy) to check against theories of stellar processes based on distant observation, calculation, and speculation. "We are like kids running a candy shop," he says.

In one raid on the candy stock, Clayton scrutinized Zinner's isotopic data on silicon carbide grains for clues to the process of nucleosynthesis—element formation—within AGB parent stars. For the most part, the isotopic ratios confirmed the current theoretical picture of the process, known as neutron capture, by which successively heavier nuclei take shape in the depths of stars. But some puzzling isotopic ratios showed up that Clayton says he can't yet explain. He is presenting his findings this week in Monterey, California, at a meeting of the Meteoritical Society.

In a still-untested use of the information embedded in the silicon carbide grains, Anders points out that by analyzing the ratio of krypton 80 to selenium 79, astronomers could take the temperature of those stellar furnaces. In a (relatively speaking) cool star, selenium 79 slowly turns into krypton 80 by neutron capture. In a hotter star, though, the selenium 79 decays to something else faster than neutron capture can build it up into krypton. The hotter the parent star, the less krypton 80 a grain should preserve.

Another result to be presented at the Monterey meeting suggests that the grains could also serve as probes of far more violent stellar environments. According to Clayton, Zinner will show that some silicon carbide particles are rich in calcium 44, an end product of the decay of radioactive titanium 44. Titanium 44 is a product of supernovae, suggesting that some of the grains condensed from supernova explosions rather than in the stellar winds of red giants.

Anders says the diamonds also carry some isotopic traces of supernovae—though not enough to convince him that they originated there. For now, the mystery remains, because the diamonds are too small to study even with the ion microprobe. With about 1000 atoms each, "they could barely make engagement rings for bacteria," says Anders.

Besides bringing tidings from other stars, the grains have much to reveal about the birth of our solar system. Indeed, Clayton says, the very existence of the grains disproves the notion, popular just 10 years ago, that the solar system condensed from a cloud of hot gas, in which no solid grains from the interstellar medium could have survived.

More specific information about our own origins is coming from isotopes in the grains, in particular the parent-daughter pair aluminum 26 and magnesium 26. Clayton says some silicon carbide grains contain a huge amount of magnesium 26, formed by radioactive decay of the aluminum isotope, which presumably originated in the parent star. Originally, he calculates, the radioactive aluminum must have made up about 10% of the total aluminum in the grains.

Harvard astrophysicist Alastair Cameron thinks that the high aluminum abundance in the grains offers a clue to the puzzlingly high magnesium 26 he has found in ordinary solar-system stuff. A heavy dose of "live" aluminum 26 must have condensed with the solar system. The grains suggest to him that it came from a single exploding AGB star. And since this radioactive aluminum has a short half-life, the stellar explosion must have taken place nearby, right before the solar system coalesced.

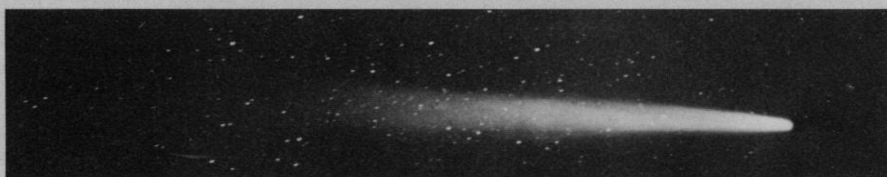
Cameron thinks that the timing may be more than a coincidence. He proposes that the star's explosion jostled the primordial nebula and triggered the birth of the solar system. "There is a rather intimate connection here," he says, "which is of great interest in terms of how we all come into being."

That particular star may have been the impetus for solar-system formation, but many other stars must have contributed material to the primordial cloud. Anders thinks the grains may reveal just how many. For a while, scientists thought five or six stars donated most of the material that formed the sun and planets. Now, Anders says, people favor a higher number. He estimates 1000, using a "back of the envelope calculation," based on the variety of grain signatures and an estimate of the number of stars that exploded in our neighborhood before the solar system began.

The grains may even reveal when that primordial material was forged. During their peregrinations in interstellar space, the grains were bombarded by cosmic rays. Anders has been estimating the ages of some of the grains by estimating their total cosmic-ray exposure, recorded in the number of carbon atoms that got knocked into an isotope of neon. Already some of the oldest appear to go back more than a billion years before the solar system, and Anders envisions finding grains that drifted through the galaxy even longer. He says a "Mount Everest complex" urges him to break the record by identifying the oldest objects on Earth.

Anders adds that while more remains to be learned from the silicon carbide, graphite, and diamond, a wealth of information about our solar system and other stars lies tied up in interstellar grains made of silicates, which he suspects lurk in meteorites even though no-one has yet been able to extract them. "If I had more time, or were a younger man," he says, "I would go after those." ■ FAYE FLAM

Scooping Starstuff From a Comet


NASA

Though astronomers are still reveling in all the information they can read in the interstellar grains that get delivered to Earth in meteorites (see main text), many dream of getting their hands on stardust from another source: comets. But because comets hardly ever fall to Earth (luckily for Earth), collecting enough comet material would mean going out to fetch it—intercepting a comet and bringing a sample back to Earth.

The European Space Agency (ESA) has laid plans to do just that on the Rosetta Mission—one of ESA's four "cornerstone" missions planned for the early 21st century. Rosetta would find a comet headed for a relatively close encounter with Earth, land on it, scoop up some samples of its icy substance, and fly the samples back home.

Why go to all that trouble? Edward Anders of the University of Chicago, who has extracted a few precious vials of interstellar grains from meteorites, says that comets make much better time capsules than do asteroids—the progenitors of meteorites. Grains have a better chance of surviving, he says, the later they entered the solar system, the further they stayed from the sun, and the lower their temperature. "We're not sure which of these factors is most important," he says, "but comets beat asteroids on all counts."

While asteroids orbit between Mars and Jupiter, comets, even ones that occasionally swoop close to the sun, spend most of their time at the far fringes of the solar system. Comets are also relative late-comers to the solar system, and they stay cold. As a result, Anders thinks comets could hold piles of interstellar grains—among them kinds of grains not yet found in meteorites.

Anders and grain specialist Donald Brownlee of the University of Washington aren't optimistic that they will ever see these ideas tested, though. They think that Rosetta, though technically feasible, is unlikely to be funded. And even if it is, it could be decades before it gets off the ground. ■ F.F.