ASTRONOMY

Dust Grains Bring Long-Lost Stars Into the Laboratory

ST. LOUIS—Slice open a hailstone, and you will see the signature of the thunderstorm that spawned it: a bull's-eye of concentric ice layers laid down by wind currents and temperature gradients within the storm. Much the same goes for tiny grains of "stardust" born in the stormy atmospheres of long-vanished stars, a research team here at Washington University has found. By picking apart these bits of grit—which formed billions of years ago around old, bloated stars and supernovas, then wafted through space and fell to Earth in meteorites—the team is reading a story of stellar turbulence in unprecedented detail.

That's just one of the ways in which these grains are bringing far-off stars into the laboratory. Only a few years ago, says Roberto Gallino of the University of Torino in Italy, researchers were still marveling at their discovery that these micrometer-sized interlopers in meteorites have isotopic compositions marking them as fossils from long-dead stars. Today, as Gallino and more than 100 other meteoriticists, astrophysicists, and astronomers discussed at a recent meeting* here, new analytical techniques have turned stardust into a bona fide astrophysical probe. Says David Arnett of the University of Arizona: "What we have here is an entirely new sort of connection between stars and us."

Aside from the light they shed on stellar atmospheres, grains spewed out by old, long-lived stars are being put to work as a new measure of the Milky Way's age. The precise balance of isotopes in the grains, reflecting how the parent stars churned and burned their nuclear fuel, has also hinted at unsuspected circulation patterns inside stars—a finding with implications for efforts to infer how elements were made in stars and even in the big bang. It may even be possible to use stardust as a probe of conditions in the nascent solar system. "It's a new science that is exploding these last 5 years," says Gallino.

PHOTOS BY T. BERNATOWICZ AND S. AMARI

Nitty gritty of stars. Sliced open, a graphite grain reveals a tiny "seed" crystal of titanium carbide, implying unexpectedly high densities in the parent star's atmosphere.

The entire field of stardust studies, says Thomas Bernatowicz of Washington University, rests on the premise of "the solar system as a big Cuisinart" that didn't quite finish the job. Like cooks heaping ingredients into a food processor, winds from nearby stars, debris flung from supernovas, and the general flotsam and jetsam of the interstellar medium all contributed dust and gas to the giant cloud that eventually formed the solar system. Ingredients from each source had their own patterns of elements and isotopes. But once the nebula collapsed into a warm, whirling disk, those patterns blended together to produce averaged abundances that, today, are about the same no matter where in the solar system we look. Here and there, though, the original ingredients didn't get perfectly homogenized.

The unmixed lumps take the form of tiny grains of silicon carbide, graphite, aluminum oxide, and other materials, now found in certain rocky meteorites. The grains betray their exotic origin with isotopic compositions that are wildly out of line with the usual solar system values (*Science*, 26 July 1991, p. 380). As geophysicist G. J. Wasserburg of the California Institute of Technology (Caltech) puts it, each bit of anomalous material "is a grain made around a star."

Painstaking analysis of these tiny bits of grit (see box) reveals which kinds of stars they come from. Certain graphite and silicon carbide grains are laced with calcium-44, a decay product of radioactive titanium-44,

* "The Astrophysical Implications of the Laboratory Study of Presolar Materials," held at Washington University from 31 October to 2 November.

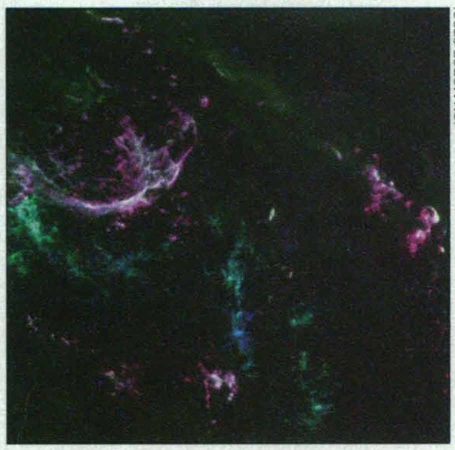
Picking Out the True Grit of Stars

The explosion of stardust studies wouldn't be possible without technologies that can identify genuine bits of stars in grit extracted from meteorites—technologies like the device built by Washington University's Larry Nittler. Just across a parking lot and up a hill from the stardust conference, Nittler showed off a riot of knobs, flanges, vacuum pumps, coaxial cables, and computer screens, all designed to map the isotopic compositions of dozens of grains at once. The apparatus lets him pluck the one bit of true stardust from mounds of ordinary material.

Nittler explains that the device plays a broad beam of ions over meteorite grains spread out on a piece of gold foil. The beam dislodges secondary ions from the grains, and the instrument analyzes the ions to determine the grains' composition and to produce maps of isotope abundances and ratios. "I can find the one grain out of 1000 that is isotopically anomalous"—a likely bit of stardust—says Nittler.

That kind of discrimination is crucial, for example, in identifying stellar grains made of oxide minerals. Oxide grains are among the most informative kinds of stardust (see main text), but they are hard to pick out from the ordinary oxides that make up meteorites. With the system, which builds on work by Washington University's Ernst Zinner and Robert Walker and by Peter Hoppe (now at the University of Bern in Switzerland), Nittler has now found 79 of the 92 presolar oxide grains identified since Caltech's Gary Huss discovered the first one in 1992.

The advance over standard grain-by-grain techniques for identifying and analyzing stardust is so huge, says Clemson University's Donald Clayton, that Nittler's forthcoming report in the *Astrophysical Journal* "is one of the great science papers of the last few years. It's going to open up a whole new realm." –J.G.



JON MORSE/STSCI

Raising dust. Gases from supernova explosions are a source of dust particles.

which Donald Clayton of Clemson University in Clemson, South Carolina, has shown must have formed in the flurry of nuclear reactions in a supernova. Some of the graphite grains that Bernatowicz and his colleagues have studied contain unusually large amounts of silicon-28 and high ratios of carbon-12 to carbon-13—two other signs of a supernova origin. Others carry the anomalously low carbon ratios characteristic of winds from the old, bloated, low-mass stars called asymptotic giant-branch (AGB) stars.

Bernatowicz, who organized the conference along with stardust pioneers Robert Walker and Ernst Zinner of the McDonnell Center for the Space Sciences at Washington University, is going beyond identifying stars to probing conditions inside them. By cutting the grains with a microtome and examining the slices with an electron microscope, he discovered even smaller particles at their center—crystals of titanium carbide, for example, that looked like they were engulfed by the graphite as it condensed, layer by layer. Says Bernatowicz, "You're pretty safe in the assumption that the titanium carbide was there first" when the graphite condensed, like dust particles caught in growing hailstones. The team realized that this sequence of formation—along with the near absence of silicon carbide, even though silicon is abundant in AGB stars—was a clue to conditions in the stellar atmosphere.

Graphite condenses at about the same temperature regardless of pressure, for example, but titanium carbide condenses more readily as the pressure goes up. Calculations by team member Katharina Lodders and others showed that for the titanium carbide to have formed first, the density of the stellar atmosphere had to be extraordinarily high—at least 100 times higher than astronomers had estimated. At those densities, AGB stars would shed mass far too quickly in the high-speed winds that astronomers have clocked blowing outward from them, unless the high densities are limited to narrow jets or knots of turbulence.

Bernatowicz says that the grains bearing the isotopic signature of supernovas are flecked with such inclusions as well, implying that supernova atmospheres also have pockets of high density. "It's really a beautiful result," says Arizona's Arnett. Recent computer models of supernovas did imply lumpy atmospheres, but "now we have a way to test [such predictions] in the laboratory."

Washington University's Larry Nittler and Caltech's Wasserburg and Gary Huss, meanwhile, are finding that another kind of grain may offer a deeper look into stars. Examining particles of aluminum oxide that seem to come from red giant stars, the researchers found that one oxygen isotope, oxygen-18, was unexpectedly scarce. The depletion suggested that before the grains condensed, the gases that formed them had been churned deep into the stars, through layers hot enough to "cook" that isotope into heavier elements. The same process would also deplete the surface gases of helium-3—an isotope that traces element-forming processes in the big bang. Such stellar churning, if it's common enough, could explain why the cosmos as a whole seems to contain less helium-3 than some scenarios of element formation predict (*Science*, 7 June, p. 1429).

Another set of oxide grains might help settle a different cosmic conundrum: the age of the universe. Various measures of cosmic age point to wildly different figures—anywhere between 8 billion and 15 billion years—so astronomers would welcome an extra indicator. The first step in extracting an age from the oxide grains is to add the 4.6-billion-year age of the solar system to the likely age—just short of 6 billion years—of the red giant stars that contributed the grains to the presolar nebula. The next is to determine how old the galaxy was when the stars formed, and a complex comparison of three different oxygen isotopes in the grains points to an answer: slightly under 4 billion years. The rough total is 14 billion years. Because the universe as a whole has to be at least that old, the result—although uncertain—is squarely on the side of an old universe.

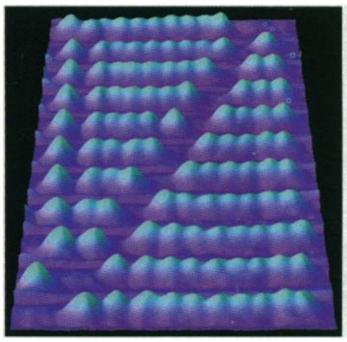
The grains have plenty of other secrets to reveal, participants at the conference emphasized. Besides offering glimpses of their stellar birthplaces, they may also hold clues to conditions in the primordial solar nebula. Patrick Cassen of the NASA Ames Research Center, for example, presented model calculations he did with his colleague Kenneth Chick showing that meteorites formed in different parts of the nebula might contain different amounts of stardust, depending on the amount of heating and mixing their ingredients had undergone. As a result, stardust counts might be used to map out the workings of the primordial Cuisinart. For astronomers facing the blizzard of data from such studies, said Zinner in summing up the conference, it all adds up to "a much harder life, but I hope a much more enjoyable life."

–**James Glanz**

DATA STORAGE

Tiny Abacus Points to New Devices

Talk about coming full circle. This week, a team of researchers at IBM's Zurich Research Laboratory reported crafting the first nanoscale abacus, some 2000 years after its macroscopic cousin first came into widespread use. Unlike a traditional abacus, a counting device consisting of sets of beads threaded on parallel wires, the IBM version is composed of spherical carbon molecules, called buckyballs, lined up along a steplike edge on a copper surface. Although the new abacus may not have quite the impact of its predecessor, it could lead to data-storage devices capable of holding vastly greater amounts of information than today's computer chips and disk drives can hold.



IBM ZURICH RESEARCH LABORATORY

Back to the future. Buckyballs lined up on a copper surface.

"The work is certainly a landmark experiment," says Stephen Minne, an electrical engineer at Stanford University in Palo Alto, California. Indeed, it represents the first time researchers have succeeded in using individual molecules at room temperature to store numerical information. The IBM group used their abacus to store numbers from 1 to 10 by sliding the buckyballs along the edge one by one, with an ultrasharp tip of a scanning tunneling microscope (STM). Still, the scientists have a long way to go before their work can be applied to real-world computing, say Minne and others. For starters, an STM tip can only move one buckyball at a time; for the technique to be useful for reading and writing huge amounts of data, researchers would need to figure out how to manipulate thousands or millions of the buckyballs in concert.

The new work, which is described in the 11 November issue of *Applied Physics Letters*, builds on plenty of previous research. Another team of IBMers, led by physicist Donald Eigler at the Almaden Research Center in California, was the first to push atoms around on a metal surface with an STM tip. But in that experiment, conducted in 1990, the researchers had to chill their sample down to just a few degrees above absolute zero to keep the surface atoms from skittering around. Earlier this year, the Zurich-based IBM team—led by physicist James Gimzewski—constructed a new member of a class of organic molecules known as porphyrins that readily adhered to metal sur-