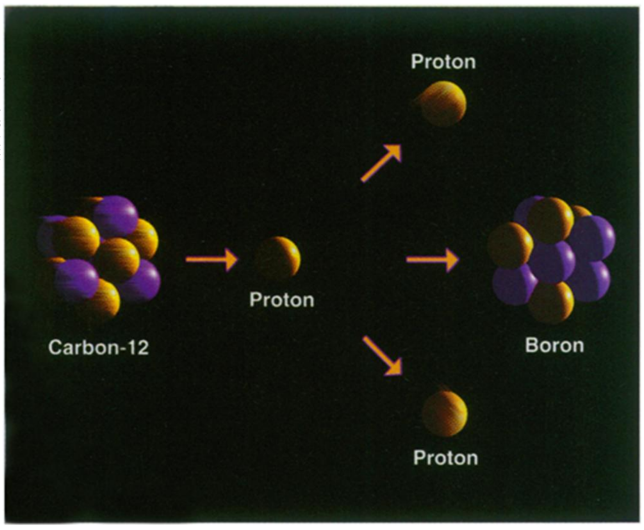
Cosmic Chemistry

Closing the gap in the origin of the elements

By RON COWEN

For the past 25 years, astronomers have puzzled over an elemental mystery.

Researchers widely accept the notion that all of the hydrogen and helium in the universe, as well as trace amounts of lithium, were produced in the Big Bang. Heavier nuclei, beginning with carbon, were forged in the furnacelike interiors of massive stars and then dumped into space when these stars exploded as supernovas. That still leaves no explanation for two lightweight elements—beryllium and boron—and the bulk of the lithium.



A high-speed carbon-12 atom accelerated from a supernova explosion strikes a stationary proton in the interstellar medium. The collision fragments the carbon atom, generating boron and two protons.

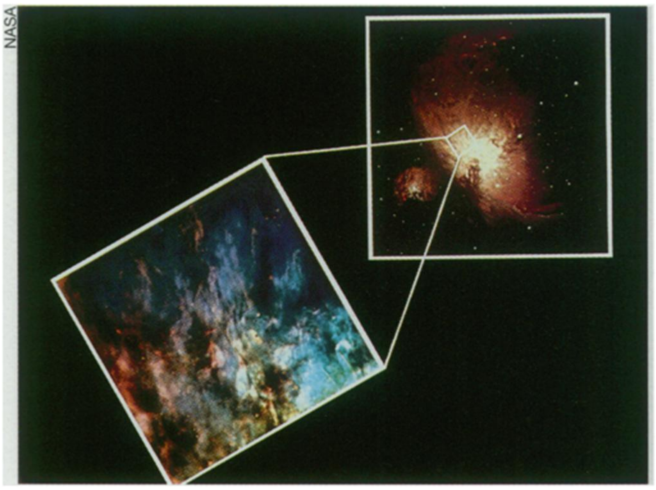
"The elements in between those produced in the Big Bang and those produced by supernovas are not very common, but it hasn't been entirely clear where they came from," notes Douglas K. Duncan, an astronomer at the University of Chicago and the Adler Planetarium & Astronomy Museum in Chicago.

In the early 1970s, astronomers came up with a theory that seemed to explain the formation of these three elements. These researchers proposed that the trio represented the debris left over when cosmic-ray protons—protons accelerated to high speeds in the galaxy—smashed into and shattered stationary carbon, oxygen, and nitrogen nuclei in the interstellar medium.

"That's what I was taught in graduate school, and that's what was generally believed," says Duncan.

Calculations showed, however, that this process alone can't generate the three elements in the abundances observed today in and near the solar system. Collisions of carbon, oxygen, and nitrogen nuclei with high-speed protons would produce twice the measured ratio of boron to beryllium and only half the ratio of the isotope boron-11 to boron-10, a sibling with one fewer neutron.

Observations with the Hubble Space Telescope have only made matters worse. Using Hubble's Goddard high-resolution spectrograph, astronomers have for the first time measured the abundance of boron in eight stars that rank among the oldest in our galaxy. The stars date from the formation of the Milky Way, some 10 billion years ago, and provide a record of boron abundance from that long-ago era.



Orion star-forming region.

To the surprise of many astronomers, the Hubble studies show that the abundance of boron way back when wasn't much lower than it is in the interstellar medium today. That finding is at odds with the notion that boron arose from the collision of high-speed protons with heavier elements. Ten billion years ago, "there wasn't very much carbon, oxygen, and nitrogen in the galaxy, so there weren't very many targets for the cosmic-ray protons to hit," notes Duncan. Boron, as well as lithium and beryllium, should therefore have been much scarcer in the distant past.

To explain how the early universe could have contained so much of the three light elements, Duncan and his collaborators have reversed the roles of the key players in the old theory. Rather than having high-speed protons slam into low-speed carbon, nitrogen, and oxygen, the researchers propose that the heavier nuclei, accelerated to high speed, shattered when they ran into low-speed protons in the interstellar medium.

"We're reversing which is the target and which is the thing hitting it," says Duncan.

That role reversal might seem to make little difference, but the new model accounts more fully for the elemental abundances seen both today and in the early universe.

In areas of the cosmos where supernova explosions were common, heavy nuclei—including carbon, nitrogen, and oxygen—would have been accelerated into space in significant numbers while remaining relatively rare in the interstellar medium at large. Protons, which are nothing more than the nuclei of hydrogen atoms, were already abundant in the interstellar medium in early times, thanks to their production in the Big Bang.

Duncan's team bases its work on an analysis of recent Hubble data as well as on previous observations reported in 1992 by Duncan, David L. Lambert of the University of Texas at Austin, and Michael Lemke of the University of Erlangen-Nuremberg in Bamberg, Germany.

Lambert says that Duncan "has [analyzed] more stars, he has more data points, but basically he gets the same result that we got the first time."

Duncan and his colleagues presented their work in September at a meeting on results from the Goddard spectrograph at NASA's Goddard Space Flight Center in Greenbelt, Md. At the same meeting, Reuven Ramaty of Goddard and his collaborators presented calculations showing that supernovas could have supplied the requisite carbon, nitrogen, and oxygen early in the history of the Milky Way.

Two separate lines of evidence support the new model. In 1994, Hans Bloemen of the Space Research Organization in Utrecht, the Netherlands, and his colleagues used a telescope aboard the Compton Gamma Ray Observatory (GRO) to analyze a series of broad emission lines from the Orion molecular cloud complex, the nearest stellar nursery to Earth (SN: 2/4/95, p. 70). The region is chock-full of massive stars and supernovas, and Bloemen says the broadness of the gamma-ray emissions and their energies indicate that they come from carbon and oxygen nuclei moving at high speeds, presumably because they've been hurled into space by supernovas.

Bloemen's interpretation may be open to question: A shorter survey of Orion by another GRO telescope has failed to detect the emissions. But if he's correct, supernovas would indeed provide a plentiful source of the speedy heavy nuclei that Duncan's team requires to produce lithium, beryllium, and boron.

In another study, Steven R. Federman of the University of Toledo in Ohio and his colleagues, including Lambert, used the Goddard spectrograph to measure the relative abundances of boron-10 and boron-11 along the line of sight to three stars in the nearby interstellar medium.

Federman's team has completed an analysis of data along the line of sight of two of the stars, one in the constellation Scorpio, the other in Orion. These stars reside in opposite parts of the sky, each some 300 light-years from Earth. The researchers conclude that the interstellar medium in Earth's neighborhood contains four times as much boron-11 as boron-10. That value, Federman adds, is similar to the ratio previously found in meteorites, which date from the formation of the solar system 4.5 billion years ago.

He notes that the new recipe, based on collisions of high-speed carbon and oxygen nuclei with low-speed protons, is required to explain the observed ratio of boron-11 to boron-10. Federman adds that collisions which follow the rules of the older model, in which high-speed protons collide with heavier, stationary atoms, make a significant, but much smaller, contribution to the abundance of the boron isotopes.

Says Federman, "The nice thing about the measurements of [his team and Duncan's] is that they're complementary. Duncan measures the elemental abundance of boron, while we measure the isotopic ratios of boron." The two studies, he says, lead to the same conclusion.

"People are fascinated in a general sense about the origin of elements," says Duncan. "'You mean that you know where the elements in my body came from?' they ask. To finally complete that picture is very appealing." □

Paleontology

Richard Monastersky reports from New York at the annual meeting of the Society of Vertebrate Paleontology

On the trail of pterosaurs

When dinosaurs looked up into the sky, they may have seen some of their distant relatives flying overhead. Called pterosaurs, these winged reptiles rode the winds throughout the dinosaurs' reign, up until the close of the Cretaceous period 65 million years ago. Paleontologists agree that pterosaurs were adept flyers, yet there is much debate over how these creatures got around on the ground.

A rash of footprint finds in the last 2 years is heating up the discussion.

Working in the western United States, Martin G. Lockley of the University of Colorado at Denver and his colleagues have found hundreds of fossilized tracks that they attribute to pterosaurs. "We seem to be finding this stuff daily in large quantities," says Lockley.

The fossils show clear impressions made by forelimbs and hind limbs, supporting the idea that pterosaurs walked on all fours like bats. While most paleontologists accept the quadrupedal pose for pterosaurs, some picture these reptiles as bipeds, running on their hind legs like birds.

Lockley ascribes the quadruped tracks to pterosaurs because of the distinctive toe and finger impressions. All later pterosaurs had a four-toed triangular foot and three short, clawed fingers. An extremely elongated fourth finger supported the wing, which pterosaurs could fold backward over their bodies. Most tracks include only imprints from the first three fingers, but recently discovered tracks in France show impressions left by the fourth finger, says Lockley. "I think this is very compelling evidence that we really are dealing with trace prints made by pterosaurs," he says.

Despite the new evidence, the debate over pterosaur locomotion marches on.

"For me, none of these are convincing tracks of pterosaurs," declares Kevin Padian of the University of California, Berkeley. Padian suggests that tracks previously labeled as pterosaurian were made by crocodiles, noting that they closely resemble impressions made by living crocodiles.

Sex and violence in the ice age world

Mammoths and mastodons, those shaggy relatives of modern elephants, thrived through the ice ages only to disappear abruptly at the end of the Pleistocene epoch, 10,000 years ago. One paleontologist is tracing the cause of their demise by looking into the mouths of the ancient beasts.

Some researchers think that climate change drove the Pleistocene extinctions. They note that great elephants and many other North American mammals died out just as the ice age ended. Others assign blame to human hunters, who first migrated to North America around 11,500 years ago.

Daniel C. Fisher of the University of Michigan in Ann Arbor is testing the scenarios by studying annual growth rings in the fossilized tusks of mammoths and mastodons. Using living elephants as an analog, he determined how long it took the extinct animals to reach sexual maturity by looking for a distinctive span of depressed tusk growth during adolescence.

The timing of maturation is important because it hints at the kinds of stresses affecting the ancient elephant kin. Many modern animals take longer to reach sexual maturity when they encounter harsh climatic conditions or food shortages. In contrast, they mature more quickly if threatened by predators.

Fisher has completed an analysis of eight specimens of mammoths and mastodons, all of which lived in the eastern Great Lakes region. Judging from this limited group, he sees signs of accelerating sexual maturation between 12,000 and 10,000 years ago—a trend consistent with the hunting hypothesis, at least for this region. "I applaud the method," says S. David Webb of the University of Florida in Gainesville. He intends to use Fisher's technique to see whether Florida specimens show a similar pattern.