Astronomy is a "big" science. It deals in big things, big distances, and big ideas. So it's a bit surprising to find astronomers exploring small things — *really* small things like subatomic particles — as they seek to write a history of the universe. Yet from the teeny space deep inside an atom to the vast chasms at the farthest reaches of the cosmos, astronomers need to understand it all if they're going to understand anything.

Astronomers do have one thing going for them: Everywhere they look in the cosmos, the rules appear the same. Three hard-won principles govern cosmology, astronomy's science of how the universe began and developed. First, the physics that works on Earth works the same way the universe over. Second, nothing about the place we occupy on Earth is unique or even special. And third, the universe is homogeneous and isotropic; in other words, the universe is similar everywhere and looks the same in every direction.

As yet, astronomers cannot fill in every detail. But they have assembled a broad understanding of how galaxies and planets and trees and cars and cats and people came to be. Similar to many human stories, cosmology tells of birth, growth, and death. It's a three-act play that ties together the creation of the elements, the formation of stars and planets, and the ultimate fate of the universe. You could call it the biggest story going.

Act 1: Creating the elements /// BY HENDRIK SCHATZ

Big or not, cosmology begins in the realm of the incredibly small. Everything in the cosmos consists of atoms, and the core of an atom, its nucleus, is tiny. A hundred billion atomic nuclei piled on top of each other would stack up no thicker than this page.

Every atomic nucleus, except hydrogen, is built from positively charged particles (protons) and particles with no electric charge (neutrons). Hydrogen is the simplest atom: it has just a single proton. Surrounding every nucleus is a whirling cloud of electrons, lightweight particles with negative charges. Everything there is to see in the universe, from stars to people, is made from these three bits of matter. When joined together in various combinations, they form the chemical elements.

But where did the elements come from? The answer varies from one to the next, but all atoms ultimately arose from a single source: the immediate aftermath of the Big Bang.

In the beginning

Following the Big Bang, the universe consisted of a primordial "soup" of energy. About one minute later, protons and neutrons condensed from this soup. Over the next few minutes, protons and neutrons fused, creating helium plus trace amounts of lithium and beryllium. Many protons remained unattached, becoming hydrogen nuclei.

So far, so good, but four elements make a skimpy ingredient list for a universe. And that goes double because when you consider the minute quantities of lithium and beryllium, it's really just two elements. (These were so rare that astrophysicists lump them and all other elements heavier than helium into a catch-all category called "metals.")

THE WISPY CRAB NEBULA is an expanding debris cloud from a supernova that exploded in A.D. 1054. The cloud, rich in newly synthesized elements, will help make new stars. JAY GALLAGHER (U. WISCONSIN)/WIYN/NOAO/NSF

THE ELECTRON is the lowest-mass stable particle. Electrons moving in a conductor make electricity.
MASS: 9.9×10^{-31} kilograms
SIZE: 5.6×10^{-15} meters

UP AND DOWN QUARKS combine in threes to make protons and neutrons.
MASS: 6.4×10^{-28} kg
SIZE: n/a

A PROTON forms the heart of a hydrogen atom. Heavier elements have more protons.
MASS: 1.7×10^{-27} kg
SIZE: 1.7×10^{-15} m

HYDROGEN, the lightest element, is simply a proton and an electron bound together.
MASS: 1.7×10^{-27} kg
SIZE: 1×10^{-10} m

Making more elements took work, and whenever it can, nature opts for the easy way. With atomic nuclei, this means settling into the lowest energy state possible. As it happens, the atom with the lowest energy state is nickel. So why isn't the universe nickel-plated from end to end? The answer lies in nuclear physics.

Atoms grow when combinations of two or three nuclei slam together. One of nature's four fundamental forces, the strong nuclear force, governs how atoms combine and break apart. In an early universe filled almost totally with hydrogen and helium, the nuclear force had no easy way to fuse nuclei into heavier elements. For example, helium nuclei have two protons and two neutrons; a helium nucleus fusing with a proton (a hydrogen nucleus) would, altogether, add up to five nuclear particles. Fusing two helium nuclei would add up to eight nuclear particles. Both combinations are unstable, spontaneously breaking apart. Likewise, two protons were unable to stay together.

Thus the universe got stuck, unable to make substances much more complex than hydrogen and helium. (Those trace quantities of lithium and beryllium formed under special circumstances which guaranteed their rarity.)

But the universe getting stuck was a good thing for us because it led to our existence. Any gas clouds in a nickel-rich cosmos would have cooled rapidly and formed cold metallic blobs, neutron stars, or black holes — not a very friendly environment for life. In our primordial universe of hydrogen and helium, however, gas clouds made stars, some of which have shined for billions of years. Stars shine because they are finishing the job the Big Bang left undone. They are slowly releasing energy by fusing hydrogen and helium into heavier elements, ultimately forming — among many, many other things — lots of nickel.

Stellar alchemy

Stars still faced a challenge making heavy elements. One form of beryllium has, for example, eight nuclear particles and is called beryllium-8; it's unstable and decays nearly instantly. The only way for it to form a heavier element is for beryllium-8 to capture a helium nucleus before decaying. Although this is an extremely unlikely situation, nuclear physics once again comes to the rescue.

When atoms collide, the result carries the combined energy of the two nuclei and their motion. If the total energy of that system — motions included — *exactly* equals the energy of a new atom, the transformation into a new element is straightforward. If there's too much energy from too much motion, however, the nuclei have to emit a particle in order to fuse, while if the energy is too low, the nuclei simply bounce apart.

The keys to making this work are both high temperatures inside a star and a huge number of available atoms. At about 100 million kelvins, a beryllium-8 nucleus can capture a helium nucleus in just the right way; their energy strikes a "resonance" that produces a carbon atom. And the trillions of atoms involved more than compensate for the very short amount of time (10^{-16} second) before beryllium-8 decays. The result is lots of carbon gets made.

As far back as 1954, Cambridge University physicist Fred Hoyle predicted this resonance based on the abundance of carbon in nature. To test Hoyle's idea,

THE TOP QUARK was discovered at Fermi National Laboratory in 1995.

MASS: 3.1×10^{-25} kg
SIZE: n/a

URANIUM, the heaviest naturally occurring element, fuels nuclear power plants and submarines.
MASS: 4.0×10^{-25} kg
SIZE: 3.5×10^{-10} m

HUMAN DNA encodes a unique pattern of information for every individual within a double helix pattern.
MASS: 1.0×10^{-24} kg
SIZE: 2.0×10^{-9} m

A CELL is the smallest independent living organism able to reproduce itself exactly.
MASS: varies by type
SIZE: varies by type

Willy Fowler and his colleagues at Caltech's Kellogg Radiation Lab set up an experiment to search for carbon resonance. In 1957, the group announced its discovery of conditions that produce beryllium-helium fusion. This removed a major roadblock in astronomers' understanding of how elements formed, and it netted Fowler a Nobel Prize in physics.

Fowler's pioneering discovery showed that most elements — from hydrogen up through nickel — are created in the bellies of stars. Stars begin by fusing hydrogen into helium and then, over millions or billions of years, they fuse heavier and heavier nuclei. The resulting elements are thrust into space by booming stellar winds or when a star explodes as a supernova, contaminating the galaxy with all those "metals." Ultimately, this process made the solar system, complete with iron, carbon, oxygen, and other constituents of life. But other elements — those heavier than nickel — have far different origins.

Heavy metal

To form heavy metals inside stars, another process besides garden-variety fusion takes place. Called the s-process (for slow process), the technique works when seed nuclei, typically iron, are struck by neutrons. Neutrons have an advantage in this kind of encounter. Because they carry no electric charge, neutrons are immune to the electric repulsion that protons feel when colliding with a nucleus. So an atomic nucleus bombarded with neutrons will eventually capture some and grow heavier. The nucleus soon becomes unstable and decays, converting one neutron into a proton and releasing a negatively charged particle (an electron) and a tiny uncharged particle (a neutrino). This adds a proton to the nucleus, which transforms it into a new element.

Yet it's not quite that cut-and-dried. Unlike protons (hydrogen nuclei), which are ubiquitous, neutrons are not as readily available in large numbers. Unattached neutrons decay into ordinary protons in about 10 minutes. Stars that formed from the debris of past supernovae, however, emit a stream of neutrons, and any nuclei in their path will capture one of them about once every year.

The slow process certainly lives up to its name, yet despite the leisurely pace, quite a few neutrons accumulate over a billion years in a galaxy full of stars. The s-process ultimately accounts for about half the heavy metals up to lead.

Going to extremes

Besides stars and the s-process, the nuclei of the remaining heavy elements come from the poorly understood r-process (for rapid process). The r-process has atomic nuclei capturing neutrons in fractions of milliseconds, which requires staggering numbers of neutrons hanging around awaiting capture. Astronomers calculate the r-process needs at least a pound of neutrons in a sugar-cube-size volume of space, plus a temperature of several billion degrees to work.

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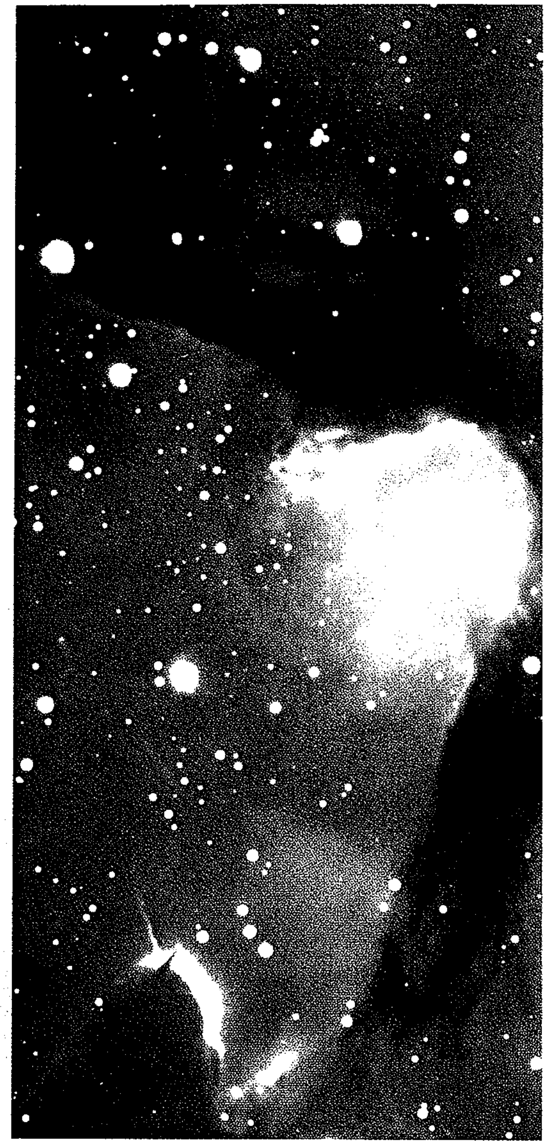
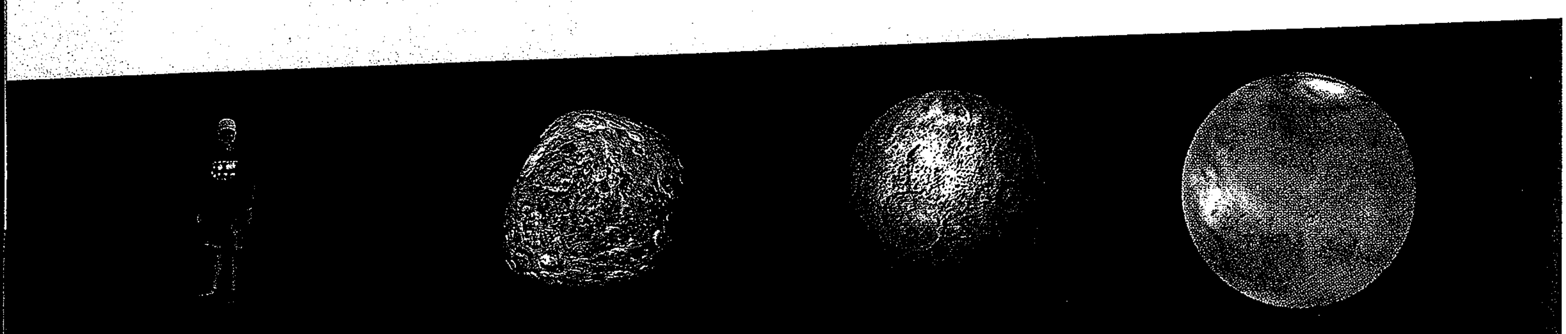


DUST AND GAS MINGLE in thick clouds such as the Trifid Nebula. Shock waves from bright, newborn stars surge through the cloud, driving lumps of dusty gas into making more stars. GEMINI OBSERVATORY



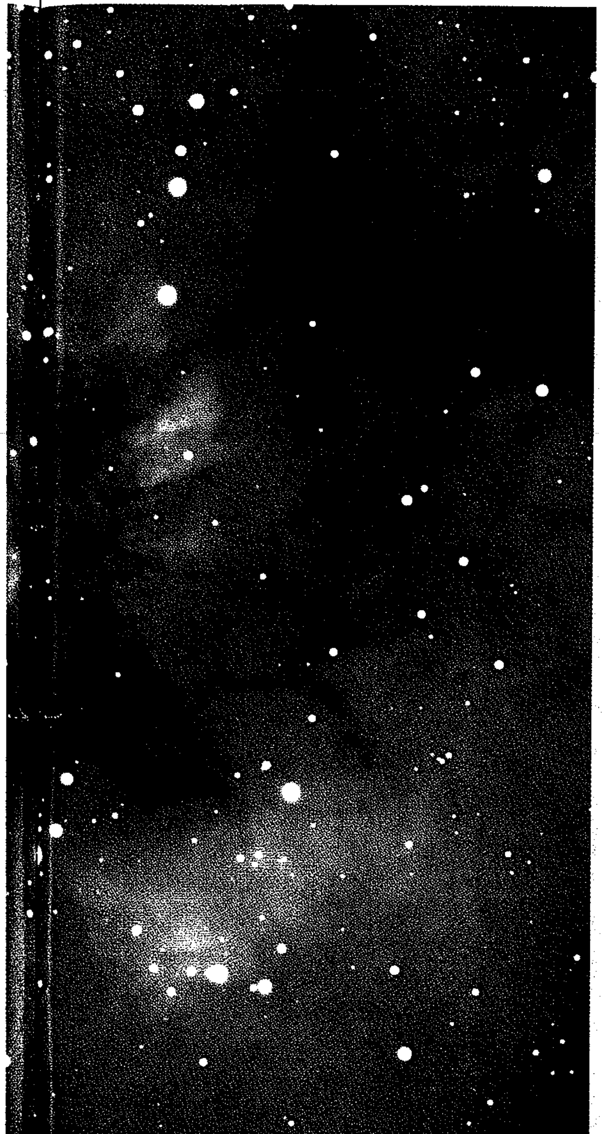
HUMAN BEINGS were the first life-form on Earth to reach for the stars.

MASS: 90 kg
SIZE: 2 m

ASTEROIDS are the smallest rocky and metal-rich objects in the solar system.
MASS: 8.7×10^{20} kg
SIZE: 9.5×10^{5} m

PLUTO is the largest known icy body in the outer solar system. Some argue it's not really a planet.
MASS: 1.3×10^{22} kg
SIZE: 2.4×10^{6} m

MARS is a terrestrial planet whose early history may have paralleled Earth's — perhaps including life.
MASS: 6.4×10^{23} kg
SIZE: 6.8×10^{6} m



Where would so many free neutrons come from? Many astronomers think neutron stars provide the answer. However, these stars are compact: a neutron star crunches the mass of the Sun into the size of a small city. Not only is a neutron star exceedingly dense — a tablespoonful would outweigh 4,000 aircraft carriers — but its extraordinarily powerful gravity binds its material tightly to the star.

But *colliding* neutron stars might free up a vast supply of neutrons. Such mergers would take place at extremely high velocities, creating titanic explosions that would release loads of neutron-rich material. Supernova explosions that form neutron stars might be another source. In each of these scenarios, the conditions ripe for the r-process could exist for a few seconds.

Could half the heavy elements in nature have been created in one second here and one second there? Astronomers can't say because they don't know the precise rate at which neutrons decay.

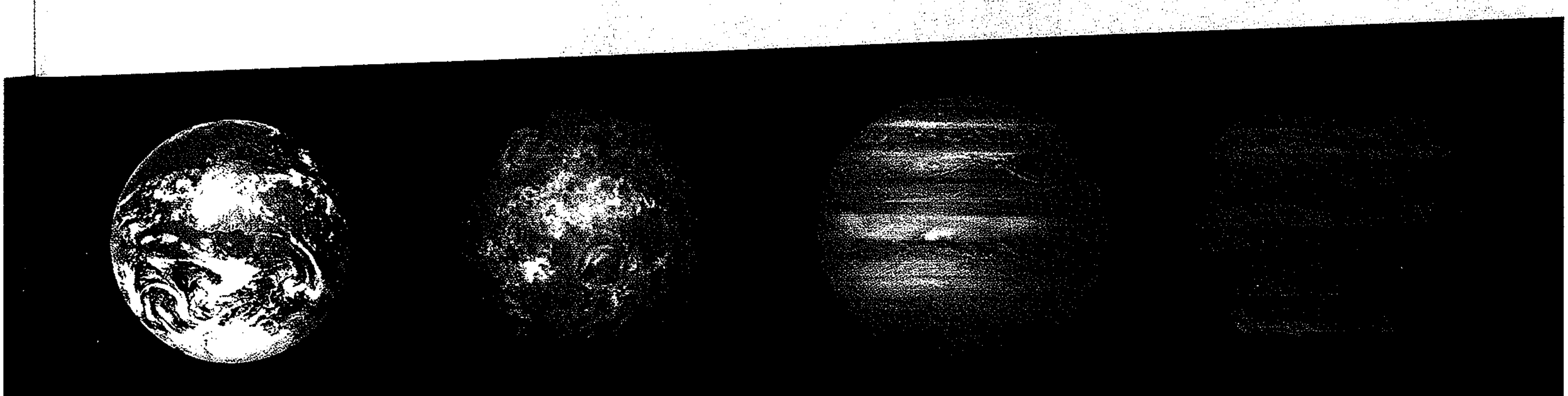
At bottom, the r-process still defies explanation, although astronomers hope to solve the puzzle relatively soon. Recent observations have uncovered numerous stars in the Milky Way's halo that provide a window into the r-process. These stars formed a long time ago from nearly pristine gas left by the Big Bang and then were polluted by a single r-process event some 13 billion years ago. The patterns of elements that astronomers observe in these stars' spectra may provide some clues into how the process works.

As astronomers are looking skyward for answers, physicists developing ground-based tests are on the verge of recreating the r-process in the lab. New, powerful accelerators — like Michigan State University's National Superconducting Cyclotron Laboratory — are gearing up for numerous experiments. Next-generation testbeds such as the proposed Rare Isotope Accelerator or an upgrade of Germany's GSI Accelerator are now on the horizon. Together with computer simulations, these tests offer real hope of understanding how heavy elements formed in the universe.

Act 2: Making stars and planets /// BY CHRIS LAWS

On the scale of the very small, the universe seems to work just fine. Our bodies are packed with protons, neutrons, and electrons, and their interactions keep us alive. But what about the pretty objects we see in the universe — stars, planets, nebulae, galaxies? These things exist on a completely different and larger scale.

Such objects not only dominate our naked-eye view of the heavens, they also occupy intellectually accessible territory. Human minds have experience with the size of a planet, and we can imagine the immensity of Jupiter-size brethren in other systems. We begin to grasp the size of a star by recognizing that the largest stars rival the size of Earth's orbit, and the smallest are similar in circumference to the size of cities or islands.



EARTH'S SIZE lets it remain tectonically active, and its position in the solar system keeps it habitable.
MASS: 6.0×10^{24} kg
SIZE: 1.3×10^{7} m

3 TO 5 EARTH MASSES is about the largest terrestrial planet that can form. Larger ones are gas giants.
MASS: 3.0×10^{25} kg
SIZE: 2.2×10^{7} m

JUPITER is our solar system's largest planet, and it is the standard used for weighing other worlds.
MASS: 1.9×10^{27} kg
SIZE: 1.4×10^{8} m

13 JUPITER MASSES is the upper limit for a planet. Above this size, nuclear reactions create stars.
MASS: 2.5×10^{28} kg
SIZE: 1.4×10^{8} m