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THE SURPRISING FATE OF THE EARTH

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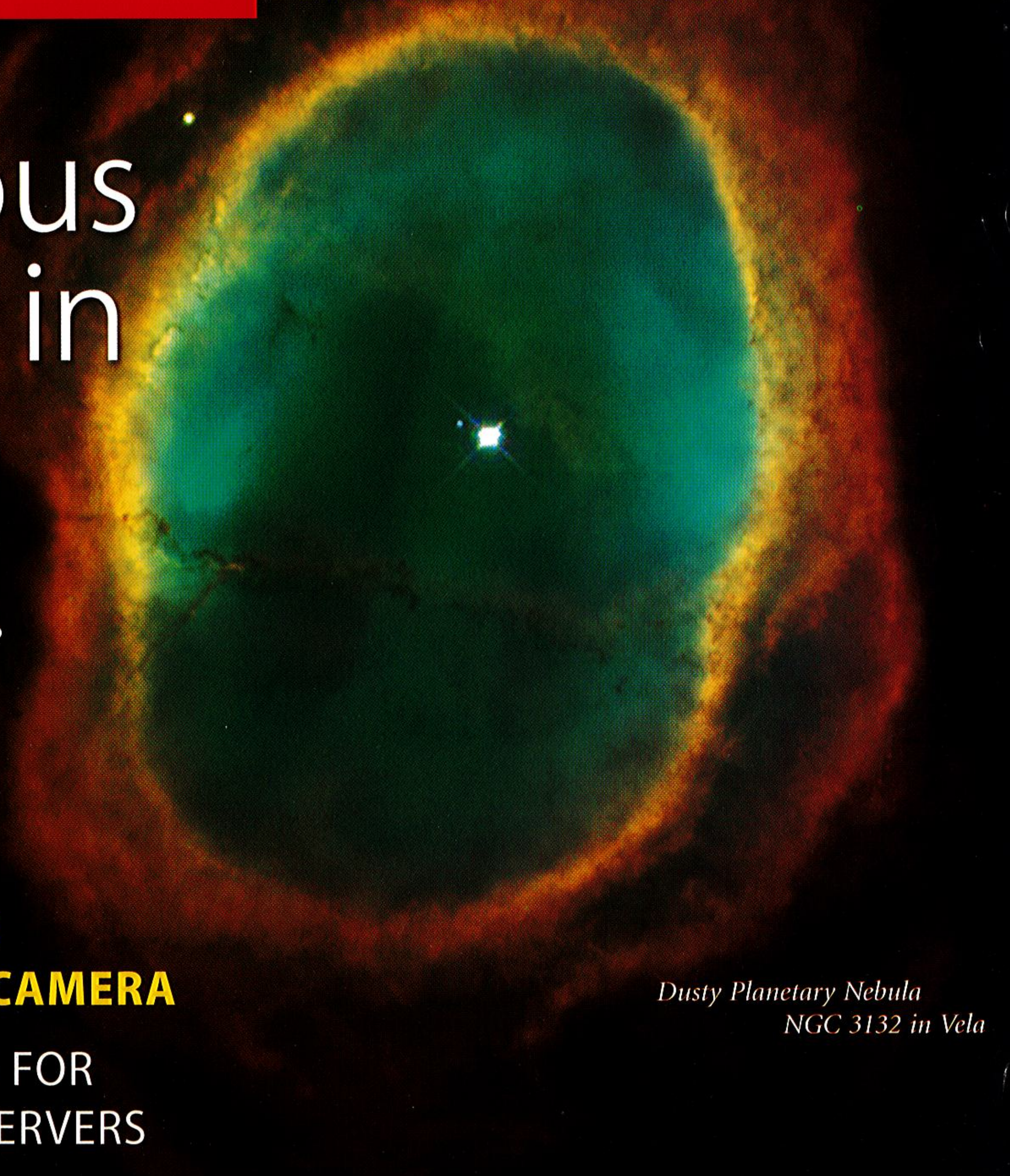
S&T TEST REPORT: A GEM OF A MOUNT

OCTOBER 2002

Precious Gems in Space

Astronomers find diamonds, rubies, and sapphires in stardust



Dusty Planetary Nebula NGC 3132 in Vela

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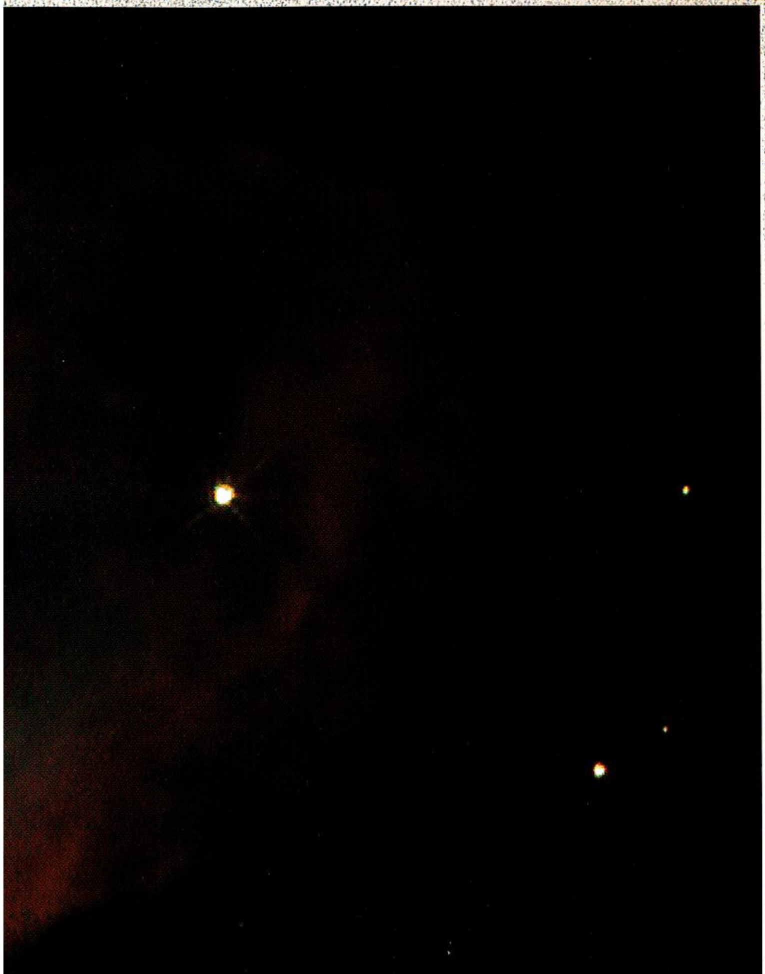
GEMS FROM

From powdered jewels to limestone and soot, stars produce vast quantities of solid particles — and no one knows how.

By Sun Kwok

THE STARS



The planetary nebula IC 4406 in Lupus, a 10th-magnitude glow in amateur telescopes, is actually a doughnut seen edge on, say astronomers who have studied this Hubble Space Telescope image. Outflowing gases are excited to glow by ultraviolet light from the hot central star, barely seen here. Many small billows of gas appear to be separated by thin ridges of dust. Where the ridges are seen edge on, they form delicate traceries in silhouette. The ridges are about 160 astronomical units wide, four times Pluto's average distance from the Sun. Many varieties of solids condense in such environments and eventually disperse through interstellar space. The nebula is 0.25 light-year wide across its short axis.

This image is a combination of exposures taken in the light of three emission lines: oxygen III (blue-green, displayed blue here), neutral hydrogen (H alpha, deep red, shown as green here), and nitrogen II (deeper red, shown red). Courtesy C. R. O'Dell, NASA, and the Hubble Heritage Team.

DIAMONDS, RUBIES, AND SAPPHIRES HAVE always been treasured for their beauty and rarity, so it may come as a surprise that stars are producing these "rare" gem minerals in vast quantities. Astronomers once thought the dust of interstellar space was relatively simple. But recent observations from ground- and space-based telescopes have found signatures of many different solids that are blowing like smoke from stars and floating in the spaces between them — from substances making up common sand to the most treasured minerals on Earth.

Diamond dust (white powder in bottom of vial) was extracted by acid dissolution from a piece of the carbonaceous Murchison meteorite. The ratio of xenon isotopes trapped in some of these tiny diamond crystals suggests that they solidified at other stars and were later incorporated into the material from which the Sun and solar system formed. Courtesy Jason Smith and the University of Chicago.

Interstellar dust is not very plentiful. It amounts to only about 1 percent of interstellar matter; the rest is gas. But dust plays a disproportionate role in many cosmic processes. Among these are the heating and cooling of nebulae — processes that regulate where stars will be born and what their masses will be — and the interstellar chemistry that creates the raw materials for planets. Dust also determines how much of our Milky Way galaxy we see, or don't. On a dark night, vast black clouds are visible silhouetted along the midline of the Milky Way, blocking most of the galaxy from our view. The gas that dominates these dark nebulae is generally transparent and invisible; what we see is the dust.

Although the presence of dust in interstellar space has been known for almost a century, its origins and chemical compositions have remained a mystery. Interstellar dust is too cold to radiate in the visible part of the spectrum, so its nature was first studied through its selective absorption of starlight. Based on an ultraviolet absorption feature in stellar spectra at a wavelength of 220 nanometers (2200 angstroms), astronomers long thought that interstellar dust is made of graphite. This may still be an ingredient, but recent infrared observations have found an amazing variety of minerals in space, especially around dying stars. Among them are some of the gemstones that have been treasured throughout human history.

Long regarded as signs of wealth, luxury, and power, gems in many cultures are thought to possess medicinal or magical powers. Modern science has shown that precious stones are nothing more than minerals made up of the same elements found in common rocks, such as carbon, oxygen, silicon, aluminum, magnesium, and iron. Their luster and colors are well understood from the physical principles of refraction, reflection, and dispersion. Their internal structures can be accurately determined through the technique of X-ray crystallography. We now know that, with a few exceptions such as amber and opal, precious stones are atoms arranged in periodic, crystalline structures. These various geometric patterns give them their unique optical properties.

According to some myths and legends, gems come from the sky. Could there be any truth to this idea? Sadly, the diamond in your ring did not originate around some other star. Geologists know very well how precious stones are formed in Earth's crust, and in any case interstellar particles are generally much too small. They typically range in size from about a micron (a thousandth of a millimeter) down to clumps of just a few hundred atoms a thousand times smaller still. However, scientists are now pondering the possibility that some microscopic gemstones now on Earth may indeed have come from space and may be older than our planet.

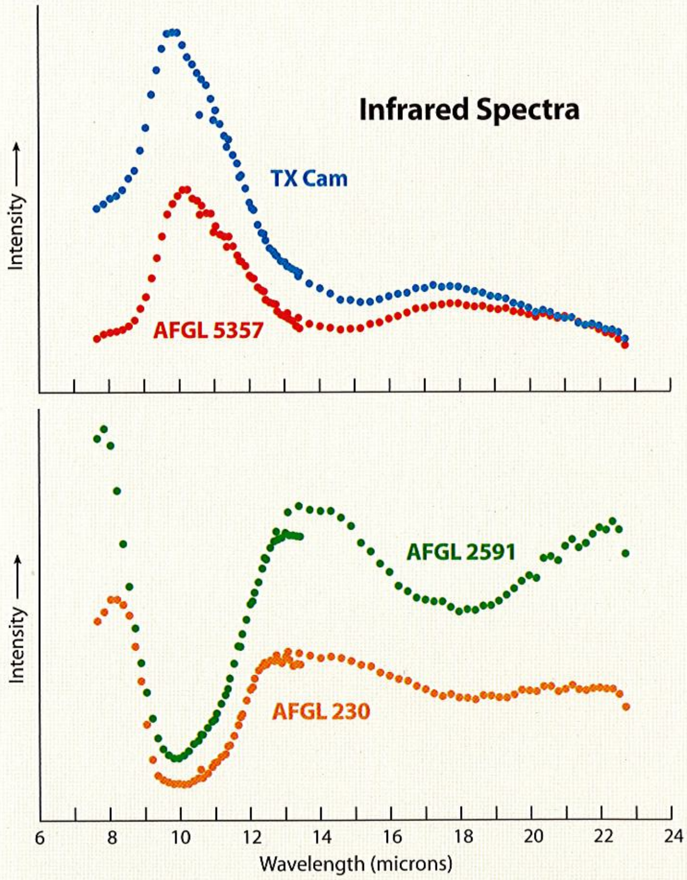
The first evidence for a such a possibility came from the study of meteorites. In 1987 researchers found that some meteorites contain diamonds a nanometer (thousandth of a micron) in size. Following this discovery, meteorite investigators turned up tiny grains of silicon carbide (SiC) and graphite. The isotopes in all these grains suggest that they did not arise within our solar system but originated elsewhere and were later incorporated into meteoritic material intact.

In 1997 scientists analyzing meteorites at Washington University in St. Louis found many corundum particles (Al_2O_3), the class of aluminum oxides to which rubies and sapphires belong. Again, the grains seemed to be interstellar in origin.

Where were they made and how did they get here? From studying stellar spectra in the infrared, we have established definite links between grains found in meteorites and the minerals being thrown out in the winds of certain old red-giant stars. We have learned that dying stars manufacture vast quantities of solid matter and distribute it throughout the galaxy. The discovery of this link between heaven and Earth is one of the most remarkable stories of modern astronomy.

Mineralogy in Space

The beginning of stellar mineralogy dates from the late 1960s and the first infrared telescopes. A number of old red giants showed an emission feature at the mid-infrared wavelength of 10 microns. These stars have masses similar to the Sun's but have evolved to such an advanced stage that they are shedding massive stellar winds and are only about a few million years from becoming planetary nebulae. The 10-micron feature was quickly identified as the signature of micron-size silicate



Above: **Mid-infrared spectra of red-giant stars obtained 20 years ago by the Infrared Astronomical Satellite. The 10-micron and weaker 18-micron features, due to amorphous silicate dust, are seen in emission in two stars (upper graph) and in absorption in two others. Courtesy Space Astronomy Laboratory, University of Calgary.**

Facing page: **Interstellar dust, once thought to be simple, contains everything from soot to silicates to sapphire. Standing out eerily against the glow of IC 2944 in Centaurus are Thackeray's Globules, discovered in 1950 and imaged in extraordinary detail by the Hubble Space Telescope. The largest mass in this image is actually two separate clouds that overlap along our line of sight. Each spans about 1.4 light-years along its longest dimension, and together they contain about 15 solar masses of gas and particulate matter.**

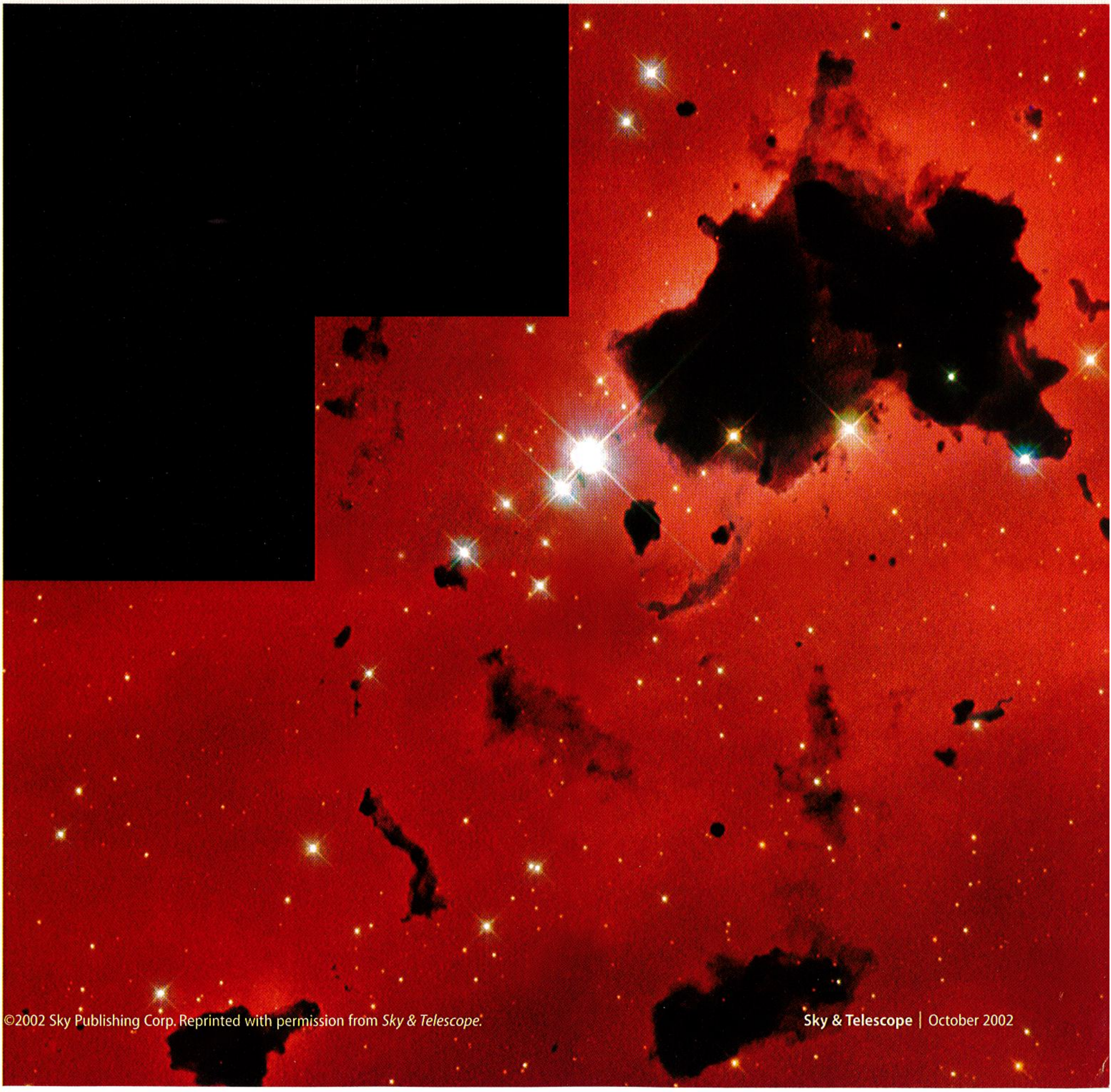
grains. Silicates comprise a wide variety of minerals based on silicon-oxygen bonds, often including magnesium and iron — many of the same substances making up common rocks.

While rock dust in space may not seem to be a big deal to geologists, it is to astronomers. Since the 1950s we have known that all atoms heavier than helium are made within stars. In the atmospheres of cool stars, some of these assemble into gaseous molecules; dozens of such chemicals have been found in stellar surroundings, first by optical spectroscopy and later by microwave and infrared spectroscopy. Astronomers can conceive many ways to make gas molecules in stellar and space environments, but not solids — certainly not under the very low-density conditions in a red giant's atmosphere, which is less than a billionth as dense as Earth's.

Worse yet, solids melt at high temperatures. Red giants may be cool by stellar standards, but their surfaces are still around 3,000°K, far hotter than the melting or vaporizing points of most metals and minerals. Apparently solid dust grains condense above the stellar atmosphere, where the temperature is less hot. However, the fact that the gas density here must be even lower makes the process even harder to understand.

The Infrared Astronomical Satellite (IRAS) opened a new era in space mineralogy in 1982. During 10 months it surveyed 97 percent of the sky in the mid- and far-infrared spectral bands. Onboard was a Dutch-built infrared spectrometer, the first to be flown in space. It obtained spectra of more than 50,000 sources, including more than 4,000 red giants in which our research group has found silicate emission at 10 and 18 microns. (The former comes from Si-O bonds vibrating by stretching and compressing; the latter is due to the bending vibration of Si-O-Si lineups.) So there is no doubt that the manufacture of silicates is very common among old stars.

While the stellar silicates show some similarity to those in Earth's crust, they are not the same. In fact, *no* terrestrial min-



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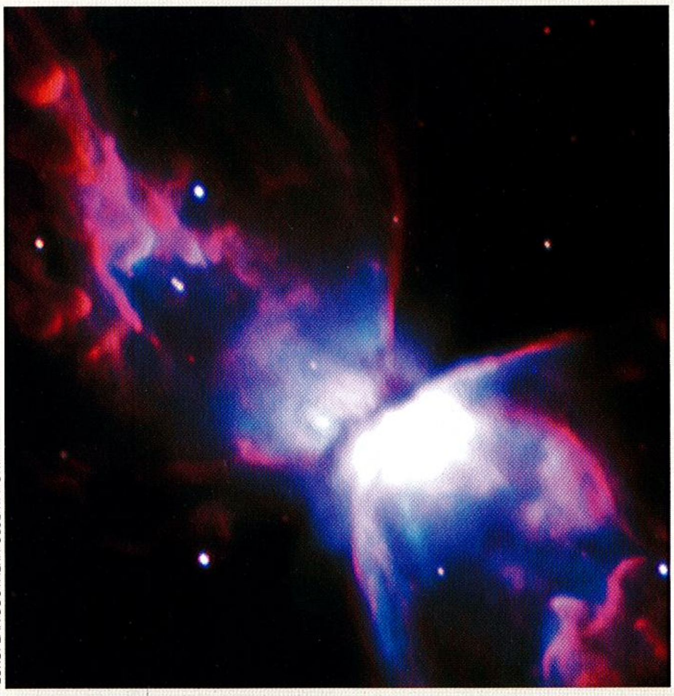
eral exactly matches the spectroscopic properties of this celestial dust. Most terrestrial silicates are in crystalline form, showing narrow, sharply defined spectral signatures not seen in their stellar counterparts. Apparently the silicon-oxygen bonds near stars are not in crystal structures but in a disorganized, "amorphous" form more like glass.

Another solid material commonly seen in old stars, especially red giants that are rich in carbon, is silicon carbide (SiC). On Earth its artificial crystal form is known as carborundum. The IRAS spectrometer found more than 700 stars displaying it. Generally speaking, old red giants show either silicates or silicon carbide, depending on whether they are oxygen- or carbon-rich.

If solid bits of silicate and silicon carbide can condense in stellar atmospheres, could other minerals be present too? The first solid materials to condense out of a hot gas ought to be those that form solids at the highest temperatures. Aluminum and titanium oxides are good candidates, not only because of their high melting points but also because of the relatively high abundance of these two elements. In the IRAS spectroscopic data, Irene Little-Marenin (Wellesley College) detected a feature at 13 microns in a number of red giants. Astronomers from the University of Amsterdam suggested that it could signal an amorphous, glasslike form of aluminum oxide, Al_2O_3. Its crystal form, corundum, is a colorless mineral that is the hardest known natural substance after diamond. Following up on this idea, and using infrared observations by NASA's Kuiper Airborne Observatory, William Glaccum (University of Chicago) suggested that the source of the mysterious feature at 13 microns is actually sapphire. This is a form of corundum in which some aluminum atoms have been replaced by titanium, giving the clear crystal a bluish color.

These suggestions were difficult to test due to a lack of good infrared laboratory spectra of corundum and sapphire. Not many facilities can do these measurements, but one that can is at the Max Planck Institute in Jena, Germany. Scientists at Jena considered rutile (titanium dioxide, TiO_2) and spinel (magnesium aluminum oxide, $MgAl_2O_4$) in addition to corundum as the possible source of the 13-micron feature. Rutile is a reasonable possibility because gaseous TiO is widely present in the optical spectra of red giants that are rich in oxygen. On Earth, very fine needles of rutile sometimes appear in rubies and sapphires, creating a star-shaped pattern of reflected light.

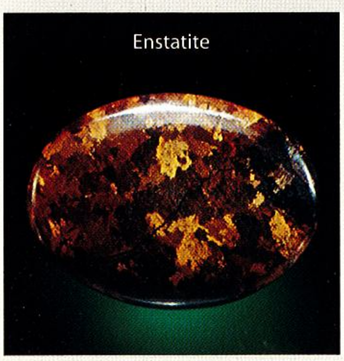
In 1995 the European Space Agency launched the Infrared Space Observatory (ISO), which carried infrared spectrometers much more sensitive than the one on IRAS. Working with colleagues from Vienna, the Jena group compared their laboratory results with the superior data from ISO and concluded that the most likely candidate for the 13-micron feature is spinel. On Earth this mineral exists in a variety of colors from

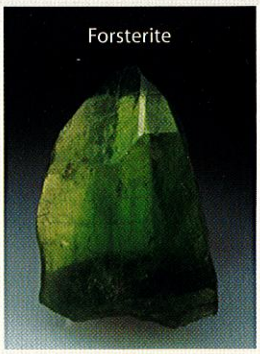


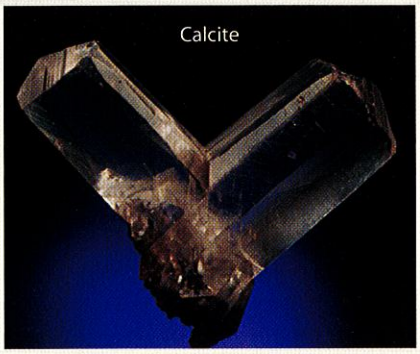
EUROPEAN SOUTHERN OBSERVATORY

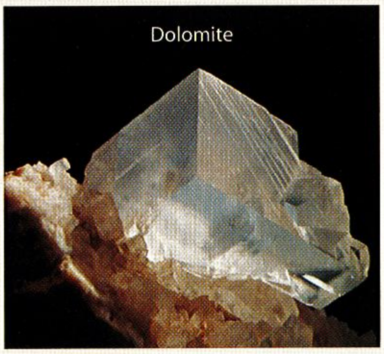
EUROPEAN SPACE AGENCY AND GARRELT MELLEMA (LEIDEN UNIVERSITY)

The butterfly-shaped planetary nebulae NGC 6302 *(left)* and NGC 6537 *(above)* display infrared spectral signatures of powdered enstatite ($MgSiO_3$), forsterite (Mg_2SiO_4), calcite ($CaCO_3$), and dolomite ($CaMg(CO_3)_2$). These minerals must have been created in ways entirely different from the geologic processes that form their crystals in the Earth, such as the ones shown below. Mineral photographs by Jeffrey A. Scovil.









red to blue, the result of some of the magnesium atoms being replaced by iron, zinc, or manganese, and aluminum atoms being replaced by iron or chromium. Red spinels are sometimes confused with rubies; the 17-carat "Black Prince's Ruby" in the British Imperial State Crown is in fact a spinel.

Whether sapphire, ruby, or spinel, old stars have clearly demonstrated their ability to synthesize gemstone dust without difficulty, even under unforgiving high-temperature, low-density conditions.

Rocks and Limestones

Despite our natural human interest in gems, we should mention some more down-to-earth minerals. One of the ISO mission's legacies is the detection of crystalline silicates and carbonates, the constituents of common rocks and limestones, respectively. Clear detections of forsterite (Mg_2SiO_4) and enstatite ($MgSiO_3$) have been made in a number of planetary nebulae, including NGC 6302 and NGC 6537 on the facing page.

Both these nebulae have butterfly or hourglass shapes. The ISO measurements were made toward the waist of the objects, where we believe most of the solid minerals lie. The gases in these nebulae are as hot as 10,000°K, and the central star of NGC 6302 is one of the hottest stars known, at about 250,000°K. How these nebulae manage to produce large quantities of crystalline silicates and carbonates is completely unknown.

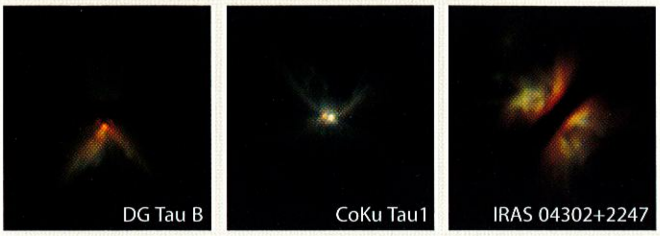
Planetary nebulae are gaseous ejecta from former red giants (both the oxygen- and carbon-rich varieties) that have reached the ends of their lives (*S&T:* July 1996, page 38). The fact that *crystalline* silicates are found in planetary nebulae suggests that something may have changed the red giants' amorphous, glassy silicate particles into crystals. Alternatively, the crystalline grains may have formed in the nebulae on their own. Since these nebulae are only a few thousand years old, condensation within them would have been rapid and efficient.

Another common class of minerals is the limestones, which on Earth are products of weathering. Calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), the main components of limestone, are believed to form in the sea. How a hot planetary nebula like NGC 6302 manages to produce large quantities of calcite and dolomite without water is a complete mystery. This issue was hotly debated at an International Astronomical Union symposium on planetary nebulae in Canberra, Australia, in November 2001. No theory has yet come close to explaining the observed abundance of these minerals.

Diamonds Are Forever

Diamond is a form of pure carbon. The abundance of carbon in the universe has long led astronomers to speculate about interstellar diamonds, so the 1987 discovery of submicroscopic diamond grains in a meteorite was seen as a nice confirmation of our suspicions that extraterrestrial diamonds do exist. On Earth diamonds are created deep underground at high pressures, temperatures, and densities. Interstellar diamonds are conjectured to form in strongly shocked gas, perhaps in supernovae, though new studies suggest that nanodiamonds may be made in protostellar disks, and possibly in the solar nebula itself (see page 25).

Diamonds are nearly transparent in visible light and also lack distinct spectral features in the infrared, so interstellar diamonds are extremely difficult to detect directly. By the end of the 20th century the outlook for finding them in space was bleak. However, in the early 1980s astronomers found a pair of



Stars are surrounded by thick dust at birth as well as at death. Young stars with visible disks, such as these 450 light-years away in Taurus, are prime astronomical hunting grounds for rocks and minerals. These infrared images were taken by the Hubble Space Telescope's NICMOS camera. Each frame is about 2,000 a.u. square. Courtesy D. Padgett, W. Brandner, K. Stapelfeldt, and NASA.

unidentified infrared features at 3.43 and 3.54 microns in young stellar objects called Herbig *Ae*/*Be* stars. The best examples of stars displaying them are HD 97048 in the Chamaeleon dark cloud and Elias 1 in the Taurus dark cloud. Using ISO, a group of Belgian astronomers observed these two stars and confirmed the ground-based results but were unable to offer any new insights into their origin.

Olivier Guillois (French Atomic Energy Commission), who has been studying the infrared properties of carbonaceous compounds, took a strong interest in these astronomical results. He searched the literature and found that a group of scientists at the Institute of Atomic and Molecular Science of the Academia Sinica in Taiwan had successfully taken infrared spectra of diamonds. The Taiwanese group, led by Huan C. Chang, irradiated synthetic diamond with hydrogen — and found that hydrogen atoms attached themselves to the corners of diamond crystals. While pure diamonds have very few infrared signatures, the hydrogenated crystals produced exactly the two emission features seen at the stars. Since interstellar gas is mostly hydrogen, it's not surprising that interstellar diamonds would be covered with it. This identification represents the first definite detection of diamond in space.

Guillois and his colleagues estimate that the region around HD 97048 contains about 100,000 to 1,000,000 trillion (10^{17} to 10^{18}) tons of diamond dust — enough to make a pile some 200 to 400 kilometers wide and tall. When we consider that on Earth we measure diamonds in units of carats (0.2 gram), such a vast quantity of diamond at a star is truly mind-boggling.

At the beginning of the 21st century we have entered a new era of stellar mineralogy. It is clear that old red giants make a variety of minerals, including some real gems. They do so under the most unfavorable conditions, at extremely low densities and high temperatures. Furthermore, the synthesis takes place on a large enough scale to strew the entire galaxy with these substances. Most amazingly, we now can hold in our hands (in the form of grains in meteorites) materials that were made beyond the solar system.

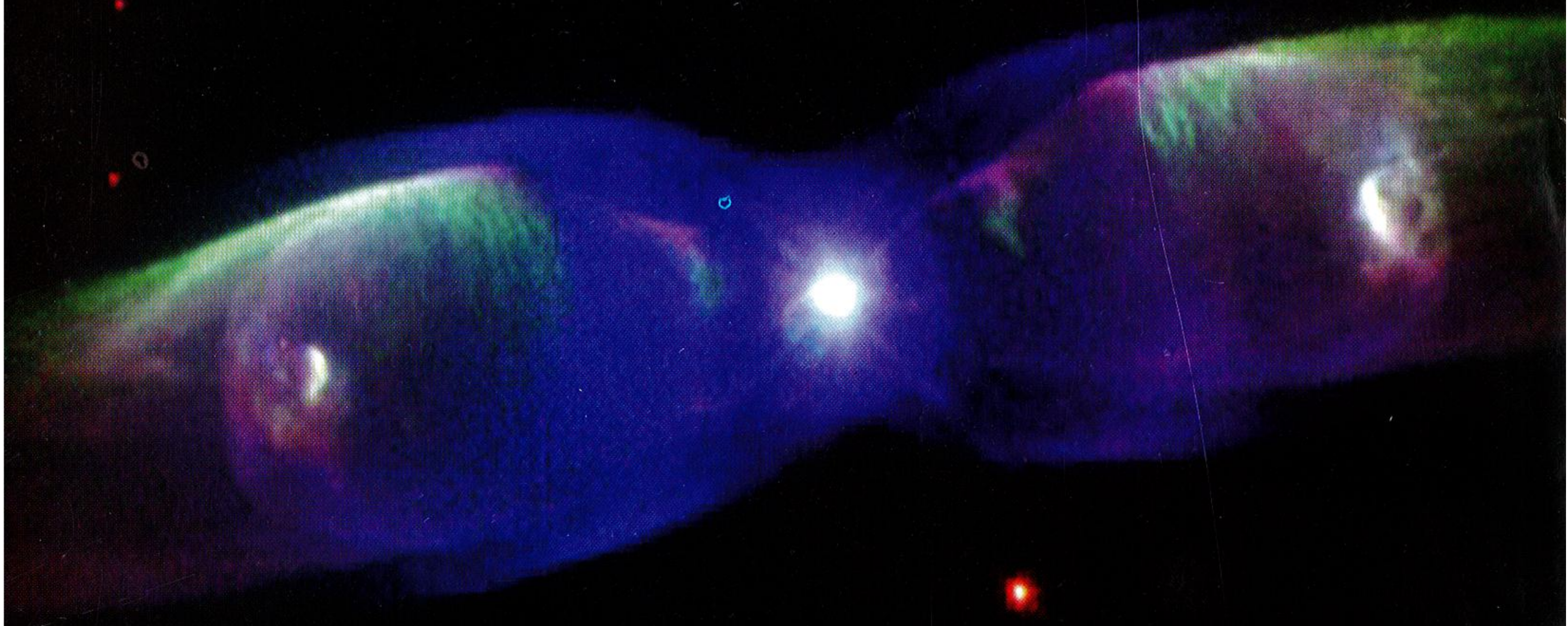
It may be centuries before humans travel to stars, but it is comforting to know that every year, stars deliver to us presents in the form of tiny gems to study and treasure.

SUN KWOK, *professor of astronomy at the University of Calgary and Killam Fellow of the Canada Council for the Arts, has done extensive research on planetary nebulae and infrared spectroscopy of stars. He recently authored* The Origin and Evolution of Planetary Nebulae *and* Cosmic Butterflies, *both published by Cambridge University Press.*

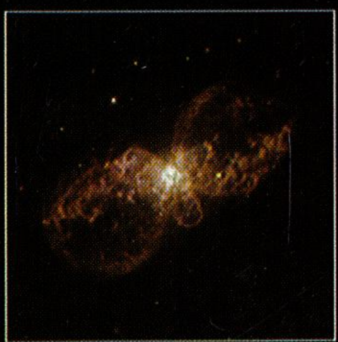
Sun Kwok

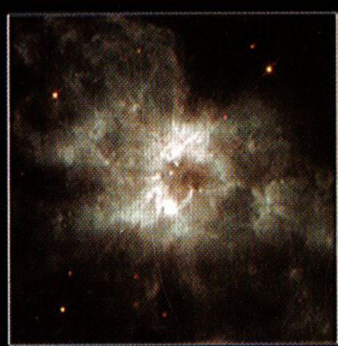
Cosmic Butterflies

The Colorful Mysteries of Planetary Nebulae



- Many spectacular images from the *Hubble Space Telescope* are showcased for the first time.
- Explains the life of stars from birth to old age.
- Covers star dust, white dwarfs, and black holes.





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