Recent observations have lent tantalizing support to a controversial idea: Earth's fossil fuels were born of dying stars.

Mining for COSMIC COAL

by Sun Kwok

Fossil fuels: They heat our homes, cook our foods, light our streets, and run our transportation. Life without them is unimaginable, even in the face of alternative, non-combustible energy sources. What might be harder to fathom is that these "fossil" fuels may not derive from the decomposition of ancient life on Earth, as scientific consensus has so long held. Instead, they may have come from the exhalations of dying stars, and were eventually packed in the belly of our planet as it formed four and a half billion years ago.

As the name implies, fossil fuels are believed to be products of broken down plant and animal debris deposited in layers near Earth's surface, and transformed through intense heat and pressure over several hundred million years. These fuels come in numerous forms: such as gas (natural gas), liquid (petroleum or crude oil), or solid (coal). They are generally found in sedimentary basins along continental shelves.

The notion that fossil fuels are of biological origin goes back to the late 19th century. And since Earth's flora and fauna only exist near its surface, deposits of oil, gas, and coal — also referred to as hydrocarbons — were expected to be confined to our planet's crust.

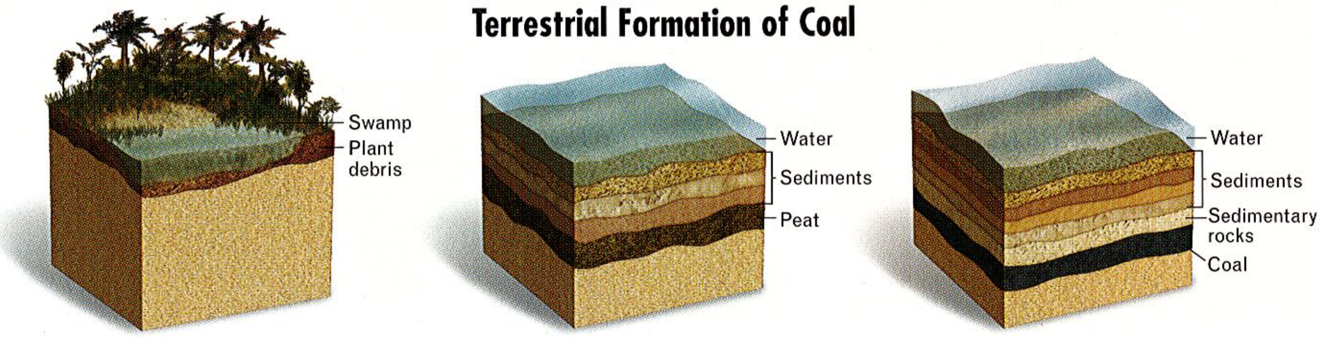
In 1977 Thomas Gold, an astronomy professor at Cornell University, challenged the notion that fossil fuels are born of biological processes. He claimed that our planet's hydrocarbons are extraterrestrial in origin, born in interstellar clouds and carried to Earth by meteoroids and/or comets.

Gold's theory ignited from a discovery in the 1970s that infant Earth was never a molten sphere, as once believed, but was gradually built up from solids — the accretion of dust and rocks in the solar nebula. If hydrocarbons were already present in the pre-solar system mix, he thought, then our developing planet would sweep them up and stow them in its interior. He thought that natural gas, in particular, must now exist at great depths below Earth's crust. These low-weight hydrocarbons would gradually "float" upward toward the planet's surface as plumes of flammable gas or, if trapped inside porous rocks, as wells of oil and gas retrievable by drilling.

If true, Gold's theory may have major ramifications. Our planet's oil and gas reserves will be much, much larger than current estimations. This, in turn, will affect exploration strategies, because these cherished hydrocarbons will not be confined

Growing astronomical evidence has led some scientists to believe that coal and other fossil fuels are of extraterrestrial origin, not from the slow decay of organisms in Earth's crustal layers. Corbis

Terrestrial Formation of Coal



Run-off of rainfall and melted snow carries dead plant material into bodies of water.

Layers of sediment evolve when sand and other materials settle, which then compacts organic material into peat.

Sediment forms an impervious layer called cap rock, which compresses peat and transforms it into coal.

All illustrations/*ASTRONOMY*: Elisabeth Rowan

to sedimentary rocks in the uppermost layers of Earth's crust, but will also bubble in reservoirs a few hundred miles deep.

Old Stars as Molecular Factories

Although no empirical evidence for Gold's hypothesis existed in the late 1970s, recent astronomical observations have injected his theory with a new dose of credence. Old stars nearing the end of their lives manufacture hydrocarbons with a degree of complexity never imagined. These stars then continue to fertilize the galactic environment with the release of large quantities of organic compounds. Because the solar system was created from an interstellar cloud, Earth may well have inherited some of these hydrocarbon-rich materials.

Hydrocarbons, as one might guess, are primarily made up of two elements: hydrogen and carbon. While the Big Bang produced hydrogen in the early moments of the universe, stars are the carbon factories. As a sun-like star ages, it becomes brighter, larger, and redder. Its central core also becomes denser and hotter — so hot, in fact, that helium atoms burn and fuse into carbon. In the last one million years or so of a star's life, these carbon atoms creep to the surface and fill the near stellar atmosphere. Such stars are then labeled carbon stars.

While astronomers have known about the stellar origin of carbon for roughly fifty years, only recently have they realized that these old carbon stars are also capable of turning carbon atoms into molecules. This discovery process began in the early 1970s, when telescopes equipped with high-frequency radio receivers first detected the simple molecule carbon monoxide (CO). Using radio receivers operating at 100 gigahertz (several hundred times higher frequency than commercial television), researchers found an old star called CW Leonis that produces and ejects trillions of tons of carbon monoxide molecules into space every second. We now know that CW Leonis is only one of many thousands of other similar stars "polluting" the Milky Way Galaxy at this very moment.

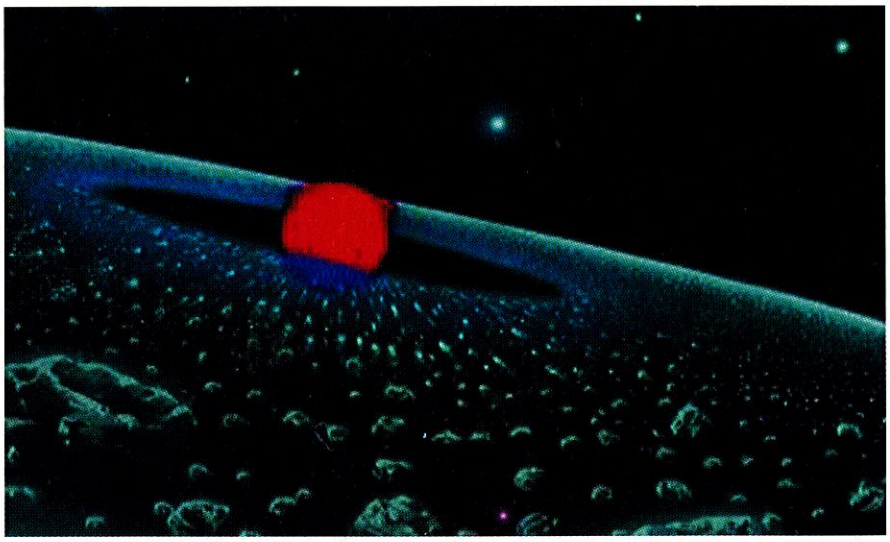
Among these carbon stars, researchers have detected over fifty molecules, including organic species such as polyacetylene radicals (C_6H, C_8H), cyanopolyynes (like HCN and HC_3N), and sulfuretted chains (C_2S, C_3S). The largest molecule, HC_9N, has an atomic weight of 123, almost twice the molecular weight of the simplest amino acid glycine. Some of these molecules are so alien to traditional chemists that a new scientific discipline called astrochemistry has evolved to study these exotic chemical species.

Astronomers have witnessed incredibly high ejection rates of these strange molecules from their parent stars, which can only mean that they are synthesized and replenished on time scales of just a few hundred years. These results are quite surprising. Researchers have come to recognize, however reluctantly, that carbon stars are extremely efficient organic-chemical plants.

Hydrocarbons and Coal from Stellar Chimneys

Further surprises were yet to come. In 1977, three astronomers at the University of California at San Diego, equipped with an infrared telescope on NASA's Kuiper Airborne Observatory, discovered several mysterious chemical-emission features in the planetary nebula NGC 7027, which is known to have descended from a carbon star like CW Leonis. Since these curious infrared features could not be matched with any known terrestrial atoms or

The carbon star CW Leonis has fathered an impressive family of carbonaceous molecules.
Harvard-Smithsonian CfA



molecules, they were dubbed Unidentified Infrared (UIR) features.

These emission features remained unidentified, as astronomers failed to appreciate the possible complexity of the carrier molecules.

Then in 1981, Walt Duley, a professor of physics at York University (now at the University of Waterloo) and David Williams of the University of Manchester (now at University College–London) suggested that the UIR features represent aromatic compounds. Aromatic compounds are molecules with ring-like structures — benzene and toluene are the most common everyday examples. (Benzene is the simplest aromatic hydrocarbon and serves as a building block for more complex polycyclic aromatic hydrocarbons, or PAHs, which are commonly used in drugs, dyes, plastics, and pesticides.) Researchers were skeptical at first because most of them found it hard to believe that such complex organic molecules could exist in deep space. After twenty years and many more observations, they have finally come to accept the aromatic origin of the UIR features, but are as yet unsure about the exact form of the aromatic compound found in these planetary nebulae. All we do know is that these mystery molecules contain a hundred or more hydrogen and carbon atoms.

Since we haven't seen these aromatic compounds in carbon stars, detecting them at a later stage of evolution — in planetary nebulae — implies that these compounds are born in the diffuse clouds surrounding the stars. In looking at theories of stellar evolution, most imply that only a few thousand years separate the stages of a carbon star and planetary nebulae. Hence, these aromatic compounds must have been transformed from simpler molecular forms over a similar, astronomically brief, timescale.

To further pinpoint the chemical process, it would be useful to study the transitional objects between carbon stars and their successive planetary nebulae. These objects, called proto-planetary nebulae, evolve rapidly and exist a mere one thousand years. Because of their rapid evolution, they are extremely rare and difficult to catch. Beginning in the early 1980s, I became interested in searching for these elusive creatures. Now, after 15 years, we have discovered approximately thirty proto-planetary nebulae.

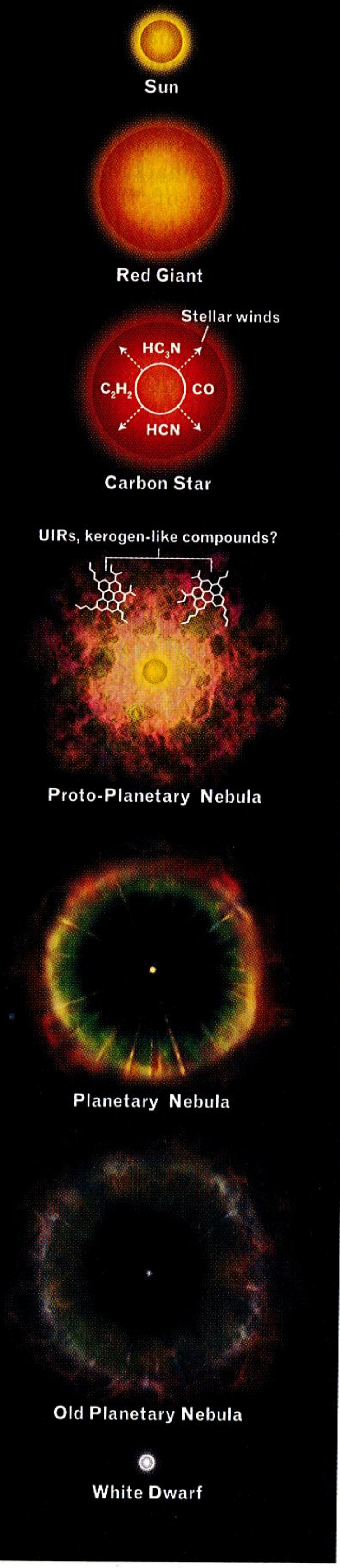
In 1995, the European Space Agency launched a satellite called the Infrared Space Observatory (ISO), which has capabilities that are well suited for hunting down and identifying these curious chemical processes inside proto-planetary nebulae. By observing a number of these nebulae, astronomers have discovered that they reveal a much richer spectrum than expected, showing signatures of so-called aliphatic chains attached to aromatic rings (aliphatic chains are commonly found in fats and hydrocarbons). It is now theorized that when these substances formed, they were made in a disorganized manner with a mixture of chemical structures. But with a little time accompanied by intense ultraviolet radiation from the parent star, these molecules soon shed part of their outer structures and become aromatic in nature.

A group of scientists led by Renaud Papoular of the Atomic Energy of France has taken great interest in these observations. They compared their infrared observations with those of coal and found amazing similarities. Coal is composed of a mixture of aromatic rings and aliphatic chains, and its black color also correlates well with our findings. Papoular's team is particularly interested in relating some astronomical results to kerogens — insoluble, tar-like, organic compounds distributed in rocks — which are thought to be the likely source of fluid hydrocarbons such as oil.

These suggestions first seemed totally incredible. Scientists have long thought coal was only created under extremely high pressure inside Earth, a far cry from the low-pressure environments found in space. Moreover, astronomers found it aesthetically unappealing that a dirty, black substance could spawn from otherwise brilliant heavenly bodies.

However, the spectral resemblance between laboratory and astronomical measurements is so strong, we now believe that even if the mystery substance we observe is not coal, it must be something shockingly similar. For example, Duley has blasted graphite with lasers and created a synthetic material called hydrogenated amorphous carbon (HAC), which also

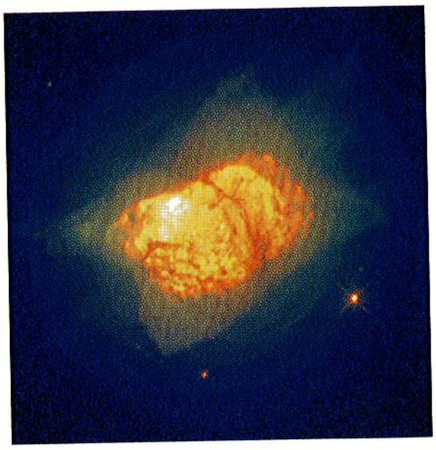
A Stellar Refinery?

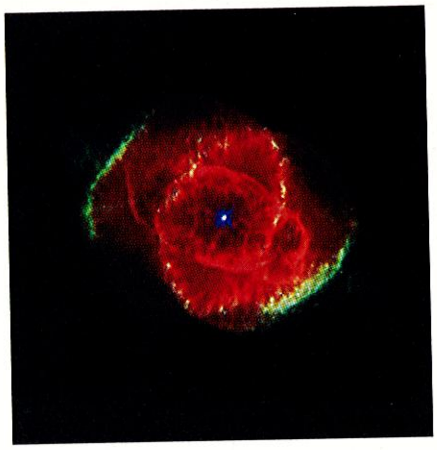


The eons-long evolution of a sun-like star through succesive stages thought to produce and distribute some of the universe's more complex carbon-based chemical species.

shows some similarity to our observed features. HAC is different from coal in that it contains fewer impurities such as oxygen and nitrogen, but the chemical structures of the two are an extremely close match. At about the same time a team of Japanese researchers synthesized another artificial coal-like substance called quenched carbonaceous composite (QCC)in the laboratory. Remarkably, QCC also shows some of the rich aromatic/aliphatic features seen in the infrared spectra of numerous protoplanetary nebulae.

These dying stars are churning out organic matter with a high degree of complexity; whether the substance is coal, HAC, or QCC, it is too early to tell. But it looks like the creation of complex organic molecules is no longer the sole domain of Earth.





Hubble captured these images of planetary nebulae NGC 7027 (left) and the Cat's Eye Nebula,NGC 6543, (right), which may hold among their splendor coal-like substances. NASA/STScI.

An Infinite Supply of Oil?

The geological community still gives Thomas Gold's theory of the abiogenic origin of fossil fuels little, if any, weight. One of its objections is that primordial hydrocarbons are unlikely to survive the high temperature and shock generated in the process of accretion during Earth's formation. In Gold's original "deep-Earth gas theory," he only considered simple hydrocarbons as primordial gas. At that time, of course, he didn't know that stars can manufacture organic matter as complex as kerogen. Solids like kerogen are certainly more resilient than any gas, and have a much greater chance of surviving the violent physical forces involved with our planet's birth.

To explain the existence of coal, Gold hypothesized that microorganisms deep inside Earth may play a role in converting hydrocarbons into coal through so-called hydrogen extraction. But if kerogen is indeed an early earthly stowaway, then this hypothesis is unnecessary. Coal evolves from kerogen through the natural loss of hydrogen, oxygen and nitrogen. Petroleum is often found in sedimentary rocks rich in kerogen and is believed to simply degrade from kerogen over time. Both processes are accompanied by a release of natural gas.

Is there enough celestial organic matter to account for Earth's known reserves of coal, oil, and gas? We know that complex hydrocarbons are routinely produced by stars and ejected in large quantities out into interstellar space. Our best estimate is that carbon stars pump out the equivalent of the mass of the sun (300,000 Earth-masses) in the Milky Way Galaxy every year. Even if a small fraction of these hydrocarbons is in the form of organic matter such as kerogen or HAC, over the several-billion-year lifetime of the galaxy, well, that's a substantial amount (over a trillion Earth-masses). The solar nebula, from which our solar system was formed, was likely to have contained remnants (possibly on the order of 1,000 Earth-masses) of these organic compounds. Whether these compounds survived Earth's birth pangs and stayed intact deep inside the planet remains uncertain. But we also have to remember that although our planet seems immense to us, it is but a speck of dust on the galactic scale. Since the total amount of carbon contained in kerogen, coal, oil and gas in our planet's crust is about 1 millionth (10^{-6}) of Earth's mass, even a small amount of extraterrestrial organic matter could easily overwhelm our known fossil-fuel deposits.

As remote as these possibilities are, we cannot help but ponder their implications. The belief that there may be a finite supply of fossil fuels plays a significant role on the world stage. Diplomatic alliances are made and wars are fought in order to secure energy supplies. Given the important consequences, how can we afford not to look further into this question? ■

Proto-planetary nebulae like CRL 618 just might be the universal birthplace of complex organic molecules. NASA/STScI

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