COMET HALE-BOPP

Stardust Memories

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The nature of comet studies has changed profoundly in the last two decades. From prosaic issues of the identities of parent molecules, molecular production rates, tail behavior, and so forth, attention has shifted to the origin of the cometary material in the solar system's nascent molecular cloud, organic matter preserved from its origin on dust grains in the interstellar medium, and questions of the origin of life on Earth and other planets. This change began in the mid-1970s, as planetary scientists around the world began to plan for spacecraft encounters with comet P/Halley on its approach to the inner solar system, and continues as we carry our quest for origins to the most fundamental level. Several reports in this issue on pages 1900–1919 (*1–7*) describe observations of comet Hale-Bopp (or more dryly, C/1995 O1), the great comet currently in our skies. Although some of this work is cast in traditional terms, some of it emerges from the hardening mold of the new paradigm; through cometary messengers from far beyond the planetary region of our solar system, life on Earth is connected to stardust.

Comets are an integral part of two scientific revolutions currently in progress. In geology, impacts on Earth by comets and asteroids are now seen as having given rise to the origin of our moon and having shaped the crust. In biology, comets are emerging as the givers and takers of life; they provided early Earth with most or all the volatiles (water, carbon dioxide, and nitrogen, for example) essential to life (*8*), as well as a major dose of complex organic molecular material that may have helped get things started about 4 billion years ago. Subsequent crust-shattering impacts pruned earliest life, perhaps to the point of complete extinction, and were followed by one or more repeated origin episodes. Infrequent but ecologically significant comet and asteroid impacts in the last 10% of Earth's history are now taken seriously as agents of the mass extinctions that abruptly and emphatically redirect biological evolution planetwide.

Many lines of evidence support the contention that comets are derived from interstellar ices that condensed on dust grains ejected from evolving stars throughout the galaxy (*9*). This icy stardust is subjected to varying degrees of radiation processing by ultraviolet light and charged particles from nearby stars, producing a rich interstellar chemistry resulting in identified organic molecules containing as many as nine carbon atoms (*10*). The more complex polycyclic aromatic hydrocarbons observed in interstellar dust may not be excited to emission in

Artist's rendition of comet Hale-Bopp showing the nucleus, which is approximately 30 to 40 km in size. [Painting by W. Hartmann]

the spectra of comets, although interplanetary dust particles, some of which are derived from comets, often contain them in abundance. Even now, 300 tons of complex organic matter in the form of comet and asteroid dust filters down through our atmosphere every year (*11*) as Earth sweeps out its annual path of nearly a billion kilometers around the sun.

The list of molecules found in comets closely parallels that for the ices of the dense clouds of the interstellar medium (*1, 9*). Notable among these are CO_2, H_2O, CO, CH_3OH, and the progenitors of the voluminous cometary CN. Methanol (CH_3OH) is of particular interest because, after H_2O, it is often the second or third most abundant component in both interstellar and cometary ices, and it is the starting point of a rich chain of photochemical reactions. Although some of the original molecules that froze onto interstellar silicon oxide grains appear to be present in comets, some of the icy material may have been photolyzed to form refractory organic solids, such as a polymer of formaldehyde and hexamethylenetetramine $(CH_2)_6N_4$ (*12*). In a wet acidic environment, these molecules are chemical pathways to amino acids.

The drama of Hale-Bopp began on 23 July 1995, when Alan Hale and Thomas Bopp independently found (*13*) the object that now bears their names at 7.1 astronomical units (AU) from the sun. Discoveries of comets so far from the sun are rare and always signal the possibility of a particularly large one (larger than Halley, which has an effective diameter of about 10 km). Evidence points to a diameter of 30 to 40 km for Hale-Bopp, based in part on the comet's especially voluminous production of gas and dust, which is greater at 7 AU from the sun than most comets yield at 1 AU (*2–4*).

In orbit since 1995, the European Infrared Space Observatory (ISO) is ideally positioned for views of the comet unobstructed by Earth's atmosphere. Crovisier and colleagues (*1*) present ISO spectra of the comet and their derivation of the nuclear spin species of the most abundant molecule, H_2O. The resulting ratio of the ortho and para states suggests that water condensation occurred at about 25 K, a temperature representative of dense interstellar molecular clouds and colder than that derived for some other comets (*9*).

An especially valuable series of measurements with radio telescopes began in France and Hawaii immediately after Hale-Bopp was discovered (*5*), giving the first opportunity to observe the onset of sublimation of nine molecules that are of special importance in driving cometary activity and composition. It will now be possible to compare quantitatively the sublimation sequence in a comet with interstellar ice analogs in the laboratory and thereby pursue the connections of comets to the interstellar medium in greater detail. The sequence of sublimation that drives comet activity is already becoming clearer. Beyond about 4 AU, evaporation of the highly volatile CO ice ejects gas-charged dust from localized regions on the comet's nucleus. Too tiny to radiate all the heat they receive from the sun, these par-

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ticles warm up inordinately and release the molecules they carry as gas.

As in the interstellar medium, much of the dust from comets consists of silicate minerals, but despite the similarities, there are puzzling differences. For example, interstellar dust shows the absorption signature of amorphous particles with a silicate composition, whereas Hale-Bopp and other comets have crystalline silicate, probably in the form of Mg-rich olivine (*4*, *6*, *14*). In the interstellar medium, HCN is seen as a gas, whereas in solid interstellar grains, a molecule designated "XCN" is observed, but "X" is unknown. In comets, HCN and CH_3CN are seen in the gas phase at radio wavelengths, as reported by Biver *et al.* (*5*), and CN emission is very strong, as reported by Wagner and Schleicher (*7*). The source of the CN is unknown; HCN and CH_3CN are part of the solution, but there must be some other source of volatile SCN producing the strong CN emmission seen by Wagner and Schleicher (*7*) and by many other investigators (*9*).

Grains of various kinds of ices are also ejected by CO. Particles of frozen H_2O were found in the coma surrounding Hale- Bopp at 6.8 AU from the sun (*15*). The infrared spectrum of the ice particles suggests that the water was probably in the amorphous state of its original condensation in the interstellar cloud. The new radio wavelength data show that water ice grains were still present at 3.5 AU (*5*), but by the time the comet reached about 3 AU, water was evaporating directly from the comet's solid nucleus.

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The tons of evaporating ices and dust grains being disgorged by Hale-Bopp each second carry the comet's encrypted secrets into the fields of view of telescopes around the world and in space, and eager astronomers are decoding the spectrum molecule by molecule, from ultraviolet through radio wavelengths. Isotopes of carbon, oxygen, and nitrogen are showing up in the molecules detected with radio telescopes (*16*), and their distributions will provide key information on the starting material of comets and the degree of chemical processing that it has experienced. The increased understanding afforded by this very bright comet bears not only upon the origin of these icy transients from beyond the planetary region of the solar system but upon our own origins as well.

References and Notes

1. J. Crovisier *et al.*, *Science* **275**, 1904 (1997).
2. D. G. Schleicher *et al.*, *ibid.*, p. 1913.
3. H. A. Weaver *et al.*, *ibid.*, p. 1900.
4. R. Rauer *et al.*, *ibid.*, p. 1909.
5. N. Biver *et al.*, *ibid.*, p. 1915.
6. T. L. Hayward and M. S. Hanner, *ibid.*, p. 1907.
7. R. M. Wagner *et al.*, *ibid.*, p. 1918.
8. A. Delsemme, in *Comets and the Origin and Evolution of Life*, P. J. Thomas, C. P. Chyba, C. P. McKay, Eds. (Springer, New York, 1997), pp. 29–67.
9. M. J. Mumma, P. R. Weissman, S. A. Stern, in *Protostars and Planets III*, E. H. Levy and J. I. Lunine, Eds. (Univ. of Arizona Press, Tucson, 1993), pp. 1177–1252.
10. W. M. Irvine, *Origins Life Evol. Biosphere*, in press.
11. G. Love and D. E. Brownlee, *Science* **262**, 550 (1993); Y. J. Pendleton and D. P. Cruikshank, *Sky Telesc.* **87**, 36 (1994).
12. M. P. Bernstein *et al.*, *Astrophys. J.* **454**, 327 (1995).
13. A. Hale and T. Bopp, *IAU Circular 6187* (1995).
14. A. T. Tokunaga and T. Y. Brooke, *Icarus* **86**, 208 (1990).
15. J. K. Davies *et al.*, *Icarus*, in press.
16. *IAU Circular 6566* (1997); *IAU Circular 6567* (1997); *IAU Circular 6568* (1997).

APPLIED PHYSICS

Single-Molecule Transistors

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Chemistry and condensed matter physics have recently converged in the development of ultrasmall devices with nanometer-length scales. The most interesting and flexible of these structures are basically three-terminal transistors. There are source and drain contacts for sending current through the device, and the third terminal is a gate electrode. An applied voltage to the gate can alter the current from an "on state" to an "off state." In comparison, off-the-shelf silicon transistors have length scales of between 0.3 and 1 μm. These newly developed nanometer-scale transistors consist of only a single molecule, approaching the ultimate limit of miniaturization. This goal was eloquently expressed by Feynman (*1*) in his famous lecture on the possibilities for new devices if one is able to manipulate matter on an atomic or molecular scale. Not only could the device density in an integrated circuit be enormously increased, but also the operation principles of a single transistor could be fundamentally different. Indeed, recent experiments (*2*–*5*) have shown that the device characteristics of a carbon-based single-molecule transistor is completely governed by the laws of quantum mechanics.

The development of electronics based on molecules has for decades been a promising direction for future nanodevices. This field, however, lacked experimental progress until about a year ago. The difficulty had been twofold. First, it appeared that all long and narrow molecules were either semiconducting or insulating. The reason is that one-dimensional electron systems undergo a Peierls transition, which is a tiny rearrangement of the atoms. However, the atomic rearrangement is precisely such that for electrons, an energy gap is opened at the Fermi energy, as in semiconductors or insulators. Luckily, chemists have recently found a long carbon-based molecule in which the Peierls transition is absent, and thus, it can be a one-dimensional conductor. This long molecule is the carbon nanotube. It is one of the fullerenes whose discoverers were awarded the 1996 Nobel Prize in Chemistry (*6*). The first obstacle was overcome by the group of Smalley, one of the laureates, at Rice University. They were able to synthesize large amounts of conducting nanotubes with a diameters of about 1 nm and lengths up to several micrometers (*7*).

The second difficulty had been attaching electrical wires to a single molecule. This technical problem could be solved thanks to fabrication developments in condensed matter physics. In condensed matter, the electronic properties of nanometer- to micrometer-scale devices has been an active research area during the last decade. This area, known as mesoscopic physics, has not only studied fundamental quantum mechanical properties but also has developed fabrication techniques for attaching wires to small pieces of material.

The synergy between the fullerene chemists and mesoscopic physicists is beautifully illustrated in the figure. The metallic strips were first fabricated with electron beam lithography techniques. Then, carbon nanotubes were randomly laid down. Inspection with an atomic force microscope allows one to pick out those devices where a single nanotube connects two metal strips. Smalley's group synthesized the nanotube seen in the figure

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