Molecules between the Stars

The discovery of chemical compounds in interstellar space has led to the new field of astrochemistry and a rethinking of how stars are born.

Chemistry dominates existence on earth—it affects the weather, the flow of energy, and most important for us, it is essential to all life processes. But until about thirty years ago, astrochemistry, or the chemistry of regions beyond the solar system, was a largely neglected field of research. The main reason is that astronomy was then primarily dependent on optical instruments, and the objects in the universe under study were those giving off optical radiation. These are the visible stars and nebulae—the gas and dust clouds between the stars—which are typically so hot that chemical compounds cannot survive in them. Molecules there are torn apart into their atomic fragments as soon as they are formed. The spectra of most stars and nebulae accordingly show lines characteristic of free atoms but no indication of molecules.

There were, however, two notable exceptions. Optical spectra of cool red stars did show complex absorption bands indicating the presence of a few simple molecules such as carbon monoxide (CO) and titanium monoxide (TiO) in their atmospheres. And the spectra of certain other stars showed features resulting from absorption by such molecular fragments, or free radicals, as methylidyne (CH), ionized methylidyne (CH⁺), cyanogen (CN), and hydroxyl (OH). Analysis showed that these molecular fragments were not in the atmosphere of the stars but rather in the cool, diffuse clouds of interstellar gas that lie between the stars and the earth. Until 1963 these were the only interstellar molecules known, and few astronomers paid much attention to them.

Among the triumphs of astrophysics in the past few decades has been the discovery that stars burn by nuclear fusion in their cores with the resultant understanding of the details of the structure and evolution of these objects. We currently have a good idea of how long a star will last before it finally burns out and dies. Chemistry plays only a minor, almost negligible role in most of the lifetime of a star except at its birth—the condensation of a star from an interstellar gas cloud—when it clearly plays a crucial role. The observation thirty years ago of optical absorption lines due to the few simple molecules in interstellar clouds already mentioned was the first piece in a complicated jigsaw puzzle of interstellar chemistry. Thanks to radio astronomers, many more pieces have been turning up in recent years at an accelerating rate. At the time of this writing, some twenty-six different molecules have been identified in interstellar space. There is good reason to hope that when all the evidence is sorted and put together, it will complete our understanding of the full life cycle of the stars.

To comprehend the relation between chemistry and star birth, we must begin with a description of the relationship between the stars and the interstellar gas that makes up about 10 percent of the mass of our galaxy. This gas, like the matter in stars, is composed mostly of hydrogen and helium with small traces of most other elements. When stars approach the end of their normal lifetimes, they first become red giants, like Betelgeuse in the constellation Orion. These aging stars have huge atmospheres that are cool and dense enough to enable tiny grains of graphite, silicates, and other chemical compounds to form. The pressure of the radiation com-
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ing from a star’s interior blows these grains out of the star’s atmosphere into interstellar space, and the grains drag along a good deal of the star’s gaseous atmosphere. This process is probably one of the mechanisms whereby vast regions of interstellar space are filled with cosmic dust and explains the dark areas seen in the Milky Way, especially in the constellations Sagittarius and Scorpius toward the center of the Galaxy. When stars finally die, they often do so with violent supernova explosions, which return most of their remaining gaseous material to interstellar space.

At the same time that some stars are dying, new stars are being born from the interstellar gas. The propensity of the gas to condense through the force of its own gravity causes it to fragment into interstellar clouds. These clouds collapse and fragment still further until the little fragments become hot and dense enough to begin burning as stars. Thus, the interstellar gas is a reservoir to which stars return much of their material at death and from which new stars are born in the Galaxy. An example of this process is found in the Great Nebula in the sword of Orion—a dense gas cloud illuminated by some very bright young stars. With infrared telescopes scientists can observe deep within the dark dust cloud behind the Orion Nebula from which visible light cannot escape. There one finds a number of luminous infrared sources that are probably newly forming protostars. Perhaps in another few million years enough young stars will form in this cloud to illuminate and heat a region of gas much larger than the present nebula. The resultant, spectacular display of hot fluorescent gas would

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bear witness to the formation of a new star cluster. The remaining gas would be so hot it would again dissipate and spread over a vast region of interstellar space. This action may currently be taking place near the young hot stars of the Pleiades cluster, which are bathed in a faint nebula that is probably the remnant of the gas cloud from which the cluster was formed.

Although we understand in general terms that gravity is responsible for the collapse of interstellar gas clouds and the formation of stars within them, the details of the star formation process remain obscure. The situation is analogous to the problem of rain—we know that all rain comes from clouds, but not all clouds produce rain. All stars come from interstellar gas clouds, but not all interstellar clouds produce stars. What are the necessary conditions for the condensation of stars, and what determines the masses of the resulting new stars?

Fortunately, astronomy is no longer limited to relatively short, visible wavelengths. Optically opaque interstellar clouds, within whose depths stars are born, become transparent to infrared telescopes at the longer infrared wavelengths. As have been mentioned, astronomers have observed infrared sources inside the Orion dust cloud and believe these to be protostars. But infrared astronomy is still in its infancy. So far it has provided some information on the temperature and luminosity of protostars, but little of the high-precision spectroscopic information that has yielded so much data about the structure and composition of optically visible stars.

Interstellar dust clouds are also transparent to radio waves, and in the past decade the technology of radio astronomy has developed to the level where high-precision radio spectroscopy is possible. A brilliant series of observations has resulted in the discovery that cool interstellar clouds are filled with molecules.

Unlike an atom, a molecule can tumble end-over-end; its component atoms can also vibrate with respect to each other in internal motions. When a molecule changes its internal motion, radiation is emitted or absorbed at a precise and characteristic frequency. Typically, these frequencies fall in the radio wave or

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infrared range. This circumstance gives each molecule a characteristic radio fingerprint by which astronomers can deduce molecular abundances deep inside an interstellar cloud, just as optical spectra are used to deduce the atomic composition of hot stars and nebulae.

A radio telescope used to identify the composition of interstellar clouds is like a cosmic nose that sniffs around where stars are born. What such a cosmic nose would smell would be the noxious vapors of such compounds as carbon monoxide (CO), hydrogen cyanide (HCN), methyl, or wood, alcohol (CH₃OH), ammonia (NH₃), ether (CH₃OCH₃), and various other molecules, all nicely preserved in formaldehyde (H₂CO). In addition to the twenty-six molecules that have already been seen and identified, a half-dozen or so radio spectral lines have been observed but have not yet been identified with known molecules.

The abundance of interstellar molecules was a great surprise to most astronomers. The environment of interstellar space is a hostile one for molecules. Ultraviolet light from stars destroys most molecules in a decade or so, much less time than that required for new molecules to form. Molecules can survive only in the cool opaque interstellar clouds where dust grains are dense enough to shield them from the high-frequency radiation of starlight.

Besides providing a sheltered environment for molecules, interstellar dust plays a vital role as a catalyst for molecule formation. Chemical reactions proceed extremely slowly at the densities and temperatures of interstellar clouds. By analyzing the radio spectrum lines from molecules, astronomers have determined that these clouds have low gas densities on the order of one million molecules per cubic centimeter, about equal to that in the best laboratory vacuum ever achieved on earth, and temperatures ranging from about -268°C. (5° above absolute zero) to -180°C. The time required under these conditions for two hydrogen atoms, for example, to collide with each other and stick to form a molecule of H₂, the ordinary hydrogen gas found on earth, is far greater than the estimated age of the universe. One hydrogen atom flying around in interstellar space might collide with

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another in a few weeks, but they would hardly ever stick together. For an $H_2$ molecule to form, the pair of atoms must emit radiation during the moment of collision. At the temperatures of interstellar gas clouds, atoms do not emit radiation when they collide with one another—they simply bounce off each other. Thus the chance for this radiative association reaction to take place is infinitesimally small. What is nearly impossible for atoms in flight, however, may not be so unlikely on a bed of graphite. Hydrogen atoms in the gas clouds are constantly running into the surfaces of the dust grains where they can stick until they find a mate and become molecules.

Once molecules have been formed, they can swap partners in a chemical exchange reaction. For example, the ubiquitous hydroxyl radical (OH) might be formed when an oxygen atom trades places with one of the hydrogen atoms in the $H_2$ molecule in the reaction $O + H_2 \rightarrow OH + H$. Such reactions in the gas might build up a rich variety of molecules in the cloud even if only $H_2$ molecules are formed on cosmic dust grain surfaces. This kind of activity, however, is strongly inhibited by the chilly interstellar environment. For atoms and molecules to change partners, the chemical bond of the original pair must first loosen, and that requires some heat. The interstellar clouds are far too frigid for much chemical exchange to take place between ordinary molecules (that is, the molecules we are familiar with on earth) or even the highly reactive radicals. But not all atoms and molecules in interstellar space are ordinary. Along with gas and dust, interstellar space contains cosmic rays, electrically charged bare nuclei of atoms that streak through the gas at almost the speed of light and strip electrons off atoms and molecules. The legacy of the cosmic rays is a small fraction of ions and ion molecules—atoms and molecules that lack one or more pieces from their neutralizing shroud of electrons and thus have a net positive charge of electricity. The electrical influence of an ion is so strong that even at the lowest temperatures it can easily disrupt the bonding of a molecule and initiate chemical reactions. In contrast to neutral atoms and molecules, the ions are con-

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stantly swapping and stealing atoms to build complicated molecules in an environment of simpler ones.

Radio and infrared observations indicate that stars form in the same dense regions of the sky in which most interstellar molecules are found. The molecules are therefore thought to play a vital role in initiating the star formation process. Gravity gives interstellar clouds a propensity to collapse, but that does not assure the formation of stars. There are many effects that resist gravity. Ordinary thermal pressure, for example, tends to make the gas clouds expand. Without some mechanism to radiate away their heat energy, interstellar clouds would reach an equilibrium between gravitational attraction and thermal pressure, and no stars would form. That mechanism may be interstellar molecules.

When molecules collide with each other, the internal motions of which they are capable are excited. Thus, unlike interstellar atoms, colliding molecules can emit radiation and are therefore able to rid interstellar clouds of their heat energy. The radio emission lines astronomers have observed, those from carbon monoxide molecules, for example, may be the very radiation by which a gas cloud gets rid of its heat energy and begins to fragment into a cluster of stars.

Although the study of interstellar chemistry is still in its infancy, it has already indicated that molecules probably play a vital role in initiating the gravitational collapse that leads to the birth of a star. It also seems likely that the chemistry of charged ions plays an important role in the formation of molecules. These ions are made by cosmic rays in interstellar space. The rays probably come from supernova explosions that occur in our galaxy every century or so when a massive star runs out of fuel and collapses. In this parting shot, a dying star sprays the interstellar medium with radiation, thereby insuring that the Milky Way remains a fertile place, where star birth can continue for eons to come.

Richard McCray is an associate professor of physics and astrophysics and a fellow of the Joint Institute for Laboratory Astrophysics of the University of Colorado and the National Bureau of Standards at Boulder, Colorado.
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