

tion but from dialogue, apprenticeship, and collaboration. Although we commonly think of scientific knowledge as a public good—available at zero cost once it has been produced—the specialized skills, education, and foreknowledge needed to use it imply that scientific information is far from free. Incentives are necessary to encourage creation, distribution, and use.

The incentives faced by individual scientists, however, do not automatically encourage them to maximize scientific progress. For example, overspecialization can be privately beneficial while erecting virtual walls between scholarly communities. If intra-disciplinary interactions substitute for inter-disciplinary ones, then the intellectual cross-pollination of ideas can suffer. Consider that the Black-Scholes equation for pricing financial options is derived from an arbitrage model related to the heat transfer equation (9). Conceivably, reducing the spillovers between thermodynamics and finance could have fore-

stalled the development of options markets. Similarly, Crick's training in physics and Watson's background in zoology helped them develop their theories of DNA (10). In general, the insularity of subpopulations negatively affects the speed at which new ideas percolate through an entire population (11).

Balkanization can be avoided. A scientist may use information technology to select diverse contacts as easily as specialized contacts. Integration or fragmentation hinges on individual preferences and factors such as whether the pressure to publish at the frontier of one's own discipline is low enough to permit time for exploration in others.

New technologies give us new options to consider. They enable both the global village and the virtual Balkans of scientific collaboration. Although no single scenario is inevitable, certain outcomes, once achieved, can be difficult to reverse. At this early stage, we can, and should, explicitly consider what we value as we shape the nature of

our networks, with no illusions that a greater sense of community will inexorably result.

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ASTROCHEMISTRY

Space Carbon: Neutral Pathways?

James Richard Heath and Richard James Saykally

The discovery of complex molecules in interstellar space in the late 1960s by Townes, Welch, and their collaborators (1) destroyed the conventional wisdom of the day and created widespread interest in the chemistry of interstellar dust clouds. On page 1508 of this issue, Kaiser *et al.* (2) heighten this interest by providing evidence that a new class of reactions—reactions between certain charge neutral precursors—may be a critical component of this chemistry.

In the 1960s it was recognized that self-shielding of dense (10^3 to 10^6 cm $^{-3}$) clouds against interstellar ultraviolet radiation permits a rich and complex chemistry to pervade these objects, but the mechanism for the formation of molecules at the ultralow cloud temperatures ($T < 50$ K) remained an enigma. This dilemma was solved in the mid-1970s by Herbst and Klemperer (3), who proposed a scheme of ion-molecule reactions, known to often possess nearly zero activation barriers, that nicely accounted for the principal observations. After the detection in dense clouds of two molecular ions, HCO $^+$

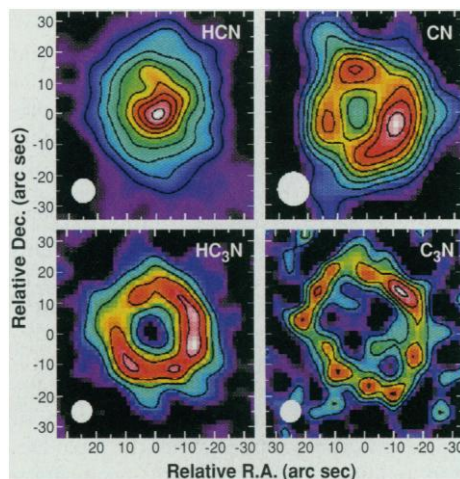
and HNN $^+$, by Snyder (4) and Thaddeus and collaborators (5), respectively, and the confirmation of these observations by microwave spectroscopy in the laboratory of Woods (6), a scheme featuring ion-molecule reactions driven by cosmic ray ionization of hydrogen followed by ion-electron dissociative recombination reactions became the paradigm for the chemistry of interstellar dust clouds. Furthermore, it became recognized that molecules were intimately involved as cooling agents in the critical processes of star formation and gravitational collapse of these objects.

More recent observations have made it clear that this picture is, however, incomplete. The detection of long-chain carbon-containing molecules like HC $_5$ N in dark dust clouds by Avery and co-workers (7) revealed a class of molecules, the high abundance of which was not readily explained by the ion-molecule scheme. The discovery of larger interstellar molecules (HC $_{11}$ N, for example) along with pure-carbon-chain species like C $_3$ and C $_5$ (8) in circumstellar shells of dying carbon stars and possibly in cold clouds (9) likewise implied that another type of chemistry must be occurring, at least under some conditions. The tentative association of polycyclic aromatic hydrocarbon molecules with the endemic unidentified interstellar

emission bands may constitute still another example (10). In summary, it now seems that much of the carbon chemistry of interstellar dust clouds is not readily explained within the context of the ion-molecule reaction scheme. This is a problem of considerable significance because carbon is the fourth most abundant element, is the critical element for life as we know it, and is most likely to be crucially involved in the nucleation of solid matter from the gaseous state.

Until very recently, reactions between neutral species have not been considered relevant to interstellar cloud chemistry (except for the formation of molecular hydrogen, which is thought to occur on dust grain surfaces). Neutral-neutral reactions are typically characterized by much higher activation barriers and lower cross sections than are ion-molecule processes. Recent studies, however, have indicated that several classes of neutral-neutral reactions may actually be very important (11). Husain's group has found that carbon atoms can insert into unsaturated carbon molecules (such as acetylene) with no activation barriers and high probability (12). It was quickly recognized that such reactions could provide a route for synthesizing many of the interstellar molecules that were not well explained by the ion-molecule chemistry. However, the incorporation of such neutral-neutral reactions into the complicated models for interstellar dust cloud chemistry leads to contradictions: neutral-neutral reactions tend to produce stable small molecules quite early in the chemical process, thus terminating molecular growth and limiting the number of complex molecules that are produced (13).

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Carbon contours. Microwave emission images of the molecule-rich circumstellar shell surrounding the carbon star IRC+10216. Shown are contour maps of the distribution of four carbon-containing molecules (HCN, CN, HC₃N, and C₃N). White circles indicate the resolution of the telescope for each emission wavelength. (Dec. = declination, R.A. = right ascension) [Images obtained using the Berkeley-Illinois-Maryland Association Millimeter Wavelength Array at Hat Creek, California (16)]

Hence, the importance of neutral-neutral reactions in interstellar and circumstellar chemistry remains an open question.

Kaiser and co-workers (2) present compelling evidence that neutral-neutral reactions are, indeed, important in certain astronomical environments. In the reaction that they have studied, C₃H is produced by a route involving neutral species. But ion-molecule routes have also been postulated as sources of C₃H.

A unique aspect of both routes is that the C₃H can be produced in either a linear (*l*-C₃H) or a cyclic (*c*-C₃H) form. The astronomical observation of both forms of C₃H is not by itself sufficient to discriminate between the two reactions. However, the abundance ratio *l*-C₃H/*c*-C₃H should be a signature of the reaction pathway, because the two structures are not isoenergetic. Kaiser *et al.* used electronic structure calculations to show that the neutral production of *l*-C₃H is exothermic by 1.5 kJ/mol, whereas the production of *c*-C₃H is exothermic by 8.6 kJ/mol. Thus, the abundance ratio should be strongly dependent on the physical environment in which the isomers are formed. In fact, abundance ratios for these isomers have been measured in two very different astrophysical environments: the cold, dark molecular cloud TMC-1 (average temperature < 10 K) and the circumstellar shell of the carbon star IRC+10216 (temperatures up to 4000 K) (see figure). Through the use of a crossed molecular beam apparatus, Kaiser and co-workers were able to approximate conditions in these two environments by

controlling the collision energy between C and HCCCH. They detected both the linear and cyclic reaction products and thus determined the temperature dependence of the reaction product branching ratio. Their observations explain the different *l*-C₃H/*c*-C₃H ratios observed in TMC-1 and IRC+10216 and thus provide strong evidence that neutral-neutral reactions do indeed play an important role in both interstellar and circumstellar environments.

The facile nature of the carbon addition reactions studied by Kaiser and co-workers may also have implications for terrestrial processes involving the (high-temperature) condensation of pure carbon vapor (14). Such processes, which can lead to the formation of fullerenes and carbon-rich soot, are remarkably fast. Small carbon clusters occur predominantly at high temperatures as linear chain structures with very low-frequency bending vibrations. This preferred form means that C_n + C_m collision complexes have a high density of nondissociative vibrational states in which excess energy may be partitioned, thus extending the lifetime of such complexes (15). Nevertheless, the chemical route to forming the first cluster with such low-frequency vibrations, C₃, is not well understood. The formation of C₃ is probably the rate-determining step in carbon condensation, because (low-pressure) carbon vapor is known to consist of carbon atoms and dimers. Carbon atom insertion into

C₂, followed by radiative or collisionally induced stabilization, may be the process that "kick-starts" high-temperature carbon condensation in both terrestrial and extraterrestrial environments.

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MOLECULAR BIOLOGY

The End of the Message—Another Link Between Yeast and Mammals

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The synthesis of messenger RNA (mRNA) from its gene requires transcription, removal of intervening sequences (splicing), and polyadenylation—a process in which an endonucleolytic RNA cleavage is coupled with synthesis of polyadenosine [poly(A)] on the newly formed 3' end. For transcription and splicing, the DNA or RNA sequences and many of the protein factors that participate are well conserved from yeast to humans. Until recently, the situation for polyadenylation appeared different. Although the reaction mechanism is similar in yeast and humans, the sequence signals in yeast mRNA

have been poorly defined and were apparently unrelated to those in mammalian mRNA precursors. This observation led to the view that the machinery that specifies the mRNA 3' end is distinct in yeast and mammals. Recent studies, three of which are described starting on page 1511 of this issue (1-3), however, provide evidence that this is not the case: The protein factors that recognize the poly(A) site on precursor mRNA are conserved between yeast and mammals.

The sequences that define the poly(A) site in mammals contain certain consensus elements (4) (Fig. 1). Foremost among these is the nearly ubiquitous and essential AAUAAA hexanucleotide, found almost invariably 10 to 30 bases upstream of the site of polyadenylation. Indeed, this motif is

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