The title of this article needs some explanation. Clearly, the universe is not entirely made of molecules and we are exaggerating. In fact, most of the mass in the universe is probably not even made of familiar matter, i.e. the atoms and molecules of which we, the Earth, the solar system, and all the stars in our own and other galaxies are composed. “Dark matter” contains about 90% of the mass of the universe and is detected only by the gravitational effects it exerts. The composition of this matter is unknown. The remaining 10% or so of matter in the universe is the familiar “baryonic” material, mostly locked in stars. Only about 1% of all matter is gaseous and distributed between the stars. And of this 1%, perhaps half is molecular. Therefore only about 0.5% of the total mass of the universe is composed of molecules. Why then do we emphasize in the title of this article the importance of molecules? Surely this is a case of the tail wagging the dog?

In fact it is not. This gaseous component is important because it is the reservoir of matter that remains to be processed into galaxies, stars and planets. For example, in the early universe protogalaxies were formed from gas clouds that contracted under their own weight to form galaxies of stars, but in the present era there is too little gas left in intergalactic space for galaxy formation to continue. Within any particular galaxy, star and planet formation continues while sufficient gas remains in the interstellar medium. However, when this reservoir is empty, a galaxy has little opportunity for further development and can only await the death of the stars that it contains. The interstellar medium of galaxies is replenished to some extent by material expelled from stars in winds and explosions, so the interstellar gas is continually enriched with heavy elements and dust that are the ashes of nuclear burning. Stars that form from the enriched interstellar gas will be richer in these heavy elements and dust that are the ashes of nuclear burning.

Many of the most interesting astronomical phenomena (e.g. the formation of galaxies, galactic collisions, formation of stars and planets and the injection of material into the interstellar medium through stellar winds and explosions) occur in (or are best traced through) matter that is at a higher-than-average density. For example, the average number density of the gas in the interstellar medium of the Milky Way is about one hydrogen (H) atom per cm$^3$ (i.e. a million per cubic metre), compared to $2.7 \times 10^{19}$ molecules cm$^{-3}$ in the air that we breathe on Earth. Processes that initiate star formation occur in clouds that are about one thousand times denser than this average interstellar density; in gas that is about a million times denser, star formation is inevitable; and the processes that control planet formation occur in gas that is about $10^{12}$ times denser than the mean interstellar gas.

Material injected into the interstellar medium from stars is also, initially, very much denser than the interstellar medium. These are the kinds of regions that many astronomers wish to study. High density implies a high collision-rate in the gas between atoms, molecules, radicals and dust grains, stimulating a complex chemistry that gives rise to the coolant molecules also tends to reduce the level of ionization in the gas, thereby reducing the ability of the magnetic field to support the gas against collapse. Consequently molecules play a key role in regions where much of the astronomical action takes place; through molecular emission we can trace the physical conditions during these events and this radiation may itself be important in modifying the physical conditions that allow these changes to continue. The motivation for studying astrochemistry is strong and although molecules are a minor component of the mass of the universe they exert a profound influence on its development because they affect and trace the transition to high density.

### Routes to cosmic molecules

The list of detected cosmic molecules (table 1) represents a challenge for astrochemists. How are these molecules made under conditions that – compared to those on Earth – seem extreme? (It is, of course, the conditions on Earth that are extreme.) Are other species, not yet detected, also likely to be present? Are there large molecules present, possibly of relevance to biology? To account for the hundred or so molecular species that we can detect in space, it is necessary to develop models of chemical networks that contain up to several hundred species interacting in several thousand reactions. The latest version of the UMIST database (Le Teuff, Millar and Markwick 2000) provides the rate coefficients of 4113 gas-phase reactions among 396 species involving the elements H, He, C, N, O, Na, Mg, Si, P, S, Cl and Fe. Neutral molecules containing up to 12 atoms (CH$_n$C$_n$N) are included; yet only a small number of these reactions have been studied in detail either theoretically or in the laboratory. There are significant differences between

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**Abstract**

Molecules play a fundamental role in many regions of our universe. The science where chemistry and astronomy overlap is known as astrochemistry, a branch of astronomy that has risen in importance over recent years. In this article we review the significance of chemistry in several astronomical environments including the early universe, interstellar clouds, star-forming regions and protoplanetary disks. We discuss theoretical models, laboratory experiments and observational data, and present several recent and exciting results that challenge our perception of the “molecular universe”.

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**The molecular universe**

Helen J Fraser, Martin R S McCoustra and David A Williams present a simple guide to astrochemistry.
results obtained with this UMIST database and that of the “New Standard Model” developed by astrochemists at the Ohio State University (Ruffle and Herbst 2000, 2001; Herbst, Terzieva and Talbi 2000). These differences are caused (inevitably) by the somewhat arbitrary selection of reactions to include in the database, the extent to which gas-grain processes are included in the models, and the uncertainty associated with many of the reaction-rate coefficients. Nevertheless, it is clear that very many species that have not yet been detected must be present in space. This might be because they are inherently difficult to detect (e.g. N$_2$ doesn’t have a dipole moment so its infrared and radio transitions are forbidden), or because the species only have a fleeting existence (e.g. CH$_3^+$ is rapidly destroyed because it is so chemically reactive), or because there is not a signature that is sufficiently specific to make an absolute identification (e.g. PAH [poly-aromatic hydrocarbon] molecules have generic spectra which can be measured but are difficult to assign to one particular PAH). Other families of large molecules, such as fullerenes and amino acids, have been detected in meteoritic samples and may also be present in the interstellar medium, although they have not yet been observed there. Just how far this complexity continues towards biological molecules is as yet unclear.

The types of reactions that play a role in cosmic chemistry are summarized in figure 1. This illustrates the breadth of chemistry that occurs

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2. The key energy sources for chemical reactions in interstellar and circumstellar regions.

- **Thermal IR sources**
  - e.g. black body emission from dust grains in molecular regions

- **Stellar UV sources**
  - e.g. local UV radiation field at edges of cloud or in diffuse medium

- **Cosmic rays**
  - e.g. dominated by fast protons and electrons generated from γ-rays from external sources

- **Dynamical shocks**
  - e.g. changes in velocity, temperature and density at the shock front (T > 200–2000 K), ionize molecular/atomic species, and splinter grains

- **Ambipolar diffusion**
  - e.g. ion-neutral friction heats the gas

- **X-rays/γ-rays**
  - Generated from highly ionized species in shock-excited gas

**Ambipolar diffusion**

- $v_n < v_c$
- $v_n > v_c$
- $v_c > v_B$

**Dynamical shocks**

- $v_n < v_c$
- $v_n > v_c$
- $v_c > v_B$

**Thermal IR sources**

- $T < 10^3$
- $10^3 < T < 10^6$
- $10^6 < T < 10^9$
- $10^9 < T < 10^{12}$

**Stellar UV sources**

- $T > 10^3$
- $10^6 < T < 10^9$
- $10^9 < T < 10^{12}$
- $10^{12} < T < 10^{15}$

**Cosmic rays**

- $T > 10^{15}$
- $10^{15} < T < 10^{18}$
- $10^{18} < T < 10^{21}$
- $10^{21} < T < 10^{24}$

In space by describing the different routes to molecule formation in a range of interstellar locations. In any astronomical environment, the most important reactions of all are those that convert hydrogen atoms (H) to hydrogen molecules (H₂). This is not only because H₂ is by far the most abundant molecule in the universe, but also because H₂ nearly always plays a key role in the formation of all the other molecular species. In the cool interstellar medium, this 2H→H₂ conversion occurs through surface catalysis (reaction h1 in figure 1), though other reaction mechanisms were important in the dust-free early universe (see below).

In high-density environments such as stellar photospheres and planetary atmospheres, three-body associations (figure 1b) dominate. At low temperatures, neutral atoms and molecules tend to be unreactive with H₂ and the chemistry is driven largely by ion-molecule reactions (figure 1d). The ionization sources are stellar UV radiation, cosmic ray impact, or X-rays from black holes or high-speed shocks in gas flows. In dark clouds, H₂ is ionized by cosmic rays to H₂⁺, which reacts rapidly with other H₂ molecules to form H₃⁺, a stable but reactive ion that easily donates its proton to almost any other species. This sets a rich chemistry underway, and provides one route for the formation of many common astronomical species (Geballe and Oka 1996).

However, the precise formation routes for most of the simpler molecules (say, up to a few atoms) are not completely understood. For example, the negative results obtained recently by the Submillimeter Wave Astronomy Satellite along many lines of sight for H₂O and O₂ (Bergin et al. 2000, Spaans and van Dishoeck 2001) took most astrochemists by surprise. Observational and theoretical upper limits on the concentrations of these molecules differ by orders of magnitude from each other. Apparently we are missing some of the key chemical routes by which these molecules might be created or destroyed, or the key physical routes by which the molecules may be trapped into ices or depleted from the gas phase. But, in general, our models of the chemistry in interstellar clouds, star-forming regions and circumstellar envelopes are now proving to be useful tools in interpreting observations and providing physical insight into these regions (as we will see in the final section of this article).

In contrast, our understanding of the formation processes for the larger molecules is poor. We can make educated guesses of the important reactions, but the results of our models do not agree well with observational evidence. For example, although we can devise appropriate networks of gas-phase reactions that provide interstellar methanol, CH₃OH, these networks fail to supply it in the quantities detected; and schemes to make the next member of the family, ethanol, C₂H₅OH, fail completely. We do know, however, that these molecules can be made in the laboratory by irradiating molecular ices, so it seems likely that surface processes and the processing of ices in the solid state are important. Large carbon-based molecules, such as the PAHs, may also be formed from the degradation of solid carbon grains in the hot gas behind interstellar shocks; in effect, these grains are probably like soot – assemblies of benzene-type derivatives and tiny pieces of graphic sheet, which are likely to reform into more stable fullerene and nanotube structures. Direct gas-phase synthesis of such large species is only feasible in the high densities found in stellar atmospheres. In fact, we observe that the envelopes of carbon stars are filled with smoke, puffing it out into space like factory chimneys.

**Energy sources and timescales in cosmic reactions**

Petrol does not spontaneously ignite. To make our cars go we need a spark to activate the chemistry, turning the hydrocarbon into water and carbon dioxide. It is similar in space: atoms of O, C and N, for example, do not spontaneously react with H₂. In fact they experience a barrier as they approach the H₂ molecule and usually “bounce off” rather than react. For reactions to occur, the atoms and molecules must approach with sufficient energy to overcome the reaction barrier – and this requires the gas to be heated to hundreds or thousands of Kelvin. Even then the chemi-
cal kinetics are complicated further by steric factors; the orientation between the reacting parties can be crucial in determining whether or not a reaction occurs, even if there is sufficient energy to overcome the reaction barrier. Reactions may occur if some ions are created, because ions often react easily with molecules, without having to overcome a reaction barrier. In each case, energy is required to drive the chemical network, either in generating ions and radicals or in overcoming the reaction barriers. Without an input of energy, the astronomical chemical engine would simply grind to a halt. So what are the possible sources of energy to drive the cosmic chemical engine? These are shown in figure 2. Each has its own specific effect and generates a characteristic chemistry. It is like the difference between diesel and petrol engines. In the diesel engine, the initial energy is generated by the rapid adiabatic compression of the fuel-air mixture, while in the petrol engine it is the spark that ignites the reactions. The outputs are chemically different, as any commuter knows. In cosmic chemistry, for example, chemistry in shock-heated gas produces molecules (such as some sulphur-bearing species) that are rarely formed in chemistry driven by slow cosmic-ray ionization. Direct thermal effects can come from direct heating of gas and dust by light from a nearby star; this heating may evaporate previously-formed ices and give a characteristic chemistry that we find in high-mass star-forming regions. The astrochemist needs to be aware of the competing or dominating energy source and to select the appropriate reaction network to describe astronomical observations and models.

It often turns out that the chemistry needs to be explored in a situation that is evolving dynamically, say, in a cloud collapsing under its own gravity, or in an expanding flow or wind from a cool star. If the chemistry is fast but the dynamical changes are relatively slow, then the chemistry may come to a quasi-steady state at any stage of the evolution. If so, this allows a great simplification. The timescales that are associated with some processes that occur in interstellar clouds and star-forming regions are given in table 2. This table shows that in diffuse clouds (at number densities around $10^5 \, \text{m}^{-3}$) the chemistry is fast compared to collapse under gravity and to the freeze-out of species on to dust grains. Therefore a chemical quasi-steady state can exist in such clouds. In gas with a density of around $10^{10} \, \text{m}^{-3}$, typical of the dense cores within molecular clouds, all the timescales are comparable. One approach in such circumstances is to put all the processes into the computing pot and stir. Relating such results to observed conditions and laboratory experiments is one of the great challenges in astrochemistry!

So far, we have indicated what is needed to model the chemistry in astronomical regions. Below, we briefly describe regions where molecules are, or have been, important in astronomical terms.

## Molecules at high redshifts

About 300 000 years after the Big Bang, or at a redshift $z \approx 1300$ (for the Standard Big Bang Nucleosynthesis Model) the universe was hot and think. The gas was dominated by atomic hydrogen, with some helium, traces of deuterium and negligible amounts of other elements. This gas was hot and could cool from very high temperatures down to about 10 000 K by collisional excitation of the electronic states in atomic hydrogen. These states subsequently radiate, thereby removing thermal energy from the gas. A gas at 10 000 K has a high thermal pressure. How did the gas in the early universe cool further, so that gravity had a chance to overcome pressure and create a protogalaxy? We now know that the cooling agent was $\text{H}_2$, with some HD, and that the molecular species were created from reactions of atomic hydrogen with the remaining electrons and protons, (see figure 3). Of course, at that time $\text{H}_2$ could not be created from surface reactions on dust as there was no dust before the stars existed. The gas-phase processes initially converted about two in a million H atoms to $\text{H}_2$ and a tiny amount of this $\text{H}_2$ was further processed to HD. Molecular hydrogen possesses low-lying energy levels (much lower than the atomic species) associated with rotational and vibrational molecular motion. Collisional excitation of these levels, followed by radiative relaxation, cooled the gas to about 100 K. $\text{H}_2$ in the early
stars were formed, stellar winds and expoli-
Big Bang (redshift of about 10). Once the first
gravitational collapse led to protogalaxy for-
compared to that at
universe was therefore able to cool the gas,
reducing the pressure by a factor of about 100
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tracers of the gas motion. The collapse under gravity of a gas cloud into a star (and its associated disk and envelope) releases enormous amounts of gravitational potential energy. This must be radiated away if the gas is not to heat up and arrest the collapse because of increased thermal pressure. The temperature of these clouds (around 10 K) is much too low for H₂ to be an effective coolant, as it was in pre-galactic gas clouds, so the most important coolant molecules are CO and its equivalents containing less abundant isotopes.

Figure 6 indicates how the CO emission that cools the cloud can also be used to trace the motions in the cloud. This figure shows that gas is still falling on to the new star, while orthogonal to that infall an outflow has been established with a continually widening angle. In about 10 000 years the outflow will have cut off the infall. The energy and momentum associated with these outflows are adequate to disperse the remnants of the dense core within which the new star was born and to rearrange the distribution of gas within the cloud. The cloud is not destroyed; rather this star formation process occurs in very localized dense clumps of the cloud, which then retains its overall integrity through several phases of star formation in different regions of the cloud.

The formation of a massive star is a much rarer and more energetic event. An external cause is apparently necessary to trigger the formation of the “high-mass” stars that are an order of ten times as massive as the Sun. This trigger might be the winds of a nearby massive star that are shocking and imploding gas in the vicinity. It is therefore particularly important to infer the nature of the collapse process that led to the formation of the massive star. At first sight this seems an impossible task since the newly formed massive star rapidly clears its birthplace of all the evidence. However, the clearing process leaves some transient debris behind, in the form of very dense and small knots of gas and dust that are warmed by the stellar radiation. The molecules that were in the pre-stellar collapsing core become frozen out on the dust and preserve in their composition a relic of the pre-stellar conditions.

These warm clumps, the so-called Hot Cores, enable astrochemists to deduce the hidden memory of high mass star-formation. Figure 7 shows an example of a Hot Core, traced with emission features from CH₃CN molecules that were released from the warming ices. The emission contours about the ultra-compact HII region surrounding the newly formed star contain information about the chemistry and freeze-out in the pre-stellar phase as well as information about the warming process caused by the onset of stellar burning (Viti and Hatchell 2002).
Stellar and circumstellar molecules

Sufficiently cool stars (with surface temperatures of only a few thousand Kelvin) have atmospheres that are almost entirely molecular. In these atmospheres the densities and temperatures are relatively high in comparison to the interstellar medium. Consequently, atoms and molecules frequently collide with sufficient energy in three-body interactions that they rearrange themselves to form the most stable and strongly bound molecules. In carbon-rich stars, carbon takes up almost all the oxygen to form CO molecules and the residual carbon is in the form of simple hydrocarbons such as CH₂ and C₃H. In oxygen-rich stars, oxygen takes up all the carbon in CO and the residual oxygen appears in metal oxides such as FeO, SiO, TiO and MgO. It is relatively straightforward to model the chemistry of these regions, as it is time-independent and depends only on known thermodynamic properties of the molecules involved. These stellar molecules have extremely rich spectra in the visible and UV, with large numbers of lines associated with the rotation-vibration band structure. Consequently, the atmosphere is almost totally opaque to radiation emerging from the star. This great stellar opacity effectively traps the momentum of the radiation field. A simple example is shown in figure 8 where the parent molecule, HCN, is concentrated in a shell around the star, whereas CN (the photodissociation product of HCN) is concentrated in a shell around the star. Reproduced by permission of A&A from Lindqvist et al. 2000.

As this flow continues, the number density of the gas and dust falls, so that radiation from the interstellar space can penetrate the envelope, ionize the species present and promote a transient population of envelope molecules. Ultimately, the same radiation will destroy those molecules as they enter interstellar space. Thus, molecules emerging from the stellar atmosphere into the envelope, the so-called parent molecules, form new molecules, the daughters, as the material travels outward to interstellar space and becomes exposed to the interstellar radiation field. A simple example is shown in figure 8 where the parent molecule, HCN, is concentrated on the star, while the daughter species, CN, is in a shell with a cavity at the centre. Observations of chemistry in circumstellar envelopes provide the severest tests of astrochemical models and the observational/theoretical interaction has made this area of astrochemistry one of the most accurate, as illustrated by Aikawa and Herbst (2000) and Millar et al. (2000). However, even these accurate models still do not account for the detected abundances of the larger species, such as HCN₁₄₅N, where n = 1–5.

Cool stars with molecular envelopes evolve ultimately into the dramatic but short-lived objects called planetary nebulae. The cool envelope then detaches from the star, which contracts, heats up and generates a fast wind. Molecules are observed either in the residual
The study of planetary atmospheres is close, however, the connection between planet-chemistry and is beyond the scope of this article.

The composition of interstellar ices has been inferred by matching spectra recorded with the Infrared Space Observatory (ISO) Short Wavelength Spectrometer (SWS) to laboratory-based spectra. Molecules in very cold ices can vibrate, but rotation is hindered, so that against a background source of radiation the molecules in the dust absorb in pure vibrational transitions, easily distinguishable from the rotation-vibration structure of free-flying gas-phase molecules. These transitions occur in the near infrared. Figure 9 shows the spectrum of embedded young stellar object W33a, with absorption features of interstellar ices along the line-of-sight, as identified from laboratory spectra. The composition of this ice is rather similar to that of several cometary bodies in our own solar system (see table 3) and, although differences exist, bears some resemblance to the composition of interstellar gas.

In regions where the interstellar ice is exposed to UV photons, cosmic rays and electron or ion bombardment, then the ice can be processed to other solid phases, and chemical reactions can be induced within the solid state. Such processing generates radicals, secondary electrons and ions in the ices, which then react further to produce more complex species such as CH$_2$OH and CH$_3$ (Ehrenfreund and Schutte 2000). These ice-coated grains are the raw material for the formation of the solid bodies that we believe were present in a protoplanetary system – dust, planetesimals, comets and planets, formed from the protoplanetary disk.

However, inside dense molecular clouds and in the dense equatorial planes of protoplanetary disks, UV photons are unable to penetrate, so the ices are predominantly processed by thermal heating, or cosmic rays. In recent years it has been realized that the techniques of modern ultrahigh-vacuum science can be applied to understanding the complex surface physics and chemistry that occurs on grains. Illustrative of such studies is recent work by the laboratory astrophysics group at the University of Nottingham. Using a customized ultra high voltage chamber and some surface probes (Fraser et al. 2002), this group has investigated a range of gas-dust interactions that are directly relevant to the interstellar medium. Early experiments on the thermal evolution of H$_2$O ice under interstellar conditions showed that it was possible for such ices to remain in the solid state to much higher temperatures and over longer timescales than had previously been assumed (Fraser et al. 2001).

More recently, as figure 10 shows, these studies have revealed the complex interplay between adsorption, diffusion, and desorption when CO is deposited on H$_2$O ice, revealing that the spectroscopy and desorption kinetics of such systems are even more complex than we thought previously (Collings et al. 2002).

---

**Table 3: Molecules in ice**

A comparison of molecular abundances in interstellar ices and cometary systems (adapted from Crovisier 1998).

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Cometary ices</th>
<th>Dark clouds (Elias 16)</th>
<th>Interstellar ices</th>
<th>Embedded YSOs (Elias 29)</th>
<th>High Mass (W33a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hale-Bopp</td>
<td>Other comets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>CO</td>
<td>20</td>
<td>6–30</td>
<td>25</td>
<td>5.6</td>
<td>9</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>5–20</td>
<td>2–10</td>
<td>18</td>
<td>22</td>
<td>14</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>0.6</td>
<td>0.7</td>
<td>1–2</td>
<td>&lt;1.6</td>
<td>2</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>2</td>
<td>1–7</td>
<td>&lt;3</td>
<td>&lt;4</td>
<td>22</td>
</tr>
<tr>
<td>H$_2$CO</td>
<td>1</td>
<td>0.2–1</td>
<td>2–6?</td>
<td>–</td>
<td>1.7–7</td>
</tr>
<tr>
<td>OCS</td>
<td>0.5</td>
<td>0.1</td>
<td>0.2</td>
<td>&lt;0.08</td>
<td>0.3</td>
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<tr>
<td>NH$_3$</td>
<td>0.7–0.18</td>
<td>0.5</td>
<td>&lt;10</td>
<td>&lt;9.2</td>
<td>15</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>0.3</td>
<td>0.4</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>HCO$_3$</td>
<td>0.08</td>
<td>–</td>
<td>27</td>
<td>–</td>
<td>0.4–2</td>
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<tr>
<td>HCN</td>
<td>0.25</td>
<td>0.05–0.2</td>
<td>0.5–10</td>
<td>–</td>
<td>&lt;3</td>
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<tr>
<td>HCN</td>
<td>0.04</td>
<td>0.01</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>HNCO</td>
<td>0.06–0.1</td>
<td>0.07</td>
<td>–</td>
<td>–</td>
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<tr>
<td>C$_2$H$_2$</td>
<td>0.1</td>
<td>0.5</td>
<td>–</td>
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<tr>
<td>CH$_3$N</td>
<td>0.02</td>
<td>0.01</td>
<td>–</td>
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<tr>
<td>HCOOH$_2$</td>
<td>0.06</td>
<td>–</td>
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</tr>
<tr>
<td>HC$_3$N</td>
<td>0.02</td>
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<tr>
<td>NH$_2$CHO</td>
<td>0.01</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>H$_2$S</td>
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<td>–</td>
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<tr>
<td>H$_2$CS</td>
<td>0.02</td>
<td>–</td>
<td>–</td>
<td>&lt;2</td>
<td>–</td>
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<tr>
<td>SO</td>
<td>0.2–0.8</td>
<td>–</td>
<td>–</td>
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<tr>
<td>SO$_2$</td>
<td>0.1</td>
<td>–</td>
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<td>–</td>
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<tr>
<td>O$_3$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;2</td>
<td>–</td>
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<tr>
<td>H$_2$O</td>
<td>?</td>
<td>?</td>
<td>1</td>
<td>?</td>
<td>?</td>
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<tr>
<td>N$_2$O</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>O$_2$</td>
<td>?</td>
<td>?</td>
<td>?</td>
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</tr>
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</table>

Note that all abundances are expressed as a percentage as compared to the abundance of H$_2$O ice. – indicates a current lack of information. ? indicates ice expected to be present but not observable.
Both these experiments suggest that the formation and behaviour of interstellar ices is more sophisticated and more diverse than current interstellar models imply. In addition to dust, gas from the interstellar cloud is also abundant in the disk. In a recent remarkable observation, highly forbidden rotational transitions were detected towards β-Pic toris, 49 Ceti, and HD135344 debris disks, taken with the Infrared Space Observatory. The dashed vertical line depicts the rest wavelengths of the H2 transitions, and the solid curve illustrates the range of potential wavelength shifts induced by grating repositioning errors or pointing offsets of the spacecraft.

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The “new” research area of laboratory astrophysics is now growing rapidly, particularly in the UK. Alongside these advances, the theoretical modelling community is developing newer, more sophisticated models of all regions of the “molecular universe”, enhancing our understanding and interpretation of astronomical objects, as well as providing laboratory astrochemists with interesting challenges to investigate. Finally, the next generation of space telescopes, satellites and exploratory missions, ensures that we will be able to observe and marvel at our molecular universe for many years to come.

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References