Molecules in space: the raw material for stars and planets

By Edwin Cartlidge, science writer

The 2018 Kavli Prize for Astrophysics goes to Ewine van Dishoeck "for her combined contributions to observational, theoretical, and laboratory astrochemistry, elucidating the life cycle of interstellar clouds and the formation of stars and planets".

A star forms when a relatively dense region of the gas that fills the space between existing stars begins to collapse under its own gravity. As the gas is compressed it heats up, to the point where the atomic nuclei within it have enough energy to overcome their mutual repulsion and fuse. The enormous heat given off in these nuclear reactions generates a pressure that counteracts gravity, eventually resulting in a stable star that shines in the night sky.

This process of fusion burning creates heavier elements from lighter ones. But the interstellar gas from which a star is made already contains a rich variety of molecules (in addition to molecular hydrogen, by far the most abundant). Ewine van Dishoeck has studied these molecules extensively, using her knowledge of chemistry to better understand how they are created, how they survive and what role they play in the formation of stars, planets and, ultimately, life.

In the early 1960s, most astronomers thought interstellar gas was almost entirely made up of atoms. A few very simple molecules had been observed – CN, CH, CH^+ and then OH – but it was thought that the hydrogen molecule itself as well as bigger molecules would be readily destroyed by ultraviolet starlight. The density of particles within interstellar clouds is higher than in surrounding space but would still be so low, the reasoning went, that any molecules that do survive would be far too thinly spread to be detectable.

Then in 1968, the physicist Charles Townes and colleagues pointed a radio telescope at the Sagittarius B2 molecular cloud, on the basis that if molecular hydrogen existed in interstellar space – as some scientists had proposed – then maybe other molecules did as well. That hunch was vindicated when the researchers first found signals from ammonia molecules and then from water. Following a slew of detections by other researchers since the 1970s, scientists have to date established the existence of around 200 types of molecule in the interstellar medium.

These discoveries implied that interstellar clouds contained at least 1000 molecules per cubic centimetre, rather than the 1-10 atoms per cubic centimetre previously thought from observations of atomic hydrogen. It also became clear that these molecular clouds contained a lot of interstellar dust – particles of matter from previous generations of exploded stars – that effectively blocks ultraviolet radiation. This extra protection and the higher densities reinforced the idea that stars could form when pockets of gas collapse in on themselves. However, this molecular basis for star formation threw up problems of its own.

For atoms to combine to form molecules in the low densities of space they need to attract one another over long distances. In other words, ions are better at forming molecules than neutral atoms are. Those ions can be created when cosmic rays slam into atoms and create ion-electron pairs. Another way for molecules to form inside molecular clouds is for atoms to stick to the surfaces of dust particles, migrate and over time come together to form new molecules.

But that still leaves the problem of how molecules survive at all in the presence of ultraviolet starlight. It was a problem that vexed theorists and where van Dishoeck first made a name for herself, in research carried out during and after her PhD in the 1980s. She showed that although some molecules are indeed broken up, others, such as water and carbon monoxide (CO), manage to "self-shield" the inner parts of molecular clouds by selectively absorbing the destructive ultraviolet radiation in the outer layers. The self-shielding and the absorption by surrounding dust allow molecules deeper in the cloud to go on and form stars.

In carrying out this research, van Dishoeck considered the case of CO, which is far less abundant in space than hydrogen but emits radiation much more efficiently. Given a certain cloud density, she calculated the probability of a given molecule being excited – through rotation, vibration or electronic transition – when struck by another molecule in the gas. By taking into account starlight's destruction of molecules, and how that varies throughout the volume of the gas, she arrived at probabilities that closely matched the intensity of radiation observed using radio telescopes (the radiation being emitted when molecules are excited).

However, having started her career as a theorist, van Dishoeck began to work increasingly with observational data. In particular, she studied infrared emissions from water detected by a series of ever more sophisticated space telescopes. Water is formed when reactants are relatively plentiful, so although rare in interstellar space generally it is abundant in star-forming regions. However, its emissions are almost entirely absorbed by the water in our own atmosphere, which means space-based observatories are needed to study it.

Scientists got their first view of the rich molecular world at infrared wavelengths with the launch of the European Space Agency’s Infrared Space Observatory in 1995. van Dishoeck used the Dutch-German built short-wavelength spectrometer to study the formation of water on the surface of dust grains, discovering that in dense molecular clouds the grains become completely covered with water ice and carbon monoxide ice.

From 2003, she then turned to NASA’s Spitzer Space Telescope to study chemical reactions in relatively light stars similar to our sun (having previously been limited to heavier objects). She and her colleagues also discovered water and other molecules in the dusty rotating disks created around still-forming stars that provide the stars with raw material from the surrounding gas and are the potential birth places of new planets.

Her observations of water intensified following the launch of an even more powerful far-infrared/submillimetre telescope, ESA’s Herschel Space Observatory, in 2009. This too she used to study a “protoplanetary disc”, the water in which binds dust grains together so that they eventually become solid bodies such as very young planets or comets, which themselves are thought to transport water to planets.

In 2011 van Dishoeck and colleagues reported measurements of cold water vapour emanating from across the disc surrounding a young and fairly close star known as TW Hydrae. Based on the strength of the infrared signals recorded by Herschel, they estimated that the vapour is being released from a reservoir of ice within the disc having a mass several thousand times that of the water covering Earth.

Impressive as these observations were, however, van Dishoeck and other scientists had realised that a larger aperture telescope would be needed to resolve star-forming sites spatially. The answer was to build a huge ground-based observatory. Known as the Atacama Large Millimeter/submillimeter Array (ALMA), this facility is located in Chile at an altitude of 5000 metres so as to be above much of the water in Earth’s atmosphere. It consists of 50 dishes, each 12 metres across, which can be connected up so as to mimic a single telescope 16 kilometres in diameter.

Using ALMA, van Dishoeck and her colleagues have observed protostellar discs around newly-formed stars on their way to forming new planetary systems in the Milky Way. They have obtained some striking images of complex dusty ring structures that perhaps point the way to individual planets within these discs. In addition to these chemistry- and physics-based studies, however, the researchers are also doing work with biological implications.

Last year, van Dishoeck’s group and an Italian/Spanish team reported having used ALMA to spot a number of emission lines from the organic molecule methyl isocyanate. This “prebiotic” molecule was located in the dust and gas surrounding several very young Sun-like stars about 400 light-years away in the Ophiuchus constellation. Since it is involved in the synthesis of peptides and amino acids, the researchers say that this molecule might help astronomers work out how life arose on our planet.

That optimism is mixed with caution, however. Although methyl isocyanate is far from the only complex organic molecule to have been detected in interstellar clouds, it is still not clear to what extent all the molecules needed for life are present in newly-made planets. In particular, despite significant searching, no-one has yet found unambiguous evidence for amino acids themselves in star-forming regions.

Many discoveries of new molecules in space need to be backed up with supporting laboratory work, so that researchers know the precise wavelengths at which those molecules emit or absorb electromagnetic radiation as well as having detailed information on molecules' collision properties, among other things. Indeed, experiments carried out as part of the latest work showed that methyl isocyanate can form on icy particles in very cold conditions like those in interstellar space.

Those experiments were carried out in a laboratory at Leiden University that was set up by experimental astrochemist Mayo Greenberg in the 1970s. One of the few labs of its type in the world, it provides the very low-density, low-temperature and stable conditions needed to approximate interstellar space. The vacuum created is still many orders of magnitude more dense than that in space but a number of tricks help bridge the gap, such as extending the lifetime of ions by embedding them in a neutral fluid.

Although van Dishoeck doesn't carry out the lab work herself, Reinhard Genzel, an astrophysicist at the Max Planck Institute for Extraterrestial Physics in Munich, says that her familiarity with that work allows her to make ever more sophisticated predictions of interstellar chemistry. ”This balance between theoretical and observational work is astounding in terms of breadth,” he says.