Creation and destruction: This photograph from the James Webb Space Telescope shows the infrared light that can be seen behind the curtain of the Orion Nebula, revealing the gas and dust structures where stars are born. Remnants of a star that exploded 500 to 1000 years ago can be seen in the left part of the image.

COLDFINGER

TEXT: HELMUT HORNUNG

Interstellar clouds of gas and dust – these are the birthplaces of stars and planets. To understand what exactly happens inside these clouds, a group led by Silvia Spezzano at the Max Planck Institute for Extraterrestrial Physics in Garching near Munich is observing different molecules in the clouds and simulating the interstellar chemistry in a laboratory. Their work provides insights into how conditions conducive to the development of life arise within solar systems.

The path to the birthplace of stars leads through the Munich subway via the 6 train to Garching Research Center Station. From there it's only a few minutes' walk to the Max Planck Institute for Extraterrestrial Physics. An elevator ride will take you to the basement, where the astrochemical laboratory is housed. "Here we reproduce the conditions that prevail in interstellar clouds," explains Silvia Spezzano. The chemist studied in Bologna and, after a year at Harvard, earned her PhD at the University of Cologne. Since 2015 she has conducted research at the Center for Astrochemical Studies (Cas) at the Max Planck Institute under the directorship of Paola Caselli.

Many of the objects studied at the Cas can be spotted in the sky with the naked eye. Take the Orion constellation, for example, which stands high in the southern firmament with its characteristic belt of three stars. On a clear winter night, a diffuse little cloud shimmers in the "scabbard" that hangs diagonally below the belt. Located approximately 1350 light years from Earth, this structure contains massive clouds of hydrogen gas, which are gathering under their own gravity and forming new stars. But to find out what's happening here on a small scale, to learn how stars really form, you have to look very closely, like Spezzano. In photos from the giant telescope, the Orion Nebula shines magnificently in saturated red. This is thanks to young, hot stars, whose radiation energy enables them to strip electrons, at least temporarily, from the hydrogen atoms that dominate star-forming regions. When the electrons bond once again with atomic nuclei, a characteristic red light is emitted.

This nebula, which is visible to the naked eye, is embedded in a much larger complex, designated OMC-1. Spezzano and her team are studying that molecular cloud, which only appears at longer wavelengths, in the infrared or radio spectrum. Like all dark nebulae, it is extremely cold, with a temperature just a few degrees above absolute zero (minus 273.15 degrees Celsius). It contains around one percent dust, a whole lot of hydrogen, and plenty of other molecules. The latter tell researchers a great deal about the processes occurring in the clouds, but the molecules are also an important prerequisite for the development of life in a solar system. Conditions on Earth are wholly different from those that prevail in the universe. And that goes for dark nebulae, too. "Astrochemical researchers have to conceive of a whole new form of chemistry," says Spezzano.

SUMMARY

The building materials of stars and planets lie in large and very cold interstellar dark clouds, which consist primarily of gas and a pinch of dust. These dark nebulae contain many molecules, the analysis of which offers insights into how the clouds develop. With the aid of spectroscopy and laboratory experiments, researchers investigate the chemical processes in dark nebulae and the development of stars and planets.

Dark nebulae exist everywhere in the Milky Way. They gather a relatively large quantity of material in a small space and absorb the light of the stars behind them, like a thick curtain. To 19th-century scientists, they appeared to be "holes in the sky". The photographs taken by Max Wolf around the turn of the last century show many of these dark nebulae. Wolf, an astronomer and pioneering astrophotographer from Heidelberg, was responsible for the development of, among other things, a statistical tool for determining the distances of these nebulae from Earth and their respective dimensions.

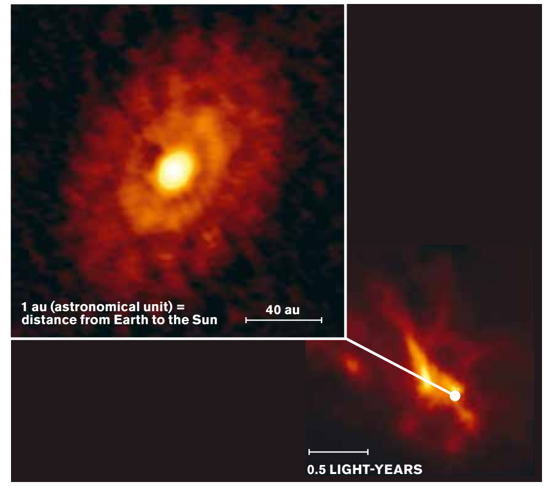
In the 1960s, researchers began using radio telescopes to probe deep into such clouds in search of specific molecules; the most common, after hydrogen, is carbon monoxide. For the first time, one could therefore observe how dark nebulae are structured and the processes that take place inside them before a new star is formed. Today, the clouds are known to contain approximately 300 other types of molecules. Among the most complex are fullerene and dimethyl ether. Spezzano is especially fascinated by the fact that a large number of organic molecules have been discovered in the universe, including amino acids and fatty acids. "All of them are ingredients of life. And they are already present in the clouds where stars and planets are formed."

She relies on spectroscopy to detect the molecules. It enables her to identify individual substances by means of a kind of fingerprint in the electromagnetic radiation of molecular clouds. Spezzano is interested in radio waves with very short wavelengths – in the millimeter range. She studies them with telescopes, such as the 30m Antenna on the Pico del Veleta in Spain's Sierra Nevada mountains and the Northern Extended Millimeter Array (Noema) observatory on the Plateau de Bure in the French Alps. In the radio spectrum, individual molecules reveal themselves by certain energies they radiate due to their rotation. This allows Spezzano to determine, among other things, how bright an astronomical molecular cloud shines at which wavelengths. Many of the thin lines found in the spectrum are characteristic of known molecules, which can be identified using an online catalog.

The lines, or fingerprints, allow researchers to determine the number of molecules of a specific kind in the cloud, the temperature of the gas, its density, and how it moves. The width of the spectral lines tells Spezzano that different parts of the cloud are swirling at speeds of several kilometers per second. The dynamics of the molecules yield information on whether the cloud is collapsing under its own gravity or drifting apart. This ultimately decides whether or not a star will form in the cloud of gas and dust.

Cold fingers

To understand this, a detailed visualization is required of the processes that occur when a star is born. Whereas simple models are based on spherical birth clouds, the matter actually seems to gather in small filaments, which permeate the gas like thin fingers. The Herschel Space Observatory observed filaments like these a few years ago. The structures are clearly the real delivery rooms of stars. How they form has yet to be explained. At an early stage, with no stellar core at the center, the cloud remains rather spread out. When a critical mass is exceeded at one position and gravity wins the upper hand against the outward-oriented thermal pressure of the particles, the cloud begins to collapse under its own gravity, the particles hurtling towards each other.



Star cradle: A gas cloud in the constellation Ophiuchus contains thin, finger-like filaments of cold molecular gas (lower right), in which fresh material flows to the densest regions (bright yellow). Star embryos mature in some of these nodes. The section appears to be about a quarter of the size of the full Moon in the sky and was photographed by the Herschel Space Telescope using infrared photography. In the center of a filament, the Alma telescope network captured a baby star, IRS 63 (upper left). Planets may be forming in its disk of gas and dust.

GRAPHIC: MPE/D. SEGURA-COX; HERSCHEL DATA FROM ESA/HERSCHEL/SPIRE/PACS/D. ARZOUMANIAN

"The ingredients of life are already in the clouds."

SILVIA SPEZZANO

What happens next in the star birth process? It takes a mere million years or so for a mature star to emerge from a molecular cloud. These are relatively fast processes, when compared with the lifetime of a star like our Sun, which lasts around 10 billion years. It all begins with diffuse clouds of interstellar material. Gravity and extremely low temperatures cause the clouds to come together and ultimately disintegrate into even denser fragments containing around 100,000 molecules per cubic centimeter. By comparison, the Earth's atmosphere contains 10 trillion molecules per cubic centimeter – a lot denser and hence much warmer than interstellar gas. The resulting pre-stellar cores are 0.3 light years in size, with temperatures of minus 263 degrees Celsius. If gravity makes the cores unstable, they collapse again and form protostars, which are initially embedded deep in a thick shell of gas and dust. The dust consists primarily of tiny particles of graphite and silica, which have one ten-thousandth of the diameter of the dust particles found on Earth. Many molecules form in the vicinity of the protostar. In addition, material flows from the cool mother cloud to the center of the core, where the material becomes even denser until a disk forms, which feeds the young protostar in the center. Researchers at the Max Planck Institute for Extraterrestrial Physics and the Institute Radio Astronomie Millimétrique in France observed how this works some time ago. They used the Noema antenna system to study a protostellar binary system in a molecular cloud in Perseus (stars often form in pairs) and observed a radiant bridge of matter connecting the outside of the shell with the inner region. Thanks to this "conveyor belt", the mass, density, and temperature of the star-embryo constantly rises. "The molecule that enabled us to discover this cosmic conveyor belt has the structural formula HCCCN, meaning it has three carbon atoms," says Max Planck Director Paola Caselli.

Astronomers often observe disk-shaped regions surrounding protostars. Theoretical models indicate that these would offer good conditions for the birth of planets. And in fact, research shows that they begin growing while the central sun is still maturing. “We used to think that the stars mature first and then, so to speak, become mothers of planets, which don’t come until later. But now we see that protostars and planets develop together from childhood like siblings,” says Dominique Segura-Cox, who previously worked at the Max Planck Institute for Extraterrestrial Physics. At the Atacama Large Millimeter Array (Alma) observatory in the Chilean Andes, her group obtained a detailed picture showing a protostellar disk with multiple holes and dust rings around star IRS 63, which is less than 500,000 years old and far from finished; it will continue to gain mass. Once the temperature in its core rises to around 10 million degrees, nuclear fusion will begin. Hydrogen will convert to helium, and a new sun will shine in outer space.

To obtain an overall picture of the growth of stars, the group at Cas in Garching is studying more and more clouds at various stages. Many such objects were observed and classified in the 1980s. “In the universe there are delivery rooms with and without babies, so to speak, that is, dark nebulae with and without stars,” says Spezzano. In both cases, researchers are registering the fingerprints of dozens of different molecules in the spectra. But there are differences; some clouds contain molecules that aren’t found in others. The amount of a given substance can also vary. The reason: as already stated, the astronomers are observing each cloud at a different stage of development. Spezzano cites methanol as an example. In clouds without stars, the temperatures in the center are low. The chemistry is on ice, so to speak, and gaseous methanol can only be found in low quantities. When a star shines in the cloud, by contrast, the central temperatures are correspondingly higher. The ice melts, the previously bonded methanol is released, and large quantities become visible and measurable.

Interstellar molecules in the lab

“We are trying to combine the pieces of several puzzles into an overall picture,” says Spezzano. This results in an interesting finding: “A protostar radiates energy, which affects its environment. We should really expect that this would completely annihilate the molecular inventory within the cloud. But this is not the case at all. Instead, many of the molecules survive the radiation and are embedded in the developing planets. “It was the same around 4.6 billion years ago, when our planetary system was born. That’s why roughly half of the water in our glasses is older than the Sun,” says Spezzano. The rest of the water originated later, during the star and planet formation process. Occasionally, the spectra indicate molecules that are not recorded in any catalog. “We call these initially unknown fingerprints ‘U-lines’, ‘U’ signifying unknown,” explains Spezzano. Researchers can then work backwards, generating previously unknown molecules under extreme conditions in the lab, measuring their spectral signature, and matching them with a U-line. For example, in cooperation with colleagues from Italy, researchers from the Cas discovered propargylamine in a cloud near the center of the galaxy. This molecule has a complex chemical formula, HCCCHNH, and is exceptionally unstable. It is extremely difficult to isolate on Earth under normal conditions. By contrast, it remains quite stable at the very low densities and temperatures typical of interstellar media, which the team led by Spezzano use for their laboratory research. This species of chemical plays a fundamental role in the formation of amino acids, which are among the most important building blocks of life. Another match was made by Spezzano’s student Judit Ferrer Asensio. She discovered deuterated acetaldehyde (for chemists: CHD-2CHO), first in the lab, then in a molecular cloud. This

Waiting for the measurement: Silvia Spezzano converses with a colleague during an experiment. On the left side of the photograph can be seen part of a vacuum chamber, where she studies how ions and molecules integrate with each other in regions where stars are born. The tests are run under space-like conditions at a maximum of minus 268 degrees Celsius.

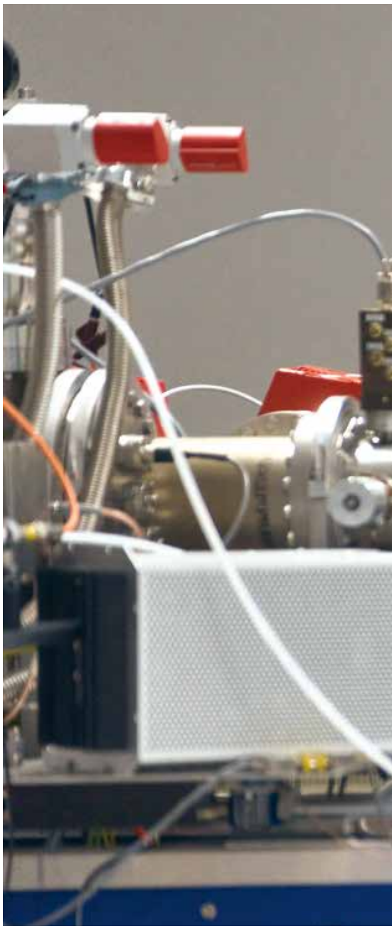


PHOTO: FABIAN VOGL FOR MPG

“Half of the water in our glasses is older than the Sun.”

SILVIA SPEZZANO

shows how important lab work is; alongside observation and theory, it is the third pillar of research at the Cas. A glass tube measuring 3 meters in length is the beating heart of the Cas Absorption Cell (Casac), one of several spectrometers in the basement of the Institute. The system studies the spectral fingerprints of molecules in the gas phase. They can also be created in plasma inside the glass cell. The spectroscopic equipment records wavelengths between 0.3 and 4 millimeters. In another room stands an instrument called Cas-Ice. An ice machine called Coldfinger lowers the temperature of molecules to a maximum of minus 268 degrees Celsius. Researchers use Cas-Ice to study different mixtures of frozen substances in the infrared portion of the spectrum. Among other things, the instrument allows for a direct comparison with observations of cosmic ice made using the James Webb Telescope.

In 2023, the space telescope registered sulfur dioxide in the atmosphere of a planet for the first time. The spectral lines of the molecule get wider as the pressure increases. This could, for example, be attributable to the presence of other molecules, such as hydrogen, water, nitrogen, or oxygen. In the lab, Spezzano's team injects this molecule into an artificial atmosphere and compares the varying line widths of sulfur dioxide with the measurements from the James Webb Telescope. “In the future, this method will allow us to recreate the complex atmospheres of smaller Earth-like planets,” says Spezzano. At the heart of such experiments lies a fundamental question, one that not only interests Spezzano, but that lately has guided the entire field of astrochemistry: how does life come into the world?

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