In the Cosmic **Chemistry Lab**

As a young girl, she was a talented painter and had a keen interest in art. The course for her future seemed set. Then she happened upon a book – a book that transported her into the vastness of space and ultimately decided her career aspirations. **Paola Caselli** thus became, not an artist, but an astrochemist. As a Director at the **Max Planck Institute for Extraterrestrial Physics** in Garching, she is still just as fascinated by cosmic clouds as she was when she was 12.

TEXT **ALEXANDER STIRN**

In the beginning was a book: *The Black Cloud*, a science fiction novel about a monster made of gas and dust that, to astronomers' amazement, would later turn out to be an intelligent life form. It was written toward the end of the 1950s by Fred Hoyle, an astrophysicist who was as brilliant as he was controversial.

At the age of 12, Paola Caselli was blown away when her teacher handed her the book. The mere thought of peering into the depths of space through a telescope, studying clouds and possibly discovering extraterrestrial life captivated the schoolgirl. Finally, Caselli realized, she had found the mission she had dreamed of – her calling in life.

Now, 40 years later, Caselli is sitting in a bright, tidy corner office just outside Munich. Nevertheless, dark black clouds are omnipresent. Using the world's biggest and most powerful telescopes, the Italian scientist, a Director at the Max Planck Institute for Extraterrestrial Physics in Garching since 2014, investigates which molecules exist in interstellar clouds, which chemical processes take place there and how they could give rise to stars, planets and perhaps even life. Caselli – black hair, black glasses and words flowing like a waterfall – is driven by an overwhelming sense of curiosity and an almost Prussian sense of discipline.

A BOOK BY FRED HOYLE DETERMINES HER CAREER

"Fred Hoyle was a visionary, an idol," Caselli says with a twinkle in her eyes that leaves no doubt as to the fascination that must have captivated her then – and how strong that enthusiasm remains today. "His book opened my eyes. I connected the dots and I knew: Okay, that's exactly what I want to do. I want to use the short time I have in this universe to better understand it."

Though peppered with physics formulas, Hoyle's first work was science fiction through and through. In 1957, when the famous British astrophysicist wrote his book, experts knew of no more than a few simple organic molecules (CN, CH, CH+) in interstellar clouds, let alone any manner of life. The field of astrochemistry, in which Caselli is at home today, didn't even exist.

Science has since come a long way. Since the early 1990s there has been little doubt that molecules exist almost everywhere in the cosmos: in the black clouds of gas and dust that stretch between the shining stars, both in our galaxy and in the depths of the universe. Chemists have also succeeded in studying the properties of these molecules in detail in the lab.

Of particular interest to astronomers is how the molecules behave when excited by radiation and colli-

Ambitious: Even as a young girl, Paola Caselli was fascinated by the cosmos and doggedly pursued a career in science. Today, she is a Director at the Max Planck Institute for Extraterrestrial Physics in Garching.

Photo: Axel Griesch

» My parents taught me a great deal, especially about how to make ends meet. But science – that I had to learn myself.

sions with other molecules, particularly hydrogen (H_2), the most abundant molecule in the cosmos: following excitation, molecules can rotate, vibrate and emit electromagnetic waves of a precisely known frequency. A "glowing fingerprint" emerges that is characteristic of each molecule.

"These fingerprints allow us to study the physics in cosmic clouds from a great distance," says Caselli. Although the clouds appear dark and usually only shimmer faintly with low energy, large telescopes can detect their characteristic radiation. The data obtained gives astrochemists information about the composition of the clouds.

And not only that: the data also reveals a lot about conditions in space. For example, if the molecules are moving relative to the Earth, the frequencies of the fingerprints are shifted slightly by a phenomenon known as the Doppler effect – similar to how the pitch of an ambulance siren changes as it races past at high speed. "If a cloud collapses, as occurs before the birth of a star, we can detect such movements from Earth," Paola Caselli says.

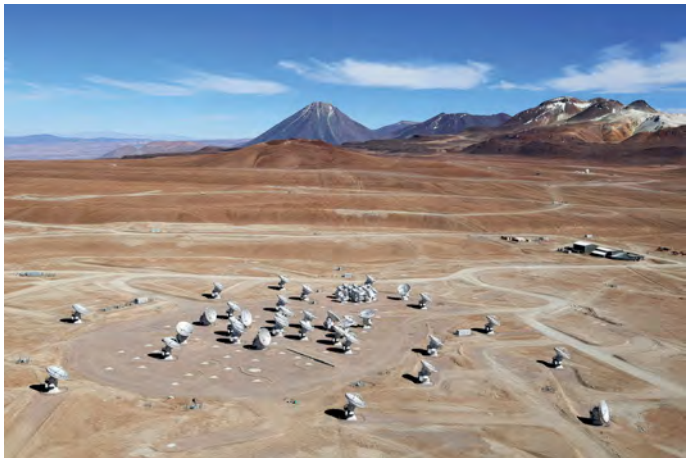
AMMONIA SERVES AS A COSMIC THERMOMETER

But molecules can do even more. Owing to its structure, a gas such as ammonia has various transitions. Several radiation lines emerge whose relative intensity depends on the ambient temperature. Astrochemists therefore use ammonia as a thermometer for measuring the temperature of distant clouds.

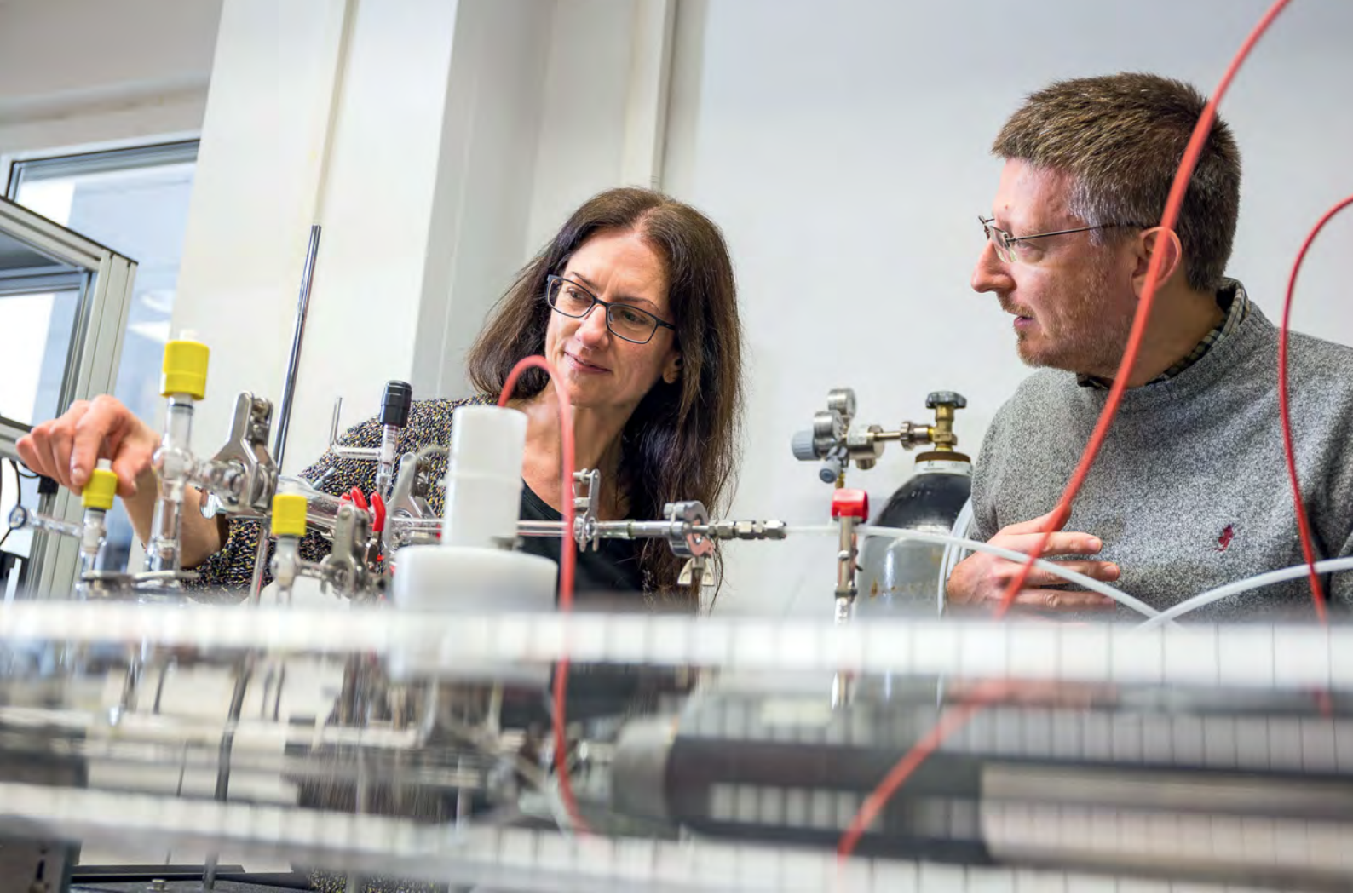
The chemical composition of the cosmic structures is also intriguing. A close look at the signals shows that most of the molecules are organic in nature, as Fred Hoyle predicted: they consist of carbon and, in many cases, nitrogen – the basic requirements for life as we know it. Some molecules are just one step away from the simplest amino acid, glycine, an important building block of proteins. Fatty acids, which are required for cell membranes, as well as nucleobases, which make up our genetic code, also exist in the primordial material of our solar system. And water is ubiquitous, too. "Basically," Caselli says, "we see everything that is needed to make up prebiotic material, everything needed to create a life form – and even from a time before life existed on Earth."

In the Tuscan seaside town of Follonica, where Caselli grew up, all this is at least as distant as the nearest stars and galaxies. Here, the closest they come to

A valuable tool: To obtain data and gain insights into cosmic molecular clouds, Paola Caselli and her team make observations using the world's biggest and best telescopes, including ALMA, an array of 66 radio antennas in the Atacama Desert in Chile (left) and the 30-meter telescope on Pico Veleta in Spain, which is operated by IRAM.



Photos: Clem & Adri Bacri-Normier (wingsforscience.com)/ESO/IRAM



The cosmos in a lab: It's not easy to replicate the conditions of cosmic gas clouds in an experimental setup, as they are extremely thin and very cold compared with the Earth's atmosphere. But Paola Caselli and her colleague Luca Bizzocchi succeeded in producing and studying reactive molecules. The light they emit can then be compared with observations of real molecular clouds in space.

exotic are the foreign tourists who stop off in Follonica on their way to the island of Elba just off the coast. Caselli's mother works there as a seamstress, mostly from home, at the same table where little Paola did her homework.

Her father also came from a family that wasn't blessed with wealth. He had no education, repaired shoes, worked in bars and shops, and eventually became a barber – an occupation that Caselli's younger brother still pursues today. "My parents are from a humble background," Paola Caselli says. "They taught me a great deal, especially how to make ends meet. But science – that I had to learn myself."

Initially, however, her focus was on art. Little Paola loved to paint, mainly with oils. She mostly painted colorful landscapes, birds and almost microscopically detailed insects. Later, in secondary school, she produced precise black-and-white images, abstract and with a calligraphic flair. "When I painted, I would completely lose myself in my work and only after five or six hours realize: Oh, maybe I should eat something," Caselli says with a laugh.

PROTOSTARS FORM AT THE CENTER OF DARK CLOUDS

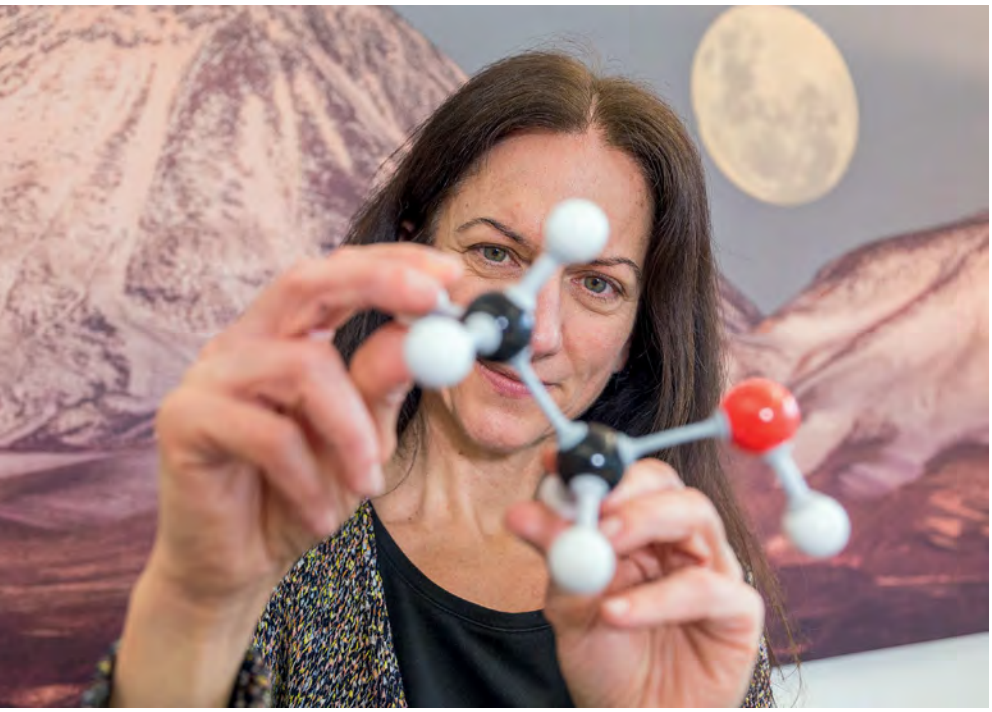
A difficult step came toward the end of secondary school. Fred Hoyle's book had long since made its impact and the previously indecisive student knew in her heart that she wanted to become an astronomer. "I decided to quit painting entirely," Caselli says. "If you want to do something, you must commit yourself fully – or just let it be."

Now, her attention is focused on the birth of stars and star systems: in the center of dark clouds, molecules gradually grow in complexity. The first delicate star structures form, known as protostars. They aren't yet dense enough to ignite the fire of nuclear fusion that lights up conventional stars; their pale light comes from molecular gas and dust that heats up and glows while raining down on the newly created protostars.

Yet the local conditions and the associated chemical reactions aren't easy to understand. At first, there are just a few thousand molecules in every cubic centimeter of space, in molecular clouds. In the end, when a protostar is born, there are one septillion particles per cubic centimeter. "We need to understand an enormous number of physical steps that occurred between those two states," Caselli says.

And that's not all: the remains of the original gas and dust clouds surround the newborn stars like a doughnut. It is precisely in those regions that planets are most likely to emerge, and with them entire star systems. The same processes that led to the birth of our solar system were at work. For Caselli, this is an extremely fascinating process: "Basically, it's about under-

Photo: Axel Griesch



Looking at our own history: Gigantic gas and dust clouds full of molecules roam the universe. So far, astrophysicists have identified around 150 chemical species, including organic compounds such as formaldehyde, formic acid and methanol. These and many other building blocks of life also accumulated in the material from which our Sun and the planets – and ultimately we humans – were formed.

standing our own history," the astrochemist says. And all this with nothing to go on but the ghostly light from distant molecules.

E-MAILS SENT OVERSEAS TO TWO PROFESSORS

Thirty-five years ago, when Paola Caselli finished secondary school and opted for science instead of art, astrochemistry itself was still in the "protostar stage." It didn't sparkle; it barely existed. Caselli went to Bologna, to one of only two astronomy departments in Italy at the time. It quickly became clear that astrophysics alone wouldn't lead her to her goal, so Caselli also attended chemistry classes, took the examinations for those and met people with whom she still works today. She completed her studies in overdrive. "Since my parents weren't rich and couldn't support me forever, I felt an obligation to not waste any time," says the Max Planck Director.

But for a master's degree in astrochemistry, it was clear that she would have to go abroad to study. One evening, Caselli was working with a telescope near Bologna. The weather was bad and there was nothing to do, so she sent two e-mails to American professors whose names she had found in the astrochemistry publications she liked best. "Those may have been the first e-mails I ever sent overseas," Caselli recalls. Both professors replied to the Italian student. Both invited her to study in the US.

Paola Caselli first went to Ohio and later to Harvard, where she completed her doctorate at the age of 28. A year later, she returned to Italy for the sake of her family. There, she obtained a permanent researcher position at Arcetri Astrophysical Observatory. "That was great, as I was close to my family, and my colleagues there were brilliant," she recalls. But it proved to be a constant battle there for students and research funding. So she returned to Harvard, and finally moved to Leeds, England, where she was offered a professorship. In other words, the usual nomadic wanderings of a scientist.

"If you want to do research, you have to seize every opportunity you're offered," she says. "Under no circumstances should you be afraid to move again and again." Not even if – as in Paola Caselli's case – you have a daughter who you have raised alone since she was three and a half years old. "Of course things are difficult sometimes, and you have to organize your life very efficiently. But children adapt quickly to new environments," says the 51-year-old. "As long as the parents are happy with what they're doing, it's okay for the kids."

Finally, in April 2014, now a Max Planck Director, she moved to Munich. There, in Caselli's corner office overlooking a stream flowing through the middle of the institute campus in Garching, there are no pictures of colorful nebulae or dark clouds. Instead, large-format photos of telescope systems adorn the walls. These are the tools of astrochemists, and Paola Caselli needs a lot of them. Depending on what excites the faraway molecules – cosmic rays, pale starlight or violent explosions – they emit radiation of different

Photo: Axel Griesch

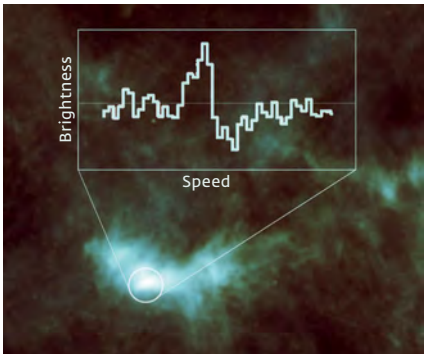
wavelengths: some secrets are revealed by radio waves or short microwaves, and others by infrared light. X-ray telescopes are also needed in order to complete the picture.

HUGE VIRTUAL TELESCOPE ON THE COMPUTER

But an assorted mix of radiation wavelengths isn't the only thing that can shed light on the molecules and their movements. To study the phenomena in detail, astrochemists also link numerous telescopes together to form what is known as an interferometer. By overlaying multiple signals, they can create a giant virtual telescope in a computer with immense resolution. In doing so, however, the big picture is lost, which is why individual telescopes are still needed. "Because we're unable to touch the clouds, it's extremely important to get as much complementary information as we can," Caselli says. "The only way to do that is by examining as many electromagnetic frequencies as possible."

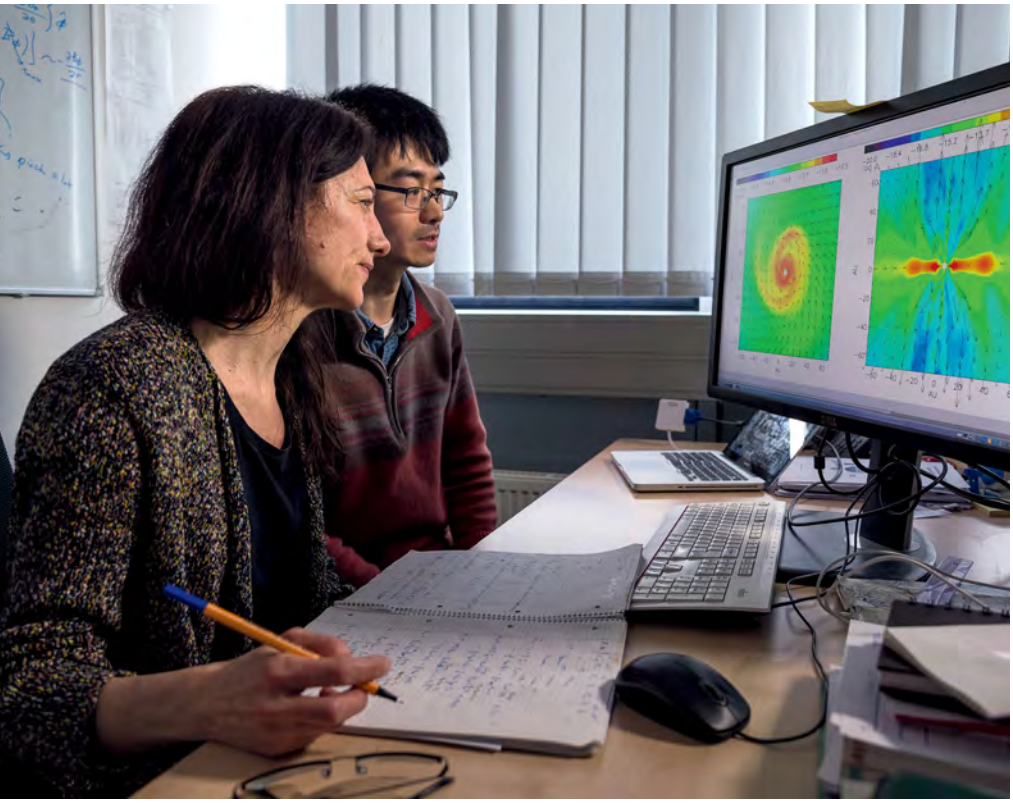
For astrochemists, this means that they are constantly on the move, visiting such far-flung corners of the Earth as Chile and Hawaii. "That can be pretty tough sometimes. You travel a lot and you have to stay up through the night and immediately comprehend what's going on. After all, you don't want to waste valuable telescope time," Caselli says. Now the researcher avoids this stress: she sends students and junior scientists – to learn, to familiarize themselves with the telescopes, but also to have a little fun exploring exotic places during their trips.

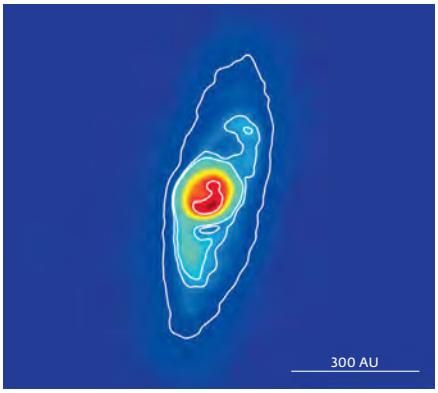
After all, having fun is crucial: "One of the most important things for young scientists is having motivation – combined with a willingness to dedicate precious time to science," Caselli says. For example, she herself had to observe the skies two Christmases in a row. The Italian researcher shakes her head. "Who would do that sort of thing if they weren't highly motivated?" So grades and letters of recommendation aren't everything for the astrochemist: "People can be as smart



In the stellar nursery: The Rho-Ophiuchi complex in the constellation Ophiuchus (top) is a shining example of the birthplace of stars. Researchers like Paola Caselli search such clouds for molecules. The smaller illustration shows the first evidence of water vapor – represented by the spectral curve – within the thick cloud in which a star will soon form. The region, named Lynds 1544, is located in the Taurus constellation and was captured using in the infrared range with the *Herschel Space Observatory*. The amount of water found in the cloud could fill around 2,000 terrestrial oceans.

Photos: Jim Misti and Steve Mazlin (acquisition), Robert Gendler (processing); ESA/Herschel/SPIRE





Back to the beginning: The group led by Paola Caselli – shown here with Bo Zhao – is concerned with the origin of stars and planets in theory and practice, on the computer and at the telescope. The bottom photo was obtained with the ALMA radio interferometer and shows a young protoplanetary disk embedded in the larger cloud in which it formed. Our solar system looked similar to this image around 4.6 billion years ago.

as they want, but if they're not enthusiastic, it won't work."

In selection interviews, Caselli therefore tries to gauge candidates' interest in the research subject and whether they have a real zeal for astrochemistry. If not? No problem. "As long as young people find a field they're passionate about, they'll be successful."

THE DAY BEGINS WITH PHYSICAL EXERCISE

When it comes to motivation and discipline, Paola Caselli sets the same high standards for herself. When it all becomes a bit too much – with work, with her daughter, who is about to graduate from secondary school and whose picture occupies a place of honor on Caselli's tidy desk – the scientist relies on good organization: "If you plan your daily routine without worrying about it too much, you don't notice how crazy it all is." Almost every day begins with exercise: on an exercise bike or stair stepper, but in any case, with stretching for the back. Even on trips, her gymnastics mat must accompany her. To save time, and because Caselli has no time for reading anyway, she listens to audiobooks while working out.

She is also disciplined when it comes to eating: healthy, not too much, and above all, fast, please. In Italy, she relates with sweeping gestures, half an hour was often wasted before everyone was ready to march off together to the cafeteria. Here in Garching, you set off at the agreed time. End of story. "I like the German way, the order, the rules," Caselli says, laughing. "I like clear messages."

Fred Hoyle, the idol with the black cloud, was different. The brilliant but controversial astrophysicist liked to make his own rules and formulate his own hypotheses. One of his most famous is that simple life forms are distributed throughout the universe, and thus also reached Earth – a theory known as panspermia. "I don't believe in it," Caselli says tersely. "It's interesting, but we need proof." So far, the only thing that is certain is that water and organic molecules regularly ride piggyback to Earth in meteorites. In the future, Caselli wants to team up with biophysicists to determine whether that is enough for life to emerge from the building blocks formed in space.

That won't be easy, and it will take time. It is, the astrochemist muses, a puzzle – a project for future generations. "It will be important to not get lost in the details," she says. "We must always keep the important questions foremost in our minds, the questions we would really like to answer. Only that will keep the motivation alive." ◀

Photos: Axel Griesch; MPI for Extraterrestrial Physics

God's law?

The future of a research team comparing Islamic family and inheritance law was at stake. The Foundation bridged a funding gap at the Max Planck Institute for Foreign and International Private Law, enabling Nadjma Yassari to continue a vital contribution to research – and do more to show how changeable Islamic law applies in Germany.

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