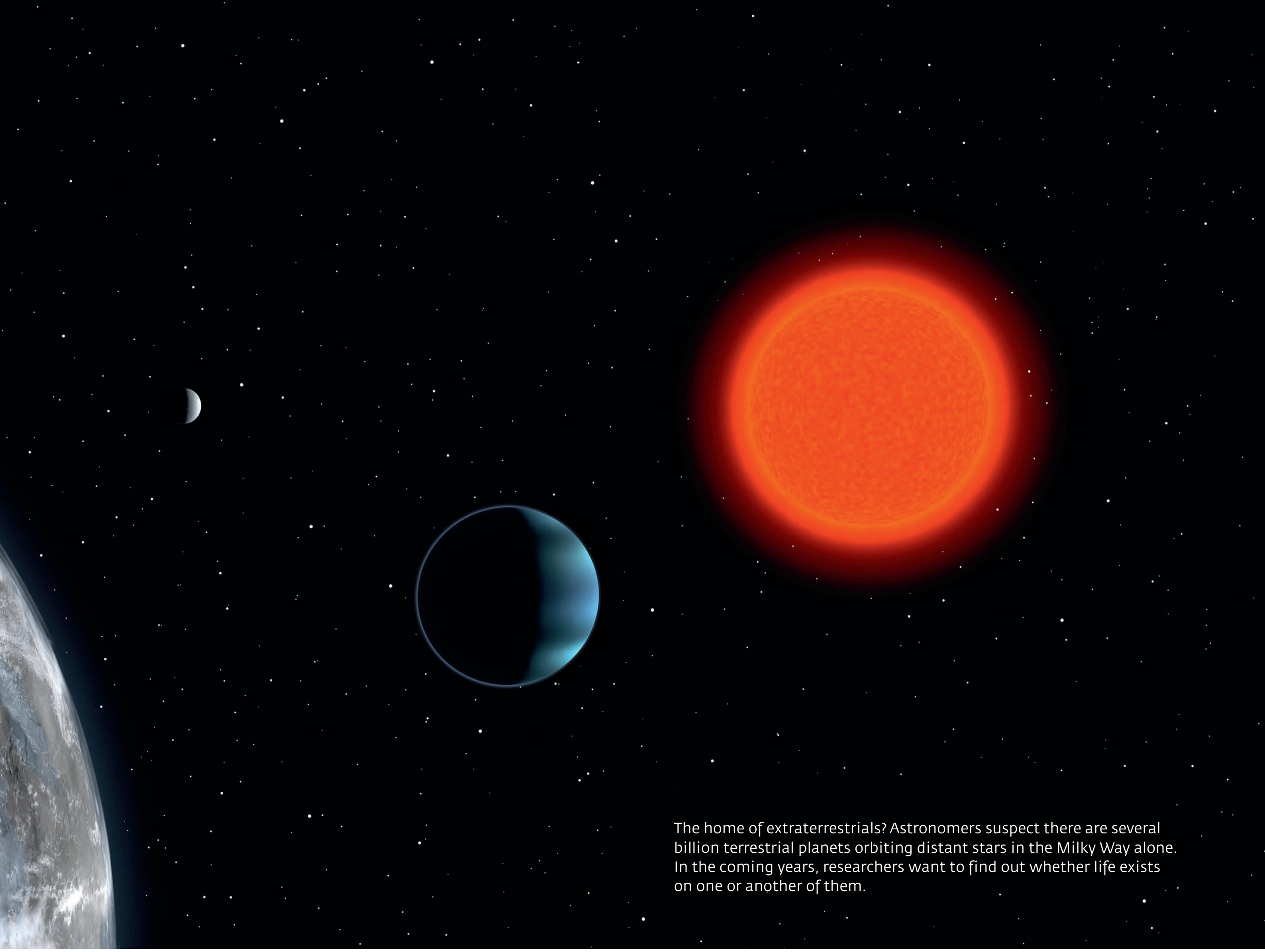
The Search for a Second Earth

To date, astronomers have discovered nearly 800 planets orbiting distant stars. So far, only three of them have been found to potentially offer life-sustaining conditions. However, there are probably many second Earths in the Milky Way. But how can traces of life be detected on exoplanets? At the **Max Planck Institute for Astronomy** in Heidelberg, **Lisa Kaltenegger** is trying to answer this question.

TEXT **THOMAS BÜHRKE**



The home of extraterrestrials? Astronomers suspect there are several billion terrestrial planets orbiting distant stars in the Milky Way alone. In the coming years, researchers want to find out whether life exists on one or another of them.

Max Planck once said of himself that, on leaving school, he could just as well have studied music as the classics. The fact that he opted for physics was thanks to his math teacher and the "desire to study the laws of nature in greater detail." Lisa Kaltenegger is certainly modest enough not to compare herself with the pioneer of quantum physics, but what they have in common are their wide-ranging interests and the impetus provided by a committed teacher.

Unlike Max Planck, Lisa actually did start with a broad range of disciplines, studying Japanese, film and media studies, business studies, engineering physics and astronomy in order to find out what fascinated her most. This meant she was constantly commuting to and fro between the University of Technology and the Karl-Franzens University in Graz. "It was a ten-minute bike ride," she says, to explain how she coped with this pentathlon of courses.

SPECTRAL FINGERPRINT OF OUR PLANET

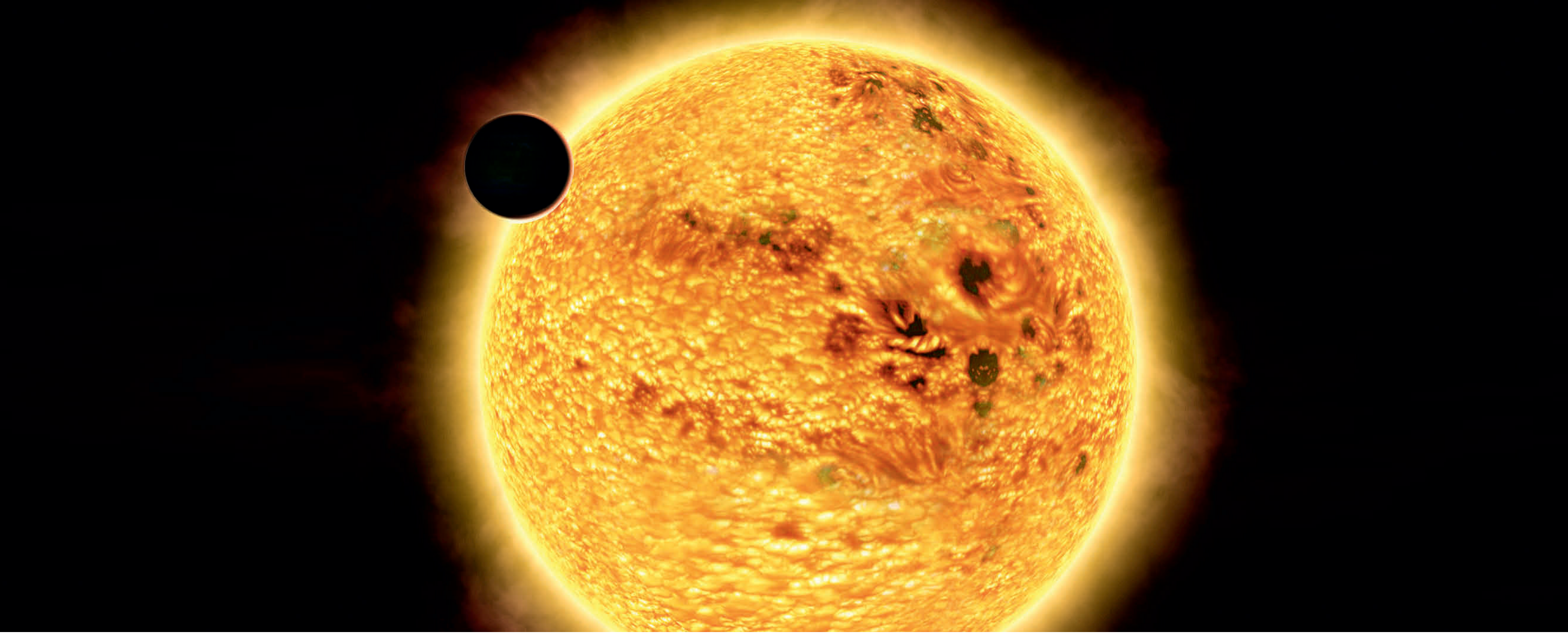
She couldn't keep this up long term, obviously, and finally she settled on engineering physics and astronomy – though a career advisor had urged against a career in the natural sciences. It would be difficult for a woman to hold her own in the field, he said.

Less than twenty years later, Lisa Kaltenegger leads an Emmy Noether Group at the Max Planck Institute for Astronomy in Heidelberg, and is simultaneously a Research Associate at the renowned Harvard-Smithsonian Center for Astrophysics, where she spends three months of the year. She is one of the most creative and competent specialists in extrasolar planets. This year she was awarded the prestigious Heinz Maier-Leibnitz Prize for physics by the German Research Foundation and the German Ministry of Research.

In 1993, American astrophysicist Carl Sagan published the spectral fingerprint of the Earth, which had been recorded with the *Galileo* space probe. Inhabitants of distant planets could also make such a spectrum of our planet and use it to deduce our existence. Conversely, it should be possible for us to search for such traces of life on one of the exoplanets.

The discovery of the first exoplanet, a celestial body orbiting a distant star, created not only a new, fast-expanding branch of astronomy in 1995, but also electrified Lisa Kaltenegger in her final year at school. This enthusiasm was encouraged by a good physics teacher who also offered courses in astronomy. >

Photo: ESO



It must be said that her home town of Kuchl, near Salzburg, Austria, is less known for astronomy than for its wood processing and agriculture. But her parents ensured lively discussion on a wide scope of topics at the dinner table.

PALEONTOLOGISTS AND BIOLOGISTS ALSO ON BOARD

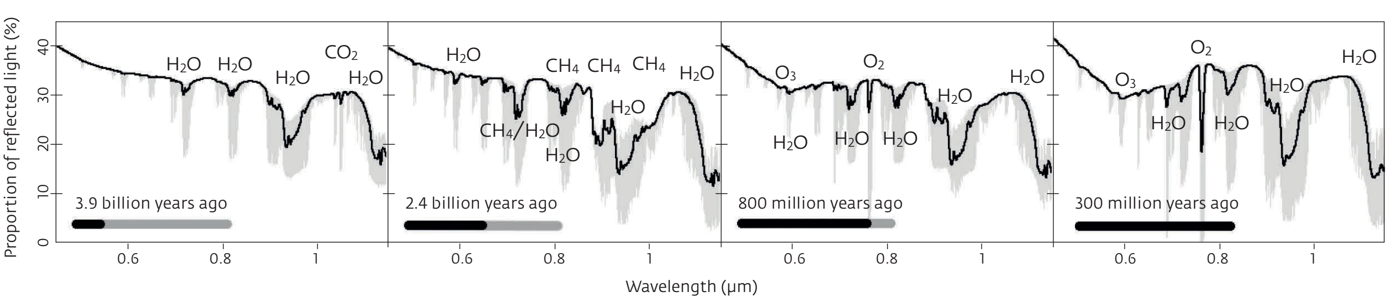
"At the end of the 1990s, nobody in Austria was working on characterizing exoplanets," says Lisa. She would have to leave the country. Research visits to the Instituto de Astrofísica de Canarias on Tenerife, Johns Hopkins University in Baltimore and the European Space Agency in the Netherlands followed. Here, she was part of a three-person design team working on the *Darwin* project, an ambitious plan to use several telescopes in space to find Earth-like planets around other stars and to characterize them. Her knowledge of both engineering and astronomy was clearly an asset in this position.

Though *Darwin* was put on ice, as was a similar NASA mission, this didn't mean that the search for a second Earth was abandoned – especially not by Lisa Kaltenegger. NASA's *Kepler* mission in particular excited her, because its fascinating discoveries greatly increased the number of potential terrestrial planets, which made missions such as *Darwin* seem more realistic again. "Discovering traces of life on another planet would be one of the truly great steps in the exploration of the universe," says Lisa.

"This great discovery would have social, religious and philosophical consequences, of course. From the scientific point of view, it would also provide the opportunity to learn something about the evolution of our own planet and to take a purely statistical look into the future of terrestrial planets," explains the Max Planck scientist.

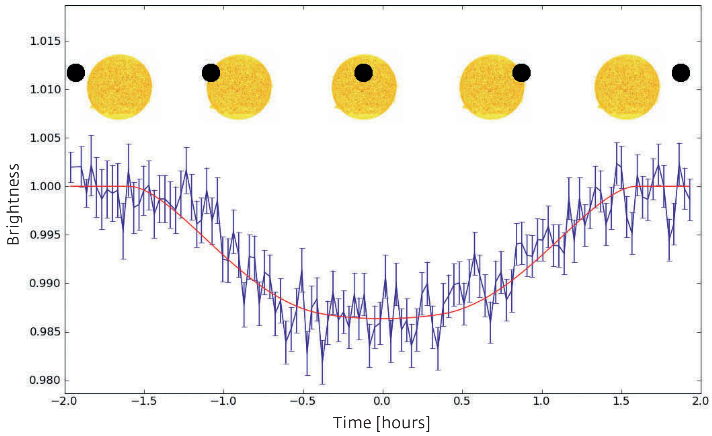
Her work also focuses on Earth's evolution in order to learn about habitable planets. The idea is simple in principle: "When we are able to investigate a distant rocky planet spectroscopically, what could be the indicators of life? We can't assume that any possible life there is at the same stage of evolution as we are now." So the first thing she did was to investigate how Earth's atmosphere had evolved since the formation of our planet, which involved close collaboration with biologists and paleontologists.

In the beginning, carbon dioxide (CO_2), nitrogen and water dominated the primeval atmosphere. When the first organisms appeared about 3.5 billion years ago, they produced methane, which enriched rapidly in the air, while the CO_2 content decreased further. About 2.4 billion years ago, the first organisms began to produce oxygen in abundance; its concentration in



Those who want to roam far from home must first be familiar with their local surroundings. This explains why Lisa Kaltenegger is studying the evolution of the terrestrial atmosphere before she transfers these findings to other, as yet unknown planets. She is particularly interested in which fingerprints would be observable in the spectra from different eras. For example, 3.9 billion years ago, in the early history of our planet, water (H_2O) and carbon dioxide (CO_2) predominated. Then the first organisms produced methane (CH_4), and later, oxygen. Its quantity grew and the increase in molecular oxygen (O_2) was accompanied by the proliferation of ozone (O_3) in the atmosphere. The concentration of oxygen, at 21 percent, has remained almost unchanged for around 300 million years.

Photo: ESA, NASA and Frédéric Pont (Geneva University Observatory); graphics: MPI for Astronomy – Lisa Kaltenegger



Stellar eclipse: There are several ways to detect exoplanets. One of them uses the transit: Seen from Earth, the planet transits in front of its parent sun – as Venus transited in front of the Sun on June 5/6, 2012. Astronomers deduce the characteristics of the exoplanet from the decreasing brightness and the light curve during the passage; under the most favorable conditions, the method also allows spectral observations of the planet's atmosphere.

Taken by Dimitris Mislis with the Oskar Lühning telescope at the Hamburg observatory

the atmosphere increased slowly at first, with fluctuations, until around 300 million years ago, when it reached about 21 percent, which has remained almost unchanged since. The increase in molecular oxygen, O_2, was accompanied by the increase of ozone (O_3). At the same time, the proportions of carbon dioxide and methane changed.

For a long time, astronomers had assumed that high concentrations of oxygen and ozone were, in themselves, certain indicators of life. But as Lisa Kaltenegger explains: "The crucial things are combinations – of molecular oxygen or ozone with a reducing gas such as methane, for example." If present in larger quantities, these gases in combination are the better biosignature. Either substance alone can also be produced inorganically – oxygen through photolysis, when light from a sun splits carbon dioxide or water, for example. But oxygen and methane react rapidly with each other and produce water and carbon dioxide or monoxide. Therefore, in combination, these gases indicate strong sources of both chemicals, which can only be explained by a biological source of oxygen on a temperate planet. If all biota on our Earth were to suddenly stop producing oxygen, the oxygen would be as good as gone within around a million years. So if oxygen is produced inorganically, its proportion, and consequently that of ozone in the atmosphere, is likely to be very low.

As a postdoc at Harvard, Lisa Kaltenegger adapted an Earth atmospheric computer model to exoplanet atmospheres and, using fossil finds, explored how the chemical composition of Earth's atmosphere varied during geological evolution. The resulting spectral fingerprint of our planet through geological time can indicate life. The surprisingly positive result was that, "For about half of Earth's history to date, extraterrestrials could have detected traces of life in our atmosphere as a combination of oxygen or ozone with methane and water."

NO GAS RECYCLING WITHOUT TECTONICS

Something similar could then also hold true for other terrestrial exoplanets. Of course, all of these considerations require that life there function according to roughly the same chemical principles as it does here: it needs liquid water and is based on carbon chemistry. "We can't simulate the effects that different forms of life not known to us would have on the atmosphere," says Lisa.

Nor can the scientist expect a second Earth to have the same physical characteristics as our planet, of course. It may, for example, be smaller or larger, hotter or cooler, drier or have more water. What is certain is that it must be a rocky planet, just like the Earth and Mercury, Venus and Mars in our solar system.

If a planet is more than twice as large and thus around ten times as heavy as Earth at the same density, it is more likely to be a gas planet, a kind of miniature Neptune. If it is very small, on the other hand, like Mars, it may not have tectonics. Yet tectonics plays a significant role in the evolution of a planet and its atmosphere. It is what allows a feedback mechanism that recycles gases like CO_2.

The lava descending into Earth's interior can bind carbon dioxide and remove it from the atmosphere. Volcanoes, in contrast, introduce CO_2 into the atmosphere again. Tectonics thus acts like a carbon dioxide buffer. If a planet doesn't have this compensation mechanism, it can become too hot even with small increases in external influences, such as an increase in the luminosity of its sun over time. On the other hand, Earth, for its part, would have been completely frozen when it was young and the Sun less luminous.

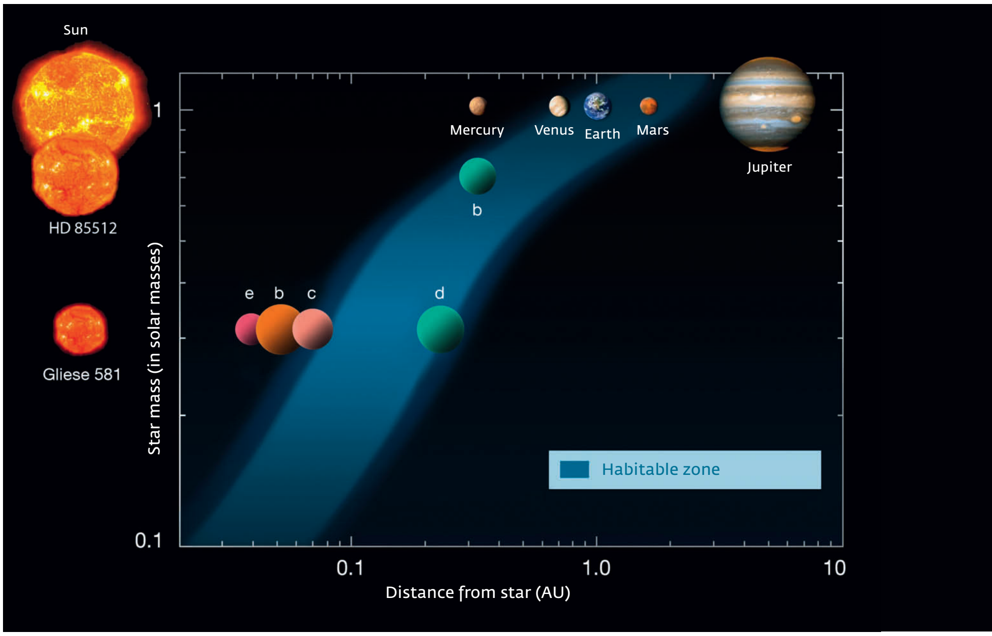
Conditions for life as we know it can be detected in the atmosphere of an exoplanet many light-years away only if it is within the so-called habitable zone. This is the zone around a star where the temperatures prevailing on the surface of a planet are such that water can exist in liquid form – a prerequisite for life – and life can produce detectable atmospheric features. The stress here is on *can*, because whether this is really the case depends on the conditions on the planet.

So the discovery of an exoplanet in the habitable zone of its sun is exciting, but by no means proof that it has an environment that is potentially habitable. Mars, which orbits our Sun on the edge of its habitable zone, is a good example of a celestial body within this region that is, as far as we know, uninhabited.

On the computer, Lisa Kaltenegger simulates possible atmospheres and their detectable spectral fingerprints for the next generation of telescopes for already detected extrasolar planets, as well as a wide grid of rocky planets, where she varies the different parameters, such as mass and radius of the planet, and luminosity and temperature of the star. The latter is also a very critical parameter because it increases with the age of the star. The luminosity of our Sun has increased by around 20 percent during the past two billion years.

The planet and its atmosphere will adapt to this gradual change. And in many cases, this will cause an exoplanet to migrate out of the habitable zone after a certain period of time as it becomes too hot on its surface. Earth won't escape this fate, either. But we still have a few hundred million years before this happens.

Astronomers have discovered around 800 exoplanets since 1995, with new ones being added nearly every day. But most of them are gas planets, which can be detected more easily due to their large mass and size. Only a few of them are what is known as a super-Earth. These are planets that can be up to ten times more massive and up to twice as big as Earth, and rocky.



A niche for life: Not every star and not every distance from it can sustain life – or at least not life as we know it. Favorable conditions, for instance where water is liquid, exist only within the habitable zone. This applies to the exoplanets Gliese 581d and HD 85512b (green spheres), for example.

Graphic: ESO

ATMOSPHERIC MODELS FOR TWO HOT FAVORITES

Two such super-Earths can be found at the edges of their respective habitable zones: Gliese 581d, which is 20 light-years away and seven times as massive as Earth, and HD 85512b, which is 36 light-years away and 3.6 times as massive as Earth. For these hot favorites, Lisa Kaltenegger used her computer model to calculate the atmospheric conditions that would enable liquid water on the surface.

The results she obtained differed greatly: On Gliese 581d, which orbits on the outer edge of the habitable zone, the CO_2 in the atmosphere alone would have to be at a pressure of seven bar in order for the greenhouse effect to heat it sufficiently. In contrast, HD 85512b, which is on the inner edge of the habitable zone, would have to be surrounded by a dense layer of clouds that block out the light of its sun to a large extent: "The clouds would have to cool the planet," explains Kaltenegger.

Both conditions change the observable spectral fingerprint significantly and give us a first small glimpse into the exciting variety of the potentially terrestrial exoplanets. Purely philosophically, it is also attractive to imagine beings that live permanently under dense cloud cover and thus never see the sky and the stars. What kind of world view would they have?

Regardless, there will ultimately be only one way to answer the question of life in the universe: through observation. Lisa Kaltenegger's dream is to soon get the first spectral fingerprint of an extrasolar rocky planet, and to then use her atmospheric models to scan for biomarkers. But even with the next generation of telescopes, this project will come up against the limits of technology and test the creativity of researchers and engineers.

Transits offer what is probably the best opportunity to study the atmosphere of an exoplanet with existing telescopes over the next ten years. They always occur when we just happen to be looking onto the edge of an exoplanetary system. Its planets then pass in front of the star once every orbit, and the stellar light gets filtered through the exoplanet's atmosphere before it reaches us.

This is how the molecules leave their spectral fingerprint in the star's light. But it is incredibly difficult to identify the biosignatures it contains, because the planetary atmosphere of rocky planets is so thin. This is easy to understand when you look at satellite pictures of Earth. Lisa Kaltenegger compares the planet and its atmosphere with an apple and its peel.

Hubble's successor, the *James Webb* space telescope, is set to offer completely new possibilities from 2018. But despite its large main mirror, measuring 6.5 meters in diameter, it approaches the limit for terrestrial planets. For a system similar to that of the Earth and the Sun, Kaltenegger and other international colleagues have estimated that a spectrum has to be recorded for about one hundred hours on average in order to detect the weak biosignatures.

Yet the transit period for Earth lasts only around 12 hours – and the planet needs about a year to orbit a Sun-

Award-winning astronomer: Lisa Kaltenegger leads an Emmy Noether Group at the Max Planck Institute for Astronomy in Heidelberg, and is simultaneously a Research Associate at the Harvard-Smithsonian Center for Astrophysics. She was awarded the Heinz Maier-Leibnitz Prize 2012 for her research into exoplanets.

like star. It would thus take 10 years to add up to a spectrum of sufficient quality. A sobering calculation, especially since it exceeds the expected life of *James Webb*.

ONLY BRIGHT STARS PROVIDE CERTAIN MEASUREMENT RESULTS

Parent stars that are smaller, cooler and more common than the Sun offer greater hope. Their habitable zone is closer to the star than is the case for the Earth. Planets therefore need only a couple of months to complete one orbit. As a result, transits occur much more frequently, which would allow more spectral acquisitions per terrestrial year despite the shorter individual period of transit in front of the star.

"So it is extremely important to find one or more optimum candidates before *James Webb* is launched," says Lisa Kaltenegger. That is why she is working on the American Transiting Exoplanet Survey Satellite (TESS) project, which is expected to search for terrestrial planets of near bright stars by 2016. This is important for the subsequent observations with *James Webb*, because only bright stars afford the opportunity to obtain a good spectrum within a reasonable period of time.

This is also the aim of the mission known as *PLAnetary Transits and Oscillation of stars* (*PLATO*), which is in the European Space Agency's selection phase together with four other satellite projects. However, its launch wouldn't happen before 2022, which would place the first *PLATO* results in the time after the nominal service life of *James Webb* had ended.

The next generation of large telescopes will offer a second possibility to discover traces of life on exoplanets. This includes primarily the European Extremely Large Telescope, and the European Southern Observatory recently gave the go-ahead for its construction in the Chilean Andes. Its main mirror will be about 39 meters in diameter and should be operational by the end of this decade.

But there is one fundamental problem here: "The spectral lines we want to detect for the terrestrial exoplanets are, of course, also produced when the star's light passes through the Earth's atmosphere," Lisa explains. Here, it will crucially depend on whether they succeed in separating the terrestrial from the extraterrestrial spectral lines. So there is still a lot to do and it is a difficult task. "But this is precisely what makes research interesting," says Kaltenegger.

For the time being, the researcher has found her scientific home at the Max Planck Institute in Heidelberg, with her Emmy Noether Group until 2015. When asked what her dream destination would be, Kaltenegger has no particular answer. Her goal isn't a specific university, nor a certain renowned institute. Not even the continent is that important to her. The decisive factor for her is the opportunity to pursue her research with as much freedom as possible, to have contact with students and be able to head an international team.

Who knows – maybe she will one day be part of the team that discovers the first traces of life on a distant celestial body. What will we then do with these findings? And what new, exciting questions will they pose at the same time? ◂

TO THE POINT

- **Of the 800 or so exoplanets discovered so far, only three, at most, offer life-sustaining conditions.**
- **Astronomers want to use spectral analysis to one day to detect traces of life on exoplanets. But the observation of such biosignatures is approaching the limits of their instruments. And what might the signature in the spectrum look like?**
- **To this end, Lisa Kaltenegger simulates possible atmospheres of extrasolar planets on the computer, varying the different parameters such as mass and radius of the planet, and luminosity and temperature of the star.**