The Turbulent Birth of Stars and Planets

Exoplanets – planets that orbit stars other than the Sun – used to be a matter of science fiction. Some 15 years ago, with the first detection of an exoplanet, they became a matter of observational astronomy. Since then, exoplanet observations have provided astronomers with intriguing clues as to the formation of stars and planets. This is invaluable information for researchers interested in planetary and star formation, such as the team led by **Thomas Henning**, Director at the **Max Planck Institute for Astronomy** in Heidelberg.

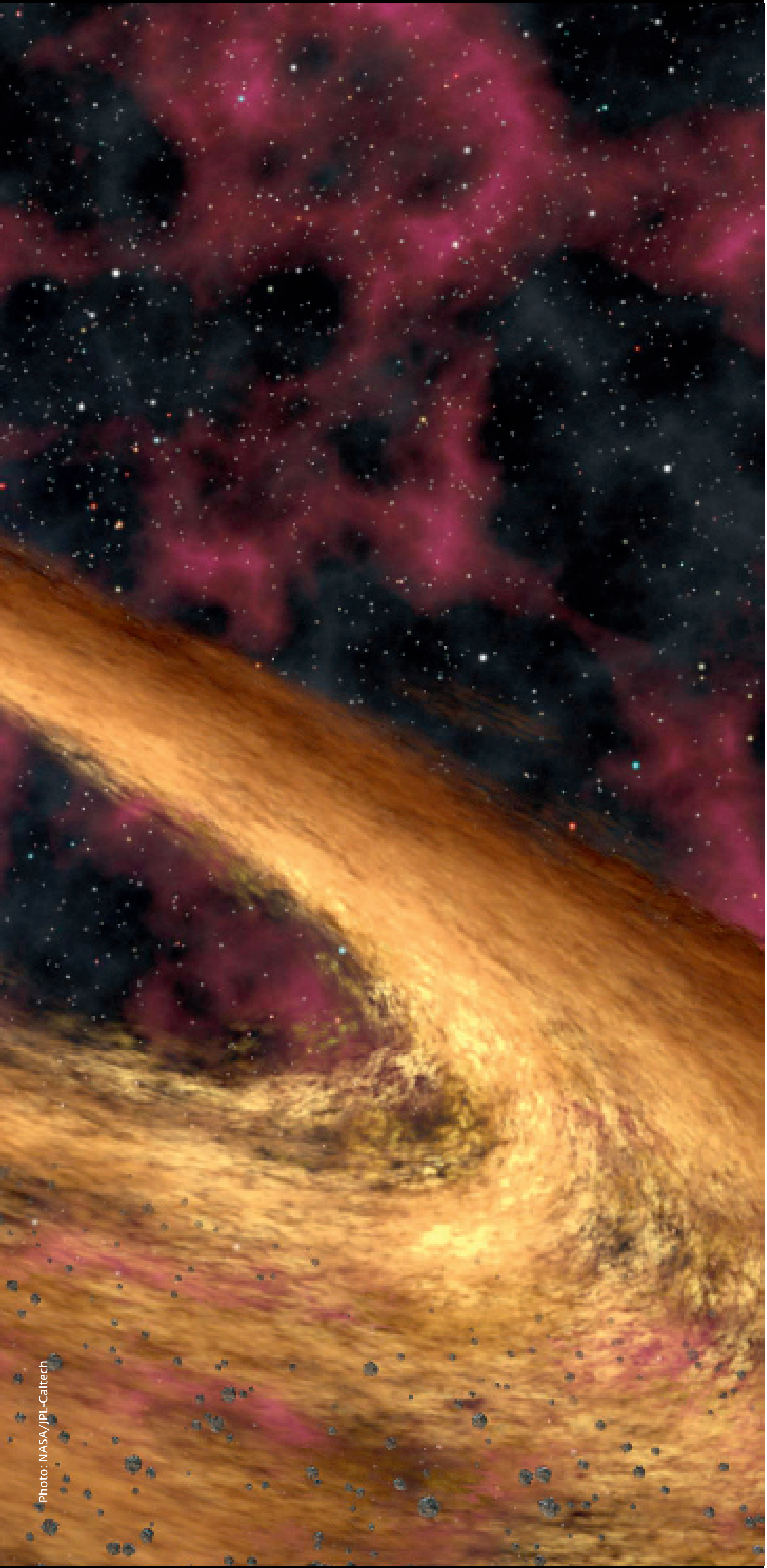


Photo: NASA/JPL-Caltech

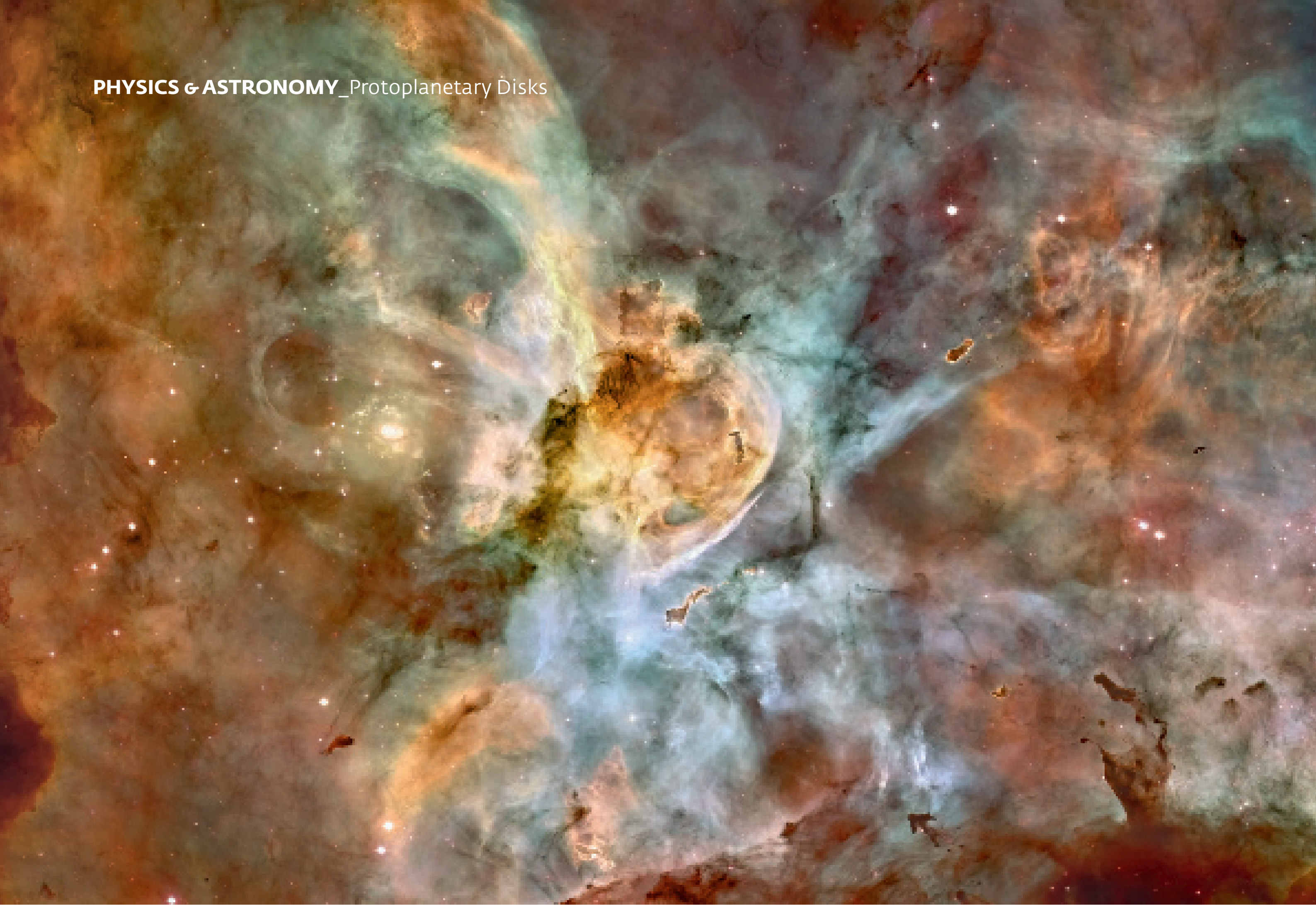
TEXT **THOMAS BÜHRKE**

The birth of planets and stars begins with clouds of gas and dust measuring many light-years in size. Such clouds can be found throughout our galactic home, the Milky Way, and for billions of years, they have acted as cosmic nurseries. In broad terms, what happens next has been known for decades: when a suitably large part of such a cloud exceeds a certain density, it begins to contract under its own gravity. Typically, such a region will not be perfectly motionless; instead, it is likely to rotate, if only ever so slightly. That is why, once contraction starts, there are two significant physical effects: contraction will reduce the cloud's overall size. But at the same time, the rotation becomes faster and faster, due to what physicists call the conservation of angular momentum – think of a figure skater who pulls her arms close to her body in order to execute a pirouette. As the speed of rotation increases, the interplay between gravity and the centrifugal force pulls the collapsing cloud into the shape of a disk.

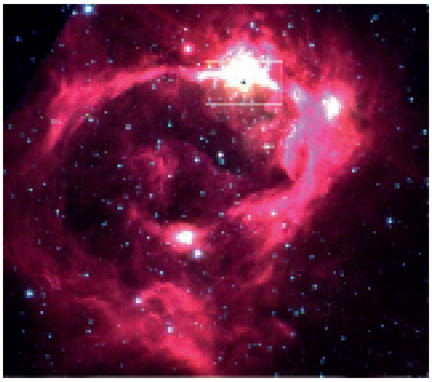
THE BIRTH FOLLOWS A PREDEFINED CHOREOGRAPHY

In the center of this protoplanetary disk, the gas reaches sufficient density and temperature for nuclear fusion to commence: a star is born. In the outer regions, gas and dust continues to swirl, with dust particles repeatedly colliding and sticking together, forming objects of rock-like consistency that grow continually in size. When these objects have reached a few kilometers in size, gravity takes over and ensures ever further growth as objects attract each other and coalesce. This is how planets, such as our own Earth, come into being.

This general picture of planet formation has been around for a number of years. But the devil is in the details, and there is as yet no physical model that can explain planet formation from beginning to end. In their search for



answers, astronomers have turned to ever more refined observations. “The *Spitzer* and *Herschel* space telescopes have supplied us with a wealth of excellent new data. It will take years to evaluate and analyze what we have observed – but when we are done, we should have a much clearer picture of what happens,” says Thomas Henning, a Director at the Max Planck Institute for Astronomy in Heidelberg and head of the institute’s Planet and Star Formation department.



A portrait of two generations: Older stars in the central region of the object RCW 34, at a distance of 8,000 light-years from Earth, and younger stars (white-edged box near the top). False-color image based on infrared data taken with the *Spitzer Space Telescope*.

The *Spitzer Space Telescope*, one of NASA’s Great Observatories, was launched in 2003 and has been trailing the Earth in its orbit around the Sun ever since. *Spitzer* is an infrared telescope, sensitive for radiation that is typically associated with warm objects. Just as *Spitzer* ran out of the coolant it needs for proper operation, in May 2009, its European successor *Herschel* was launched. With a mirror measuring 3.5 meters in diameter, *Herschel* is the largest space telescope yet, and just like *Spitzer*, it specializes in collecting and analyzing the infrared radiation emitted by objects such as planets and nebulae.

The Max Planck Institute for Astronomy played a significant role in the construction of one of the three *Herschel* instruments, the far-infrared camera *PACS* – building on a long history of expertise in infrared astronomy, which also features key contributions to *Herschel*’s predecessor, the *ISO* satellite. Incidentally, this expertise also gained the Heidelberg group generous access to *Spitzer* observational data, which is quite unusual for a European research group and a strictly American project. “We were involved in a key program for the observation of protoplanetary disks, for which we carried out practically the entire analysis of the spectroscopic data,” says Henning.

WITH INFRARED RADIATION INTO THE HEART OF DARKNESS

When *Herschel* began its operations, Henning and his colleagues found an ideal opportunity to build on their earlier *Spitzer* observations in the framework of the *Herschel* program “Early phases of star formation.” The astronomers set their sights on a cloud of gas and dust with the name G011.11-0.12,

Photos: NASA/ESA (top); NASA / JPL-Caltech (bottom)

Heavenly glory: The Carina Nebula, at a distance of some 7,500 light-years from Earth, is one of the most beautiful star formation regions in the Milky Way. It contains at least a dozen young stars, each of which is 50 to 100 times as massive as the Sun. Thomas Henning, Director at the Max Planck Institute for Astronomy in Heidelberg, is investigating the early phases of star birth – although not with this telescope, which he uses to share the fascination of astronomy with the public and, in particular, with students.

Photo: Hardy Müller (right)

or G011 for short. Previous observations had shown that G011 contains a number of newly born stars, making it an ideal target for studying the early phases of star formation.

An ideal target, that is, for observations in the infrared: In visible light, clouds like this are completely opaque, showing up as solid black against a starry background. Infrared radiation, on the other hand, can penetrate gas and dust. What you see of such a cloud depends heavily on the wavelength.

Following a fundamental law of physics, all bodies emit thermal radiation, and at temperatures between absolute zero (0 Kelvin, which corresponds to minus 273 degrees Celsius) and about room temperature, most of this radiation is emitted at infrared wavelengths. Henning and his colleagues made use of this principle when observing G011. *Spitzer* had already provided some images at relatively short wavelengths: at 8 micrometers, the cloud still appears dark, but in observing at successively longer wavelengths, the astronomers could peer ever more deeply into the cloud. The unique images obtained with *Herschel* at wavelengths between 70 and 350 micrometers revealed, hidden deep in the interior, 24 regions of increased density, so-called pre- or protostellar cores.

The temperatures of these cores, as derived from the infrared data, varied between 16 and 26 Kelvin, only slightly warmer than their environment, at 12 Kelvin. The masses of these cores ranged from 1 to 240 solar masses. Evidently, within the next million or so years, the cloud will transform into a star cluster, teeming with stars of various masses. “We can study in great detail the physical conditions at the very beginning of gravitational collapse,” says Thomas Henning.

20 YOUNG STARS IN A HOT GAS BUBBLE

Another interesting finding is that star formation proceeds in a very economical manner. Only around 10 percent of the available gas mass is turned into stars, leaving plenty of raw material for the formation of subsequent generations of stars.

While, in G011, a few regions have already taken the first steps toward collapsing under their own gravity, the question remains whether such a collapse will happen spontaneously or requires some external trigger.

As to the possible nature of such an external trigger, consider the star forma-

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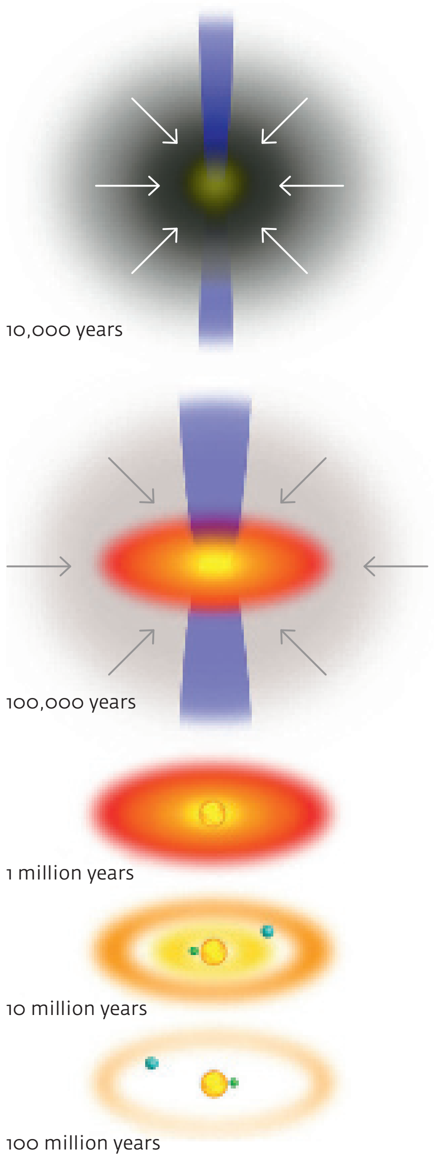
tion region RCW 34, at a distance of some 8,000 light-years from Earth: a large, hot gas bubble containing some 20 young stars. In fact, the stars are likely responsible for the existence of the bubble, blowing away the surrounding gas with their intense radiation and a steady stream of particles known as "stellar wind". Near the top of the bubble is a cloud of gas and dust in which additional stars are being born.



Stages of stellar evolution: First, a nearly spherical cloud collapses. Since it rotates, centrifugal forces will pull it apart, resulting in a disk. In the center, matter collapses further to form a star, while the disk becomes the birthplace of planets.

Graphic: Subaru

Using spectroscopy, the astronomers were able to determine the age of the stars and stars-to-be in RCW 34. Surprisingly, there is a systematic trend, with objects inside the bubble being a few million years older than those at the edge. The researchers hypothesize that stars of the first generation in this nebula pushed matter outward, triggering the formation of a second generation of stars near the edge of the cloud.

PROTOSTELLAR DONUTS

Are such external influences – candidates include not only young stars, but also expanding clouds of matter resulting from so-called supernova explosions, in which more massive stars end their lives – necessary in order for new stars to form? Thomas Henning is convinced that external triggers play a supporting role at best: "Turbulence in the clouds is perfectly sufficient to cause affected regions to contract and achieve critical density." But how does this turbulence come about?

Stars and nebula in our cosmic neighborhood orbit the center of our home galaxy, the Milky Way, with objects closer to the center moving faster than their more distant cousins. Since interstellar gas clouds can span up to several light-years, different regions within those clouds will move at different speeds, leading to turbulent flows of gas and dust.

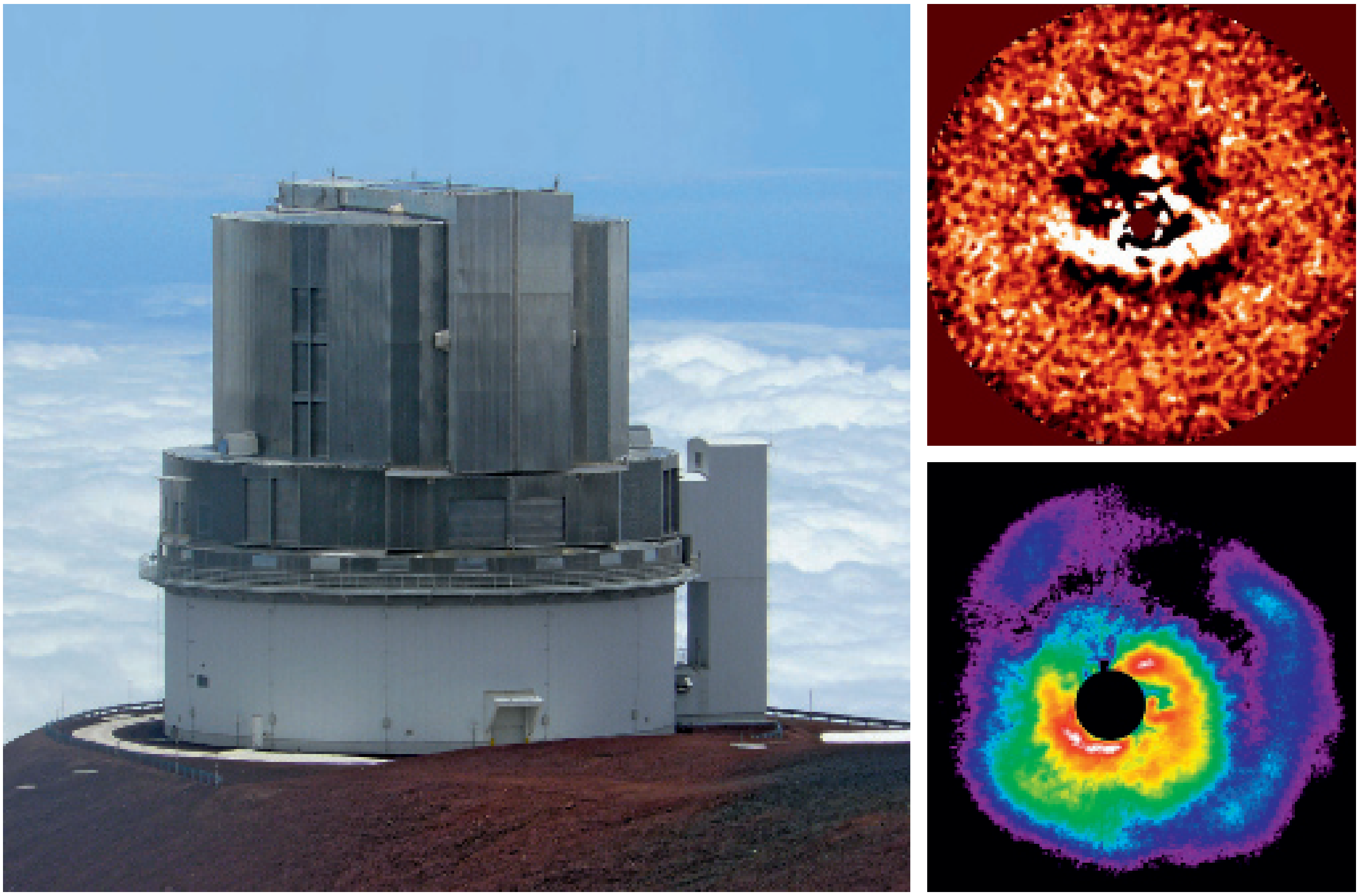
In fewer than one million years, the protostellar cores of G011 will have condensed sufficiently for protostellar disks to form around nascent stars. These disks are the birthplaces of planets. Many other young stars in the galaxy have already reached this stage, and have been rewarding targets for observation.

In many cases, the existence of these disks can be deduced only indirectly from characteristic infrared radiation emitted by their constituent dust particles. Since the disks are heated by the central object, the temperature of the disk's inner regions is significantly higher than at the outer rim. By the fundamental laws of thermal radiation, this means that infrared radiation from the interior region will be emitted mostly at shorter wavelengths than is the case for the outer zones. In cases where emission at shorter infrared wavelengths was missing, astronomers concluded that the disks in question must feature a large central hole.

Direct evidence for this model was, however, lacking – at least until last year, when an international research group headed by Christian Thalmann and Johan Olofsson from the Max Planck Institute for Astronomy finally succeeded in producing a direct image of such a disk. Thalmann and his colleagues utilized a special camera on the Japanese *Subaru* telescope in Hawaii to observe the young star LkCa 15. The image showed a disk with a large central gap. In fact, the gap is so large that it could quite comfortably accommodate the orbits of all the planets in our own solar system.

A second set of observations with *Subaru*, again involving the Heidelberg astronomers, led to the discovery of a smaller type of disk. The disk around the star AB Aurigae, at a distance of 470 light-years from Earth, is about the size of our solar system. It consists of nested rings that are arranged somewhat asymmetrically around the star.

Another discovery, again by Max Planck researcher Olofsson and colleagues, involves the young star T Chamaeleontis (T Cha), at a distance of 330 light-years from Earth. Using the *Very Large Telescope* of the European Southern Observatory (ESO) in Chile, the astronomers found that a portion of the disk material has formed a thin dust ring at a distance of just 20 million kilometers from the star –



Insights: Using the Japanese *Subaru* telescope in Hawaii, Heidelberg-based Max Planck astronomers and their colleagues have managed to capture astounding images of protoplanetary disks, such as the ring-shaped disk around LkCa 15 (above) and the smaller disk around the star AB Aurigae with its much more complicated structure.

about one-third the orbital radius of Mercury, the planet closest to our Sun. Behind this ring extends a wide, dust-free region, up to about 1.1 billion kilometers from the star. That is where the outer part of the disk begins.

CLOSE TO THE LIMITS OF OBSERVATION

Even before these direct sightings of donut-shaped disks, astronomers had discussed the possible causes for the formation of such gaps. One possibility involves the central star's radiation causing the dust particles to evaporate: Alternatively, a nearby (and as yet undiscovered) star could have swept up the dust. The most likely option, however, is that a planet has formed around the star, sweeping up gas and dust and, in the end, incorporating whatever material it has attracted. "That, of course, is the most interesting possibility," says Thomas Henning.

Early this year, an international team actually found evidence for this latter scenario. Near the outer edge of the large gap in the disk around T Chamaeleontis, they found what could be an orbiting body. It is located about a billion kilometers away from its central star, a distance comparable to that between Jupiter and the Sun. But these observations are at the limits of what is technically feasible for the astronomers. They were thus unable to determine beyond all doubt exactly what this object is. It may be a newly formed planet.

That planets grow in protoplanetary disks is, by now, an undisputed fact. In the case of some older stars, scientists have managed to observe a few exoplanets directly. In a few cases, it was even possible to detect substances such as water, sodium, methane and carbon dioxide in their atmospheres. But they have not yet succeeded in pinning down the evolutionary link – a young planet inside the disk that served as its birthplace.

Until recently, the astronomers had observed only the dust component of protoplanetary disks. But this accounts for only about a hundredth of the total mass. Most of the disk mass is in the form of gas, which is very difficult to observe, since the radiation emitted by the atoms and molecules is so extraordinarily weak.

Yet the gas plays a major role in the development of the overall disk and in the formation of planets. For instance, it exerts friction on the tiny dust particles, slowing them down at different rates depending on particle size. The resulting different speeds of the particles increase the likelihood of collisions, thus accelerating the growth of the particles.

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Photos: Subaru (3)

At the Max Planck Institute in Heidelberg, astronomers and engineers are also involved in developing and constructing new instruments, including adaptive optics systems that can mitigate the effects of atmospheric turbulence, resulting in ground-based images of unparalleled sharpness. Adaptive optics plays a key role in the search for extrasolar planets and disks.

Photo: Hardy Müller

Furthermore, gas is the key ingredient of giant planets, such as Jupiter and Saturn, which gather significant amounts of gas when forming their enormous atmospheres. For these reasons, astronomers are very interested in learning the typical lifetimes of such gaseous disks. The result would impose a strong constraint on the timescale of planet formation.

The astronomers in Heidelberg dug deep into their bag of observational tricks to address this question. In several star clusters with members aged between about 1 million and 20 million years, they determined the dust and gas quantities in the disks. What they found was surprising: the amounts of gas and dust decreased almost exactly in parallel, and rather quickly at that: disk matter largely disappeared within, at most, 10 million years. "That puts very strict limits on the timescale of planet formation," explains Henning. And, as all these statements should apply equally to the formation of our own solar system, it imposes strict limits on the timescale of our own planetary origins, as well.

150 TYPES OF MOLECULES IN INTERSTELLAR CLOUDS

Last but not least, there is an aspect of the analysis of the gaseous components of disks that has a direct bearing on questions about the origins of life on Earth and elsewhere. In large interstellar clouds, astronomers have thus far found around 150 types of molecules, including complex organic substances. Not so in the protoplanetary disks, where, so far, no such chemical compounds have been observed. This leaves highly interesting questions unanswered: Can the complex precursor molecules of life survive the early phases of planet formation? Are they present in the circumstellar disks, and can they possibly make it to the surfaces of the young planets unharmed?

Detecting the more complex building blocks of life lies beyond the capabilities of today's telescopes. However, using some sensitive radio telescopes, as well as *Spitzer* and *Herschel*, the researchers at the Max Planck Institute for Astronomy have at least been able to take some baby steps toward that goal: they managed to observe simple molecules such as carbon monoxide and water in protoplanetary disks. Now they are putting their hope in the next generation of telescopes, notably the *Atacama Large Millimeter Array* (ALMA). ALMA is a compound telescope consisting of nearly 70 separate radio telescopes that can be moved into different positions. ALMA is currently under construction in Chile and will gradually be put into operation in the coming years.

Hubble's successor, the *James Webb Space Telescope*, promises another shift in cosmic perspective. The Heidelberg-based Max Planck researchers are involved in this project, too, developing key components of the MIRI instrument, which will work in the medium infrared range – and is expected to be good for more than one observational surprise. ◀

GLOSSARY

Galaxy
The collection of billions and billions of stars to which our own planetary system belongs. The Milky Way Galaxy (from the Greek word *gala* for milk) consists of 150 to 200 billion suns, as well as interstellar gas and dust clouds. It features several spiral arms and, if viewed from the top, would look like a disk with a diameter of about 100,000 light-years. Viewed from the side, the disk is only about 1,000 light-years thick. At the heart of the Milky Way sits a gigantic black hole. The central bulge is surrounded by a spherical region (the so-called halo) that contains 150 globular clusters.

Very Large Telescope (VLT)
An array of four telescopes, each with a main mirror measuring 8 meters in diameter, complemented by several auxiliary telescopes. The VLT is designed for observations in visible light up to the mid-infrared. Light collected by these telescopes can be combined, in effect creating a single virtual telescope with ultra-high resolution – the *Very Large Telescope Interferometer* (VLTI). The observatory is situated atop the 2,635-meter-high Cerro Paranal in the Chilean Andes, and is operated by the European Southern Observatory (ESO).

Protostellar cores
Stars form inside interstellar clouds of gas and dust that collapse under their own gravity. Ultimately, a concentration of mass known as a protostellar core develops, which attracts additional matter and contracts ever further, transforming gravitational energy into heat. The result is a protostar that emits infrared radiation. Around such a protostar, matter will typically contract to form what is known as a protoplanetary disk: the birthplace of future planets.

James Webb Space Telescope
The *James Webb Space Telescope* (JWST) is the intended successor to the *Hubble Space Telescope*. With its 6.5-meter-mirror, it is set to peer much deeper into space than its predecessor, receiving infrared light from planetary systems-in-the-making, as well as the most distant galaxies. However, due to financial reasons, the project was recently put on hold by the American space agency, NASA. It is questionable whether the JWST can start as planned in 2018.