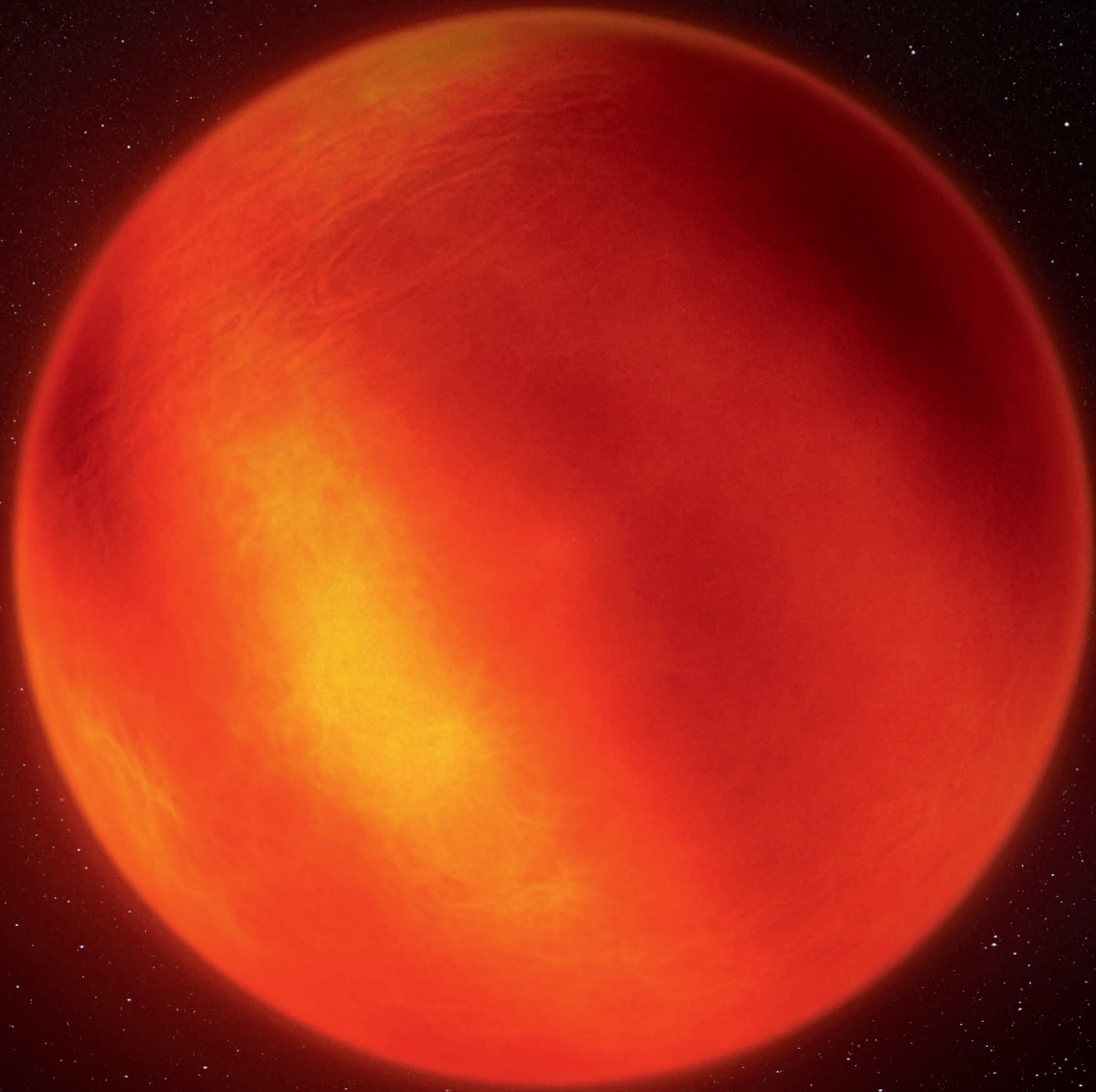


# Neither Star nor Planet

They are often eclipsed by more attractive topics, like black holes or exoplanets. Even the name itself is less than sensational: brown dwarfs. But **Viki Joergens** and her colleagues from the **Max Planck Institute for Astronomy** in Heidelberg have gained fascinating insights in this research field.



TEXT THOMAS BÜHRKE

**T**he Milky Way probably has roughly as many brown dwarfs as it has planets. Astronomers don't know the precise number, as these celestial bodies are small and very dim, and thus difficult to observe. They have, however, really shaken our tried and tested definitions of the terms "star" and "planet" of which we have grown so fond. Spots form on their surface like the spots on the Sun, and clouds form as if they were planets. "This is one of the most important characteristics of our research field: there are countless overlaps with the properties of both planets and stars," explains Viki Joergens, who has been investigating these celestial bodies for more than ten years now.

Back in 1962, Shiv Kumar, who was then working as a post-doc at the Goddard Space Flight Center of the US space agency NASA, set the ball rolling. He asked himself how small a star can actually be, and what properties bodies that are just below this threshold possess. The fundamental characteristic of stars consists in the multi-step fusion of hydrogen to helium in their central region.

This process releases energy that, in the form of heat, creates an outward pressure against the gravity acting inward. If these two pressures balance, the star is stable. Our Sun has been in this phase for around 4.5 billion years.

To reach this state in the first place, the celestial body must have a certain minimum mass; otherwise, the pressure and temperature aren't sufficient to ignite the hydrogen fusion and maintain

it. As Japanese theoreticians Chu-shiro Hayashi and Takenori Nakano discovered back in 1963, this process requires a star to have at least 7 to 8 percent of the solar mass, corresponding to 75 times the mass of the planet Jupiter.

But bodies that are just below this threshold should initially still be sufficiently hot to fuse heavy hydrogen (deuterium) to helium-3 and thus generate energy. However, the raw material deuterium is present only in small quantities, so that the fire is extinguished after just a few million years. From then on, the celestial body slowly cools down. "Eventually, all brown dwarfs are approximately the size of Jupiter," says Joergens.

### THE HYDROGEN FUSION STARTS DEEP IN THE INTERIOR

In order for this deuterium burning to start, the body must have at least 13 times the mass of Jupiter. This represents the lower mass threshold of brown dwarfs according to the current definition of the International Astronomical Union. These objects thus form the link between planets and stars in a range of around 13 to 75 Jupiter masses.

Astronomers spent more than 30 years looking in vain for these failed stars until they finally found the first representative of this class of objects in 1995. Approximately 2,000 brown dwarfs have since been identified – some with surprising properties. "One of the most topical questions concerns their birth," says Joergens.

Stars are formed when individual regions in the interior of a large cloud of gas and dust contract under the effects of gravity. The core of such a cloud rotates and forms a disk. The material in the cloud center becomes more and more compressed until hydrogen fusion begins. The young star is then stable.

Dust particles collide with each other in the disk that still surrounds them, clump together and finally grow into asteroids and planets. Earth and the gas planet Jupiter were also formed in this way. And the terms "star" and "planet" are defined in accordance with this scenario: a star is a stable ball of gas that generates energy in its interior through nuclear fusion; planets aren't able to do this, are smaller, and orbit their sun. But which formation path do brown dwarfs choose?

"Since young stars are initially still surrounded by a disk of dust, the obvious thing was to look at whether brown dwarfs can also be surrounded by a disk," explains Viki Joergens. The Heidelberg-based astronomers used *Herschel*, the space telescope of the European Space Agency (ESA), for this project. Equipped with a 3.5-meter diameter main mirror, it was the largest telescope ever launched into space. It was in operation from June 2009 for nearly four years, at which point the helium for cooling the instruments was exhausted.

*Herschel* observed exclusively in the region of mid- to far infrared at wavelengths ranging from 70 to 500 micrometers. "This is where the thermal radiation of cool dust, among other

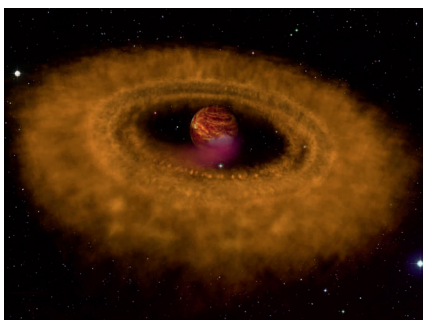
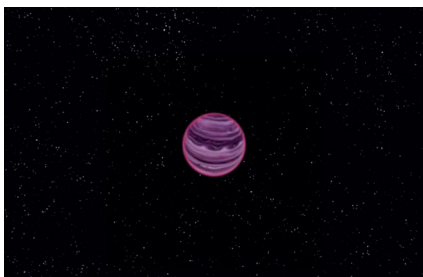
View of a brown dwarf: These linking elements between stars and planets have been keeping astronomers busy for over half a century.





above: Presentation in the team: Viki Joergens (standing) and her colleagues Ian Crossfield, Niall Deacon and Esther Buenzli (from left).

below: The cosmos in art: The object PSO J318.5-22 (top) has around seven times the mass of Jupiter and travels through space alone, meaning without a parent sun. The picture of OTS44 (bottom) illustrates that this object, just two million years young, formed in a similar way to stars, namely from a disk of gas and dust. Even today, considerable quantities of matter still fall onto OTS44.



things, can be observed, as we expect it to be emitted by the disks of brown dwarfs," says Joergens.

PACS, one of the three instruments aboard *Herschel*, was built under the direction of the Max Planck Institute for Extraterrestrial Physics with crucial contributions from the astronomers in Heidelberg. In return, they received guaranteed observation time with PACS. Working with colleagues from the University of Texas, they commenced a program to search for dust disks around brown dwarfs – with great success.

"For 36 of 47 carefully selected brown dwarfs, we found infrared emissions that originate from such disks," says Viki Joergens. And the initiator of the project, Max Planck Director Thomas Henning, adds: "We therefore succeeded in carrying out the first survey for such disks in the infrared region, and in narrowing down their masses."

"We find that disks around brown dwarfs have masses ranging from just below one Earth mass up to one Jupiter mass," says Joergens; Jupiter, on the other hand, has 300 times more mass than Earth. However, not all the disk material is used to form planets. It therefore isn't possible for large gas

planets such as Jupiter to form in the disks of brown dwarfs, but smaller rocky planets may very well do so. But to date none have been discovered.

Surprisingly, brown dwarfs follow a law that was discovered for young stars: the disks of dust always have around 1 percent of the stellar mass. Viki Joergens' observations show that this applies down to a central mass of only 12 Jupiter masses. Thus, in this respect, brown dwarfs don't differ from their big brothers. They are apparently also formed in the same way and not like planets. If this relation also existed for our Sun, it is possible to conclude from this that only around 10 percent of the dust was converted into planets.

Since brown dwarfs appear to overlap seamlessly with the range of the planets at the lower threshold of around 13 Jupiter masses, the Max Planck astronomers from Heidelberg searched through the *Herschel* observations to see whether any of the representatives with the lowest mass had a disk – and found a celestial body at a distance of 530 light-years with the designation OTS44. The intensity of its far-infrared radiation had to originate from a disk of at least 10 Earth masses. In addition, the researchers discovered that the ob-

ject, only two million years young, was still picking up matter from the disk, as young stars do.

Interestingly, OTS44 has only around 12 Jupiter masses and is thus still in the classical mass range of the planets. However, the object doesn't orbit a star, but moves freely through space – a key piece of information for theories of star formation. "OTS44 can be designated either as a very low-mass brown dwarf or as a free-floating planet. In my view, there is no difference here, because the line between brown dwarfs and planets should be drawn with the aid of the formation history," says Joergens. But this isn't known in all cases.

### THE SIGNATURE CHANGES OVER TIME

This was shown by a finding made with the Pan-STARRS1 telescope on Hawaii: At the end of 2013, a group of astronomers that included Niall Deacon from the Max Planck Institute for Astronomy discovered a celestial body that had only seven times the mass of Jupiter. The object with the catalog number PSO J318.5-22 at a distance of 80 light-years is travelling alone through space without a parent star. Did it also form like a star?

But the scientists haven't yet detected any processes that are known from star formation, so it is still possible that PSO J318.5-22 was born as a planet and ejected from the system afterward. Theoretically, this can take place through the gravitational effect of a star passing nearby, or also as a result of instabilities in a young system with several planets.

Size comparison: The image shows the Sun, a red dwarf star, three brown dwarfs and Jupiter (from left) to scale. If the deuterium fusion extinguishes in a brown dwarf, it contracts further until the freely moving electrons in the interior build up a quantum mechanical counter-pressure and prevent the body from shrinking any further. This is the case when it is approximately the size of Jupiter.

The important mass determination of a brown dwarf is a particularly tricky task and can't be managed with the old, familiar rules of stellar physics. Whereas there is a clear relationship between the measurable luminosity and the mass of a star during the phase of stable burning, this isn't the case for brown dwarfs: They form as hot balls of gas and cool down over time. Their light becomes weaker and weaker as they cool, and their spectral signature changes.

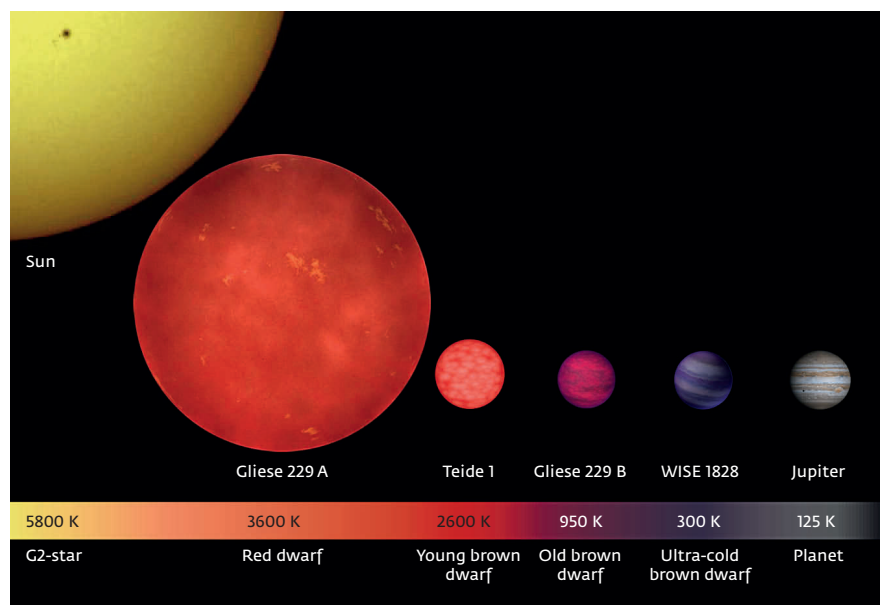
The heavier a brown dwarf, the hotter it was during its formation. Thus, it isn't possible to unequivocally determine from its temperature whether it is a young, low-mass brown dwarf or an old, massive one without knowing its age: a brown dwarf one billion years old with 70 Jupiter masses has the same temperature as a body only 200 million years old with 15 Jupiter masses, for example. The astronomers must therefore somehow determine the age of brown dwarfs in order to then deduce the mass from models.

With OTS44, this was possible because it is part of a star formation region

of known age in the Chameleon constellation in the southern sky. With PSO J318.5-22, on the other hand, the astronomers were able to measure the motion in space. In the process, they ascertained that it used to belong to a group of young stars that formed around 12 to 21 million years ago. But the researchers can't always hope for such fortunate circumstances, and this makes the interpretation of observational data more difficult.

Although there have been many new findings concerning brown dwarfs in the past, questions about their formation remain unanswered. While all results of observations currently indicate that brown dwarfs are formed like stars in the center of a collapsing cloud of gas and dust, some theoreticians believe that the cloud fragments aren't massive enough to be able to contract under their own gravity.

The researchers therefore devised different explanations. Most are based on the assumption that brown dwarfs are the consequence of a rudely interrupted star formation. This could occur by dynamic interactions in a group of

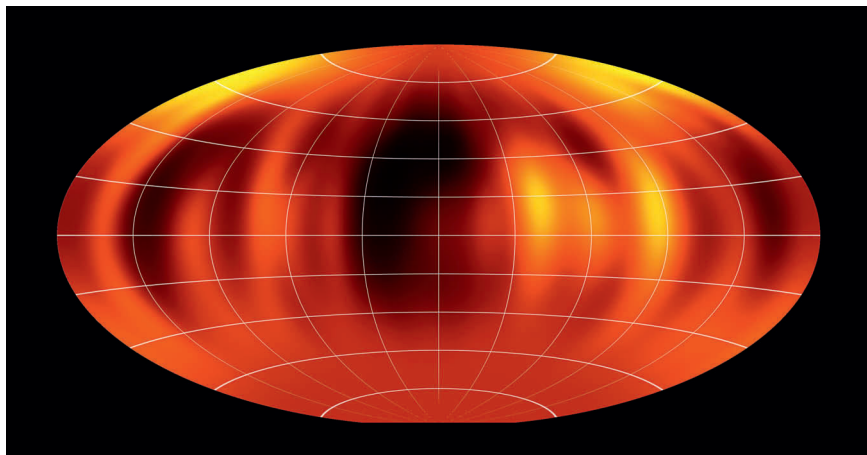






above: Focus on exotic bodies in space: Viki Joergens, Ian Crossfield, Amelia Bayo, Niall Deacon, Esther Buenzli and Joshua Schlieder (from left) investigate the physical properties of brown dwarfs.

below: Panoramic chart of a strange world: Astronomers in Ian Crossfield's team reconstructed this surface image of the brown dwarf Luhman 16B from data they obtained with the Very Large Telescope of the European Southern Observatory (ESO).



stars that formed together if one of the members is ejected from this system before it has reached adulthood.

It would also be conceivable that there is a further, very hot star in the vicinity of a forming star. Its intense UV radiation could then vaporize the gas

cloud from which the emerging sun is still collecting gas, and deprive the newcomer of "food." According to these scenarios, brown dwarfs are failed stars in the true meaning of the word.

From the previous observational data, however, Viki Joergens concludes

that there is no need to devise a special mechanism for the formation of brown dwarfs. The frequency of binary systems, which she investigates, is also interesting in this respect. The researcher was one of the first to use high-resolution spectroscopy to look for companions of brown dwarfs. Very large telescopes are necessary to apply this method, which is known from the search for planets.

Joergens and her colleagues started to scan brown dwarfs for companions with one of the 8-meter telescopes of the Very Large Telescope of the European Southern Observatory in Chile; these should become evident in the spectrum by virtue of a Doppler shift. Although the researchers haven't yet found a brown dwarf with a planet, what they have found is one of the very few binary brown dwarfs, whose radial velocity orbit they were able to determine in full.

Astronomers have known for some time that around two-thirds of all stars exist in binary or multiple systems. With brown dwarfs, this proportion is only 10 to 20 percent, as was shown by Joergens' survey, among others. However, the tendency toward togeth-

erness seems generally to decrease with decreasing mass. Astronomers in Heidelberg discovered a few years ago that only 25 percent of stars with very low mass, so-called M-dwarfs, are in binary systems. In this sense, brown dwarfs follow the trend set by the stars – they prefer life as a single with decreasing mass.

Brown dwarfs only ever appear as featureless points, even on images taken with the largest telescopes. The first surface map of a brown dwarf is therefore a sensation. It belongs to a binary system whose discovery by American astronomer Kevin Luhman from Pennsylvania State University in March 2013 caused a stir. It's located at a distance of 6.5 light-years from the Sun – only two other stellar systems are closer.

Despite the proximity of the brown dwarfs, called Luhman 16A and 16B, it isn't possible to observe any features on their surfaces directly. With the aid of a clever technique, two international teams working with Ian Crossfield and Beth Biller from the Max Planck Institute for Astronomy have succeeded for the first time in drawing up something like a weather chart of one of the two celestial bodies. Clouds form in the atmosphere despite the high temperatures of more than 1,000 degrees Celsius. These clouds obviously don't consist of water, like on Earth, but of heavy elements such as iron and minerals.

Crossfield applied a method called Doppler imaging, which works as follows: Initially, the light of the brown dwarf is dispersed into its spectral colors. Lines that originate from the substances contained in the atmosphere then appear in this spectrum. Since the brown dwarf rotates, one half is always moving toward us and the other half away from us. This is evident as a Doppler shift in the spectrum. Furthermore, the regions near the equator rotate fast-

er than those at higher latitudes, and this can also be seen in the spectrum.

Crossfield analyzed these changing spectral signatures with a computer program and used them to create two-dimensional surface maps. "It's probably a non-uniform cloud cover – not unlike that of the planet Jupiter," says the scientist.

## RESEARCHERS ARE LOOKING DEEP INTO THE ATMOSPHERE

Beth Biller and her colleagues didn't use a spectrograph in their work, but recorded light variations in the two brown dwarfs simultaneously in seven different wavelength ranges. Although the two-dimensional information was lost with this method, the researchers were able to look deep into

the atmosphere: the seven wavelength ranges very probably correspond to different atmospheric layers with differing temperature.

"The cloud structure varies depending on how deep one looks into the atmosphere – this means there is definitely more than just one cloud layer," says Biller. For the first time, theoreticians can now compare their models for the cloud structure of brown dwarfs with observations.

These fascinating new findings on the formation of brown dwarfs, the weather in their atmospheres, and free-floating planets open up new prospects for research. And not least, the Max Planck astronomers in Heidelberg have also succeeded in moving the brown dwarfs slightly out of the shadow of the black holes and into the limelight. ◀

### TO THE POINT

- Brown dwarfs are a sort of halfway house between star and planet. At a mass below 75 Jupiter masses, no atomic fire burns in their interior.
- Brown dwarfs apparently form in gas and dust clouds and are therefore born in the same way as stars.
- Brown dwarfs prefer to be single. While around two-thirds of all stars exist in binary or multiple star systems, the proportion for brown dwarfs is only 10 to 20 percent.
- Max Planck astronomers recently succeeded in mapping the surface of a brown dwarf for the first time. This weather chart shows clouds in the atmosphere; but temperatures of more than 1,000 degrees Celsius mean they consist, not of water, but of heavy elements, such as iron and minerals.

### GLOSSARY

**Doppler effect:** When a celestial body moves toward us or away from us, its light spectrum shifts to shorter (blue) or longer (red) wavelengths, respectively. Sound exhibits the same phenomenon: when a police car is moving toward us, the pitch of the siren is higher (shorter acoustic wavelength) than when it's moving away from us.

**Spectroscopy:** One of the most important methods to determine the physical state and the chemical composition of a distant star. With the aid of an optical device (a prism, for example) the radiation of an object is dispersed according to its energy. Spectrometry provides quantitative data on the concentration of elements, pressure and electric or magnetic fields, for example.