# A story of planet formation

■ An artist's impression of a protoplanetary disc – an early stage in the formation of planets. Credit: ESO/L Calçada.

Until recently, the idea of finding planets orbiting distant stars was science fiction; we now know of over five thousand. *Carolin Kimmig* tells us more.

**One** of the most fundamental questions we can ask as humans is where we come from, which is closely related to the question of how the Earth came into existence. This then begs the question of how planets form in the first place. Only 30 years ago, not a single planet orbiting a star – other than the Sun – was known, and some astronomers believed they didn't exist. Then in 1995 the first planet was discovered around a star like the Sun. In the past three decades, researchers have found many of these extrasolar planets (or exoplanets for short), with more than 5,380 detected so far. Today, we know that it is rare for a star not to have planets, but the journey of discovering the plethora of exoplanets is a different story. This story focuses on how these planets come into existence.

Planets can only form in discs of gas and dust around stars, known as protoplanetary discs, so to understand the formation of a planet, we must take a closer look at those discs. But to understand how protoplanetary discs form, we first need to consider the formation of stars. A star forms out of a cloud of gas and dust, a so-called molecular cloud, which can collapse into a star due to its own gravity. If the molecular cloud is rotating even slightly in the beginning, a disc can form. As the cloud collapses, the rotation will become much stronger due to the conservation of angular momentum. If you sit in a spinning swivel chair with your arms stretched out, then suddenly pull your arms in, you will spin faster than before, as angular momentum is conserved. The same principle applies to molecular clouds in the star formation process: the rotation of the molecular cloud intensifies as the cloud shrinks, leading to the formation of a protoplanetary disc.

The beauty and variety of protoplanetary disc structures can be seen using telescopes such as the Atacama Large Millimeter Array, or ALMA, in northern Chile. In observations, most discs are not uniform but show structures such as bright rings, dark rings (called gaps), spirals running through the disc, or features that are not symmetrical, for example a bright speckle, or a dark region on one side of a disc. There are a multitude of discs with such structures, and no two are alike. To explain the variety and where the structures come from is a major part of the research in this field.

**Nothing ever stays the same**

The Universe is very dynamic; everything is in motion and changes constantly. So do protoplanetary discs which change and evolve in time. The large variety of their shapes, sizes, and structures suggests that they are changing on time scales of a couple of ten thousand to a hundred thousand years. This may seem like a long time but is considered short in astrophysics, as many processes in the universe take several million to a billion years.

There are several physical processes causing protoplanetary discs to evolve. First, the discs are always rotating. As nothing in the universe is perfectly uniform and symmetrical, whirls and swirls start to appear. This turbulence in these discs is one of the main factors causing evolution.

Another key factor for disc evolution is a planet that has either already formed or is currently forming within the disc. The nascent planet interacts with the material in the disc and stirs everything up, causing gaps, rings, and spiral structures. These gaps occur because big planets push the gas and dust away from its orbit, leaving the orbital region of the planet empty. The gaps appear dark in observations. At the edges of a gap, disc material can pile up, appearing as bright rings. Spiral structures originate at the location of the planet and are caused by density waves that propagate through the disc in a spiral shape.

As forming planets cause these structures, they can sometimes be used as an indicator of a planet's presence in a disc, even though the planet might not be directly seen. For this, researchers often use computer simulations to model planet and disc interactions and compare them to the observed structures. A bonus of these simulations is that they allow us to calculate changes over time, whereas observations can only show a current snapshot in time.

However, structures in a disc are not always due to planets. For example, structures can occur when a magnetic field is present. Such a magnetic field could originate from the star or be a background field from the surrounding galaxy. A magnetic field can lead to particles being launched into space, like a wind, leading to what are called magnetic disc winds. Because these particles take away angular momentum from the disc, the wind can change the appearance of the disc depending on the strength, shape and extent of the magnetic field.

Winds away from the disc can also occur when there is no magnetic field present. Such winds can be caused by the star's radiation warming the disc. This heat causes some particles to detach from the disc leading to an eventual dissolution of the disc, comparable to the evaporation of water, in a process called photoevaporation.

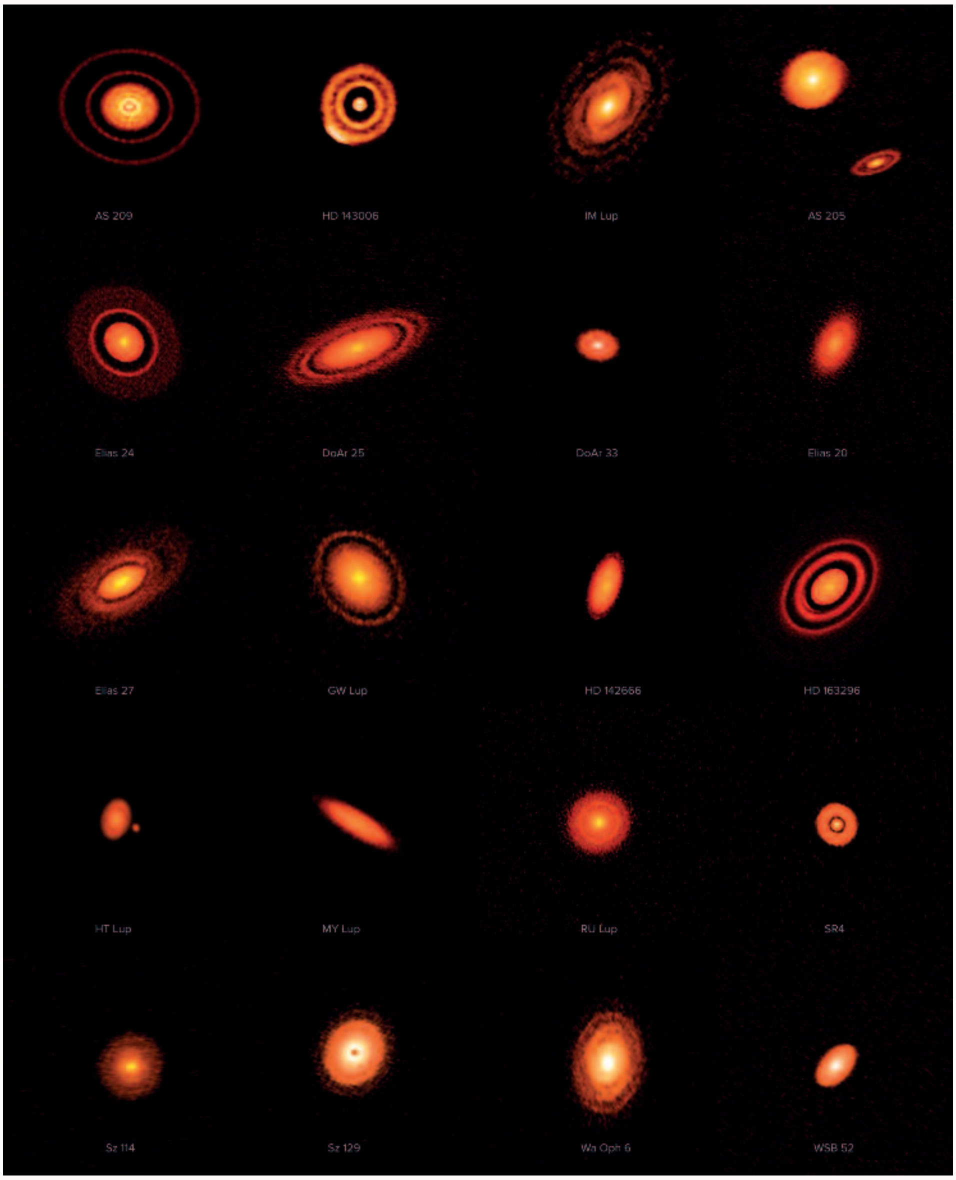
A different process leading to structures in a disc is due to the so-called "snowline". The snowline is the location in a disc where water sublimates from solid ice to gas. It occurs because the temperature of the disc falls the farther away it is from the central star. The snowline is located at the point where the temperature is exactly the sublimation temperature. Sublimation occurs when a material changes from a frozen solid to a gas without passing through the intermediate liquid state as it does on Earth where our atmospheric pressure allows a liquid to exist.

Such snowlines also exist for molecules other than water, so there can be more than one snowline in a disc. Simulations have shown that snowlines can also lead to gaps and rings. Currently, observations do not show good matches with this theory and finding the reason for this difference in simulations and observations is an ongoing research question in this field.

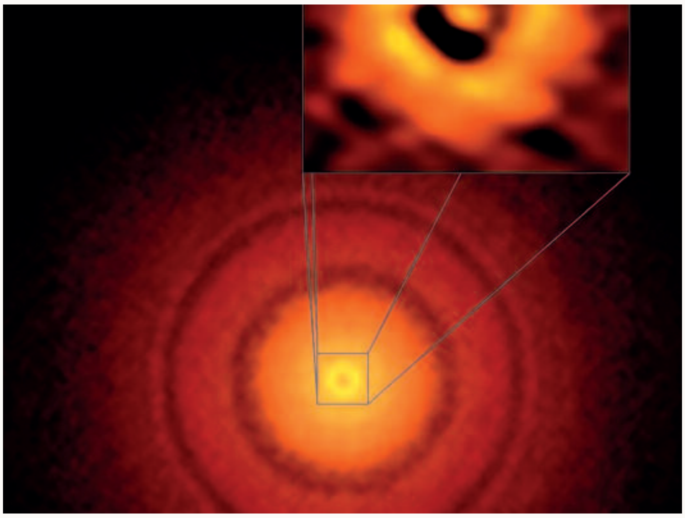
All these processes set the conditions, such as local density, temperature, and pressure, for planet formation in protoplanetary discs.

**How is a planet born?**

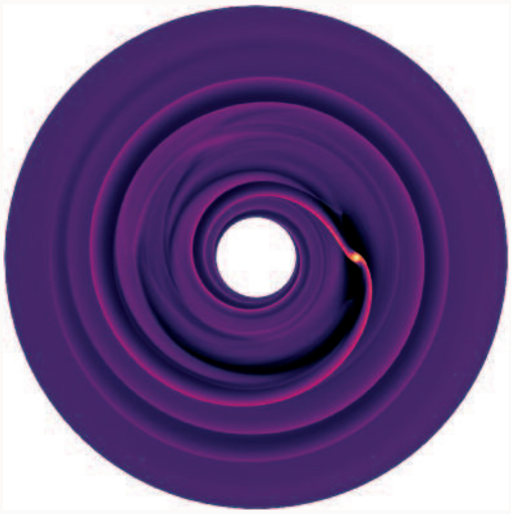
Even something as big as a planet starts small, with the tiniest little dust particle. So how do these dust particles grow into a planet? The first step of planet formation is dust sticking together to form dust bunnies, rather like the ones we see in our homes. In a disc, the surrounding pressure can then compress the dust bunnies into small pebble stones.




▶ Observations of multiple protoplanetary discs showing structures. Credit: ALMA (ESO/NAOJ/NRAO), S Andrews et al.; NRAO/AUI/NSF, S Dagnello.



▲ ALMA's best image of a protoplanetary disc to date. This picture of the nearby young star TW Hydrae reveals the classic rings and gaps that signify planets are in formation in this system. The inset shows the nearest dark gap to the star, at about the same distance as the Earth from the Sun, suggesting that a protoEarth could be forming there. Credit: S Andrews (Harvard-Smithsonian CfA); B Saxton

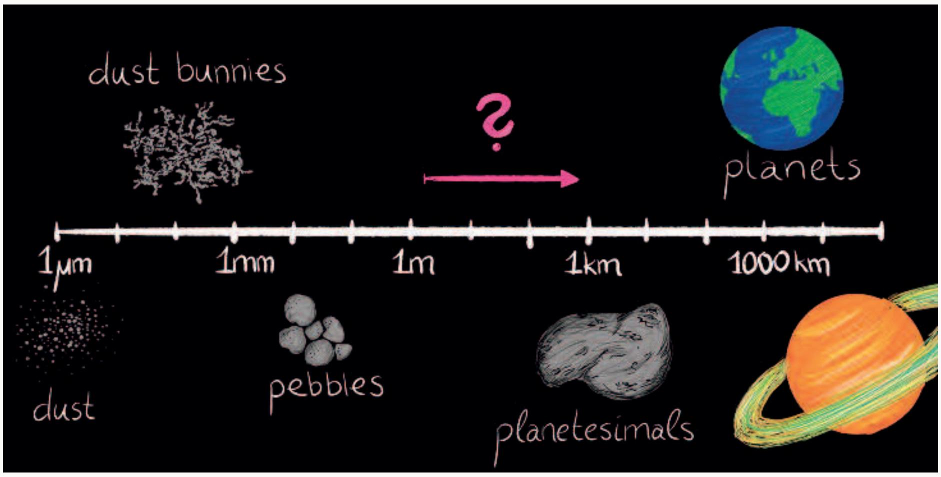


▲ Simulation of a planet (bright dot on the right side) in a protoplanetary disc showing spiral structures (note that the star in the centre is not shown).
Credit: Carolin N Kimmig; FARGO3D: Benítez-Llambay & Masset 2016.(NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO).

The next step of planet formation is more complicated. If you throw two pebbles onto each other, you do not expect them to stick together, and if you throw them hard enough, they might even break into small dust particles again. This step is one of the biggest challenges in understanding planet formation, because once a clump has grown to a large kilometre-sized boulder called a planetesimal, its gravity is strong enough to collect dust particles, pebbles, and smaller rocks. The challenge is how to get pebbles to grow into planetesimals and this is still not fully answered. One hypothesis for enabling pebbles to grow into planetesimals is if the pebbles are coated in ice. This ice coat would make them stickier so that they can grow larger. To tackle this idea, some research groups are performing experiments to test the sticking properties of pebbles under different conditions.

We know from our Solar System that there are several types of planets. Planetesimals that grow larger than ten times the mass of Earth have the power to attract a huge part of the gas from the disc. These become gas giants like Jupiter, Saturn, Uranus and Neptune. Other planetesimals stay smaller and more compact and become rocky planets like Mercury, Venus, Earth and Mars. Some rocky planets can collect an atmosphere while others may stay without one.

After their formation, planets do not necessarily stay in the same orbit. They can wander through the disc, a process known as planetary migration. Planetary migration is caused by the same planet–disc interaction that causes disc structures. State-of-the-art research shows that most physical processes leading to planetary migration cause the planet to migrate towards the star. This helps explain why many planets have been observed very close to their star. However, there are also observations of planets far away from the star that show indications that they formed much closer. Therefore, there must also be processes enabling planets to move away from the star. Some theories have been proposed and tested in simulations; however, most models still show migration towards the star, making this one of the ongoing research topics in the field.




◀ A measuring stick for planet formation from dust (left) to planets (right).
Credit: Carolin N Kimmig.

**All things come to an end**

We can see that our planetary system around the Sun is now no longer embedded in a disc. So what happened to the disc? Clearly much of the disc material was captured in the planets. The rest of the material slowly dissipated and became interstellar matter due to photoevaporation in the protoplanetary disc. All that is left are the fully formed planets in our Solar System.

The process of forming a planet is difficult, with many obstacles and setbacks along the way. However, current research is new shedding light onto how planets form and evolve. The numerous possibilities and processes playing a role in planet formation show that every single planet, including our Earth, is unique.

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