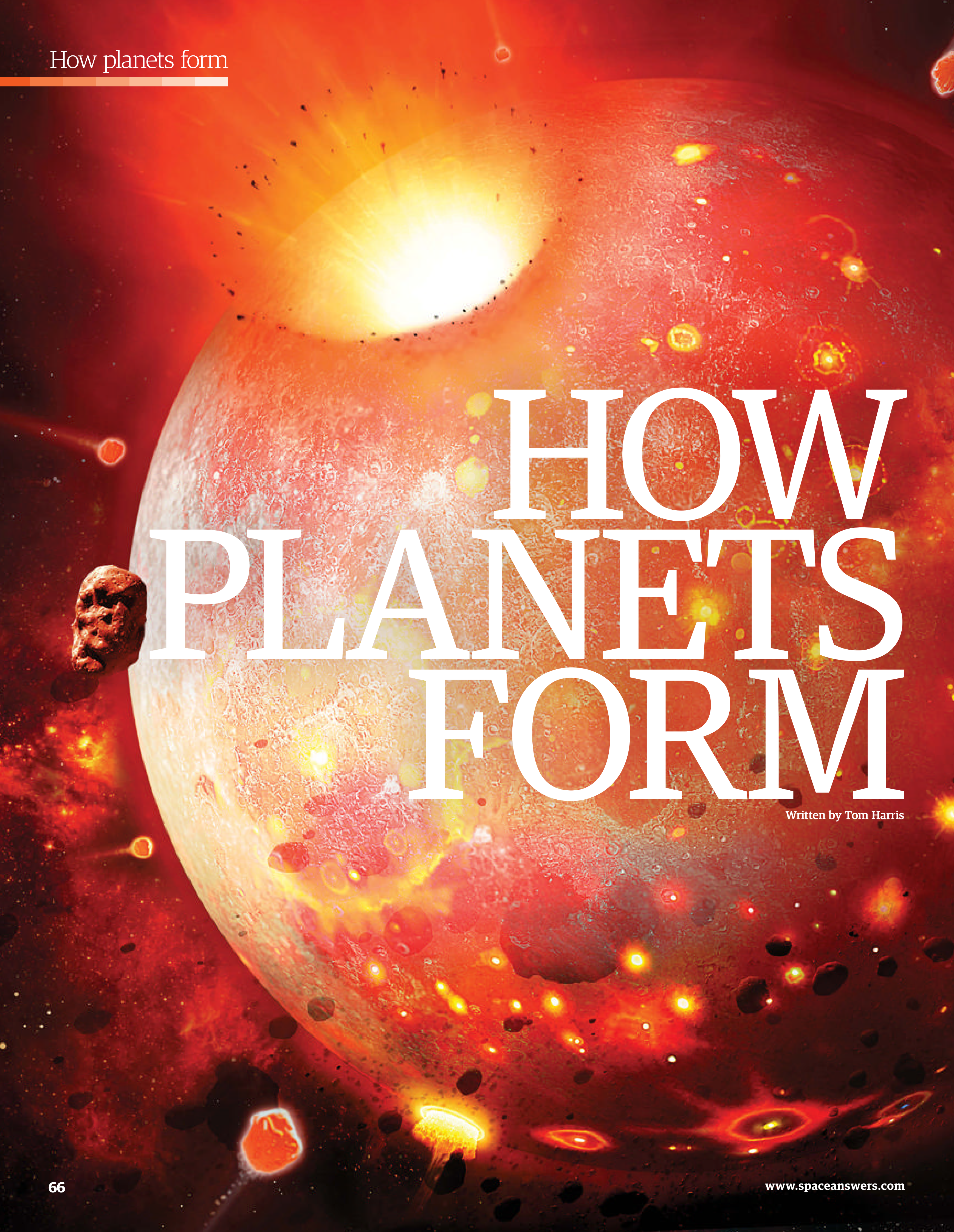


HOW PLANETS FORM

Written by Tom Harris

Discover how our home, along with our Solar System neighbours and every other planet in the universe, was born from a chaotic cloud of dust and gas

In a sense, planetary birth is a side effect of a larger birth: the formation of a star. Stars form from nebulas, massive clouds of gas and dust dominated by hydrogen and helium. Now and then, a disturbance in a nebula concentrates an area of gas and dust into a denser knot of material. If the knot is big enough and dense enough, it will exert enough gravitational pull to collapse in on itself. The huge volume of super-dense gas concentrates at the knot's centre, and the gravitational energy heats it up to form a protostar. With sufficient mass, the energy of the protostar increases, eventually initiating a nuclear fusion reaction and graduating to a proper star.

Meanwhile, according to the solar nebula theory, surrounding gas and dust form a protoplanetary disc, or proplyd, around the protostar. When the protostar first begins to form, the surrounding material is still an unordered, slowly churning cloud. But the protostar's growing gravitational pull accelerates the cloud's movement, causing it to swirl around the centre. As the swirling mass speeds up, it flattens out, forming a thin disc, packed with all the material that will eventually coalesce into planets.

As well as explaining how planets form, the solar nebula theory also explains why solar systems take the form they do. The planets all revolve in the same direction around a central star, in the same plane, because that's how the material disc originally swirled around the protostar.

Exactly how it all comes about is still up for debate, and there may actually be many different planet formation processes. The prevailing understanding, called the accretion model, is that planet formation begins when individual bits of matter in the disc clump together into bigger chunks. The accretion model seems to be correct at least in the case of rocky terrestrial planets, like Earth and Mars, which form from silicates and heavier metal, such as iron and nickel.

Astronomers generally agree that a planet like ours begins with an invisible piece of dust. Microscopic grains in the disc grow by condensation, the same process behind snowflake formation. In condensation, individual heavy gas atoms or molecules stick to a grain, rapidly expanding its size into a more substantial solid particle.

When the particles are very small and light, turbulent gas motions stir them up, swirling them outside the flat plane of the proplyd. But when they reach sufficient mass they're heavy enough to settle into the relatively thin rotating disc. In the crowded disc, particles collide more frequently, speeding up the growth of larger and larger chunks.

At about the point a chunk of solid matter grows to a kilometre across, it graduates to a planetesimal. A planetesimal is massive enough that its gravitational pull attracts smaller chunks of matter, accelerating the rate of growth. The result is a relatively small number of planetesimals steadily capturing the smaller chunks and particles in the disc.

When a terrestrial planetesimal grows large enough, the energy of many collisions along with radioactive material it's accreted heat everything to melting point. As a melted mass, the planetesimal's structure can reform. In a process called differentiation, the force of gravity concentrates the melted metals into an inner core, surrounded by an outer crust of lighter rocky silicates. The result is a protoplanet, an asteroid-like mass with distinct layers. Over time, gravity evens out the protoplanet's shape, forming it into a sphere.

A terrestrial planet might form an atmosphere layer through outgassing. Essentially, heat from the planet's interior core unlocks gases trapped in the planet's solid and molten interior. Planets might then add to this atmosphere through encounters with other solar system bodies.

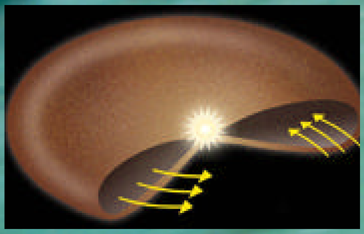
As the diversity of our own Solar System demonstrates, atmospheres vary a great deal. Any particular atmospheric recipe requires not only the right mix of planetary matter, but also a precise balance of planetary size and proximity to the central star. When a smaller planet orbits very close to a star, like Mercury, the sun's heat blasts away any atmosphere, leaving a barren rock. Meanwhile, a planet like Mars is so far from the Sun that all its water is locked up in ice. But just a bit further in, you get Earth - a planet that's the right size and in the right position to form a robust atmosphere that could support life.

While there is general agreement among astronomers that terrestrial planets formed along these lines, the origins of Jovian gas giant planets, like Jupiter and Saturn, are less certain. One possibility is they start out the same basic way as terrestrial planets, steadily accreting solid matter to form a massive protoplanet. If it grows large enough - about 15 times the size of Earth - such a protoplanet exerts a strong enough gravitational pull to capture hydrogen and helium gas in the proplyd. The gaseous mass then sweeps up more material, growing into a Jovian behemoth.

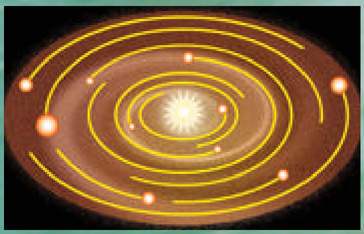
There is a relatively small supply of heavy metals and silicate in a proplyd, making it unlikely that a protoplanet could accumulate enough metal and rocky material to reach the size necessary to hold on to hydrogen and helium gas. Instead, this model says, the initial planetary core of a Jovian planet forms out of frozen hydrogen compounds, such as methane, ammonia and water. Near the centre of a proplyd, the developing protostar makes it too hot for hydrogen

Origins of a solar system

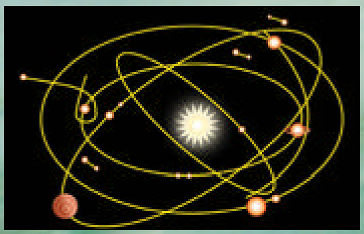
Gas giant, the accretion model



1. Dirty snowballs
Dust grains and bits of frozen hydrogen compounds condense and then collide and stick together, forming bigger and bigger icy planetesimals.

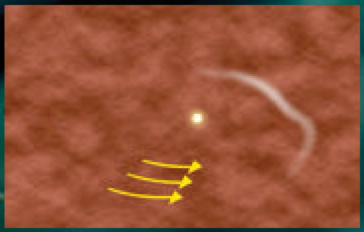


2. Capturing gas
Some planetesimals grow so big that their gravitational pull captures hydrogen and helium gas in the protoplanetary disc.

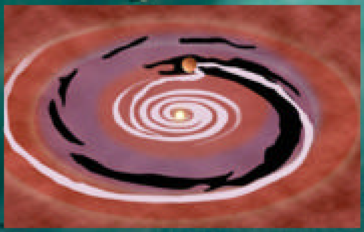


3. Too big to fail
The gas giants grab a huge supply of the disc's hydrogen and helium gas. Their massive gravity pulls in or scatters remaining planetesimals.

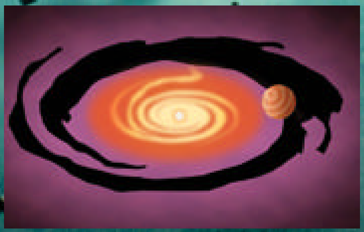
Gas giant, gas collapse model



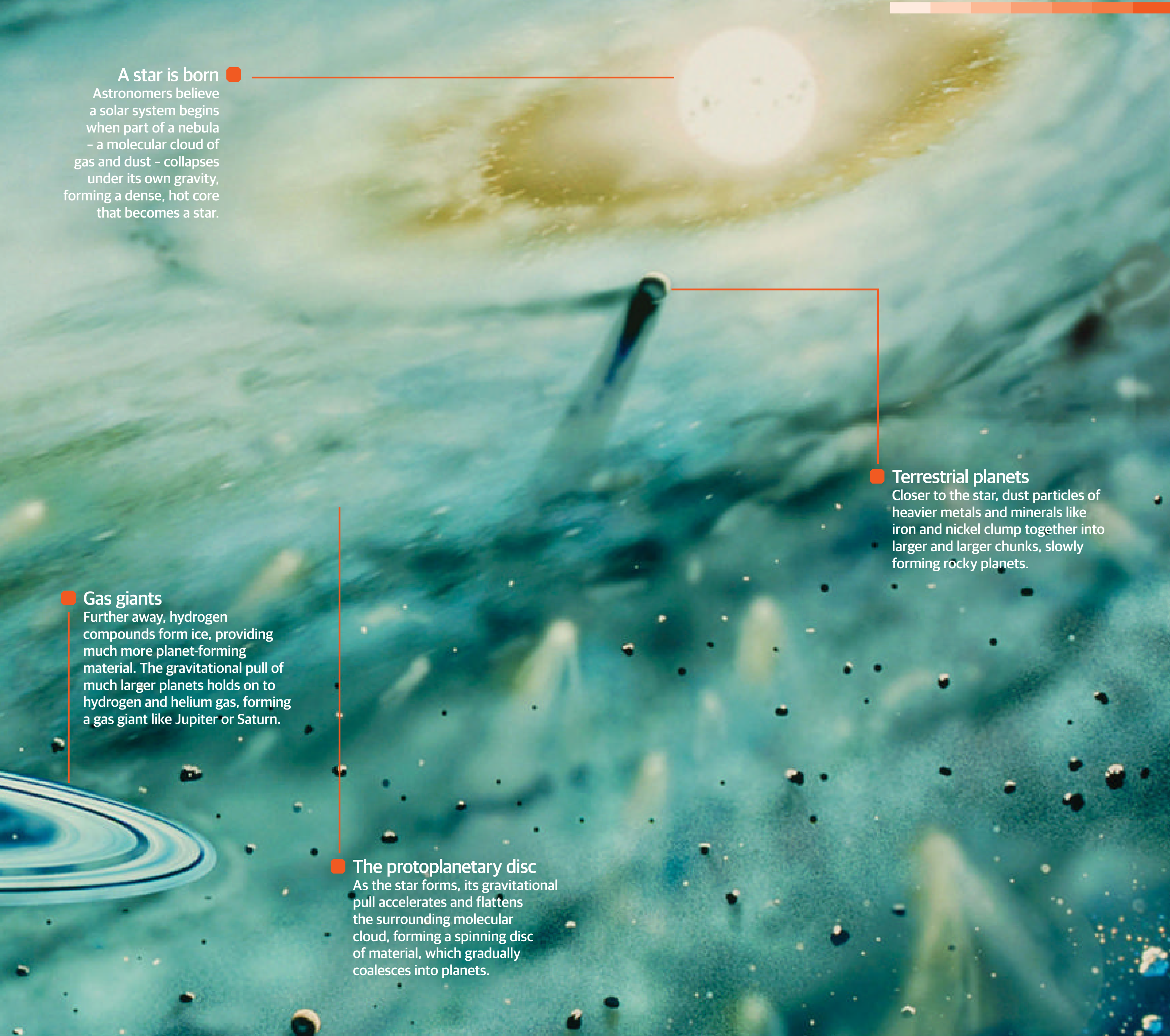
1. Concentrations in the disc
In the disc of gas and dust that forms around a protostar, the dynamics of the rotation cause uneven distribution of hydrogen and helium gas.



2. 'Instant' planet
A clump of dense gas collapses under its own gravity to form a gaseous planet. The new planet picks up dust and ice, which collect into a solid core.



3. Glutton for gas
As the planet makes its way around the disc, its strong gravitational pull sweeps up more gas, making it bigger and bigger.



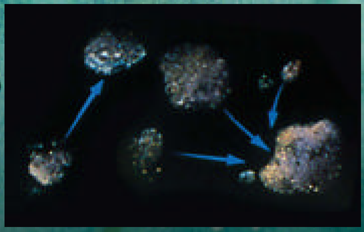
A star is born
Astronomers believe a solar system begins when part of a nebula – a molecular cloud of gas and dust – collapses under its own gravity, forming a dense, hot core that becomes a star.

Terrestrial planets
Closer to the star, dust particles of heavier metals and minerals like iron and nickel clump together into larger and larger chunks, slowly forming rocky planets.

Gas giants
Further away, hydrogen compounds form ice, providing much more planet-forming material. The gravitational pull of much larger planets holds on to hydrogen and helium gas, forming a gas giant like Jupiter or Saturn.

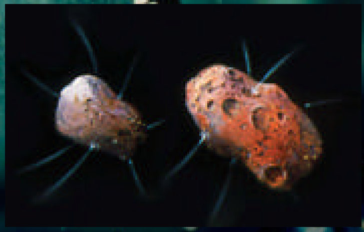
The protoplanetary disc
As the star forms, its gravitational pull accelerates and flattens the surrounding molecular cloud, forming a spinning disc of material, which gradually coalesces into planets.

A terrestrial world is born



1. Let's stick together
Mineral and metal dust particles throughout the molecular cloud collide and clump together, forming larger rocky particles.

2. Running with the crowd
As trillions of these particles rotate around the developing star, they're constantly colliding, forming bigger asteroid-like pieces through accretion.



3. Forming a planetesimal
When a rocky chunk grows to about 1km across, its gravitational pull is able to attract other pieces, speeding up the accretion process.

4. Graduating to a protoplanet
Intense heat melts the rocky material. During melting, elements like iron and nickel concentrate at the centre of the planet, giving it distinct layers.

compounds to condense into frozen solids. They remain in gaseous form and so do not accrete to developing planetesimals. But if you move far enough away from the hot protostar, past what's called the frost line, the temperature drops low enough that hydrogen compounds can freeze. With a much more abundant supply of solid material, large icy protoplanets can form and capture the swirling hydrogen and helium gas.

The organisation of our Solar System supports this theory. The inner planets, Mercury, Venus, Earth and Mars are all relatively small and rocky, suggesting forming giant icy or gaseous planets wasn't possible close to the Sun, while the outer planets, Jupiter, Saturn, Uranus and Neptune, are much larger.

The chief argument against the accretion model for Jovian planets is timing. In well-supported models of solar system evolution, there simply isn't enough time to grow the massive icy cores before the developing solar system loses the bulk of its hydrogen and helium gas supply. While the lighter gases are the dominant material during the proplyd's early life, their days are numbered. In the case of our own Solar System, some 10 million years after the Sun first formed as a protostar, the energy of nuclear fusion reactions likely produced powerful solar winds that would have cleared out the remaining gas in the proplyd. That's a tight window for Jovian gas giants to form.

And neighbouring stars may lead to the window shrinking even further. Astronomers believe that stars generally form in clusters that contain massive, hot stars. Calculations say radiation from these stars would accelerate the evaporation of gaseous material in nearby proplyds, shrinking the period of plentiful hydrogen and helium to between 100,000 and 1 million years. That doesn't appear to be enough time for a Jovian gas giant to form through the accretion model, yet observations of distant solar systems show that these gas giants are very common.

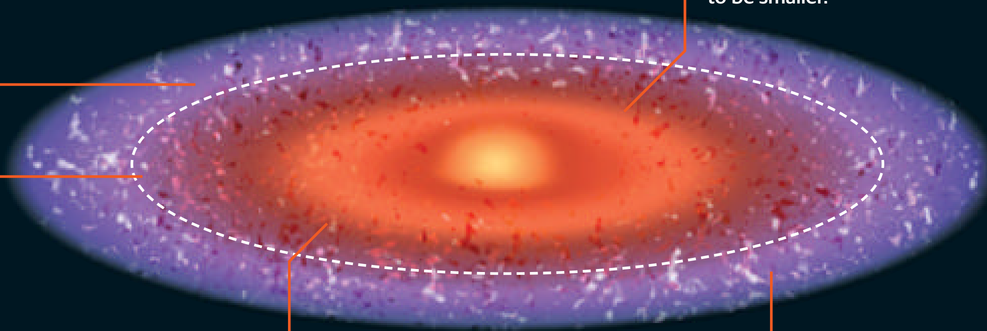
An alternative theory, known as the gas collapse model, presents a faster formation scenario. According to this model, gas giants form directly from the swirling hydrogen and helium in a developing proplyd. As the material revolves around the protostar, turbulence in the disc distributes it unevenly. This unevenness forms knots of dense gas. When enough gas is concentrated tightly enough, its dense mass causes it to collapse in on itself, forming a giant gas ball. To put it another way, the gas giant is like a failed star. It forms the same basic way as the protostar, but doesn't have sufficient mass and energy for a nuclear fusion reaction.

The embryonic planet's gravitational pull takes over from there, sweeping up massive amounts of gas, as well as any solids in the vicinity, quickly adding to its bulk. Collected ice and metals condense at the planet's centre, forming a solid core after the gas has accumulated, rather than before. The whole process might happen as quickly as a few hundred years.

Observations of Jovian exoplanets (planets located outside our Solar System) have given some credence to this model - or at least challenged the Jovian accretion model. In the wave of exoplanet discoveries over the past 25 years, one of the biggest surprises has been the so-called 'hot Jupiters', Jovian gas giants that orbit very close to their suns. These planets would seem to contradict the notion that gas giants only form beyond the frost line. However, they may have formed further out, but then migrated towards their suns.

A host of exoplanet discoveries have given astronomers a much bigger picture of the range of possible planets, which has yielded new clues about how planets might form. But examining the end results can only tell them so much. Fortunately, we're likely entering a new era of direct proplyd observation, thanks to advances in telescopic technology. The new Atacama Large Millimeter/submillimeter Array (ALMA) radio telescope in Chile, which should be fully operational in March, has already yielded unprecedented images of planet formation in progress. As new discoveries follow, astronomers expect to fill in more pieces of the puzzle, taking us ever closer to understanding how our planet, and by extension all of us, came to be.

The frost line explained



Mainly gas
A protoplanetary disc is primarily made up of hydrogen, helium and various hydrogen compounds, such as water and ammonia.

Hot and rocky
Closer to the centre of a protoplanetary disc, the developing star makes it too hot for gases to freeze into a solid. Forming from a limited supply of metals and rocky material, inner planets tend to be smaller.

The frost line
The frost line marks the distance from the star where temperatures drop low enough for hydrogen compounds to freeze.

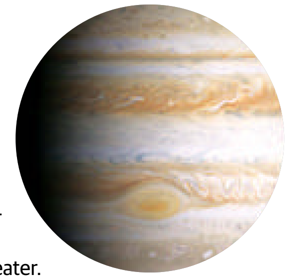
Hydrogen and helium gas
Hydrogen and helium gas exists throughout the protoplanetary disc, but temperatures never drop low enough for it to solidify. Only immense gravitational pull can condense it into a planet.

Icy planets
Beyond the frost line, gaseous hydrogen compounds like methane and ammonia condense into icy solids, which may form planetesimals.

Types of planets

Terrestrial
Terrestrial planets like Earth and Mars are rocky planets with metal cores and high densities. They are smaller than gas giants and have slower rotation periods. In addition, their smaller size means they are less likely to have moons.

Gas giant
At a further distance from their orbiting star, gas giants are able to accrete more matter in their formation, giving them a large size and mass. For example, Jupiter is 11 times larger than Earth, and has a volume 1,300 times greater.

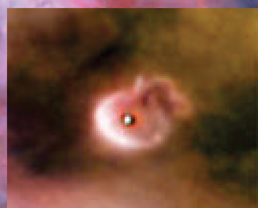


Dwarf planet
Smaller than a true planet, the difference between an asteroid and a dwarf planet comes down to its shape. To be a dwarf planet, a body must have sufficient mass to achieve hydrostatic equilibrium, when it will become spherical.

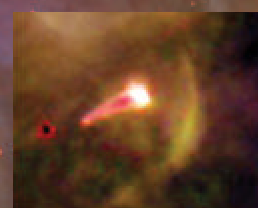
Planet formation in action

Our nearest star-forming region is the Orion Nebula, a massive cloud of gas and dust around 1,500 light years away. The striking nebula is visible to the naked eye - and positively breathtaking as seen through the Hubble Space Telescope. Hubble's sharp images, like this one from 2009, have revealed 42 protoplanetary discs (proplyds) where planet formation is now in progress. Theta^1 Orionis C, the nebula's brightest star, heats nearby proplyds, giving them a bright glow. Proplyds forming further away are too dim to see, but their dark dust blocks out parts of the bright nebula in the background, creating silhouettes astronomers can study.

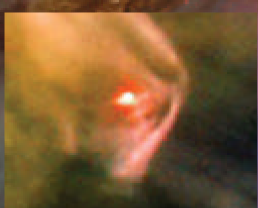
132-1832
Developing far from Theta^1 Orionis C, 132-1832 is one of the darker proplyds in the nebula.



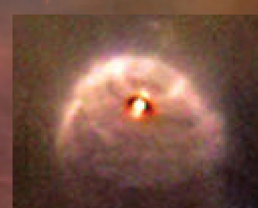
206-446
Astronomers believe this bright proplyd's distinctive ponytail-style plume is a jet of matter streaming out from the disc's centre.



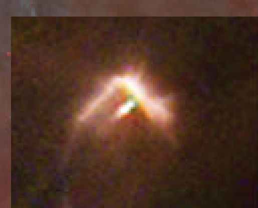
180-331
Proplyd 180-331, another bright disc near Theta^1 Orionis C, also sports a flowing jet of matter, giving it a tadpole shape.



106-417
Stellar wind from the massive Theta 1 Orionis C interacting with gas has formed a shockwave around this ear-shaped proplyd.



181-825
But the best shockwave sculpture has to be 181-825's distinctive galactic jellyfish form.



231-838
Like 106-417, the bright proplyd 231-838 is surrounded by a shockwave, giving it a boomerang shape.

"The origins of Jovian gas giant planets, like Jupiter and Saturn, are less certain"

Discovering a protoplanet

Dr Simon Casassus of the University of Chile talks us through these fascinating images of a protoplanetary disc in action more than 450 light years away

In January, the University of Chile published images showing a protoplanetary disc in action around HD 142527, a young star over 450 light years away. Can you describe the data shown in the image?

This is a protoplanetary system seen face-on. In red is the thermal emission from rocks or tiny pebbles or sand grains. The size of these particles is about one millimetre. The rest of the colours are gaseous. In green, we see the Formyl ion molecule and in blue we have carbon monoxide. In a lighter blue, there are two filaments crossing the cavity that converge on the centre where the star would be. Those filaments are faint compared to the rest of the nebula, but they are there. This is the first time we've seen such cavity-crossing flows. The other first is the (darker) blue, the diffused carbon monoxide, which is slightly less dense material, more rarified gas.

We think that (gas) giants have formed first through a rocky core... a super-Earth exoplanet, something like ten times the mass of the Earth, which is massive enough to attract and hold the gas in the disc, so it sucks away a cavity, which goes into the body of the planet. So the planet grows at the expense of the disc and clears away a cavity. The size of the cavity we see in this system suggests it's been carved out by several planets. This is what the hydro-simulations tell us. The race is on to detect those protoplanets and thereby confirm the whole theory.

The planet is growing and at the same time clearing away this cavity. The way it manages to keep on growing is by sucking material from the outer regions. This material falls on to the star and crosses the planets as they fall, because they're being perturbed by the gravitational interference from the planets. They catch some of the falling material. But the rest of it just overshoots and reaches the inner disc, which is the other side of the cavity. The rate of inflow of material here is just about right to sustain the continuous growth of the star.

Does this reflect something that happens in most cases of planet formation or is this a special case?

We don't know. Before we can extrapolate to other planetary systems, and before we can conclude that for sure the early Solar System looked like this, we have to find some other examples. This is the first time we have seen these radial flows and this residual gas inside a planetary cavity, and we detected the features at the limit of the capabilities for ALMA in its first year of operations. So we need to study it in more detail and collect similar data around other young stars.

Was there any data in your findings that challenged existing models of planet formation?

That's a hard question because there are so many different models of planet formation. But there are some versions of planet formation which predict very late formation of planets, slower than tens of millions of years, and this one is about two million years.

Is it possible that our own Solar System followed a similar sequence of events?

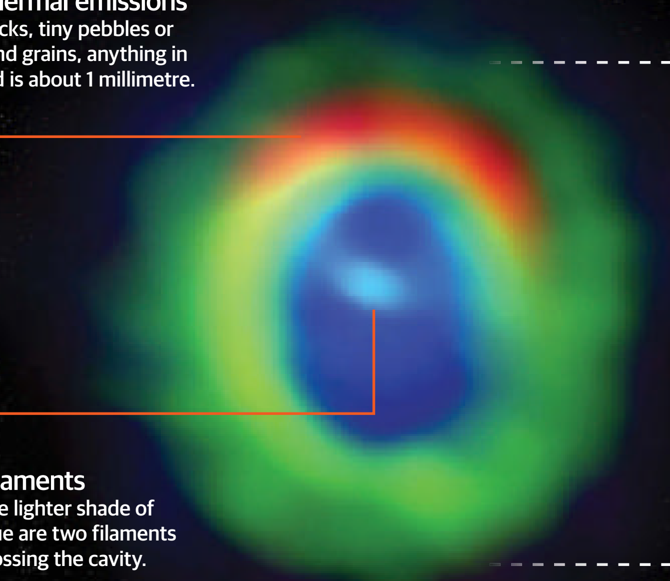
Could be. That's what's so astonishing. If you consider this nebula, it's a protoplanetary disc around the star called HD 142527. In this system the protoplanets are formed really far out from the star. Our hydro-simulations tell us that the protoplanets form around 100AU from the star, whereas Jupiter is at 5AU [from our Sun]. So, is this system comparable to our Solar System? At first, you would say, no, because it's so much bigger. But you also have to think about planet migration. Newborn planets migrate. It is possible for a gaseous giant to migrate from the outer regions at 100AU down to 5AU.

Are there other theoretical phenomena that you're looking to see in future observations?

Yes. There are proto-lunar discs, the circumplanetary discs, which we hope to detect. This would be a way to pinpoint the location of protoplanets.

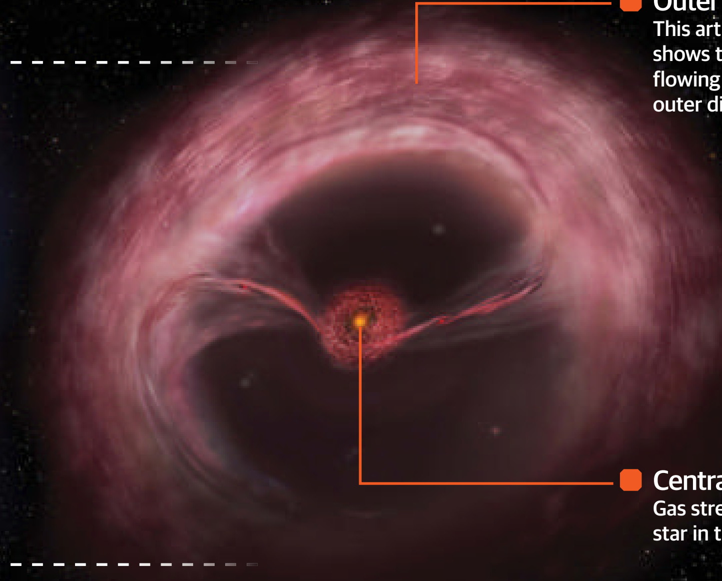
What's next for your team?

We are still analysing this data. And then I'm expecting the rest of the ALMA data and also complementary infrared observations. In the hope of detecting the protoplanets, we applied a variety of techniques.



Thermal emissions
Rocks, tiny pebbles or sand grains, anything in red is about 1 millimetre.

Filaments
The lighter shade of blue are two filaments crossing the cavity.



Outer disc
This artist's impression shows the gas streams flowing from the outer disc.

Central star
Gas streams flow to the star in the disc's centre.