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A STAR IS BORN

A Lecture by

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A STAR IS BORN

HEATHER COUPER

Many years ago, I remember going to a seminar on star formation at Cambridge. I only dimly recall the speaker's words, but they were along the lines of: "There are so many effects opposing star formation that the difficulties seem almost insuperable. However, it's obvious from the structure of the Galaxy that nature has no such difficulties".

How absolutely right he was! Our Galaxy - one of billions in the Universe - has created 200 thousand million stars alone, of which our Sun is one. But how does it do it? Where do the raw materials come from? And can we ever see it happening?

Fortunately, the aftermath of starbirth is all around us. Take a look, for instance, at the constellation of Orion: the middle fuzzy 'star' in his sword is in fact a huge star-factory, lit up by the glare from young stars inside. This fan-shaped cloud of gas and dust, whose traceries extend some fifteen light years into space, is known as the Orion Nebula. On a dark, moonless night you can easily see it with the unaided eye, while even the smallest of telescopes reveals the clutch of stars at the nebula's heart - 'the Trapezium'. It is their intense ultraviolet radiation that excites the surrounding cloud to glow, like the shining gas in a neon tube. Astronomers believe that these stars are less than half a million years old.

We live in a part of our Galaxy where starbirth is busily taking place. As a result, our skies are studded with nebulae, which astronomers have classed, catalogued, and given romantic names: the Rosette Nebula, the Lagoon Nebula, the Pelican Nebula, the Eagle Nebula and the North America Nebula (which really does look like a celestial United States).

Even two centuries ago some astronomers, like the great star-gauger Sir William Herschel, were suspicious that nebulae were linked with the birth of stars. Writing about the Orion Nebula he mused that it was: 'more fit to produce a star by its condensation than to depend on the star for its existence'. We now know, however, that nebulae come quite a long way down the road in the story of how stars were born. They are a sign that starbirth has already taken place. So what happens *before* stars get to the stage of lighting up their natal gas cloud?

Until just a few years ago, astronomers didn't know. The problem lay with the raw materials that go to make up stars. Mixed in with the gas is a 'fog' of solid particles, like little flecks of soot. Interstellar dust cuts dramatic black swathes across the photographs of many nebulae: in fact, the 'Trifid' nebula is so-called because dust lanes divide it into three. Unfortunately for astronomers, stars like the darkest and most undisturbed conditions possible to come into being - in other words, right inside the densest, most impenetrable gas and dust clouds. Even the most powerful telescopes in the world could not hope to reveal the goings-on inside one of these. That is, until astronomers were able - literally - to see star formation in a new light: infrared.

Infrared is an upmarket term for 'heat radiation'. It's what you feel when you turn on an old-fashioned electric fire: the warmth from the element before the red glow begins. In fact, it was another discovery made by Sir William Herschel, who found that if he spread sunlight out into a spectrum, and placed a thermometer beyond the red end of the spread of colours, it registered an increase in temperature. Herschel concluded that he was witnessing the effects of invisible radiation: 'below red', or 'infrared'.

All astronomical bodies, no matter how cool, emit some of their energy in the form of infrared radiation. Astronomers reasoned that embryonic stars - 'protostars' - would be prime candidates. Their infrared radiation would even be able to escape the dust cloud that cocooned them, giving astronomers a glimpse of actual starbirth at long last. 'Protostars are the Holy Grail of infrared astronomy,' commented astronomer Gareth Wynn-Williams back in 1982.

The problem, then, was knowing where to look. Although some infrared radiation from space does reach us, most of it is absorbed by the water vapour in our atmosphere. Infrared telescopes are perched on the highest sites on Earth, where the water vapour is frozen out. But our atmosphere still blocks off much of the longer infrared wavelengths, where we would expect protostars to be brightest. What astronomers needed was a sensitive infrared survey made from *above* the atmosphere, so that they could pinpoint suspect starbirth sites to follow up later.

The survey was not long in coming. In 1983, two centuries after Herschel's discovery of infrared, a revolutionary new satellite went into orbit about the Earth. A collaborative venture between Britain, the Netherlands, and the United States, IRAS (the Infrared Astronomical Satellite) was the closest thing to a vacuum flask ever sent into space, and the first satellite ever to seek out infrared sources. In order to kill its *own* infrared radiation, and to protect it from the heat of the Sun, IRAS's telescope was surrounded by a dewar containing liquid helium at -270°C. IRAS could function as long as its helium coolant lasted. After ten months - almost twice the satellite's design lifetime - the helium finally ran out.

During those ten months, IRAS discovered a quarter of a million new sources - among them a treasure-trove of objects of a kind hitherto unknown to astronomers. There were galaxies giving out a hundred times more heat than light; rings of dust in the Solar System; several brand-new comets; and - for those in quest of the Holy Grail - hundreds of infrared sources embedded in nearby dark dust clouds.

At last, astronomers had targets to aim for - and on Hawaii the crackdown began. The 14,000-foot summit of Mauna Kea is the best infrared site in the world, and it is here that the largest observatory complex of all is beginning to take shape. The latest arrival, tucked in a sheltered hollow a little way off the summit, is Britain's James Clerk Maxwell Telescope, the JCMT. Strictly speaking, the JCMT is not an infrared telescope. It looks more like a conventional radio telescope, a 'mini Jodrell Bank'. Its 50-foot dish - made up of 276 aluminium panels - detects 'millimetre waves': wavelengths midway between radio waves and infrared.

The JCMT is following up IRAS's discoveries directly. It homes in on the target areas, tunes into signals from gases deep inside the dense clouds, and tracks the gases swirling inwards as they begin to collapse and make a star.

A neighbouring telescope in Hawaii, the United Kingdom Infrared Telescope, sees starbirth at a later stage, when the dusty turmoil begins to die away. These telescopes, and many others around the world, have finally provided the missing pieces of the jigsaw. Thanks to IRAS's search-and-destroy mission, we can now tell the story of how a star is born.

The key to starbirth is gravity - and what it does to the matter scattered amongst the stars. The spaces between the stars are not quite empty, but filled with the lightest sprinkling of gas and dust. This material is unbelievably tenuous. While an average matchboxful of air contains literally billions of billions of atoms, one full of space would contain just two or three.

This barely-there matter, however, is the future stuff of stars. Star-stuff has all the time in the Universe on its side. Over millions of years, the tendrils of gas that drift like wraiths of smoke begin to build and collect into something more substantial. Like billowing smoke from a bonfire, these clouds grow to become black and impenetrable - a result of the sooty dust that is mixed in. We see these clouds only as silhouettes against the distant stars. One of the most obvious of these is the well-named Coalsack, a black patch in the Milky Way, next to the Southern Cross.

Deep inside a cloud like this, it is cool, dark and still. Conditions could not be better for gravity to begin to assert itself. With nothing in the way to oppose it, gravity starts to squeeze the cloud's central regions tight. Slowly but surely, the gas begins to feel the bite, and the collapse becomes unstoppable. Under the strain, the centre of the cloud breaks up into hundreds of fragments - dense balls of gas measuring between a tenth of a light year and a light year across, which contain enough matter to make a star up to fifty times the mass of our Sun.

At this stage it is cool - no more than 10° above the absolute zero of temperature (-273°C) - and so it is not a star. But theory tells us that it is already too dense to disperse into space. It is destined to become a protostar in less than 100,000 years - an eternity for us, but hardly an hour in the lifetime of a star. IRAS researcher Chas Beichman concludes: 'once you have a dense core you are going to have a star form there.'

The IRAS survey included a long, hard look at these 'dense cores'. And it found that over half had infrared sources inside them; they had collapsed so much that they were giving out their own heat. These are undoubtedly protostars - the youngest that we can observe.

When does a protostar turn into a star? The answer is when it can generate enough energy to stop it from collapsing. Heat alone will not do. But there comes a time when the protostar's central temperature, which has been climbing steadily under the extreme compression, reaches 10 million °C. that's when the protostar reaches the point of no return. Its core is so hot that the gas there is forced to undergo fusion reactions. Its nuclear fires ignite, energy floods through, and the inpull of gravity is - temporarily, at least - vanquished. A star is born.

But astronomers don't get to see a young star suddenly flash into life, as was once thought. The reason is that starbirth is a much more violent and chaotic process than at first realized. Even at the protostar stage, the gas and dust collapsing to make the star doesn't fall in neatly and evenly. It forms a rotating ring - an accretion disc - around the fledgling star. By the time the star has 'properly' formed, this disc has grown to be some three times the size of the Solar System, and about one-fifth as massive as the Sun.

This disc is so substantial that the young star plays hide-and-seek, disappearing and re-appearing behind its dusty veils. But the accretion disc has a life of its own, too, as astronomers are just starting to discover. Some discs produce as much energy as the Sun itself. At the moment, no one is certain where the energy comes from. It is just possible that it could arise from nuclear reactions in the densest parts of the disc, involving deuterium. This form of hydrogen 'burns' to helium at a lower temperature than is needed for normal hydrogen fusion.

All this activity in the disc tends to overshadow the emergence of the star itself. But the young star has the last word. It, too, is giving out energy at a prodigious rate. In fact, when the Sun was a protostar, it had the same temperature as it has today, but it was about ten times brighter. This is a result of matter still steaming inwards from the inner parts of the accretion disc; when it hits the protostar's surface, it liberates vast amounts of light and heat.

As the protostar ages, it begins to give out a violent 'wind' of thin, hot gas. Because the protostar is girdled around the equator by its accretion disc, the gas can only escape from the protostar's poles. As a result, the protostar develops two 'beams' steaming away from its north and south poles. Chas Beichman calculates that these beams are powerful enough to blow away the surrounding cloud of gas and dust. As the shreds of the gas cloud disperse, the young star is finally exposed, in Beichman's words, 'like a chicken hatching from an egg'. 100,000 years after entering its protostar stage, the young star emerges to greet the gaze of the Universe.

The newborn star does not face its début alone. Because of the way its parent cloud fragmented during its early collapse, the star is born with a host of brothers and sisters. They are clustered tightly together, like a clutch of eggs in a nest. All around them are the rags and tatters of their natal cloud - but now they are decked out carnival-fashion. Gone forever is the brooding dark cloud. In its place is a brilliantly-glowing nebula, shocked into shining by powerful ultraviolet radiation from its young progeny inside.

This is the loveliest side to starbirth, and one that we can all see. The nebulae that dot our corner of the Galaxy - a hotbed of star formation - are glorious sights through a small telescope, and are among the most photographed objects in the Universe.

Such beauty conceals the fact that the violence is still continuing. Even as we watch, nebulae like the Orion Nebula and the Rosette are being torn to shreds by hurricane-force winds blowing off the young stars. In just a few moments of cosmic time they will be gone, their gases dispersed into space. But they will have the chance to make stars next time around in some other part of the Galaxy.

Meanwhile, the young stars are growing up. But it will be some time before they leave the nest. Gravity is still at work; this time holding together the clutch of stars in what's called an 'open cluster'. These clusters are much smaller - and younger - than the giant, ancient globular clusters that form our Galaxy's outer skeleton. But what they lack in stars they make up for in beauty and variety. The brightest stars in open clusters are hot, blue stars, which look irresistibly like jewels scattered over deep black velvet.

One of the loveliest open clusters of all is the Pleiades (Seven Sisters), on view from October to March, which Tennyson described as 'fireflies tangled in a braid'. They look like a tiny, misty patch in the sky (which many people took to be Halley's Comet in 1985-6!), but, after a little while, you'll find it easy to discern the separate stars. Most people can see six, arranged in the shape of a miniature 'Plough' (it's possible that the 'seventh sister' has faded). Those with keen sight may even be able to pick up eleven or twelve. These are just a fraction, however, of the 300 or so stars that make up the cluster, as a glance through binoculars will readily confirm. Astronomers estimate that they are about 60 million years old - mere babes in cosmic time, but a long way down the road from the hurly-burly of star formation.

Near the Pleiades are two more open clusters. The V-shaped Hyades ('head' of Taurus, the Bull) is more dispersed than its compact neighbour, and, having no blue stars, lacks its sheer glitz. All the indications are that it is an older cluster - perhaps more than eight times older - whose stars have begun to wend their own paths through space. Even older - at 1000 million years - are the stars that make up the Praesepe cluster in neighbouring Cancer. This sparse group of stars is barely visible to the naked eye, except as a misty blur. Unspectacular though the cluster may be, the name foisted upon it by ancient Chinese astronomers hardly seems fair - they called it 'the exhalation from piled-up corpses'!

The stars of Praesepe are already one-fifth of the Sun's age and are becoming respectable citizens of the Galaxy. They are shedding the gravitational chains that have confined them from birth, and starting to 'go it alone'. When a star reaches the Sun's age, there is very little to remind it of its birth. We have no idea, for instance, which, if any, of the Sun's neighbouring stars were born along with it.

But some stars *do* carry with them a reminder of their birth, which affects the way they grow up. The majority of the stars - some sixty per cent - are not single, but double. They were born together as a pair, and stick together for life. The Sun, however, is a single star. Instead of having a stellar companion, it has a family of planets. There are some astronomers who believe that the two situations may be mutually exclusive. If there is sufficient mass close to a protostar, another star will form alongside; but if there is not, planets will come into being instead. And even if planets *can* exist in a double star system, their orbits about their two suns will be very complex. Almost certainly, life could never evolve on a planet such as this; the extremes of climate would be too hard to assimilate.

Astronomers believe that the planets in our Solar System originated in the accretion disc around the young Sun. Like those we detect around other young stars, this disc was a swirling jumble of matter. Sometimes the dust and rubble collided and broke up. At other times, it stuck together, building up bigger aggregations. In time, construction triumphed over destruction. Knots of rubble and debris began to grow, steadily attracting more material as they grew bigger. Close in to the young Sun, it was too hot to make much headway. The gas and dust was too fast-moving to build up anything more substantial than small worlds like the Earth. Further out, however, where the material was cooler and slower-moving, the debris piled up. Most of it went into making Jupiter - a vast body bigger than all the other planets put together. Had there been rather more material where Jupiter now lies, a body massive enough to sustain nuclear reactions could have been created - another star. As it is, the Sun ended up instead with planets: nine bodies too small to have power sources of their own.

How common are planets around other stars? Is our Solar System a freak, or do planets form naturally as by-products of starbirth? We know at least that every young star has the right raw materials in its accretion disc. But how many of them manage to carry the process through to making new worlds?

It is impossible, with our present telescopes, to see planets circling other stars. The contrast between a star and its planets - coupled with their close proximity to each other - rule out all direct search techniques. But there are other approaches. Our own Solar System, for instance, still contains substantial pieces of rubble: small bodies like comets and asteroids that are leftovers from the old accretion disc. It is also lightly sprinkled with dust, just as you would expect of any former building site. All this rubble gives out infrared radiation. Were an IRAS from another civilization to look at the Sun, it would see it surrounded by a warm disc of debris. The scientists operating this extraterrestrial IRAS would know immediately that this could not be an accretion disc, for the Sun is a mature star. Instead, they would come to the conclusion that the Sun had a family.

With this in mind, IRAS looked at a number of nearby 'mature' stars to search for tell-tale signs. It detected discs around some forty of them. Those around the bright stars Vega and Fomalhaut appeared to be particularly well-developed, but it was Beta Pictoris that scooped the headlines.

News of a possible disc around Beta Pictoris filtered down to astronomers Brad Smith and Rich Terrile, who were on an observing run in Chile. They were testing out a new 'coronagraph': an instrument designed for looking at faint extensions, like rings, around the planets in our own Solar System. Rich Terrile recalls acting on impulse. 'It was almost dawn. We didn't really have time to think - we just decided to go for Beta Pic there and then.'

When they processed their coronagraph picture - taken on a guessed exposure of six minutes - Smith and Terrile were astonished to see what appeared to be 'propellers' sticking out of the star. Here was the disc that IRAS had detected, presented edge-on to our line of sight. It was the first time anyone had actually seen a disc of matter circling a mature star.

Are there planets as well as rubble? We have no way of knowing: our present generation of instruments cannot tell. But the discovery proves that some stars, at least, appear to have followed the same course of action as our Sun. In fact, even as I write these words - almost a year after giving the original lecture - news has broken that astronomers in Geneva may have discovered a Jupiter-mass planet orbiting the sunlike star 51 Pegasi. It is not another Earth - but if there really is a planet there, it may be one of several. It reassures us that planet-formation *is* a normal part of starbirth, and that we can expect to find other worlds out there.

(ASTRO-1)