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EXPLORING THE MILKY WAY

A Lecture by

PROFESSOR HEATHER COUPER BSc DLitt(Hon) FRAS
Gresham Professor of Astronomy

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To the ancients, the hazy band of light that spans the sky on a clear night held no mysteries. If anything, their explanation for it was somewhat down-to-earth. They told the legend of Hercules, one of Jupiter's illegitimate offspring, who was desirous of immortal life. Unfortunately for him, his mother was a mere mortal. Jupiter took pity on the child, and informed him that suckling at the breast of a goddess would ensure immortality. So Hercules crept up to the sleeping Juno - but the goddess was woken by his approach, and the stream of milk splashed across the sky. So was created what was literally the Milky Way.

Despite the ancients' delightful certainty, only this century was the Milky Way's nature fully realised. Ever since Galileo first turned a telescope to the sky in 1609, astronomers had known that the Milky Way was made of stars, but they were unsure how to reconcile these distant and apparently crowded stars with the brighter stars that we can pick out with the naked eye. 18th century philosophers like Thomas Wright and Immanuel Kant hazarded commendably accurate guesses, but most professional astronomers of that time were busy studying the solar system.

It was left to an amateur astronomer, the great William Herschel, to tackle the question scientifically. Using his large home-made telescopes, he carefully counted the number of stars visible in different directions, to see just how they were distributed in space. He even hit on the correct explanation of the layout of the Milky Way, but later abandoned this idea.

By the start of the 20th century, however, enough strands of evidence had come together to show that the band of the Milky Way is just an edge-on view of the distant stars that make up our home Galaxy. The discovery of millions of other galaxies spread throughout space - each a separate star-island with a membership running into millions - also helped astronomers to gain a perspective on our own.

With hindsight, the broad-brush picture of our Milky Way Galaxy is surprisingly simple. It is a disc-shaped system of stars, gas and dust wheeling slowly in space once in 200 million years. From the side, it would look like a spindle, widening towards the central bulge. A bird's-eye view would reveal the beautiful Catherine-wheel shape of a typical spiral galaxy, so wide that a ray of light would take 100,000 years to cross it.

From intergalactic space it would be very difficult to spot the Sun, for it is just one out of the Galaxy's 200,000 million stars, and not a very brilliant one at that. The Sun is situated in an unceremonious position in the galactic suburbs some two-thirds of the way out from the centre. We live in the outer part of the Galaxy's disc, and it is this positioning that gives rise to the band of the Milky Way in our skies. Looking into the thickness of the disc all around us, there are stars as far as we can see, tailing off into a misty blur. These distant stars appear to be crowded together, but this is only an effect of perspective. When we look above or below the disc, the stars quickly run out: beyond is just empty space.

The disc is the most obvious part of the Galaxy, but it is far from being the only component - or even the most important part. It is surrounded by a giant 'halo', a vast spherical region some

300,000 light-years across, which is the ghost of the original gas cloud that collapsed to form the Milky Way. Now the halo is populated by stars so old and dim that it is difficult to see them at all - except where they congregate into the aptly named 'globular clusters': spherical collections of stars containing up to a million stars each. These are the Galaxy's first citizens; the stars that formed some 13,000 million years ago, when a cloud of gas fresh from the big bang began to turn into a galaxy.

But the ghostly halo may be more substantial than it seems. The motion of the gas and stars in the disc of our Galaxy suggests that they are under the influence of gravitational forces far stronger than could be mustered by the visible matter in the Galaxy. There must be a huge amount of 'dark matter'. We cannot detect the dark matter with any kind of telescope that exists at present, and it makes its presence felt only by its gravitational pull. According to recent calculations, we see only one-tenth of the Galaxy's total mass; the remaining nine-tenths is the dark matter that resides, presumably, in the halo.

What could make up this dark matter? It would be convenient if it took the form of gas left over from the Galaxy's formation; but the halo is, in fact, more or less free from gas of any kind. At the moment, astronomers are investigating several very different possibilities. The halo may be chock-a-block with some kind of elementary particle: these could be something we know about already, like neutrinos (which would then have to possess a certain amount of mass, contrary to some experiments in the laboratory), or particles that physicists have predicted theoretically but have yet to find in nature. These particles rejoice under names like axions and gravitinos. Or there may be huge numbers of individual astronomical objects that produce very little light or other radiation. Black holes spring immediately to mind, as they are the ultimate in very dark objects. But a multitude of objects like Jupiter would do just as well. Planets floating freely in space would produce practically no radiation of their own.

The disc of our Galaxy is much better understood than the halo. It is the Galaxy's newest neighbourhood. Its star population contains a fair sprinkling of older inhabitants, but many of these are relegated to its outer fringes, above and below the galactic plane. In fact, the whole distribution resembles a series of tide marks, with stars of younger and younger age marking the stages of its formation, as it collapsed from a fat gas cloud to a thin disc. The central plane of the Galaxy is marked by the youngest stars: it is the region where the stars of the Galaxy are still forming.

Here the spaces between the stars are filled with invisible, tenuous gas, the raw material of future stars. There are only half a dozen atoms in a matchboxful of space, on average, but in time these isolated atoms - mainly hydrogen and helium, but increasingly atoms of carbon, nitrogen and oxygen processed in stellar furnaces and ejected into space - will clump together in huge clouds to produce the next generations of stars. The immediate products of starbirth are all around us: we are lucky enough to live in a region of the Galaxy where our skies are bright with young nebulae, sparkling star clusters and dazzling, but short-lived, blue supergiant stars.

These spectacular youngsters have a scientific use too: they allow us to investigate the geography of the Galaxy. We know, by investigating other spiral galaxies, that these kinds of objects are closely grouped into spiral arms, while older stars are spread more evenly over the disc. When we measure the distances to the young objects near the Sun, and plot them out on a map of the Galaxy, we find that they bunch into three distinct bands - one at about the Sun's distance from the galactic centre, one closer in, and the other rather further out. These, without a doubt, mark the positions of the three nearest spiral arms of our Galaxy. The Sun is a member of the Orion Arm - along with the bright nebulae and young stars that make up the striking figure of Orion, the hunter. It is flanked by the Sagittarius Arm, closer to the galactic centre, and the Perseus Arm farther out.

Optical telescopes give us a grandstand view of the inhabitants of these arms. But it is difficult to work out what is going on further away in our Galaxy. The problem is not just that objects look fainter when they lie at a greater distance, but that our vision is also clouded by particles of dust in space. These confine our view to a region only 10,000 light-years across - only one-tenth the size of the Galaxy.

At first, dense regions of dust seemed to be a veritable blessing. These dark clouds (like the Coal Sack near the Southern Cross) look to the naked eye like starless voids, and many 19th century astronomers thought them to be 'tunnels' through which we could peer vast distances into space. Ironically, these dark regions are in fact dense patches of dust which block off the light from more distant objects.

These dark clouds are the densest regions of 'fog' in the Galaxy; but the dust particles are spread out more thinly everywhere else in the disc, to produce a general, if only slight, interstellar 'mist'. On average, this dims a star by one magnitude (reducing its light by 60%) for every 3,000 light-years of its distance. But the dust is far from uniformly spread, and the amount of obscuration is unpredictably uneven.

Most astronomers believe that this 'dust' consists of small particles of rock (silicates) and soot (carbon), coated with ice, and each less than a micron across. They condensed from old red giant stars, which are continually losing gases from their surfaces into space. Although it can be prominent in the dense clouds, the dust makes up only 0.1% of the Galaxy's mass.

As far as the fog-bound astronomers on Earth are concerned, the grains of dust have one very big thing in their favour - they are small. So, while they form a barrier to light waves, whose wavelengths are roughly the same size as the dust grains, they are practically transparent to radiation of longer wavelengths. An astronomer 'tuning in' to the Galaxy at infra-red or radio wavelengths will not 'see' any dust grains at all, and can look straight across the Galaxy.

But, even so, our position gives us only a worm's eye view of our star city. Radio astronomers still have to face the complicated task of disentangling dozens of signals piled on top of each other along the same line of sight, and that is one reason why the exact shape of the Galaxy is open to debate even now. At least nature has co-operated by providing a strong clear signal to help in the job of mapping. It comes from the cold hydrogen gas that pervades the space between the stars.

About one-tenth of the detectable mass of our Galaxy (ignoring the dark matter) is in the form of interstellar gas, mainly hydrogen. Although the hydrogen is invisible to our eyes, the signal that it gives out at a precise wavelength of 21.1 cm is a veritable beacon to radio astronomers. Its real selling point as a mapping signal is that it is a single wavelength, not a broad band of wavelengths like visible light. Astronomers measuring its intensity and the slight Doppler shifts from the 21.1 cm rest wavelength (caused by the motions of gas clouds towards or away from us) can tell not only how much gas there is, but how far away it lies.

In the 1920s, the Dutch astronomer Jan Oort was one of the first to produce evidence that our Milky Way Galaxy is a spiral, by studying the motion of stars near the Sun. His pioneering spirit came to the fore again in the 1940s, when the Germans occupied The Netherlands and closed the observatories. Undaunted, Oort insisted on holding his astronomy group together by tackling purely theoretical problems. Oort realised that radio astronomy could extend his own researches into the structure of the Galaxy: an American researcher had found radio waves coming from space a few years earlier, but professional astronomers had not followed up this lead. What was needed, Oort argued, was a signal from gas in space that he could tune in to. He set this problem to a student, Hendrik van de Hulst, who calculated that hydrogen atoms would produce the 21 cm wavelength. In 1951, several radio astronomy groups around the world succeeded in picking up this radiation from the hydrogen in space, and so began to lay bare the spiral backbone of our Galaxy.

The study of hydrogen produced a broad-brush picture of our Galaxy - but astronomers more recently have found a better way to pin down the details of the spiral arms. The problem with hydrogen is simply that there is so much of it - we find it everywhere, between the arms (though more thinly) as well as in the arms. In the 1960s, radio astronomers discovered they could pick up radiation at particular wavelengths from other gases in space - not single atoms, this time, but molecules. The molecules can only survive in places where they are safely hidden from disrupting ultra-violet radiation - in the centres of the black clouds in space. And we know that dark clouds are strung like beads along the spiral arms of galaxies. So astronomers have now tuned into a convenient signal, from carbon monoxide at a wavelength of 2.6 mm, to produce the first detailed maps of our Galaxy, not just in our vicinity, but right across to the far side of the Milky Way.

By observing radio waves from nearby dark clouds, astronomers have been able to find out just what is going on in their murky depths. First, they have detected signals from an astonishing number of different molecules - a rich and varied collection consisting not just of two or three atoms, but up to thirteen atoms strung together. To date, over sixty varieties have been discovered.

Some are very simple, like carbon monoxide (CO), water (H_20) and cyanogen (C_2N_2). Others are decidedly complex, such as methyl cyanoacetylene (CH_3C_2CN) and cyanohexatri-yne ($HC_2C_2C_2CN$). There is even ethyl alcohol (C_2H_5OH) - in one cloud complex alone there is enough to fill the Earth with neat whisky! To understand what is going on, astronomers are working closely with chemists - although the interstellar chemistry laboratory is rather different from what we are used to on Earth. A research chemist can often produce a reaction only by heating the substances, to encourage the molecules to swap their atoms. But, in the interstellar clouds, temperatures are not far above absolute zero. Reactions must proceed extraordinarily slowly - but, unlike the laboratory chemist, nature has millions of years in which to perform these experiments.

The dark 'molecular clouds' are the maternity wards of the Galaxy: in the centre, gas is tightly compressed into clumps, which then pull themselves together by their own gravity. In the process, the clumps become hot, and shine brightly at infra-red wavelengths. These clumps are not yet stars, for they have not switched on the central nuclear furnaces that give a star its permanent source of energy. Astronomers call them 'protostars'. Like radio waves, infra-red can penetrate the surrounding dust, and this radiation should provide a sure guide to the presence of protostars - the 'Holy Grail' for astronomers studying starbirth.

Unfortunately, even though this radiation can travel through light-years of dark dust, and then through thousands of light-years of interstellar space, it runs into an obstacle when it meets the thin layer of the Earth's atmosphere. Water vapour and carbon dioxide in the air readily absorb the radiation. Only by working on chilly mountain tops - or, better, with telescopes in space - can astronomers study the infra-red sky. A real breakthrough came in 1983, with the Infra-red Astronomical Satellite (IRAS) - a refrigerated telescope in orbit around the Earth. IRAS surveyed the whole sky, and picked out half a million sources of infra-red.

Astronomers interested in starbirth looked eagerly through IRAS's results to find sources of infra-red that lay deep in dark clouds. There they picked out the first protostars. Further study of these is providing clues to the way in which our own planetary system was formed, and the first results indicate that planets are a natural by-product of the birth of stars, so that worlds like the Earth may well be common in the Galaxy.

Although the details of starbirth are now becoming clear, astronomers still are not sure how the interstellar material becomes compressed into molecular clouds in the first place. One possible agent is the shock from a supernova. We can see the effects of supernovae in the general interstellar medium, which has a structure rather like a Gruyère cheese. It is made up of great arcs and loops of gas that are punctuated by low-density bubbles - regions swept clean by ancient supernova explosions. Around the edges of the bubbles are denser clouds - some sufficiently compressed that stars could form within.

Supernovae can trigger the birth of stars in their own vicinity; but there is a Galaxy-wide process at work as well. According to the 'density wave theory', the beautiful pattern of the spiral arms marks a huge set of shock waves travelling around the Galaxy. Stars do not reside permanently 'in an arm' or 'between arms': as each star travels around the centre of the Galaxy in its own orbit (once every 250 million years, in the Sun's case), it passes in and out of the spiral arms.

The stars making up any particular spiral arm are, therefore, constantly changing. Although the constant interchange seems to suggest that the arm will quickly lose its identity, gravity ensures that this is not the case. The very existence of the arm means that gravity is stronger here - because of the bunching of the stars - than outside. As the stars move around the Galaxy, they are actually pulled quickly towards an arm, and then, once inside, are slowed down. Getting out of an arm is a slow business, too, against the force of the arm's extra gravity. Then it is a glide between arms before being accelerated on to the next. The net result is that a star spends longer in a spiral arm, and so at any given time more stars live in the arms than between them. The arms are density fluctuations in the Galaxy's disc where the gravity is higher. Computer calculations show that once this perturbation is set up, it will slowly propagate around the Galaxy at its own pace, preserving its spiral shape as the stars drift through the pattern.

Although the stars - as the main component of the disc - set up the spiral pattern, they are not as affected by it as is the gas in space. When the gas from the region between the arms enters an arm, it cannons into the gas already there - setting up a shock wave that compresses the gas (and the dust it contains) into the dense molecular clouds that are the sites of starbirth. That is why we find regions of starbirth strung along the spiral arms; and why astronomers can, conversely, use these regions to map out the spiral arms of the Galaxy.

There is one final region of our Galaxy that we are only just beginning to understand: the very centre. Like other spiral galaxies, the Milky Way has a large central bulge of stars that is some

25,000 light-years in diameter and 10,000 light-years thick. It is composed of old red stars which formed long ago, shortly after the collapse of the large gas cloud that formed the Galaxy. Unlike the surrounding disc, the bulge has virtually no dust and gas. Until quite recently, astronomers considered it to be an inert, uninteresting place, and its innermost regions could anyway never be seen: the dust grains in our Galaxy's disc produce more than thirty magnitudes of absorption along the way - that means that the centre is dimmed many thousands of millions of times.

Mapping the spiral structure of our Galaxy with the 21 cm hydrogen radiation back in 1957, Jan Oort was able to penetrate closer to its centre than ever before. He noticed something strange. Instead of spinning uniformly around the centre, some of the spiral arms he could detect appeared to be moving outwards - away from the centre. Intrigued, he plunged on inwards. He found several more gas clouds, some of them fragments of arms, even jets, which all shared this outward motion.

As the resolution of radio telescopes improved in the 1960s, other astronomers reported peculiar features close to the centre of the Galaxy. Surrounding the very centre, and 1,500 light-years across, there is a ring of dark clouds, rich in molecules: it is expanding at a rate of half a million kilometres per hour. Embedded in this ring are huge star-forming clouds, each ten times the size of the Orion Nebula. Inside the ring - in a part of the Galaxy not famed for its abundance of interstellar gas - is an extended region of hot hydrogen centred on the Galaxy's heart.

There are stars here in mind-boggling quantities. Although we can never see them with ordinary telescopes, infra-red astronomers, slicing through the intervening dust, report that the stars appear to be forming within a light-year of the galactic centre. Surrounding the centre is a dense cluster of a million ancient red and yellow stars, so tightly packed that the distance between neighbours dwindles from the four light-years we find in the neighbourhood of the Sun to just four light-*days*.

In the very centre of all this, there lurks a source of radio waves that is powerful but extremely small - less than the span of Jupiter's orbit about the Sun. Many astronomers believe that this core is dominated by a massive black hole, some three million times more massive than our Sun, which was created early in our Galaxy's history. Black holes are potent engines. Gas and stars that come too close are snatched, torn, swirled, heated, accelerated. The debris forms an accretion disc - a whirlpool of hot gases - that glares fiercely before its matter disappears into the black hole for ever. It is this glare that radio astronomers may be picking up from the direction of our galactic centre.

The power of an accretion disc can show itself in other ways, for example as shock waves that could drive away the surrounding gas clouds at explosive speeds. Perhaps these shocks have caused the formation of the young stars near the Galaxy's heart, and they could be responsible for the outward moving gas streams further out. By backtracking the motion of this gas, some astronomers claim that the accretion disc has had violent spasms of activity several times in the past twenty million years, presumably when a large lump of gas - perhaps a sacrificial star - has fallen into the accretion disc.

Not everyone agrees. Other astronomers point out starbirth itself is a violent process. IRAS discovered some galaxies undergoing an immense hiccup of starbirth - so intense that their output of infra-red radiation is one hundred times more powerful than their light. Although the

Milky Way is not a 'starburst galaxy' of this magnitude, perhaps a mini-starburst at its centre is responsible for most of the strange events there.

Only further research will show which idea is correct. But it is fascinating, and not a little exciting, to realise that our Galaxy, for so long regarded as a serene unchanging whirlpool of stars, has a violent secret hidden in its heart.

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Gresham College, Barnard's Inn Hall, Holborn, London EC1N 2HH
Tel: 020 7831 0575 Fax: 020 7831 5208
e-mail: enquiries@gresham.ac.uk