A Walk Around the Neighbourhood:

Understanding the Nature and Structure of the Milky Way

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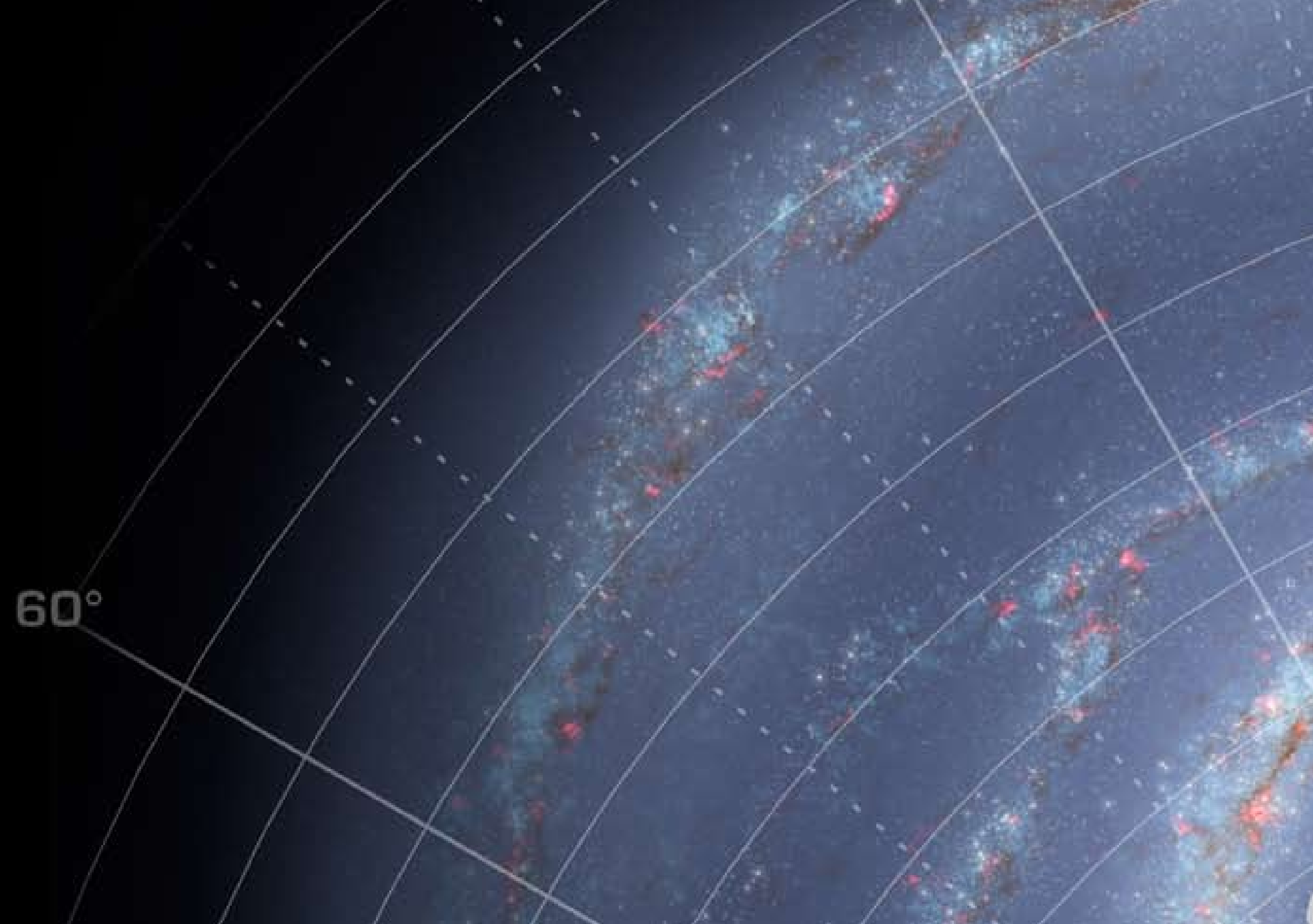

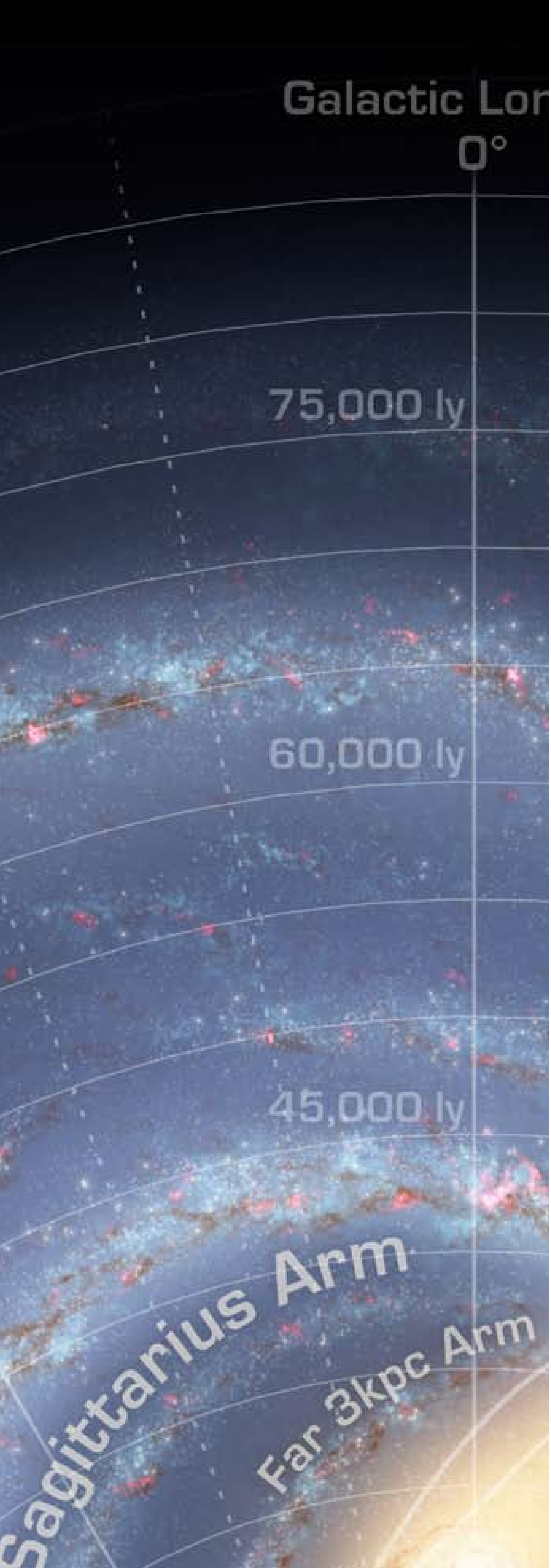

We live in a hefty spiral-patterned galaxy called the Milky Way. Though we can all see the Galaxy on a nightly basis, we know surprisingly little about our home. Some very important questions about the shape and structure of the Milky Way remain unanswered: Exactly how big is the galaxy? Where is the Sun in relation to the Galactic Centre? If we could look at the Milky Way from above what would it look like and how many spiral arms would it have? How does the Milky Way evolve and how do we interact with our neighbours? I will take us on a walk around the Milky Way revealing what we do know about the structure of the galaxy and how it lives its life. I will finish with some of the things we hope to learn in the next decade as new telescopes become available and help us solve the mysteries of our home.

One of the first things you might do upon moving into a new house is take a walk around the neighbourhood. What's around the corner? Where's the nearest shop? How far to the school? Even though we've been living in our home galaxy, the Milky Way, since the beginning of time we don't really know much about the neighbourhood. We can't go out and explore the neighbourhood because the neighbourhood is far too big. Just going to the star next door would take about 30,000 years. Instead, most of what we know about the Milky Way neighbourhood comes from astronomy and its mostly ground-based telescopes. In this chapter I will try to give you a brief tour of the Milky Way, hopefully answering questions about what the Milky Way looks like, how it lives its life, and how it interacts with some of its nearest neighbours.

The Milky Way as a galaxy

Stars are grouped throughout the universe in islands called galaxies. Galaxies take on a variety of different shapes, but many look like large pinwheels. The closest galaxy is the one in which we live, the Milky Way. Most of us are probably familiar with the Milky Way as a great band of white-ish stars stretching from horizon to horizon. On a dark night, particularly in the Southern Hemisphere, the Milky Way is the most striking feature in the sky. Figure 1 is a wonderful example of how the Milky Way looks in the night sky both in the Northern and Southern Hemispheres. Our name for this band of stars comes from the Latin name for it: "via lactea", meaning milky road or milky way. We often refer to the Milky Way by its Greek derived name "The Galaxy", which also means "milky".

Studying the Milky Way is simultaneously made easy by its close proximity and difficult because we are deeply embedded within the Galaxy. Even with years of study we are still struggling to understand the basic properties and structure of the Galaxy. We do know that the Milky Way is a rather hefty galaxy, made up of something like 200 to 300 billion stars and weighing in at about 600 billion times the mass of the Sun or a little over 1×10^{42} kg. Mass estimates for the Milky Way are based on measuring the rotational speed of the Galaxy as far out as possible and using basic laws of gravity (Kepler's Laws) to estimate the mass enclosed in the orbit.

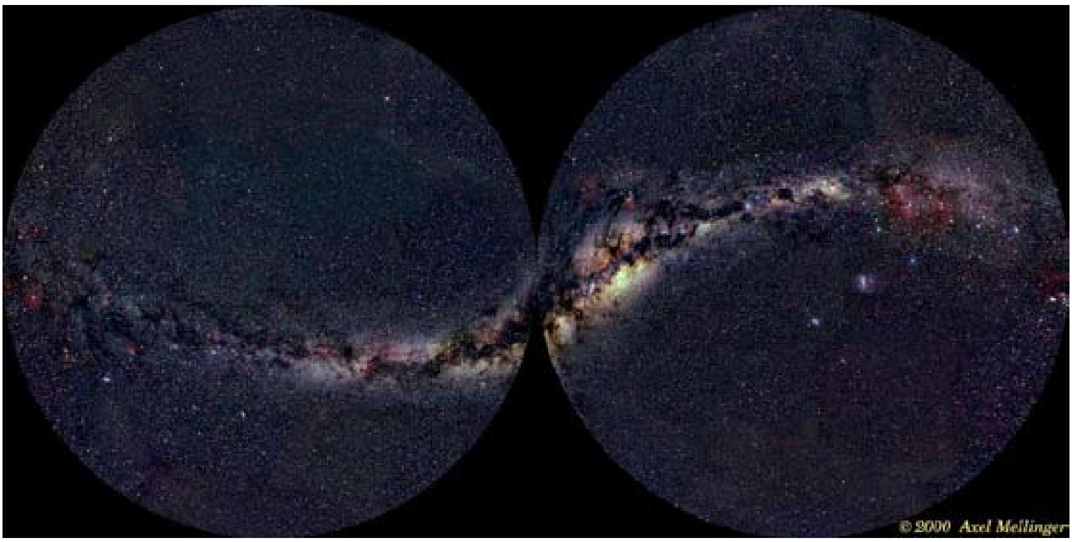

Figure 1: Images of the Milky Way in the night sky taken from both the Northern and Southern Hemispheres. The Milky Way stretches from horizon to horizon as a band of "milky" white stars and the occasional dust cloud that blocks out the starlight from behind the clouds. Also visible here are the Large and Small Magellanic Clouds as light purple spots near the centre of the right-hand image. These are some of our nearest galaxy neighbours.

Image credit: Axel Mellinger / http://home.arcor-online.de/axel.mellinger/

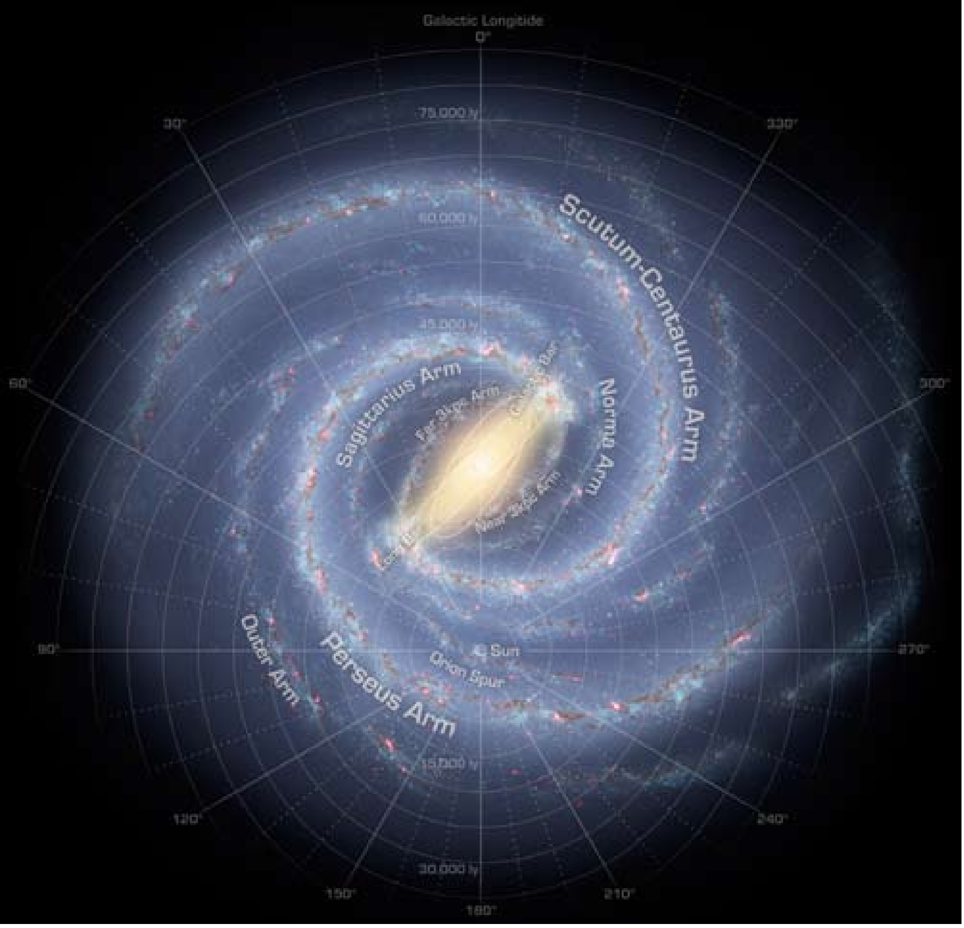

Figure 2: Artist's impression of the Milky Way as it might appear if we could fly out of it and look back down. The model used here is assembled from many pieces of information about the spiral structure and bar structure of the Galaxy. The position of the Sun is marked and most of the spiral arms are named.

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Taking measure of the Milky Way diameter is in many ways even more tricky. Most of what we know about the structure of the Galaxy more than a few thousand light-years[1] from the Sun comes from measurements made of radio and infrared radiation, which pierce through the fog of the Galaxy's interstellar gas and dust. Because the Milky Way is viewed as a relatively thin band of stars on the sky we have long known that it must be a disk-like structure. In fact, the Milky Way has dimensions somewhat like a compact disc. The stars lie in a disk of diameter about 100,000 light-years (LY) with a thickness of only about 1000 LY. Surrounding the disk is a spherical ball of mostly gas and a few stars called the halo. This halo is important to the evolution of the Milky Way as a whole and we'll come back to it later.

The Sun lies about 26,000 LY from the centre of the Galaxy, but this number has been the source of great uncertainty for the entire history of Milky Way studies. The most recent measurement, painstakingly made with one of the world's largest optical telescopes, Keck, give a value of 26000 LY with an error range of 2000 LY (Ghez et al 2008). Other reliable measurements suggest values as low as 24,700 LY or as high as 27,600 LY. Most other properties of the Galaxy's structure, including the full extent of the disk and its height depend on the Galactic Centre distance so it is crucial to measure it as accurately as possible.

We also know that the Milky Way is shaped like a pinwheel in what is known as a barred spiral-type galaxy. Each one of the arms of the pinwheel is made up of very bright, massive stars. While the space between spiral arms also has many stars, these are generally smaller and less bright. The result, if we could see the Milky Way from above, might look like the artist's impression shown in Figure 2. The number and position of these arms has been

1 A light-year is the distance light travels in one year or 9.5×10^{12} km.

very difficult to determine and the model assembled in Figure 2 is our best guess from the data available to us. The problem of determining what the Milky Way spiral structure has been likened to the problem of trying to see the forest through the trees. We can easily see the trees, but we can't walk around the forest and map it out so it is very difficult to assess what the forest, as a whole, would look like.

Some aspects of the spiral model of the Milky Way are very new. For example, it was only in 2005 through results coming out of the Spitzer Space Telescope that we realised just how prominent the bar of the Milky Way is. Measurements of old stars traced in the infrared by Spitzer revealed that the bar extends about 14,000 light-years on both sides of the centre of the Galaxy at an angle of about 45 degrees to the line between the Sun and the Centre of the Galaxy (Benjamin et al. 2005). Other new features are the most distant spiral arm, shown in Figure 2 to the bottom right. This spiral arm was discovered entirely as a gaseous spiral arm in 2004 by researchers using radio telescopes here in Australia (McClure-Griffiths et al. 2004). The arm spirals outwards from about 60,000 light-years from the Galactic centre to 80,000 light-years, putting it beyond the known extent of the disk of stars in the Milky Way. If we could see the arm in visible light on the sky we would see it traced through 70 degrees of angle on the sky.

The components of the Milky Way: stars, gas, dust, magnetic fields

The Milky Way that we see in the night sky is dominated by stars. However, there is much more to the Milky Way than the stars. Stars make up the bulk of the mass of the Galaxy, but gas and dust between the stars play important roles in the evolution of the Galaxy, including the formation of new stars. About 5% of the mass of the Galaxy is in the form of the gas and dust between the stars, the interstellar medium (ISM). Of that, almost 9 out of every 10 particles (atoms or molecules) are hydrogen. Hydrogen is the lightest element there is, so if we were to count by mass, about 40% of the mass of the ISM is atomic hydrogen. The rest of the ISM is made up of progressively heavier elements and even molecules like Carbon Monoxide, Ammonia, Formaldehyde, etc. In the densest areas of the ISM, complex molecules, referred to as dust, exist. It is this dust that forms the dark patches along the Milky Way that we view in the night sky. These complex molecules block the light from stars behind them and make dark constellations.

The ISM is a varied place. The gas has densities varying from 0.001 atoms per cubic centimetre up through "dense" regions with 1 million atoms or molecules per cubic centimetre. And while these so-called "dense" regions have a lot of matter for interstellar gas, they are still much less dense than most things on Earth. Air at sea level, for example, has a density of about 10^{19} molecules per cubic centimetre. That's thirteen orders of magnitude more dense than a dense area of interstellar space! Even the best vacuum that we can produce on Earth results in about 10^{10} molecules per cubic centimetre. Not only does the density vary, but the temperature also varies to keep roughly in step with the density so that there is equal pressure in most parts of interstellar space. The relationship between pressure, P, the density, n, and the temperature, T, is given by the familiar gas law: $\mathbf{P=nkT}$, and k is Boltzmann's constant. For example, in regions where the density is about 1 atom per cubic centimetre the temperature is about 5000 degrees and in areas where the density is 0.001 atoms per cubic centimetre the temperature is nearly one million degrees.

The ISM isn't static, either. The gas within the galaxy is constantly in motion. All of the gas in the Galaxy rotates about the centre of the Galaxy. This rotation is caused by tight orbits around the mass contained within the orbit. Near the Sun the rotational speed is 220 km/s or 792,000 km/hr! On top of that there are small-scale motions that move gas about with velocities of up to 1000 km/s.

While the stars act like the rock of the earth, the gas acts like the atmosphere for the Galaxy. It is through the gas that information about temperature and pressure – Galactic weather systems – are conveyed from one place to another. So how do these weather systems develop? We'll discuss that in the next section when thinking about how the Milky Way lives its life.

How Does the Milky Way Live its Life?

The formation and evolution of galaxies like the Milky Way is a topic of current study. How do the bits and pieces of cold gas left floating around the Universe come together to form a galaxy? What influences how galaxies live their lives? Although we don't have clear answers about how the Milky Way formed, there has been enormous progress in the past few years on studying how the Milky Way lives its life. It is the interstellar gas that largely controls the lifecycle of the Milky Way. After all, it is from the gas that stars form and it is to the gas that the stars return when they die. We know that most stars are formed in clouds of molecular gas, which are the densest areas of interstellar space. It is only in these dense areas that enough matter can accumulate in a small enough area for gravity to pull it together in a tight ball so that nuclear fusion can ignite the gas as a star. The topic of how exactly stars form is an interesting one and one that dominates a great deal of astrophysical research, but we'll leave that topic for another day. Right now, we'll focus just on how gas cools and condenses to form molecular clouds, what disrupts gas in the Milky Way and whether that gas flows in or out of the Galaxy.

Disrupting Interstellar Gas

The basic cycle of life and death in the interstellar medium is shown in Figure 3. Most of interstellar space is filled with diffuse (density of 1 atom per cubic centimetre), warm (temperatures of ~5000 K) atomic hydrogen. This gas is disrupted by a variety of forces and interstellar processes.

The first process we discuss disrupts the gas on scales of tens to thousands of light-years.

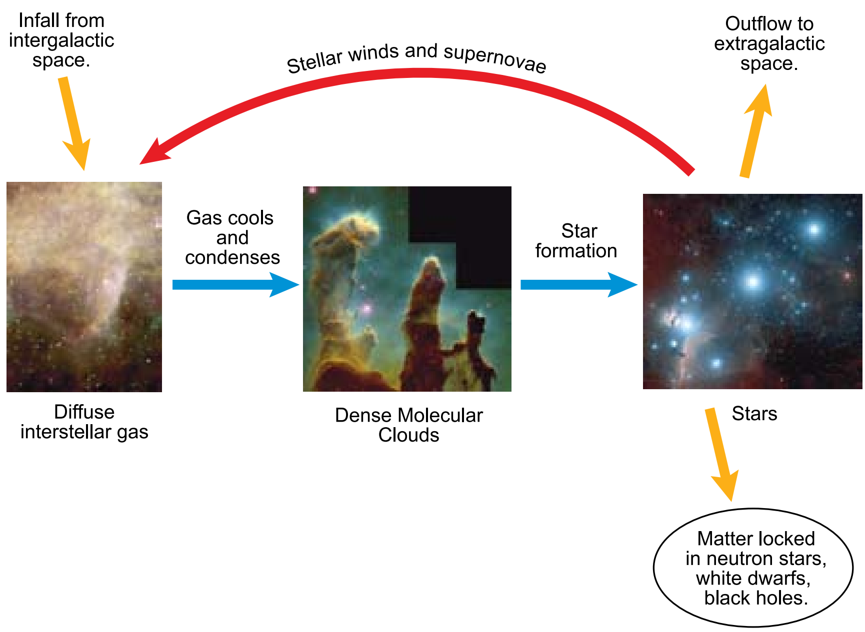

Figure 3: Cartoon diagram of the evolution of gas in the interstellar medium. This diagram shows how gas moves through its various stages, such as diffuse interstellar medium to molecular clouds and on to stars and what processes effect how the gas makes these transitions. Blue arrows represent processes where gas must cool and red arrows represent processes that can heat the gas.

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This takes the form of energetic outflows associated with massive stars. Massive stars are usually classified as stars more than about eight times the mass of the Sun. Massive stars have a particularly powerful effect on diffuse gas both through their stellar winds and also the supernova explosions that mark the end of their lives. All stars blow a wind of protons and electrons off their surface, pushed outwards by the enormous pressure of radiation from the star. For stars like the Sun this wind is reasonably benign, and the Earth's magnetic field is enough to mostly shield the surface of the Earth from its effects. Massive stars, though, are quite a lot more powerful! These stars have stellar winds that move one-millionth the mass of the Sun per year outwards at velocities of up to 1000 km/s. Massive stars live relatively short lives, only lasting 100 million to 1 million years depending on their mass, but over the course of their lives they will blow out 10^{38} Mega-Joules (MJ), or 10^{37} kWh, of energy. To put that in perspective, an atomic bomb blast carries 10^{8} - 10^{11} MJ of energy and the average Australian household consumes about 85 MJ each year. The extraordinary energy output of stellar winds has a huge impact on the diffuse interstellar gas, by heating, ionising and displacing it. Stellar winds around a small number of stars effectively blow bubbles into the interstellar gas, creating so-called "stellar wind bubbles". Figure 4 shows a stellar wind bubble around the star complex, RCW 79, which is about 70 light-years in diameter and filled with hot gas from the stars that blew the bubble. The bright rim of the bubble is made mostly of dust that glows in the infrared after being excited by the ultraviolet radiation coming off the stars in the centre (Churchwell et al 2006).

Figure 4: Stellar wind bubble blown around the massive star complex RCW 79 as imaged by the Spitzer Space Telescope's GLIMPSE project. The bright red rim is made mostly of interstellar dust that glows in the infrared. The object has a diameter of about 70 light-years and was probably formed over the course of about 1 million years.

NASA/JPL-Caltech/E Churchwell (University of Wisconsin-Madison)

After a lifetime of blowing powerful stellar winds, massive stars end their lives in spectacular supernova explosions. These explosions take only a matter of minutes but during that time the star expels the majority of its mass, leaving behind a neutron packed core or sometimes a black hole. The expelled matter flies outwards from the star at velocities up to 10,000 km/s carrying another 10^{38} MJ of energy into the diffuse interstellar gas. The gas immediately surrounding the supernova is heated to millions of degrees and ionised before it starts moving outwards like a gigantic snowplow sweeping up all of the gas in front of it in a wall of rapidly moving and condensing gas. These supernova driven snowplows can push for ten thousand years or more. Because massive stars tend to live in groups together the interstellar medium can feel the effects of several hundred massive stars whose stellar winds and supernovae have evacuated regions up to a thousand light-years across, called superbubbles or supershells. An example of a gigantic supershell is shown in Figure 5. This image shows diffuse atomic hydrogen gas in the interstellar medium where the dark region in the centre is the largely evacuated supershell spanning almost 2000 light-years (McClure-Griffiths et al 2003).

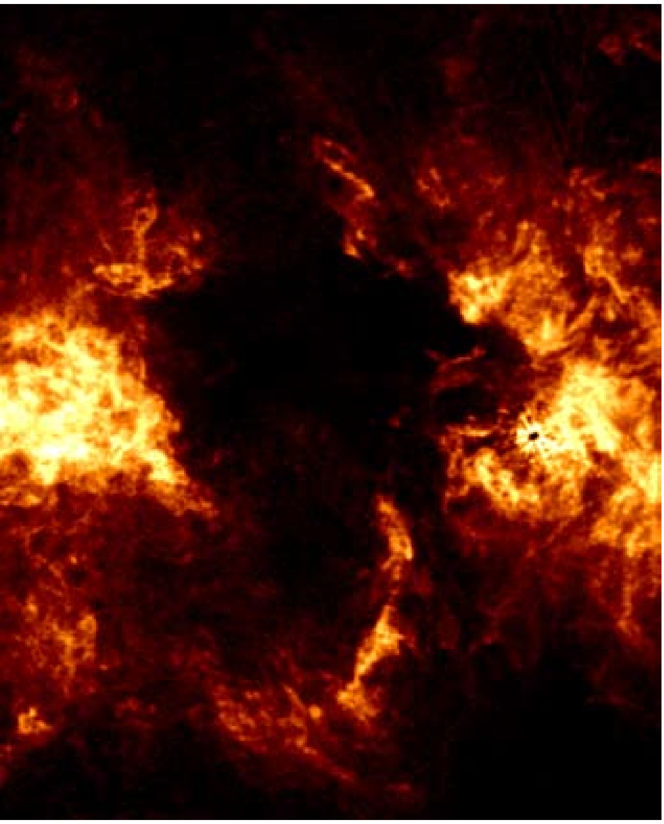

Figure 5: Gigantic supershell GSH 277+00+36 imaged shown in diffuse atomic hydrogen emission. The bright areas are where gas has been swept up by hundreds of stellar winds and supernovae leaving a largely evacuated cavity (dark black) in the centre. The cavity has a diameter of nearly 2000 light-years.
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Through the actions of stellar winds and supernova explosions massive stars are good recyclers. Most of their mass is expelled back into the interstellar medium where it can be recycled into new stars. Nothing in space is a perfect recycler, though. A small fraction of the mass of the stars remains irretrievably locked up in the form of neutron stars and black holes. This locked-up mass has important implications for the lifecycle of the Galaxy so we'll come back to it later.

Condensing Interstellar Gas

In order to complete the recycling of expelled interstellar matter into stars the ordinary diffuse matter needs to become dense molecular clouds. We know that stars are formed in molecular clouds. So in order for stars to form it is critical that the diffuse matter that fills most of interstellar space must first condense to form molecules and large molecular cloud complexes. On the largest scales, gas is condensed by the spiral pattern of the Galaxy that moves like a wave through the disk. In the same way that waves move through the ocean, very large waves move in a spiral pattern through the disk of the Galaxy. These waves are responsible for the pinwheel or spiral pattern that we infer for the Milky Way and see in many other galaxies. At the crests of the spiral waves the ordinarily diffuse gas is compressed to form the giant molecular cloud complexes and eventually the very bright, massive stars that are characteristic of spiral arms in galaxies. These spiral waves operate on the scale of the Galaxy – that is many thousands of light-years.

Bubbles and superbubbles like those described above are also important in sweeping together enough gas to form molecular clouds. The powerful snowplow action of an expanding superbubble can increase the density of the interstellar gas from the one particle per cubic centimetre to at least several thousand particles per cubic centimetre and that may be enough for gravity to take over and pull together even more matter to make a dense molecular cloud. Recent observations suggest that this process is indeed happening in both of the objects shown in Figures 4 & 5. New stars have already formed out of the molecular material swept up along the edges of the bubble shown in Figure 4 (Churchwell et al 2005) and along the walls of the object in Figure 5 there are small molecular clouds. We assume that it is only a matter of time before these form stars.

Gas moving into and out of the Galaxy

Another key part of the Milky Way lifecycle is how gas moves into and out of the Galaxy. The Milky Way is not a closed box – there is a constant outflow of material and this is more than compensated for by a constant influx. The question of how gas escapes the disk of the Galaxy has been a long-standing topic of research. Basic calculations show that given how much gas lies in the Galactic halo above the disk, if there weren't significant outflow to push up against the halo it would collapse onto the disk under its own weight. And yet, there is no evidence that the halo in the Milky Way – or in any other galaxy – is collapsing. So what is holding the halo up? One source of outflow for the Milky Way is the very superbubbles that we discussed above. Superbubbles around many massive stars can grow very large indeed. In fact they can grow so large that their diameters exceed the thickness of the Galaxy. Once a supershell becomes ~2000 light-years across it finds itself expanding into a much less dense medium and its expansion effectively runs away. The situation is very similar to an atomic bomb explosion; as long as the explosion is expanding outwards close to the surface of the Earth the explosion pathway is roughly spherical. However, as the explosion continues to expand upward in the Earth's atmosphere it encounters less and less material to push against and is able to push faster in that direction. This leads to the 'mushroom clouds' that we associate with atomic blasts. An expanding superbubble extending into the Galaxy's atmosphere displays the same sort of behaviour, sometimes forming a 'mushroom cloud' or at the very least breaking open with channels leading away from the Galactic disk to the halo.

Examples of both types of objects are visible in the Milky Way. Figure 6 shows a classic mushroom cloud object of atomic hydrogen gas from the Northern Milky Way, which may have been formed through stellar winds and supernovae in the disk (English et al. 2. The object shown in Figure 5 and discussed above is the other type of large superbubble where the 'mushroom cap' is not visible but the object definitely breaks into multiple (one at the top and two below) dark channels that lead up to the halo of the Galaxy. This latter type of object is often called a "chimney" because the hot gas filling the interior of the superbubble can vent out the chimneys created by the breaking superbubble. This flow of hot gas is absolutely essential for supporting the halo against collapse under its own weight. The vented gas also supplies a

Figure 6: A mushroom-shaped cloud of hydrogen poking ~1000 lighyears out of our galaxy may have been formed by exploding stars.
Jayanne English et al/U Manitoba/CGPS

source of heating and distributes gas enriched by supernovae around the Galaxy. Calculations show that we need dozens of chimneys to support the Milky Way halo. In recent years there have been a number of searches for these chimney-like objects but the number of known chimneys can still be counted on one hand. So either another process must help provide support for the halo or our observations are missing many chimneys.

You might worry that if gas is flowing out of the disk of the Galaxy like air out of a leaking tyre that the Milky Way would eventually run out of gas. In fact, the situation is even worse than that. Not only is gas leaking out of the disk but also matter is continually locked into a non-gaseous state in the neutron stars, black holes and white dwarfs that mark the end of stars' lives. So, if gas is leaking out of the disk and more gas is locked away in an irretrievable state how does the Milky Way continue to have gas enough to form stars? The answer to that question is something that drives a great deal of modern Milky Way research. We can perform some very simple calculations that show that the rate at which new stars are formed in the Milky Way should have exhausted all of the interstellar gas and star formation should have ceased long ago. And yet, we know that this is not true as we observe gas in the present-day Galaxy and continuing star formation. This gas supply problem is not solved but there are some indications that there is a slow trickle of gas from extragalactic space and the Galactic halo itself that makes it way on to the disk to feed our gas hungry Galaxy.

The gas flowing into the Galaxy takes several forms. One form are so-called "high velocity clouds", which litter the Galaxy's halo and get their name because they are moving quickly with respect to the Galaxy. These clouds of cool hydrogen were discovered in the 1960's and it was immediately realised that they might be a potential source of gas influx. Despite that, it has taken many years to find clear examples of high velocity clouds interacting with the Milky Way. One of the nicest recent examples is shown in Figure 7, which is of a large cloud of cold hydrogen called Smith's Cloud that is on a collision course with the Milky Way. Smith's Cloud is 11,000 light-years long and 2,500 light-years wide. At present it is only 8,000 light-years from the Milky Way disk and moving towards the disk at more than 240 km/s, aimed to strike the Milky Way's disk at an angle of about 45 degrees. The cloud contains enough hydrogen to make a million stars like the Sun; so it is clear that objects like these have a role to play in keeping the Galaxy well fed (Lockman et al. 2008).

You may be wondering where hydrogen clouds like Smith's Cloud come from. For clouds as massive as this there are two main hypotheses: first, that they are left over from the formation of the Milky Way and second, that they have been pulled off nearby galaxies that interact with the Milky Way (see Wakker & van Woerden 1997). The first hypothesis works with the idea that the Milky Way came together from many smaller building blocks, put together something like Lego. The building blocks are gravitationally attracted to a central mass and as they fall in they start spinning, which gives our Galaxy its rotation. Invariably

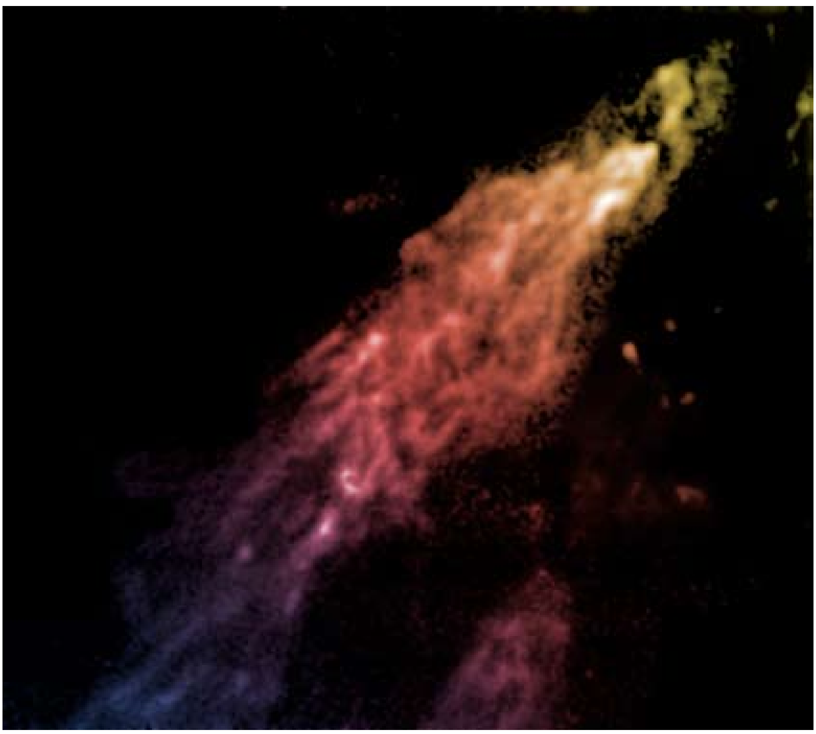

Figure 7: Hydrogen gas in the high velocity cloud, Smith's Cloud. The comet-like shape indicates the cloud's direction of motion, which is inclined at about 45 degrees to the disk of the Milky Way. The cloud is travelling at more than 240 km/s and will collide with the Galaxy in about 40 million years.

Courtesy: Bill Saxton/NRAO/AUI/NSF

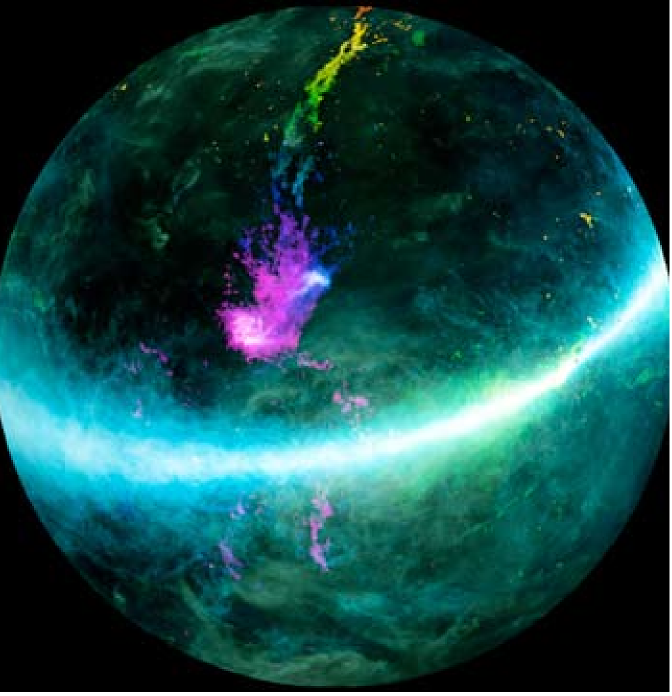

Figure 8: Atomic hydrogen gas in the Southern sky showing the Magellanic Stream as the almost vertical band in blue through orange at the centre of the image. The Magellanic Stream trails behind the Large and Small Magellanic Clouds presumably pulled off these low mass neighbouring galaxies by the intense gravitational force of the Milky Way.

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not all of the building blocks come together at once and some are left to trickle into the Milky Way over time. Some high velocity clouds are almost certainly of this origin.

The second origin for high velocity clouds is that large chunks of gas are stripped off other galaxies as they pass near the Milky Way. This is also known to occur. One excellent example is the Magellanic Stream, shown in Figure 8 on an image of the Southern sky in hydrogen gas. The Magellanic Stream is the long vertical stripe of gas running from blue through to orange down the centre of the image. This gas is stripped off the Large and Small Magellanic Clouds, which are small galaxies neighbouring (about 150,000 light-years away) the Milky Way. Each galaxy has a mass of 1/10 (or less) the mass of the Milky Way so as they pass near the Milky Way our Galaxy steals material from them, which streams behind their direction of motion like the tail of a comet. This stripped material slowly makes its way onto the disk of the Galaxy to feed its star formation habit.

Another form of gas influx is from matter condensed directly from the halo. As we discussed above, chimneys can expel hot gas from the disk up into the Galaxy's halo. Most of this gas doesn't escape the Galaxy's gravitational field so it remains in the halo floating around for millions of years. Over time the gas may cool and as it does, gradually condense much like raindrops, before it falls back onto the Galactic disk (Shapiro & Field 1976). The direct evidence for this activity is very difficult to come by, but nonetheless we assume that it must be happening at least to some degree in the Milky Way.

All of these methods: gas leftover from the formation of the Milky Way, gas stripped off nearby galaxies, and cooling halo gas can provide some gas influx for the Milky Way. However, if we add up all of the cool gas we observe in the halo of the Milky Way we find that there still is not enough to fully feed the star formation of the Milky Way over its history (Putman 2006). Clearly either the influx rate was much higher in the past, which is unlikely, or we are missing some gas. Current research is underway to discover the "missing" gas.

What are the big remaining mysteries and prospects for future discovery?

The structure and nature of the Milky Way are far from completely understood. There are a number of big mysteries that remain about the Galaxy's structure and how it operates. For example, we still don't have a very good idea about how many spiral arms there in the Milky Way and exactly where they are. The map presented in Figure 2 is our current best guess, but most Milky Way researchers would argue that a lot of work needs to be done to convince ourselves that this is a valid guess. Even relatively simple things like the distance to the centre of the Galaxy are still being refined with recent changes of up to 10%. More difficult questions like, where exactly is the edge of the Milky Way disk are very much up in the air. On the topic of the nature of the Milky Way there are many things that we still don't understand. Some of these we have identified here, such as: how do molecular clouds form from diffuse atomic gas? Where are all of the chimneys that are needed to hold up the halo? Where is the missing mass of the Galactic halo that is needed to continue to fuel star formation in the Milky Way? And lying at the heart of many questions about the life of the Milky Way is the role of magnetic fields, which we have not discussed at all here. The Milky Way is threaded with a magnetic field, much like the Earth is threaded with a magnetic field. We believe that the magnetic fields of the Milky Way control how gas moves around, how molecular clouds form, even how stars form, but we know very little about this elusive component.

The future is bright for a better understanding of the Milky Way. The next fifteen years will see a variety of new telescopes, each one very well suited to answering some of the big questions about the Milky Way. In just a few years time we will see the Atacama Large Millimetre Array start operating in Chile, adding answers to the key questions of how molecular clouds form and how stars from these clouds. In Australia we hope to host Square Kilometre Array by 2020, which will be able to get at those elusive magnetic fields amongst many other things. Space based telescopes will measure distances to tens of thousands of stars giving us a much better idea of the Milky Way spiral structure. And finally Extremely Large optical telescopes will be built in the next decade with the hope of being able to explore in other galaxies the processes that we can see in the Milky Way. The next fifteen years will hopefully bring about a revolution in our understanding of the Milky Way!

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