
GALAXY
MAPPING THE COSMOS
JAMES GEACH

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The bright band of the Milky Way glows over Chajnantor Plateau in the Chilean Atacama, home of the Atacama Large Millimetre Array (ALMA). We are embedded within a great disc of stars, our cosmic habitat, which can be seen in this long-exposure image that includes a view of the dense, central bulge of the galaxy. Dark patches along the bright band betray the presence of obscuring interstellar dust, blocking out the light from stars behind.

ONE

Cities Beyond

Imagine standing on a tall hill on the outskirts of a great city. Around you is a scattering of isolated settlements, sometimes nestled together into quiet hamlets. Looking citywards, laid out before you is a vast, glittering labyrinth of streets, parks and high-rises: a dense and sprawling conurbation, focused on a distant hub of glistening skyscrapers. But the most striking thing about this metropolis is its silence: you don't see another soul or hear any sirens; there is no distant urban murmur. The city appears to be eerily dormant. Yet it's all almost within reach, waiting to be explored. But for now you are isolated, marooned in the suburbs, and all you can do is gaze and wonder at the complexity and richness just beyond.

Turning your back on the city before you, the vista gives way to an expanse of flat, open country, stretching away to the horizon. Save for the occasional outlying village and town clinging to the suburbs, the city seems to be alone in an empty land. But the distant expanse lures your gaze. You strain your eyes, and see that there are a number of faint glints on the horizon. There are more in every direction you look, and you come to realize that the city is not alone, that the world must be much bigger than you thought, and that there might be other cities just like yours.

So it is with our own galaxy and other galaxies in the universe. This is a book about those galaxies: what we know and what we don't yet know. We live in *a* galaxy, of which the Earth, Sun and solar system are just a minute component, but the universe is teeming with other galaxies of different sizes and shapes. Our best estimate is that there are something like 200 to 500 *billion* galaxies in the universe. As we will see, many galaxies are like our own, but others are very different. The goal of an extragalactic astronomer is to understand how those galaxies came to be.

Perhaps the most extraordinary thing about galaxies is not the galaxies themselves, but the tremendous distances between them. In fact, only rather recently did humans determine that galaxies were self-contained entities separated by vast gulfs of space. Since this discovery, our understanding of galaxies, their formation and evolution has accelerated at an astonishing rate, so much so that we can now perform – and, more importantly, interpret – the most extraordinary experiments and measurements. We can detect the ripple-like fluctuations encoded in the relic radiation from the Big Bang that represent the very seed points for galaxy formation; we can observe the explosive deaths of stars in far-flung galaxies and track their fading brightness to provide information on the overall evolution and fate of the universe, as well as the evolution of the galaxies themselves; and we are now gearing up for experiments that aim to measure the cosmic signature of the moment that the very *first* stars formed in the first galaxies. We will touch upon some of these themes.

It is often said that we are in a golden age of research into the origin, evolution and fate of galaxies. It's remarkable to think that we, as a species, have only just become properly aware that other discrete star systems exist beyond the local collection of stars we call the Milky Way. Just as the stars you see in the night sky are almost unimaginably distant from the Earth, so the external galaxies are unimaginably distant again from the Milky Way. This is a view of the universe that was only experimentally confirmed in the early years of the twentieth century.

At first, we charted the galaxies nearest to us: the ones that, by virtue of their proximity, loom relatively large and bright in the sky. Aided by technology, and pushed forward by a deep, driving desire to understand the universe, a century later astronomers have now surveyed millions of galaxies, mapped their distribution in space, analysed their contents and measured their motions. We can now detect galaxies billions of times fainter, and in frequencies of light orders of magnitude beyond the biological capabilities of the human eye, the tool our ancestors relied on when our species first became curious about the contents of the sky.

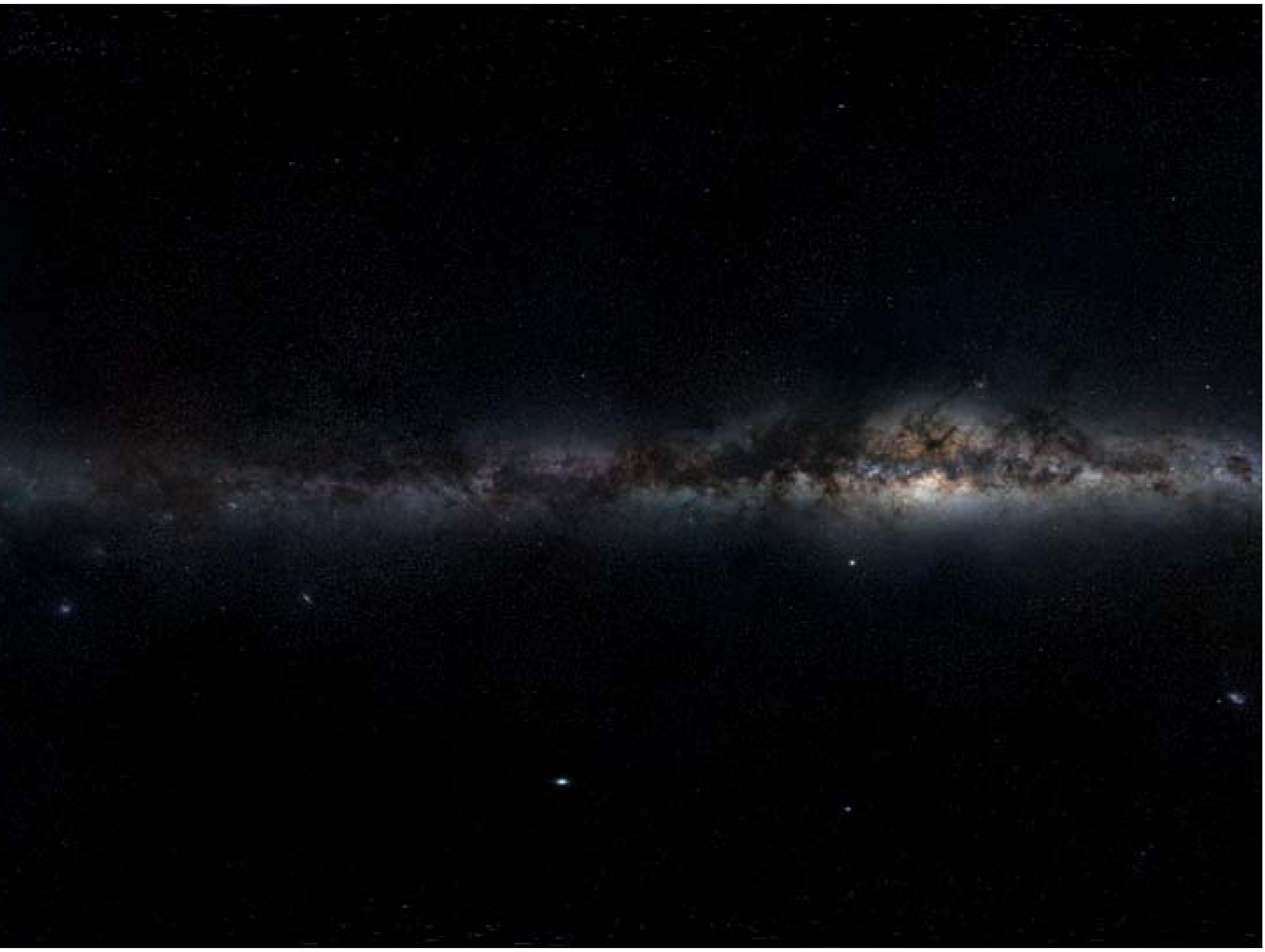
But what is a galaxy? What are galaxies made of? How big are they? How did they form? Why are there different types and how have they changed over time? These simple questions form the bedrock of the field of galaxy evolution. We will explore these questions over the course of this book, but one thing that needs to be made clear right away is that many of these questions are still being answered. There are many mysteries waiting to be solved. That is what makes this field the most exciting in astronomy, and perhaps in all of science. There is the feeling of the frontier about it. I will try to bring you not only the cutting edge of observations and theory, but also an insight into the nuts and bolts of astronomical research. How is it done, what tools do we use and what do astronomers actually do day to day? To begin this journey, let's start at home, and the city before us.

Via Lactae

Look up into the sky on a clear, dark night, preferably when there is a new (that is, no visible) moon, and you are far away from any urban glow. Be patient. It takes a few minutes for your pupils to dilate, becoming better accustomed to the darkness and more adept in soaking up the faint illumination coming from beyond the atmosphere. Now use your eyes to scan from horizon to horizon. You will notice that the density of stars increases, and the sky brightens slightly, in a band that stretches across the sky. You are looking into the dense, starry plane of our galaxy, dubbed *Via Lactae* – Milky Way – by the first classical astronomers. We have taken our first step into galactic astronomy. The stars 'above' us are not distributed haphazardly in space, but organized into an ordered structure. In the case of our galaxy, that structure is a disc within which we are embedded. That glowing band you see is the light from billions of stars that the eye cannot resolve individually, but combined en masse into a diffuse glow, which is brighter where the disc is denser. If you look towards the constellation Sagittarius, you are peering into the very heart of the galaxy, the densest concentration of material: a bulge of stars that sits at the hub of the great disc.

Crossing the Milky Way at an angle of about 60 degrees, you may see another faint band of light, emanating from the horizon where the sun has just set, or is about to rise. This time we are seeing light emitted from another plane: the ecliptic, or orbital, plane of our solar system. This is called zodiacal light: sunlight scattered off myriad rock and dust particles trapped in the disc of the solar system. The angle of the ecliptic relative to the starry band of the Milky Way reflects how the orientation of the orbital plane of the solar system is tilted relative to that of the galaxy. A plane within a plane.

Our solar system is located about two-thirds of the distance from the hub of the galaxy to the outer edge, well away from the densest concentration of stars at the centre. The disc is not completely flat, so when we look in *any* direction away from the Earth we see the relatively nearby stars above



A panoramic image of the Milky Way in visible light, clearly showing the disc and bright (but partially dust-obscured) bulge. Ours is a large spiral galaxy.

and below and all around us. Although they are all at different distances from the Earth, to our eyes the stars appear to be stationary points of light of various brightness on the inside of a huge sphere that surrounds the Earth. Indeed, this was the picture astronomers had for many years: these were 'fixed stars' on the 'celestial sphere'. Actually, on closer inspection, many stars actually appear to move across the sphere by small, but easily measurable, amounts, and we say that these stars have 'proper motion'. This is because they really are moving rapidly in space, and the signature of this is a year-on-year change in position on the sky that can be tracked with careful observation. For the casual observer, and on a human time-scale, stars generally do indeed appear fixed, but if you were to go to sleep and reawaken in a few million years' time, the constellations you would see would look different from the way they do today. The galaxy, and its contents, are in motion.

What the human eye cannot reveal is the three-dimensional distribution of the stars: they are scattered at various distances from us throughout space, not on the surface of some thin shell surrounding the Earth, as was once thought. It's important to note that most of the constellations are not physical associations of stars, but chance alignments of stars at different distances that happen to form recognizable patterns to us. An astronomer on a distant planet in some other region of the Milky Way would see a different set of constellations.

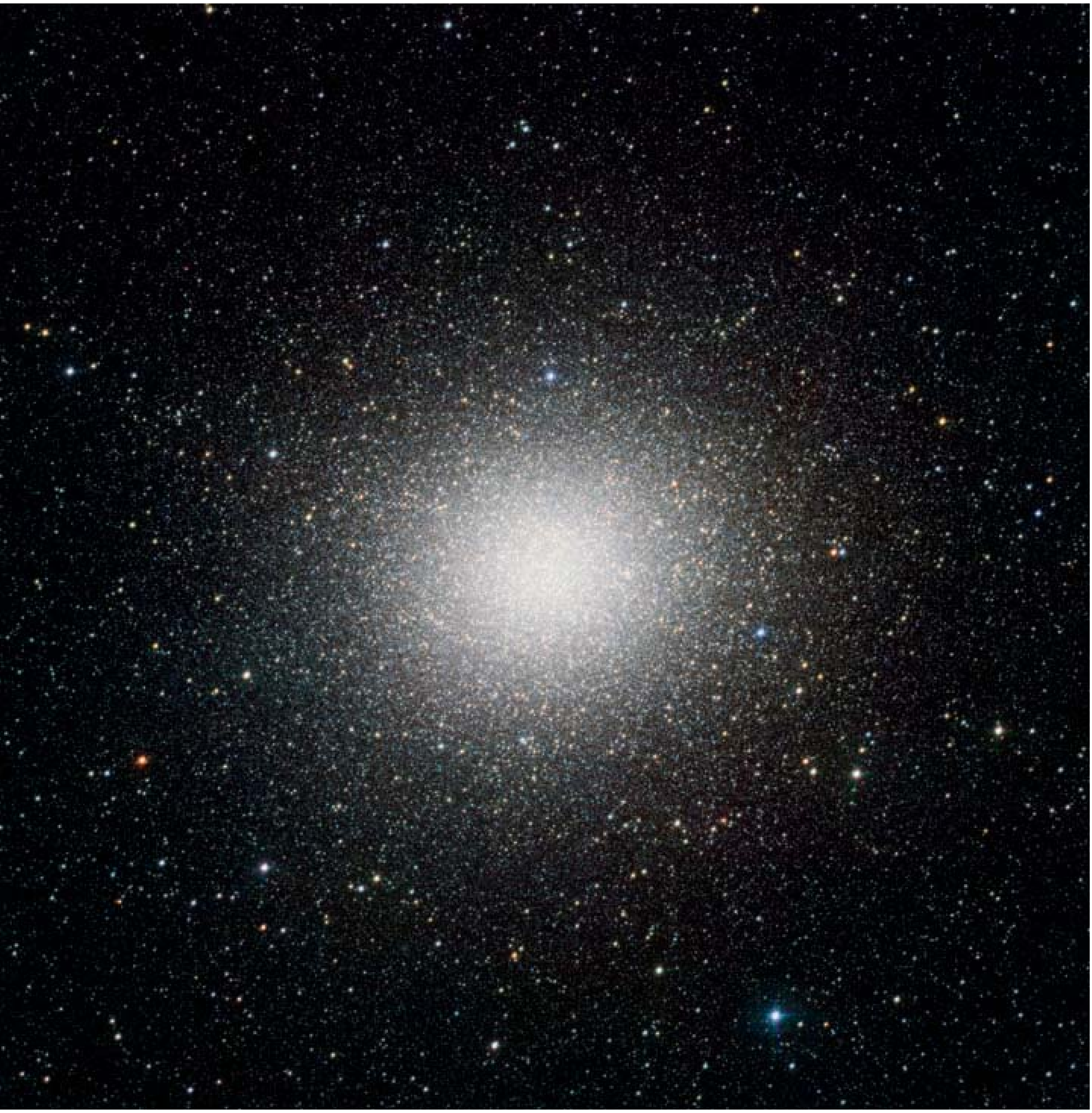
Some collections of stars *are* physically associated with each other. Binary systems are two stars in orbit around each other, and appear as a close pair on the sky, often so close that it is hard to separate them by eye, or with one star much brighter than the other, drowning out the companion (the bright star Sirius is an example of such a system). A large fraction of the stars in our galaxy are in binary systems. There are also larger groupings of stars, called clusters, which form because many stars can be born in the same place, bursting into life from the collapsing clouds of gas that are the crucibles of stellar matter in galaxies. A famous example is the Pleiades cluster, also known as the Seven Sisters, in the constellation of Taurus. The stars in the Pleiades formed fairly recently, are extremely luminous and in relatively close proximity to each other, making the Pleiades easily visible to the naked eye.

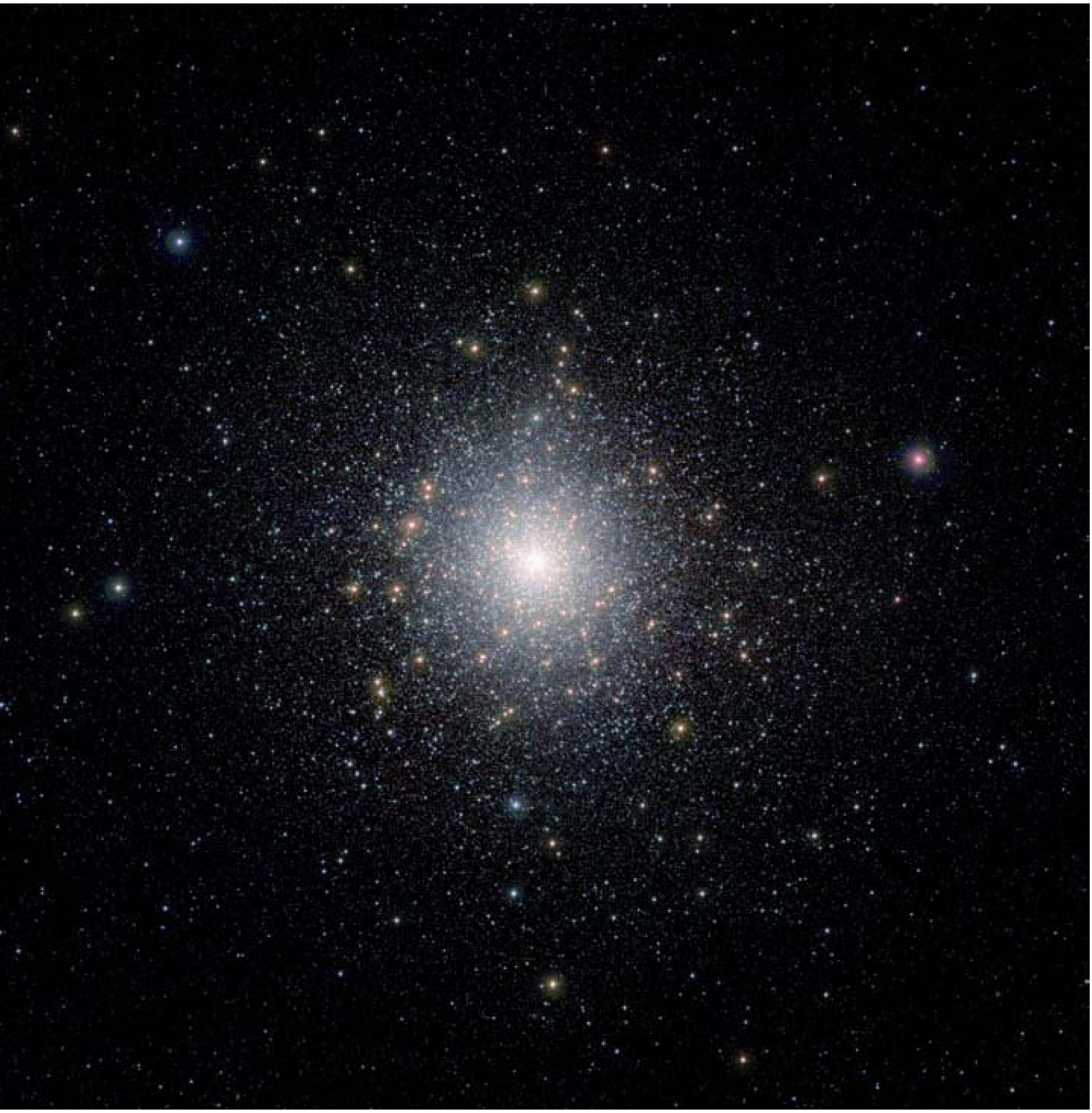
Scattered around the disc of the Milky Way, in an environment called the 'halo', we also find very dense balls of stars called globular clusters. Globular clusters contain hundreds of thousands of stars and are quite mysterious objects. The stars in each ball are held together by gravity, and the globular clusters themselves are gravitationally bound to the Milky Way, zipping about like flies around a dinner plate. The formation of globular clusters is still quite poorly understood, but they represent some of the oldest components of the galaxy, and therefore hold valuable clues about the formation of the Milky Way, and indeed other galaxies. A small telescope or binoculars will reveal some of the famous globular clusters, and they are among the most spectacular galactic sights.

The largest globular cluster in the Milky Way, Omega Centauri, a collection of 10 million stars in the 'halo' – the environment surrounding the disc – of the galaxy. There are about 200 known globular clusters in our galaxy, and they represent some of the oldest galactic components, although their origin is unclear. Omega Centauri might be the remnant of a dwarf galaxy that was accreted onto the Milky Way in the past. As such, it provides archaeological clues to the history of the formation of our galaxy.

The three-dimensional positions of the stars near to the Earth have been mapped using one of the oldest methods of distance measurement in astronomy: parallax. It's worth quickly explaining parallax, because the definition neatly provides us with the basic unit of measure for professional astronomers, the parsec. We will refer to the parsec later on when exploring the vast scales of the other galaxies. It's not complicated: it's just a unit of measure encompassing a very large number of metres that would be too cumbersome to write down longhand, just as we don't measure car journeys in centimetres.

Close one eye and focus on the tip of your thumb held at arm's length. Now open the closed eye and shut the other. It looks as though the position of your thumb has changed relative to the background. This is parallax, and is simply the shift in the apparent position of an object when viewed along different sightlines. By knowing the difference in position of viewpoints, in this case the distance between your eyes, and the shift in *apparent* position of the target object, we can work out the actual distance via some simple trigonometry. Your brain is doing this constantly, and is in part what gives us depth perception. We don't notice depth in the star field the same way that we do in our local environment because all the stars are so far away that apparent changes in their positions are tiny. The trick *can* be done with stars, but for astronomical parallax measurements, we require much longer





separations of our sightlines and excellent, high-precision measurements of the stars' positions on the sky. As it turns out, nature has handed us a simple technique to do just this. Every six months we all change position by 300 million kilometres when the Earth is on the opposite side of the Sun during its annual orbital path. By observing the position of some distant star once, then repeating the measurement six months later, we can pull off the same thumb trick: the position of our eyes has changed. Of course, you don't have to wait the full six months, but this will give the longest possible baseline and the most accurate measurement of apparent displacement, and therefore the most accurate measurement of distance using this method.

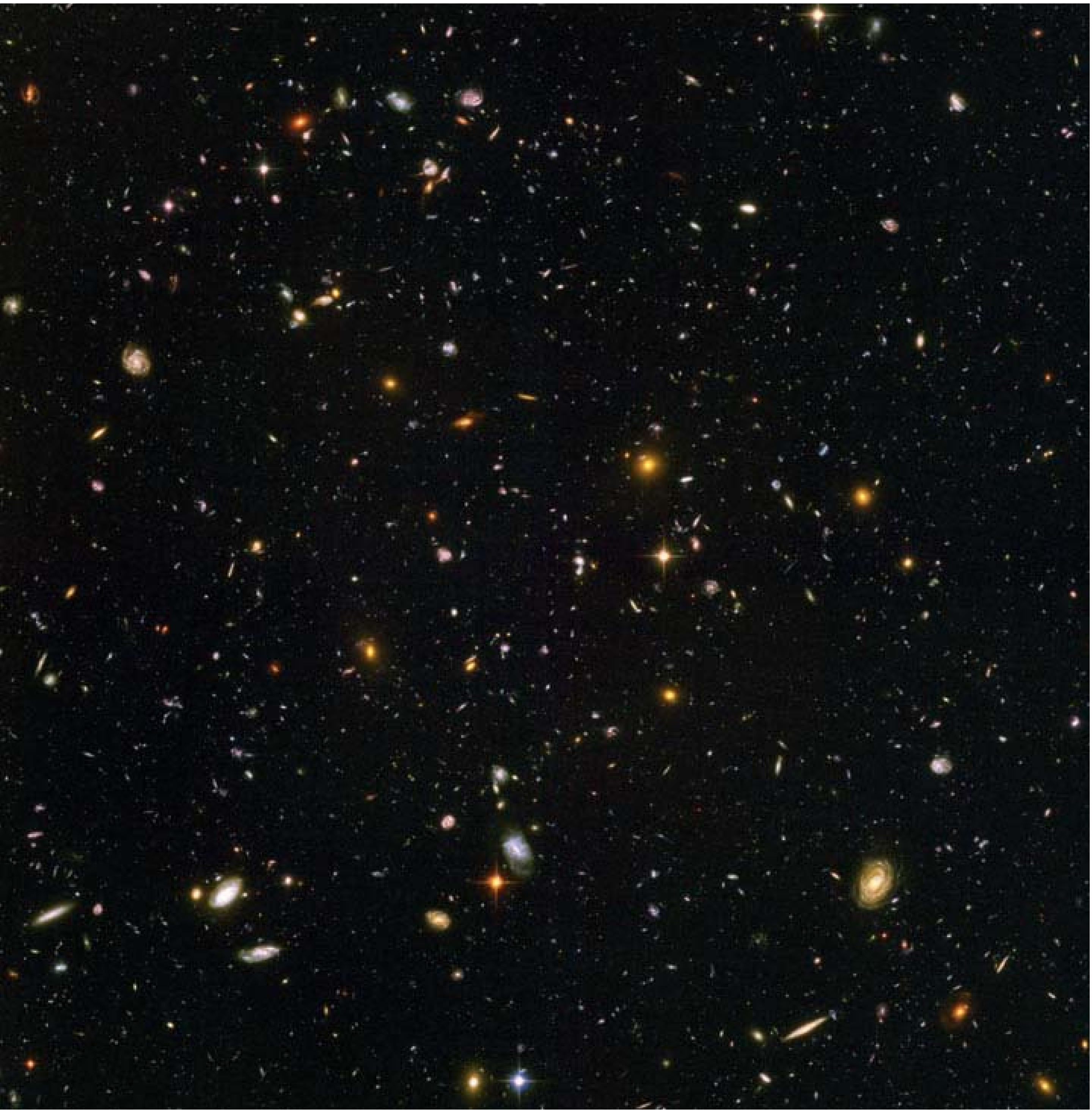
Globular cluster 47 Tucanae (often referred to as 47 Tuc) is one of the most famous objects in the sky, visible with the naked eye in the southern hemisphere. It is imaged here in near-infrared wavelengths of light, and shows millions of stars concentrated into a dense ball. Remarkably, the full extent of this cluster is the same size as the full Moon on the sky, despite being around 350 billion times more distant. All these stars are held into their 'globular' configuration by gravity – they are orbiting a common centre of mass. In turn, this cluster is gravitationally bound to the Milky Way. All massive galaxies are surrounded by a posse of several hundred to several thousand globular clusters for very massive galaxies (such as ellipticals). The cluster 47 Tuc is a popular target for astronomers because it contains many interesting populations of stars. You will notice many bright stars that appear yellow/orange in this image. These are red giant stars: massive stars in a phase of stellar evolution where most of the hydrogen gas has been consumed, which are now burning helium, physically expanding to a super size in the process. Their red colour is related to their relatively cool surface temperatures (as far as stars go), of around 4,000 degrees. Betelgeuse in the constellation of Orion is an example of a red supergiant. Stars such as this provide windows onto a critical phase in stellar evolution.

When we measure the positions of stars, and indeed when we chart any object in the sky, we work in a coordinate system of angles. This relates back to the idea of a celestial sphere, a hypothetical huge screen enveloping the Earth onto which all the distant astronomical sources are 'projected'. Astronomers work in a similar system of latitude and longitude that is used on the curved surface of the Earth. This time, the grid lines are on the inside of the surface of that sphere (imagine standing at the centre of the Earth and seeing lines of latitude and longitude above you). These are called lines of Right Ascension and Declination. Just as locations on Earth can be described by pairs of latitude and longitude, we define the coordinates of objects on the sky in pairs of Right Ascension and Declination (or 'RA' and 'Dec.'), and the angular distance between any two coordinates in this system is the distance along part of a circle running along the inside of this sphere, called a Great Circle, with the longest possible separation being 180 degrees. As a guide, the width of the full moon takes up about half a degree on this sphere. Often astronomers will put a picture of the full moon next to large astronomical images for a handy angular scale comparison.

We can make finer divisions than degrees: like an hour can be divided into 60 minutes, one degree can be subdivided into 60 'minutes of arc', or arcminutes, and one arcminute can be divided into 60 arcseconds. One arcsecond is about the same as the width of a strand of hair viewed from a distance of 10 metres. We can go further and divide more; in theory as much as we want, but in practice the smallest separations we can measure on the sky are set by instrumentation, which limits the accuracy, or resolution, with which we can pinpoint a given position. Those 'proper motions' of stars are often measured in units of thousanths of arcseconds, so you can see that these small changes in position are basically imperceptible to the unaided eye.

Now, consider a hypothetical star observed on this celestial screen. Imagine that we have measured its position once, and then wait six months and measure its position again, and work out the difference. The change in our physical viewing position is two times the Sun–Earth distance. If the apparent change in the star's position is two arcseconds, then we define the distance to the star to be one parallax second, or one parsec (shortened to 'pc'). It's a pretty elegant unit of measurement, rooted in geometry. So parallax measurements are one way we can measure the true distance to stars, but since the apparent change in position gets smaller and smaller the further away a star is, there gets a point where accurate measurements cannot be made. In other words, parallax only works as a distance measure within a fairly small volume around us. You may be more used to hearing about distances in astrophysics measured in light years, the distance light travels in one year in a vacuum. Actually, except in some cases, extragalactic astronomers tend to use the parsec rather than the light year. It's more empirical because the definition is rooted in a geometric measurement. For comparison, though, one parsec is equivalent to just over three light years. The nearest star to the Sun, Proxima Centauri, is 1.3 parsecs away, and there are a few hundred stars within ten parsecs. The positions and parallaxes of over 2.5 million stars (and their proper motions) were mapped out with a European satellite called Hipparcos (an acronym for High Precision Parallax Collecting Satellite, but also a reference to Hipparchus, the ancient Greek astronomer), which operated between 1989 and 1993. The newly launched satellite Gaia is now performing a new survey charting the positions of a *billion* stars in the galaxy, providing the most accurate and complete view of the three-dimensional

The Hubble Ultra Deep Field, a window onto the very distant universe. Nearly every point of light in this image is a galaxy, detected when Hubble gazed at a single, small area of sky (about 10 per cent of the diameter of the full Moon) for an extremely long exposure. Details in relatively nearby (but still very distant) galaxies can be seen, with clear spirals and ellipticals apparent, but the most distant galaxies are difficult to detect, appearing very small (sometimes just a few pixels across), faint and red in colour. Nevertheless, detecting these distant galaxies is essential to learn about the properties of galaxies when the universe was very young: the light from the most distant galaxies in this image was emitted when the universe was half a billion years old. We are looking into the past.



layout of our cosmic habitat. Still, this only just scratches the surface of the total number of stars in our galaxy: Gaia will measure about 1 per cent of all the stars in the Milky Way. It's a bit like peeking out of the door and checking out where all the houses are in your neighbourhood, but still, Gaia is an incredible leap forward in this area. The galaxy contains many more stars than we can measure parallaxes for, and most of these are in the direction of that bright Milky Way band.

Look away from the Milky Way band and you are starting to look out above or below the galactic disc and towards truly deep space. Extragalactic space. Far beyond the nearby stars, and beyond the disc, there is a dark and silent chasm that contains more galaxies. Many more. Hundreds of *billions* more. Sadly, we never have a clear view of them, because in any direction we look, we're peering out through our own galaxy, which is full of stuff (not least our blazing Sun, which dominates our sky). Extragalactic astronomy is like being in a forest, standing underneath a giant oak and trying to see the trees in some distant woodland beyond. To observe all other galaxies, we have to look out in directions that point above and below the dense, starry disc of our own galaxy. The region of sky in the direction of the galactic plane is so bright and thick with intervening matter that it is effectively opaque to the light from the distant universe. To study other galaxies, we don't even bother looking in that direction. We call it the 'Zone of Avoidance'.

The Chandra Deep Field South is the name of an extragalactic survey region that has received significant observational investment from many different telescopes. It is known as a 'blank field'. The aim was to point at a part of the sky where there were no known points of interest (say, a large nearby galaxy), so that astronomers could conduct an unbiased, blind survey of a large number of galaxies seen at different 'redshifts'; that is, different cosmic epochs. This optical image is about the size of the full Moon, and has an exposure time of about two days. There is a scattering of stars as we peer out through our own galaxy, but the vista reveals myriad galaxies beyond. We are one of many.

The contents of a galaxy

So, our galaxy is a vast collection of stars organized into a disc-like structure. It's not immediately obvious to us that this is the case, because we as observers are deeply embedded within the disc itself. When we look out at the night sky we're just seeing the nearest stars to us and so don't get the full picture, just as you wouldn't appreciate the vast extent of the Amazon rainforest by standing in the middle of it. However, we can see the whole forest by studying other, distant galaxies that are far enough away for us to be able to see them in their entirety. To learn about other galaxies, we need to understand a bit more about what makes up a galaxy in addition to the stars. The Milky

Way, it shouldn't surprise us to learn, is a fairly average galaxy. A quick overview of its contents will set us up for our exploration of other galaxies in the universe.

We've already seen that the stars in the Milky Way are distributed in a disc. At the hub of this disc, there is a more spherical bulge of stars, called, well, 'the bulge'. If the Milky Way were a fried egg, the bulge would be the yolk. For reasons that we'll explore later, the stars in the bulge are different from the stars in the disc: they're older, on average. Within the disc itself, the stars are not smoothly distributed – there are higher-density regions that follow a spiral pattern similar to the spiral of a hurricane or snail shell, and this is where we find the youngest stars: new stars are forming in patches within the spiral arms of the disc.

Just as the Earth orbits the Sun, the entire disc of the Milky Way rotates like a spinning plate, carrying the entire solar system on a galactic orbit. At the radius of our Sun, the rotation speed of the disc is about 200 kilometres per second, and it takes about a quarter of a billion years for us to orbit the hub of the galaxy once. So since its formation, the Earth has made nearly twenty full orbits of the Milky Way. As we will see more and more, our galaxy, and other galaxies, are dynamic entities, never at rest.

A wide view of the central region of the Milky Way showing the bright background stellar field smoky with interstellar dust, which is thickest in the plane of the disc. Here and there we can see patches of diffuse emission: blue light from young stars scattered and reflected by the gas and dust in their vicinity, and the red-pink glow of ionized hydrogen (HII) around the sites of formation of new stars.

What of the other contents of the galaxy? Among and between the stars is gas of various densities and temperatures, and this makes up the environment we call the interstellar medium. The gas is mainly hydrogen, the simplest, lightest and most abundant element in the universe, composed of a single proton and electron bound together. There are three main 'phases' of gas in galaxies: atomic gas, which is just gas composed of an ensemble of individual atoms; molecular gas, gas composed of ensembles of two or more atoms that have bonded together into molecules; and ionized gas, which is gas composed of atoms that have been irradiated or energized such that one or more of the electrons in the atoms has been stripped away. Although the majority of the gas in the interstellar medium is hydrogen, there are also other trace elements present: carbon and oxygen, for example (luckily for us). These trace elements were not present at the start of the universe but have been formed over time through the process of galaxy evolution; in particular the cycling of gas in generations of star formation.

In the disc of our galaxy the younger stars are distributed the way they are because of the underlying distribution of gas. The stars are born in giant clouds of molecular hydrogen, and one cloud can birth a generation of many stars. Since the gas clumps together under the influence of gravity, this gives rise to discrete patches of star formation throughout the disc of the galaxy, and specifically within the spiral arms, where the density of gas is highest. A star ignites when gravitational collapse pulls enough gas in close

concentration for a dense 'cold molecular core' to be formed. When the density of this environment is high enough, atoms within the core can fuse together, releasing vast amounts of energy when they do so. This is star formation. Many stars can be born at once as a collapsing cloud randomly fragments due to turbulence and other variations in the density of gas within it. A clutch of stars born close together becomes a cluster, gradually drifting away from each other over time.

Not all star clusters are globular. This is an 'open' cluster of stars in our galaxy called NGC 3603. In the disc of galaxies like our own, stars are born in giant clouds of molecular gas, which – during gravitational collapse – can spawn many stars in one go, resulting in clusters like this (although not all stars are born in clusters). Surrounding the cluster can be seen the glow of interstellar gas (the light is from the elements hydrogen, sulphur and iron), energized by the radiation emitted by this collection of young, massive stars. Understanding the exact physics of the details of star formation by studying regions of active stellar growth in our own galaxy provides vital information for the interpretation of star-forming galaxies in the distant (and early) universe.