

The Milky Way galaxy

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Summary

Our Galaxy is typical of the galaxies that dominate star formation in the present Universe. It is a barred spiral galaxy – a still-forming disc surrounds an old and barred spheroid. A massive black hole marks the centre of the Galaxy. The Sun sits far out in the disc and in visible light our view of the Galaxy is limited by interstellar dust. Consequently, the large-scale structure of the Galaxy must be inferred from observations made at infrared and radio wavelengths. The central bar and spiral structure in the stellar disc generate significant non-axisymmetric gravitational forces that make the gas disc and its embedded star formation strongly non-axisymmetric. Molecular hydrogen is more centrally concentrated than atomic hydrogen and much of it is contained in molecular clouds within which stars form. Probably all stars are formed in an association or cluster, and energy released by the more massive stars quickly disperses gas left over from their birth. This dispersal of residual gas usually leads to the dissolution of the association or cluster. The stellar disc can be decomposed to a thin disc, which comprises stars formed over most of the Galaxy's lifetime, and a thick disc, which contains only stars formed in about the Galaxy's first gigayear. The Galaxy has two distinct populations of globular clusters, and an attendant host of dwarf spheroidal galaxies. Both globular clusters and dwarf spheroidal galaxies give rise to tidal streams. Globular clusters appear to contain no dark matter, while dwarf spheroidal galaxies are dominated by dark matter. Stars account for more than half of the gravitational force that holds the Sun in its roughly circular orbit, but the rest is probably attributable to a roughly spherical halo made up of still undiscovered elementary particles.

1 Introduction

Galaxies vary enormously in size from objects that contain only 100 000 stars, to ones with hundreds of billions of stars. The smaller galaxies are much more numerous than the larger ones, but not by a sufficient factor to compensate for their lower luminosities. So most of the luminosity in the Universe is contributed by galaxies that lie just below the top of the scale. The Sun lies in just such a galaxy, the Milky Way galaxy.

Galaxies can usefully be considered to be made up of two components: a *spheroid* and a *disc* (Figure 1). The spheroid is made up of stars that move around in a disorganised way, rather like a swarm of bees. Its name derives from its only moderately non-spherical shape. The disc is a highly flattened structure in which stars move on nearly circular orbits around the centre and never go far from the system's equatorial plane. The *morphological type* of a galaxy is determined by the relative contributions of these two components to the system's total luminosity. *Early-type galaxies* are dominated by their spheroids: in the extreme case of an *elliptical galaxy* casual inspection reveals only a spheroid, although very precise measurements may reveal a disc deeply buried inside the spheroid. In the case of a very *late-type galaxy*, there may be no detectable bulge, only a disc.

Besides the relative importance of disc and bulge, early- and late-type galaxies differ in their rates of star formation and the mean age of their stars: early-type galaxies have little or no cold, dense gas from which stars can form, so their rates of star formation are small and nearly all their stars are old. Late-type galaxies possess cold, dense gas so they have on-going star formation and significant populations of young stars. In each batch of freshly formed stars, there will be both massive stars (masses up to $100 M_{\odot}$) and low-mass stars (below about $2 M_{\odot}$). Massive stars are extremely luminous, blue and short-lived, while low-mass stars are long-lived, red and faint. Consequently, early-type galaxies are red and their brightness distributions are smooth because they are generated by enormous numbers of individually faint stars. Late-type galaxies, by contrast, are blue and their brightness distributions are patchy, because a scattering of extremely luminous stars can make a particular region much more luminous than another of equal size.

The Milky Way is a moderately late-type galaxy in which about 90% of the luminosity is contributed by the disc, while the centre of the system is dominated by a spheroid, that is often called the *bulge* – from the outside it would look something like the galaxy shown in the middle panel of Figure 1. The Sun sits quite near the rim of the luminous part of the disc, so the Galaxy appears as a band of stars across the sky, marking directions in which we see out into the disc (Figure 2). The bulge lies in the constellation Sagittarius in the southern sky.

The distance to the Galactic centre is still not precisely known, but the best available value is now 8.3 *kiloparsecs*, roughly 25 000 light years (Gillessen et al. 2009). The disc has a mass $\sim 6 \times 10^{10} M_{\odot}$, while that of the bulge is $\sim 10^{10} M_{\odot}$ (Launhardt et al., 2002). Studies of the Milky Way frequently make use of *Galactic coordinates*, (l, b) , for the celestial sphere; the *latitude* b is the angle between a line of sight and the Galactic plane, with positive values lying to the north of the plane. The *longitude* l is the angle between the projection of the line-of-sight into the plane and the direction to the Galactic centre (Figure 3). Thus the Galactic centre has coordinates $(l, b) = (0, 0)$.

2 Recognition of the size of the Milky Way

Since time immemorial our ancestors have been familiar with the Milky Way as a band of light that stretches right across the sky on a dark night. Galileo first showed that this band is constituted of myriads of faint stars, but it was less than a century ago that astronomers finally grasped that the Milky Way is a galaxy like those that in the early 19th century had been catalogued in great numbers by the Herschels. Two problems were responsible for the delay in recognising what the Milky Way really is: the usual difficulty of measuring astronomical distances, and a lack of awareness of the existence of an obscuring interstellar medium.

The central plane of the disc contains most of the Galaxy's supply of cold, star-forming gas. This gas is extremely heavily polluted by ejecta from stars: if it were compressed to the density of air (i.e., by a factor $\sim 10^{21}$) one could see only a few cm through it because light is absorbed by particles of *dust* (a better name might be smoke) suspended in the gas. Even at the extremely low densities characteristic of interstellar space, we can see only of order a kiloparsec through this gas, which should be compared with the 8.3 kpc to the Galactic centre. Hence at optical wavelengths we cannot see through the disc to the bulge. This obscuration by dust strongly influenced the growth in our understanding of the Milky Way. In the first

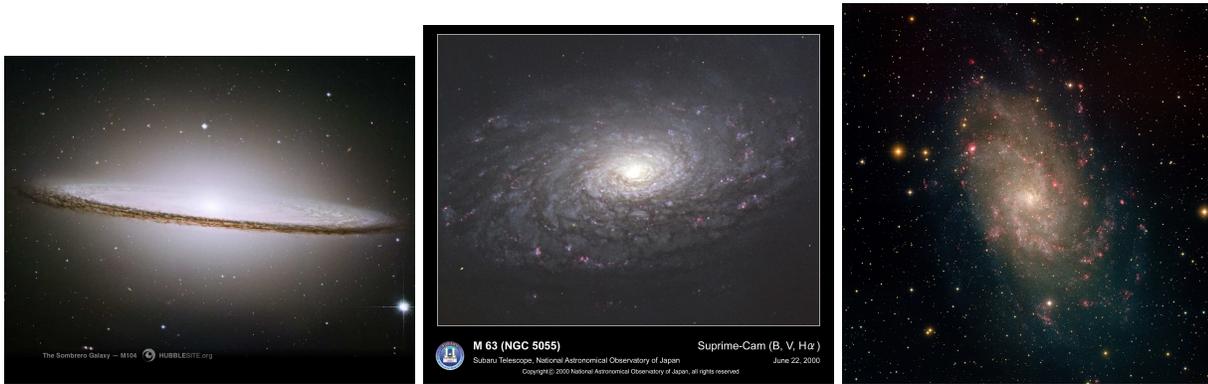


Figure 1: Disc galaxies with spheroids of decreasing prominence. On the extreme left is the Sombrero galaxy, M104, which is dominated by its spheroid. In the centre is M63 with a much smaller but clearly visible bulge. On the right is M33, which has no discernible spheroid. Credits: M104 – NASA and the Hubble Heritage Team (STScI/AURA); M63 copyright Subaru Telescope, National Astronomical Observatory of Japan. All rights reserved. M33 – T.A. Rector (NRAO/AUI/NSF and NOAO/AURA/NSF) and M. Hanna (NOAO/AURA/NSF).

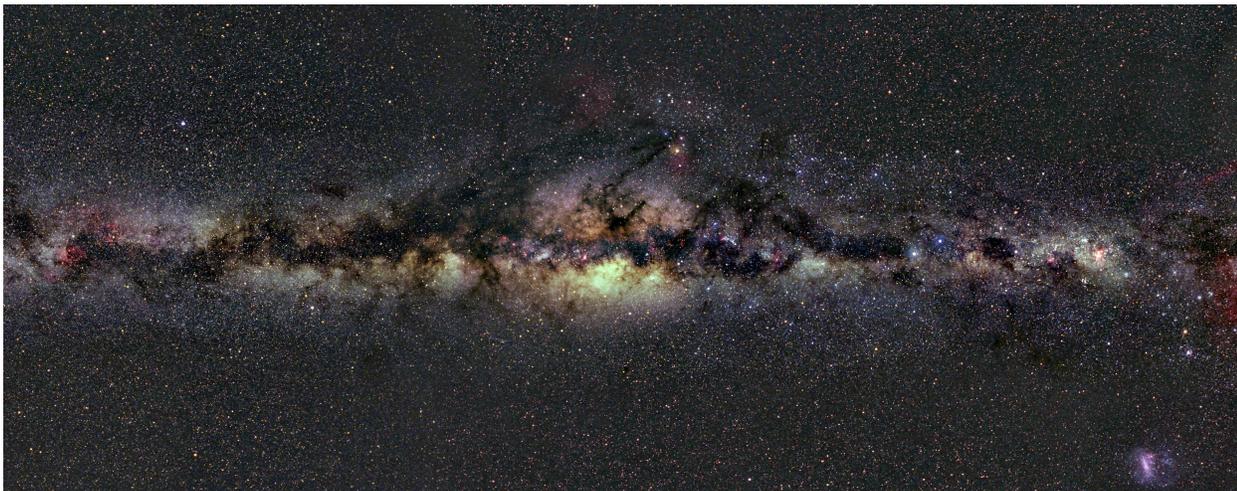


Figure 2: The Milky Way in visible light is a patchwork of regions made bright by myriads of stars, and regions blanked out by foreground dust. The concentration of stars towards the Galactic plane is evident, as is the decrease in star density as one moves away from the Galactic Centre, which is in the middle of the image. (Image courtesy of Axel Mellinger)

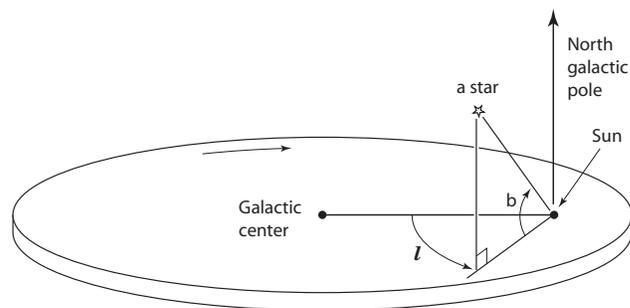


Figure 3: The definition of Galactic coordinates. (From Binney & Tremaine, 2008)

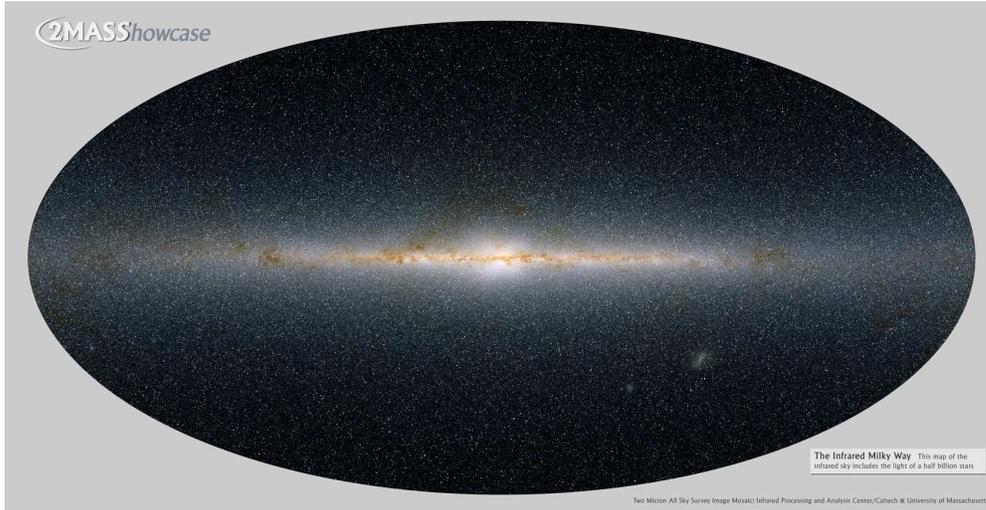


Figure 4: The Galaxy in near-infrared light. The whole sky is shown, so what is shown at extreme right and left is what lies behind your head as you look at the Galactic Centre, which appears in the middle of the image. The light comes from myriads of stars, only a few of which are resolved by the telescope into points of light. Credit: Two-micron Survey Infrared Processing and Analysis Center/ Caltech & University of Massachusetts.

decades of the 20th century, before astronomers knew of interstellar dust, it was thought that we lived near the centre of a disc of stars that was about 2 kpc in radius. The objects that we now know to be external galaxies were thought to lie within this disc, so the latter was thought to constitute the whole Universe – this world picture is called Kapteyn’s Universe after the Dutch astronomer who led an international effort to map it. In the 1920s evidence for obscuration by interstellar dust mounted, and it was demonstrated that external galaxies lie far outside the bounds of Kapteyn’s Universe. These two advances made it natural to interpret the Milky Way as an object similar to some external galaxies. The decisive step in this direction was taken in 1927 by another Dutch astronomer, Jan Oort, who interpreted the motions of nearby stars in terms of differential rotation within a disc of stars that is ~ 10 kpc in radius. A global view of the Galaxy was first obtained in the 1950s following the detection of hydrogen at radio frequencies (at a wavelength of 21 cm) using technology that had been developed for radar in the Second World War: interstellar gas is almost transparent to radio waves, so by scanning the sky with radio telescopes in the Netherlands and Australia it was possible to study the large-scale structure of the Galactic disc. Normal stars cannot be usefully studied at radio wavelengths, so our first clear view of the Galactic bulge came in 1991 in near-infrared data taken by the COBE/DIRBE satellite. The angular resolution of the COBE/DIRBE data was poor ($\sim 0.5^\circ$) and a much sharper image was subsequently obtained from the 2MASS infrared survey of the sky (Figure 4). In this picture one clearly sees the stellar disc and the bulge, and some dark wisps of obscuration by dust, which is very much weaker at near-infrared than at optical wavelengths, but not negligible.

3 The Centre

A black hole of mass $4.4 \times 10^6 M_\odot$ sits at the centre of the Milky Way (Gillessen et al. 2009). Weak radio and X-ray radiation emerges from its location, and it takes its name, Sgr A*, from the catalogue entry of the radio source that we now know is associated with the black hole. We know a black hole is there because we can study the motion of luminous stars as they orbit in its powerful gravitational field; a star called S2 has now been followed through one complete orbit around Sgr A* (Figure 5). The orbit is highly eccentric and accurately fitted by a Kepler ellipse, demonstrating that it is moving in the gravitational field of point mass.

A crucial distance from a black hole is the *Schwarzschild radius*, r_s , interior to which light is trapped by

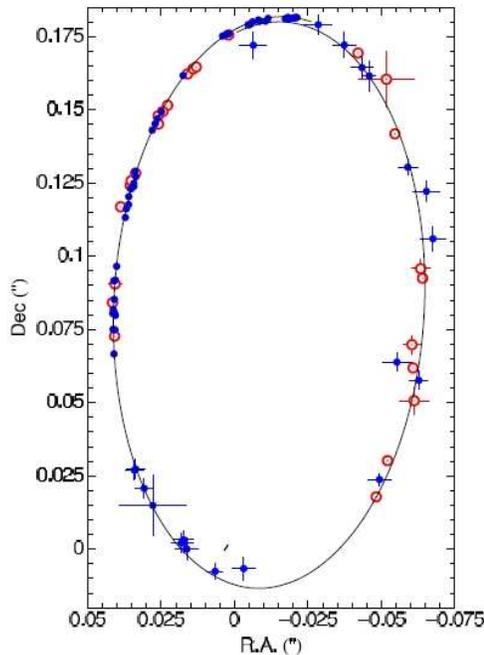


Figure 5: The orbit of S2 around the black hole that dominates the Galactic centre. The orbit has a period of 15.2 yr and the data points cover the period 1994–2008. The orbit’s semi-major axis and eccentricity are 0.119 arcsec and 0.87. The data points in the upper left part of the orbit have tiny error bars because these are the most recent data and were obtained with the latest technology. (From Gillessen et al 2009).

the hole’s gravitational field. For Sgr A* $r_s = 10^7$ km. The closest that S2 comes on its orbit is 2×10^{10} km, so although at this point it is moving at 6000 km s^{-1} , relativistic effects are not large along this orbit.

S2 is one of the most luminous stars in a star cluster that surrounds Sgr A*, and it is young. It comes as a surprise to find young stars so close to Sgr A* because theory suggests that density inhomogeneities in a protostellar cloud could not grow into stars so near to a huge point mass.

4 The bulge-bar

Moving out from Sgr A* we enter a region that is dominated by the Galaxy’s spheroid. This is strongly non-axisymmetric; in fact, it resembles a cigar more than a saucer, so it is called the bar. The bar’s long axis lies in the Galactic plane, and its nearer end is at positive longitudes (Figure 6); the angle between the long axis and the Sun-centre line is $\sim 25^\circ$. In the diagram stars stream clockwise around the bar, and the figure of the bar rotates in the same sense but more slowly – it completes a rotation in about 100 million years. This picture has emerged from two types of observation. On the one hand the line-of-sight velocities of gas clouds that move in the plane show unmistakable signs of moving in the bar’s rotating gravitational field (see below). On the other hand photometry of the inner galaxy shows asymmetries between the Galaxy’s left and right sides that arise because the left-hand, nearer end of the bar subtends a bigger angle on the sky than the further, right-hand end. Moreover, individual stars in the left-hand end of the bar are closer to us and therefore brighter than corresponding stars in the right-hand end (Figure 7).

The pattern of gas density and star formation in the plane is structured by the bar’s rotating gravitational field. This field defines a *corotation radius* r_{cr} at which a star on a circular orbit around the centre in the underlying axisymmetric gravitational field of the Galaxy would have the same angular velocity as the long axis of the bar: such a star would ride with the rotating gravitational field of the bar. Gas clouds that orbit just outside r_{cr} tend to pick up energy from the bar and be pushed outwards. On the other hand, gas clouds are constantly colliding with one another and dissipating energy through friction, and this energy loss causes

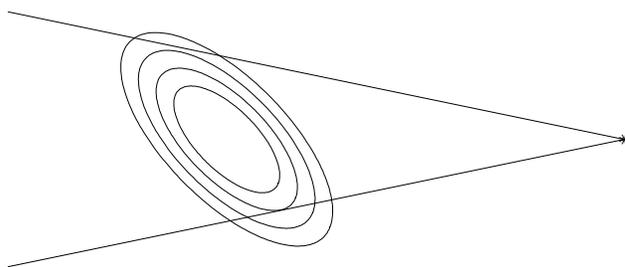


Figure 6: Schematic of the Galactic bar, indicated by elliptical contours of constant density. The Sun is the star on the right and from it two lines of sight are marked that make equal angles with the Sun-Centre line. The lower line of sight (at positive longitude l) intersects the nearer end of the bar and crosses the bar's major axis closer to the Centre than the line of sight at negative longitude.

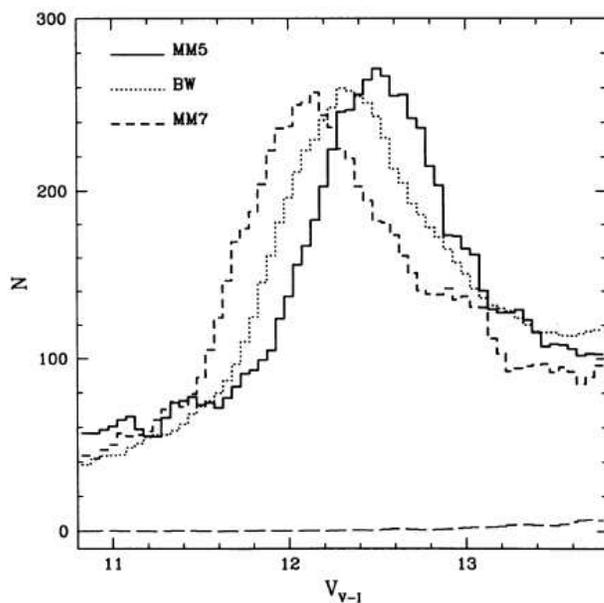


Figure 7: The distributions of apparent magnitudes of stars seen in three fields. The full curve is for a field at $l = -4.9^\circ$, $b = 3.4^\circ$, while the dashed curve is for $l = 5.5^\circ$, $b = 3.4^\circ$. The peak of the dashed curve lies at a brighter magnitude than the peak of the dashed curve, indicating that the peak stellar density is reached at smaller distances at positive than negative longitudes on account of the orientation of the bar with respect to the Sun-Centre line. The dotted curve is for “Baade’s window”, which lies at $(l = 1^\circ, b = -3.9^\circ)$. (From Stanek et al. 1994)

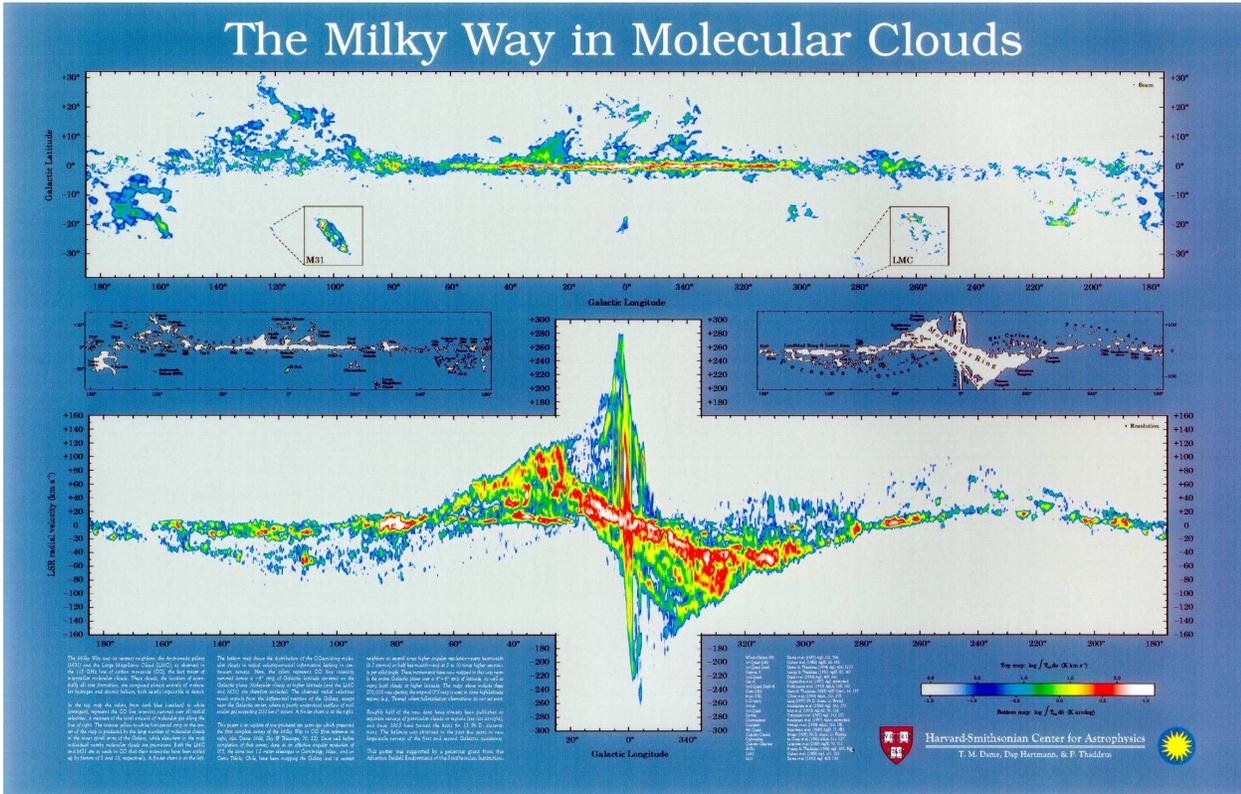


Figure 8: The distribution of molecular hydrogen in the Milky Way traced with the 2.6 mm line of carbon monoxide. The upper panel shows the intensity of CO emission summed over all velocities in the plane of the sky. The emission is very strongly confined to the Galactic plane. The lower panel shows the intensity within Galactic latitude $|b| < 2^\circ$ as a function of longitude (horizontal coordinate) and line-of-sight velocity. The spike of emission in the middle of the lower panel comes from the nuclear molecular disc, a region of intense star formation ~ 200 pc in radius. The broad swath of emission running from $l = 25^\circ$ to $l = 335^\circ$ (-25°) is from the giant molecular ring, which encircles the bar. The narrow ridge of emission that crosses $l = 0$ at $v \simeq -80$ km s $^{-1}$ is from the “3 kpc arm”. (Credit: T.M. Dame, Dap Hartmann & P. Thaddeus, Harvard-Smithsonian Center for Astrophysics.)

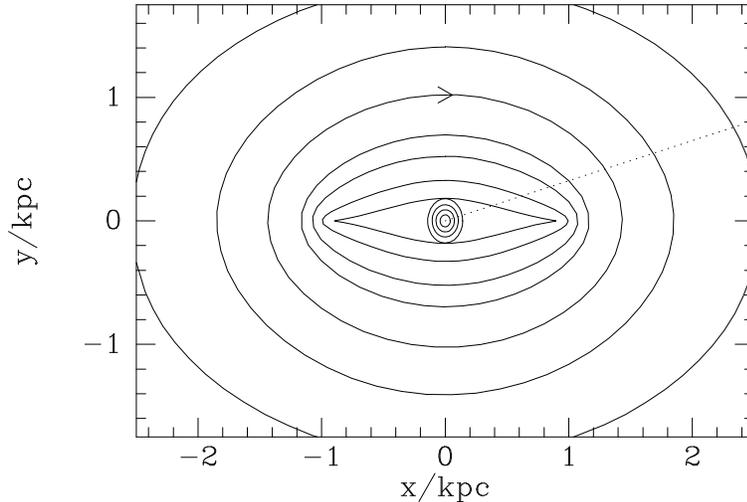


Figure 9: Orbits in a simple rotating bar potential. The orbits are plotted in the frame of reference that rotates with the figure of the bar, and in this frame they are closed. Inside $r \simeq 200$ pc there is a family of only mildly elliptical orbits whose long axes are perpendicular to the bar. The gas that forms the nuclear molecular disc moves on these orbits. The dotted line points to the location of the Sun. (From Binney & Merrifield 1998)

them to drift inwards. The outward thrust from the bar and the frictional inward drift balance just outside r_{cr} , and gas accumulates here. This accumulation of gas near r_{cr} is conspicuous in the lower panel of Figure 8 as a band of emission that slopes from upper left to lower right at $|l| < 25^\circ$. Much of the Galaxy's star formation takes place in this ring.

Inside r_{cr} the bar causes gas clouds to move on orbits that are elongated with the bar and become increasingly elongated as one moves inwards (Figure 9). Collisions between clouds on these orbits causes them to move inwards rather rapidly, so the region occupied by these orbits is one of low gas density and little star formation (left panel of Figure 10). About 200 pc from the centre the orbits of gas clouds become abruptly rather circular (Figure 9) and the inward drift of clouds slows. Consequently, at $r \sim 200$ pc gas builds up – in the lower panels of Figures 8 and 10 this region of high gas density shows up as the central vertical spike that extends to $|l| \sim 2^\circ$. Curiously in Figure 8 the spike is redder at upper left than lower right, signalling that $\sim \frac{3}{4}$ of the gas lies at $l > 0$. Despite this lop-sidedness (which is not understood) the gas is thought to be organised into a mildly elliptical disc, the *nuclear molecular disc*.

In the nuclear molecular disc stars form in abundance. Our knowledge of the resulting stellar population is poor because it is heavily obscured at optical wavelengths, but Figure 11, which shows this region imaged in radio waves, attests to the high level of star formation by showing numbers of blisters associated with *supernova remnants*, spherical cavities in the interstellar medium that have been blasted when a massive star exploded at the end of its short life. Another noteworthy feature of Figure 11 is the bright streaks that run perpendicular to the plane at various points. These streaks are regions in which relativistic electrons are spiralling around magnetic field lines, and they suggest that in this region the magnetic field runs perpendicular to the plane. By contrast, near the Sun, the field runs broadly within the plane. Magnetic field lines are expected to be oriented in the direction in which gas flows, so field lines running perpendicular to the plane imply that 30 pc from the centre gas is flowing away from the plane. Figure 12 confirms this inference by showing as a grayscale the intensity of emission at $8 \mu\text{m}$ by warm dust and as contours the intensity of radio emission at 3 cm in a region 1.5° (220 pc) square around the centre. In the north the contours bulge outwards between $l \sim 0.3^\circ$ on the left and $l = -0.7^\circ$ on the right. This is emission from hot gas that is flowing upwards, away from the plane. This gas can be traced to kiloparsec distances from the plane by its soft X-ray emission (Bland-Hawthorn & Cohen, 2003). Similar outflows are seen when some external galaxies are imaged in X-rays or the Balmer α emission line of hydrogen (Strickland et al., 2004).

Although our view of most of the central region is heavily obscured at optical wavelengths, there are

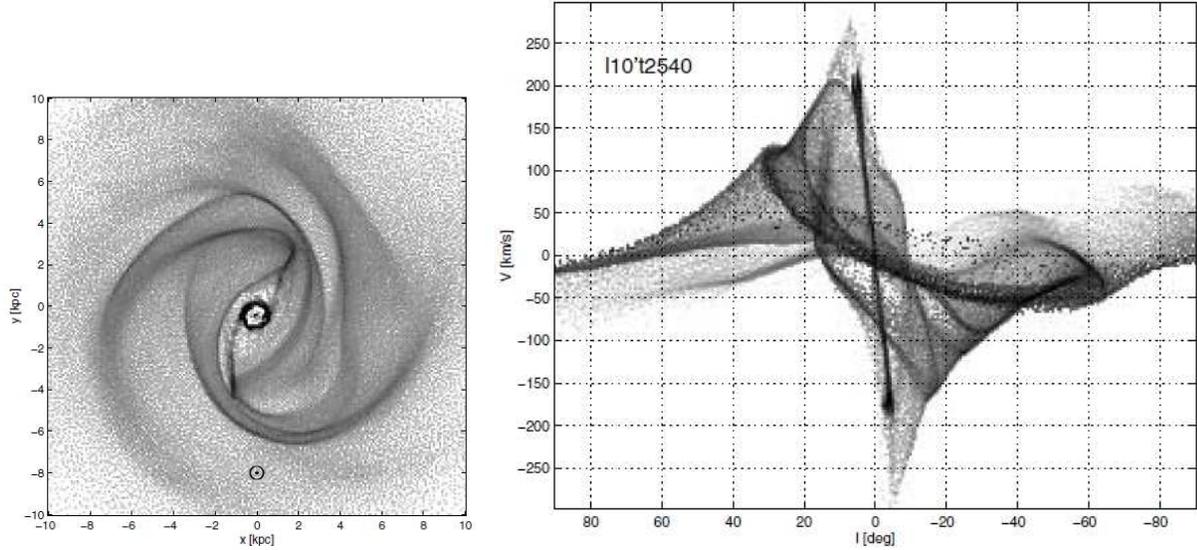


Figure 10: Left panel: the density of gas that is flowing in a model Galaxy. Right panel: the line-of-sight velocity of the gas as a function of Galactic longitude. (From Fux 1999)

some “windows” of low obscuration within which optical spectra of bulge stars can be obtained. From these spectra one can infer the ages and chemical compositions of observed stars. It is found that all the stars have ages $\gtrsim 9$ Gyr (Ballero et al., 2007). The great ages of these bulge stars imply that star-formation in the bulge has for most of the age of the Galaxy been confined to the heavily obscured regions within which star formation occurs today. Moreover, stars formed in this region have not migrated sufficiently away from the plane to enter one of the windows of low obscuration.

4.1 History of the bulge

When galaxies started to form, their gas had very low abundances of elements other than hydrogen and helium. Over time the interstellar abundances of carbon, oxygen, iron and the other elements heavier than helium (which astronomers refer to as *metals*) increased as the interstellar medium became polluted by ejecta from old and dying stars. Hence the chemical compositions of stars allow us to trace the history of star formation, since very metal-poor stars must have been formed early on, and metal-rich stars more recently.

Bulge stars observed in low-obscuration windows show a wide range of metal abundances, implying that the bulge’s stars were not formed all at once, but over a period long enough for the first stars to finish their lives and enrich with metals stars that formed later. On the other hand the great ages that are directly measured for stars in low-obscuration windows implies that early in the life of the bulge, the star-formation rate was much higher than it is now. This last inference is confirmed by the fact that in bulge stars the abundance of iron relative to that of oxygen is lower than it is in stars near the Sun. This implies that second and third generations of stars formed before the abundance of iron was boosted by *type Ia supernovae* – white dwarf stars composed of oxygen and carbon that explosively convert this material into iron and nickel. Of order a billion years elapses after a generation of stars forms before its type Ia supernovae substantially enrich the interstellar medium with iron. Hence from the underabundance of iron relative to oxygen in bulge stars, we infer that star formation in the bulge was essentially complete within a billion years.

5 Globular clusters

About 160 globular clusters orbit within the Galaxy. These clusters contain from several thousand to in excess of a hundred thousand stars. They show little if any rotation and are rather nearly spherical. Their

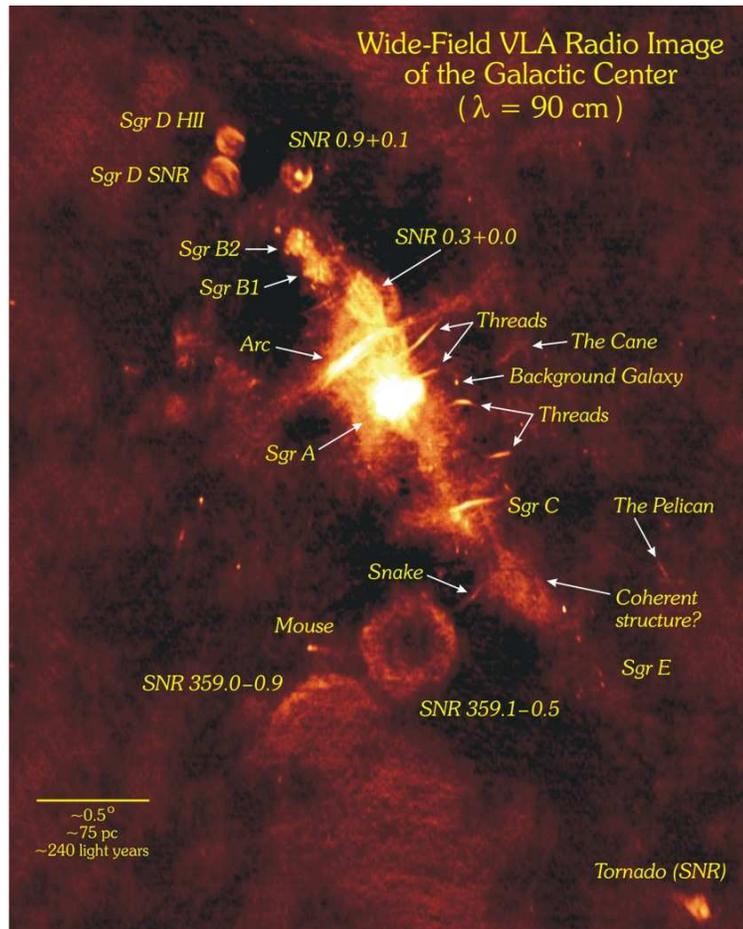


Figure 11: The central Galactic plane viewed radio waves of 90 cm wavelength. Most of this radiation comes from electrons that spiral around lines of magnetic force at close to the speed of light. The elongation of bright regions is thought to indicate the direction of the field lines. Several supernova explosions have blasted holes in the interstellar medium that show up as circles of brightness that are marked “SNR”. Image courtesy of NRAO/AUI and N.E. Kassim, Naval Research Laboratory

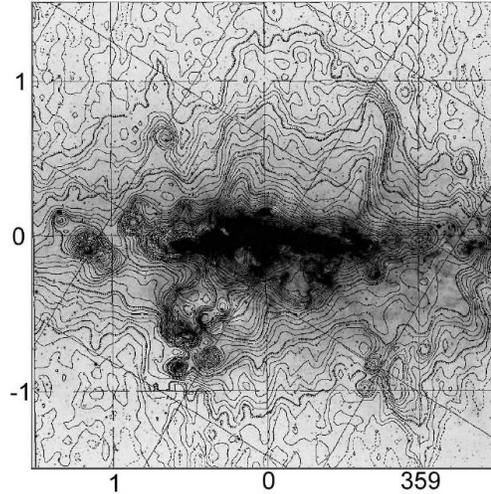


Figure 12: The greyscale shows emission at $8\ \mu\text{m}$ from hot dust in a region 3° (434 pc) square around the Galactic centre. The contours show the intensity of radio emission at 3 cm. The bulging contours to the North of the centre are the signature of gas heated by intense star formation in the nuclear molecular disc that is flowing out of the disc. (From Bland-Hawthorn & Cohen 2003)

radial profiles display a wide range of central concentrations from Messier 15 (M15), in which the central density continues to rise towards the centre down to the smallest radii probed, to fluffy clusters such as Pal 5 (Figure 13). Their central velocity dispersions are of order $6\ \text{km s}^{-1}$, and in any given cluster the dispersion σ decreases outwards. The outward decline of σ is consistent with all the cluster’s matter being in stars – in this respect they differ markedly from dwarf spheroidal galaxies (see below), which show no sign of the outward decline in velocity dispersion that is predicted by models in which light is a fair tracer of mass.

In the 20th century globular clusters were fundamental to the development of the theory of stellar evolution, because to an excellent approximation each cluster consists of stars with common age and metallicity, but differing masses. As self-gravitating ensembles of near point masses that have short crossing times, globular clusters have also been important laboratories for stellar dynamics.

A key stellar-dynamical process is *two-body relaxation*: when the orbit of a star through the cluster is deflected by the gravitational field of another star, the two stars exchange energy and we say the stars have had an *encounter*. These energy exchanges drive the cluster towards thermodynamic equilibrium in the same way that molecular collisions in air restore thermodynamic equilibrium after it has been disturbed, for example by stirring or local heating. In thermodynamic equilibrium, the velocity distribution of particles (a Maxwellian) is non-zero right up to infinite velocity, but in a self-gravitating system there is a finite escape velocity, v_e : a star that after an encounter is moving faster than v_e will escape the system. Hence stars are constantly *evaporating* from a star cluster. A star that loses energy in an encounter will sink inwards. If it loses energy in a second encounter, it will move still further inwards. Hence, in addition to driving evaporation, two-body encounters lead to the formation of a high-density cusp at the centre of the cluster. The sharply peaked central density of M15 (right hand panel of Figure 14) is believed to have evolved in this way long after the cluster formed.

In thermodynamic equilibrium the root-mean-square (rms) speed of a particle of mass m scales as $1/\sqrt{m}$. Hence stellar encounters tend to slow down more massive stars and speed up less massive stars. These changes of speed lead to the massive stars sinking to the cluster’s centre and the less massive stars populating its halo, and possibly evaporating. The segregation of stars by mass can be studied in globular clusters through the radial distributions of stars of different spectral types.

Evaporation is not the only process that removes stars from clusters. The gravitational field of the Galaxy raises tides on clusters in just the same way that the gravitational field of the Moon raises tides on the ocean: on the side of the cluster that is closest to the Galactic centre, the gravitational field is larger than on the further side. Hence the cluster is stretched along the line that joins the cluster to the Galactic

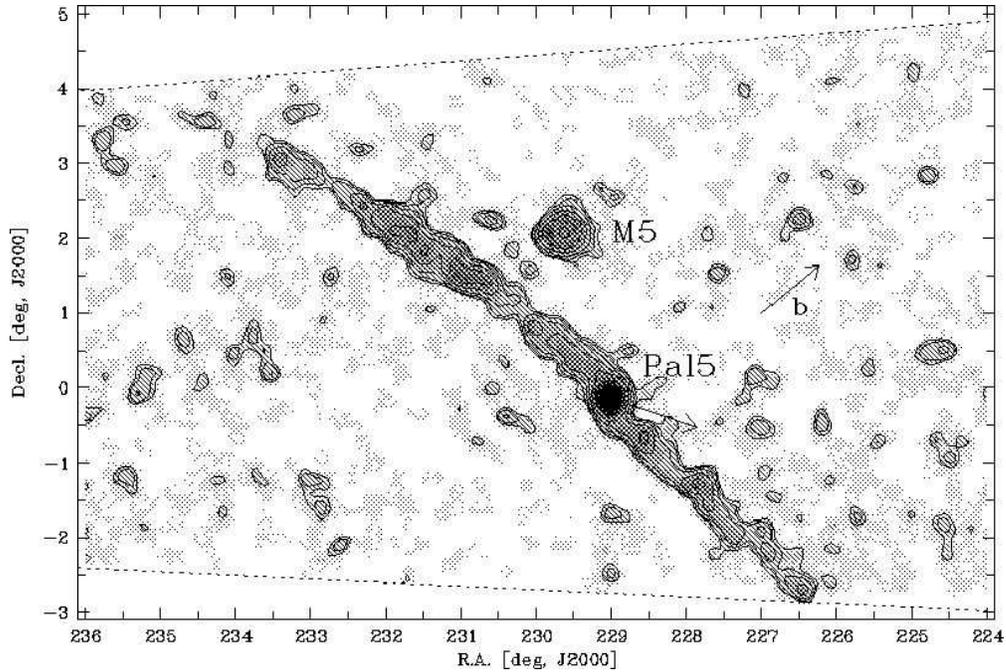


Figure 13: The density on the sky of main-sequence stars with distances similar to that of the globular cluster Palomar 5. The cluster itself is the dark blob marked “Pal 5” and from it run up to the left and down to the right tails of stars that have been pulled from the cluster by the Galaxy’s gravitational field and are on orbits through the Galaxy similar to that of Pal 5, but are either leading Pal 5 or lagging it. (From Odenkirchen et al 2003)

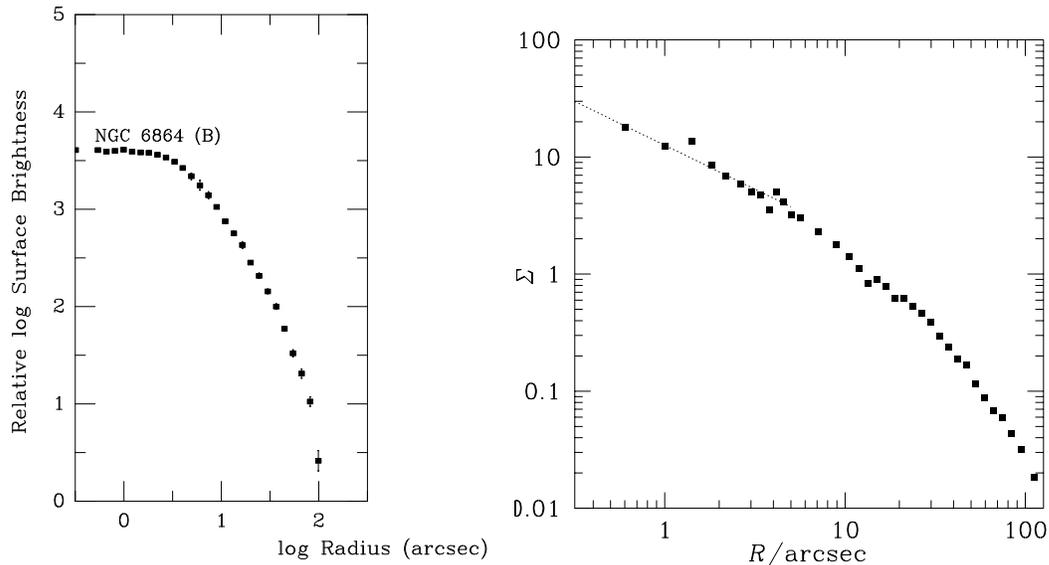


Figure 14: Density of stars on the sky as a function of distance from the cluster centre: NGC 6864 (left) and M15 (right). Whereas the surface brightness is constant near the centre of NGC 6864, in M15 it continues to rise all the way to the centre. (After Binney & Merrifield 1998)

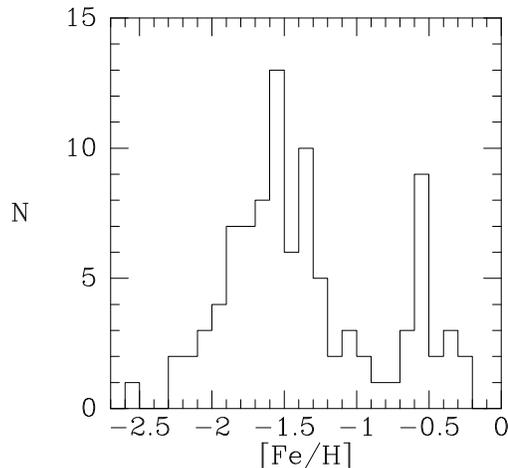


Figure 15: The metallicity distribution of the Galaxy’s globular clusters is bimodal. The low-metallicity population centred on $[\text{Fe}/\text{H}] = -1.5$ is that of the halo clusters, while the more metal-rich population is that of the “disc” clusters. (From Binney & Merrifield 1998)

centre. This stretching increases as the cluster approaches the Galactic centre on an elliptical orbit, peaking at *pericentre* (the point of closest approach to the centre). At this point some stars become detached from the cluster and subsequently orbit the Galaxy independently of it (although on orbits similar to the cluster’s own). Recently it has become possible to map clusters out to extremely low surface brightnesses, revealing *tidal streams* formed in this way around some globular clusters (Figure 13). Many tidal streams have been discovered recently, including the Orphan Stream shown in Figure 13. Such streams offer one of the most promising tools for probing the Galaxy’s gravitational field far from the disc and considerable progress is expected in this area in the next few years.

The metallicity distribution of the globular-cluster population is strongly bimodal (Figure 15), with peaks at $[\text{Fe}/\text{H}] \simeq -0.5$ and $[\text{Fe}/\text{H}] \simeq -1.5$. Similar bimodality has been detected in the globular-cluster populations of several other galaxies. When this bimodality is used to decompose the cluster population into metal-rich and metal-poor components, it is found that the two components have distinct spatial and kinematic properties: the metal-rich population is confined in space to $|z| < 3$ kpc and $r < 8$ kpc and has significant rotation, while the metal-poor population is approximately spherically distributed and extends out to $r \simeq 100$ kpc. In recognition of this fact, the metal-rich clusters are called *disc clusters* and the metal-poor ones *halo clusters*. The globular-cluster populations of many external galaxies show similar bimodality but the origin of this phenomenon is unknown. In all Galactic globular clusters the abundance of iron is low relative to that of oxygen compared to the Sun. This finding implies that globular clusters ceased to form stars before the first cluster stars exploded as type Ia supernovae.

The halo clusters are all extremely old – the data for the large majority of clusters are consistent with ages equal to the cosmologically-determined age of the Universe, 13.7 Gyr. Significantly smaller ages ~ 10 Gyr are obtained for a minority of clusters. There is no evidence that among halo clusters age is correlated with either metallicity or galactocentric distance. There are indications that some disc clusters are a few Gyr younger than the Universe.

6 Satellites

The Milky Way is one of two galaxies that dominate the Local Group of galaxies; the other dominant galaxy is the Andromeda Nebula, Messier 31 (M31). The Local Group contains dozens of smaller galaxies. A few of these are conspicuous and have been known for over a century – the Small and Large Magellanic Clouds (SMC and LMC), the Triangulum Nebula, M33, and two close companions of M31, NGC 205 and M32. The great majority of the galaxies in the Local Group are inconspicuous and the list of the known ones

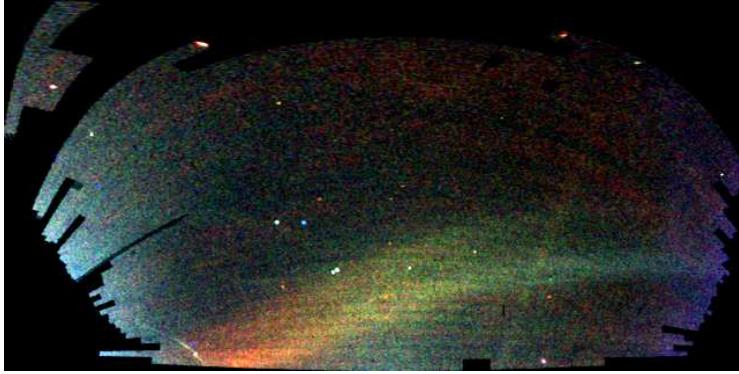


Figure 16: A false-colour representation of the density of faint stars near the North Galactic pole. Regions of higher star density are brighter. The densities of stars in three ranges of apparent magnitude (and therefore typical distance) are plotted in the three primary colours, so the overall hue indicates the dominant distance category, with red most distant and blue least distant. The Sagittarius stream arcs from bottom left to middle right. In the right-hand half of the figure it is clearly split into two bands. A much narrower stream runs steeply up from $\alpha \sim 164^\circ$, $\delta = 0$; this is the Orphan Stream. (Image courtesy Vasily Belokurov after one in Belokurov et al., 2006)

has recently been lengthening rapidly as advances in observational technique make it possible to discover galaxies with extremely low surface brightnesses. Some of these low-surface-brightness objects are on orbits that carry them inside the Milky Way, and systems of this type may have played a significant role in the Galaxy’s evolution.

An instructive example is the Sagittarius Dwarf, the centre of which is only ~ 24 kpc from the Sun but was not discovered until 1995 because it lies behind the bulge. It is moving almost perpendicular to the plane from south to north, and is elongated along its orbit for the same reason that the globular cluster Pal 5 is. Remarkably, its tidal stream wraps right round the Galaxy: Figure 16 is an image of the stream as it passes over the North Galactic pole. On the right-hand side of the image, the stream is clearly double, indicating that it passes through this region *twice*. It seems that the Sagittarius dwarf is in the final stages of being tidally disrupted by the Galaxy.

Dwarf spheroidal galaxies are particularly interesting from the perspective of “dark matter” (Section 8), because stars are believed to make only a very small contribution to the gravitational fields of these systems. The evidence for this is the magnitude of a typical stellar velocity dispersion ($\sim 10 \text{ km s}^{-1}$) and the very low characteristic space density of stars; if the only mass were that contributed by stars, the velocity dispersions of these systems would be lower than they are, especially at the largest radii probed by the observations. Figure 17 shows this fact by plotting alongside the data models based on the assumption that light traces mass and the mass-to-light ratio is the same as that of the Sun (dotted lines), and what one expects if the stars are just test particles in the mass distribution that is predicted by the Cold Dark Matter (CDM) cosmological model (full lines).

Another respect in which dwarf spheroidal galaxies differ from globular clusters is their histories of star formation: whereas all the stars in globular clusters formed in a single burst, in several dwarf spheroidals the stars are known to have a wide spread of ages. Thus dwarf spheroidals have either been capable of sustaining star formation over extended periods, or have experienced more than one burst of star formation.

A prerequisite for star formation is a stock of gas. Globular clusters contain very little gas because winds from the surfaces of member stars are generally moving faster than the local cluster escape velocity v_e . We do not know what the escape velocities of dwarf spheroidals are, but they cannot be smaller than of order twice the velocity dispersion σ , and we have seen that in dwarf spheroidals σ does not decrease outwards as it does in globular clusters. Thus dwarf spheroidals are better able to retain gas, and hence to sustain star formation, than globular clusters. Another factor makes it extremely hard for a globular cluster to retain any gas: twice on each orbit of the Galaxy a globular cluster passes through the Galactic plane. Unless the radius of such a passage is large, gas in the plane will sweep any gas out of the globular cluster.

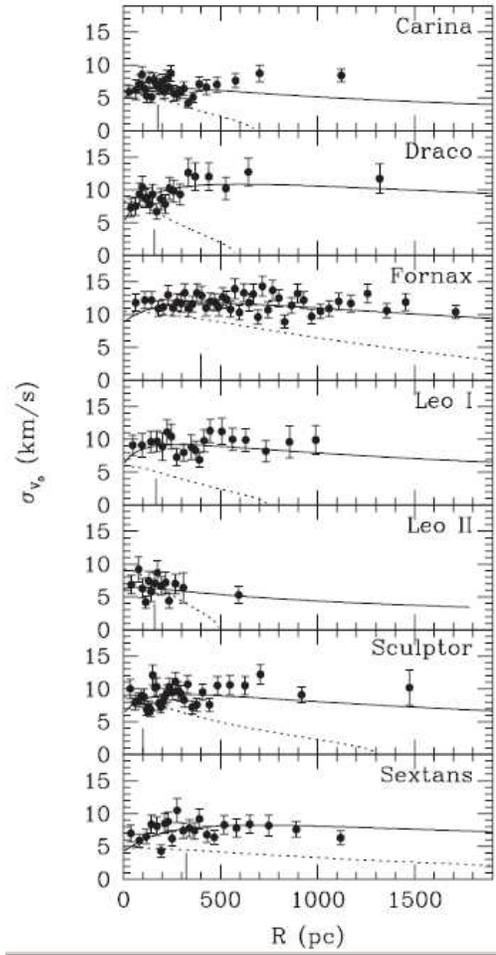


Figure 17: Velocity dispersion as a function of radius in seven dwarf spheroidal galaxies. The dotted lines show the profiles expected if the stars were fair tracers of the mass. The full curves show the prediction of a model in which the mass mass is concentrated in dark-matter particles. (Walker et al., 2007)

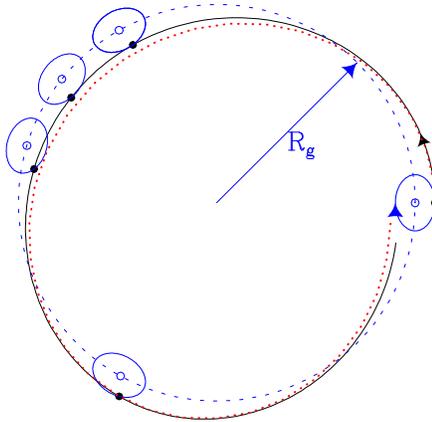


Figure 18: The dotted red curve shows an orbit in a model Galaxy. The full curve is the approximation to this orbit that is obtained by combining anticlockwise circular motion of the guiding centre around the dashed blue circle of radius R_g with clockwise motion around the small ellipses. The larger the ellipse, the greater is the star's random velocity.

Most observed dwarf spheroidals do not contain significant quantities of gas, however. Thus, although they probably retained gas for extended periods in the past, at some stage they lost their gas. The Local Group contains a number of low-luminosity galaxies that still contain gas and star formation; these systems may be the progenitors of dwarf spheroidals. Gas stripped from these galaxies to make dwarf spheroidals may help to sustain star formation in the Galaxy's disc (see below).

Dwarf spheroidal galaxies sometimes possess one or two globular clusters, and some of the Galaxy's complement of clusters have undoubtedly been acquired by stripping such clusters from their original hosts.

7 The disc

Near the Sun we can study the Galactic disc in exquisite detail by measuring the positions, velocities, chemical compositions and ages of individual stars.

It is useful to decompose the velocities of disc stars into two components: circular motion around the Galactic centre of a *guiding centre* and random motion with respect to the guiding centre, which itself can be decomposed into components within and perpendicular to the plane (Figure 18). Interesting correlations are observed between the amplitudes of these random motions and the ages of stars. The older a population of disc stars is, the larger the random velocities of its stars, from which we infer that stars are born on nearly circular orbits within the plane, and over their lives they migrate to more eccentric orbits and orbits with larger inclinations to the plane.

The most metal-poor stars are all old, but not all metal-rich stars are young. This observation contradicts the predictions of the simplest models of the chemical evolution of the disc, in which the interstellar medium starts metal-free and is steadily enriched. Hence these models predict a tight relationship between age and metallicity: the metallicity of a star should simply reflect the metallicity of the interstellar medium at its date of birth. The existence of old, metal-rich stars reflects the fact that at any time the metallicity of interstellar gas decreases as one moves outwards: at small radii, interstellar gas was polluted more rapidly than at larger radii, so high-metallicity stars were born sooner. Old, high-metallicity stars seen near the Sun have migrated here from small radii (Schönrich & Binney, 2009).

In contrast to the case of the bulge, where star-formation all but ceased within a billion years of starting, in the disc star-formation has continued at a slowly declining rate for at least ten billion years. In the simplest model of chemical evolution, a given region of the disc starts with a quantity of gas, which reduces in mass and increases in metallicity as successive generations of stars form and synthesise metals. So long as the time in which the mass of gas significantly reduces is small compared with the time (tens of Myr) required for a generation of stars to produce its harvest of metals, we can predict from this picture the fraction of

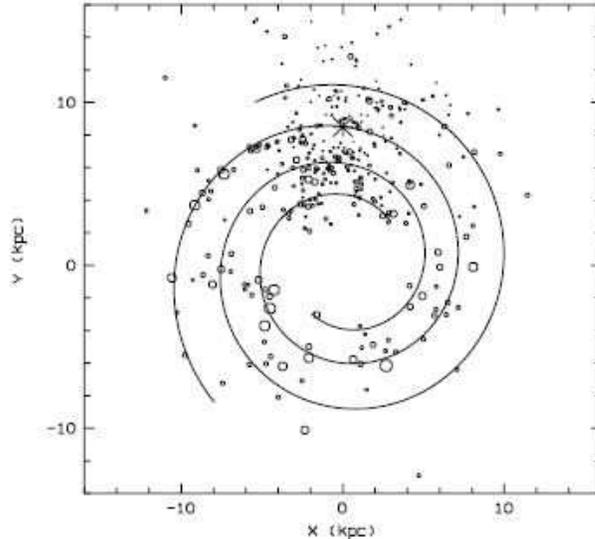


Figure 19: A possible structure of spiral arms traced by star-forming complexes. The Sun is at $(x = 0, y = 8.5)$. Examining this figure one should bear in mind that it is easier to trace features near the Sun than in remote parts of the Galaxy, so the figure shows more detail near the Sun. (From Russeil 2003)

stars that have metallicities in a given band without knowing the history of the conversion of gas to stars: that is, we expect the same metallicity distribution regardless of whether the rate of star formation has been constant, or rapidly decreasing in time, or has paused for extended periods. Unfortunately, this theoretical prediction conflicts with the observed distribution of stars with respect to metallicity in the sense that there are many fewer metal-poor stars than are predicted by the simple model.

There are two possible resolutions of this conflict: either the gas from which the disc formed had non-negligible metallicity, or the disc has been drip-fed with gas at a rate similar to the rate at which it has turned gas into stars. The fact that the star-formation rate has not decreased by a large factor over the disc's life supports the drip-feed hypothesis, as does the identification of external disc galaxies that are gas-poor and bereft of star formation in circumstances in which it would be difficult for them to acquire gas (Chung et al., 2009). Thus there is strong circumstantial evidence that the continuing star formation in the disc is sustained by inflow of gas. On the other hand it is also likely that stars that lived before the disc started to form had pre-enriched its gas to some extent.

7.1 Spiral structure

Our position within the disc, from which lines of sight into the disc are heavily obscured by dust, makes it difficult for us to trace the Galaxy's spiral structure. The dots in Figure 19 show the locations of clusters of young stars that should lie in spiral arms; spiral arms have also been traced in other ways with similar results. In some regions it is clear that the dots lie along a well defined spiral curve, but in other regions the dots could be randomly scattered, or joined by smooth curves with a variety of shapes. The curves in Figure 19 show a four-armed pattern of ridge-lines that provides an acceptable but less than convincing fit to the data. The spiral structure of external galaxies is classified as either "grand-design" or "flocculent"; Figure 19 indicates that it is unclear which designation is appropriate for the Milky Way. Since the disc stars rotate clockwise in the figure, the arms trail, as in external spiral galaxies.

Radio-frequency observations of atomic hydrogen (HI) and carbon monoxide (CO) provide valuable insights into non-axisymmetries in the gas disc, which are jointly generated by spiral structure and the bar. Unfortunately, the interpretation of the data is complex because what is measured is the amount of gas moving with each velocity along each line of sight – Figure 20 shows this distribution of emission by HI for each longitude l and latitude $b = 0$. If the velocity field of the gas were known, the measured line-of-sight

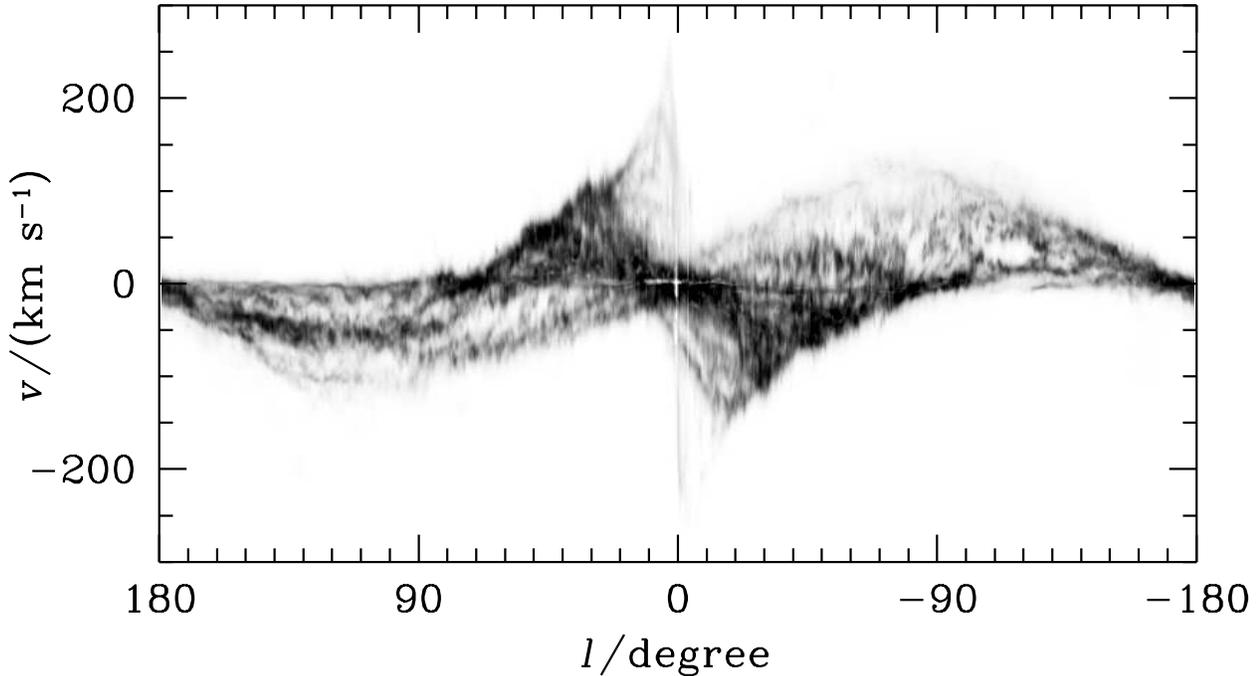


Figure 20: The intensity of emission at latitude $b = 0$ in the 21 cm line of atomic hydrogen. The waviness of the edge of the dark region at $(0 < l < 90, v > 0)$ and $(0 > l > -90, v < 0)$ reflects disturbance of gas clouds from circular orbits by spiral structure. Dark ridges trace individual spiral arms. (From Binney & Merrifield 1998)

velocities could be used to infer the distance to each element of emission, and then we could work out the density of gas throughout the disc; ridges of enhanced density in Figure 20 would correspond to spiral arms. The problem with this program is that we do not know the velocity field a priori, but must determine it from the same data. If gas clouds are assumed to move on circular orbits at a speed $v_c(r)$ that is an unknown function of radius, it is fairly straightforward to determine the appropriate function, but spiral structure ensures that clouds do *not* move on circular orbits, so this procedure is flawed. However, when a theoretical model of a galaxy with spiral structure is “observed” in the way we observe the Milky Way (right panel of Figure 10), spiral arms give rise to ridges of enhanced emission in the theoretical analog of Figure 20. Moreover, spiral structure leads to ripples in the edge of the region of dense emission very similar to those visible in Figure 20. Unfortunately, the potential of this line of enquiry to uncover the Galaxy’s spiral structure has yet to be fully exploited.

Spiral structure is not just decoration for a disc galaxy; it profoundly affects the evolution of the disc because it is associated with a spiral distortion of the galaxy’s gravitational force-field. This distortion deflects the velocities of gas clouds and stars from simple circular orbits. As a result, gas clouds crash into each other and are compressed at points that trace the leading edges of spiral arms. Stars form from the compressed gas, so the mean rate of star formation within the disc depends on the amplitude of the spiral structure. The deflection of stars by the spiral distortion of the galaxy’s gravitational field has several effects. First, it gives rise to the spiral pattern in the density of stars within the disc that itself causes the original spiral distortion of the gravitational field. Second, it is largely responsible for the increase in the random velocities of stars that we discussed above. Third it mixes the disc radially, both by increasing the random velocities of stars, and by causing stars to change their guiding centres. The random motions of gas clouds are strongly damped by cloud–cloud collisions, but the guiding centres of clouds are probably changed by spiral structure just as are those of stars. Hence spiral structure probably radially mixes both the gas and stellar discs. In particular, it is probably responsible for the presence near the Sun of old, metal-rich stars noted above (Sellwood & Binney, 2002).

7.2 Interstellar gas

About half of the Galaxy's stock of interstellar gas is contained in clouds of molecular gas inside the solar circle. The gas density is high in the nuclear molecular disc of radius ~ 200 pc and in the molecular ring of radius ~ 5 kpc, both of which yield prominent features in Figure 8. Molecular clouds consist primarily of molecular hydrogen (H_2), but because H_2 molecules have no convenient spectral lines, molecular gas is invariably traced through molecules of carbon monoxide (CO) or carbon sulphide (CS) which emit readily observed spectral lines. Since the observed molecules are only trace constituents of the clouds, one needs to know their abundance relative to H_2 to infer the mass of a cloud. Unfortunately, these abundances, which depend on a variety of parameters including metallicity, are uncertain. The total mass of molecular gas is of order $10^9 M_\odot$.

The density of molecular gas is very non-uniform, and may be imagined to be concentrated into a large number of discrete molecular clouds – in the lower panel of Figure 8 each cloud generates a vertical streak. The vertical extent of the streak gives the range of velocities within the cloud. This range is found to be roughly proportional to the square root of the total line emission from a cloud, and for a typical cloud of mass $10^4 M_\odot$ is of order 2.5 km s^{-1} (Strong et al., 1988).

The temperature of molecular gas can be estimated from the intensity of emission observed in different spectral lines, and proves to be $\lesssim 30$ K. At this temperature the speed of sound in the gas is $\lesssim 0.3 \text{ km s}^{-1}$ so the motions of gas within each cloud are extremely supersonic. This fact is surprising, because in any fluid supersonic motions are strongly damped. How are the supersonic motions in interstellar clouds maintained? The current view is that individual clouds are transient structures that are constantly forming and disrupting. Clouds assemble when gas streams within the disc collide and gas is compressed. Stars form in the dense gas and then energy released by the most massive and luminous of these stars disperses the remaining gas.

Stars disperse molecular gas in two ways. First they heat it mechanically by blasting it with high-velocity outflowing gas. Second they heat it and dissociate its molecules by exposing it to ultraviolet radiation; this process is not unlike the way morning sun burns away a ground fog. The Galaxy converts gas to stars rather slowly because a molecular cloud is dispersed after only a small fraction of its mass has been turned into stars. Much remains to be understood about the internal structure and dynamics of molecular clouds and their relation to star formation.

Comparison of Figures 8 and 20 shows that the Galaxy's stock of HI is less centrally concentrated than the molecular gas: features at $l \gtrsim 80^\circ$ that are prominent in HI are hard to trace in CO, while the nuclear molecular disc at $|l| < 2^\circ$ is scarcely visible in HI. The greater central concentration of CO is related to the way in which dust shields gas from ultraviolet radiation. The ultraviolet photons that dissociate H_2 molecules into HI are strongly absorbed by dust grains. At large galactocentric radii the gas density is lower, so the dust grains are further apart and ultraviolet photons have a greater chance of penetrating deep into a cloud by slipping between dust grains. Hence at large radii most of the gas is in atomic form. Since stars can only form from cold, dense molecular gas, a low fraction of molecular gas implies a low rate of star formation at large radii.

A significant fraction of the Galaxy's HI probably lies of order a kiloparsec above or below the plane, because large-scale outflows of gas from regions of recent star formation push gas away from the plane and the gas takes a significant time to fall back to the plane. We observe this process in action in external galaxies that resemble the Milky Way and there are indications that it occurs in the Galaxy too, but interpreting the relevant observations is hard in the case of the Galaxy.

7.3 Moving groups, associations and star clusters

When a molecular cloud collapses, a cluster of stars is formed with a mass that depends on the mass of the parent cloud. Low-mass clouds yield small clusters that are identified observationally as *OB associations*; groups of luminous, short-lived stars. Rare, massive clouds yield massive *open clusters*.

While the original molecular cloud was bound by its gravitational field (that is why it collapsed to form stars), the stars to which it gives birth are usually not gravitationally bound to each other, because so much of the cloud's mass (and hence gravity) has been dispersed by the luminous stars. If the association is not bound, it gradually disperses. When it is young it is easily identified by the presence within it of luminous, short-lived stars. Once these have died the association can only be identified from the velocities of the remaining stars, which will be very similar, even though the stars may cover a large part of the sky. At this

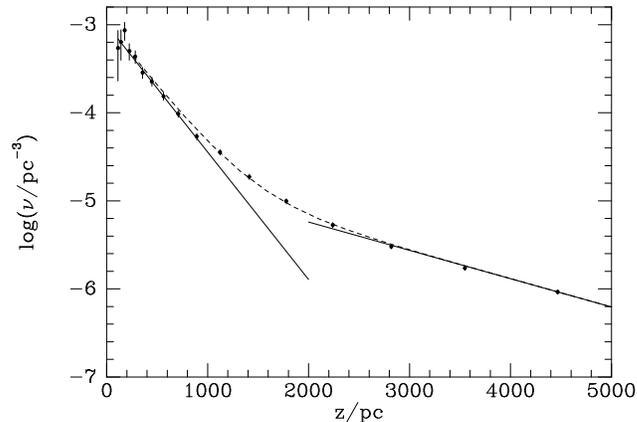


Figure 21: The density of stars at the Sun’s radius as a function of distance $|z|$ from the plane. The data points (from Gilmore & Reid 1983) can be fitted by a sum of two exponential profiles (with scale heights 300 pc and 1350 pc); the sum is shown by the dashed line, while straight lines show the individual exponentials. (From Binney & Merrifield 1998)

stage the association is called a *moving group*. It is thought that *all* stars are born in associations, most of which disperse. In the next decade the number of accurately known velocities of stars will increase enormously, and we expect to be able to unravel much of the history of star formation in the disc by identifying large numbers of groups of stars that formed together but are now dispersed around the disc.

It sometimes happens that many of the stars formed during the collapse of a molecular cloud remain bound after luminous stars have blown away the remaining gas; an open cluster has formed. Open clusters are extremely useful because they contain stars of a variety of masses that all have very similar ages and chemical compositions.

Stars would evaporate (see §5) from even an isolated open cluster at an appreciable rate because the timescale for evaporation decreases with cluster mass. Encounters with molecular clouds and spiral arms significantly hasten the loss of stars by open clusters: the gravitational field of a passing cloud or arm shakes the cluster and decreases the binding energies of its stars. Consequently, open clusters often live less than a billion years.

7.4 The thick disc

A plot of the density of disc stars versus the logarithm of distance from the plane appears to consist of two straight-line segments: within 500 pc of the plane, a straight-line fit implies that the density of stars decreases with distance z like e^{-z/z_0} with scale-height $z_0 \simeq 300$ pc, while around $z = 1.5$ kpc a straight-line fit yields $z_0 \simeq 1$ kpc (Figure 21). This observation suggests that the disc is made up of two sub-components, the *thin disc* with scale height 300 pc, and the *thick disc* with scale height 1 kpc. Studies of the velocities and chemical compositions of stars near the Sun support this interpretation: the thin disc contains stars of all ages and a range of metallicities greater than a factor 3–4 below solar, while the thick disc consists of stars that are all old and are metal-poorer than the Sun by a factor in excess of 3–4.

While the thin disc is clearly the cumulative product of the star formation that we see continuing today, the origin of the thick disc is less clear. One possibility is that it started life as a thin disc and became thick when a massive object such as a satellite galaxy spiralled towards the centre about 9 Gyr ago, scattering disc stars onto more eccentric and more inclined orbits as it went. Another possibility is that it is made up of stars that formed before type Ia supernovae had synthesised much iron (Schönrich & Binney, 2009).

7.5 Local mass density

Individual stars near the Sun oscillate perpendicular to the plane with amplitudes that are jointly determined by the speeds at which the stars pass through the plane and the strength of the disc’s gravitational field,

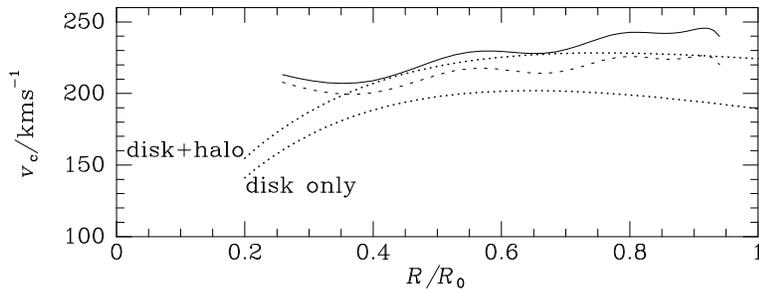


Figure 22: The wavy curves show the circular speeds one infers from tangent velocities listed in Malhotra (1995) under the assumption that the local circular speed is $\Theta_0 = 241 \text{ km s}^{-1}$ (full curve) or $\Theta_0 = 220 \text{ km s}^{-1}$ (dashed curve). The undulations are artifacts that arise because gas clouds have been assumed to move on circular orbits rather than the slightly elliptical orbits associated with spiral structure (cf Figure 20). The lower dotted curve shows the circular speeds generated by a disc in which the surface density decreases exponentially with radius with a scale length $r_d = 2.5 \text{ kpc}$. In this disc the local surface density is $\Sigma_{1.1} = 56 M_\odot \text{ pc}^{-2}$. The upper dotted curve is for the combination of this disc with a dark halo with characteristic mass $M_0 = 6 \times 10^{11} M_\odot$ and scale length $r_s = 22 \text{ kpc}$.

which is proportional to the disc’s local mass-density. Hence by measuring the vertical speeds of stars and the vertical thickness of the disc, one can weigh the disc. This programme has yielded three numbers: the mass density in the plane ($0.10 \pm 0.01 M_\odot \text{ pc}^{-3}$; Holmberg & Flynn 2000), the amount of mass that lies within 1.1 kpc of the plane ($74 \pm 6 M_\odot \text{ pc}^{-2}$; Holmberg & Flynn 2004), and the surface density of the disc ($56 \pm 6 M_\odot \text{ pc}^{-2}$). The surface density of the disc is smaller than the estimate of the mass that lies within 1.1 kpc of the plane because the models used to obtain these estimates included an allowance for a spherical “halo” of dark matter (to be discussed below). The quoted uncertainties of the individual numbers indicate that the vertical dynamics of the disc is consistent with the existence of a dark halo, but does not provide compelling evidence for it. If we take the density in the plane to be $0.1 M_\odot \text{ pc}^{-3}$ and assume that away from the plane the density falls off like the star density plotted in Figure 21, then we predict that within 1.1 kpc of the plane there should be $61 M_\odot \text{ pc}^{-2}$, so light is a reasonable tracer of mass near the disc.

8 The dark halo

The circular speed, v_c , within the Galaxy can be extracted from data like that shown in Figure 20 and knowledge of the circular speed at the location of the Sun, Θ_0 . The latter is not securely known; the most reliable value is obtained by measuring the apparent motion of Sgr A*, which reflects the motion of the Sun. If the distance to the Galactic centre is 8.3 kpc, the motion of Sgr A* implies that $\Theta_0 = 241 \pm 11 \text{ km s}^{-1}$ (McMillan & Binney 2009). The full curve in Figure 22 shows the resulting plot of circular speed versus radius for $\Theta_0 = 241 \text{ km s}^{-1}$, while the dashed curve shows the circular speeds if $\Theta_0 = 220 \text{ km s}^{-1}$. These estimates are based on the assumption that gas clouds move on circular orbits. Actually spiral arms perturb the velocities of clouds from v_c by of order 7 km s^{-1} , and neglect of this effect gives rise to the undulations in the curves of v_c in Figure 22. If these undulations are neglected, it is evident that v_c is gently rising interior to the Sun’s location, the rise being more pronounced for the larger value of Θ_0 .

The surface brightnesses of external galactic discs are found to decrease outwards as e^{-r/r_d} , where r_d is the *disc scale length*. If we assume that the surface brightness of the Galaxy’s disc obeys the same law, then r_d can be determined from counts of stars in a survey of the infrared sky; the result is $r_d \simeq 2.5 \text{ kpc}$ (Robin et al. 2003). If we now assume that the local surface density is $56 M_\odot \text{ pc}^{-2}$ and that mass follows light, the mass of the disc, $M_d = 6.1 \times 10^{10} M_\odot$, follows, and we can calculate the circular speeds that the disc alone generates. The lower dotted curve in Figure 22 shows these speeds. This curve not only lies below the observationally determined curve, but interior to the Sun’s location it is gently falling, rather than rising. In fact, at the Sun the gravitational force generated by the disc is smaller than the measured rotation curve requires by a factor $(190/241)^2 = 0.62$. It is believed that the balance of the required force is made up by a

dark halo.

Evidence for dark halos first emerged from measurements of the velocities of galaxies that occur in clusters of galaxies: already in 1933 the Swiss astronomer Fritz Zwicky pointed out that gravity could prevent the galaxies of clusters flying apart only if the clusters contained almost ten times as much mass as was expected to reside in the galaxies' stars. In the 1980s the evidence for dark halos around individual galaxies was made solid by studies of radio emission by atomic hydrogen (HI) around galaxies – many spiral galaxies have discs of HI that extend far beyond the optical image of the galaxy. The measured velocities are consistent with gas clouds that are moving on circular orbits around the galaxy, and the speed of these orbits does not decline with radius $r^{-1/2}$ as would be expected if the galaxy's mass were concentrated in the optical image, but is roughly independent of radius, which implies that the clouds are moving through an extended distribution of matter in which density $\rho \propto r^{-2}$ (van Albada et al., 1985).

Unfortunately a major difficulty obstructs a convincing measurement of whether the circular speed of the Milky Way stays high beyond the Sun, as Figure 22 suggests. The problem is determining the radius r of any object whose velocity can be measured. In an external galaxy r follows trivially from the object's position on the sky and the galaxy's inclination to the line of sight. In the Milky Way this geometrical argument fails completely, and a direct distance determination is needed. Until recently, the best available technique has been to infer the distance from the apparent brightness of a star whose luminosity can be inferred from its spectral type. This approach is limited both by the precision with which the luminosities of stars can be inferred from spectra, and uncertainty in the amount of obscuring dust along the line of sight. Distances based on “trigonometric parallaxes” (the tiny shift on the sky in the position of a star as the Earth moves around the Sun) are in principle much more reliable, and are gradually becoming available to sources sufficiently distant to probe the Galaxy's rotation curve beyond the Sun (e.g., Reid et al. 2009). However, to this point the evidence is no more than consistent with the circular speed remaining fairly flat beyond the Sun, as we would expect if the Milky Way was a typical spiral galaxy.

Powerful support for the concept of a dark halo is provided by cosmology: a wealth of data, from measurements of the cosmic microwave background, to measures of the clustering of galaxies, and to observations of distant supernovae, point to a cosmos in which the dominant source of gravity is particles that do not interact with electromagnetic waves (and are therefore invisible or “dark”) and early on have small random velocities (and thus are “cold”). Simulations of the clustering of these particles under the influence of their mutual gravitational attraction indicate that galaxies should be embedded in dark-matter halos with a universal density profile that is roughly of the form $\rho = M_0/[4\pi r(r_s + r)^2]$, where the “scale radius” and characteristic mass M_0 vary from halo to halo but are strongly correlated with one another, so dark halos can be considered to form a one-parameter family quantified by M_0 (Navarro et al., 1997). For the Milky Way's halo these quantities have been estimated to be $r_s \sim 22$ kpc and $M_0 \sim 6 \times 10^{11} M_\odot$ with uncertainties of order a factor of two (Klypin et al., 2002). The mass of the dark halo within the “virial radius” (~ 260 kpc) at which dark matter should cease to be in a statistically steady state is roughly $1.6M_0 \sim 10^{12} M_\odot$. Near the Sun this halo contributes $\sim 14 M_\odot \text{ kpc}^{-2}$ to the mass within 1.1 kpc of the plane, which is consistent with the difference between the dynamically determined mass within this distance of the plane, $(74 \pm 6) M_\odot \text{ kpc}^{-2}$, and the estimated contribution to this surface density from stars and interstellar gas, $(56 \pm 6) M_\odot \text{ kpc}^{-2}$. The upper dotted curve in 22 shows the circular speeds generated by the combination of an exponential disc and this dark halo. These speeds are in rough agreement with the observationally estimated ones if the local circular speed is $\Theta_0 \sim 220 \text{ km s}^{-1}$, but are on the low side if Θ_0 is as large as its currently favoured value.

We know from experiments with nuclear interactions that dark matter exists: twenty six years after Wolfgang Pauli predicted the existence of neutrinos to conserve energy and momentum in 1930, they were experimentally detected. Recent measurements of the flux of neutrinos generated in the Sun have established that neutrinos have non-zero rest masses, so there must be a contribution to the mass of the Galaxy from neutrinos. However, the masses of neutrinos are so small that these particles had large random velocities when gravitational clustering began, with the result that they cannot comprise the dark halos of galaxies. None the less, their existence is a proof of principle: Nature does include particles that only interact through the “weak” and gravitational forces. Consequently, it is reasonable to ask whether other, more massive, particles exist with only these interactions. Theories of sub-atomic physics that are firmly based on experimental fact predict the existence of such particles. These particles are thought to be ~ 100 times as massive as a proton (consequently about as massive as a silver atom). Because they are so much more massive than a neutrino, they are much less likely to be made in a nuclear reaction, so evidence for such particles did not surface in

parallel to evidence for neutrinos.

The local density of dark matter, $\sim 4.3 \times 10^{-19} \text{ kg m}^{-3}$, corresponds to a number density $\sim 2.7 \times 10^3 \text{ m}^{-3}$ of particles with 100 times the proton’s mass. Thus as the Earth moves at 30 km s^{-1} on its orbit around the Sun, which is itself moving through the dark halo at $\sim 240 \text{ km s}^{-1}$, vast numbers of dark-matter particles must be streaming through our laboratories. In fact the flux should be of order $6.4 \times 10^8 \text{ m}^{-2} \text{ s}^{-1}$. These particles interact with ordinary matter through interactions that are not so much “weak” as short-range. Consequently, as a dark-matter particle whizzes through a laboratory, it has a small chance of smashing into an ordinary atom. If, however, an impact does occur, it is with such violence that it can readily be detected. If the target area of each ordinary atom is $10^{-48} A^2 \text{ m}^2$, where A is the number of neutrons and protons in the nucleus, collisions will occur at a rate of order one per tonne of ordinary matter per year. Searches for these events are currently under way at several laboratories around the world, and a couple of collisions may even have been observed (Ahmed et al., 2010).

Glossary

2MASS – the 2-micron all-sky survey. A ground-based survey of near-infrared light (which is dominated by starlight).

b Galactic latitude

CO – Carbon monoxide. Widely used as a tracer for the much more abundant H_2 molecule.

COBE – *Cosmic Background Explorer*; a NASA satellite that surveyed the sky at near to far infrared wavelengths and discovered the fluctuations in the density of the early universe from which galaxies later grew. Its Diffuse Infrared Background Experiment instrument (DIRBE) provided the first clear view of the large-scale distribution of Galactic stars.

corotation radius – the radius at which a circular orbit in the underlying axisymmetric potential moves around at the same angular speed as a non-axisymmetric disturbance such as a bar or a spiral arm.

dark matter – matter comprising particles that interact only by gravity and the “weak” force. Neutrinos are one constituent of dark matter but observations imply that the major constituent is much more massive particles.

disc cluster – a globular cluster with $[\text{Fe}/\text{H}] \gtrsim -1$.

dwarf spheroidal galaxy – a low-luminosity galaxy that has no interstellar gas or ongoing star formation. Like globular clusters, dSph galaxies orbit through, and are tidally stripped by, the Galaxy. Unlike globular clusters, most of their mass is made up of dark matter.

$[\text{Fe}/\text{H}]$ – the standard measure of metallicity.

guiding centre – an imaginary point on a circular orbit around which a star on an eccentric orbit gyrates.

halo cluster – a globular cluster with $[\text{Fe}/\text{H}] \lesssim -1$.

HI – atomic hydrogen. Formed when H_2 molecules are dissociated by photons of ultraviolet light. Readily detected by its hyperfine transition at 21 cm wavelength.

H_2 – molecular hydrogen. Forms when hydrogen atoms meet on the surface of a dust grain.

kiloparsec – a thousand parsecs, roughly 3 0000 light years.

l – Galactic longitude.

magnitude – a measure of the apparent brightness of a star on a logarithmic scale: an increase of 2.5 magnitudes corresponds to a *decrease* in flux by a factor 10.

metallicity – the abundance of elements heavier than helium relative to iron. Since these elements are made in stars, the metallicity of interstellar gas has increased since the birth of the Galaxy. It is commonly quantified by the iron abundance $[\text{Fe}/\text{H}]$, which is defined to be $\log_{10}[(n_{\text{Fe}}/n_{\text{H}})_{*}] - \log_{10}[(n_{\text{Fe}}/n_{\text{H}})_{\odot}]$, so $[\text{Fe}/\text{H}] = -1.5$ implies that in the star Fe is less abundant than in the sun (relative to H) by a factor $10^{1.5} = 31.6$.

nuclear molecular disc – a gas-rich disc centred on Sgr A* and roughly 200 pc in radius. It has a high rate of star formation.

parallax – the shift in the position of a star on the sky as the Earth moves round the Sun.

parsec – standard astronomical unit of distance equal to 3.08×10^{16} m \simeq 3 light years. At this distance a star moves on the sky around an ellipse with semi-major axis 1 arcsec.

relativistic – moving at a speed comparable to the speed of light. Shock waves caused by supernova explosions accelerate electrons and ions to relativistic speeds.

S2 – a luminous star whose orbit around Sgr A* has been tracked for a complete cycle.

Schwarzschild radius – The radius, equal to $2GM/c^2$, interior to which light cannot escape from the gravitational field of a point mass M .

Sgr A* – the radio source associated with the black hole at the very centre of the Galaxy.

supernova remnant (SNR) – bubble of expanding hot gas around the site of a supernova explosion.

tidal stream – a highly elongated distribution of stars that have been torn from a satellite galaxy or a star cluster by the Galaxy's gravitational field.

thick disc – disc formed by old stars with relatively low abundances of iron relative to oxygen and carbon. As the name indicates, the vertical scale height of this disc is a factor 3–4 larger than that of the thin disc.

thin disc – disc formed by stars in which the abundances of iron and oxygen have a similar ratio to that in the Sun. The vertical scale height of this disc is ~ 300 pc.

type Ia supernova – an explosion of a carbon-oxygen white dwarf star that is driven by the conversion of the star's atoms into nickel and iron atoms. The star is completely shattered by the explosion.

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Biographical Sketch

James Binney earned his BA degree at the University of Cambridge in 1971. After two semesters in Freiburg i Breisgau he wrote a doctoral thesis on the formation of galaxies in Oxford, graduating in 1975. He was a Lindemann Fellow at Princeton University 1975/6, a Fellow by Examination of Magdalen College Oxford 1975–1979, a Visiting Assistant Professor at Princeton University 1979–1981 and has been on the Faculty of Oxford University and a Fellow of Merton College since 1981. He was awarded the Maxwell Prize for 1986 by the Institute of Physics and the Brouwer Award for 2003 by the American Astronomical Society. In 2000 he was elected a Fellow of the Royal Society of London. His books include *Galactic Dynamics* with Scott Tremaine (Princeton University Press 1987 & 2008) and *Galactic Astronomy* with Michael Merrifield (Princeton University Press 1998).

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