2 Introduction

The blackout of Los Angeles from 1942 enabled Walter Baade (1944) to resolve the brightest stars in M31 and two of its companions. He found them to be red giants, similar to those seen in globular clusters, rather than the blue giants that are the most luminous stars near the Sun. Baade concluded galaxies comprise two stellar populations, *Population I* typified by the Solar neighbourhood, and *Population II* typified by globular clusters. He assumed that blue giants are young because they are associated with dust and gas, so he inferred that Population I is still being formed, while Population II was formed in the past.

In the years between Baade's seminal paper and the Vatican conference in 1958 the concept of a stellar population struck deep roots. Spectroscopic observations and the emerging theory of stellar evolution showed that Population I contains young, metal-rich stars, whereas Population II stars are all old and metal-poor. Population I stars are all on nearly circular orbits, whereas Population II stars are generally on highly inclined and/or eccentric orbits. Moreover, within Population I the ages, metallicities and random velocities of stars are correlated in the sense that younger, more metal-rich stars have orbits that are more nearly circular than those of older, more metal-poor stars.

Thus by 1958 Baade's original simple dichotomy had blossomed into a concept that connects stellar evolution and the progressive enrichment of the interstellar medium (ISM) with heavy elements, to the pattern of star formation in the Galaxy and the Galaxy's dynamical evolution. Much of contemporary astrophysics is still concerned with using this connection to infer the history of galaxies, especially our own.

At this point it is useful to define two terms. A *simple stellar population* is a group of stars that are formed at a single time from gas of given chemical composition. Globular clusters are the objects that most nearly realise the definition of single stellar population. Galaxies always have more complex stellar populations. For example, the Galactic bulge contains stars that have a measurable spread in age, even though they are all old, and cover a significant range in metallicity. We can consider a *compound population* such as that of the bulge to be a superposition of a large number of simple stellar populations. The population of the solar neighbourhood is a compound population that differs from that of the bulge in that it contains very young stars as well as old ones.

An obvious question is whether the compound population of the solar neighbourhood can be represented as a sum of simple stellar populations, one for each time in the history of the disc. Remarkably this is not possible because the stars of a given age have a significant spread in metallicity.

Within any annulus around the Galactic centre, interstellar gas is believed to be well mixed and to have a well-defined metallicity, which increases over time, most rapidly at small galactocentric radii. Therefore the stars that form in an annulus within a small time interval constitute a simple stellar population. The spread in metallicity of the stars near the Sun that have a given age implies that the simple stellar populations that form in different annuli mix over time. This mixing is probably driven by spiral structure and the Galactic bar, so by decomposing the compound stellar population of the disc into simple stellar populations and taking account of the uncertainties affecting metallicities and stellar ages, it should be possible to learn about the Galaxy's dynamical and chemical history.

So far the word *metallicity* is used as if it were a one-dimensional variable. In fact, while stars that are deficient relative to the Sun in, say, iron by a factor 100 will be strongly deficient in sodium or magnesium by a substantial factor, that factor may differ appreciably from 100, and we can learn a lot from what that factor actually is.

The basic application of this idea is to measure $[\alpha/\mathrm{Fe}]$[1], which is the abundance relative to iron of the α nuclides (^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca). The α nuclides are synthesised alongside Fe in stars more massive than $\sim 8\,M_\odot$ that explode as *core-collapse* supernovae $\lesssim 30\,\mathrm{Myr}$ after the star's birth, scattering a mixture of α nuclides and Fe into the interstellar medium (ISM). Consequently, any episode of star formation that lasts longer than 30 Myr will contain stars with both α nuclides and Fe synthesised in massive stars that formed earlier in the episode. Some fraction of stars with masses $< 8\,M_\odot$ explode as type Ia supernovae $\sim 1\,\mathrm{Gyr}$ after the star's birth, and these supernovae scatter mainly Fe into the ISM. So if a star-formation episode lasts longer than 1 Gyr, it can lead to the formation of stars enhanced in Fe relative to the α nuclides, or low $[\alpha/\mathrm{Fe}]$. In general, Population II stars have higher $[\alpha/\mathrm{Fe}]$ than Population I stars, indicating that the objects to which they belong formed on timescales shorter than 1 Gyr. In the case of globular clusters this deduction can be verified by showing that the cluster's stars are distributed in the colour-magnitude diagram as we would expect if they were all formed at the same time. This time-scale of 1 Gyr is well established in the solar vicinity, but might be much smaller in other environments and other types of galaxies.

The gas clouds that give rise to low-mass star clusters and associations may be enriched by only a handful of supernovae, with the result that many of the cluster's stars have abundance patterns that reflect peculiarities of the enriching supernovae. Thus if one looks in great detail at the abundances of stars in a given cluster, one may see a pattern that is unique to the cluster, in the same way that

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[1] where the bracket notation [X/Y] refers to the logarithmic ratio of the abundances of elements X and Y in the star minus the same quantity in the Sun

the members of a particular tribe may reveal a characteristic genetic sequence. Moreover, clusters and associations are subject to disruption, and stars that were once in a cluster may now be widely distributed within the Galaxy. By looking for abundance patterns – genetic fingerprints – in field stars, it may be possible to identify members of a cluster that was disrupted long-ago.

Thus depending on the criteria used to define a stellar population, it can range in scale from the members of a disrupted star cluster to Baade's original Population I, which is made up of stars formed over 10 Gyr from material that has a wide range of abundances of Fe and the α nuclides. However, in every case the members of a stellar population have a common history and similar dynamics; moreover, with appropriate observational material they can usually be identified from their spectra with little regard to their phase-space positions. Galaxy models of the sophistication that will be required in the middle of the next decade to make sense of the Gaia catalogue, will probably interpret the Galaxy as made up of a series of related populations, each with its own distribution function (DF) $f(x, v, t)$ that gives the probability density with which the population's stars are distributed in phase space at time t. As the Galaxy ages, diffusive phenomena will cause f to become less sharply peaked in phase space, and therefore the DFs of different populations to overlap more and more. Notwithstanding the overlapping of their DFs, the populations will retain their integrity because their member stars will be identifiable by their chemical imprints.

Observational techniques which have traditionally been restricted to targets in the Galaxy are becoming feasible for increasingly distant objects. In particular, we are beginning to be able to study the stellar populations of Local Group galaxies in sufficient detail to be able to decipher their hosts' star-formation histories. This work gives insight into the histories of galaxies that cover a wide range of morphological types, from gas-rich star-forming galaxies such as the Large Magellanic Cloud and IC 1613, to red and dead galaxies such as M32. Moreover, a large fraction of the current star-formation in the Universe takes place in groups similar to the Local Group, and in fact in galaxies similar to our own, so understanding the Local Group is the key to understanding a significant fraction of the Universe.

The smaller galaxies of the Local Group show abundant evidence of interactions with the Group's two massive members, M31 and the Galaxy, so studies of Local Group stellar populations should reveal the impact that interactions have on star-formation rates and the build up of heavy elements.

A cosmological framework is essential for any discussion of galaxy formation, and the Lambda cold dark matter (ΛCDM) theory provides the standard framework. In this theory baryons comprise $17 \pm 1\%$ of the matter in the Universe (Spergel et al., 2007), the rest being made up of matter that does not experience strong or electromagnetic interaction but at redshift 3100 begins to clump and eventually forms the dark halos within which visible galaxies form after redshift ~ 10. Vacuum energy ('dark energy'), currently dominates the mean cosmic energy density: it contributes $76.3 \pm 3.4\%$ of the energy density with $\sim 24\%$ of the energy density contributed by matter (Spergel et al., 2007); baryons account for only 4.6% of the energy density. On account of the repulsive gravitational force that vacuum energy generates, the expansion of the universe has been accelerating since a redshift ~ 0.5.

Events similar to those we hope to uncover through studies of Local Group stellar populations, can be observed as they happen at redshifts 0.5–3. These facts make it important to address the question 'what does the Local Group look like to observers who see it at redshifts 0.5, 2 or 3?' This is a thoroughly non-trivial question, but one that could be answered given a sufficient understanding of the Local Group's stellar populations. Answering this question would enable our understanding of high-redshift observations to take a big step forward, for we would then know which objects were evolving towards analogues of the Local Group, and which will merge into rich clusters of galaxies. So the stellar populations of the Local Group are templates from which a much broader understanding of the Universe can be fashioned.

In this Report, we examine the issues raised above as follows. In Section 3 we examine the current state of our knowledge of the structure of the Galaxy, and our knowledge of the processes which have shaped and which continue to shape its stellar populations and gas. At the end of Section 3 we sketch the current picture of how the Galaxy was assembled from its building blocks. In Section 4 we describe how the Galaxy can be used as a laboratory in which to study the processes that shape galaxies, and to constrain theoretical models of galaxy formation and evolution. In the course of Sections 3 and 4, we identify a number of limits on our current knowledge, and hint at future work that would overcome these. These issues are brought into sharp focus in Sections 5 and 7, where we identify the top remaining questions, and suggest how possible solutions might be provided by investment in new facilities, planned and yet to be planned. In Section 6 we review ground- and space-based facilities that have played and/or will play a major role in achieving our scientific goals. The major recommendations of the Working Group are drawn together in Section 7.

Since the original motivation for this Report was a desire on the part of ESO and ESA to consider projects that would complement the Gaia mission, the panel's expertise lays primarily in stellar and dynamical astronomy and this fact may have led to a relative neglect of such important areas as high-energy astrophysics and studies of the interstellar medium.

3 Outline of the current state of knowledge of the field

3.1 The main structures of the Galaxy

Our Galaxy is a late-type spiral, as is directly evident from the high concentration of stars, gas and dust into a narrow strip strung across the night sky. Just as directly, we know from the changing surface brightness of this flattened structure with longitude, that the Sun is at a significant distance from the centre of the Galaxy. Our best estimate of that distance has been lowered gradually over the time-scale of a generation of astronomers: the most recent value for 7.62 ± 0.32 kpc (Eisenhauer et al., 2005), to be compared with the figure of 10 kpc accepted 40 years ago.

The Galaxy is conventionally decomposed into: (i) a bar/bulge that has a luminosity $1 \pm 0.3 \times 10^{10} L_{\odot}$ and extends out to ~ 3 kpc (Launhardt et al., 2002); (ii) a nearly spherical halo that extends from with the bulge out to of order 100 kpc and is studded with globular clusters; (iii) a disc that defines the Galactic plane and is probably confined to radii $R \lesssim 15$ kpc. The disc is often decomposed into two components, a *thin disc*, in which the density falls with distance $|z|$ from the plane exponentially with scale height $\sim$ 300 pc and a *thick disc*, which is characterised by a vertical scale height $\sim$ 900 pc (Cabrera-Lavers et al., 2005; Jurić et al., 2008). The thin disc is patterned into spiral arms but even now, the final word on the number and positioning of the arms present has not been spoken. Beyond the Sun the thin disc is warped.

The baryonic mass of the Galaxy is thought to be less than $\sim 10^{11} M_{\odot}$, with 3/4 of it in the Galactic disc, and nearly all the rest in the bulge. Sgr A*, the black hole at the centre of the Galaxy, is estimated to have a mass of $(3.6 \pm 0.3) \times 10^{6} M_{\odot}$ (Ghez et al., 2005, adopting the Eisenhauer et al. (2005) distance).

The major mass component in the Galaxy is believed to be the *dark-matter halo*. This is constrained by measurements of the space motions of Galactic satellites and remote globular clusters, and is thought to be $1 - 3 \times 10^{12} M_{\odot}$ (Wilkinson & Evans, 1999; Sakamoto et al., 2003; Battaglia et al., 2005). The mass within 50 kpc, i.e. the distance to the Large Magellanic Cloud (LMC), is only about a quarter of the total (Sakamoto et al., 2003, $5 - 5.5 \times 10^{11} M_{\odot}$). The dark-matter radial profile is much shallower (roughly $\propto R^{-2}$) than that of the luminous Galactic disc component for which is modelled by an exponentially decreasing surface density, with scale length $2 - 3$ kpc (e.g. Drimmel & Spergel, 2001; Robin et al., 2003; Jurić et al., 2008).

3.1.1 The halo

The halo comprises old stars that have heavy-element abundances less than a tenth of the solar value. Its radial density profile is close to a power law $\rho \propto r^{-2.8}$ and it is slightly flattened at the Galactic poles to axis ratio ~ 0.8 (Jurić et al., 2008). Despite being flattened, near the Sun its net rotation is consistent with zero (Figure 1); further out it may rotate slightly in the opposite sense to the disc (Carollo et al., 2007).

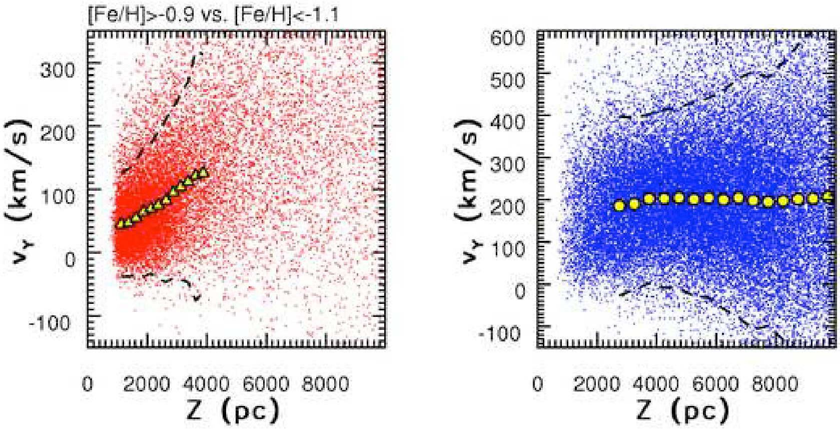

Figure 1: Top row Fig 11 of Ivezic et al. (2008). The rotational velocities of 18 000 stars with [Fe/H] > -0.9 (left) or [Fe/H] < -1.1 (right) plotted against height $|z|$. Symbols indicate medians and dashed lines 2σ boundaries at fixed $|z|$. Stars plotted in the left panel are associated with the disc and those in the right panel with the halo (see Figure 3).

Bell et al. (2008) find that a smooth model of the halo's luminosity density can account for only $\sim 60\%$ of the total luminosity: the halo is rich in substructure. Some substructures are certainly the debris of objects that have been tidally shredded by the Galaxy (Section 3.3.6 below), as is evidenced by the tidal streams of the Sgr dwarf spheroidal galaxy, which wraps more than once around the Galaxy (Chou et al., 2007) and of the Magellanic Clouds, which arches right over the southern hemisphere (Putman et al., 2003). The globular clusters Pal 5 and NGC 5466 are known to have significant tidal tails (Odenkirchen et al., 2002; Belokurov et al., 2006a) and an exceptionally long and narrow tail suffers from disputed parenthood (Belokurov et al., 2007b; Jin & Lynden-Bell, 2007; Sales et al., 2008).

The majority of halo stars are on plunging orbits, so near the Sun we see stars that spend most of their time at large galactocentric radii as well as stars that spend time well inside the solar circle. On account of the prevalence of plunging orbits, any gradients in the halo are of necessity weak.

The metallicity distribution of halo stars is broad, but peaks at abundances far below solar: in the inner halo the peak lies around [Fe/H] $= -1.6$, while further out it lies near [Fe/H] $= -2.2$ (Carollo et al., 2007). Near the Sun, halo stars are found with metallicities down to at least [Fe/H] $= -5.5$ (Frebel et al., 2005). Recently Carollo et al. (2007) revived the idea that out to distances $\sim 4\,$kpc, the stellar halo may be described by two broadly overlapping components. The inner component has a peak metallicity [Fe/H] $= -1.6$, is flattened and with a small amount of prograde rotation, while the outer component has a lower peak metallicity ~ -2.2, is rounder and in net retrograde rotation. The dominance of the inner-halo population in the solar neighbourhood would explain why extremely metal-poor stars in magnitude limited objective-prism surveys are so rare.

Extremely metal-poor stars (*EMP stars*) are of special interest as they give insight into the formation of the first stars. They show some surprising properties:

- Around 20% of EMP stars show unexpected large [C/Fe] and often [N/Fe] enhancements with respect to the Sun (the so-called *carbon-enhanced metal-poor stars*, Beers & Christlieb, 2005). For the most metal-poor ones, this has been taken as evidence of a different initial mass function (IMF), or for pollution by stellar winds from massive stars even at $Z = 0$, as may be possible if such stars were fast rotators (Meynet, 2007).
- Cayrel et al. (2004) showed that normal (i.e., not C-enhanced) stars with $-4 <$ [Fe/H] < -2 display a striking degree of chemical homogeneity (Figure 2). This uniformity challenges the view that the whole Galactic halo formed from the successive swallowing of smaller stellar systems with independent evolutionary histories (Gratton et al., 2003).
- Those same stars have large [N/O] ratios, and show a large scatter in [N/O] (roughly 1 dex) as well as in the r- and s-process elements (Spite et al., 2005). This observation has triggered the development of models of the effect of rotation on stellar evolution at very low metallicity (Meynet, 2007; Limongi & Chieffi, 2007).

3.1.2 The bulge

The bulge dominates the Galaxy interior to $\sim 3\,$kpc. Unfortunately, much of it is highly obscured at optical wavelengths, so it has been intensively studied

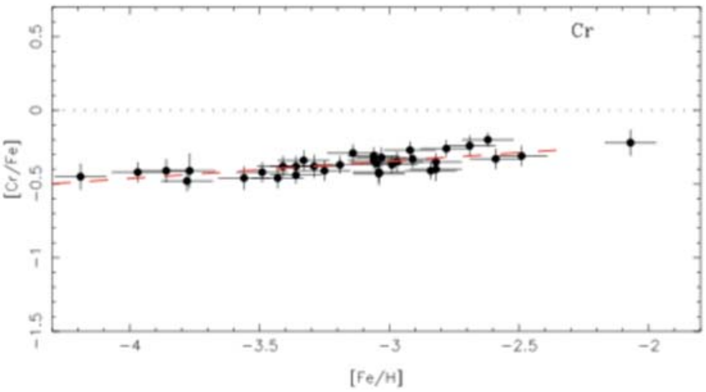

Figure 2: [Cr/Fe] vs. [Fe/H] measured in extremely metal-poor stars by Cayrel et al. (2004). Note that the very small scatter in these abundance ratios can be completely explained by the observational uncertainties, thus suggesting the absence of intrinsic scatter. The reality of the [Cr/Fe] trend with metallicity is still a matter of debate.

along a restricted set of lines of sight that are less obscured. These intersect the bulge $\gtrsim 300\,\mathrm{pc}$ above or below the plane, so the region in which the disc and bulge intersect has still to be adequately explored. Lines of sight to the bulge contain many disc stars in the foreground, especially at the lowest latitudes. Distance errors can lead to these stars contaminating "bulge" samples. The bulge is geometrically and chemically complex: its main body is barred, gas-poor and comprised of old stars with a wide spread in metallicity, while its inner region is gas-rich and the site of active star formation.

The bulge has the peanut shape that in external galaxies is associated with a bar, and both photometry (Blitz & Spergel, 1991; Binney et al., 1997; Stanek, 1995; Babusiaux & Gilmore, 2005) and gas kinematics (Binney et al., 1991; Bissantz et al., 2003) confirm that it is barred. The bar is oriented such that the near end of the bar lies at positive longitudes, and at its extremities it may become less thick and blend into the disc. The key parameters are its semi-major axis length a, its axis ratios and the the angle ϕ between the bar's major axis and the Sun-centre line. Bissantz & Gerhard (2002) find $a \sim 3.5\,\mathrm{kpc}$, $15^\circ < \phi < 30^\circ$, and axis ratios 1:0.35:0.3, while López-Corredoira et al. (2005) find $20^\circ < \phi < 35^\circ$ and axis ratios 1:0.5:0.4. Most recently Rattenbury et al. (2007) find $24^\circ < \phi < 27^\circ$ and ratios $1 : 0.35 : 0.26$. With these parameters the nearer end of the bar is $\sim 5\,\mathrm{kpc}$ away along $l = 17^\circ$.

Outside the innermost $\sim 1^\circ$, the bulge mainly comprises an old population; the dispersion in ages is small (Ortolani et al., 1995; Zoccali et al., 2003). The distribution of abundances is wide, ranging from [Fe/H] $= -1$ to 0.5 and peaking at [Fe/H] ~ -0.2 (Fulbright et al., 2007; Lecureur et al., 2007; Zoccali et al., 2008). In the bulge, [α/Fe] remains high to a higher [Fe/H] than in the disc; in Section 3.4.3 we shall see that this indicates that the timescale of star formation was shorter in the bulge than in the disc. Zoccali et al. (2008) have demonstrated that the metallicity decreases by 0.25 dex along the minor axis between $b = -4°$ and $b = -12°$, suggesting a mix of different bulge populations.

Within 1° of the Galactic centre, the nature of the bulge changes dramatically because here the *central molecular disc* contains dense, cold gas from which stars continue to form. Because it is so highly obscured, this region is best known from radio-frequency studies of the ISM (Section 3.1.5) and little is known about its stars.

3.1.3 The disc

With a mass $\sim 5 \times 10^{10} M_\odot$ the disc is the most massive stellar component of the Galaxy and the site of most current star formation. It defines the Galactic plane, and holds most of the Galaxy's stock of gas. Dust in this gas hides most of the disc from optical telescopes. The Sun lies near the outer edge of the optically luminous part of the disc, within ~ 15 pc of the plane.

Ivezic et al. (2008) probed the Galaxy with stars that were selected in the colour-magnitude plane to be predominantly fairly distant F and G dwarfs. In Figure 3 from their work there is a triangular region in the lower half of the diagram within which halo stars fall (stars fainter than $g = 18$ and more metal-poor than $u - g = 1$) while disc stars occupy an elliptical region at upper right (brighter than $g = 17.5$ and more metal-rich than $u - g = 1$). Spectroscopic calibrations of the $u - g$ metallicity indicator imply that halo stars are more metal-poor than [Fe/H] $= -1$ and disc stars more metal-rich. Hence the disc covers the same metallicity range as the bulge. At top right of Figure 3 the ridge-line of the disc stars slope up and slightly to the right, indicating that the disc becomes more metal-rich as the plane is approached. Unfortunately the photometry (from the *Sloan Digital Sky Survey; SDSS*) provides poor discrimination of metallicity in the region [Fe/H] ~ -0.5 so it is hard to determine from it the upper limit on the metallicity of disc stars. Thus although the disc extends at least 2.5 kpc above the plane, chemistry clearly separates it from the halo.

Near the Sun the disc's vertical density profile is accurately fitted by the sum of two exponentials in $|z|$ (Gilmore & Reid, 1983) with scaleheights $h_{\text{thin}} = 300$ pc and $h_{\text{thick}} = 900$ pc (Jurić et al., 2008). This observation led to the idea that the disc is a superposition of distinct components, the thin and thick discs. Obscuration

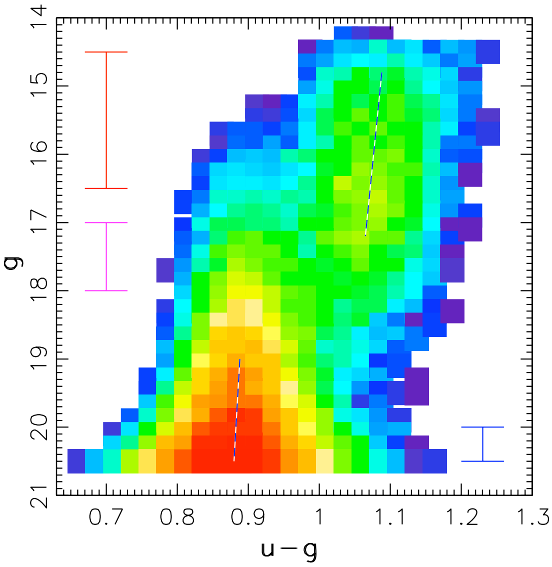

Figure 3: The $u - g, g$ plane for F and G stars ($0.2 < g - r < 0.4$) from Ivezic et al. (2008).

within the plane makes it difficult to determine the radial density profiles of these components with confidence, but by analogy with external galaxies the vertical scaleheights are assumed to be independent of radius and the densities are assumed to decrease exponentially with radius. With these assumptions Robin et al. (2003) conclude from near infrared (NIR) star counts that the thin disc has scale length $L_{\text{thin}} = (2.53 \pm 0.1)\,\text{kpc}$, while from SDSS photometry Jurić et al. (2008) find $L_{\text{thick}} = 3.6\,\text{kpc}$[2]. An outer limit to the stellar thin disc at $15 \pm 2\,\text{kpc}$ has been inferred from the DENIS NIR star counts (Ruphy et al., 1996). Less is known about the extent of the thick disc.

The physical reality of the distinction between the thin and thick discs is hotly debated, and the debate is confused by a lack of agreement as to how these structures should be defined. If we define the thick disc to be a structure that has a double-exponential density profile with the parameters determined from SDSS photometry, then $\sim \frac{1}{4}$ of disc stars belong to the thick disc, which accounts for essentially all disc stars at $|z| > 1.5\,\text{kpc}$. The fraction of local stars that belong to the thick disc is very uncertain: estimates range between 2% (Robin et al., 2007) and 12% (Jurić et al., 2008) depending on the assumed value of h_{thick} (the larger h_{thick} is, the smaller the proportion of local stars that belong to the thick

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[2] Jurić et al. (2008) also find $L_{\text{thin}} = 2.6\,\text{kpc}$ in agreement with Robin et al. (2003), although the thin disc does not contribute heavily to the SDSS star counts.

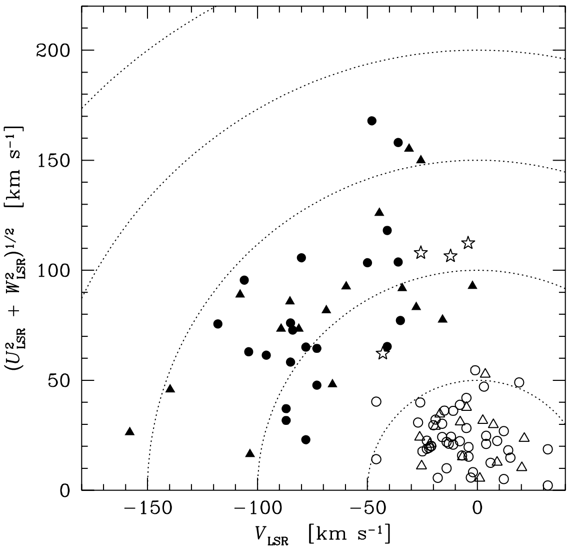

Figure 4: Fig 1 of Bensby et al. (2005) showing stars near the Sun kinematically identified as belonging to the thin disc (open symbols) and thick disc (filled symbols). The stars mark 'transition objects'.

disc). When the thick disc has been defined in terms of the vertical density profile, the question is whether it is possible to identify which local stars belong to the thick disc in a physically well motivated way. A kinematic criterion such as that illustrated in Figure 4 is often used to separate thin and thick disc stars near the Sun. Dynamical models would connect the spatial and kinematic definitions of the two discs, but we currently lack models of sufficient sophistication to forge this connection.

Spectroscopic determinations of abundances in nearby stars are interpreted as showing that thick-disc stars (identified by their kinematics) have higher [α/Fe] than thin-disc stars (Fuhrmann, 2008; Soubiran & Girard, 2005). On the other hand, there is a large overlap in iron abundance between the two populations. It is still a matter of debate whether the iron abundance of the thick disc extends up to the solar value – Bensby et al. (2007) argue that it extends to above solar, while in the volume-complete sample of Fuhrmann (2008) the most metal-rich thick-disc stars have [Fe/H] ~ -0.2.

Within the distance range 7 − 9 kpc that they probed, Edvardsson et al. (1993) found a slight inward increase in [α/Fe]. It is unclear whether this phenomenon reflects a gradient within the thin disc of changes with radius in the proportions of stars belonging to the two discs (Nissen, 2005). To resolve this question, [α/Fe] must be determined in much larger samples of stars spanning a larger galactocentric range, with a precision ~ 0.05 dex.

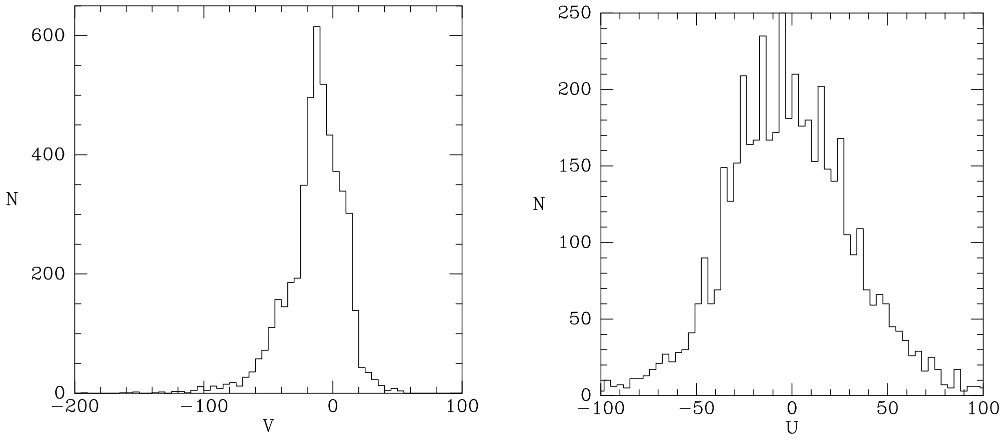

Figure 5: Distributions of U and V in the Geneva-Copenhagen Survey (from data published in Nordström et al., 2004). Stars with $V > 0$ move round the Galaxy faster than the local circular orbit.

In the solar neighbourhood the velocity distributions of disc stars are approximately Gaussian in the radial and vertical directions, but skew in the direction of Galactic rotation (Figure 5 and Section 3.3.4). Both the velocity dispersion and surface density of disc stars are thought to increase inwards, and these increases inevitably make the V distribution skew because many more stars have their apocentres near the sun and pericentres far in, than there are with pericentres near the Sun and apocentres far out.

Figure 1 shows that the further from the plane you go, the more strongly the median rotation of the disc lags behind that of the Sun. This figure, which is consistent with the findings of Girard et al. (2006), suggests that the entire thick disc lags solar rotation, and that near the Sun thick-disc stars can be identified by their low rotation. The rotational lag of the thick disc has been variously reported as $-100\,\mathrm{km\,s^{-1}}$ (Wyse & Gilmore, 1986), $-50\,\mathrm{km\,s^{-1}}$ (Fuhrmann, 2004) to as low as $-20\,\mathrm{km\,s^{-1}}$ (Norris, 1987). The slope of the line of median symbols in Figure 1 provides an explanation of this ambiguity.

The further a star rises above the plane, the larger its vertical velocity W as it crosses the plane, so Figure 1 implies that near the Sun stars with large $|W|$ should tend to have strongly negative V. Such a trend is not evident in the sample of Nordström et al. (2004).

The clearest relation of this type is Stromberg's linear relationship between

$\langle V \rangle$ and the square of the total velocity dispersion of main-sequence stars bluewards of $B - V = 0.6$ (e.g. Dehnen & Binney, 1998). Such stars have lifetimes smaller than the age of the Galaxy and are generally considered to be members of the thin disc.

There is clear evidence of coherent streams in the thick disc (Helmi et al., 2006). For example, the Monoceros ring is a structure in the outer disc with a nearly circular orbit, and it is probably related to the Canis Majoris over-density (Martin et al., 2004). It is not yet clear whether the thick disc is dominated by streams or if these are just froth on a smooth background (Gratton et al., 2003). The stars in streams are believed to have formed outside the Galaxy (Section 3.5.3).

Whereas all thick-disc stars are thought to be older than ~ 9 Gyr, freshly formed stars have been added to the thin disc at a fairly constant rate over at least the last 9 Gyr (Section 3.5.3). Stars are now formed on nearly circular orbits that do not go far from the plane. Gradually the fluctuating gravitational fields of spiral arms and giant molecular clouds increase orbital eccentricities and inclinations, so that the random velocities of disc stars increase with age.

Standing shocks in the ISM along the leading edges of spiral arms are thought to be responsible for much of the star formation in the disc. Hence the density of the youngest stars (e.g., OB stars), is strongly peaked along spiral arms (Figure 9).

3.1.4 Fossil populations

Stars with initial masses smaller than $\sim 8\,M_\odot$ eventually produce white dwarfs. Slightly more massive stars end their lives as neutron stars. Both types of fossil can make a noticeable contribution to the mass density in their local environments. For example, in the solar neighbourhood white dwarfs are believed to contribute $\sim 6\,\%$ to the local mass-density (Flynn et al., 2006). In high-density environments, two-body interactions will cause fossil stars that are more massive than living stars to sink towards the gravitational centre of the system, where they can begin to dominate the mass density. This effect is most relevant to neutron stars, which have masses $\sim 1.4\,M_\odot$, and will sink towards the centre of a globular cluster or, indeed, the Galactic centre star cluster in which Sgr A* is located (Freitag et al., 2006).

The neutron stars, when radiating as pulsars, provide an additional service as probes of the free electron density distribution within the Galaxy: essentially, pulsar radio-flux dispersion measures can be combined with H II region data (treated as spiral arm tracers) and independent distance determinations to pulsars in the Galactic plane and in globular clusters to establish a map of n_e (Taylor & Cordes

(1993) since updated by Cordes & Lazio (2002)). One of the more arresting results first obtained by Taylor & Cordes (1993) is the existence of a broad ring of free electrons with mean Galactocentric radius of 3.7 kpc, and typical n_e comparable to that found in spiral arms. However the impact of their explosive origins on the kinematics of neutron stars and the short lifetimes of supernova remnants mean such objects are not directly useful as tools for Galactic archaeology. Both supernova remnants and high-mass X-ray binaries are of value in tracing present day star formation.

In contrast, white dwarfs are too faint to have any role as tracers of Galactic structure, but they do provide a valuable record of a stellar system's star formation history, simply because they cool so very slowly. It is in principle possible to determine age from a white dwarf's luminosity and colours, as long as the effects of mass and chemistry on the cooling and atmospheric properties are known. The main impediments to obtaining good statistics on white dwarf masses and ages, from which rates of star formation in earlier epochs might be inferred, are sample incompleteness (because old white dwarfs are extremely faint) and difficulties in modelling the properties of the coolest white dwarfs. Nevertheless, this approach has been used with success recently to date globular clusters (Hansen et al., 2004, see also Section 3.4.1), underlining its considerable potential for studies of the star-formation and dynamical histories of the solar neighbourhood. In a similar fashion very old, unevolved low mass stars are also fossils in the sense of encoding within their surface abundance patterns the physical conditions prevailing at the time and place of their formation.

3.1.5 Gas and dust content

The gas and dust content of the Galaxy is mainly concentrated in the Galactic thin disc along with most of the stars, contributing around one-fifth of the disc mass.

The main gas phases are the cold molecular phase at temperatures of 10–50 K, encountered most strikingly in the densest regions associated with spiral arms, and the warmer ($\sim$ 80 K) atomic phase of the diffuse clouds that show a related distribution. Mapping of these phases has been accomplished mainly through CO and H I 21cm radio emission surveys that have also become key tools in uncovering the Galactic rotation law and for distance estimation. The works of Dame et al. (2001) and Kalberla et al. (2005) are recent comprehensive examples. While, to lowest order, the velocity field described by such surveys is well modelled as created by rotation on circular orbits, there are also signs of influence by the bar, and peculiar effects due to spiral arms and the warp.

The basic properties of the H I gas layer are largely as summarised by Dickey & Lockman (1990). The H I scale height in the solar neighbourhood, at 100–200 pc, is somewhat smaller than that of the stellar thin disc, but shows strong growth outside the Solar Circle – a characteristic shared with the stellar disc. Also in an analogy to the distinction between the stellar thin and thick discs, there is evidence that atomic gas persists to above ∼1 kpc from the plane. But these averages hide a lot of structure on smaller scales. The radial extent of the gas disc may be greater than that of the stellar disc: Levine et al. (2006) trace spiral structure out to ∼ 25 kpc. But this is not accompanied by much molecular gas, since very little CO is found outside the Solar Circle. The local molecular scale-height, at under 40 pc, is appreciably less than that of H I (Stark & Lee, 2005).

Looking inwards, up the density gradient, the gas surface density peaks at galactocentric radius $R \sim 4\,\mathrm{kpc}$, where a large fraction of the gas is molecular rather than atomic (the *molecular ring*). Within the molecular ring there is a dearth of gas because here the bar eliminates circular orbits. Any gas that leaks into this radius range from outside is quickly driven in to $R < 400\,\mathrm{pc}$, where it accumulates in the central molecular disc. As a consequence of the high density of molecular gas in this central disc, it is a region of active star formation. This star formation is so far not fully explored because this region is highly obscured by dust.

There is a greatly improving picture of the distribution of dust within the Galactic plane: from COBE/DIRBE data we have a useful mapping of column-integrated extinctions (Schlegel et al., 1998) and, with the aid of 2MASS data, much better semi-empirical three-dimensional maps (Drimmel & Spergel, 2001; Marshall et al., 2006). The dust distribution largely follows that of H I.

Ionised (H II) regions exist in close association with molecular clouds and are the classic markers of star forming regions seated mainly in the thin disc. They are known from radio recombination line and continuum surveys and have also been picked out, now at ∼ arcsecond spatial resolution, in recent Hα surveys (Parker et al., 2005; Drew et al., 2005). At lower spatial resolutions a more global picture emerges that essentially reproduces the spatial scales derived from mapping neutral gas, but there is much structural detail, at both high and low Galactic latitudes, often linked to star-forming activity. This is revealed particularly vividly in WHAM data (Haffner et al., 2003) which combines sensitive imaging with velocity information.

The hottest gaseous phase of the Galactic ISM is made up of the loops and bubbles of $\sim 10^6$ K coronal-phase gas that betray supernova blastwaves and similar. They are seen to higher Galactic latitudes than most cool gas. But such break-outs may take with them filaments of cold gas at speeds of up to $100\,\mathrm{km\,s^{-1}}$, as described in the *galactic fountain* model (Bregman, 1980). The extent to which coronal-temperature gas carries metals out of the Galaxy into the intergalactic medium is not known, but X-ray observations of clusters of galaxies suggest that this may be a major process.

Some of the best evidence for the mainly out-of-plane high velocity clouds comes from studies based on H I 21 cm data (e.g. Kalberla & Haud, 2006). For decades after their discovery, the distances to these clouds and their origin was uncertain (van Woerden et al., 2004), but it is becoming clear that most are not as distant or as massive as was once speculated – almost all are at $R \lesssim 20\,\mathrm{kpc}$ and have masses $M \lesssim 10^7 M_\odot$. Some are filaments of H I that have been ejected from the disc by ejecta from young stars, while others are so metal-poor that they must be dominated by material that is entering the Galaxy for the first time (Wakker et al., 2007a).

3.1.6 OB associations and open clusters

Short-lived luminous O and B stars – often but not always associated with H II regions – map out regions of currently high star formation rate (the spiral arms), while lower-mass, longer-lived stars have a much more uniform azimuthal distribution, and more accurately map out the Galactic disc's mass distribution. Yet the disc contains stellar groupings on a variety of scales that introduces a rich irregular substructure. Broadly speaking, this substructure will have descended from the preceding gas distribution, given that stars form where over-densities of gas are able to collapse. Three particular levels of clustering are recognised: in order of increasing spatial scale and overall mass, these are the open clusters, OB associations and moving groups.

Open clusters are the most easily discerned of these three classes because of their small size and moderate youth, which results in a higher surface density of stars being seen, within a small angular extent on the sky. Their chemical composition is, to a good approximation, uniform (e.g. Paulson et al., 2003; De Silva et al., 2007), and the age spreads of one to a few million years that can sometimes be found within them are negligible from the perspective of Galactic archaeology. The catalogue of open clusters by Dias et al. (2002) lists 1629 of them, with the ages of most being under 1 Gyr, and only a few as old as 10 Gyr. They serve as precious but biased records of stellar and Galactic evolution. The oldest open clusters provide a lower limit to the age of the thin disc. These tend to be found at high galactocentric radius and/or larger distance from the Galactic plane, where they are less subject to the disruptive interactions that are otherwise frequent. Nevertheless, the opportunity to access bound clusters spanning a wide age range has been crucial in revealing a lack of evidence for an age-metallicity relation within the Galactic disc (e.g. Friel, 1995, and the many other papers by this author) which constrains theories of its origin and evolution.

In addition open clusters provide important constraints on the stellar initial mass function (see further discussion in Section 3.2). Recently Kroupa (2007) has provided arguments as to why no open cluster on its own perfectly exhibits the stellar IMF: to recover this it is important to combine observations of numerous clusters and support the endeavour with some theoretical modelling.

OB associations are recognisable as over-densities of rare, massive stars on spatial scales up to 100 pc, often subtending several degrees on the sky. They are more extended than open clusters. Even though the massive stars appear to be so prominent within them, it has come to be recognised that the IMF in OB associations appears to be essentially the same as in less massive clusters (Massey et al., 1995, and works since). Despite their relative youth ($\lesssim$ 50 Myr), the stellar space densities within them are sufficiently low that the members are readily unbound through interactions with other disc objects. Indeed, direct measurements of the expansion have been made for a number of OB associations. Furthermore age spreads are more apparent (Massey et al., 1995) hinting at more complex origins. It has been shown to be useful to independently measure the dynamical and evolutionary ages of OB associations, as this can expose the dissolution process that undoubtedly affects star clusters on all scales (Brown, 2002).

It has recently become evident that the Galaxy is home to some examples of brilliant, very massive and compact clusters analogous to the super star clusters that were first picked out in external galaxies. As in the extragalactic examples these are contained within the inner disc and bulge: they are more massive than $10^4\,M_\odot$, only a few parsecs across, and are usually highly obscured. The Arches cluster near the Galactic Centre is an example (Figer et al., 2002). Westerlund 1 located in the inner disc is another, and has been mooted as a globular cluster progenitor (Clark et al., 2005). They are mainly distinguished from more common OB associations by their compactness.

3.1.7 The globular clusters

About 160 globular clusters orbit within the Galaxy (Harris, 1996). Each one contains from several thousand to in excess of a hundred thousand stars. They show little if any rotation and are named for being rather nearly spherical. Their radial profiles display a wide range of central concentration from 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. Their velocity dispersions, centrally as large as $12\,\mathrm{km\,s^{-1}}$, decrease outwards – consistent with all the cluster matter being in stars.

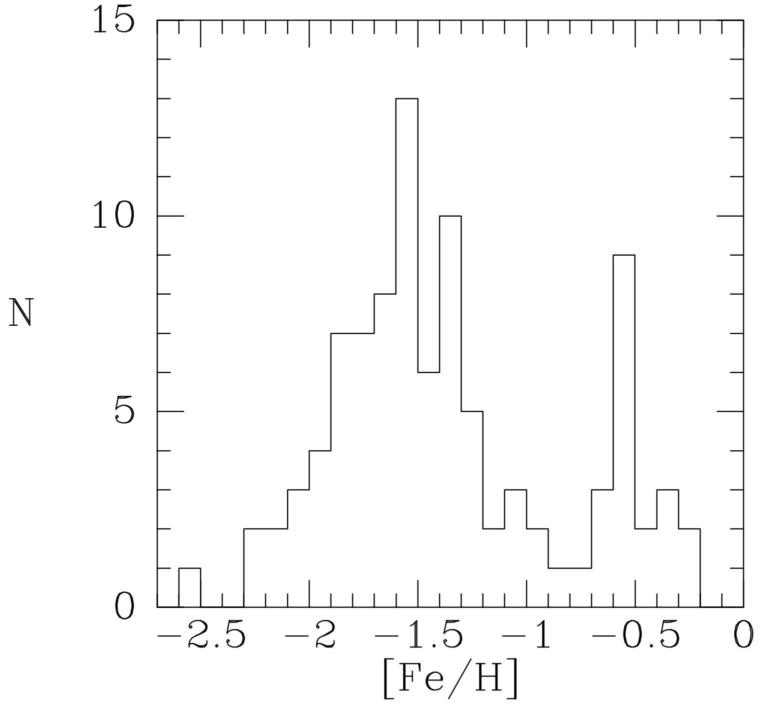

Figure 6: Metallicity distribution of the Galaxy's globular clusters (from data published in Armandroff, 1989).

Although globular clusters are often thought of as halo objects, at least 20% of them seem to be associated with the thick disc (Zinn, 1985). The bimodal metallicity distribution of the globular-cluster population (Figure 6), with its peaks at [Fe/H] $\simeq -0.5$ and [Fe/H] $\simeq -1.5$ ties in with this. When chemical properties are used to decompose the cluster population into metal-rich and metal-poor components, it is found that the two components also have distinct spatial and kinematic properties: the metal-rich population is confined in space to distances from the Galactic plane $|z| < 3\,\mathrm{kpc}$ and $R < 8\,\mathrm{kpc}$ and has significant rotation (the disc clusters), while the metal-poor population is approximately spherically distributed and extends out to $R \simeq 100\,\mathrm{kpc}$ (the halo clusters). All globular clusters are α-enhanced relative to the Sun.

High precision spectroscopic studies do not reveal star-to-star variations in a cluster as far as heavy elements like Fe-peak, s- and r-elements are concerned. In contrast, a wide star-to-star variation is detected for light elements from Li to Al

(Gratton et al., 2004; Sneden, 2005). The scenario now accepted is that the first generation of stars in globular clusters would have abundance patterns similar to the ISM from which the protocloud formed (with abundances of the light elements compatible to those observed in their field contemporaries), whereas the second generation contains stars born out of material polluted to different degrees by the ejecta of either asymptotic giant branch (AGB) stars (e.g. D'Antona & Ventura, 2007) or fast rotating massive stars (Decressin et al., 2007). The choice of the right polluters is currently debated and it is clear that to advance in this field it will be necessary to couple both the dynamical and chemical aspects of the globular cluster formation and evolution. If rapidly rotating massive stars are the right polluters, then the evidence for two generations implies a small age spread of $\sim$ 10 Myr, whereas if AGB stars are the polluters the age spread could be larger.

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, 13.4 Gyr. Significantly smaller ages ($\sim$ 10 Gyr) are obtained for a minority of clusters (Pal 12 for instance) whose assignment to the halo is controversial (Pritzl et al., 2005). There is no evidence that, among halo clusters, age is correlated with either [Fe/H] or galactocentric distance (Richer et al., 1996).

Many globular clusters are on eccentric orbits along which the strength of the Galaxy's tidal pull varies strongly. With accurate photometry from the SDSS survey it became possible to track streams of stars that have been torn from clusters at pericentre, where the Galactic tide is strong (Odenkirchen et al., 2001). Streams of stars that have been tidally stripped from globular clusters and dwarf spheroidal galaxies offer one of the most promising tools for probing the Galaxy's gravitational field far from the disc.

Finally, it should not escape attention that some globular clusters are very peculiar, showing extended horizontal branch morphologies and evidence of multiple stellar populations. The well-known long-standing example of this is the cluster ω Cen, but more recent work is beginning to identify an appreciably longer list of clusters presenting similar phenomenology (Lee et al., 2007). These may be construed as the signatures of accretion or satellite-galaxy merger events (Mackey & Gilmore, 2004; Lee et al., 2007).

3.1.8 The satellites

The Galaxy, as a dominant member of the Local Group, has its fair share of dwarf galaxy satellites. They are low-metallicity gas-poor objects, showing patterns of alpha-element enhancement that are different from those seen within the Galaxy or its globular cluster system. The Large and Small Magellanic Clouds (LMC and SMC) are the most massive and best known of these satellites at distances of respectively 50 kpc (Freedman et al., 2001) and 61 kpc (Hilditch et al., 2005). The LMC's dynamical mass at $\sim 6 \times 10^9 \, M_\odot$ (Kunkel et al., 1997) amounts to just ∼1 % of the Galaxy's mass within a radius of 50 kpc. These dwarf irregulars are important as sites of extensive star-forming activity at average metallicities significantly below those of the Galactic disc ($[\mathrm{Fe/H}] \sim -0.5$ and ~ -0.8 for the LMC and SMC respectively). The Magellanic Stream, a debris trail of neutral gas and stars, was recognised as linking the Clouds to the Galaxy by Mathewson et al. (1974). This highly extended filamentary structure can be seen in retrospect as prototypical of high velocity clouds. Interestingly, recent proper motion measurements of both the LMC and SMC have raised the question as to whether they may be experiencing their first passage past the Galaxy (Besla et al., 2007).

The list of low mass mainly dwarf-spheroidal satellites has reached double figures and, at the present time, is growing very fast – along with identifications of streams linked to them (see e.g. Belokurov et al., 2007a). There is little doubt that we are presently in a vigourous phase of discovery. There is nevertheless still a shortfall in that predictions would indicate up to ∼500 might be found (e.g. Moore et al., 1999). The Fornax dwarf-spheroidal galaxy is among the most distant satellites at ∼ 150 kpc, and retains its own modest system of globular clusters.

3.2 Present day star-formation census

The question of how stars form, and what factors may determine the result of the process, is a central preoccupation in astrophysics. It is pertinent to all epochs in the history of the Universe and poses problems on many length scales. It is detected at high redshift in the youngest galaxies accessible to us and it is clearly an important part of galaxy formation. A more central issue to this report is that we live in a galaxy within which star formation is a prominent and continuing process that strongly shapes its present-day properties. Because the business of planet-building is caught up in the process of star birth, we are driven also to understand it at the (astronomically) more intimate scale exemplified by the Solar System.

Within the Galaxy we can access worked examples of individual objects near the Sun, as well as open up sites of star formation for inspection on the scales of either star clusters or of spiral arms winding around the Galactic thin disc. The outline picture of how stars form through progressive cloud collapse and disc-mediated accretion is well-established for low mass stars, for which there has long been good access to an array of nearby young clusters. The Taurus-Auriga star-forming region, ∼ 140 pc away, was the first to be intensively studied, giving rise