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GALAXY FORMATION: CLUES FROM THE MILKY WAY

G. Gilmore[1]

RESUMEN

Las poblaciones estelares son el registro fósil de la evolución galáctica. La interpretación de este registro en el Grupo Local permite la determinación confiable de la física que controla la evolución de aquellas galaxias que son típicas de la materia luminosa en el Universo, y es un ingrediente esencial para entender los datos, necesariamente limitados, a altos corrimientos al rojo. En nuestra Galaxia, las cuestiones clave son los sitios y los tiempos de formación y coalescencia de las poblaciones estelares más viejas: el halo, el disco grueso y el bulbo, así como su translape y sus relaciones evolutivas, si las hay. Se reseñan resultados nuevos sobre la función inicial de masa estelar a altos corrimientos al rojo, sobre las poblaciones estelares en el bulbo galáctico, y sobre la historia de coalescencia en el disco galáctico.

ABSTRACT

Stellar Populations are the fossil record of Galactic evolution. Interpretation of this record in the Local Group allows one to determine reliably the dominant physics controlling the evolution of those galaxies which are typical of the luminosity in the Universe, and is an essential prerequisite to understanding necessarily limited data at high redshifts. In our Galaxy, the key issues are the places and times of formation and merger of the oldest stellar populations : the halo, thick disk and bulge - and their overlaps and evolutionary relationships, if any. New results on studies of the stellar initial mass function at high redshift, the stellar populations of the Galactic bulge, and the merger history of the Galactic disk are reviewed.

Key Words: **GALAXY FORMATION — GALAXIES: MILKY WAY — STARS: INITIAL MASS FUNCTION**

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1. INTRODUCTION

We are fortunate that the Milky Way itself, and more generally the galaxies of the Local Group, appear typical of the 'mean' population in the Universe. Detailed studies of the systematic properties of galaxies, leading eventually to the concept of the 'fundamental plane', have shown that galaxies form well-defined families (Figure 1). Thus, we may immediately deduce that galaxy formation models should produce 'Local Group-like' and 'Milky Way-like' systems without special effects. Conversely, detailed study of the Local Group can contribute to the general study of galaxy formation and evolution, and the nature and distribution of dark matter on small scales.

Topics of relevance here where local studies are proving especially significant include the nature of the Galactic Bulge: what is its age, abundance and assembly history? Stellar studies locally of course are of critical general significance: only locally can we determine the stellar Initial Mass Function directly in a wide range of environs. This function directly controls the chemical and luminosity evolution of the Universe. Galactic satellite galaxies are proving the most suitable environs to quantify the nature and distribution of dark matter, and to test the small scale predictions of hierarchical galaxy formation models. The Galactic disk itself, of course, is a key test of angular momentum distributions, chemical evolution, and merger histories.

2. THE GALACTIC BULGE

The Milky Way galaxy provides a unique opportunity to learn about the formation, the structure and the evolution of galaxies. The central parts of the galactic bulge and disk have remained elusive, though, due to the extremely high extinction at short wavelengths and poor spatial resolution at longer wavelengths (Figure 2). Most of the current belief that the stellar content of the galactic bulge is old, $\gtrsim$ 10 Gyr, and metal-rich, $[M/H]$ ~solar, results from studies in low extinction regions (e.g. Baade's Window) at galacto-centric radii $R > 500$ pc (eg Rich 1998a). With the advent of infrared (IR) cameras and adaptive optics techniques, the exploration of the galactic centre has revealed the presence of massive stars that indicate recent star formation (Genzel et al. 1994). Yet data concerning the relationship between the central parsec of the galaxy and the bulge, halo and disk remain scarce.

[1]Institute of Astronomy, Cambridge, U.K.

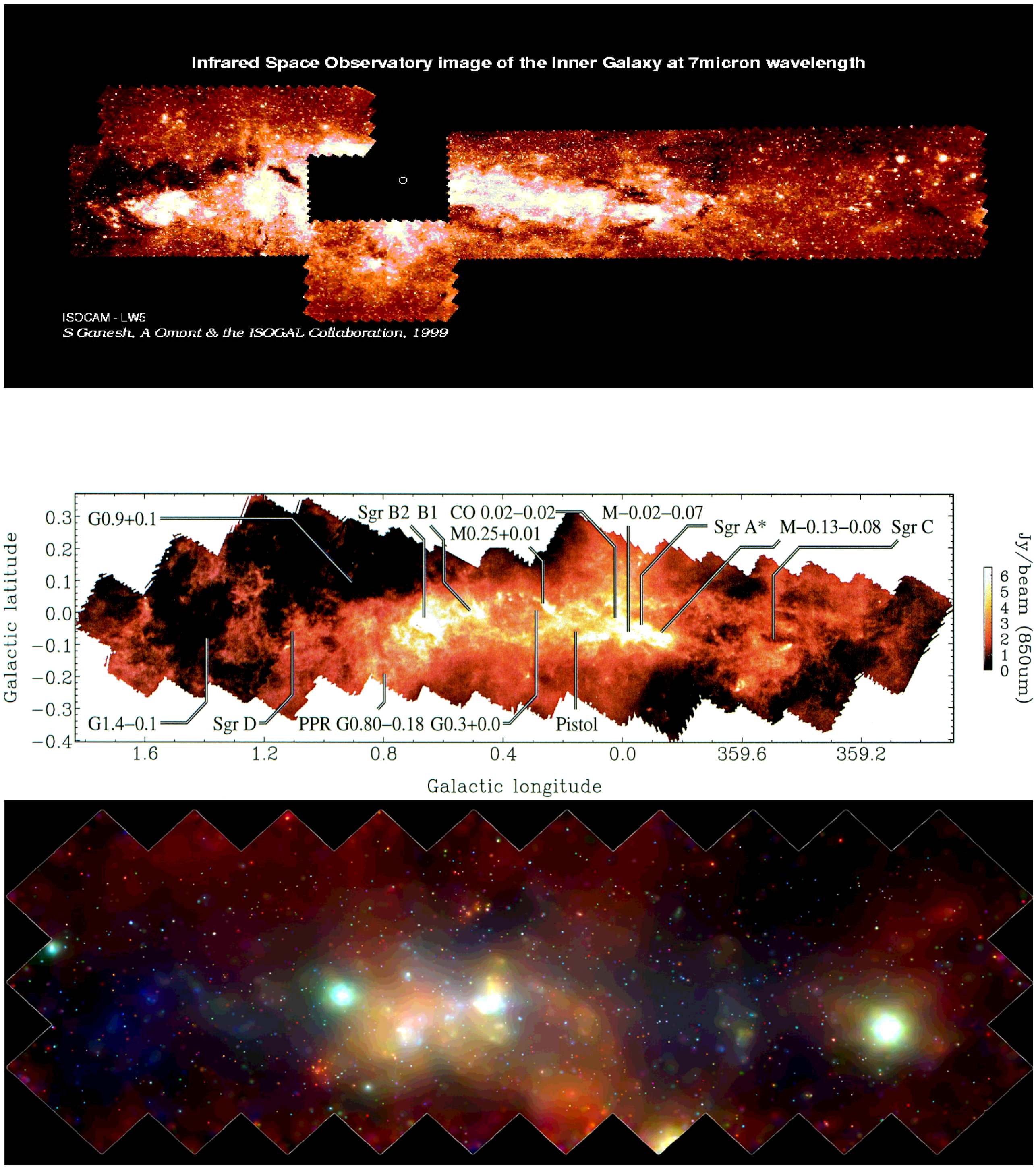

Fig. 2. Three views of the young, star-forming Galactic Bulge: TOP: the 7micron ISOGAL image. Bright features in the image indicate star formation and/or young stellar regions; MIDDLE: a SCUBA map from Pierce-Price et al. 2001, highlighting regions of active continuing star formation, and illustrating the considerable molecular gas reservoir; LOWER: the CHANDRA view, dominated by hot gas and supernova activity. See color Plate 5.

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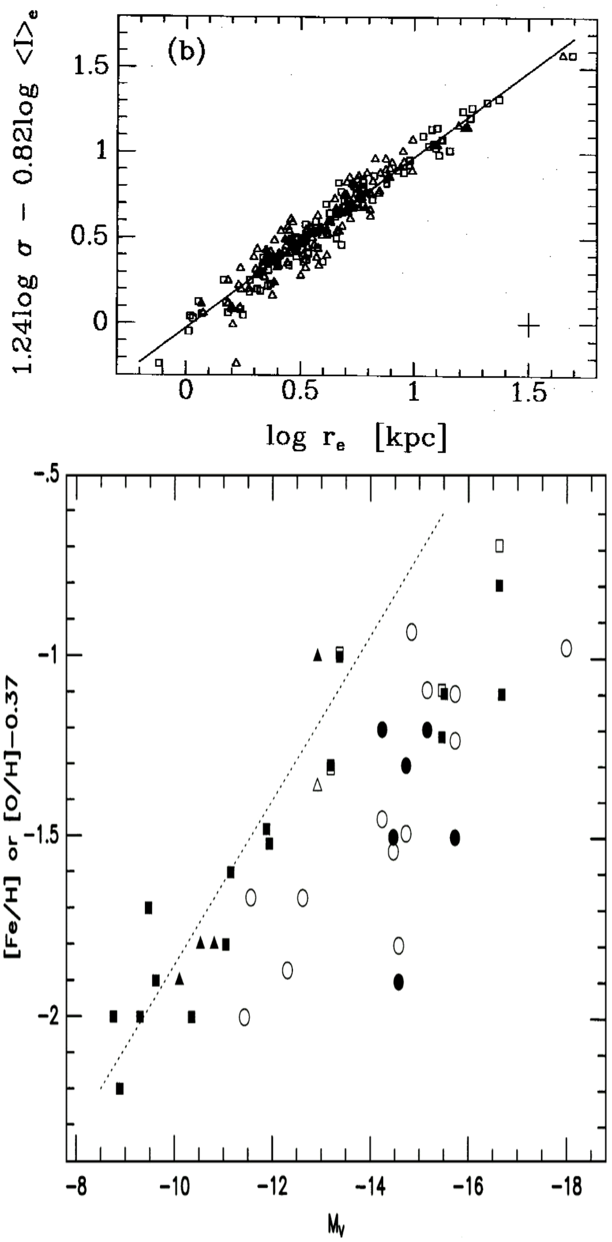

Fig. 1. UPPER: Edge-on view of the fundamental plane of spheroids, from Jørgensen et al. (1996). *Boxes:* Ellipticals. *Triangles:* Bulges (S0s). Typical error bars are shown. LOWER A plot of [Fe/H] (filled squares) or [O/H] - 0.37 vs absolute V-band magnitude. The dotted line is a rough fit to the [Fe/H]-MV relation for the dSph and transition objects. Sagittarius corresponds to the points near (MV,[Fe/H]) (-13.4,-1.0). Square symbols refer to dSph or dE galaxies; triangles refer to transition galaxies (denoted dIrr/dSph in Table 1); circles refer to dIrr systems. Filled symbols correspond to [Fe/H] abundances determined from stars, while open symbols denote oxygen abundance estimates from analyses of HII regions and planetary nebulae. [From Mateo 1998.] These systematic relations, with little scatter for galaxies without active current star formation, show that the galaxies of the Local Group should be fair samples of galaxies in general.

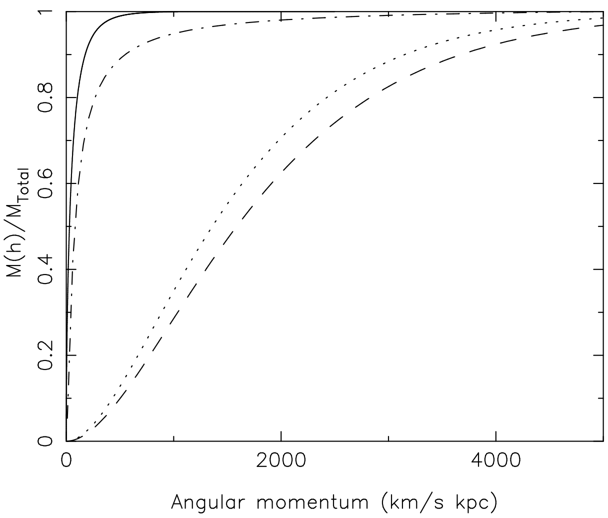

Fig. 3. Galactic populations angular momentum cumulative distribution functions, showing bulge/halo and thin/thick disk dichotomy. This indicates disparate evolutionary histories.

There are clear similarities and distinctions between fundamental properties of the different Galactic stellar populations, such as age, metallicity, star formation history, angular momentum (Figure 3) which allow study of their individual histories. This is arguably one of the greatest advantages of studies of Local Group galaxies: one is able to disentangle the many different histories which have led to a single galaxy.

What we observe today is the time-integrated history of star formation, gas flows, and mergers in the galaxy, and it may be envisaged that the formation of the different components of the galaxy — halo, bulge, nucleus and disk — are not independent events. Common preconceptions about the bulge being an old, metal-rich small elliptical galaxy are being challenged (Wyse et al. 1997). For instance, recent near-IR photometry and spectroscopy of stars in the inner bulge ($R \lesssim 500$ pc) suggest the presence of an intermediate-age population ($t \sim 1$ to 2 Gyr: e.g. Frogel 1999a). Did these stars form in the bulge, or in the nucleus? Is there any connection between the star formation history and the formation of galactic structures such as a bar (Blitz et al. 1993) or tri-axial bulge (Nakada et al. 1991)?

The galactic bulge is fundamentally typical of all bulges in late-type spirals (Frogel 1990). In particular, it is very similar to that of M31 and M32 (Davies et al. 1991; DePoy et al. 1993; Davidge 2000b, 2001; Rich 2001) and the central nuclei of M33 (Mighell & Rich 1995; Mighell & Corder 2002; Stephens & Frogel 2002) and NGC 247 and NGC 2403 (Davidge &

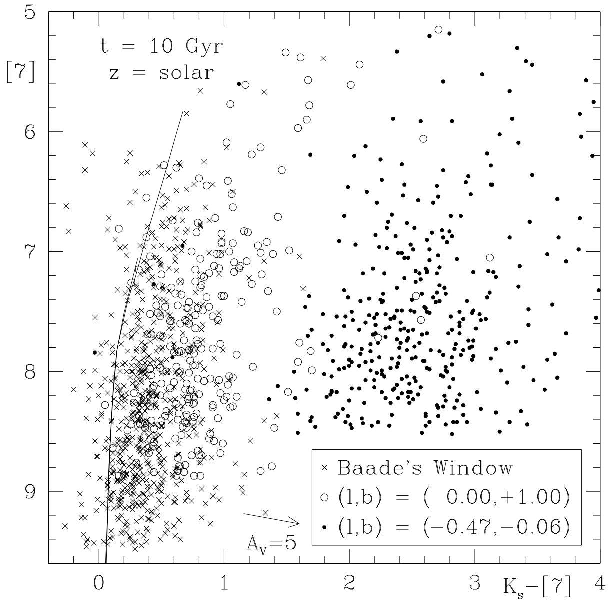

Fig. 4. ISOGAL mid-IR colour-magnitude data, illustrating the ability to distinguish extinction from intrinsic stellar properties. Many of the brightest sources here are intermediate-mass OH/IR and luminous AGB stars. ISOGAL provides for the first time an opportunity to define the spatial distribution of intermediate age stars, with masses greater than $\sim 1\,M_\odot$. From van Loon et al. 2002

Courteau 2002), which all seem predominantly old and metal-rich but most of which do contain bright AGB stars and possibly even younger populations. Rich & Mighell (1995) ask the question why the integrated light of the bulge of M31 is so red despite the presence of an intermediate population. This is probably due to the fact that the integrated light results mainly from the red giants of ~solar mass, and in addition from the many red dwarfs that have been formed in any generation of stars. This explains why observations of distant bulges show an old, metal-rich content, whereas observations of spatially resolved stellar populations in nearby bulges increasingly show the presence of younger as well as metal-poorer stellar populations — see also Lamers et al. (2002) for the bulge of M51 and Rejkuba et al. (2001) for the giant elliptical NGC5128.

A major recent study of the Galactic bulge, vastly less affected by forground dust extinction than all earlier studies, has recently been completed by the ISOGAL consortium (van Loon et al. 2002).

Near- and mid-IR survey data from DENIS and ISOGAL were used to investigate the structure and formation history of the inner 10° (1.4 kpc) of the Milky Way galaxy. Synthetic bolometric corrections

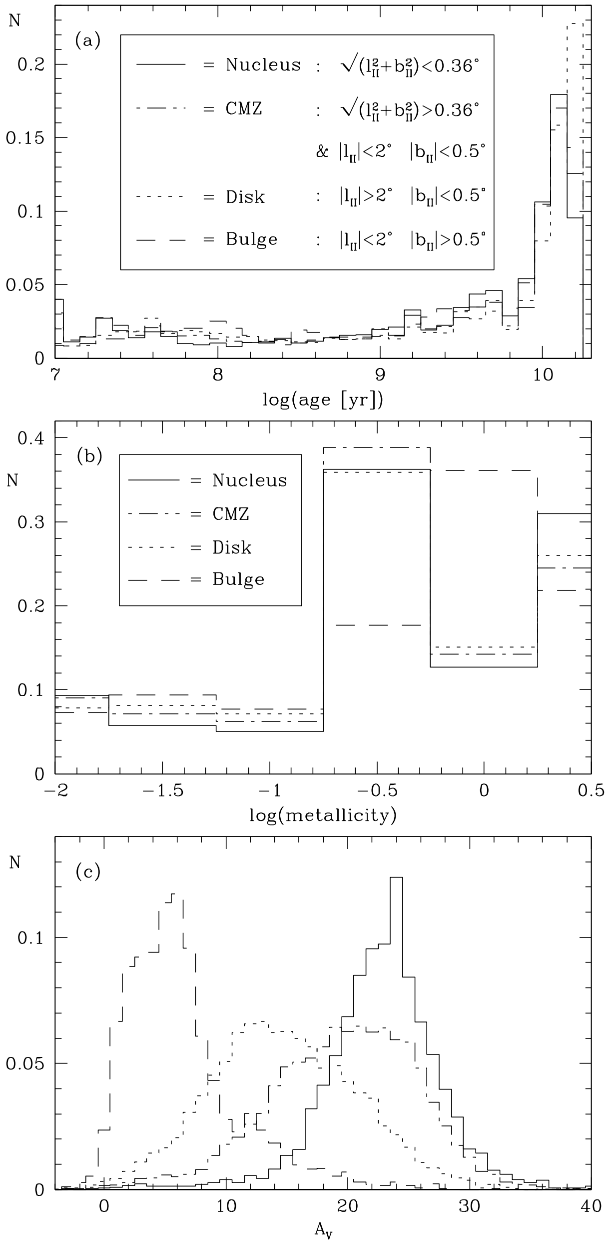

Fig. 5. Analysis of the ISO ISOGAL inner bulge mid-IR photometric survey. The normalised (a) age (b) metallicity and (c) extinction distributions for the nucleus, central molecular zone, disk and bulge. From van Loon et al. 2002

and extinction coefficients in the near- and mid-IR were derived for stars of different spectral types, to allow the transformation of theoretical isochrones into observable colour-magnitude diagrams. The observed IR colour-magnitude diagrams could then be used to derive the extinction, metallicity and age for individual stars (Figure 4). The inner galaxy is dominated, as expected, by an old population ($\gtrsim 7$

Gyr). In addition, an intermediate-age population (~ 200 Myr to 7 Gyr) was detected, which is consistent with the presence of a few hundred Asymptotic Giant Branch stars with substantial mass loss. Furthermore, young stars ($\lesssim$ 200 Myr) are found across the inner bulge. The metallicities of these stellar population components could also be derived (Figure 5).

These results can be interpreted in terms of an early epoch of intense star formation and chemical enrichment which shaped the bulk of the bulge and nucleus, and a more continuous star formation history which gradually shaped the disk, perhaps also involving accretion of sub-solar metallicity gas from the halo. A possible increase in star formation ~ 200 Myr ago might have been triggered by a minor merger. Ever since the formation of the first stars, mechanisms have been at play that mix the populations from the nucleus, bulge and disk. Luminosity functions across the inner galactic plane indicate the presence of an inclined (bar) structure at $\gtrsim$1 kpc from the galactic centre, near the inner Lindblad resonance. The innermost part of the bulge, within ~ 1 kpc from the galactic centre, however seems azimuthally symmetric. This is inconsistent with standard galaxy bar models from the literature.

3. THE STELLAR INITIAL MASS FUNCTION

In addition to its possible relevance to dark matter problems, the initial mass function (IMF) of low-mass stars in a wide variety of astrophysical systems is of considerable intrinsic interest (see e.g. papers in Gilmore & Howell 1998). For example, the form of the IMF at high redshift is of crucial importance for such aspects of galaxy formation as the understanding of background light measurements (e.g. Madau & Pozzetti 2000), galaxy luminosity and chemical evolution.

Low-mass stars, those with main-sequence lifetimes that are of order the age of the Universe, provide unique constraints on the Initial Mass Function (IMF) when they formed. Star counts in systems with simple star-formation histories are particularly straightforward to interpret, and those in 'old' systems allow one to determine the low-mass stellar IMF at large look-back times and thus at high redshift.

The faint luminosity function and low-mass IMF of stars formed recently are in practise however difficult to establish; in very young systems, one must often deal with the complexities of infrared luminosity functions, while the interpretation of field star counts is complicated by the errors in luminosity

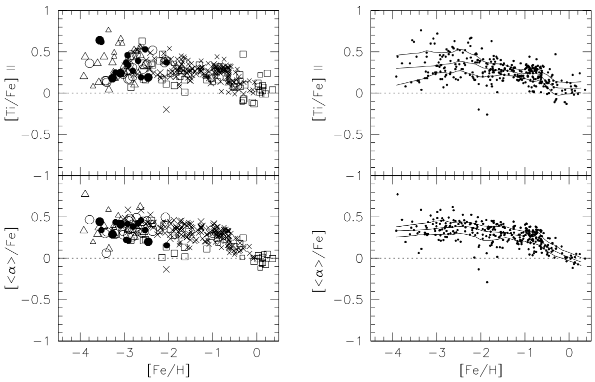

Fig. 6. Element ratios as a function of metallicity. The approximately constant ratios for stars below [Fe/H]~ −1 imply a metal-poor hign mass IMF which is close to Salpeter in slope for all abundances. Data from Carretta et al. (2002).

introduced by distance uncertainties and unknown metallicity spreads.

In spite of that, recent heroic-scale efforts (cf. Muench, Lada & Lada 2000), have quantified the local young IMF over three decades in mass, extending well below the hydrogen-burning stellar mass limit. Somewhat unexpectedly, the available data are consistent with a mass function indistinguishable from that of the globular clusters (von Hippel et al. 1996; Reid et al. 1999; Gilmore 2001; Kroupa 2002; but see Eisenhauer 2001 for the view that the IMF does vary). Thus, the low-mass IMF is apparently invariant to first order with time and metallicity.

The high-mass IMF can be studied directly for current star formation, and indirectly at high redshifts. The indirect method exploits the sensitivity of the element-dependent yield of a Type II supernova to progenitor initial mass. Thus, observed element ratios in metal-poor old stars may be interpreted to deduce the IMF slope for stars of the enriching earlier generation, with mass $\gtrsim 10\,\mathrm{M}_\odot$. Analyses of this type have been reported by several groups (eg Wyse and Gilmore 1988). A recent example of the type of data used is shown in Figure 6. The conclusion is that the high-mass metal-poor IMF was not very different, if at all, from that of stars forming today: an approximately Salpeter IMF is deduced.

3.1. *The IMF in ancient environments*

A direct test of the invariance of the low mass stellar IMF to environment at high redshifts is provided by comparison of the faint stellar luminosity function in a dSph galaxy with that of a stellar system that has similar stellar age and metallicity distributions and which is known to contain no dark matter. Empirical comparison of such luminosity functions minimises the need to use the highly uncertain and metallicity-dependent transformations between mass and light (see D'Antona 1998 for a discussion of this last point). Recently Wyse etal (2002) have reported the results of such a direct comparison.

As a class, the dwarf spheroidal (dSph) companions of the Milky Way, defined by their extremely low central surface brightnesses and low integrated luminosities (e.g. Gallagher & Wyse 1994), have internal stellar velocity dispersions that are in excess of those expected if these systems are in virial equilibrium, provided that their gravitational potentials are provided by stars with a mass function similar to that observed in the solar neighbourhood (see Mateo 1998 for a recent review). The most plausible explanation for the internal stellar kinematics of these galaxies is the presence of gravitationally dominant dark matter, concentrated on small length scales, leading to mass-to-light ratios a factor of ten to fifty above those of normal old stellar populations. The Draco dSph is clearly dominated by an extended dark matter halo (Kleyna et al. 2001). This dark matter must be cold to be dominant on such small scales ($\lesssim$ 1 kpc; cf. Tremaine & Gunn 1979; Gerhard & Spergel 1992; Kleyna et al. 2001). Could some of the dark matter be baryonic? Low mass stars have high mass-to-light ratios; indeed stars of mass 0.3 $M_\odot$ and metallicity one-hundreth of the solar value – of order the lowest mean metallicity measured for stars in dSph – have V-band mass-to-light ratios of 24 in solar units (Baraffe et al. 1997), and higher metallicity stars are even fainter. Of course faint stars could be viable dark matter candidates only if the stellar initial mass function (IMF) in these systems were very different from the apparently invariant IMF observed for other stellar systems, such as the solar neighbourhood or globular clusters (cf. Gilmore 2001).

The stellar population of the Ursa Minor dwarf Spheroidal (UMi dSph) is characterized by narrow distributions of age and of metallicity (e.g. Olszewski & Aaronson 1985; Mighell & Burke 1999; Hernandez, Gilmore & Valls-Gabaud 2000), with a dominant component that is similar to that of a classical halo globular cluster such as M92 or M15, i.e. old ($\gtrsim$ 10 Gyr) and metal-poor (mean [Fe/H] ~ -2 dex).

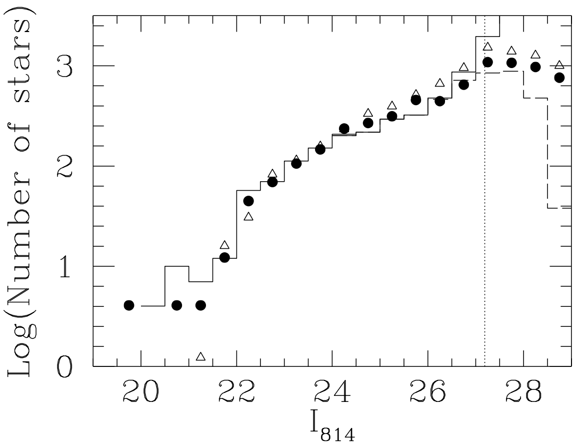

Fig. 7. The luminosity function of the UMi dSph galaxy, and that of two old metal-poor globular clusters (M15, M92). The similarity shows that the stellar IMF is not a function of environment. (from Wyse et al. 2002.)

However, in contrast to globular clusters, which have typical $(M/L)_V \lesssim 3$ (e.g. Meylan 2002), the internal dynamics of the UMi dSph are apparently dominated by dark matter, since the derived mass-to-light ratio is $(M/L)_V \gtrsim 60$, based on the relatively high value of its internal stellar velocity dispersion (Hargreaves et al. 1994; see review of Mateo 1998).

Faint star counts in the Ursa Minor dSph thus allow determination of the low-mass IMF in a dark-matter-dominated external galaxy in which the bulk of the stars formed at high redshift (a lookback time of 12 Gyr, the stellar age, corresponds to a redshift of $\gtrsim 2.5$ for a 'concordance' Lambda-dominated cosmology; e.g. Bahcall et al. 1999).

The results of Wyse etal are shown in Figure 7. The main-sequence stellar luminosity function of the Ursa Minor dSph, and the implied IMF down to ~ 0.3 $M_\odot$, is indistinguishable from that of the halo globular clusters M92 and M15, systems with the same old age and low metallicity as the stars in the Ursa Minor dSph. The available (indirect) limits on the high-mass IMF, inferred from elemental abundance ratios, are also consistent with the same IMF in these two very different classes of systems. However, the globular clusters show no evidence for dark matter, while the Ursa Minor dSph is apparently very dark-matter dominated.

4. MERGER HISTORIES, MERGER PARTICIPANTS

Mergers and strong interactions between galaxies happen, and may well be the dominant process in the determination of a galaxy's current Hubble type, particularly in the context of modern hierarchical-clustering theories of structure formation (e.g. Silk & Wyse 1993). The recently discovered (Ibata, Gilmore & Irwin 1994) Sagittarius dwarf spheroidal galaxy is inside the Milky Way Galaxy, is losing a significant stellar mass through tidal effects (Ibata et al. 1997), forming star streams in the halo (Mateo, Morrison & Olszewski 1998; Ibata et al. 2001; Yanny et al. 2000), but having little effect on the present structure of the bulk of the Galactic disk.

In the standard hierarchical clustering and merging picture of galaxy formation a thick disk is an expected outcome of a significant merger. Depending on the mass, density profile and orbit of the merging satellite, 'shredded-satellite' stars may retain a kinematic signature distinct from that part of the thick disk that results from the heated thin disk. Satellites on prograde (rather than retrograde) orbits couple to the rotating thin disk more efficiently, and thus a merger with such a system is favored as the mechanism to form the thick disk (Quinn & Goodman 1986; Velazquez & White 1999). If any kinematic trace of the now-destroyed satellite galaxy is visible, it will be seen in the mean orbital rotational velocity of stars. The actual lag expected from the shredded-satellite depends predominantly on the initial orbit and the amount of angular momentum transport in the merger process, and is not *ab initio* predictable in a specific case.

The outcome of a merger of two stellar systems depends on several factors, most importantly the mass ratio and density contrast. During a merger, energy, momentum and angular momentum are re-distributed so that the common aftermath of a merger between a large disk galaxy and a smaller, but still significant, satellite galaxy (more massive than the Sagittarius dwarf spheroidal galaxy) is a heated disk and a disrupted satellite (Quinn & Goodman 1986; Velaquez & White 1999). This is currently the most plausible model for the origin of the thick disk in our Galaxy (see reviews in Gilmore, Wyse & Kuijken 1989; Majewski 1993) and those of other galaxies; the stochastic nature of the merger process allows for a wide variety of, and indeed non-existence of, thick disks in external galaxies, as observed, provided only a small number of merger events are involved.

In general however, excluding special initial conditions, such as a circular orbit at large distance (see Walker, Mihos & Hernquist 1996), satellite debris stars will be on orbits characterised by lower net rotational streaming about the Galactic Center than that of the typical scattered former thin-disk star at a given distance from the Galactic center. In order to support themselves against the Galactic potential with less angular momentum support, the shredded-satellite debris must then have larger random motions (equivalent to pressure) than do the typical thick disk stars: this is seen in numerical simulations of this process (Walker et al. 1996). It is these kinematics which allow their detection: stars with the highest amplitude of vertical motions (the satellite debris?) will be preferentially found farther from the plane than are most thick disk stars (the heated thin disk?). If a population of former satellite stars exists, and the satellite was on an initial non-circular orbit consistent with cosmological simulations (van den Bosch et al. 1998), the apparent mean rotational velocity of stars far from the plane (the debris) will be less than it is for stars near the Sun, in the 'classical' thick disk. This situation is easily distinguished from the possibility that all stars form a single, coherent, thick disk, in which case the rotational velocities of the most distant thick disk stars, far from the plane, will not differ significantly from those nearby. This second model is inconsistent with recent observations.

Determination of the stellar populations in the Galactic thick disk tests this model, and so constrains the merger history of the Milky Way, Current indications are that the Galactic thick disk is composed of only very old stars, ages $\gtrsim 10$ Gyr, equivalent to forming at a redshift of $\gtrsim 1$ (Wyse 2000). This implies that the event that formed it from the thin disk, which now contains stars of all ages, occurred a long time ago, with little subsequent extraordinary heating of the thin disk. If this model is valid, it may be possible to identify stars captured from the accreted galaxy, and to distinguish them from those formed in the early thin disk of the Milky Way. This would allow tight constraints on what merged, and when it merged, and on the early star formation in an extended disk. These are important tests of hierarchical clustering theories of structure formation.

Gilmore, Wyse and Norris (2002; Figure 8) have recently reported first results from a survey with the AAT/2dF designed to quantify the origins of the thick disk, and to test the merger model of its formation. They detect a substantial population of stars on orbits that are intermediate between those of the canonical thick disk and the canonical stellar halo.

Their data for the brighter stars and the model are in tolerable agreement showing the well-established canonical thick disk lag of less than 50 km/s. However, there is an obvious disagreement for the fainter stars, in that the typical star shows a mean lag behind the Sun of ~ 100 km/s. The peak

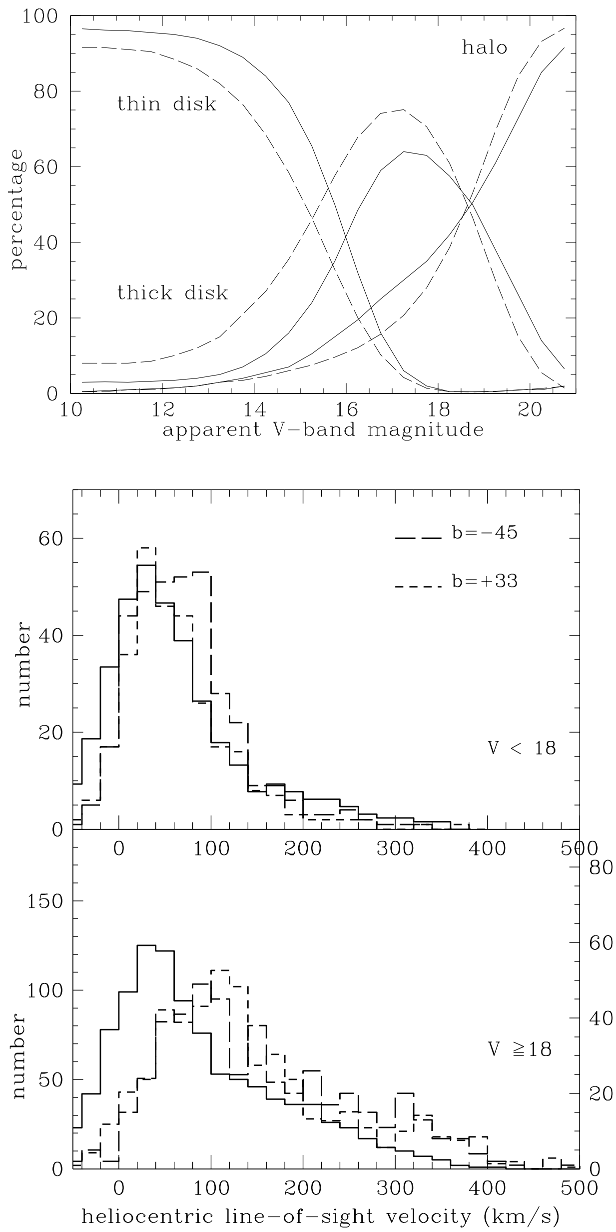

Fig. 8. UPPER: star count predictions as a function of apparent magnitude, at high Galactic latitudes. LOWER: Radial velocity histograms for F/G stars in two lines-of-sight, compared to model predictions. The kinematics of the brighter stars, with apparent magnitude less than 18 in the V-band, are shown in the top panel and the kinematics of the fainter stars are shown in the bottom panel. The solid histograms result from random sampling Gaussians with 'standard' kinematics. The short-dashed histograms are the data for a field in which at these distances the heliocentric line-of-sight velocity corresponds to $\sim$ 80% of rotation velocity, while the long-dashed histograms are the data for a second field in which it corresponds to $\sim$ 70%. In the lower panel the y-axis scale on the right-hand-side refers to the long-dashed histogram. Data from Gilmore, Wyse & Norris 2002.

of the observed distribution is significantly displaced from the model predictions. This disagreement is not sensitive to the adopted normalisations or scale heights for the thick disk and halo, but indicates the need for a substantial revision in the standard kinematical model of the Milky Way.

Gilmore et al. note that they have not detected a small perturbation superimposed on a smooth well-understood background, but rather intrinsic complexity in the kinematic distribution function of stars ascribed in standard models to the thick disk. They also note that the predictions of the Gaussian halo fail to reproduce the local peak in the data at around 300 km/s, which is suggestive of a retrograde halo stream (velocities above $\sim$ 180 km/s in these lines-of-sight are retrograde), as may be produced by accretion of a small satellite (e.g. Helmi et al. 1999).

5. CONCLUSIONS

A worthwhile galaxy formation algorithm must be able naturally to reproduce the best observed galaxies, those of the Local Group. The challenges to the dramatically successful CDM hierarchical model from the Local Group are demanding, and are currently at the limit of what the models can predict. Such issues as the number of local dwarf galaxies and the inner CDM profiles of the dSphs are well known demanding challenges for CDM models. Other Local group information is also important: what is the stellar Initial Mass Function, what is the distribution of chemical elements, what is the age range in the Galactic bulge, when did the last significant disk merger happen... All these challenge our appreciation of galaxy formation and evolution, and in turn provide the information needed to refine the models. The partnership between local observations and ab initio theory is close, and developing well.

6. ACKNOWLEDGEMENT

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G. Gilmore, Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, U.K.

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