The outer Galaxy: stellar populations and dark matter

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Abstract. The Galaxy’s stellar populations are naturally classified into six ‘types’, of which five have been observed. These are the thin disk (Pop I in the historical scheme), a discrete thick disk (Pop I.5), the metal-rich bulge, which was not named in the Baade sequence, the rare field halo (Pop II), a population currently being accreted into the very outer halo filed (Pop Sgr?) and a hard to discover initial enriching Pop III. Each of these forms a group with astonishingly tight correlations between chemical element ratios and other parameters. It is very hard to understand how the observed properties of any one of these populations can be the sum of many discrete histories, except for the minor continuing outer halo accretion. All these stellar populations are embedded in dark-matter, and allow the properties of dark matter to be measured on small scales. Intriguing and unexpected consistencies in the properties of this dark matter are being revealed.

1. Stellar Population Types

In the Milky Way we can identify five stellar populations with properties that constrain the star formation history, the chemical evolution history (flows, feedback..) and the mass assembly history of the Galaxy. There may even be a sixth type, sometimes called Pop III, as yet undetected directly but postulated to provide the first chemical enrichment.

- The thin disk, also known as Baade’s Population I. This is composed of stars and gas on high angular momentum orbits, moving about the center with close to the circular velocity, and thus with only low amplitude random motions. Such a cold thin system presumably formed by dissipational collapse of gas, in a potential that is changing slowly, and conserved angular momentum to spin-up as it collapsed (see Fall & Efstathiou 1980; Mo, Mao & White 1998). The origins of disks are however not clear: hierarchical merging models predict significant angular momentum transport and generate disks that are too small (Navarro & Steinmetz 1997). Appeal to some suitable process of ‘feedback’ can be implemented to prevent much of the angular momentum losses from the proto-disk, but at the expense of delaying the collapse to centrifugal equilibrium (e.g. Eke, Efstathiou & Wright 2000) and thus predicting few old stars in disks, and no extended high-redshift disks. Late perturbations to the thin disk cannot be too strong, or the disk will be destroyed (e.g. Ostriker 1990). The properties of stars in the thin disk are important tests of merging histories and energetic dynamical processes. The age and metallicty distributions of the disk, well-defined only at the solar neighbourhood, point to extended in-
fall of metal-poor gas, and steady star formation from a redshift of $\sim 1.5$ (e.g. Binney et al. 2000) to the present.

- The thick disk - this was identified as a separate component some 25 years ago (Gilmore & Reid 1983). The dominant population is old, as old as the globular cluster 47 Tuc, $\sim 12$ Gyr, and of intermediate metallicity in the mean, $[Fe/H] \sim -0.6$, with a significant spread. The chemical enrichment history revealed by the pattern of element ratios is distinct from that of stars in the thin disk (Bensby et al. 2007, this meeting). A plausible origin for the thick disk is a moderately violent dynamical event such as a minor merger; the old mean age for the thick disk limits such events to have occurred only long ago, an important constraint – and a problem, if found to be a typical result – for CDM models. Thick disks are often observed in resolved stars in other galaxies (e.g. Mould 2005; Yoachim & Dalcanton 2005) but their properties remain to be robustly determined.

- The central bulge - interestingly, though probably most stars in the Universe are in spheroids, this was not in the classic Baade list of stellar populations. The dominant stellar population in the bulge of the Milky Way is old and metal-rich, with a broad spread in metallicities. Elemental abundances are available for remarkably few stars, given the capabilities of current telescopes, but where available point to a fairly rapid enrichment, being dominated by products of Type II supernovae. This, together with the old age and high (phase-space) density, point to in situ formation, in a ‘starburst’, though a star formation rate of $\sim 10M_\odot yr^{-1}$ is all that is required, at high redshift. In some way, this is connected to the formation of the supermassive black hole at the Galactic Center. The relationships between the overlapping ‘bulge’, ‘bar’ and the thin and thick disks in the inner kpc or so remain unclear.

- The stellar halo, also known as Baade’s Population II. This is a dominantly old and metal-poor component, with Type II dominated element ratios, indicating a short duration of star formation in each of the star-forming entities that created the halo. The negligible scatter in the ratio of alpha elements to iron for stars with a range in Galactocentric orbits of some tens of kpc is startling, and suggests in situ formation from a single well-mixed ISM over scales of that size during halo formation. Accretion to the dominant inner Population II halo can only have occurred at early times (Unavane, Wyse & Gilmore 1996). The bulk of the Population II halo may be connected to the stellar bulge; one can tie gas outflow from halo star-forming regions, required to provide the low mean metallicity, to gas inflow to the central regions to form the bulge. The low angular momentum of proto-halo material means that it will only come into centrifugal equilibrium after collapsing in radius by a significant factor. The predicted mass ratio of bulge to halo is around a factor of ten, just as would be expected, and the specific angular momentum distributions of stellar halo and bulge match (Wyse & Gilmore 1992; see Figure 1 here).

- The outer parts of the halo, although containing only a small fraction of even the rare halo stars, have a more complex structure and history (e.g
the ‘Field of Streams’, Belokurov et al 2006). There are clear indications of significant accretion, most dramatically due to the Sagittarius dwarf (Ibata, Gilmore & Irwin 1994) which is currently populating the outer halo with mostly intermediate-age and metal-rich members. It is quite unclear what the progenitor of Sgr would have looked like a few Gyr ago.

- Population III – which we take to mean stars formed from primordial gas, precursors to ‘galaxy’ formation. Where are the low-mass Pop III stars? On-going searches for extremely low metallicity stars in the Galactic halo have not found any strong indications of a separate population (e.g. Beers et al. 2005), but have identified a few stars with extreme deficiencies in iron, and relatively strong carbon (e.g. Aoki et al. 2007). The origins of this abundance pattern are unclear. There is little observational evidence in favour of significant variations in the stellar IMF for any of the components discussed above, but there is theoretical prejudice that primordial stars might form with a narrow range of masses, around \( \sim 200 \, M_{\odot} \) (e.g. Bromm & Larson 2004). The supernovae from such stars would provide elemental abundance patterns in the stars they enrich that do not match those of the extremely metal-poor stars, indicating that much remains to be learned.

- Population Zero: the dark matter

2. Dark Matter on small scales

The Milky Way satellite dwarf spheroidal (dSph) galaxies are the smallest dark matter dominated systems in the universe. Several groups have underway dynamical studies of the dSph to quantify the shortest scale lengths on which Dark Matter is distributed, the range of Dark Matter central densities, and the density profile(s) of DM on small scales. An updated overview of results will be presented in Gilmore et al (2007).

All mass distribution analyses based on the Jeans’ equations - as most are to date - involve an inherent degeneracy between mass and (stellar tracer) orbital anisotropy. Nonetheless, the observed properties of all the dSph studied to date, including their half-light radii, the amplitude of their central velocity dispersions, and the flatness of their velocity dispersion profiles, require, purely from observations, a quite remarkable similarity among the least luminous galaxies, even though they exist over several magnitudes in absolute magnitude.

Exploiting this similarity in both optical sizes and kinematic properties, there is a simple consistency argument which links the observed distribution of sizes of small galaxies, the clear distinction in size and phase-space density between star clusters and galaxies of the same total luminosity, and all the available dSph galaxy dynamical analyses. Our current results suggest some surprising regularities: the central dark matter density profile is typically cored, not cusped, with scale sizes never less than one hundred pc; the central densities are typically \( 10 - 20 \text{GeV/cc} \) if the mass is cored, and less than \( \sim 1\text{TeV/cc} \) even if the dark matter is cusped. No galaxy is found with a dark mass halo less massive than \( \sim 10^{7} M_{\odot} \).

All the dSph analysed by all groups to date show very similar, and surprisingly low, central dark matter mass densities, with a maximum value of
Figure 1. Adapted from Wyse & Gilmore 1992, their Figure 1. Angular momentum distributions of the bulge (solid curve), the stellar halo (short-dashed/dotted curve), the thick disk (long-dashed/dotted curve) and the thin disk (long-dashed curve). The bulge and stellar halo have similar distributions, as do the thick and thin disks. Does this hold for external galaxies, pointing to fundamental relationships between bulge and halo, and thick and thin disks?

\[ \sim 0.5 M_\odot pc^{-3} \]

\[ \sim 20 \text{GeV/cc} \]

Interestingly, the rank ordering of the central densities, though not robustly determined, seems in inverse order to system total luminosity, with the least luminous galaxies being the most dense. This is of the opposite sign to some CDM predictions. The low maximum mass density is also intriguing, given that some currently favoured dark matter candidate particles are of Higgs scale, TeV mass - their corresponding volume density must be very low indeed.

These consistencies were suspected, largely based on the results of Figure 2 here, before the recent flurry of discoveries of several very low luminosity dSph galaxies, and the availability of several new kinematic studies. Interestingly, the validity of the conclusions is becoming stronger as the sample and the dynamic range are improved, suggesting some underlying general properties of dark matter on the smallest scales are within observational reach (Gilmore et al 2007 -submitted)

We are discovering many more dSphs, which we and other groups are analysing to test the generality of these results.
Figure 2. Derived inner mass distributions from Jeans’ eqn analyses for four dSph galaxies. Also shown is a predicted \( r^{-1} \) density profile. The modelling is reliable in each case out to radii of \( \log(r)\text{kpc} \sim 0.5 \). The unphysical behaviour at larger radii is explained in the text. The general similarity of the four inner mass profiles is striking.

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