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Galactic Surveys in the Gaia Era

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Abstract. The final astrometric data from the Gaia mission will transform our view of the stellar content of the Galaxy, particularly when complemented with spectroscopic surveys providing stellar parameters, line-of-sight kinematics and elemental abundances. Analyses with Gaia DR1 are already demonstrating the insight gained and the promise of what is to come with future Gaia releases. I present a brief overview of results and puzzles from recent Galactic Archaeology surveys for context, focusing on the Galactic discs.

Keywords. Galaxy: formation, evolution, structure

1. The Fossil Record: Galactic Archaeology

Galactic Archaeology, or Near-Field Cosmology, is possible due to the long life-times of low-mass stars and the fact that the kinematics and chemical abundances of such stars contain information about conditions at their birth. Nearby stars older than 10Gyr probe redshifts greater than 2 and are found throughout the Galaxy and its retinue of satellites. Photospheric elemental abundances are largely unchanged throughout the lifetime of a star (setting aside mass transfer in close binaries, and the very low level of pollution through accretion of ambient material through which the star passes) and hence reflect those of the interstellar gas from which the star formed. Certain orbital properties, such as energy and angular momentum, are approximate adiabatic invariants in realistic potentials and structure in chemical and kinematic phase space persists after coordinate space structure is erased by mixing (due to the finite velocity dispersion of the structure). The multivariate distribution functions of different Galactic components overlap, so that large samples of stars with well-understood selection functions are required. The study of resolved stars of all ages within one galaxy (limited at the present to members of the Local Group) as a means to decipher how galaxies evolve is complementary to the direct study of the integrated light of galaxies at high redshift: evolution of a few galaxies compared to snapshots of different galaxies at different times.

The detailed study of stellar populations in the Milky Way and satellite galaxies (also M 31) is of particular importance to efforts to identify signatures of dark sector physics. Different candidate dark matter particles make very different predictions for structure formation on, and below, the scales of large galaxies, while on large scalles, where gravity dominates the physics, there is little divergence (see the review by Ostriker & Steinhardt, 2003). These small scales are just those on which tensions are found between the predictions of ΛCDM models without fine-tuning and observations (e.g. Weinberg *et al.* 2015). Much current effort is directed both at investigations of alternative dark matter candidates and investigations of more complex/improved baryonic physics, particularly stellar feedback, to modify the distribution of dark matter. Baryonic physics is imprinted on the fossil stellar populations and more sophisticated models within the ΛCDM framework are being developed to test against the increasingly detailed and comprehensive observational data.

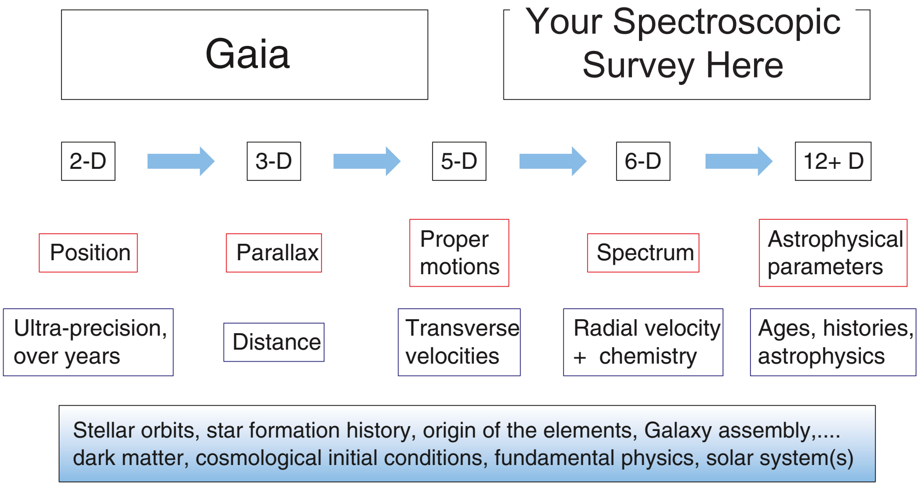

Figure 1. Illustration of the increase in dimensionality of the parameter space within which resolved stellar populations may be studied with the combination of astrometric and spectroscopic data. The observational quantities obtained from each type of data are in the boxes outlined in red, with the derived astrophysical quantities in the blue-outlined boxes. The 12+ dimensions of 'Astrophysical parameters' refers to the spectroscopic gravity, effective temperature and many individual elemental abundances that may be estimated from the spectra. The 'big-picture' physics questions that may then be addressed are in the blue-shaded box below. Adapted from Gilmore *et al.* (2012), their Fig. 2.

As I will discuss below, using the Galactic discs as examples, the distribution of stars in $n-$dimensional space is a complex function of how the Galaxy formed and evolved. The power of the combination of Gaia astrometric data with spectroscopic data is illustrated in Fig. 1, modified from the overview of the Gaia-ESO survey (Gilmore *et al.*, 2012).

There are several recent, on-going and planned stellar surveys using highly multiplexed spectrographs, each with its own niche defined by the selection function and characteristics of the spectra (such as resolution, wavelength coverage). One hopes that consistent conclusions will be reached from analyses of the different datasets. Those targeting brighter stars, such as the RAVE survey (see Kunder *et al.*, 2017 plus Andrea Kunder's contribution to this volume), the GALAH survey (see Martell *et al.*, 2017), the APOGEE survey (see Allende-Prieto's contribution to this volume) and the LAMOST survey (see Martin Smith's contribution to this volume) have significant overlap with the sample of the Tycho Gaia Astrometric Solution of Gaia DR1 and the range of talks and posters in this conference give a flavour of the wealth of science questions that can be addressed with these data, and point to the future analyses that will be enabled with the full Gaia dataset.

On-going and planned ground-based multi-band imaging surveys such as PanSTARRS1 (Kaiser *et al.* 2010), the Dark Energy Survey (Abbott *et al.* 2016) and LSST (Abell *et al.* 2012), together with space-based surveys from current and future missions, further extend the dimensionality of the dataset. Of course, the Gaia photometry and positions by themselves contain new information (for example see Deason's contribution to this volume for a clever use of photometry flags in Gaia DR1 to identify variable stars). This is truly an exciting time for Galactic astrophysics.

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2. The Milky Way Discs: What can we learn from (old) disc stars?

Thin stellar discs are fragile and can be disturbed by external influences such as companion galaxies and mergers, in addition to internal gravitational perturbations such as spiral arms, bars and Giant Molecular Clouds. Stellar systems are collisionless and thus cannot 'cool' once heated, unlike gas whuch can radiate away energy in excited internal degrees of freedom. The vertical structure of the thin disc - with 'structure' intended to refer to all aspects, including number density, age distribution, chemical abundance distribution and kinematics - encodes the history of heating and minor merging/satellite accretion, relative rates of dissipational settling and star formation, adiabatic compression and further heating. The radial structure reflects the relative rates of star formation and gas flows, as a function of location, and contains imprints of the angular momentum distribution and re-arrangement. The thick disc probes the earliest phase of disc star formation and the nature, and rate, of the transition between the thick and thin discs constrain the duration of more significant mergers and associated heating and/or turbulent conditions, subsequent gas cooling and accretion to (re-)form a thin disc. Interactions with gravitational perturbations, particularly satellites, do not only heat and thicken stellar discs, they can also excite warps and 'bending' and 'breathing' modes in the thin disc (for example Widrow *et al.*, 2014). Some radial spreading of the disc is created as angular momentum is transferred from a satellite to disc stars; this change in mean orbital radius occurs together with transfer of random energy into the orbit i.e. associated heating (e.g. Bird *et al.* 2012). Induced radial displacement of stars can also occur without a change in the orbital circularity, due to interactions between stars and a perturbation (such as a transient spiral arm) at the corotation resonance of the perturbation (Sellwood & Binney 2002); this maintains the thinness of discs while stars move within them, and is commonly referred to as Radial Migration (even though other types of interaction can also cause a star's mean orbital radius to change). The outer regions of thin discs can be built-up by outward radial migration, and the quantification of this contribution to the stellar population at large radius, compared to *in situ* star formation, is of obvious importance.

2.1. *Vertical Structure: The Local Milky Way Thick Disc*

The thick disc was initially defined geometrically, through fits to star counts at the South Galactic Pole; two separate exponentially declining density laws were required (Gilmore & Reid 1983), with the thick disc having a significantly larger scale height than the thin disc. This geometric thick disc was subsequently shown (by many authors, see reviews by Gilmore, Wyse & Kuijken, 1989; Majewski, 1993) to have kinematics intermediate between those of the thin disc and stellar halo: the mean orbital rotation velocity about the Galactic centre lagging that of the thin disc by ~ 50 km/s, and the vertical velocity dispersion being ~ 40 km/s, consistent with the estimated scale height of ~ 1 kpc (there is a degeneracy between scale-height and local normalization in the fits to the star counts, but the scale-height has to be consistent with the kinematics and inferred mass surface density). These kinematics are too hot to have resulted from heating due to present-day internal disc perturbations (e.g. spiral arms, GMCs). A discontinuous trend in age-velocity dispersion from thin to thick disc suggested an exceptional heating event to form the thick disc. Early (multi-object) spectroscopic studies determined a mean metallicity for the thick disc of ~ -0.5 dex, with 'alpha-enhanced' elemental abundances ($[\alpha/\mathrm{Fe}] > 0$). The redder turn-off colour compared to the stellar halo (see Fig. 2, with this metallicity, implies that most thick disc stars are similar in age to the stellar halo, $\sim 10 - 12$ Gyr, thus forming at redshifts greater than 2. Since there are stars of

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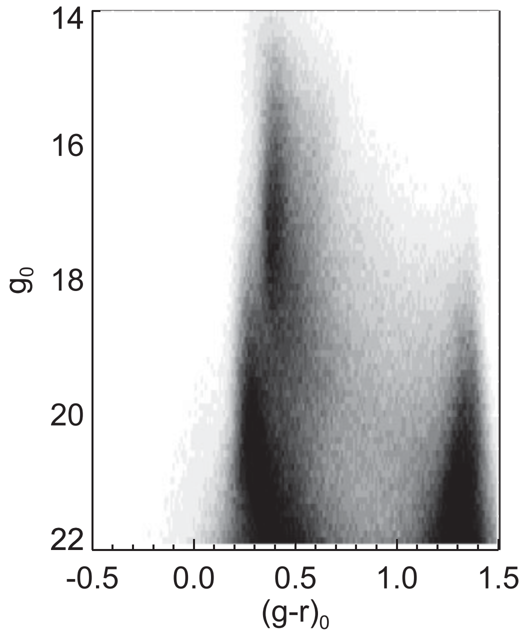

Figure 2. Taken from Jayaraman *et al.* (2013), showing star counts at intermediate latitudes across the SDSS Equatorial stripe. Each of the halo and thick disc show a well-defined - and distinct - blue edge, marking the main sequence turnoffs.

significantly younger ages in the local thin disc, which would be scattered into the thick disc should there have been a significant merger, or indeed any strong heating event, subsequent to their formation, the dominant old age in the (geometric) thick disc limits any such event to have occurred only at early epochs. The derived stellar mass of the thick disc is a significant fraction, in the range of 20% to 50%, of the thin disc mass, i.e. greater than $10^{10}M_{\odot}$. The narrow range of ages of the bulk of stars in the thick disc implies a high past star-formation rate.

2.2. *Chemically Defined Thick and Thin Discs*

More precise elemental abundance measurements for larger samples of stars have revealed that local (thin and thick) disc stars separate into two sequences in the plane of [α/Fe] against [Fe/H]. Differences in the patterns of elemental abundances largely reflects differences in star formation history (e.g. Gilmore & Wyse 1991), and the two sequences indeed are in line with the inferred star formation histories of the thick and thin discs, albeit that the extent of the overlap in iron abundance is large. Further, the mean properties of chemically defined 'high-alpha' and 'low-alpha' discs compare well with those of the geometrically defined discs: the 'high-alpha' sequence is on average more metal-poor, consists of older stars, has 'hot' kinematics, and is taken to represent the thick disc, while the 'low-alpha' sequence is more metal-rich, contains young to old stars, has 'cold' kinematics and is taken to represent the thin disc (e.g. Bensby *et al.* 2014; Martig *et al.* 2016a). Indeed, the more metal-poor stars in the 'high-alpha' sequence (which actually have enhanced values of [α/Fe]) have old ages and heights above the plane $\sim$ 1 kpc (Martig *et al.* 2016b) just as do stars in the geometrically defined thick disc. The two sequences merge at the metal-rich end(s), and there is real ambiguity about the assignment - and origins of - the metal-rich high-alpha stars, which also tend to be younger

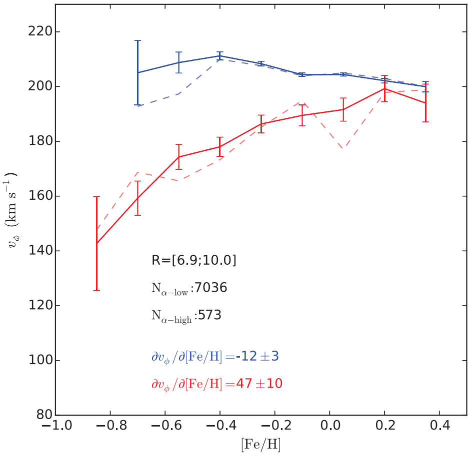

Figure 3. Taken from Kordopatis *et al.* (2017), showing the different trends of azimuthal streaming (rotation) velocity (v_ϕ) with iron abundance for stars in each of the two elemental abundance sequences (blue indicates the 'low-alpha' or thin disc sequence, while red indicates the 'high-alpha' or thick disc sequence). The data are from the APOGEE survey, in lines-of-sight selected to probe this velocity component without the use of tangential velocities, which are more uncertain prior to the improved proper motions and distances that Gaia will provide.

(e.g. Haywood *et al.* 2013, Chiappini *et al.* 2015). The younger stars at higher heights in the outer disc (Martig *et al.* 2016b) probably reflect flaring of the thin disc.

The distinctiveness of the kinematics of the two elemental abundance sequences is seen clearly in the very different trends of rotational velocity with iron abundance, illustrated in Fig. 3. Again we see the sequences merging at high iron abundances. The trend of increasing rotational velocity for decreasing iron abundance in the 'low-alpha' (thin disc) sequence is understandable as a consequence of the combination of a negative radial metallicity gradient and epicyclic motions, conserving orbital angular momentum - a star observed close to its perGalacticon, on an inward epicyclic excursion, will have a higher orbital rotation velocity and have a lower metallicity than the disc where it is observed, and *vice versa* for a star observed close to its maximum outward epicyclic excursion. The opposite trend for the 'high-alpha' (thick disc) sequence must reflect how the thick disc formed and evolved (see e.g. Schönrich & McMillan, 2017).

2.3. *The (Geometric) Thick Disc and the Earliest Phase of Disc Evolution*

Stars in the (geometric) thick disc are old, and formed at lookback time of ~ 10 Gyr, corresponding to redshift ~ 2: the epoch of peak cosmic star formation. The high stellar velocity dispersion and inferred short duration of star formation implies that the thick disc likely formed prior to equilibrium/virialization of the Milky Way's dark halo, during the epoch of active assembly/mergers, leading to highly turbulent conditions in the ISM (cf. Jones & Wyse 1983, Gilmore 1984, Brook *et al.* 2012, Bird *et al.* 2013, Ma *et al.* 2017). The derived stellar mass ($M_* > 10^{10} M_\odot$) and star-formation rate (several $M_\odot$/yr) are similar to those derived for star-forming discs observed at redshift $\sim$ 2. These high-redshift galaxies show clumpy, turbulent ionized gas discs, in organized rotational motion with amplitude of $\sim 100 - 200$ km/s, and a high internal velocity dispersion, $\sim 50 - 100$ km/s (e.g. Wisnioski *et al.* 2015). Lower redshift star-forming gas discs show higher values of rotational velocity to random motions, and higher specific angular momentum (Swinbank *et al.* 2017). How this translates into the evolution of an individual disc

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consisting of stars and gas is model-dependent. The fossil record from discs in nearby galaxies provides the best guide.

2.3.1. *The Old Age of Thick Disc Stars Limits Recent Merger/Heating Events*

Mergers heat the thin stellar disc and input stars formed up to that epoch into the (geometric) thick disc (and perhaps the stellar halo). There are stars of a broad range of ages in the thin disc, reflecting continuous star formation since early times. The dominant old age of stars in the (geometric) thick disc implies that there has been no significant merger since the redshift at which the look-back time equals this old age of thick disc stars. An age of ~ 10 Gyr means a quiescent merger history since redshift ~ 2 (Wyse 2001). Such a quiet merger history is consistent with there being no evidence of a significant dark or stellar accreted disc (e.g. Ruchti *et al.*, 2015). Minor mergers/interactions, for example that ongoing with the Sagittarius dwarf spheroidal, affect primarily the outer thin disc, inducing outer spiral structure, warping and/or flaring (e.g. Purcell *et al.* 2011).

The underlying assumption of this dating technique gains support from the recent analysis by Ma *et al.* (2017) of the age structure of the thin/thick discs formed in their simulation of the formation of a Milky Way-mass disc galaxy in ΛCDM. Their model galaxy incurred its last significant merger at redshift ~ 0.7, a lookback time of ~ 6Gyr. Fig. 4 of Ma *et al.* shows that across the radial extent of the disc the mean age of stars at heights 1-2 kpc above the mid-plane is $\sim 4 - 7$ Gyr, with mean metallicity in the range -0.3 dex to the solar value. This mean age, for what would be identified as the geometric thick disc, indeed reflects the timing of the last significant merger ~ 6Gyr ago (plus time for the merger/heating to complete), and the high mean enrichment is also consistent with a later heating event in the simulation than implied for the Milky Way.

Accurate and precise (old) stellar ages are crucial in this estimation of the timing of the last significant merger and the parallax data from Gaia will be extrenely important (see Tayar *et al.* 2017 for a discussion of the biases that must be dealt with in the estimation of ages for red giant stars based on astrosiesmology-based gravities). Distances are also of course fundamental to the determination of the vertical stucture. See Mackereth *et al.* 2017 for a recent pre-Gaia analysis of the age-metallicity structure of the discs from APOGEE data. The quiescent merger history inferred for the Milky Way is not typical in ΛCDM and we also need more detailed predictions of the merger history of typical Milky Way-mass disc galaxies, as a function of the orbit and mass ratio of the satellite/subhalo, from galaxy formation models, to interpret the derived observational limits.

3. Radial Structure: the Outer Disc

3.1. *The Ringing Disc*

A wealth of structure in the outer stellar disc has been revealed by the imaging data of SDSS (e.g. Belokurov *et al.*, 2006)) and Pan-STARRS (e.g. Slater *et al.*, 2014 and Bernard *et al.*, 2016). Systematic variations in star counts above and below the nominal mid-plane were identified by Xu *et al.* (2015) and interpreted as rings and radial waves in the disc. The 'Monoceros Ring', which had been speculated to be a remmant of an accreted satellite (e.g. Peñarrubia *et al.*, 2005) is clearly more simply an apparent overdensity due to structure within the thin disc. Oscillatory kinematic features in thin disc stars have also been identified in several kinematic surveys (e.g. Widrow *et al.*, 2012 and Williams *et al.*, 2013). These plausibly reflect breathing/bending modes of the perturbed thin disc (Widrow & Bonner 2015), excited due to interaction by either internal perturbations, such as spiral structure and/or the bar (Debattista, 2014) or external perturbations, perhaps the Sagittarius dwarf spheroidal (Gómez *et al.*, 2013; see also Widrow *et al.*,

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2014). These oscillations, combined with flaring of the thin disc, may extend to high enough distances from the plane that even apparent 'halo' substructure may actually consist of the perturbed thin disc (Li *et al.*, 2017).

There are several mechanisms by which a sub-population of thin disc stars can be scattered/heated into the halo, such as through binary interactions. This could be the explanation behind the discovery of rare metal-rich high-velocity stars (e.g. Hawkins *et al.*, 2015). As is always the case for the analysis of objects with extreme values of the parameters characterizing their parent population (kinematics and chemistry in this case), the accuracy and precision of those values are critical.

The main lesson is that overdensities in star counts and kinematic substructure are not necessarily tidal debris from satellites. Again, a more comprehensive understanding will be available with improved distances, three-dimensional velocities and ages from the Gaia data.

3.2. *Internal, Secular Evolution to Re-arrange Discs?*

As noted above, radial migration (Sellwood & Binney, 2002) can move thin-disc stars across distances that are of order the disc scale-length, during the lifetime of the disc, without associated kinematic heating (maintaining orbital circularity and the thinness of the disc). This mechanism is more effective for stars on closer-to-circular orbits, less so for populations of higher velocity dispersion/lower angular momentum orbits (e.g. Solway, Sellwood & Schönrich, 2012; Vera-Ciro *et al.*, 2014; Daniel & Wyse, 2017). The efficiency of radial migration also obviously depends on the parameters of the perturbation(s) driving it, such as amplitude, duty cycle, pattern speed and wave number (e.g. Daniel & Wyse, 2015; Debattista, Roskar & Loebman, 2017). The chemical evolution of the disc can be strongly affected (Schönrich & Binney, 2009). The existence of a significant population of thin-disc stars in the solar neighbourhood with super-solar metallicities is consistent with outward radial migration bringing stars from the inner, higher-metallicity, regions of the disc to the outer disc (e.g. Kordopatis *et al.*, 2015). The global importance of radial migration in the evolution of discs is uncertain, with simulations showing both a minimal influence (Bird *et al.*, 2013), and a very important role (Minchev *et al.*, 2012). It is clearly important to isolate the important phyical effects causing these different conclusions, and test the predictions of the models in detail.

4. Concluding remarks

'More data are needed': accurate and precise positions, distances, space motions, ages, and chemical abundances are all critical to the characterisation of the present stellar populations of the Galaxy and to the eventual understanding of the roles of different physical processes in its evolution. Happily this is what the combination of astrometric data from Gaia and data from large spectroscopic surveys promises to deliver. When analysing these data, we need to be clear to what we are referring when using the terms halo/bulge/thin disc/thick disc, since entities defined through different parameters (e.g. spatial distribution, chemistry) may have different histories.

There are truly exciting times ahead: wonderful observational data for stars plus improved simulations of galaxy formation in cosmological context(s), complemented by increasingly detailed data for high-redshift discs in formation.

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