Galactic Archaeology: Current Surveys and Instrumentation

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Abstract. I present an overview of the science goals and achievements of ongoing spectroscopic surveys of individual stars in the nearby Universe. I include a brief discussion of the development of the field of Galactic Archaeology - using the fossil record in old stars nearby to infer how our Galaxy evolved and place the Milky Way in cosmological context.

1. Introduction: The Fossil Record

Galactic Archaeology is the study of the properties of old, low-mass stars nearby, to unravel the evolution of the Milky Way, a typical large disk galaxy. Low-mass stars (of mass similar to, or less than, that of the Sun) have main-sequence lifetimes of at least $10^{10}$ yr. This is of order the age of the Universe, so that most low-mass stars ever formed remain today. Indeed there are copious numbers of stars nearby that have ages of order 10 Gyr; equating these ages to lookback times (for the concordance cosmology) reveals that these stars formed, and thus reflect conditions, at redshifts greater than 2. These stars retain some memory of the initial early conditions at which they form, and thus the early stages of galaxy evolution. The chemical elemental abundances in the stellar photospheres of main sequence stars are essentially conserved, modulo mass transfer in close binary systems. Orbital angular momentum about the $z$–axis is an approximate integral of the motion (exact in a time-independent axisymmetric potential) and kinematic signatures can persist over many orbital times. Studying low-mass stars nearby offers a complementary approach to direct study of galaxies at high redshift: evolution of one galaxy through time versus snapshots of different galaxies at different times. Data from resolved stars allow the derivation of metallicity independent of age and provide strong constraints on the stellar Initial Mass Function, breaking degeneracies often encountered in the analysis of the integrated light of galaxies.

The information that can be extracted from the stellar fossil record pertains to a range of physical processes, including

- The merging history of the galaxy, which is dependent on the nature of Dark Matter through the power spectrum of primordial density fluctuations
- The star-formation history - which may be quite different from the mass assembly history
- Chemical evolution, with associated constraints on stellar ‘feedback’
- The relative importance of dissipative gas physics compared to dissipationless processes
2. A Survey of Surveys

There have been many stellar surveys which share the same ‘big picture’ science goals - to decipher the evolutionary history of the Milky Way - but which adopt a variety of approaches. They have targeted different components and/or used different tracers such as clusters, main sequence turn-off stars, red giant stars, blue horizontal stars and red clump stars. The surveys also differ in which phase-space coordinates can be studied: 2D or 3D spatial coordinates, 1D or 3D kinematics, overall metallicity or detailed elemental abundances. Ideally the survey would be capable of analyzing the sample in as many properties as possible. The quality and quantity of data also distinguish different surveys, and experience has emphasized the need to understand, and minimize, both systematic and random uncertainties. As capabilities have improved, larger samples sizes have enabled analyses of parameters to go beyond simple means and dispersion to the full distribution functions - there is much physics in the detailed shapes, and in ‘extreme objects’.

I will give a brief survey of surveys, focusing on the disks of the Milky Way.

2.1. Pioneering Precursors

At this conference we are discussing surveys of stars with sample sizes in the millions. Early surveys - essentially those prior to the advent of multi-object spectrographs in the mid 1980s - were limited to samples of a few hundreds of stars, observed in the immediate solar vicinity, or used globular clusters as more distant, intrinsically luminous tracers (assuming their members were described by delta functions in age and metallicity). The enduring lessons from these surveys were not always the immediate ones. The pioneering study by Eggen et al. (1962) (hereafter ELS) demonstrated how analysis of kinematics and chemical abundances could provide insight into how the Milky Way Galaxy formed. That study analyzed data for a sample of 221 nearby main-sequence stars, derived photometric metallicity estimates from UV-excess and used that as a proxy for age. They noted a strong anti-correlation between each of orbital angular momentum and vertical velocity and metallicity, which they famously interpreted as evidence for rapid collapse of a monolithic star-forming gas cloud from a short-lived halo phase to a centrifugally supported disk. This conclusion was challenged by Searle & Zinn (1978) (hereafter SZ) based on inferences from a sample of ~ 50 Galactic globular clusters, with metallicity indicators (mostly taken from the literature) and photometry below the horizontal branch. These data showed no evidence for a metallicity gradient in the outer halo (defined by Galactocentric distances greater than 12 kpc), not obviously consistent with the strong anti-correlation between kinematics and metallicity found in the field stars. Further, SZ found that the morphology of the horizontal branch, as measured by the relative numbers of stars redward and blueward of the RR Lyrae gap, varied within the population of outer-halo globulars, even at fixed metallicity. The inner-halo clusters did not show such an effect. The ‘second parameter’ (metallicity being the first) affecting the colors of horizontal branch stars was taken
to be age, with the observed range implying an age spread of several Gyr for the outer halo. This is at odds with the rapid collapse of ELS. Searle & Zinn proposed their data implied that the globular clusters of the outer halo formed in ‘transient protogalactic fragments’ that were accreted ‘some time after collapse of its central regions’. This of course is reminiscent of the later infall of satellite galaxies predicted in ΛCDM models.

It was clear from their apparently contradictory conclusions that it was not possible that both ELS and SZ could be correct. We now have a better understanding of the biases that can arise in proper-motion selected samples such as that used by ELS (see, for example, Bond 1970; Carney et al. 1989). We also now have ages of globular clusters that are derived from fitting of the main-sequence turnoff and spectroscopic metallicities; these have revealed that while age indeed is the most plausible ‘second parameter’, all metal-poor globular clusters are old, while the metal-rich ones have a range of ages and have more disk-like kinematics (e.g. Dotter et al. 2011; Leaman et al. 2013). Several of each of the younger and older clusters are associated with the Sagittarius dwarf (Ibata et al. 1997), validating that some part of the outer halo cluster system is accreted. The bulk of the stars in the halo are indeed old, although that does not mean that they formed in the Galaxy a long time ago. The moral of the story is that good understanding and control of selection biases are critical, as are large enough samples with accurate and precise enough data.

The limitations of small sample sizes and large uncertainties in metallicity estimates are manifest in the ease with which Tinsley (1975) could fit the cumulative metallicity distribution of nearby stars (which shows the famous ‘G-dwarf problem’ - the lack of metal-poor long-lived stars compared to predictions of the Simple Model) with very different models. Cumulative distributions, appropriate for such limited data, do not provide sufficient discrimination among models.

### 2.2. Moving Beyond the Solar Neighborhood

The advent of scanning machines for automated measurement of positions and photometry from photographic plates facilitated the analysis of wide-area star counts to faint magnitudes. The density law at the South Galactic Pole, based on distances from photometric parallax, including models of the vertical metallicity gradients, was shown by Gilmore & Reid (1983) to require an additional component to the standard thin disk plus spheroid of existing models (e.g. Bahcall & Soneira 1980). This ‘thick disk’ identified by Gilmore & Reid was proposed by them to be part of the stellar halo, albeit ‘Intermediate Population II’. The multivariate dependence of the stellar luminosity function led to inevitable arguments about the robustness of this star-count analysis. Subsequent studies characterized the thick disk as distinct in kinematics and metallicity from both the stellar halo and (old) thin disk (e.g. Wyse & Gilmore 1986; Ratnatunga & Freeman 1989; Carney et al. 1989). Not only the field stars were better described by models including a distinct third component, improved data for the globular cluster system of the Milky Way - long taken as tracing the stellar halo, as noted above - showed that they too showed a distinct ‘disk’ component (Zinn 1985). The stars of the thick disk were found to be predominantly old and plausibly trace the earliest phase of disk formation (Jones & Wyse 1983), perhaps even providing a self-consistent solution to the ‘G-dwarf problem’ (Gilmore & Wyse 1986).
2.2.1. Near and Far

The advent of multi-object fiber spectrographs, using first manual plug-plate technology then automated positioners, opened the way for spectroscopic metallicities and line-of-sight velocities for large samples of stars, with the early generations of MOS in the 1980s providing simultaneous spectra for around one hundred stars within a field-of-view of a degree or so. A joint analysis of the kinematics and metallicity distributions of a sample of F/G main sequence stars in the local solar neighborhood with a corresponding sample of stars several kiloparsec away in the thin disk/thick disk interface, allows decomposition into thick and thin disks where the distributions overlap. Such an analysis, with sample sizes still only in the hundreds in each line-of-sight (Wyse & Gilmore 1995), allowed the identification of metal-poor thin disk stars and metal-rich thick disk stars, with the assignment of a star to a given disk component being based on kinematics and location within the Galaxy. The extents of the metallicity distributions in these regimes provide important constraints on models of disk evolution (e.g. Wyse & Gilmore 1995; Snaith et al. 2015). The joint distribution of colors and spectroscopic metallicities for statistically significant samples of F/G main sequence thick-disk stars allows an estimate of the ‘turnoff’ age to be made. Such an analysis consistently shows the thick disk to be predominantly old, with typical ages in the range of 10-12 Gyr - the same as 47 Tuc, the prototypical ‘thick disk’ globular cluster.

2.3. Back Nearby, Larger Samples

Wide-field imaging in narrow- and intermediate-band filters, such as the Strömgren system, has the potential to provide very large samples of stars with photometric metallicity and age estimates (Strömgren 1987). The Geneva-Copenhagen Survey (Nordström et al. 2004; Casagrande et al. 2011) of local thin disk stars (∼14,000 F/G stars within ∼40 pc) with Strömgren photometry, parallaxes from Hipparcos, proper motions and line-of-sight velocities (hence full 3D space motions) have revealed the wealth of information in joint age-kinematics-metallicity analyses. The large scatter in the age-metallicity relationship hinted at in earlier samples (e.g. Wallerstein 1962, discussed below) was definitively confirmed, as was the lack of change with time in the mean metallicity of the local disk. These data demonstrated the existence of stars with disk-like kinematics over the range of lookback times reaching almost to the cosmic ‘dark ages’, with many old stars nearby. The large sample size also revealed details of substructures in the disk that are defined by kinematics, moving coherently, but are unlike ‘moving groups’ in that they have a large internal range of age and metallicity. These signatures are best explained by internal resonant interactions between field disk stars and spiral arms and/or the bar.

2.4. Substructure

Larger samples, with well-understood errors, allow the identification and characterization of substructure in multi-dimensional kinematic-chemical-age phase space. Imaging surveys play a crucial role, in both defining the morphology in coordinate space and supplying targets for follow-up spectroscopy. The ‘Field of Streams’ in the distribution of faint turnoff stars isolated by Belokurov et al. (2006) in the Sloan Digital Sky Survey (SDSS) imaging data was critical in determining the extent of larger-scale substructure in the field stars of the Galaxy (see also Newberg et al. 2002) and to the discovery of ‘ultra-faint’ dwarf galaxies (although the numbers of newly discovered
faint satellite galaxies still are not sufficient for easy compatibility with the predictions of $\Lambda$CDM models). The streams, tracing substructure that has yet to mix dynamically, are dominated by tidal debris from the Sagittarius dwarf galaxy, which was originally discovered as a moving group (Ibata et al. 1995) in a MOS survey of the Galactic bulge. The ‘stream’ structure closer to the plane of the Galactic disk, in the Monoceros line-of-sight, is most likely composed of stars that belong to the Galactic disk (e.g. Xu et al. 2015) rather than to a disrupted galaxy.

Structure in kinematic phase space survives longer than does structure in coordinate space, with structure in chemical space the most persistent. Multi-object spectroscopy is required to characterize substructure – and indeed to determine the underlying structure. Surveys should be designed to sample all expected ‘interesting’ scales, while still being able to make serendipitous discoveries. This requirement leads to sample sizes of at least ten thousand (e.g. Jayaraman et al. 2013). The dedicated survey mode, pioneered by the Sloan Digital Sky Survey, has allowed total sample sizes in the hundreds of thousand.

2.5. Dedicated Survey Mode

The Sloan Digital Sky Survey transformed the sociology of much of astrophysics away from PI-led observing programs to survey science. The initial SDSS spectroscopic survey observed stars only as calibrators for the galaxy redshift survey. The first SDSS dedicated stellar spectroscopic survey, SEGUE (Yanny et al. 2009, red fields in Fig. 1), utilized these low-resolution spectrographs ($R \sim 1800$) with ~ 600 multiplexing to obtain wide wavelength coverage spectra of ~ 240,000 stars in several target spectral types and evolutionary phases (selected from the SDSS imaging data), including G dwarfs, Blue Horizontal Branch stars and K Giants. The fields were chosen to sparse-sample the sky, probing the large-scale (tens of kpc) structure of the main stellar components of the Galaxy. The pencil-beams of SEGUE-2 (Eisenstein et al. 2011, purple fields in Fig. 1) were selected to probe high-latitude substructure.
The spectra from the SDSS surveys provide line-of-sight velocities to around 10 km/s. The values of the stellar atmospheric parameters are obtained through a dedicated pipeline (Lee et al. 2008), developed for the broad range of targets and giving metallicity estimates to $\sim 0.2$ dex, and for high signal-to-noise spectra, an estimate of the relative abundance of the ‘alpha-elements’ (created by successive addition of helium nuclei - alpha particles - in the interiors of massive stars) to iron to similar accuracy and precision (Lee et al. 2011). The SEGUE data for $\sim 7,000$ main-sequence turnoff stars at distances from the Sun of several kiloparsec were used to characterize further the thick and thin disks, determining the large-scale radial metallicity gradient as a function of vertical distance from the mid-plane (Cheng et al. 2012). Those authors found that radial gradient to flatten with height, such that the thick disk has approximately constant mean metallicity, as a function of radius.

The RAVE survey of $\sim 500,000$ bright stars is described in more detail in this volume by Georges Kordopatis (see also Steinmetz et al. 2006; Kordopatis et al. 2013). On a philosophical/sociological note, the RAVE survey was supported by the institutions and personal research grants of the participants and took advantage of the opportunity offered by the withdrawal of government support for the UK Schmidt, part of the worldwide transferral of resources to larger (and larger) facilities. It is clear that 4 m class telescopes - and smaller - still have a critical role to play, particularly in spectroscopic surveys. The 6 degree field-of-view of the UK Schmidt telescope and the $\sim 100$ multiplexing capability of the 6dF spectrograph match well with the surface density of bright ($I < 12$) stars across much of the sky. Further, moderate resolution ($R \sim 7000$), reasonable signal-to-noise spectra of such stars can be obtained in around one hour, allowing a large sample to be studied in a reasonable time (several years). The almost contiguous sampling on the sky contrasts with the approach of the SEGUE surveys (as shown in Fig. 1) and allows both small-scale and large-scale gradients/substructure to be studied. A selection of the major scientific results is given in Georges Kordopatis’ contribution, including the complexity in the velocity distribution function of the thin disk. The compression/rarefaction pattern of the vertical velocities has recently been shown to be reflected in the stellar density distribution, manifest in the SDSS imaging data. The star counts of main-sequence stars show asymmetries above and below the nominal Galactic Plane ($b = 0^\circ$), consistent with a toy model in which the plane of the disk is actually offset, alternating up and down at different radial ranges, by around 100 pc, i.e. roughly a third of the vertical scale-height of the thin disk (Xu et al. 2015). This lends support to the interpretation of low-latitude features such as the Monoceros Stream/Ring as being simply structures within the disk (Xu et al. 2015), rather than being tidal debris from accreted satellite systems.

I will return briefly to the SDSS-III APOGEE survey (Eisenstein et al. 2011) below; this is described in more detail in Carlos Allende Prieto’s contribution to this conference. The LAMOST survey was presented in the conference by Yongheng Zhao.

2.6. Elemental Abundances: Beyond Metallicity

Different chemical elements are produced through the evolution of stars of different (main sequence) masses and hence ejected into the interstellar medium on different timescales. The elemental abundance distributions therefore contain much more information about the star-formation history and the stellar Initial Mass Function than does the ‘metallicity’ distribution (e.g. Tinsley 1979; Gilmore & Wyse 1998; Matteucci & Chiappini 2001). In particular, the alpha-elements are produced by short-lived massive
Figure 2. Schematic of the expected pattern of elemental abundances for a self-enriching, well-mixed star-forming system, indicating the turndown from the ‘Type II plateau’ at the time (measured from the onset of star formation) at which Type Ia supernovae have contributed significant iron to the interstellar medium. The iron abundance corresponding to this time depends on the past star-formation rate. The value of the ‘Type II Plateau’ depends on the massive-star IMF due to the dependence of the yields on progenitor mass. The observed lack of scatter in real data implies little room for IMF variations (plus good mixing).

stars that end their lives in core-collapse supernovae, with the ejected mass of such elements being a function of the mass of the progenitor star. Core-collapse supernovae also eject a fixed, relatively small mass of iron and the mass-averaged yields over the range of progenitor stellar masses (above \( \sim 8 M_\odot \)) enrich the interstellar medium with ‘alpha-enhanced’ (i.e. the ratio of alpha-elements to iron is greater than than in the Sun) gas, \([\alpha/Fe]\sim +0.3\) for typical yields and typical massive-star IMF slope. Stars that form during the early stages of a star-formation event, when the enrichment is dominated by core-collapse (Type II) supernovae, will therefore form from gas which is alpha-enhanced, and hence will have photospheric abundances that are alpha-enhanced.

Type Ia supernovae, resulting from accretion onto a white dwarf from a companion (either a non-degenerate binary companion or a second white dwarf) that increases its mass to above the Chandrasekhar limit, are delayed with respect to the core-collapse supernovae and continue to occur on longer timescales (model-dependent, but continuing many Gyr after birth of the progenitors). These also produce a fixed mass of iron per event, but the explosive nucleosynthesis of these events leads to an ejected mass in iron that is approximately ten times that ejected by a core-collapse supernova, and little ejected mass in alpha-elements. Stars that form later in a star-formation event, after the interstellar medium has been enriched by iron-rich material from Type Ia supernovae, will have photospheric abundances that are less alpha-enhanced than those formed earlier (assuming a self-enriching system with no flows). The star-formation history is thus encoded in the pattern of elemental abundances. Elemental abundances are more
straightforward to derive than are estimates of stellar ages, and thus normally the iron abundance is used as a proxy for age - albeit that there is known to be significant scatter, of uncertain origin, in the local age-iron abundance relationship (Nordström et al. 2004; Casagrande et al. 2011).

A schematic plot of the predicted pattern of elemental abundances is shown in Fig. 2 (based on an earlier figure in Wyse & Gilmore 1993). Core-collapse supernovae all explode within a short time after the onset of star-formation (\(~40\) Myr) and with good mixing in the interstellar medium the next generation of stars to form will be enriched with a (massive-star) IMF-average yield of metals. An invariant IMF will produce a 'plateau' in \([\alpha/Fe]\) at lowest values of \([Fe/H]\) with the value of the plateau reflecting the distribution of stellar mass for the progenitors of core-collapse supernovae, being higher for a massive-star IMF that favors the most massive stars (see, e.g. Wyse & Gilmore 1992, for a discussion of how one may exploit this dependence, plus the very low amplitude of observed scatter, to constrain IMF variations). The downturn at higher values of \([Fe/H]\), due to the addition of iron (but low ejected mass in alpha-elements) from Type Ia supernovae, occurs at a fixed time but at an iron abundance that depends on the past star-formation and enrichment rate.

2.6.1. The Solar Neighborhood

Wallerstein (1962) carried out a pioneering survey of nearby (bright) field G stars, obtaining elemental abundances from a curve-of-growth analysis. As may be seen from Fig. 3, he indeed found a population of more metal-poor stars that have enhanced alpha-to-iron ratios, relative to the solar value (\([\alpha/Fe]>0\) is 'enhanced'), consistent with forming during the (short-duration) epoch when the enrichment was dominated by core-collapse (Type II) supernovae. The stars in this sample are bright enough to have trigonometric parallaxes, and comparison with isochrones showed that there exist metal-rich old stars, a result which is now well-established. The distribution in \([\alpha/Fe]\) at low values of iron abundance, showing two sequences, is also now a robust result, as we return to below. In another precursor to modern results, Wallerstein investigated the kinematics of the stars and found that \([\alpha/Fe]\) was a better predictor of orbital angular momentum than was \([Fe/H]\): the 'high-alpha' metal-poor stars are on more eccentric orbits than are the 'low-alpha' metal-poor stars.

Indeed several recent surveys of local stars with elemental abundances derived from high-resolution spectra (e.g. Fuhrmann 2011; Adibekyan et al. 2013; Bensby et al. 2014) have confirmed these early results, finding a clear separation into two sequences in the \([\alpha/Fe], [Fe/H]\) plane, particularly at iron abundances below the solar value. Again, the two sequences show different kinematics and age distributions and are usually associated with the thick disk ('high-alpha' sequence) and the thin disk ('low-alpha' sequence).

2.6.2. Non-local samples

The separation in the elemental abundance plane was however challenged by Bovy et al. (2012b,a) who analyzed the distributions of elemental abundances derived from the SDSS SEGUE data (low-resolution spectra), probing distances of several kiloparsec from the Sun, and proposed that there was instead a continuum of ‘mono-abundance populations’ (see also Norris 1987). This was difficult to reconcile with the results from the higher resolution, higher signal-to-noise data for the local stars. There was an ob-
Figure 3. Elemental abundances for a sample of around 30 field G stars, from the pioneering study of Wallerstein (1962) (© AAS; reproduced with permission). Note the reversal of the $x$–axis compared to modern convention.

vious need for a sample of more distant stars with more precise elemental abundances, derived from high-resolution, high signal-to-noise spectra, to match the local samples.

Further, the selection and subsequent successful launch of the Gaia astrometric satellite strengthened the scientific case for a spectroscopic survey for (the fainter) stars for which Gaia would provide astrometric (and photometric) data only. The complementarity of ground-based spectroscopic surveys and space-based astrometric surveys is illustrated in Fig. 4, taken from Gilmore et al. (2012). This led to the Gaia-ESO survey (Gilmore et al. 2012), allocated 300 nights on the VLT (over 5 years, starting January 2012) to obtain high-resolution ($R > 16,000$) spectra of an intended sample of $10^5$ faint field stars (typically $r \sim 18$) in all major components of the Milky Way, plus a sample of brighter stars in (open) star clusters. The field star targets are mostly F/G dwarfs and K giants, selected from VISTA imaging. Most of the spectra are obtained using FLAMES/GIRAFFE, with a multiplexing of 110 and field-of-view of 25 arcmin.

That there are indeed two distinct sequences in elemental abundances for stars that probe the Galaxy several kiloparsecs from the Sun is shown in Fig. 5. These sequences are also distinct in kinematics (Recio-Blanco et al. 2014; Kordopatis et al. 2015). This result will (presumably!) be strengthened by the larger samples available from later data releases, and by the addition of Gaia astrometric data.

The near-IR capability of the APOGEE survey allows the study of stars in the thin disk at lower latitudes than feasible in optical surveys, and thus a larger range of radial coordinate for given range of distances from the Sun. The high-resolution, high signal-to-noise spectra ($R \sim 30,000$) provide precise estimates of the abundances of individual elements, with internal errors in [α/Fe] around 0.03 dex for red clump stars (Nidever et al. 2014, see also Allende Prieto’s contribution to this conference). Again, the APOGEE data reveal two distinct sequences in elemental abundances, populated by stars with distinct kinematics, as manifest in the locations of the stars with respect
Figure 4. Illustration of the gain in physical probes with the combination of astrometry from the Gaia satellite and wide-area spectroscopic surveys, in this case the Gaia-ESO survey (Gilmore et al. 2012).

to the Galactic mid-plane. The radial coverage of the APOGEE survey further showed the thick disk (‘high-alpha’) sequence to be more centrally concentrated within the Galaxy than the thin disk (‘low-alpha’) sequence. This inferred shorter scale-length for the thick disk would lead to a larger mass, for given local normalization. The spatial variations of the elemental abundance patterns in the Gaia-ESO survey are under investigation (Kordopatis et al. 2015).

The GALAH survey with the HERMES high-resolution spectrograph on the AAT is obtaining elemental abundances and kinematics for a large sample of stars in the thin disk, as described in this volume by Sarah Martell, with a major goal to identify past star-formation events through chemical tagging.

2.6.3. Subaru Prime Focus Spectrograph Galactic Archaeology Survey

The Subaru Prime Focus Spectrograph (PFS) project was presented in the conference by Masahiro Takada, with an emphasis on the proposed extragalactic surveys. There will also be a Galactic Archaeology component, with science goals of constraining the nature of dark matter through investigations of the density law in the Milky Way and selected satellite galaxies, and of the evolutionary histories of each of the Milky Way and the Andromeda galaxy, including estimations of their merger histories.

As described in Takada et al. (2014), the PFS project will take advantage of the wide FoV (~ 1.4 deg) of the Subaru 8 m telescope, to feed a 3-arm (blue, red, near IR) low-resolution ($R \sim 2000$) spectrograph with over 2,000 fibers. These low-resolution spectra suffice for the derivation of line-of-sight velocities and stellar chemical abundances (iron, carbon) with errors similar to those of the SDSS SEGUE surveys. The Galactic Archaeology survey will also utilize a medium resolution ($R \sim 5000$) mode for the red arm. This medium resolution mode will enable the derivation of the abundances of several of the alpha-elements, using the techniques developed by Kirby and collaborators (Kirby et al. 2008, 2009).
Figure 5. Elemental abundances from the first internal data release of the Gaia-ESO Survey (Recio-Blanco et al. 2014). Errors increase top to bottom. The top panel shows the distribution for the ~200 stars with errors on [α/Fe] below 0.03 dex and errors on metallicity ([M/H]) below 0.07 dex. The sample size increases as the error cut is relaxed - the third panel shows ~1000 stars with maximum errors in [α/Fe] and in [M/H] of 0.05 dex and 0.15 dex respectively. The bottom panel shows the ~2,000 stars for which the error on $T_{\text{eff}}$ is below 400K, the error on log g is below 0.5 dex and the signal-to-noise is at least 15.

Given the location of the telescope in the Northern hemisphere, targets in the Milky Way include the relatively understudied outer disk, of particular interest in terms of constraining the importance of internal secular effects such as stellar radial migration (Sellwood & Binney 2002), or 'compression waves' and 'breathing modes' of the disk (Widrow et al. 2014). Standard cold dark matter dominated models of galaxy formation predict that the outer regions form later and accretion of high-angular momentum material - in the form of both satellite systems and gas – is expected at late times, such that the outer disk should be where significant substructure should be found. The moderate resolution mode will be used to complement the Gaia astrometric data for stars that are brighter than $V \sim 20$, obtaining line-of-sight velocities and alpha-abundances (and estimates of the stellar overall metallicity, surface gravity and effective temperature). Wider volumes around known substructure in the Galaxy will also be targeted, to provide better discrimination between external and internal mechanisms for their creation.

The PFS GA survey will also target fainter stars in the low-resolution mode, including searches for substructure in metallicity-kinematic phase space. The distant
giant stars will also be used in constraining the overall potential well of the Milky Way, and also allow us to determine the edge of the Milky Way halo.

The Andromeda galaxy (M31), the other large disk galaxy in the Local Group, will also be a major component of the (low-resolution) survey. We aim to determine the large-scale properties of M31, plus distinguish plausible tidal debris from substructure created from disturbances to M31 itself. This will facilitate analysis of the merger/accretion history. PFS will obtain spectroscopic metallicity estimates for individual stars in M31, in contrast to photometric metallicities (e.g. Ferguson et al. 2002; Gilbert et al. 2014; Ibata et al. 2014) or those obtained from stacking/co-adding of spectra of many stars (e.g. Guhathakurta et al. 2006) that have previously been used to determine metallicity distributions in M31. PFS is synergistic with HyperSuprimeCam and a dedicated narrow-band (pre)imaging survey will be carried out, across the face of M31, to provide dwarf/giant separation (gravity sensitivity) so that foreground (dwarf) stars in the Milky Way may be rejected from the spectroscopic targets. Ibata et al. (2014) discuss the complications and biases that can result when analyzing broad-band photometric data in isolation.

The wide field and high multiplexing capability of PFS allow study of the nearest dwarf spheroidal satellite galaxies to out beyond their nominal tidal radii, necessary for estimates of the total mass and to determine the amplitude of possible tidal effects. We will again carry out narrow-band (pre)imaging with HyperSuprimeCam to identify likely foreground contamination. The medium-resolution mode will be employed to obtain alpha-abundances and line-of-sight velocities. The chemical abundances are critical to constrain baryonic feedback, especially the strong energy injection invoked in models that seek to modify the inner dark matter profile (e.g. Governato et al. 2012).

3. Conclusions

The several ongoing or imminent surveys of nearby stars (will) provide transformative datasets to decipher how normal disk galaxies such as the Milky Way and M31 form and evolve. They will yield unique insight into the nature of dark matter, by both derived density profiles and merger histories. Contemporaneous high-redshift surveys are quantifying the stellar populations and morphologies of galaxies at high lookback times, and large, high-resolution simulations of structure formation are allowing predictions of Galaxy formation in a cosmological context, ready for testing. These three astrophysical approaches to understanding our place in the Universe are complemented by the (re-start of) the LHC, which should reveal ‘physics beyond the Standard Model’ that could produce a dark matter particle. Exciting times indeed.

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