Galactic Archeology – requirements on survey spectrographs

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Abstract. Galactic Archeology is about exploring the Milky Way as a galaxy by, mainly, using its (old) stars as tracers of past events and thus figure out the formation and evolution of our Galaxy. I will briefly outline some of the key scientific aspects of Galactic Archeology and then discuss the associated instrumentations. Gaia will forever change the way we approach this subject. However, Gaia on its own is not enough. Ground-based complementary spectroscopy is necessary to obtain full phase-space information and elemental abundances for stars fainter than the top few percent of the bright part of the Gaia catalogue. I will review the requirement on instrumentation for Gaia follow-up that Galactic Archeology sets. In particular, I will discuss the requirements on radial velocity and elemental abundance determination, including a brief look at potential pit-falls in the abundance analysis (e.g., NLTE, atomic diffusion). This contribution also provides a non-exhaustive comparison of the various current and future spectrographs for Galactic Archeology. Finally, I will discuss the needs for astrophysical calibrations for the surveys and inter-survey calibrations.

1. Introduction

We can approach the problem of formation and evolution of galaxies in several ways: by observing the properties of galaxies back in time, by simulating the formation and evolution of structure in the universe, or by looking in our own backyard. The first approach has seen impressive progress in the last decades using ever-deeper observations to probe the properties of the first galaxies and to charter their evolution till today (Conselice 2014). The second approach has been equally successful. Large simulations have shown that the Cold Dark Matter theory (ΛCDM) is remarkably able to correctly predict the large-scale structure of the universe as observed today (Springel et al. 2005; Vogelsberger et al. 2014). However, it has not (yet) met with equal success on small scales (see, e.g., Genel et al. 2014). One reason for this could be that we do not fully understand how baryons influence the processes that lead to actual galaxies (Vogelsberger et al. 2014).

Understanding the formation and evolution of galaxies is therefore foremost about understanding how the baryons are distributed. The universe is dominated by dark matter and hence the distribution of baryons is governed by their mutual interactions as well as the gravity from the dominant dark matter. Baryons largely reside in stellar disks in galaxies, understanding these disks then becomes a key to solving the question of galaxy formation and evolution across the ages of the universe.

The Milky Way is one of billions of galaxies. As a galaxy it is not very remarkable. In fact its a rather typical galaxy and it is the one galaxy we can study in exquisite detail.
Therefore, it provides a fundamental test-bed for our theories of galaxy formation and evolution (Freeman & Bland-Hawthorn 2002; Rix & Bovy 2013). Indeed, it is on these the smallest scales where the firmest tests of ΛCDM can be done (e.g., Marinacci et al. 2014).

The data from the astrometric ESA satellite Gaia is set to change the investigation of the Milky Way as a galaxy forever. Gaia is measuring distances and on-sky motions for a billion stars in the Milky Way and has been collecting scientific data since July 2014. A first data release is planned for 2016, with an expanded release in mid-2017.

To make a major breakthrough in understanding the evolution of the Milky Way and its components, detailed information beyond positions and velocities (i.e. Gaia) is essential. Such data is provided by a new generation of spectroscopic surveys designed to obtain high quality spectra for millions of stars: APOGEE (Ahn et al. 2014), GALAH (De Silva et al. 2015), 4MOST (de Jong et al. 2014), and WEAVE (Balcells et al. 2010). Additional spectra of lower spectral resolution will be obtained with instruments such as PFS (Takada et al. 2014) and DESI (Poppett & DESI Collaboration 2015). All these spectra will give full 3D motions, elemental abundances and stellar parameters, such that ages can be determined for turn-off stars. Asteroseismic data offer the possibility to obtain ages for red giant stars (Chaplin & Miglio 2013). Figure 1 shows how the information about the Milky Way stellar populations is build up as information is added.

2. Requirements on the design of a multi-object spectrograph from Galactic Archeology

When considering the design of a new multi-object spectrograph for Galactic Archeology a number of things are very desirable to have. The stellar spectroscopist interested in elemental abundances in stars and in the stars themselves will be wanting high resolution, large wavelength coverage, and good sampling of the spectra while those working on the kinematics and dynamics of the Milky Way would prefer as many stars

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1The data release scenario for Gaia is available at http://www.cosmos.esa.int/web/gaia/release.
as possible with velocity and some abundance information. These partly contradictory requirements should then be possible to fit into a design that meets the throughput criteria.

**What do I want to measure and to what precision?** This can seem as a rather obvious question, but it is one of the very first questions that must be answered in order to set the requirements for the multi-object spectrograph. For Galactic Archeology, two measurements are of immediate interest: 1) radial velocities; 2) elemental abundances to some precision (and maybe accuracy).

Let’s first look at what requirements we may have on the measurement on radial velocities. Most large spectroscopic surveys are today, as discussed in Sect. 1, driven to be complementary to Gaia (Turon et al. 2008). Gaia will deliver parallaxes and proper motions down to $V \sim 20$. The spectra taken on board Gaia will deliver radial velocities down to $V \sim 15.2$ for a G2 stars. At that magnitude the errors in radial velocities are already large (around 15 km s$^{-1}$)$^2$. Thus, there is a direct need to complement Gaia with radial velocities obtained from the ground to get the full 3D motion for a large fraction of the stars down to $V \sim 20$. Such radial velocities are readily obtainable and errors should be around 2 – 3 km s$^{-1}$ to match the errors in Gaia’s proper motions all the way down to $V \sim 20$.

![Figure 2](image_url)

**Figure 2.** [$\text{Mg/Fe}$] as a function of [$\text{Fe/H}$] for stars within 25 pc of the sun analysed by Klaus Fuhrmann (presented in a series of papers, e.g., Fuhrmann 2011, and here represented by a collection of his data). The gap between the upper and the lower trends is about 0.2 dex. The two straight lines (one horizontal and one slanted) delineates the data from Nissen & Schuster (2010). They study stars in the solar neighbourhood with typical halo kinematics and find that some follow the "classical" $\alpha$-enhanced high trend, whilst about half of their stars follow a decreasing trend. **Note:** This is not an extension of the thin disk. The stars have clear halo kinematics.

Secondly, let’s look at what requirement we might want to set from the point of view of elemental abundances. Our approach here is to look at well-known data from the solar neighbourhood and assume that we at least wish to be able to obtain data that can distinguish the features seen in the solar neighbourhood. The assumption being that it is rather likely that similarly sized features will be present also in other parts of

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$^2$As described on the web-page for Gaia science performance. These numbers were read of that page on 6 May 2015. [http://www.cosmos.esa.int/web/gaia/science-performance](http://www.cosmos.esa.int/web/gaia/science-performance).
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the Galaxy. A pertinent example is given by the various data by Klaus Fuhrmann (presented in a series of papers, e.g., Fuhrmann 2011, Fig. 2). As we can see, the difference between his two trends is about 0.2 dex. Another example in the solar neighbourhood is provided by Nissen & Schuster (2010). They study stars in the solar neighbourhood with typical halo kinematics and find that some follow the "classical" $\alpha$-enhanced high trend, whilst about half of their stars follow a decreasing trend (Fig. 2). Again, the typical size of the separation is about 0.2 dex. These are a very secure result and by now reproduced in other studies (e.g., Bensby et al. 2014).

Thus, a brief tour of the solar neighbourhood shows us that we need to be able to resolve differences in elemental abundances of about 0.2 dex in a statistically significant manner. This can be achieved by either observing a large number of stars with errors not much smaller than the separation, or by observing a smaller number of stars at much higher precision. This is discussed in some detail in Lindegren & Feltzing (2013).

2.1. Resolving power and signal-to-noise ratio

Radial velocities in a big spectroscopic survey are best measured from lines that remain strong and well defined in a large variety of stellar types. Such lines include the three Ca II triplet lines in the NIR (at 849.8, 854.2, and 866.2 nm) and the three so called Mgb lines (at 516.7, 517.2, and 518.3 nm). Radial velocities are readily measured from these strong lines (e.g., in RAVE, Kordopatis et al. 2013). An increased resolving power improves the precision in the measured radial velocities. In general $\sigma_{RV} \propto R^{-3/2}$ (technical note by M. Irwin for WFMOS and P. Bonifacio, priv. comm.), this means that the precision in radial velocities for a resolving power of 7,500 is a factor 0.76 smaller than for a resolving power of 5,000 (keeping the SNR $\lambda^{-1}$ and wavelength coverage fixed). Such resolving power is also relatively well matched to what is needed for extra-galactic science (Takada et al. 2014). Instruments like DESI and PSF are mainly designed for the extra-galactic science and have thus lower resolution, whilst, e.g., the design of the low-resolution spectrographs in 4MOST is primarily driven by the need to complement Gaia and hence has a goal of 7,500.

Good elemental abundances with high precision are typically recovered from spectra of high to very high resolving power (say 40,000 to 100,000) accompanied with high signal-to-noise ratios, typically > 250 per reduced pixel, and in some cases significantly higher (see, e.g., Meléndez et al. 2014; Bensby et al. 2014, for two examples). Such high resolving power would come at the expense of very short wavelength coverage of the spectrograph. Most current and future multi-object spectrographs have therefore made a compromise and settled for a lower resolving power but with a larger wavelength coverage (e.g., WEAVE, HERMES/GALAH; Balcells et al. 2010; De Silva et al. 2015, respectively). That spectra with an $R \sim 20,000$ are capable of delivering good elemental abundances has been shown by the Gaia-ESO Survey analysis of the FLAMES/GIRAFFE spectra and early results from the GALAH survey.

Signal-to-noise and resolving power can be traded off against each other. If we consider a single line for which we wish to derive an elemental abundance from it can be shown that the relative error in the retrieved equivalent width, $W_\lambda$, is $\propto R^{-1/2}$ (Gustafsson 1992). This error is directly proportional to the error in the elemental abundance derived for this line. This means, e.g., that by going between $R \sim 16,000$ and $\sim 23,000$ the error in the retrieved $W_\lambda$ (and hence in the error for the derived elemental abundance) decreases by a factor 0.834, everything else being equal. Thus,
a lower resolving power can (to some extent) be compensated by a longer integration
time resulting in a higher signal-to-noise ratio.

2.2. Wavelength coverage

However, how to reach a suitable compromise on wavelength coverage and resolving
power? This is not a very easy question and here we will only be able to outline some
aspects of how to proceed from a science requirement to a requirement on wavelength
coverage (and indirectly resolving power) for a spectrograph.

Figure 3 and Table 1 show compilations of the wavelength coverage for a number
of current and planned survey facilities operating in the optical. In addition two spec-
trographs, APOGEE and MOONS, have opted for NIR wavelength coverage in order to
be able to study stars in the Galactic plane where interstellar extinction is heavy (Ahn
et al. 2014; Cirasuolo et al. 2014). We do not discuss these two instruments any further
in this section.

Table 1. Summary of wavelength coverage and resolving power ($R$) for spectro-
graphs with low resolving power, including the low resolution (LR) spectrographs
for WEAVE and 4MOST. Please note that some of these values are subject to change
as the final design of the spectrographs is developed (DESI, WEAVE, and 4MOST).
WEAVE and 4MOST both have the goal of 7,500 in resolving power.

| Spectrograph | $\lambda$-range [nm] | $R$ | # fibres in LR | Reference/Website |
|--------------|----------------------|-----|---------------|-------------------|
| SEGUE        | 380 – 920            | 1800| 640           | York & SDSS Collaboration (2000) |
| RAVE         | 841 – 879.5          | 7500| 150           | https://www.rave-survey.org/     |
| LAMOST       | 370 – 900            | 1800| 4000          | http://www.lamost.org            |
| PFS          | 380 – 1260           | 1900| 2400          | Takada et al. (2014)             |
|              | 380 – 670            |     |               |                                 |
|              | 650 – 1000           | 2400|               |                                 |
|              | 970 – 1260           | 3500|               |                                 |
| DESI         | 360 – 980            | 4000$^2$| 5000        | http://desi.lbl.gov             |
| WEAVE LR     | 366 – 959            | 5000| 1000          | Dalton et al. (2014)            |
| 4MOST LR     | 390 – 930            | 5000| 1600          | de Jong et al. (2014)           |

For the low resolution spectrographs the wavelength coverage is rather similar for
all the instruments. For Galactic Archaeology the blue end is of a specific interest as
very metal-poor stars have most of their spectral features below about 460 nm (see,
e.g., Frebel & Norris 2013, for a definition of very metal-poor). The region can be
used to find and/or characterise the overall properties of the very metal-poor stars. In
addition, some interesting elemental abundances, e.g., Sr can be derived (see, e.g., Lai
et al. 2007). Hence, even a spectrograph with relatively low resolving power, e.g.,
SEGUE and DESI, can be a highly useful tool in Galactic Archaeology. To obtain radial
velocities the Mgb triplet lines and the Ca II NIR triplet lines are very useful as they
are present in essentially all late type stars and across all metallicities. Hence, from
the point of view of Galactic Archaeology a first requirement on the wavelength coverage

$^2$R as measured in the infra-red.
of a low-resolution spectrograph must include these lines. This is not a very strong requirement. For the characterisation of metal-poor stars inclusion of the region below 400 nm with the Ca H&K lines is necessary.

For the high-resolution spectrographs (typically, \( R \sim 20\,000 \) for these instruments) the wavelength coverage varies. Sometimes considerably. The now more than ten year old FLAMES/GIRAFFE instrument has full coverage in the high-resolution mode of the optical spectral range, but cut up into 22 set-ups, each with an effective wavelength range of \( \sim \lambda/22 \) (Pasquini et al. 2002, and Fig. 3). For the Gaia-ESO Survey two regions were chosen for the Milky Way science (one region centred at 548.8 nm and one centred on the Ca ii triplet lines in the NIR, Gilmore et al. 2012). The Ca ii triplet lines in the NIR was specifically chosen to enable determination of surface gravity. As the total wavelength coverage is limited it is important to ensure that gravity and temperature sensitive spectral features are available in the wavelength region.

![Figure 3. Wavelength coverage in the optical for a number of current and future survey instruments with high resolving power that can be used for Galactic Archeology. The compilation is not meant to be exhaustive but illustrates the type of wavelength coverage available to do our science. For WEA VE we also include the third band that is possible to use instead of the bluest band. This has mainly been designed for extra-galactic studies. A number of interesting spectral features are indicated at the top of the plot, and light grey lines show their position. G stands for the G-band, Mgb for the Mg triplet lines, Ca I for the gravity sensitive line at 616.2 nm, and Ca II for the Ca II triplet lines in the NIR. The positions of the Ca H&K lines are marked by dotted lines and the position of the interstellar NaD lines are shown as a dashed line. The width of the line indicating the position of the H\( \alpha \) line shows the region that needs to be included in order to sample the whole wings, including taking a radial velocity of up to 400 km s\(^{-1}\) of the star into account.

HERMES, which is used for GALAH, WEA VE and 4MOST have made rather different choices of wavelength coverage (compare Fig. 3). The total wavelength coverage of HERMES is about 1000 nm divided into four roughly equal wavelength ranges, covering lines useful for stellar parameters (e.g., H\( \alpha \)) as well as a multitude of elemental abundances (De Silva et al. 2015). HERMES is set apart from the other upcoming instrument designs by the inclusion of the oxygen triplet lines around 777 nm. This is a unique feature, which will allow the GALAH team to derive oxygen abundances for
their whole sample. The oxygen triplet is plagued by analysis difficulties but most of these have recently been overcome and hence the inclusion of this region, which holds little other information, is highly valuable to Galactic Archeology.

The WEAVE and 4MOST designs have partly been driven by the wish to include studies of very metal-poor stars (i.e., stars with $[\text{Fe/H}] < -1$). Such stars have essentially all spectral features that are possible to analyse in the blue, below around 450 nm (see, e.g., Sneden et al. 2003, for an example of a complete analysis of a very metal-poor stars). Of particular interest are the CH-band at [429:432] nm, the Ca H&K lines, Sr II, Ba II (Caffau et al. 2013, and Hansen et al. submitted). The final designs have to take into account finite CCD sizes and constraints from the optics. 4MOST have opted for a bluer cut-off end including the Y line at 395.0 nm and the Ca H&K lines at 396.8 and 393.3 nm, whilst WEAVE has opted for a wider coverage in the blue channel reaching further in to the red, thus making sure several interesting species, such as Ba II at 455.4 nm, are fully included. Both instruments include the G-band and the bluest Sr II (compare Fig. 3). It is a difficult task to select this wavelength region as almost every line represents a unique opportunity. Thus, there is hardly any perfect tradeoff. A paper discussing the trade-offs for the blue channel is submitted (Hansen et al.).

The reddest channel in WEAVE and 4MOST are quite similar, with WEAVE being the wider one. Both include the $H_\alpha$ line (sensitive to effective temperature) and the Ca I line at 616.2 nm (sensitive to surface gravity, Edvardsson 1988). In addition, 4MOST has a green channel that is specifically designed to ensure the inclusion of a) additional features sensitive to surface gravity (Mgb lines), b) that the number of Fe II lines suitable for analysis in disk turn-off dwarf and red clump stars included in the green and red channel is at least ten to get a separate test on surface gravity, and c) similarly, that there are at least 10 Fe I lines with high and low excitation energies, respectively, included in the combined green and red channels to give an independent measure of effective temperature. The full discussion of possible choices of wavelength coverage for 4MOST and how this selection process can be quantified leading to an optimised wavelength range will be presented in a forthcoming paper by Ruchti et al. (in prep.).

3. Analysis of stellar spectra in large surveys – promises and pitfalls

The possibility to derive a good elemental abundance from a stellar spectrum is hampered by numerous problems; including departures from Local Thermal Equilibrium (LTE), lack of atomic data, an inability to account for the full 3D structure of the stellar atmosphere. These issues are the subject of many studies. In this brief review we give the reader a few pointers to selected studies. A series of recent papers explore the issues of NLTE in the determination of iron abundance, stellar parameters, and ages (Bergemann et al. 2012; Lind et al. 2012; Ruchti et al. 2013; Serenelli et al. 2013). Differences in abundances derived in LTE compared to so called averaged 3D plus NLTE models show differences of up to 0.4 dex for warmer stars as we move from sub-solar metallicities down to –3 dex (Ruchti et al. 2013). For two recent reviews of NLTE calculations for other elements see Bergemann & Nordlander (2014) and Mashonkina (2014). Magic et al. (2013) provides details on the new grids of 3D model atmospheres that are being developed and are now also being adapted in detailed elemental abundance work. An early application is discussed in Collet et al. (2007). Application to large number of stars is becoming feasible, e.g., averaged versions are now included in some abundance pipelines used in on-going surveys.
Diffusion in the stellar atmosphere is still little explored, but has been shown to have a clear effect on stars in globular clusters at varying metallicities, such that stars at the turn-off and on the sub-giant branch are depleted in iron and in titanium (Michaud et al. 2013, and references therein). Empirically it has been shown that the effects can be as large as 0.2 dex (Korn et al. 2007; Gruyters et al. 2013; Önehag et al. 2014). However, given that the effects of diffusion as observed in these clusters, is roughly the same for all elements, a differential approach where abundance ratios are compared reduced the "error" between turn-off and red giant branch stars to a much lower level, of the order 0.05 dex or less.

Such large uncertainties resulting from a lack of knowledge of the physics might feel discouraging in the context of Galactic Archeology, where, as discussed in Sect. 2, we aim at a precision in relative abundance of less than 0.05 – 0.1 dex (depending on the science question). However, given the significant progress in recent years and the on-going efforts in understanding the physics inside stars and stellar atmospheres the future is bright with real possibilities to overcome the difficulties in achieving a homogenous analysis that is able to combine data from stars of very different evolutionary stages and metal-content into a combine picture of what the Milky Way looks like.

Just as with diffusion, differential studies remains an important way to mitigate some of the errors introduced by our limited knowledge of the physics involved. By studying only stars with very similar stellar parameters it is possible to, ot first order, mitigate issues such as NLTE and lack of knowledge of the structure of the stellar atmosphere. Examples where this approach has enabled the discovery of interesting abundance trends and differences include Nissen & Schuster (2010) and Nissen (2015).

4. Calibrating Galactic surveys

Observations of science calibrations have two main purposes for Galactic Archeology:

**Astrophysical calibrators** – which provide a means to calibrate the spectral analysis in terms of stellar parameters, elemental abundances and, potentially, age.

**Inter-survey calibrators** – which provide a means to put the survey onto the same abundance scale as other Galactic spectroscopic surveys.

In addition we should add **Basic calibrators**, i.e., observations that allow us to get rid of sky lines, telluric absorption lines and to obtain a stable wavelength solution enabling good radial velocity measurements. Basic calibrators are typically dealt with in any observing strategy, regardless of the science goal. Hence, there are by now well-proven methods to provide a stable velocity solution for the spectra. Correction for sky and telluric lines is important, even critical, for some of the Galactic Archeology goals (e.g., when an important line falls in the region effected). Inclusion of a few fast rotators or white dwarfs in each field is normally deemed an efficient way to deal with the tellurics. Alternatively, models of the Earth’s atmosphere can be used to correct for this (one recent example and application can be found in Kausch et al. 2015). To correct for sky lines, numerous sky fibres are normally included in each observation.

4.1. Astrophysical calibrators

More interesting, from the point of the analysis of the stars, is the calibrators that allows us to ensure that our analysis (from the raw spectra to the final elemental abundances)
does a good job. These are the astrophysical calibrators. Several groups of stars could be used for this. Each with its own pros and cons.

1. Stars with very well-defined properties, such as the Gaia-benchmark stars.
2. Fields of stars with very high-quality data available for a large number of stars, such as the Kepler field or certain open clusters.
3. Fields of stars with some useful data available, this includes most globular and open clusters but also fields observed by other surveys.

The Gaia benchmark stars are stars with fundamental parameters, such as effective temperature, derived from basic observations such as the radius of the star. The list was originally put together for the purpose of providing fundamental calibrators for the Gaia astrometric mission, they have also been extensively used in current spectroscopic surveys, e.g., in the Gaia-ESO Survey (Smiljanic et al. 2014). A paper listing their metallicities have been published in Jofré et al. (2014b) and a list of the stellar parameters can be found in Jofré et al. (2014a).

Several efforts to obtain further fundamental measurements of stars are on-going. There are plans to further capitalise on such efforts and establish additional fundamental calibrating stars across the HR-diagram. Recent results include Creevey et al. (2015).

Another approach might be to combine asteroseismology and various photometric systems (Casagrande 2015). Even if stellar parameters derived through such means might not be fully as fundamental as those from direct measurements this might still be a highly desirable route to explore in order to enlarge the set of benchmark stars to ensure a complete coverage of the HR-diagram at a wide range of metallicities.

The stars with well-defined properties, the benchmark stars, are fundamental for providing a sound basis for the analysis pipelines. Open and globular clusters serve a similar purpose as they provide stars of the same age and well-defined abundances along the evolutionary sequence, providing a unique opportunity to check the self-consistency of the pipeline that provides the stellar parameters (but see Sect. 3).

4.2. Inter-survey calibrators

Finally, we need observations that makes sure that we can combine the different Galactic surveys. This can be achieved with the help of the astrophysical calibrators, if they are numerous enough, or alternatively specific observations could be devoted to this. The key aspect is, of course, that the stars used for this task must have been observed by each of the surveys that should be combined. As we wish to ultimately combine all surveys, data that will be most useful as inter-survey calibrators are fields of stars along the equator, i.e., fields that can be easily observed with surveys covering either the Northern hemisphere or the Southern hemisphere of the sky.

Typically, we will think of open and globular clusters for such purposes. Clusters are excellent for testing and validating the analysis tools as they include stars at many evolutionary stages and all stars are at the same distance. However, globular clusters are not well distributed on the sky. Most are observable from the South only as they

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3 For this set of stars a library of high-resolution, high signal-to-noise spectra have been prepared (Blanco-Cuaresma et al. 2014). These spectra are publicly available and can be used inside any survey for, e.g., for testing purposes. They can be downloaded from http://www.blancocuaresma.com/s/benchmarkstars/.
cluster around the Galactic Centre. Open clusters are spread all over the sky, but with a strong concentration around the Galactic plane. Observing directly in the plane is difficult for the surveys operating in the optical thanks to the high extinction. Hence, it is likely best to select open clusters slightly off the plane. In addition, there are only a relatively small range of the Galactic plane that is observable from both the Northern and the Southern hemisphere.

On-going and completed surveys have already observed a significant number of globular and open clusters. Future surveys need to consider how to best relate to that data as well as enlarging the possible inter-surveys calibrating fields. One potential would also be to include regular science fields from other surveys and use these as inter-survey calibrators. This might seem a little sub-optimal, but if the main aim is to ensure that a certain type of star looks the same in each of the surveys (and not thinking about precis or accurate stellar parameters) this might be a fruitful way forward. The fields observed in GALAH should be possible to adapt to the deeper surveys, such as 4MOST and WEAVE. To go from the deeper to the shallower surveys might, on the other hand, prove too time-consuming to be realistic.

4.3. Asteroseismic fields

Several Milky Way fields now have asteroseismic observations. These fields have been observed by CoRoT and Kepler (Auvergne et al. 2009; Borucki et al. 2010), and new fields will be observed in the Kepler II campaigns\(^4\). In the future PLATO will provide several fields (Rauer et al. 2014).

The interesting aspect of the seismic data is that the surface gravity of the star and its age can be determined with very high precision (Chaplin & Miglio 2013). This is highly valuable information for many purposes and a very exciting prospect for astrophysical calibrations of Galactic Archeology. Indeed, as these fields have such rich seismic data sets they will be, and already are, natural targets for spectroscopic surveys. APOGEE is observing the Kepler field and will also look at the Kepler II fields, so is GALAH. The Gaia-ESO Survey has observed both the inner as well as the outer CoRoT field. Hence, these fields provide a very good opportunity for cross-calibrating the spectroscopic surveys as long as the same stars have been observed.

Targets in the Kepler II fields are relatively bright and hence accessible to all surveys. Prime Kepler II targets have \( V < 14 \) (Victor Silva Aguirre, priv.com.).

The asteroseismic fields are large and several contains one or more open clusters as they are interesting targets for the seismic analysis. The fields are typically larger than the FoV of WEAVE or 4MOST. To obtain good cross-calibrations there is a need to start inter-survey discussions now to ensure that the same actual stars are observed.

5. Summary and what’s next?

To conclude, instrumentation for Galactic Archeology in the form of massively multiplex spectrographs is now being realised on a large scale with massive surveys of both the Southern and the Northern hemisphere. These surveys will provide excellent complimentary data to the parallaxes and proper motions from Gaia, enabling full

\(^4\)Further links to the campaigns can be found at http://keplerscience.arc.nasa.gov/K2/.
phase-space information as well as further information on stellar parameters and elemental abundances. Ages are crucial for disentangling the formation history of the Milky Way. For turn-off stars ages can be determined using stellar isochrones, whilst asteroseismology offers the promise of ages for red giants stars.

However, the effort to carry out large surveys should be matched by efforts to improve our analysis techniques and our understanding the physics inside stars and their atmospheres. We also need to spend more effort in establishing benchmark type stars across the whole HR-diagram. Such stars are needed for several purposes and can be used in analysis methods such as the Cannon (Ness et al. 2015).

Going beyond the currently planned survey instruments it is interesting to ask the question: What’s next? RAVE and SEGUE provided relatively large number of targets at low or modest resolution. The next step has been to increase the resolving power in the instruments, e.g., WEAVE, HERMES, 4MOST, as well as increasing the number of fibres, e.g., 4MOST and DESI. What is the next desirable step? Is it to provide even more fibres over an even bigger field? Is it to provide fewer fibres but with increased resolving power? Or, would a single slit instrument on a large, 8–10 m, telescope be a better way to provide the next steps in Galactic Archeology?

Many of the current surveys are or will provide great catalogues that need to be followed up at higher resolution and/or higher signa-to-noise ratios. On the other hand, Gaia will provide additional, still unknown targets. Those we can easily think of are stars that appear to cluster in phase-space, e.g., moving groups or dispersed stellar clusters. What is the best way to follow-up such targets? These stars are likely not clustered on the sky. Hence, there appear to be a case for a single slit high-resolution, high signal-to-noise ratio spectrograph for survey and Gaia follow-up.

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