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Panoramic High Resolution Spectroscopy

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Abstract. Stellar populations in galaxies are vast repositories of fossil information. In recent years it has become possible to consider high resolution spectroscopic surveys of millions of stars. New high resolution multi-object spectrographs on 4-8m class telescopes (HERMES, WFMOS) will allow us for the first time to make large and detailed chemical abundance surveys of stars in the Galactic disk, bulge and halo, and apply the techniques of chemical tagging to recovering the fossil information left over from galaxy assembly. These instruments will have strong synergies with the GAIA astrometric satellite due to launch in 2011. The level of detail made possible by these future facilities will be necessary if we are to fully understand the physical processes involved in galaxy formation.

1. WFMOS and Galactic Archaeology

WFMOS is a proposed large wide-field multi-object fiber spectrometer to go at the prime focus of Subaru in a collaborative arrangement between Subaru and Gemini. WFMOS has high and low resolution modes, and is the top-priority next-generation instrument for Gemini. The high resolution spectrometer of WFMOS will have a resolution of about $R = 40,000$, fed by about 1000 fibers. We can hope for a SNR of about 100 per resolution element for stars of $V = 17$ in a 4-hour exposure.

Why would one want a high resolution multi-object spectrometer ? Galactic archaeology is the primary science driver. The goals of galactic archaeology are to seek signatures or fossils from the epoch of Galaxy formation, to give us insight into the processes which took place as the Galaxy formed. Specifically, we aim to reconstruct the star-forming aggregates that built up the disk, halo and bulge of our Galaxy. For some of these aggregates, their debris can be recognised kinematically as stellar moving groups. For others, the dynamical information was lost through disk heating processes during the formation and evolution of the disk, but they are still recognizable by their chemical signatures; ie by their detailed distributions of abundances of many different chemical elements.

As an example of reconstructing such ancient star-forming aggregates, we can start with the galactic halo. The halo is a slowly rotating spheroidal component of metal-poor stars, and is believed to be built up at least partly by accretion of small metal-poor satellite galaxies. Most halo building events occurred long ago, but some are still ongoing and sometimes directly visible: the Sgr dwarf is a well-known example of an ongoing halo accretion event. The halo represents only a few percent of the Galactic stellar mass, but is of great interest for galaxy formation because of its old age and low chemical abundance. Halo events are relatively easy to reconstruct dynamically, at least in principle, because they are minimally affected by dissipation and dynamical heating processes. Also, the long orbital periods for halo stars allow dynamical substructures to remain visible for longer times.

Accreted objects leave long-lived kinematic substructures in the galactic halo. These substructures are usually too faint to see in configuration space (although the Sgr dwarf provides a counter-example) but they are visible in phase space or integral space (eg the space of energy E and angular momentum L_z) (see Helmi 2008). In this way, we can identify the remnants of dispersed systems which contributed to building up the stellar halo.

We can extend this approach of reconstruction to other components of the Galaxy, such as the Galactic disk. Understanding disk formation is very important, because most of the Galactic stellar baryons are in the disk. Driver et al (2007) show that this is also holds in the nearby universe: the majority of stars are in disks.

1.1. The Galactic Disk

The Galactic halo shows kinematical substructure, believed to be the remains of accreted objects that built up the halo. The galactic disk also shows kinematical substructure, usually called moving stellar groups (eg Eggen 1996). The stars of the moving groups are all around us, and are identified by their common space motions relative to the sun. Not all of the stellar moving groups are of interest for galactic archaeology. Some are generated by dynamical resonances associated with the Galactic bar or spiral structure: the Hercules moving group is the best-known example of such a resonant substructure (eg Dehnen 1998). Other groups are indeed the debris of star-forming aggregates, now dispersed and phase-mixed into extended regions of the Galactic disk. Such groups, like the chemically homogeneous HR1614 moving group, are potentially very valuable for galactic reconstruction (eg De Silva et al 2007a). Some moving groups are believed to be the debris of infalling satellites as seen in ΛCDM simulations. The relatively rich and metal-poor Arcturus moving group may be an example (Navarro et al 2004).

Although the disk does show some kinematic substructure in the form of moving stellar groups, a lot of dynamical information was undoubtedly lost in the dissipation that led to disk formation and the subsequent heating and rearrangement by spiral waves and giant molecular clouds. Many dispersed star-forming aggregates in the Galactic disk will no longer be recognizable dynamically. However we are not restricted to dynamical techniques. Much fossil information is locked up in the detailed distribution of chemical elements in stars. The thick disk is particularly interesting in this context.

1.2. The Galactic thick disk

Thick disks appear to be ubiquitous in disk galaxies (eg Dalcanton & Bernstein 2002). The Galactic thick disk has a mass of about $10 - 15\%$ of the thin disk. Its scale height is about 1 kpc, compared to the 300 pc scale height of the thin disk. In the solar neighborhood the thick disk lags the rotation of the thin disk by about 30 km s^{-1}. Its stars are older than 10 Gyr and are significantly more metal-poor than the thin disk: the mean [Fe/H] value of the thick disk near the sun is about -0.7 and its metallicity distribution extends up to about -0.3, with a long metal-poor tail extending down to about -2.2. The thick disk stars are significantly enhanced in α-elements relative to the thin disk, indicating that they underwent a rapid epoch of chemical evolution (see Freeman & Bland-Hawthorn 2002 for an overview).

Thick disks in other galaxies appear to be old ($> 6-10$ Gyr) and moderately metal-poor. Their formation is not yet understood. They could be the remains of an early stellar thin disk heated long ago by accretion events or minor mergers. Alternatively they may be the stellar debris of ancient merger events, or the product of star formation associated with early large gaseous accretion events. Understanding how thick disks form is an important goal.

1.3. Chemical tagging

The debris from ancient star-forming events in the thin disk and thick disk will have phase mixed into an annulus around the Galaxy, suffered dynamical heating and orbit-swapping by spiral structure, and be now mostly unrecognizable kinematically. However the stars in the debris of chemically homogeneous star-forming aggregates will maintain their chemical identity: the abundance distribution over many chemical elements will be preserved. Even if we cannot recognize their stars from their kinematics, we can identify them from their common chemical signature. Using these chemical signatures to identify stars with common origins is known as chemical tagging (Freeman & Bland-Hawthorn 2002).

The detailed abundance pattern in the stars of a star-forming aggregate reflects the chemical evolution of the gas from which the aggregate formed. This depends on the history of enrichment of this gas by multiple generations of supernovae which provide different yields (depending on mass, metallicity, detonation details, ejected mass ...) and also by AGB stars and stellar winds (eg Kobayashi et al 2006). For the thick disk stars, we can use their detailed chemical abundance distributions to tag or associate them to common ancient star-forming aggregates with similar abundance patterns.

For chemical tagging to work, some conditions must be satisfied:

- stars form in large aggregates: this is believed to be true
- aggregates are chemically homogenous
- aggregates have unique chemical signatures defined by several groups of elements which do not vary in lockstep from one aggregate to another. A sufficient spread is needed in the detailed abundance distributions from aggregate to aggregate so that chemical signatures can be distinguished within the accuracy achievable by high resolution spectroscopy (about 0.05 to 0.1 dex differentially)

Testing the last two conditions were the goals of de Silva's work on open clusters: they appear to be true. For example, the rms dispersion in [Fe/H] for Hyades cluster stars is 0.04 dex (Paulson et al 2003) and the rms dispersion of most element ratios to iron, [X/Fe], is about 0.03 dex (De Silva 2006). A similarly small dispersion was found for stars in the cluster Coll 261 and for stars of the HR 1614 moving group (De Silva 2007a, 2007b). The abundances of the various elements did not vary in lockstep: each aggregate showed its own distinct chemical signature.

How many distinct star formation sites might there have been for the stars of the thick disk ? It will be feasible with WFMOS to observe stars down to $V = 17$ for a chemical tagging program. This limit defines a horizon out to which we can work: for dwarf stars, this corresponds to a distance of about 3 kpc. Out to this horizon, the mass of thick disk stars is about 2×10^9 $M_\odot$. We can estimate the order of magnitude of the number of star forming sites within our observable horizon by assuming that stars form in large aggregates of say 10^5 $M_\odot$. We would then expect to find the debris of about 2×10^4 dispersed aggregates in the thick disk, each with its own chemical signature.

Can we detect $\sim 10^4$ different thick disk sites using chemical tagging techniques ? We would need about 7 independently varying chemical elements or element groups, each with about 4 measurable abundance levels to get enough independent cells (4^7) in chemical abundance space. Are there 7 such independent elements or element groups ? From De Silva's studies of abundances in open clusters and the HR 1614 group, and from many other studies, it appears that there are at least 7 such groups:

- light elements like Na,Al
- Mg
- other alpha-elements like O, Ca, Si, Ti
- Fe and Fe-peak elements, with some variations within the Fe-peak
- light s-process elements like Sr and Zr
- heavy s-process elements like Ba
- r-process elements like Eu

Abundance variations in some of these element groups are seen from cluster to cluster (e.g. Carney & Yong 2005, De Silva et al 2006, 2007a,b).

As another application of these techniques, we note that chemical tagging may be the only way to assess definitively the importance of the Sellwood & Binney (2002) orbit swapping process, in which transient disturbances move stars from one near-circular orbit to another. Recent simulations by Roskar et al (2008) have demonstrated how significant this process could be for redistributing stars in the disk.

2. A Model Survey

Although the concept for the WFMOS high resolution spectrometer is still being developed, we can outline a model stellar survey to use chemical tagging techniques to detect the debris of ancient star forming sites. Assume that the WFMOS high resolution spectrometer is fed by 1000 fibers over a 1 square degree field. At a V magnitude of 17, the typical stellar density at a galactic latitude of 30° is about 1000 stars per square degree, matching the number of fibers. The fractional contribution from the galactic components is about 80% thin disk dwarfs, 0.5% thin disk giants, 10% thick disk dwarfs, 5% thick disk giants, and about 1% halo dwarfs, 2% halo giants. Disks dwarfs are seen out to distances of about 3 kpc, disk giants to 40 kpc and halo giants to 60 kpc.

About half of the thick disk stars pass through our 3 kpc dwarf horizon. Assume that the debris of all of their formation aggregates are now azimuthally mixed right around the Galaxy, so that all of these formation sites are represented within our horizon. (For the Galactic halo, most of the WFMOS stars are giants visible out to 60 kpc, so we sample most of the volume of the halo).

Simulations (Bland-Hawthorn & Freeman 2004) show that a random sample of 10^6 stars brighter than $V = 17$ would allow detection of about 20 thick disk dwarfs from each of about 500 star formation sites, and 30 halo giants from each of about 100 star formation sites. We note here that a smaller survey means less stars detected but from a similar number of sites. The survey would also include a large number of thin disk dwarfs to map the kinematical and chemical transition between the thin and thick disks. Chemical tagging may also be possible for the thin disk stars, with detection of about 20 stars in each of about 5000 sites, using elements which show some scatter in their [X/Fe] - [Fe/H] correlations as demonstrated by the open cluster abundance distributions.

With 1000 stars per field × 1000 fields, and each field requiring an integration of about 4 hours to reach the required S/N, such a survey would take about 500 clear nights. It could in principle be done in parallel with other large survey programs which use the low resolution spectrometers. This is just an order of magnitude indication of the likely scope of a chemical tagging program to identify ancient galactic substructure. All aspects of such programs need detailed modelling to determine the optimal numbers of stars, regions of the Galaxy, and range of stellar magnitude and color.

3. WFMOS and GAIA

GAIA will provide astrometry for about a billion stars. At magnitude $V = 17$, the uncertainties in the parallaxes and proper motions are expected to be about 25 μas and 20 μas yr^{-1} respectively. This corresponds to a 10% distance error at a distance of 4 kpc and a 4 km s^{-1} transverse velocity error at 40 kpc. All of the stars in the WFMOS sample will then have accurate 3D motions, and accurate distances will be available for all of the older main sequence stars and subgiants in the sample. WFMOS and GAIA together will give accurate abundances, 3D space motions and direct isochrone ages for most of the subgiants in the samples of old thin disk, thick disk and halo stars.

4. Conclusion

The ultimate goal of the proposed WFMOS high resolution survey is unravelling the star formation history of the disk and halo via chemical tagging. In the shorter term, the data products would include

- distribution in (position, velocity, chemical) space for about a million stars, and isochrone ages for about 100,000 stars
- distribution of [Fe/H], [α/H] and element ratios [X/Fe] for vast numbers of stars from each galactic component: bulge, thin and thick disks, halo
- detailed abundance gradient data for each component
- chemical and kinematical correlations in the inner and outer thick and thin disks.

Subaru and Gemini have the opportunity here to do something really groundbreaking and unique. This is the first time that such large high resolution spectroscopy programs can be contemplated. WFMOS provides an opportunity to enter a new and potentially very productive region of observational parameter space.

The Subaru and Gemini communities have great opportunities for PI science from such a very large uniform stellar data set. The scientific goals and input catalog should be carefully planned in collaboration with the communities, following an announcement of opportunity by Subaru/Gemini.

5. HERMES

Finally, I would like to mention a related instrument HERMES which is planned for the 4-m AAT. It uses the existing 2dF fiber positioner with 400 fibers, so the fiber density is about $400/\pi$ per square degree. This is well matched to stars with V $\sim$ 14 at intermediate galactic latitudes. The spectral resolution will be about 30,000. The instrument is currently planned to provide several hundred Ångstroms of spectrum with a resolution of about 30,000. At V $\sim$ 14, a 60 minute integration is expected to give a SNR of about 100 per resolution element. Although the telescope and number of fibers are smaller than for WFMOS, HERMES will be a useful survey instrument. For example, one could imagine a large stellar survey down to V = 14, covering 10,000 square degrees around the Galactic south polar cap. In about 3000 pointings (400 clear bright nights), it could acquire spectra of 1.2×10^6 stars.

Again, there is a synergy with GAIA. For these bright stars (V $\sim$ 14), the astrometry promises to be even more precise, with parallax and proper motion uncertainties of about 10 μas and 10 μas yr^{-1} respectively. This corresponds to a 1% distance error at a distance of 1 kpc (the typical distance of FG dwarfs in the sample) and a 0.7 km s^{-1} velocity error at 15 kpc (the distance of the faintest halo giants in the sample). We could expect to have accurate distances, abundances, radial and transverse velocities and, using the SkyMapper photometric survey, accurate temperature-(absolute magnitude) data for all stars in the sample. This would provide an independent check that stars in chemically tagged groups have common ages.

In addition to the large survey program, HERMES enables a variety of PI science. Some of this science would utilize the potential of high resolution spectra of lower SNR (eg Carney et al 1987) for measuring accurate radial velocities and mean metallicities of fainter stars. Examples include

- abundances of large samples of stars in the outer disk of the Galaxy: detecting the evolution of the galactic abundance gradient via stars of different ages.
- chemical evolution in the Galactic bulge, complemented by astrometry from the JASMINE mission.
- kinematics and chemical properties of stars in globular clusters, open clusters and superclusters: membership, dynamics, internal age-metallicity correlations and detailed abundance distributions.
- dynamics of the outer disk of the Large Magellanic Cloud.

GAIA is likely to detect a vast amount of phase space substructure. As with WFMOS, the HERMES survey will help to determine which phase-space substructures are the debris of remnant star forming events and which are dynamical artifacts (resonances).

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