Chemical Abundances in the Universe:
Connecting First Stars to Planets
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Spectroscopic surveys to measure Galaxy evolution

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Abstract. Galaxies are complex non-linear systems, evolving on all time-scales. Isolating whatever set of physical processes was important at each major phase of their evolution requires artefacts which resolve the timescales of dominant physical processes. These are the chemical elements, and stellar kinematics. I consider what surveys are required to make progress in Galaxy evolution mapping, in the era of Gaia.

Keywords. Surveys, stellar spectroscopy, Gaia, galaxy evolution

1. What do we want next? Why that?

Galaxy evolution is both an observational and a numerical science. The observational aspects are being advanced rapidly by photometry, and by spectroscopic surveys at both high and low dispersion. This will be revolutionised soon by Gaia. Gaia, scheduled for launch in Spring 2012, will deliver its first results in 2014/15 - essentially Hipparcos-quality astrometry and HST-quality spatial resolution, for the one billion stars, asteroids, QSO, compact galaxies,... brighter than magnitude 20, in addition to real-time alerts of variable sources throughout the mission. Considering what survey data is optimal to complement Gaia is clearly timely. The appropriate way to do this is to consider what scientific questions Gaia will address. This essentially is to quantify and distinguish the past history of star formation and system assembly by location - bulge, thin disk, disk bar, nucleus, thick disk, halo....

Star formation histories can be derived from analysis of precision colour-magnitude-distance-metallicity data [eg Hernandez *et al.* (1999)], so manifestly a high priority is to determine abundances for large sample of stars near the main-sequence turnoff, for which Gaia will provide complementary data. Mapping star formation histories to assembly histories requires knowledge of kinematics, and especially of chemical element ratios - element ratios quantify robustly the order in which gas was accreted and became stars, often resolves interesting timescales, and is our only measure of ancient gas flow and mixing lengths. More generally than these specific examples, one can consider what big questions are of interest, and then deduce what complementary information is essential to address them.

Galaxy formation and evolution in standard ΛCDM models starts with the collapse of perhaps $\sim 10^{6-8}\mathcal{M}_\odot$ overdense regions (the characteristic mass of 'the first objects' is the subject of much on-going work), eventually producing large galaxies like the Milky Way, which emerge as the end-point of a process of hierarchical clustering, merging and accretion. Detailed simulations of the formation of a present-day disk galaxy demonstrate both what is consistent with observation, and the sensitivity of much prediction to as-yet poorly known or described (sub-grid) physical processes, especially that mix of processes collectively called 'feedback'.

One type of feedback, iterative feedback between models and observations, is driving positive progress in identifying what we cannot predict, and hence where improved observations are essential to guide progress. This form of feedback clearly has a substantial effect on astrophysical progress. The relevant precision observations are focussed on our only available local records of star formation and baryon assembly over time, which are the chemical element abundances and the kinematics of stars.

Considering which astrophysical questions are least-well posed, and where the disagreement between simple prediction and observation is greatest, defines both the scale of required next-generation observations, and which subset of observation space is likely to provide the greatest progress. Combining that with known future observational advances - especially the astrophysical products of the Gaia mission, can help us answer the planners' request to say what we want next. Actually, we know what we want next - massive amounts of high-quality data. What we need to define is how much data on which targets. For that one needs also to ask: why?

A starting point to illustrate which specific surveys are likely to be most productive is to look at a deliberately over-simplified version of galaxy evolution model predictions, to then compare with observation, and notice the most severe inconsistencies.

Generic predictions (all of which have multiple approaches to their modification) for disk galaxies include the following:

- Extended disks form late, after a redshift of unity, or a lookback time of ~ 8 Gyr, in order to avoid losing too much angular momentum during active merging at earlier times; observation shows thin disks, even in their outer parts, to be generally very old, implying very early formation.
- A large disk galaxy should have many hundreds of surviving satellite dark haloes at the present day, which will disrupt the inner disk; observationally, satellites are less common and more massive than anticipated.
- The stellar halo is formed from disrupted satellites; the Sgr dwarf and many other lumps and bumps support this in teh outer halo, but the dominant halo field star element ratios are strongly inconsistent.
- Minor mergers (a mass ratio of $\sim 10-20\%$ between the satelite and the disk) into a disk heat it, forming a thick disk out of a pre-existing thin disk, and create torques that drive gas into the central (bulge?) regions, observationally, thick disks seem common on disk galaxies, but are not thin-disk extensions - a single merger seems implicated.
- More significant mergers transform a disk galaxy into an S0 or even an elliptical; observationally, late-type disk galaxies are extremely common.
- Subsequent accretion of gas can reform a thin disk; young disks are hard to find.
- Stars can be accreted into the thin disk from suitably massive satellites (dynamical friction must be efficient) and if to masquerade as stars formed in the thin disk, must be on suitable high angular momentum, prograde orbits; no useful observational limits are yet available.

Given that list, a simple comparison with local observations, and some straightforward astrophysics, it is feasible to identify the scale of observational requirements. The detailed comparison with observations is provided in the many contributions to this Symposium. Here I just note the elementary astrophysics, and draw conclusions.

1.1. *The evolution of Stellar Populations*

Quantifying the evolution of the Galaxy requires that we deduce the past history of star formation, chemical enrichment, and baryon material assembly. This can be achieved by exploitation of the chemical element clock, which recognises that different chemical elements are created on different timescales. Fortunately, element creation timescales

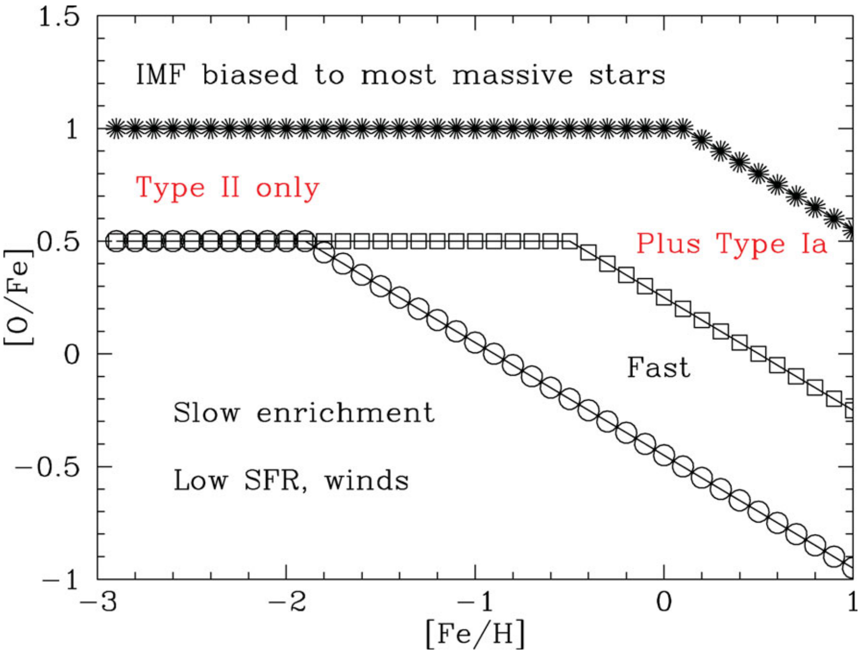

Figure 1. A summary overview of the dominant processes affecting chemical element ratio distributions in stellar populations. While only alpha elements are presented here for clarity, similar analyses for each family of elements can distinguish the dominant physics associated with the specific element creation and distribution timescale. This figure is adapted from Figure 1 of Gilmore & Wyse (1991).

are comparable to galaxy assembly timescales, which define star formation timescales, and so measurement of chemical element ratios provides sufficient temporal resolution to quantify galaxy evolution. Quantifying the assembly history of dark matter is even more fundamental, but remains indirect, largely from general deductions about assembly histories of stellar systems, and from kinematic and phase-space substructure analyses.

What information do we actually need? Leaving aside spatial distributions and kinematics as self-evident, the most fundamental is to define the generic distribution function of "metallicity", for example [Fe/H], for each identifiable structural component of the Galaxy. Some progress is possible here from photometric studies, rather approximately using the SDSS-derivation of the well-known ultra-violet excess UBV technique $\delta_{0.6}$, more accurately using the Stromgren narrow-band technique ($uvby$) or the various similar systems. These techniques work well for quick-look results on very large samples, have a spectacular multiplex advantage, and with suitable care can define mean and sometimes even a dispersion in abundances. It is a mistake to overstate their value: the broader the band the poorer the information content, and all these systems saturate at low and high abundances. To do better one needs higher resolution than the $\mathcal{R} \approx$ 10-50 available photometrically.

In Figure 1 is a top-level summary of the evolutionary patterns of a system with no substantial gas inflow, and with efficient mixing. This indicates what types of information is available from spectroscopy, and implies what we need to quantify observationally. We now consider this fuigure, starting at the lowest abundances.

Perhaps the least-appreciated aspect of this figure is the sensitivity of the amplitude of the alpha elements to the stellar initial mass function. This means that we have available direct and robust information on the high-mass stellar IMF at every metallicity, down to very low values appropriate to the first stars in the Universe, and whatever stellar contribution was involved in reionization of the Universe at redshits of order 10–20. This fundamental information requires determination of the distribution function of elements in low metallicity stars. Astonishing progress is being made here, in part from detailed follow-up of huge low-dispersion surveys used to identify good candidates, and in part from detailed studies of specific dwarf galaxies. Similar studies of the Galactic bulge should find even more extreme objects, if the model predictions are correct. Discussion of the current studies is elsewhere in this volume, so I just note one thing here: the distribution function of alpha elements is strongly asymmetric, with a clear upper bound, and a tail down to solar-like values. While some few high values are found, these are consistent with the failure of assumptions about well-mixed gas, and well-sampled IMFs. Looking at Figure 1, one sees the evidence for a universal high-mass IMF with plausible yields is strong, and getting stronger. Interestingly, this result is frequently interpreted to deduce limits on the assembly history ot the Galactic field halo. In fact it provides no information at all on that. The only information is on the stellar IMF, and a minimum scale of mixing of the ISM. The surface density of these extreme stars is so low their detailed analysis will remain a topic for specific studies - the role of surveys will be to identify candidates.

1.1.1. *The Galactic halo and satellites*

To study the Galactic halo one needs to look at metallicities where most halo stars are found. that is, to study the halo one needs to study the true distribution function of elements in the range $-2 \leqslant$[Fe/H]$\leqslant -1$. This is a much neglected region of parameter space, where substantial progress could be made. A high quality survey ($\mathcal{R} \geqslant 20000$) is needed. One can quantify numbers. The halo metallicity distribution function (DF) is roughly gaussian, with mean -1.5 dex, dispersion about 0.5 dex. Gaussians can be physically generated - by processes involving the central limit theorem - or can be generated by observational error. It is the deviation away from a gaussian which contains the information. To quantify this at the few percent level where one could usefully test assembly models requires consistent data on 10000 stars. Given that, one would then be in a position to ask more specific follow-up questions, and in particular to quantify the metal-rich end of the halo DF. A sample of this size is eminently achievable in feasible observing campaign, even with current low-multiplex echelle spectrographs. Data reduction will need some automation!

1.1.2. *The thin disk*

High quality spectroscopy of nearby GFK stars has become a productive industry (e.g., Edvardsson *et al.* 1993; Feltzing & Gustafsson 1998; Chen *et al.* 2000; Nissen *et al.* 2000; Fulbright 2002; Reddy *et al.* 2003, 2006; Takeda 2007; Ecuvillon *et al.* 2004; Gilli *et al.* 2006; Bensby *et al.* 2003; Ramírez *et al.* 2007; Fuhrmann 1998, 2004, 2008). The remarkable outcomes are the narrowness of the thin disk abundance distribution, and the essentially scatter-free distribution of the abundance ratios for thin disk stars at given [Fe/H]. For example, Reddy *et al.* (2003) failed to detect cosmic scatter in the abundance ratios. This has strong consequences for Galactic disk evolution, invalidating most obvious models. It also invalidates most obvious observational strategies: apparently one's ambition to apply 'chemical tagging' to identify stars' places of origin is doomed to fail. The stellar IMF is remarkable uniform, ISM mixing remarkably efficient, star formation remarkably uniform, the local disk remarkably old.

There is much kinematic substructure in the Galactic disk, some large-scale gradients and much still inconclusive discussion of radial migration and late satellite accretion. there is a bar and a warp. It seems the next step in advancing knowledge of the thin disk is to quantify the abundance distribution function in these subsystems, and especially far from the solar neighbourhood - at least one scale length radially in and radially out. This, while feasible, will require studies of giants through much extinction, and will not be easy.

1.1.3. *The thick disk*

The thick disk was defined through star counts more than 25 years ago (Gilmore & Reid 1983) and is now well-established as a distinct component, not the tail of the stellar halo or of the thin disk. Its origins remain the source of considerable debate. Locally, some $\sim 5 - 10\%$ of stars are in the thick disk; the vertical scale-height is ~ 1 kpc, and radial scale-length ~ 3 kpc. Thick disks with roughly similar properties are seen in the resolved stellar populations of many nearby spirals (e.g. Yoachim & Dalcanton 2006, 2008). Thus quantitative analysis of the Galactic thick disk is of wide implication. Given its convenience - high latitude, nearby - large survey samples could be readily achieved. Defining the abundance and kinematic (sub-)structure would be a direct test of galaxy models, and the early accretion history of the Galaxy.

Stars in the solar neighborhood can apparently be reliably labelled, at least probabilistically, into thin and thick disks stars. Although the distributions of the velocity components and metallicities overlap, considering kinematics (UVW) as well as [Fe/H], makes their definition clear. The age distributions have probably very little overlap (see, e.g., Fig. 24 in Reddy *et al.* 2006), while the alpha element distributions also seem disjoint. Is it really true that the Galaxy has two discreet disks? Where is the evidence for whatever process amplified the distinction? Again here, large samples are needed to define the wings of the distribution functions, and any substructure.

One can imagine a survey of a galactic slice, covering mid-latitudes from longitudes 90 to 270, and so sensitive to the crucial angular momentum orbital vector. This might be 500–1500pc above the Galactic plane, covering both the thick disk and halo, and whatever else is in there we have yet to notice (see eg Gilmore, Wyse & Norris (2002)). Again, a prelimary survy of order 10,000 stars would be suffient to define what we know, to quantify the apparently remarkable consequences for early galaxy mergers, and define the next stages for further progress.

1.1.4. *The inner disk and Bulge*

Remarkably little remains known of the inner disk, the Galactic nucleus, and the bulge. Studies are finally becoming underway. These suggest an old alpha-enhanced population in the bulge, with a solar-like mean abundance, and a broad metallicity distribution function. Given the diversity of types of galactic bulge, and the range of formation mechanisms (Kormendy *et al.* (2009)), all of which may apply, one should presume a very complex system. Very substantial efforts will be needed to make progress here, since we know so little as yet.

2. Summary

Gaia is coming. Substantial and fundamental advances in our understanding of galaxy (and Galaxy) formation, assembly and evolution, and much more, will become feasible. In order to get full-value from the Gaia opportunity complementary surveys are critical. These include near-IR photometry, to help define extinction, high spatial resolution imaging in crowded regions, to match Gaia's spatial resolution to complementary data, and most of all spectroscopy.

There are two major spectroscopic needs. The biggest, in numbers, is $\mathcal{R}$ ∼5000 spectroscopy for kinematics, and approximate abundances, for stars fainter than about 16. Gaia will survey 1 percent of stars in the Galaxy. If only 10% of Gaia stars have kinematics the science yield will be seriously diluted. But that is already 10^8 spectra. Not an easy challenge.

Higher dispersion and S/N are needed for the essential element-ratio surveys. These provide most of the quantitative astrophysics, and merit most effort. But again, the numbers are large. Several times 10,000 stars are necessary. This is a big challenge! But one that might be met by scaling: most faint stars in Gaia are actually relatively nearby intrinsically low-luminosity. The distance range they sample can efficiently be studied using more luminous stars. Rather faint giants (if they can be identified reliably, probably using reduced proper motion sampling) and distant turnoff stars are the most suitable tracers, and reduce the numbers to feasible levels. An initial survey of a few thousand stars in each of a few tens of distance intervals will be appropriate to define what is then needed. Is that viable? Why not! There are several thousand hours available each year on each telescope. Even small multiplex gains will then soon deliver 10,000 spectra. While they are being obtained, higher-multiplex systems can be built, allowing the order of magnitude advance at a time when we will know much better what questions to ask.

Surveying in distance intervals, not in magnitude intervals, is a practical approach to the Gaia challenge.

References

Bensby, T., Feltzing, S., & Lundström, I. 2003, *A&A*, 410, 527

Chen, Y. Q., Nissen, P. E., Zhao, G., Zhang, H. W., & Benoni, T. 2000, *A&AS*, 141, 491

Ecuvillon, A., Israelian, G., Santos, N. C., Mayor, M., Villar, V., & Bihain, G. 2004, *A&A*, 426, 619

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, *A&A*, 275, 101

Feltzing, S. & Gustafsson, B. 1998, *A&AS*, 129, 237

Fuhrmann, K. 2004, *Astronomische Nachrichten*, 325, 3

Fuhrmann, K. 1998, *A&A*, 338, 161

Fuhrmann, K. 2008, *MNRAS*, 384, 173

Fulbright, J. P. 2002, *AJ*, 123, 404

Gilmore, G. & Reid, I. Neill, 1983, *MNRAS*, 202, 1025

Gilmore, G. & Wyse, R. F. G. 1991, *ApJL*, 367, L55

Gilmore, G., Wyse, Rosemary, F. G., & Norris John, E. 2002, *ApJL*, 574, L39

Gilli, G., Israelian, G., Ecuvillon, A., Santos, N. C., & Mayor, M. 2006, *A&A*, 449, 723

Hernandez, X., Valls-Gabaud, D., & Gilmore, G. 1999, *MNRAS*, 304, 705

Kormendy John, Fisher David, B., Cornell Mark, E., & Bender Ralf, 2009, *ApJS*, 182, 216

Ramírez, I., Allende Prieto, C., & Lambert, D. L. 2007, *A&A*, 465, 271

Reddy, B. E., Lambert, D. L., & Allende Prieto, C. 2006, *MNRAS*, 367, 1329

Reddy, B. E., Tomkin, J., Lambert, D. L., & Allende Prieto, C. 2003, *MNRAS*, 340, 304

Takeda, Y. 2007, *PASJ*, 59, 335

Yoachim, Peter, Dalcanton Julianne, J. 2006, *AJ*, 131, 226

Yoachim, Peter, Dalcanton Julianne, J. 2008, *ApJ*, 682, 1004