The Gaiasphere and the limits of knowledge

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Abstract. At the heart of a successful theory of galaxy formation must be a detailed physical understanding of the dissipational processes which form spiral galaxies. To what extent can we unravel the events that produced the Galaxy as we see it today? Could some of the residual inhomogeneities from prehistory have escaped the dissipative process at an early stage? To make a comprehensive inventory of surviving inhomogeneities would require a vast catalog of stellar properties that is presently out of reach. The Gaia space astrometry mission, set to launch at the end of the decade, will acquire detailed phase space coordinates for about one billion stars, within a sphere of diameter 20 kpc – the Gaiasphere. Here we look forward to a time when all stars within the Gaiasphere have complete chemical abundance measurements (including $\alpha$, $s$ and $r$ process elements). Even with such a vast increase in information, there may exist fundamental – but unproven – limits to unravelling the observed complexity.

1. Introduction

Eddington once remarked that ‘the contemplation in natural science of a wider domain than the actual leads to a far better understanding of the actual.’ Our intuition is that any dynamical phase early on in the history of the Galaxy which is dominated by relaxation or dissipation probably removes more information than it retains. This remains largely true for controlled experiments within terrestrial laboratories for the reason that it is exceedingly difficult to track fluid particles, for example, in order to unravel the process under study. However, at least in principle, the situation may be more tractable in astrophysics in that individual stars carry information about the birth site at the time of their formation. Nature offers us a vast untapped reservoir of information in the detailed chemical abundances stored within stellar atmospheres.

The fossil evidence of galaxy formation is not restricted to chemical abundances alone. In our review, “The New Galaxy – Signatures of its Formation,” we stress the importance of new observations across a wide range of parameter space (Freeman & Bland-Hawthorn 2002). We are coming into a new era of galactic investigation, in which one can study the fossil remnants of the early
days of the Galaxy in a broader and more focussed way, not only in the halo but throughout the major luminous components of the Galaxy. The goal of these studies is to reconstruct as much as possible of the early galactic history.

What do we mean by the reconstruction of early galactic history? We seek a detailed physical understanding of the sequence of events which led to the Milky Way. Ideally, we would want to tag (i.e. associate) components of the Galaxy to elements of the protocloud – the baryon reservoir which fueled the stars in the Galaxy.

Our approach is anchored to observations of the Galaxy, interpreted within the broad scope of the CDM hierarchy. Many of the observables in the Galaxy relate to events which occurred long ago, at high redshift. Fig. ?? shows the relationship between look-back time and redshift in the context of the ΛCDM model: the redshift range ($z < \sim 6$) of discrete sources in contemporary observational cosmology matches closely the known ages of the oldest components in the Galaxy. The Galaxy (near-field cosmology) provides a link to the distant universe (far-field cosmology).

Here we address the prospect of chemically ‘tagging’ stars to common sites of formation, in order to reconstruct star clusters which have long since dispersed. High resolution spectroscopy at high signal-to-noise ratio of many stellar types reveals an extraordinarily complex pattern of spectral lines. The spectral lines carry key information on element abundances that make up the stellar atmosphere. Some of these elements cannot arise through normal stellar evolution, and therefore must reflect conditions in the progenitor cloud at the time of its formation. A cornerstone of near-field cosmology must be to explore how much of the Galaxy’s past can be reconstructed from the chemical signatures in stellar atmospheres.

2. Chemical signatures

A major goal of near-field cosmology is to tag individual stars with elements of the protocloud. For many halo stars, and some outer bulge stars, this may be possible with phase space information provided by Gaia. But for much of the bulge and the disk, secular processes cause the populations to become relaxed (i.e. the integrals of motion are partially randomized). In order to have any chance of unravelling disk formation, we must explore chemical signatures in the stellar spectrum. Ideally, we would like to tag a large sample of representative stars with a precise time and a precise site of formation.

Over the last four decades, evidence has gradually accumulated (Fig. ??) for a large dispersion in metal abundances [$X_i$/Fe] (particularly n-capture elements) in low metallicity stars relative to solar abundances (Wallerstein et al. 1963; Pagel 1965; Spite & Spite 1978; Truran 1981; Luck & Bond 1985; Clayton 1988; Gilroy et al. 1988; McWilliam et al. 1995; Norris et al. 1996; Burris et al. 2000). Elements like Sr, Ba and Eu show a 300-fold dispersion, although [$\alpha$/Fe] dispersions are typically an order of magnitude smaller.

In their celebrated paper, Burbidge et al. (1957 – B2FH) demonstrated the likely sites for the synthesis of slow (s) and rapid (r) n-capture elements. The s-process elements (e.g. Sr, Zr, Ba, Ce, La, Pb) are thought to arise from the He-burning phase of intermediate to low mass (AGB) stars ($M < 10M_\odot$),
although at the lowest metallicities, trace amounts are likely to arise from high
mass stars (Burris et al. 2000; Rauscher et al. 2001).

In contrast to the s-process elements, the r-process elements (e.g. Sm, Eu, Gd, Tb, Dy, Ho) cannot be formed during quiescent stellar evolution. While some doubts remain, the most likely site for the r-process appears to be SN II, as originally suggested by B2FH (see also Wallerstein et al. 1997). Therefore, r-process elements measured from stellar atmospheres reflect conditions in the progenitor cloud. In support of Gilroy et al. (1988), McWilliam et al. (1995) state that ‘the very large scatter means that n-capture element abundances in ultra-metal poor stars are products of one or very few prior nucleosynthesis events that occurred in the very early, poorly mixed galactic halo’, a theme that has been developed by many authors (e.g. Audouze & Silk 1995; Shigeyama & Tsujimoto 1998; Argast et al. 2000; Tsujimoto et al. 2000).

Supernova models produce different yields as a function of progenitor mass, progenitor metallicity, mass cut (what gets ejected compared to what falls back towards the compact central object), and detonation details. The α elements are mainly produced in the hydrostatic burning phase within the pre-supernova star. Thus α yields are not dependent on the mass cut or details of the fallback/explosion mechanism which leads to a much smaller dispersion at low metallicity.

There is no known age-metallicity relation that operates over a useful dynamic range in age and/or metallicity. (This effect is only seen in a small subset of hot metal-rich stars). Such a relation would require the metals to be well mixed over large volumes of the ISM. For the foreseeable future, it seems that only a small fraction of stars can be dated directly. Arguably, the most promising stellar chronometers make use of radioactive dating or asteroseismology. Nucleo-cosmochronology is not yet a precise science but has potential for future development (Sneden et al. 2001a; Goriely & Arnould 2001).

3. Reconstructing ancient star groups

We now conjecture that the heavy element metallicity dispersion may provide a way forward for tagging groups of stars to common sites of formation. With sufficiently detailed spectral line information, it is feasible that the ‘chemical tagging’ will allow temporal sequencing of a large fraction of stars in a manner analogous to building a family tree through DNA sequencing.

Most stars are born within rich clusters of many hundreds to many thousands of stars (Clarke et al. 2000; Carpenter 2000). McKee & Tan (2002) propose that high-mass stars form in the cores of strongly self-gravitating and turbulent gas clouds. The low mass stars form within the cloud outside the core, presumably at about the same time or shortly after the high mass stars have formed. The precise sequence of events which give rise to a high mass star is a topic of great interest and heated debate in contemporary astrophysics (e.g. Stahler et al. 2000).

A necessary condition for ‘chemical tagging’ is that the progenitor cloud is uniformly mixed in key chemical elements before the first stars are formed. Another possibility is that a few high mass stars form shortly after the cloud assembles, and enrich the cloud fairly uniformly. Both scenarios would help to
ensure that long-lived stars have identical abundances in certain key elements before the onset of low-mass star formation.

For either statement to be true, an important requirement is that open clusters of any age have essentially zero dispersion in some key metals with respect to Fe. There has been very little work on heavy element abundances in open clusters. The target clusters must have reliable astrometry so as to minimize ‘pollution’ from stars not associated with the cluster (Quillen 2002).

If our requirement is found not to be true, then either the progenitor clouds are not well mixed or high mass stars are formed after most low mass stars. A more fundamental consequence is that a direct unravelling of the disk into its constituent star groups would be impossible, in other words, the epoch of dissipation cannot be unravelled after all.

Consider the (extraordinary) possibility that we could put many coeval star groups back together over the entire age of the Galaxy. This would provide an accurate age for the star groups either through the color-magnitude diagram, or through association with those stars within each group that have $[\text{n-capture}/\text{Fe}] \gg 0$, and can therefore be radioactively dated. This would provide key information on the chemical evolution history for each of the main components of the Galaxy.

But what about the formation site? The kinematic signatures will identify which component of the Galaxy the reconstructed star group belongs, but not specifically where in the Galactic component (e.g. radius) the star group came into existence. For stars in the thin disk and bulge, the stellar kinematics will have been much affected by the bar and spiral waves; it will no longer be possible to estimate their birthplace from their kinematics. Our expectation is that the derived family tree will severely restrict the possible scenarios involved in the dissipation process. In this respect, a sufficiently detailed model may be able to locate each star group within the simulated time sequence.

Freeman & Bland-Hawthorn (2002) argue that, in addition to open clusters, the thick disk is an extremely important fossil of the processes behind disk formation. The thick disk is thought to be a snap-frozen relic of the early disk, heated vertically by the the infall of an intermediate mass satellite. Chemical tagging of stars that make up the thick disk would provide clues on the formation of the first star clusters in the early disk.

4. Chemical abundance space

An intriguing prospect is that reconstructed star clusters can be placed into an evolutionary sequence, i.e. a family tree, based on their chemical signatures. Let us suppose that a star cluster has accurate chemical abundances determined for a large number $n$ of elements (including isotopes). This gives it a unique location in an $n$-dimensional space compared to $m$ other star clusters within that space. We write the chemical abundance space as $\mathcal{C}(\text{Fe/H}, X_1/\text{Fe}, X_2/\text{Fe}, \ldots)$ where $X_1, X_2 \ldots$ are the independent chemical elements that define the space (i.e. elements whose abundances are not rigidly coupled to other elements).

The size of $n$ is unlikely to exceed about 50 for the foreseeable future. Hill et al. (2002) present exquisite data for the metal-poor star CS 31082-001, where abundance estimates are obtained for a total of 44 elements, almost half the
entire periodic table (see also Cayrel et al. 2001). In Fig. ??, we show what is now possible for another metal-poor star, CS 22892-052 (Sne den et al. 2001a). The $\alpha$ elements and r-process elements, and maybe a few canonical s-process elements at low [Fe/H], provide information on the cloud abundances prior to star formation, although combinations of these are likely to be coupled (Heger & Woosley 2001; Sneden et al. 2001a). There are 24 r-process elements that have been clearly identified in stellar spectra (Wallerstein et al. 1997).

The size of $m$ is likely to be exceedingly large for the thin disk where most of the baryons reside. For a rough estimate, we take the age of the disk to be 10 Ga. If there is a unique SN II enrichment event every 100 years, we expect of order $10^8$ formation sites. Typically, a SN II event sweeps up a constant mass of $5 \times 10^4 M_\odot$ (Ryan et al. 1996; Shigeyama & Tsujimoto 1998). Simple chemical evolution models indicate that this must be of the right order to explain the metallicity dispersion at low [Fe/H] (Argast et al. 2000). Roughly speaking, there have been $10^3$ generations of clouds since the disk formed, with about $10^5$ clouds in each star-forming generation, such that cloud formation and dispersal cycles on a $10^7$ yr timescale (Elmegreen et al. 2000).

Whereas the total number of star clusters over the lifetime of the thin disk is very large, the size of $m$ for the stellar halo (Harding et al. 2001), and maybe the thick disk (Kroupa 2002), is likely to be significantly smaller. Our primary interest is the oldest star clusters. Reconstructing star clusters within the thick disk is a particularly interesting prospect since the disk is likely to have formed within 1–1.5 Ga of the main epoch of baryon dissipation (Prochaska et al. 2000).

The task of establishing up to $10^8$ unique chemical signatures may appear to be a hopeless proposition with current technology. But it is worth noting that more than 60 of the chemical elements ($Z > 30$) arise from n-capture processes. Let us suppose that half of these are detectable for a given star. We would only need to be able to measure two distinct abundances for each of these elements in order to achieve $10^9$ independent cells in $C$-space. If many of the element abundances are found to be rigidly coupled, of course the parameter space would be much smaller.

It may not be necessary to measure as many as 30 elements if some can be found which are highly decoupled and exhibit large relative dispersions from star to star. Burris et al. (2000) demonstrate one such element pair, i.e. [Ba/Fe] and [Sr/Fe]. It is difficult at this stage to suggest which elements are most suited to chemical tagging. In part, this depends on the precise details and mechanism of formation of the n-capture elements at low [Fe/H].

The element abundances [X$_i$/Fe] show three main peaks at $Z \approx 26$, $Z \approx 52$, and $Z \approx 78$; the last two peaks are evident in Fig. ?? . There have been suggestions that the r-process gives rise to random abundance patterns (e.g. Goriely & Arnould 1996) although this is not supported by new observations of a few metal poor stars. Heavy r-process elements around the second peak compared to the Sun appear to show a universal abundance pattern (Sneden et al. 2000; Cayrel et al. 2001; Hill et al. 2002). However, Hill et al. find that the third peak and actinide elements ($Z \geq 90$) are decoupled from elements in the second peak. We suspect that there may be a substantial number of suitable elements ($\sim 10$) which could define a sufficiently large parameter space.
Our ability to detect structure in C-space depends on how precisely we can measure abundance differences between stars. It may be possible to construct a large database of differential abundances from echelle spectra, with a precision of 0.05 dex or better; differential abundances are preferred here to reduce the effects of systematic error.

5. Chemical trajectories

Our simple picture assumes that a cloud forms with a unique chemical signature, or that shortly after the cloud collapses, one or two massive SN II enrich the cloud with unique yields which add to the existing chemical signature. The low-mass population forms with this unique chemical signature. If the star-formation efficiency is high ($\gtrsim 30\%$), the star group stays bound although the remaining gas is blown away. If the star-formation efficiency is low ($\lesssim 10\%$), the star cluster disperses along with the gas. In a closed box model, the dispersed gas reforms a cloud at a later stage.

In the closed box model, each successive generation of supernovae produce stellar populations with progressive enrichments. These will lie along a trajectory in C-space which can be identified in principle using minimum spanning tree methods (Sedgewick 1992). The overall distribution of the trajectories will be affected by fundamental processes like the star formation efficiency, the star formation timescale, the mixing efficiency, the mixing timescale, and the satellite galaxy infall rate.

As we approach solar levels of metallicity in $\text{[Fe/H]}$, the vast number of trajectories will converge. By $\text{[Fe/H]} \approx -2.5$, AGB stars will have substantially raised the s-process element abundances; by $\text{[Fe/H]} \approx -1$, Type Ia supernovae will have raised the Fe-group abundances. Star clusters that appear to originate at the same location in this C-space may simply reflect a common formation site, i.e. the resolution limit we can expect to achieve in configuration space. The ability to identify common formation sites rests on accurate differential abundance analyses (Edvardsson et al. 1993; Prochaska et al. 2000).

Even with a well established family tree based on chemical trajectories in the chemical C-space, this information may not give a clear indication of the original location within the protocloud or Galactic component. This will come in the future from realistic baryon dissipation models. Forward evolution of any proposed model must be able to produce the chemical tree.

However, the C-space will provide a vast amount of information on chemical evolution history. It should be possible to detect the evolution of the cluster mass function with cosmic time (Kroupa 2002), the epoch of a starburst phase and/or associated mass ejection of metals to the halo (Renzini 2001), and/or satellite infall (Noguchi 1998).

As we go back in time to the formation of the disk, we approach the chemical state laid down by population III stars. The lack of stars below $\text{[Fe/H]} \approx -5$ suggests that the protocloud was initially enriched by the first generation of stars (Argast et al. 2000). However, the apparent absence of any remnants of population III remains a puzzle: its stars may have had a top-heavy initial mass function, or have dispersed into the intra-group medium of the Local Group. If
one could unravel the abundances of heavy elements at the time of disk formation, this would greatly improve the precision of nucleo-cosmochronology.

6. Candidates for chemical tagging

Chemical tagging will not be possible for all stars. In hot stars, our ability to measure abundances is reduced by the stellar rotation and lack of transitions for many ions in the optical. The ideal candidates are the evolved FGK stars that are numerous (10%) and intrinsically bright. These can be observed at echelle resolutions \( R > 30,000 \) over the full Gaia sphere. Moreover, giants have deep, low density atmospheres that produce strong low-ionization absorption lines compared to higher gravity atmospheres. Even in the presence of significant line blending, with sufficient signal, it should be possible to derive abundance information by comparing the fine structure information with accurate stellar synthesis models. Detailed abundances of large numbers of F and G subgiants would be particularly useful, if it becomes possible to make such studies, because direct relative ages can be derived for these stars from their observed luminosities.

It is not clear at what \([\text{Fe/H}]\) the r-process elements become swamped by the ubiquitous Fe-group and s-process elements. At a resolution of \( R \sim 10^5 \), many r-process elements can be seen in the solar spectrum, although the signal-to-noise ratio of about 1000 is needed, and even then the spectral lines are often badly blended (Kurucz 1991; 1995). Travaglio et al. (1999) suggest that the s-process does not become significant until \([\text{Fe/H}] \approx -1\) because of the need for pre-existing seed nuclei (Spite & Spite 1978; Truran 1981), although Pagel & Tautvaisiene (1997) argue for some s-process production at \([\text{Fe/H}] \sim -2.5\). Prochaska et al. (2000) detected Ba, Y and Eu in a snapshot survey of thick disk G dwarfs in the solar neighbourhood with \(-1.1 < [\text{Fe/H}] < -0.5\). This survey only managed to detect a few transitions in each element although their spectral coverage was redward of 440nm with SNR \( \approx 100 \) per pixel at \( R \approx 50,000 \). Longer exposures with \( R \sim 10^5 \) and spectral coverage down to 300nm would have detected more heavy elements.

7. Future progress

In our view, observations of nucleosynthetic signatures of metal-poor stars provide a cornerstone of near-field cosmology. Success in this arena requires major progress across a wide front, including better atomic parameters (Truran et al. 2001), improved supernova models, better stellar synthesis codes and more realistic galaxy formation models. There are no stellar evolutionary models that lead to a self-consistent detonation and deflagration in a core-collapse supernova event or, for that matter, detonation in a thermonuclear explosive event. Realistic chemical production at the onset of the supernova stage requires a proper accounting of a large number of isotope networks \( (400-2500) \) that cannot be adequately simulated yet. Modern computers have only recently conquered relatively simple \( \alpha \) networks involving 13 isotopes. The inexorable march of computer power will greatly assist here.
There is also a key experimental front both in terms of laboratory simulations of nucleosynthesis, and the need for major developments in astronomical instrumentation. Many authors (e.g. Sneden et al. 2001b) have stressed the importance of greatly improving the accuracy of transition probabilities and reaction rates for both heavy and light ion interactions. This will be possible with the new generation of high-intensity accelerators and radioactive-beam instruments (Käppeler et al. 1998; q.v. Manuel 2000).

Progress on all fronts will require iteration between the different strands. Already, relative r-process and α element abundances for metal-poor stars have begun to constrain the yields for different stellar masses and associated mass cuts of progenitor supernovae (Mathews et al. 1992; Travaglio et al. 1998; Ishimaru & Wanajo 2000).

Detailed high resolution abundance studies of large samples of galactic stars will be crucial for the future of fossil astronomy. But we stress that in order to access a representative sample of the Gaiasphere, this will require a new generation of ground-based instruments, in particular, a multi-object echelle spectrograph with good blue response on a large aperture telescope. There is a real need for a high-resolution spectrograph which can reach hundreds or even thousands stars in a square degree or more. The Gemini Wide Field proposal currently under discussion provides an opportunity for this kind of instrument (S. Barden, personal communication). The instrument will be expensive and technically challenging, but we believe this must be tackled if we are to ever unravel the formation of the Galaxy.

Could some of the residual inhomogeneities from prehistory have escaped the dissipative process at an early stage? We may not know the answer to this question with absolute certainty for many years. But it is an intriguing thought that one day we may be able to identify hundreds or even thousands of stars throughout the Gaiasphere that were born within the same cloud as the Sun.

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Figure 1. Look-back time as a function of redshift and the size of the Universe (Lineweaver 1999) for five different world models. The approximate ages of the Galactic halo and disk are indicated by hatched regions.
Figure 2. Mean relative abundance ratios of light s-process elements (top panel), heavy s-process elements (middle panel), and r-process elements (bottom panel) as functions of [Fe/H]. In each panel, the dotted horizontal lines represent the solar abundance ratios of these elements. The references for the data points are given in Wallerstein et al. (1997). [We thank C. Sneden for preparing this figure.]
Figure 3. CS 22892-052 n-capture abundances (points) taken from Sneden et al. (2000) and scaled solar system abundances (solid and dashed lines) taken from Burris et al. (2000). Many of the heavy elements conform to the solar system r-process abundance pattern, although some elements show the hallmark of the s-process. This figure was originally presented in Sneden et al. (2001a).