PROCEEDINGS OF SCIENCE

Astroarchaeology

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The goal of astroarchaeology or Galactic archaeology is to unravel the history of assembly of the Milky Way, using fossil remnants of ancient star formation events which have disrupted and are now dispersed around the Galaxy. Recent studies of chemical abundances of stars in individual (undispersed) open and globular clusters show that their abundances appear to be homogeneous to the level at which they can be measured, at least for elements heavier than Al. The technique of chemical tagging can be used to identify the fossil remnants of old dispersed clusters from their element abundance patterns over many chemical elements. We plan to use the new HERMES multi-object high resolution spectrometer on the Anglo Australian Telescope to measure abundances for up to 30 elements in about a million stars. This program is called GALAH (Galactic archaeology with HERMES) and we hope to begin the pilot study in mid-2013.

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1. Galactic archaeology

The goal is to learn about the formation and evolution of the Galaxy, using the stellar relics of ancient star formation and accretion events. After their birth-clusters dispersed, these relic stars may have lost much of their phase space information because of dynamical heating and radial migration. We know however that almost all bound open and globular star clusters are chemically homogeneous for elements above Al. The detailed chemical composition over many elements of the surviving stars of such star forming events is likely to be conserved, and the relic stars from a particular star forming event are likely to have the same detailed distribution of element abundances. This provides a way to recognize relic stars from old long-dispersed star formation sites.

I will start with some general points about the Galactic components, and then look at some more specific issues in Galactic archaeology.

2. Galactic Components

Almost all spirals appear to have a thick disk component, in addition to their defining thin disks. In large spirals like ours, the thick disk mass is typically about 10% of the thin disk. Near the sun, the abundance ranges of the thick and thin disk stars overlap. The thin disk stars have [Fe/H] in the range -0.7 to $+0.5$, while most of the thick disk stars have [Fe/H] between about -1 and -0.3, with tails extending to -2 and -0.1. The stars of the thin and thick disks have different motions, different density distributions and different distributions in the [α/Fe]–[Fe/H] plane, where [α/Fe] is the relative abundance of the α-elements Mg, Si, Ca and Ti. In the [Fe/H] interval over which the two disk components overlap (about -0.7 to -0.1), the thick disk stars are distinctly more α-enhanced, indicating that their chemical evolution occurred more rapidly. Near the sun, all of the stars of the thick disk appear to be old, with ages in excess of about 10 Gyr.

We know that the Galactic thin disk shows a mean abundance gradient of about -0.07 dex kpc^{-1}. Near the sun, the thin disk stars cover a wide age range, up to about 10 Gyr. Their age-metallicity relation (Figure 1) shows that stars of almost all ages up to about 10 Gyr cover a broad abundance range, with [Fe/H] values between about -0.7 to $+0.5$ and only a weak trend of increasing abundance with decreasing age. The current belief is that the most metal-rich thin disk stars near the sun did not form near the sun but rather formed in the more metal-rich inner Galaxy and migrated radially out to the solar neighborhood. Radial migration is a big issue in Galactic archaeology right now. It is believed to be driven by the torques of the Galactic bar and spiral arms, which can move stars radially from one near-circular orbit to another (Sellwood & Binney 2002), but we do not know how important radial mixing has been in determining the current state of the Galactic disk. This question can be answered using the techniques of Galactic archaeology.

Measuring stellar ages is a vital part of Galactic archaeology. When we identify the fossil relic stars of dispersed star forming event, we will need to estimate their ages in order to build up a picture of the assembly of the Milky Way. Gaia will be an important part of such work. It will give us accurate stellar distances, and we can hope to measure the ages of the relics from their color-magnitude diagrams. Measuring accurate ages for individual stars is still difficult at the present time. Near the sun we can use subgiants and stars near the main sequence turnoff, for which

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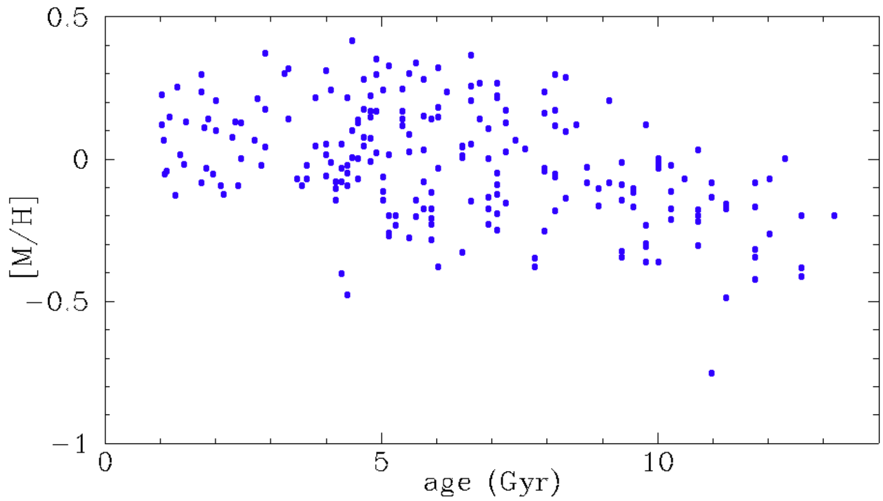

Figure 1: The Age-Metallicity relation for subgiants near the sun (Wylie de Boer & Freeman, unpublished)

ages can be estimated from isochrones. These stars are too faint to study at larger distances, and we therefore know relatively little about the age-metallicity distribution of the disk away from the solar neighborhood. We can use giant stars to study the chemical properties of the disk at larger distances from the sun, but we cannot measure isochrone ages for giants. Asteroseismology ages for giants are not yet very accurate but will improve.

The bulge of our Galaxy is archaeologically interesting. Small boxy bulges like the bulge of the Milky Way are now not regarded as the products of mergers. They are believed to have formed about 8 Gyr ago via bar-forming and bar-buckling instabilities of the early disk. The disk forms an elongated bar structure at its center, which then buckles vertically and settles into the long-lived boxy shape. These instabilities of the disk redistribute the disk stars into the bulge. The different components of the early inner disk (thick disk, old thin disk, younger thin disk) end up trapped dynamically within the bulge structure. Their distribution within the bulge depends on their initial phase space distribution before the instability. We can see these components in the metallicity distribution function of the bulge stars (Figure 2). The same three components are seen all over the bulge, but their relative weights change with position in the bulge. In this way, the bulge provides a fossil image of the early inner Galaxy.

3. Galactic archaeology of disk substructure

The Galactic disk near the sun shows some kinematical clumping or substructure (Figure 3). These clumps represent stars that have some degree of common motion, and they are usually called stellar moving groups. The stars of the moving groups are all around us: they are seen as concentrations in velocity but not in position.

Some of these groups are the debris of old disrupted star clusters in the disk. Examples include the HR 1614 and Wolf 630 moving groups (De Silva et al 2007, Bubar & King 2010). These groups are now dispersed into extended regions of the Galaxy, and their stars are chemically homogenous and have common ages. These particular groups are about 2 Gyr old but still retain some kinemati-

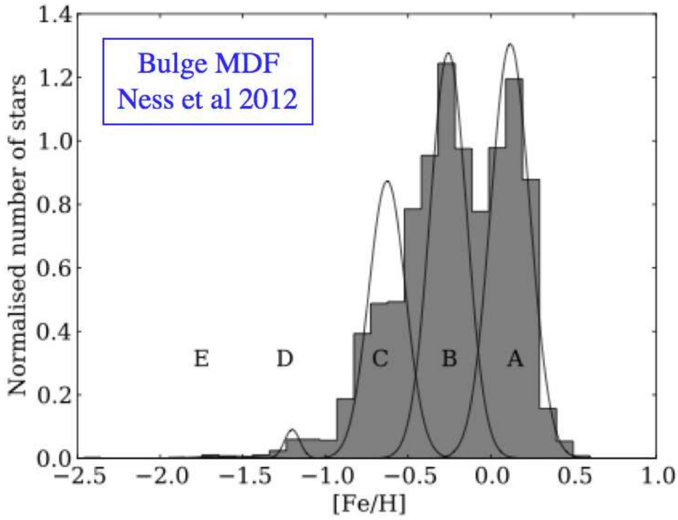

Figure 2: The metallicity distribution function for the Galactic bulge. Ness et al (2012) propose that component C comes from the stars of the early inner thick disk, B from the inner thin disk and A from the cold metal rich part of the thin disk which is dynamically very responsive. Two more metal-poor components D and E are also present: they are believed to come from the metal-poor thick disk (D) and the inner halo (E).

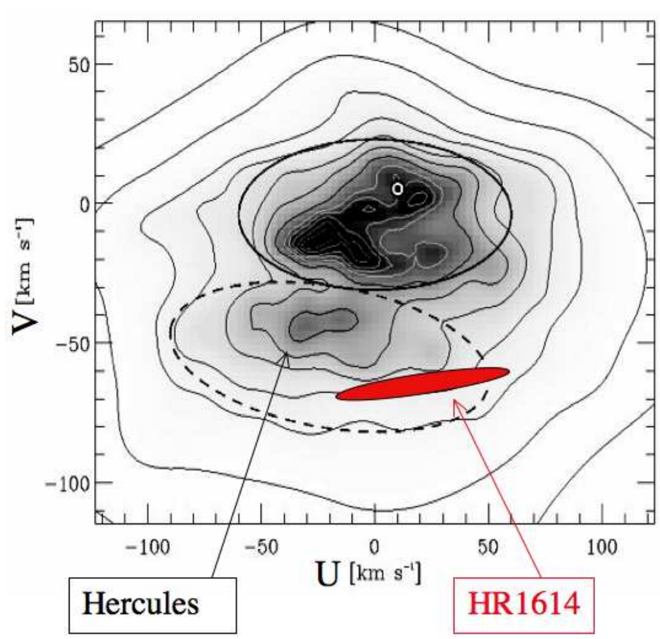

Figure 3: The density distribution of stellar kinematics of stars near the sun (adapted from Dehnen 1999). U and V are the stellar velocity components in the radial and azimuthal directions respectively, relative to the Local Standard of Rest. The substructure near (0,0) is dominated by relatively young stars. The Hercules feature and the HR 1614 moving group are labelled: see text.

cal identity. We can expect to find many older groups of this kind which have lost their kinematical identity but still preserve their chemical identity. These are the relics of the star formation history of the Galaxy, and are of great interest for Galactic archaeology.

Other moving groups are associated with dynamical resonances associated with the pattern speed of the Galactic bar or spiral structure. The Hercules group seen in Figure 3 is an example. Its stars are chemically a typical sample of the nearby disk, with a wide range of chemical abundances. These dynamical groups are of limited interest for Galactic archaeology.

Some moving groups may be the debris of infalling dwarf galaxies which were accreted by the Milky Way and were then tidally disrupted. Such events are commonly seen in CDM simulations of galaxy formation. Part of our goal is to identify such debris using chemical techniques, even if the debris has lost its kinematical identity, because this provides a way to make a direct estimate of the accretion history of the Milky Way.

In summary, although the disk does show some surviving kinematic substructure in the form of moving stellar groups, a lot of dynamical information was lost in the the subsequent heating and radial mixing by spiral arms and giant molecular clouds. Groups like the HR 1614 group are rare examples of dispersed clusters which are still identifiable both chemically and kinematically, although not spatially. Most older dispersed aggregates would not now be recognizable dynamically and chemical techniques provide the only way to recognize their debris. Using element abundance information in this way is called *chemical tagging*. The technique has not yet been widely used, but here is a recent example in which chemical techniques are used to help identify stars which appear to have been born together, and to work out what kind of parent object they came from.

Wylie de Boer et al (2012) used chemical tagging techniques to identify the nature of the Aquarius stream (Williams et al 2011). This is a stream of halo stars identified from the RAVE survey. The stars appear to be coming directly towards the sun from near $l = 50^\circ,\ b = -60^\circ$, and the stream extends along the line of sight from 200 pc to 10 kpc. The question is whether the stream is the debris of a disrupted globular cluster or a dwarf galaxy. From its chemical properties, the stream appears to be the debris of a globular cluster. Its stars are homogeneous in heavy elements, with a dispersion in [Fe/H] of 0.09 dex. They show the Na-O anticorrelation that is seen in almost all globular clusters. The distribution of the stream stars in the Ni-Na plane (Figure 4) is different for globular clusters and dwarf spheroidal galaxies (this is believed to come from the slower star formation rate in dSph galaxies than globular clusters). The Aquarius stream stars appear to be more consistent with globular cluster debris than with the dSph galaxies.

4. Chemical Tagging

The idea of chemical tagging is to use the detailed chemical abundances of stars to tag or associate them to common ancient star-forming aggregates whose stars have similar abundance patters (Freeman & Bland-Hawthorn 2002). The detailed abundance pattern over many elements reflects the chemical state of the gas from which the aggregate formed. In this way, chemical studies of the stars in the Galactic disk can help to identify stars that are part of the debris of common dispersed star-forming aggregates, and also those which came in from outside in disrupting satellites.

A vital part of the chemical tagging process is that star clusters are known to be chemically homogeneous in the heavier elements, to the level of precision with which it is presently possible

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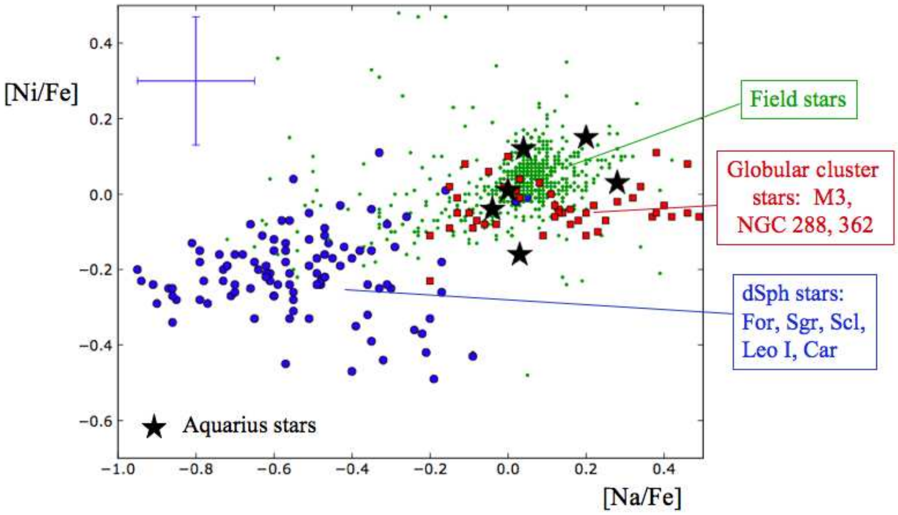

Figure 4: The Na-Ni distribution for globular cluster stars, dwarf spheroidal galaxy stars, field halo stars and stars of the Aquarius stream (black star symbols) (Wylie de Boer et al. 2012). The stars of the Aquarius stream are in the same part of the distribution as the globular cluster stars.

to measure (e.g. De Silva 2009, Pancino et al 2009). The element abundances within individual clusters have observed dispersions that are significantly less than 0.1 dex. This should make it relatively easy to identify the debris of disrupted star clusters via chemical tagging.

As a guide to what to expect for the abundance distributions of disrupted dwarf galaxies, we can look at the element abundances in surviving dwarf spheroidal galaxies. This is more complex (e.g. Venn et al. 2008). The accreted dwarf galaxies underwent a period of chemical evolution before they were captured and disrupted by the Galaxy. Each appears to have had a different star formation history. The [Fe/H] abundance range of the stars is different from galaxy to galaxy, according to the usual mass-metallicity relation for dwarf galaxies. The distribution of their stars in the [X/Fe]–[Fe/H] plane is well defined for an individual galaxy but differs in structure from galaxy to galaxy, depending on their star formation history. (Here X is the abundance of some element other than Fe.)

We can think of a chemical space (C-space) of abundances of elements: e.g. Na, Mg, Al, Ca, Mn, Fe, Cu, Zr, Ba, Eu . . . . With the HERMES instrument, abundances for up to about 30 elements will be measurable. Not all of these elements vary independently from star to star; many vary together in near-lockstep. The dimensionality or number of independent dimensions of this chemical space is 8 to 9 (Ting et al. 2012).

Most disk stars inhabit a sub-region of this space. Stars that came from chemically homogeneous aggregates like dispersed clusters will lie in tight clumps in C-space. Stars which came in from satellites will lie on tracks in C-space which are different from each other and may be different enough to stand out from the stars of the Galactic thin and thick disks.

With this chemical tagging approach, we will be able to reconstruct old dispersed star-forming aggregates in the Galactic disk, and may be able to put observational limits on the satellite accretion history of the Galaxy. This kind of chemical tagging experiment needs a high resolution spectro-

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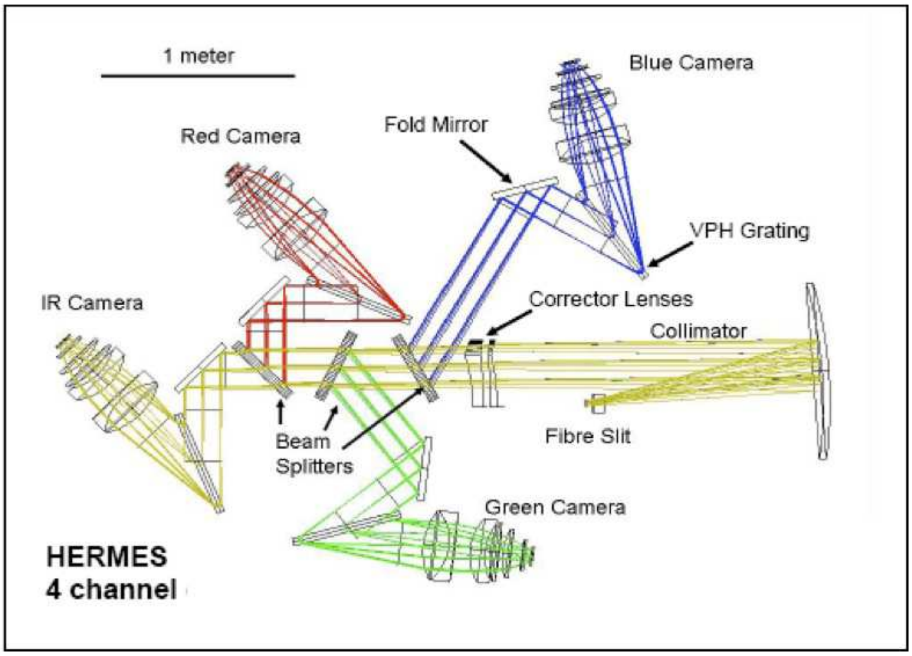

Figure 5: Optical design of the HERMES four-band high-resolution spectrograph

scopic survey of about a million stars (see section 6), homogeneously observed and analysed. This is the prime science driver for HERMES.

An important goal of the GALAH survey is to identify how significant mergers and accretion events were in building up the Galactic disk and bulge. Cold Dark Matter simulations predict a high level of merger activity, which conflicts with some observed properties of disk galaxies. The observational goal of the survey is to find the debris of groups of stars, now dispersed, that were associated at birth, either because they were born together in a single Galactic star-forming event, or because they came from a common accreted galaxy.

5. HERMES

HERMES is a new high resolution fiber-fed multi-object spectrometer on the AAT. It has two resolution modes (resolving power 28,000 and 45,000), and four non-contiguous spectral bands covering a total of about 100 nm between about 470 nm and 790 nm. The bands were carefully chosen to permit the measurement of abundances of as many elements as possible from the major element groups and nucleosynthetic processes. The fiber positioner is the existing 2-degree field positioner, with about 390 fibers over π square degrees. First light at the telescope is expected in early 2013. The optical layout is shown schematically in Figure 5. The instrument has a single collimator and four VPH gratings and cameras, with the bands separated by dichroic beam splitters. Each camera has a 4×4K E2V CCD detector. The wavelengths of the individual bands are given in Table 1.

Band	λ_{min}	λ_{max}
Blue	471.8	490.3 nm
Green	564.9	587.3 nm
Red	648.1	673.9 nm
IR	759.0	789.0 nm

Table 1: Wavelength intervals for the four HERMES bands

	Dwarf	Giant
Thin disk	0.58	0.19
Thick disk	0.11	0.07
Halo	0.02	0.03

Table 2: Fractional contribution to the GALAH sample from Galactic components

6. Galactic archaeology with HERMES

We are planning a stellar survey (the GALAH survey) of about a million stars, using the HERMES instrument. The faint limit for the survey is $V = 14$, chosen to match the typical stellar density to the fiber density. The survey will cover about half of the accessible sky, with $|b|$ greater than about 10°. The instrument specifications are to give spectra with SNR = 100 per resolution element (R = 28,000) at $V = 14$ in a one-hour exposure. The program would then take about 400 clear bright nights.

The details of the actual survey, like the adopted resolution, the exposure times, and the galactic fields, depend on how well the instrument works, which we will not know until it is on the telescope. The primary motivation for the survey is the chemical tagging experiment described above. We can be sure, however, that a sample of a million stars, with high resolution spectra, uniformly reduced and analysed, and with accurate radial velocities from HERMES and accurate parallaxes and proper motions from Gaia, will be an invaluable long term resource for a huge range of Galactic and stellar science, much of which we have not yet thought of.

The stars in such a survey will have a double-peaked temperature distribution, with one peak dominated by stars near the main sequence turnoff and the other by clump giants. Table 2 shows the expected fractional contribution from the giants and dwarfs from each of the main Galactic components. The old disk dwarfs are seen out to distances of about 1 kpc, the clump giants to about 5 kpc, and the brightest halo giants to about 15 kpc.

Our goal is to identify debris of disrupted clusters and dwarf galaxies. Assume that these objects disrupted long enough ago so that their debris is now azimuthally mixed right around the galaxy. The GALAH survey has a horizon which depends on the type of star. About 9% of the thick disk stars and about 14% of the thin disk stars pass through our 1 kpc dwarf horizon, and we are assuming that all of the disrupted objects whose orbits pass through a ± 1 kpc-wide annulus around the Galaxy at the solar circle are represented within our horizon.

Simulations (Bland-Hawthorn & Freeman 2004, Bland-Hawthorn et al. 2010) show that a random sample of a million stars with $V < 14$ will allow detection of about 20 thick disk dwarfs from each of about 3000 star formation sites, and about 10 thin disk dwarfs from each of about 30,000 star formation sites. These numbers are indicative only and depend on the upper and lower mass limits for the mass spectrum of the disrupted objects. A smaller survey would mean less stars from a similar number of star formation sites.

Is it possible to detect the debris of about 30,000 different star formation sites, using chemical tagging techniques ? Are there enough independent cells in C-space to make this possible ? The answer appears to be yes. We would need about 7 independent chemical element groups, each with about 5 measurable abundance levels, to get enough independent cells (i.e. 5^7: 4^8 would also be sufficient). The abundance spread in each of the thin and thick disks is at least 0.5 dex, and we expect to be able to measure the element abundances differentially to an accuracy of about 0.05 dex, giving more than 10 measurable abundance levels. The dimensionality of chemical space is now known to be 8 to 9, and we discuss this further in the next section.

6.1 The dimensionality of the GALAH chemical space

We expect to be able to measure abundances for at least 25 elements (Li, C, O, Na, Al, K; Mg, Si, Ca, Ti; Sc, V, Cr, Mn, Fe, Co, Ni, Cu, Zn; Y, Zr, Ba, La, Nd, Eu), with a few more elements in some stars. The HERMES spectral bands (BGRI) were chosen to ensure measurable lines of these elements, which represent most of the major element groups and nucleosynthesis processes. The bands also include the Hα and Hβ lines.

The variation of these elements from star to star is highly correlated, and the number of independent dimensions of this C-space is much less than 25. Ting et al. (2012) made a principal component analysis (PCA) of element abundances from catalogs of metal-poor stars, metal-rich stars, open clusters and also of stars in the Fornax dSph galaxy. The PCA included detailed simulation of the effects of observational errors, element by element, on the apparent dimensionality of the C-space. The outcome is that the HERMES C-space has dimensionality of 8 to 9 for all these samples, but the principal components change from sample to sample.

The principal components are vectors in the C-space of the element abundances [X/Fe], and these vectors are identifiable with nucleosynthetic processes. The principal components are eigenvectors of the correlation matrix, and are all orthogonal in the C-space: therefore the higher components are projections on hyperplanes normal to the more prominent components.

The number of significant principal components is similar for metal-rich and metal-poor stars, but the actual components are different. The structure of the main components reflects the dominant nucleosynthetic processes for each sample (see Ting et al. 2012 for a detailed discussion). The interpretation of the first principal component (the component with the largest eigenvector) is clear, but it is not so obvious for the others because of the projection.

For example, for the sample of low-metallicity stars with $-3.5 <$ [Fe/H] < -2 (excluding the carbon-enhanced metal-poor stars), the first principal component includes all of the n-capture elements and the alpha-elements. It is probably related to core-collapse SN producing alpha-elements plus the r-process contribution to n-capture elements. The second component shows an anticorrelation of alpha-elements with Fe-peak and n-capture elements, and may be related to "normal" core-collapse SN which do not contribute to the r-process.

The Ting et al. (2012) PCA components are based on samples of a few hundred stars which had not always been homogeneously analysed. The homogeneously observed and analysed GALAH

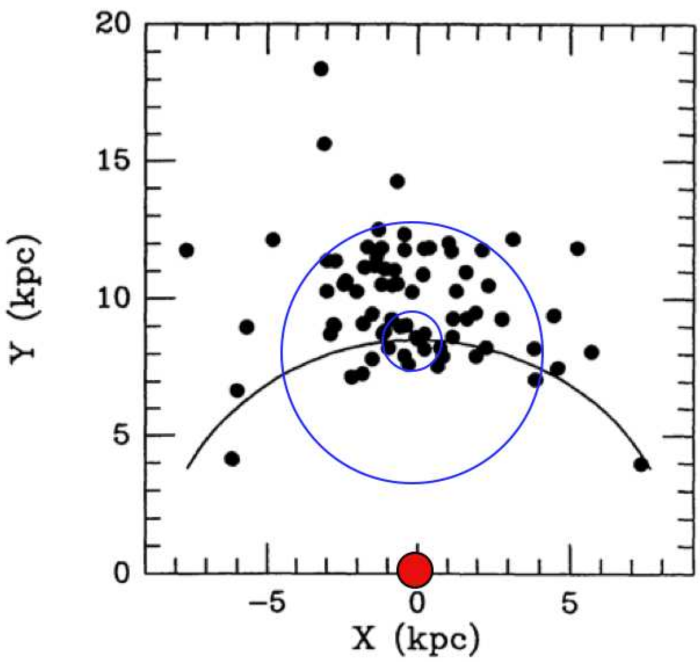

Figure 6: The location of old open clusters projected on to the Galactic plane. The red circle shows the Galactic center. The sun is at the center of the blue circles. The smaller blue circle shows the horizon for HERMES old turnoff stars, and the larger circle shows the horizon for clump giants. Most of the older clusters in the inner disk have been disrupted. The sample of HERMES clump giants in the inner disk is expected to include the debris of many disrupted clusters. Adapted from Friel (1995).

sample of about a million stars will help to delineate the nature of the principal components more clearly.

Ting et al. also compared the C-space for open clusters, which have Galactocentric radii from 6 to 20 kpc, with the C-space for metal-rich stars in the solar neighborhood. The C-space for the clusters has about one more dimension that the stars near the sun. We may find for the GALAH sample that the C-space for the more widely distributed giants (see Figure 6) has more dimensions than the C-space for the dwarfs, which cover a smaller area of the Galaxy, similar to the area covered by the Ting metal-rich sample.

7. Chemical tagging in the inner Galactic disk

Although young open clusters are present in the inner Galaxy, the old ($>$ 1 Gyr) surviving open clusters lie mostly in the outer Galaxy, beyond a radius of about 8 kpc (Figure 6). The absence of old open clusters in the inner Galaxy is usually attributed to the stronger disruptive influence of the Galactic tidal field and interactions with giant molecular clouds in the inner Galaxy. This suggests that we may expect to find the relics of many disrupted open (and globular) clusters in the inner disk. The inner disk may then be a good place to apply chemical tagging techniques to recover cluster debris, using GALAH giants in the inner disk. We expect about 200,000 survey giants to lie in the inner regions of the Galaxy.

Disrupted clusters will provide a strong test of the importance of radial mixing for the evolution of the disk. Open clusters are on near-circular orbits when they are young. In the absence of radial mixing effects, their dispersed debris would still be on near-circular orbits and be confined to a fairly narrow annulus around the Galaxy. On the other hand, the influence of radial mixing would be to spread the debris of individual clusters over a larger range in radius. In this way, the radial extent of the chemically tagged debris of disrupted clusters of various ages will give a direct measure of how much radial mixing has actually contributed to the evolution of the Galaxy.

The Na/O anticorrelation is unique to globular clusters, and will help to identify the debris of disrupted globular clusters

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