OPEN CLUSTERS AND THE GALACTIC METALLICITY DISTRIBUTION

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ABSTRACT

We compiled an open cluster catalogue, having 119 objects with ages, distances and metallicities available. From this sample a Galactic disc iron radial gradient of about -0.063 ± 0.008 dex kpc^{-1} was derived, which is quite consistent with the most recent determination of oxygen gradient from nebulae and young stars. By dividing clusters into age groups, we show that iron gradient was steeper in the past, which is consistent with the recent result from Galactic planetary nebulae data, and also consistent with inside-out galactic disc formation scenarios. Based on our clusters sample, no significant evidence was found for the existence of AMR in the Galactic disc.

Key words: Galaxy: evolution; Galaxy: formation; Open clusters: general.

1. INTRODUCTION

Since the seminal work of Eggen et al. (1962), great progress has been made in understanding the formation and evolution of the Milky Way galaxy. The progress comes, on one side, from observations concerning chemical abundances in stars (and clusters), gas clouds and, on the other side, from improved knowledge relevant to galaxy formation and evolution.

In the last decade, a number of successful models have been developed relating to the chemical evolution of the Milky Way galaxy, but some important differences exist. One of them concerns the history of abundance gradients along the Galactic disc: were they steeper or flatter in the past? Different predictions were made by various models, although most of them claim that they could reproduce the majority of the observational properties both in the solar neighbourhood and on the whole disc.

Neither is the situation settled observationally. Estimated ages of various types (PNI, PNII, PNIII) of planetary nebulae (PN) span a large fraction of the age of the Galaxy. Observations of the abundances of those objects across the Milky Way disc could, in principle, provide some information on the time evolution of the abundance gradient (Maciel & Köppen 1994; Maciel & Quireza 1999; Maciel & Costa 2002).

On the other hand, open clusters (OCs) have long been used to trace the structure and evolution of the Galactic disc (Friel 1995). Since open clusters could be relatively accurately dated and we can see them to large distance, their [Fe/H] values serve as an excellent tracer to the abundance gradient along the Galactic disc as well as many other important disc properties, such as Age-Metallicity Relation (AMR), abundance gradient evolution, disc age and so on (Carraro et al. 1998).

In this paper, we compiled an open cluster catalogue, having 119 objects with ages, distances and metallicities available. This could provide statistically more significant information to the Galactic disc formation and evolution, such as the age-metallicity relation, abundance gradient and its time and/or spatial evolution.

2. ABUNDANCE GRADIENT FROM OPEN CLUSTERS

2.1. The Abundance Gradients

The first radial metallicity gradient using open clusters was given by Janes (1979) based on DDO and UBV photometric data of 41 disc objects. The derived gradient is -0.05 dex kpc^{-1}. Panagia & Tosi (1981), by matching theoretical isochrones to HR diagrams of 20 clusters with age less than 1 Gyr, derived an iron abundance gradient of -0.095 dex kpc^{-1}. A similar result was also obtained by Cameron (1985) based on 37 clusters with mixed ages.

By introducing a weighting system in order to evaluate and compare the published parameters in the Lyngå (1987) Catalogue of Open Clusters data, Janes et al. (1988) determined some basic parameters of 413 open clusters, such as ages, distances, linear diameters and so on. Among them, 87 open clusters have metallicity data. They have derived a gradient about -0.133 dex kpc^{-1}. By separating the clusters into age groups, it is found that young clusters have a much smaller gradient than that of older clusters. Besides, all those authors found some indications that the gradient became shallower in the direction of the Galactic centre and steepened in the outer parts of the Galaxy.

Friel & Janes (1993, hereafter FJ93) presented their results from a spectroscopic study of a sample of giant stars in 24 open clusters. They derived a galactocentric radial abundance gradient of [Fe/H] of about -0.088 dex kpc^{-1}. A subsequent revision of the FJ93 result was presented by Friel (1995), using additional spectroscopic results and a more uniform set of cluster properties. From a sample of 44 clusters, Friel (1995) derived an iron gradient of -0.091 dex kpc^{-1}. At the same time, Piatti et al. (1995) derived a much smaller gradient, -0.07 dex kpc^{-1}, from a sample of 63 open clusters with a wide range of ages. These results are quite consistent with the recent revision of Friel (1999) to their earlier data. Another gradient result was recently presented by Carraro et al. (1998). The metallicities of all selected 37 clusters were obtained spectroscopically. The final gradient was about -0.085 dex kpc^{-1}, agreeing with earlier result of FJ93. By dividing the sample into age bins, it was found that the present-day gradient is a little shallower than the past one, while the middle epoch seems to display a steepening of the gradient.

The presence of a linear gradient for open clusters has been questioned by Twarog et al. (1997, hereafter TAA97). TAA97 put forth an alternative description, namely, step function, for the radial abundances distribution of the open clusters. Within their work, a set of 76 clusters with abundances based upon DDO and/or moderate dispersion spectroscopy has been transformed to a common metallicity scale and used to study the local structure and evolution of the Galactic disc. They found that the metallicity distribution of clusters with Galactocentric distance is best described by two distinct zones, with a sharp discontinuity at $R_{GC} = 10$ kpc. Between R_{GC} = 6.5 kpc and 10 kpc, the clusters have a mean metallicity of 0.0 dex with, at best, weak evidence for a shallow gradient over this range, while those beyond 10 kpc have a mean value of about -0.30 dex. This two-step distribution seems quite similar with the nebula results of Simpson et al. (1995). However, a careful check with cluster ages shows that the sample inside 10 kpc is heavily weighted towards clusters younger than 1 Gyr, while the outer clusters are predominantly older. Neglecting this two-step phenomena, a least square fitting results in a gradient about -0.067 dex kpc^{-1} between 6 and 15 kpc if cluster BE21 was excluded (because both metallicity and distance of this object are quite uncertain).

The existence of radial iron abundance gradients is also confirmed by our new up-to-date sample. The result is shown in Figure 1a. By equal-weighted least-square fitting, we derived a radial abundance gradient of -0.063 ± 0.008 dex kpc^{-1}, which agrees well with most of the previous open cluster results. And it is also similar to the gradients obtained from other tracers (see a summary in Hou et al. (2000)). The existence of a gradient along the Galactic disc provides a good opportunity to test theories of disc evolution and stellar nucleosynthesis. It suggests that the role of the Galactic bar in inducing large-scale radial mixing and therefore flattening the gradient has been rather limited; alternatively, the bar could be too young ($<$1 Gyr) to have brought any important modifications to the gaseous and abundance profile. However, we must note that our current knowledge of the iron gradient as derived from open clusters is far from being clear. Open clusters span a wide range of ages, from several millions

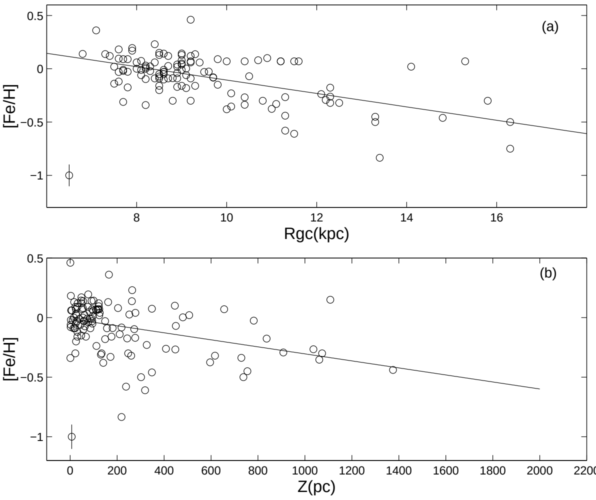

Figure 1. (a) Radial and (b) vertical abundance gradient for 118 open clusters. The least-square fitting results in a gradient of -0.063 ± 0.008 dex kpc^{-1} and -0.295 ± 0.050 dex kpc^{-1}, respectively. The typical error bar for [Fe/H] is about 0.1 dex, as shown in the lower left corner of the figures. When deriving the vertical gradient, the radial gradient has been corrected.

of years to several Gyr; therefore, they do not trace the young component of the Galactic disc. The result we obtained is somewhat an averaged one (over age). The obtained similarity of gradients between iron and other elements, such as oxygen, is quite surprising, since the sites of nucleosynthesis for iron and oxygen are quite different. It is well known that iron is mainly produced in Type Ia supernovae (SNe Ia), while oxygen is largely a product of SNe II, that is, from massive stars. So the abundance history is very different for those two types of elements. The gradient similarity might be simply coincidental, but further investigation should be made into the nature of the production of those elements.

We also derived a vertical abundance gradient of -0.295 ± 0.050 dex kpc^{-1} (Figure 1b). This is consistent with the result of Carraro et al. (1998).

2.2. Gradient Evolution

The behavior of gradient evolution along the Galactic disc is a major problem for different chemical evolution models. An open cluster system is an ideal template for this analysis because OCs have relatively well determined ages, distances and metallicities. In Figure 2a, we show gradients for two sub-samples with cluster age $<$ 0.8 Gyr (80 clusters) and $\geq$ 0.8 Gyr (38 clusters), respectively. The fitting results are -0.024 ± 0.012 dex kpc^{-1} for younger clusters, -0.075 ± 0.013 dex kpc^{-1} for older ones. If we take the mean age for the youngest and oldest clusters as 0.00 Gyr and 6.00 Gyr, respectively, (this is somewhat arbitrary, just for illustration purpose) in our sample, we can estimate an average flattening rate of 0.008 dex kpc^{-1}Gyr^{-1} during the past 6 Gyr. This rate is quite consistent with that from recent PN data for

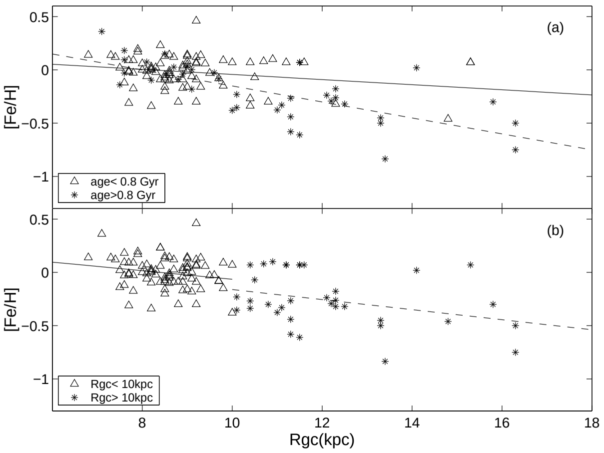

Figure 2. (a) Time evolution of the iron gradient. Triangles show clusters with age less than 0.8 Gyr, stars show clusters with age greater than 0.8 Gyr. The gradients are -0.024 dex kpc^{-1} and -0.075 dex kpc^{-1}, respectively. (b) Gradients for inner disc (within 10 kpc) and outer disc clusters. The corresponding gradients are -0.040 dex kpc^{-1} and -0.047 dex kpc^{-1}, respectively.

[O/H] (Maciel & Costa 2002; Maciel et al. 2002), and is also in good agreement with the model result of Hou et al. (2000) who derived a flattening rate for [Fe/H] of about 0.006 dex kpc^{-1}Gyr^{-1} for the last 10 Gyr.

The time evolution of the abundance gradient along the Galactic disc is crucial in discriminating different theoretical models that adopt various prescriptions for the time dependence of the star formation rate and the infall. Our current open cluster sample could surely provide some insights on this subject. The time-flattening tendency we obtained supports the inside-out disc formation scenarios, with infall timescale dependent on radius from the disc centre (Boissier & Prantzos 1999; Hou et al. 2000; Chang et al. 2002).

In Figure 2b, we divide clusters into inner (< 10 kpc) and outer groups. The corresponding gradients are -0.040 ± 0.022 dex kpc^{-1} and -0.047 ± 0.023 dex kpc^{-1}, respectively. We can see that the inner disc exhibits roughly the same (or a bit smaller) gradient as the outer part. This result is also consistent with the abundance gradient determined by using Cepheids in the solar neighbourhood (Andrievsky et al. 2002). However, in our sample, the innermost cluster is located at a galactic-centre distance of about 6.8 kpc, so it is necessary to have more inner clusters data (between 3 kpc and 7 kpc) in order to further check the gradient behavior for the inner disc. If the Galactic bar does play the role, then the inner gradient could be flatter than the outer part.

Our cluster sample is nearly 50% more than that of TAA97, and we did not find evidence of any abrupt discontinuity. A similar conclusion was reached by Friel (1999), using high-resolution abundance determinations for metallicity calibration.

3. AGE-METALLICITY RELATION

The age-metallicity relation (AMR) for the Galactic disc provides useful clues about the chemical evolution history of the Milky Way, and also puts an important constraint on the theoretical models of the disc. The observed abundance data generally show a decrease of the stellar metallicity with increasing stellar age, indicating a continuous growth of the metals in the ISM during the life of the Galaxy. The early study on AMR for nearby stars by Twarog (1980) found that the mean metallicity of the disc increased by a factor of five between 12 and 5 billion years ago and has increased only slightly since then. This was also confirmed by latter photometric survey of Meusinger et al. (1991). With the high resolution spectroscopic data, Edvardsson et al. (1993) showed a plot of iron abundance versus relative ages for the 189 stars in the solar neighbourhood. The overall trend of a slowly increasing abundance with decreasing age was consistent with the previous photometric results. However, the most striking feature of their result is the large scatter around the average trend, which marks a weak correlation between age and metallicity. This spread was, as they pointed out, in part due to selection bias for the programme stars, and at least partly intrinsic, since the mean errors in [Fe/H] measurement and logarithmic age derivation are much less than the scatter.

In a recent paper, Feltzing et al. (2001) have re-examined the Galactic AMR in the solar neighbourhood based on a sample of 5828 dwarfs and sub-dwarfs from the Hipparcos Catalogue. They found that the solar neighbourhood age-metallicity diagram is well populated at all ages and especially that old, metal-rich stars do exist, which have been omitted in previous samples. This indicates a complete lack of enrichment over the age of Galactic disc among the fields stars in the solar neighbourhood.

Using open clusters to explore the AMR has the main advantage both in abundance and age determinations since one is dealing with a group of stars and the result is less susceptible to individual errors (Carraro et al. 1998). Cameron (1985) was the first to probe the AMR from open cluster data, and found no age-metallicity relation based on his cluster sample. This is not surprising since the metallicity of the Galactic disc increased only slightly during the past 5 Gyr, while his sample of 38 clusters contained no objects older than 5.1 Gyr. More recently, Carraro et al. (1998) compiled a relatively homogenous sample of 37 open clusters. The data have more expanded cluster ages up to 9 Gyr. After correcting for the radial abundance gradient, the derived AMR showed a similar trend to that of nearby stars.

In this paper, we present a new open cluster catalogue with much more objects. The results, based on this larger sample, would be statistically more reliable. The derived AMR, already corrected by a radial metallicity gradient, independent of age, is plotted in Figure 3. Unfortunately, it is difficult to draw any conclusive indication for AMR based on this plot because of the deficiency of very old clusters. More observational efforts should be made to find more older clusters.

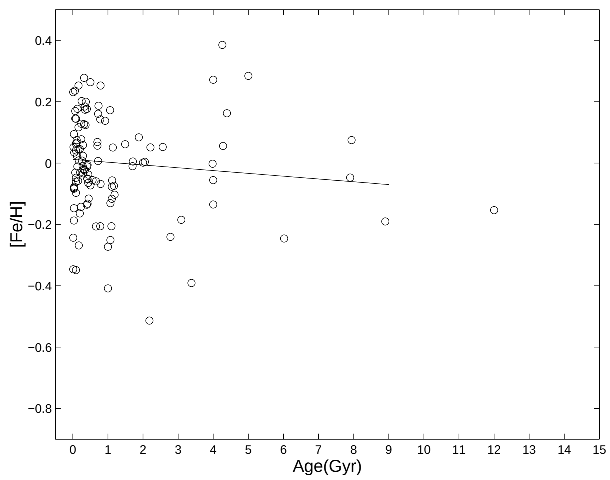

Figure 3. Age-Metallicity Relation (AMR) for the 118 open clusters after correcting for the radial gradient. The solid line is a least-square fitting for the open cluster data.

The significant spread of the AMR seems real, but its origin is not yet clear. For the scatter in the AMR of nearby stars, many possible causes have been suggested, such as orbital diffusion of stars, inhomogeneous chemical enrichment in the Galaxy evolution, overlapping of different galactic substructures and so on. All the above mentioned effects may contribute the observed scatter, while for open clusters, the result should not be very sensitive to orbital diffusion effects (Corder & Twarog 2001). Therefore, the scatter of AMR along the Galactic disc from both clusters and field disc stars is an essential feature in the formation and evolution of the Milky Way.

4. SUMMARY

We derived an iron radial gradient about -0.063 ± 0.008 dex kpc^{-1} based upon a newly compiled open cluster sample, which is quite consistent with the most recent determination of oxygen gradient in nebulae and young stars. By dividing clusters into age groups, we show that iron gradient was steeper in the past, which is consistent with the recent result from Galactic planetary nebulae data. The spatial variation of the gradient was also explored. When the clusters were divided into inner and outer groups, we found that the abundance gradient was a bit shallower inside 10 kpc. But the innermost cluster in our sample is in R_{GC} = 6.8 kpc; we need more data of clusters in the inner region. This could be helpful to judge the radial flow effect on the current galactic chemical evolution model.

For the AMR, based on the new sample data, no strike slope in AMR was found, which is consistent with the previous results. This probably reflects that the star formation history is quite quiescent during the past 10 Gyr. However, the paucity of metallicity of very old open clusters made it impossible to give a definite conclusion based on the current sample.

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