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Letter to the Editor

The first chemical abundance analysis of K giants in the inner Galactic disc*

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ABSTRACT

Aims. The elemental abundance structure of the Galactic disc has been extensively studied in the solar neighbourhood using long-lived stars such as F and G dwarfs or K and M giants. These are stars whose atmospheres preserve the chemical composition of their natal gas clouds, and are hence excellent tracers of the chemical evolution of the Galaxy. As far as we are aware, there are no such studies of the inner Galactic disc, which hampers our ability to constrain and trace the origin and evolution of the Milky Way. Therefore, we aim in this study to establish the elemental abundance trend(s) of the disc(s) in the inner regions of the Galaxy.

Methods. Based on equivalent width measurements in high-resolution spectra obtained with the MIKE spectrograph on the Magellan II telescope on Las Campanas in Chile, we determine elemental abundances for 44 K-type red giant stars in the inner Galactic disc, located at Galactocentric distances of 4–7 kpc. The analysis method is identical to the one recently used on red giant stars in the Galactic bulge and in the nearby thin and thick discs, enabling us to perform a truly differential comparison of the different stellar populations.

Results. We present the first detailed elemental abundance study of a significant number of red giant stars in the inner Galactic disc. We find that these inner disc stars show the same type of chemical and kinematical dichotomy as the thin and thick discs show in the solar neighbourhood. The abundance trends of the inner disc agree very well with those of the nearby thick disc, and also to those of the Bulge. The chemical similarities between the Bulge and the Galactic thick disc stellar populations indicate that they have similar chemical histories, and any model trying to understand the formation and evolution of either of the two should preferably incorporate both of them.

Key words. Galaxy: disk – Galaxy: bulge – Galaxy: formation – Galaxy: evolution – stars: abundances

1. Introduction

The inner Galactic disc is one of the least studied regions of the Milky Way because of high interstellar extinction and contamination by background Bulge stars. Apart from a few studies of bright hot OB stars (e.g., Daflon & Cunha 2004) and Cepheids (e.g., Luck et al. 2006), which both trace the most recent young disc stellar population, almost no information is available about the detailed abundance structure of the inner Galactic disc. Open questions are for instance, whether the inner Galactic disc shows the same clear kinematic and chemical dichotomy as the Galactic disc in the solar neighbourhood, where the thin and thick discs stand out as two distinct stellar populations?

Recent studies have revealed that the Galactic bulge and the Galactic thick disc have very similar abundance trends, which reflect similar, and possibly even shared, chemical histories (Meléndez et al. 2008; Bensby et al. 2009, 2010; Alves-Brito et al. 2010). A restriction of these studies is that their thick disc samples have been observed in the solar neighbourhood, and if the Bulge has a secular origin (e.g., Kormendy & Kennicutt 2004; Howard et al. 2009), models show that it likely has to be from gas and stars in the inner parts of the Galactic disc (e.g., Rahimi et al. 2010). Both the inner and the local disc will help us put constraints on how these Galactic components formed, if we can verify the existence of an inner Galactic thick disc and differentially compare it with the Bulge.

Here we will present the first results regarding detailed elemental abundances in 44 red giant stars that are located at 4–7 kpc from the Galactic centre. They have been analysed using the same method as in the recent study of red giants in the Bulge and nearby thin and thick discs by Alves-Brito et al. (2010). We will focus on four α-elements (Mg, Si, Ca and Ti) and omit most of the analysis details and results for other iron-peak elements for a coming publication.

2. Sample selection and observations

One of the caveats in trying to observe the inner Galactic disc in the direction of the Galactic centre is that it is very likely that the sample will be contaminated by background Bulge stars. However, by pointing towards regions on either side of the Bulge, contamination is avoided even if the estimated distances are greatly in error. Therefore, our targets are located at Galactic longitudes $330°-340°$ and $20°-30°$ (see left panel of Fig. 1).

* This paper includes data gathered with the 6.5 m Magellan Telescopes located at the Las Campanas Observatory, Chile.

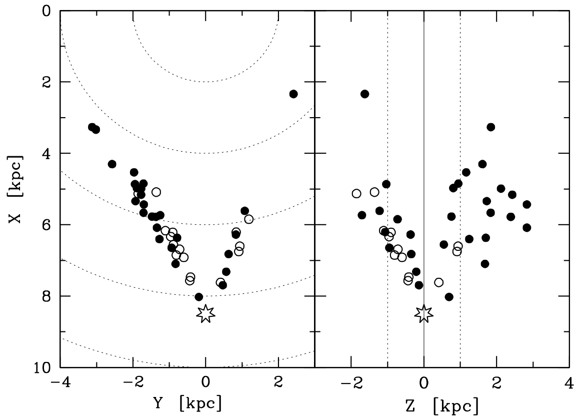

Fig. 1. The location of the stars in Galactic X, Y, and Z coordinates (distances based on spectroscopic parallaxes). Symbols as in Fig. 2.

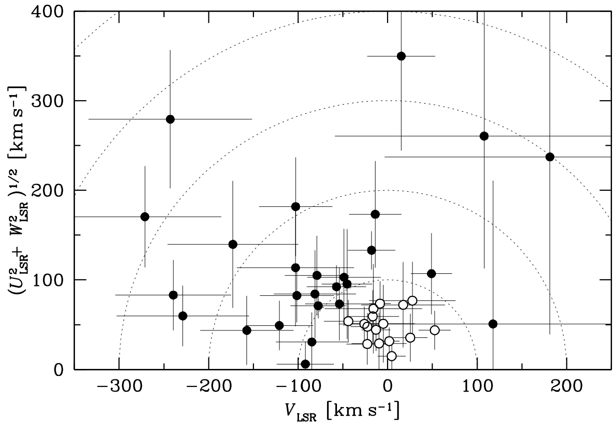

Fig. 2. Toomre diagram for 43 of the 44 stars (one does not have measured proper motions). Open circles indicate stars that move on more or less circular orbits confined to the plane ($v_{tot} < 85$ km s^{-1}), and filled circles those that move on orbits that are highly eccentric and/or reach far from the Galactic plane ($v_{tot} > 85$ km s^{-1}).

Because dwarf stars at these distances are too faint to be observed with high-resolution spectrographs we targeted bright red giants. There is a clear separation between dwarfs and giants in the de-reddened[1] $(J-K)$ and $(J-H)$ colour space (Bessell & Brett 1988), and we utilised the selection criteria of Majewski et al. (2003), who successfully selected distant K and M giants from the 2MASS catalogue. To make the sample as homogeneous as possible and use early spectral types (to avoid TiO bands that gets strong for later types), we selected stars with $0.85 < (J-K)_0 < 0.88$. This is the intrinsic colour for a K4 giant (Bessell & Brett 1988). The corresponding intrinsic $(V-K)$ colour for a K4 giant is 3.26 (Bessell & Brett 1988), and its absolute magnitude is $M_V \approx -0.45$ (Keenan & Barnbaum 1999), giving $M_K = -3.71$. The 2MASS Ks magnitudes were transformed to standard K magnitudes through $K = Ks + 0.044$ (Grocholski & Sarajedini 2002), and after correcting for extinction[1] the distances can be estimated using: $K_0 - M_K = -5 + 5\log d$.

We selected 44 K giants from the 2MASS catalogue that had estimated Galactocentric distances of 3-7 kpc. During two observing runs in 2007 May and July, high-resolution spectra were obtained for all 44 giants with the MIKE spectrograph at the Magellan II telescope on Las Campanas in Chile, using a 0.5″ wide slit. This resulted in spectra with $R \approx 55\,000$, covering the entire optical spectrum from 3500 to 10 000 Å. Typical signal-to-noise ratios are $S/N \approx 100$ pixel^{-1} at 6000 Å.

3. Analysis

Stellar parameters and elemental abundances were determined using exactly the same spectroscopic methods as outlined in Alves-Brito et al. (2010). In short, the analysis is based on equivalent width measurements and the ATLAS9 model stellar atmospheres by Castelli et al. (1997). The effective temperature ($T_{\rm eff}$) is found by requiring an excitation balance of the Fe I line abundances; surface gravity ($\log g$) by requiring ionisation balance between abundances from Fe I and Fe II lines; and the microturbulence (ξ_t) by requiring that the Fe I line abundances from are independent of reduced line strength.

We find that all stars have effective temperatures in the range $4000 < T_{\rm eff} < 4500$ K and surface gravities in the range $1 < \log g < 2.5$, i.e. typical of K giant stars. Typical uncertainties are 75 K in $T_{\rm eff}$, 0.3 dex in $\log g$, and 0.2 km s^{-1} in ξ_t, and $\sigma_{\rm [Fe/H]} = 0.14$, $\sigma_{\rm [Mg/Fe]} = 0.07$, $\sigma_{\rm [Si/Fe]} = 0.10$, $\sigma_{\rm [Ti/Fe]} = 0.13$, and $\sigma_{\rm [Ca/Fe]} = 0.14$ in the abundance ratios.

With spectroscopic stellar parameters at hand, "spectroscopic" parallaxes were re-calculated through

$$\log\pi = 0.5([g] - [\mathcal{M}] - 4[T]) - 0.2(K + BC_K - A_K + 0.25). \quad (1)$$

Here the notation $[X] \equiv \log(X/X_\odot)$, and the bolometric correction is given by $BC_K = -6.75\log(T_{\rm eff}/9500)$ (Buzzoni et al. 2010). We assume that the giants all have $\mathcal{M} = 1\,M_\odot$. Assuming that the uncertainties in the stellar parameters and the reddening correction are uncorrelated, the uncertainties in the distances are calculated to be 30%. Then we calculated the space velocities ($U_{\rm LSR}$, $V_{\rm LSR}$, and $W_{\rm LSR}$) using our spectroscopic parallaxes, the proper motions from the UCAC3 catalogue (Zacharias et al. 2010), and radial velocities as measured from the spectra. Uncertainties in the space velocities were calculated based on the assumption that the uncertainties in the distances and the proper motions are uncorrelated. Finally, Galactic orbits were calculated with the GRINTON integrator (Carraro et al. 2002; Bedin et al. 2006), which gives the minimum and maximum distances from the Galactic centre ($R_{\rm min}$ and $R_{\rm max}$), the maximum distance from the Galactic plane ($Z_{\rm max}$), and the eccentricity of the orbit (e).

4. Results and discussion

4.1. Distinct populations in the inner disc?

In the Toomre diagram in Fig. 2 the stars have been coded according to the simple assumption that those with $v_{tot} > 85$ km s^{-1} are thick disc stars, and those with lower velocities are thin disc stars (e.g., Fuhrmann 2004). Because we do not know the properties of the inner thick disc, the coding should not be taken literally. It is also obvious that the errors in the calculated space velocities make this classification uncertain. Hence, we just coded those stars that move on more circular orbits and those that have more kinematically hot orbits. Below we will call them kinematically hot stars (black circles) and kinematically cold stars (empty circles).

In Fig. 3a we see that stars with distances greater than 2.5 kpc from the Sun have consistently high [α/Fe] values ($\alpha \equiv$ (Mg + Si + Ti)/3)). These distant stars are all located around or more than 1 kpc from the plane (Fig. 1), and they are

[1] Extinctions were calculated as (A_K, $E(J-H)$, $E(J-K)$) = $(0.28, 0.34, 0.54)E(B-V)$, where $E(B-V)$ is from the maps by Schlegel et al. (1998), corrected using Eq. (1) of Bonifacio et al. (2000).

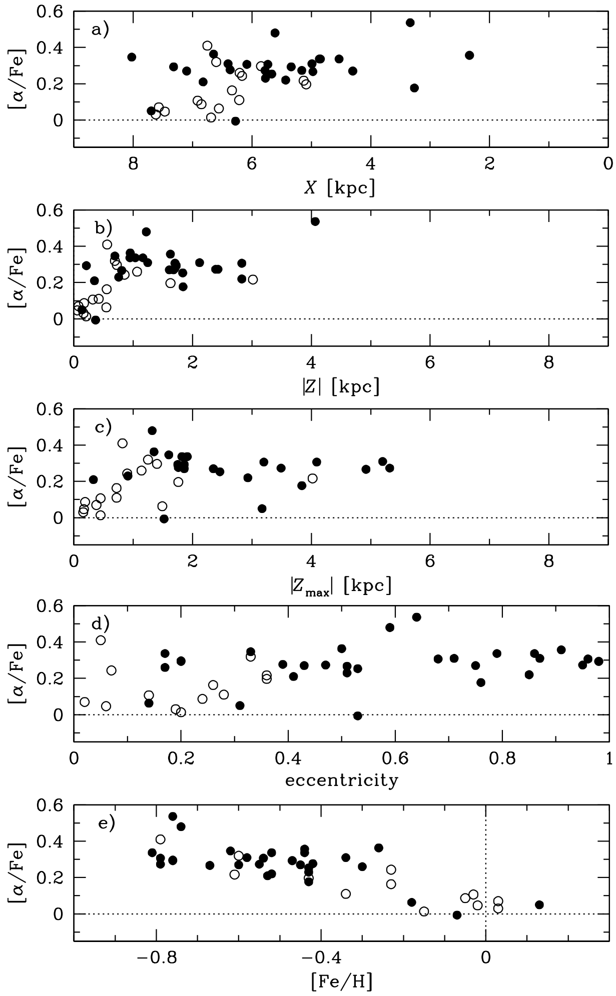

Fig. 3. [α/Fe] versus X, $|Z|$, $Z_{\rm max}$, e, and [Fe/H]. Symbols as in Fig. 2.

essentially all kinematically hot stars. Then we see in Fig. 3b that all stars located more than 1 kpc from the plane have high [α/Fe] values, and that most of these are kinematically hot stars. We also see a few kinematically hot stars that are located close to the plane and also have low [α/Fe] values. However, Fig. 3c shows that these stars have kinematic properties that allow them to reach as far as ∼2 kpc from the plane. At the same time, stars that are close to the plane, have low [α/Fe] values, and are kinematically cold, stay within 1 kpc from the plane. We also note that we have a few stars with high [α/Fe] values, which are kinematically hot, but which remain close to the the plane. These are stars that have highly eccentric orbits. Figure 3d then shows that stars that move on highly eccentric orbits all have high [α/Fe] values, and are all classified as kinematically hot. For stars with less eccentric orbits there is a gradual decrease in [α/Fe] as the orbits become more circular. With a few exceptions, the stars with the least eccentric orbits have the lowest [α/Fe] values. Figure 3e shows that stars with low [Fe/H] have high [α/Fe], with a flat trend that eventually starts to decrease for metallicities higher than [Fe/H] ≈ -0.3. Also, the stars with cold kinematics generally have higher [Fe/H] and lower [α/Fe].

These connections and correlations between kinematics and chemistry that we see for the inner disc sample is what we see for disc stars in the solar neighbourhood. Stars with orbits that are highly eccentric and/or reach far from the plane generally have high [α/Fe] values, and those on more circular orbits, which stay closer to the plane, have low [α/Fe] values. Stars with these properties are generally classified as thick disc and thin disc stars, respectively (e.g., Bensby et al. 2005; Fuhrmann 2004). That we see the same correlations in the inner Galactic disc strongly suggests that we have two distinct disc populations also in the inner disc, an inner thin disc and an inner thick disc, similar to those in the solar neighbourhood.

4.2. The Galactic bulge – thick disc connection

In Fig. 4 we show the detailed abundance trends for four α-elements, comparing the 44 inner disc K giants to the Bulge giants and nearby thin and thick disc giants from Alves-Brito et al. (2010). We emphasise that all stars in these plots have been analysed with the exact same methods, allowing truly differential comparisons between the different populations.

We note that especially the Mg abundance trend shows very little scatter, and that the inner disc giants have high [Mg/Fe] ratios for [Fe/H] < -0.3 and lower enhancements for higher [Fe/H]. This is a signature of enrichment by massive stars at low metallicities, and a delayed contribution from low mass stars at higher metallicities, consistent with the same signature seen in the nearby thick disc (e.g., Feltzing et al. 2003). This points to the existence of an inner thick disc and moreover that this thick disc does not differ much in terms of abundance trends, from the thick disc we see in the solar neighbourhhod. The same trend that is seen for Mg can also be seen in the Si and Ti plots, but with larger scatters. No clear trend can be seen in the Ca plot.

Furthermore, the abundance trends of the inner disc appear to be very similar to those of the Bulge. This inevitably points to a possible connection between the thick disc and the Bulge, implying they both might have formed at the same time (e.g., Genzel et al. 2008), sharing a similar star-formation rate and initial mass function. A possible scenario could be that the sub-solar part of the Bulge has a secular origin, and has formed from inner disc material (e.g., Shen et al. 2010).

The agreement between the Bulge and the thick disc has recently also been seen in studies that compare Bulge stars with nearby thick disc stars. For instance, Bensby et al. (2010) presented a detailed abundance analysis of 15 microlensed dwarf stars in the Galactic bulge. These stars were found to share the same abundance trends as were traced by kinematically selected thick disc dwarf stars in the solar neighbourhood (Bensby et al. 2003, 2005, and 2010, in prep.). Similarly, Meléndez et al. (2008) and Alves-Brito et al. (2010) found very good agreement between the abundance trends of red giants in the Bulge and thick disc red giants in the solar neighbourhood (see also Ryde et al. 2010). Similar to this study, the analysis methods of these studies are internally fully consistent (same methods, model stellar atmospheres, atomic data, etc.). They compare dwarfs with dwarfs, and giants with giants. Other studies of red giants in the Bulge (e.g. Fulbright et al. 2007; Zoccali et al. 2006; Lecureur et al. 2007) have found that the Bulge is significantly more α-enhanced at higher metallicities than thin and thick disc stars. As discussed in Bensby et al. (2010) and Alves-Brito et al. (2010), it is likely that those studies suffer from problems with the analysis (especially line blending). They also compare their Bulge giant samples with disc dwarf samples. The combined effect is that their Bulge stars seem spuriously more enhanced in the α-elements than the thick disc stars.

We further note that none of the inner disc giants are as metal-rich as some of the most metal-rich Bulge giants. As the metallicity distribution of the thick disc peaks at [Fe/H] ≈ -0.6 (Carollo et al. 2010), it is not surprising that our sample does not contain many metal-rich (thick disc) stars. Instead the upper

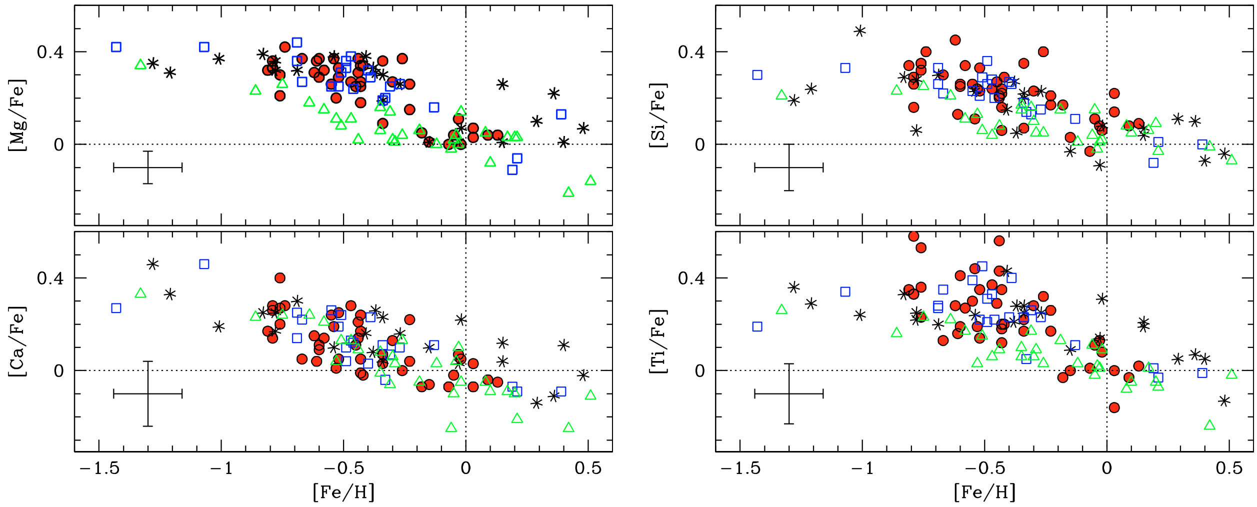

Fig. 4. Abundance trends for our inner disc giants (red filled circles) together with Bulge giants (asterisks), nearby thin disc giants (green empty triangles); and nearby thick disc giants (blue empty squares), all from Alves-Brito et al. (2010). Typical error bars are shown in each plot.

metallicity limit appears to be close to, or slightly above, solar values (similar to what is seen for nearby thick disc dwarfs stars, Bensby et al. 2007). A possible connection between the thick disc and the metal-rich part of the Bulge is therefore dubious. In that case, the metal-rich parts of the Bulge must have another origin, which possibly could be from accreted (extra-galactic?) material (see, e.g., the models by Rahimi et al. 2010). Evidence for two co-existing formation scenarios within the Bulge was recently shown by Bensby et al. (2010) and Babusiaux et al. (2010). With our result for the inner Galactic disc, the bonds between the the metal-poor part of the Bulge and the Galactic thick disc have grown even stronger.

5. Summary

We have presented the first detailed elemental abundance study of K giants in the inner Galactic disc. Our sample consists of 44 stars positioned 4–7 kpc from the Galactic centre, and up to 3 kpc from the Galactic plane. The three main results are:

– Based on elemental abundances and kinematics, we find it likely that the inner Galactic disc has two distinct stellar populations: a thin disc and a thick disc.
– The abundance trends of the inner Galactic thick disc are similar to those of the thick disc in the solar neighbourhood.
– We confirm, now using inner disc giants, the chemical similarity between the Galactic thick disc and the metal-poor Bulge.

Finally, our results do not preclude the possibility that the local thick disc could be in part produced by radial mixing of inner disc stars (Schönrich & Binney 2009).

In a forthcoming paper we will present the analysis of the current sample in detail and also add abundance results for more elements. That study will also include another similar sample of giant stars, but located in the outer Galactic disc.

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