

Chemical abundance gradients from open clusters in the Milky Way disk: results from the APOGEE survey

Katia Cunha^{1*}, Peter M. Frinchaboy², Diogo Souto¹, Benjamin Thompson², Gail Zasowski³, Carlos Allende Prieto⁴, Ricardo Carrera⁴, Cristina Chiappini⁵, John Donor², Anibal García-Hernández⁴, Ana Elia García Pérez⁴, Michael R. Hayden⁶, Jon Holtzman⁷, Kelly M. Jackson², Jennifer A. Johnson⁸, Steven R. Majewski⁹, Szabolcs Mészáros¹⁰, Brianne Meyer², David L. Nidever¹¹, Julia O’Connell², Riccardo P. Schiavon¹², Mathias Schultheis⁶, Matthew Shetrone¹³, Audrey Simmons², Verne V. Smith¹⁴, Olga Zamora⁴

¹ Observatório Nacional - MCTI, Brazil

² Texas Christian University, USA

³ NSF AAPF, Johns Hopkins University, USA

⁴ Instituto de Astrofísica de Canarias and Universidad de La Laguna, Spain

⁵ Leibniz-Institut für Astrophysik Potsdam, Germany

⁶ Observatoire de la Cote d’Azur, France

⁷ New Mexico State University, USA

⁸ The Ohio State University, USA

⁹ University of Virginia, USA

¹⁰ ELTE Gothard Astrophysical Observatory, Hungary

¹¹ University of Arizona, USA

¹² Liverpool John Moores University, UK

¹³ McDonald Observatory, University of Texas, USA

¹⁴ National Optical Astronomy Observatory, USA

Received XXXX, accepted XXXX

Published online XXXX

Key words Chemical abundances – Metallicity gradients – Open clusters – APOGEE survey

Metallicity gradients provide strong constraints for understanding the chemical evolution of the Galaxy. We report on radial abundance gradients of Fe, Ni, Ca, Si, and Mg obtained from a sample of 304 red-giant members of 29 disk open clusters, mostly concentrated at galactocentric distances between ~ 8 –15 kpc, but including two open clusters in the outer disk. The observations are from the APOGEE survey. The chemical abundances were derived automatically by the ASPCAP pipeline and these are part of the SDSS III Data Release 12. The gradients, obtained from least squares fits to the data, are relatively flat, with slopes ranging from -0.026 to -0.033 dex kpc^{-1} for the α -elements [O/H], [Ca/H], [Si/H] and [Mg/H] and -0.035 dex kpc^{-1} and -0.040 dex kpc^{-1} for [Fe/H] and [Ni/H], respectively. Our results are not at odds with the possibility that metallicity ([Fe/H]) gradients are steeper in the inner disk ($R_{GC} \sim 7$ –12 kpc) and flatter towards the outer disk. The open cluster sample studied spans a significant range in age. When breaking the sample into age bins, there is some indication that the younger open cluster population in our sample ($\log \text{age} < 8.7$) has a flatter metallicity gradient when compared with the gradients obtained from older open clusters.

Copyright line will be provided by the publisher

1 Introduction

The chemical evolution of a galaxy depends on many global variables; some of the more important ones being the star formation history, the infall and outflow of gas, and the initial mass function. These variables may differ from one galaxy to another, change as the galaxy evolves, and, combined with the existence of more star formation in the center of the galaxy, can result, for example, in the overall radial decrease of the metallicity across the galactic disk (e.g. Chiappini 2002). Such metallicity gradients are commonly seen

in spiral galaxies and represent important observational constraints for models describing the formation and the chemical evolution of a galaxy (e.g., Minchev et al. 2014; Kubryk et al. 2015; Stanghellini et al. 2015).

In the Milky Way, abundance gradients can be measured in a variety of populations, such as the young population of OB stars, H II regions and Cepheids; Planetary Nebulae; cool unevolved stars and red-giants in the field and in open clusters. The red giants which are members of open clusters, in particular, offer the advantage that their ages and distances can be better constrained than for field stars. In addition, open clusters span a large range of ages, from Myr

* Corresponding author: kcunha@on.br

to Gyr, and can be used to gain insight into the time evolution of gradients in the Galactic disk. In this paper, we report on the radial abundance gradients of Fe and Ni, as well as the alpha-elements O, Mg, Si and Ca from open clusters observed by the Apache Point Observatory Galaxy Evolution Experiment, the APOGEE survey.

2 Apogee observations

The APOGEE survey (Majewski et al. 2015) was one of the four surveys in the Sloan Digital Sky Survey, SDSS-III. The APOGEE multi-object spectrograph collected data during bright time between 2011 - 2014 and observed over 150,000 red giants from all stellar populations in the Milky Way. The APOGEE spectra have a resolution $R = \lambda/\delta\lambda \sim 23,000$ and spectral coverage between $\sim 1.5 - 1.7$ micron.

APOGEE targeted a large sample of stars in disk open clusters. These observations constitute the Open Cluster Chemical Analysis and Mapping (OCCAM) survey, a homogeneous and uniform dataset within the APOGEE survey that can be used to study abundance gradients. The sample discussed here contains 304 red-giants, which are members of 29 open clusters, covering galactocentric distances roughly between 7–23 kpc, but mostly concentrated between ~ 8 -15 kpc and with ages ranging from ~ 200 Myr to 10 Gyr (Dias et al. 2002). A future paper describing the studied sample will be presented in Frinchaboy et al. (2016).

3 Results and discussion

3.1 Abundances and comparisons with the literature

The chemical abundances and metallicities of the individual stars in our sample were derived automatically by the APOGEE Stellar Parameters and Chemical Abundance Pipeline - ASPCAP (Garcia Perez et al. 2015); these are part of the most recent SDSS-III Data Release, DR12¹.

Figure 1 shows comparisons of our average abundances for Fe, Ni, O, Ca, Si and Mg with results from other optical studies in the literature for the following clusters: NGC 6819 (Bragaglia et al. 2001); Berkeley 29 (Carraro et al. 2004); NGC 6791 (Carraro et al. 2006; Bragaglia et al. 2014); NGC 2243 (Jacobson et al. 2011a); NGC 2420, NGC 2158, NGC 7789, NGC 188 and M67 (Jacobson et al. 2011b). The mean differences between our results and the literature ($\langle \text{DR12} - \text{Literature} \rangle$) and corresponding dispersions for each element are indicated in the panels. For all elements, except Mg, the mean offsets are smaller than 0.1 dex.

Overall, the average iron abundances from DR12 and the literature agree within ~ 0.1 dex. For two of the clusters, however, the derived metallicities are larger than those in Jacobson et al. (2011b) by ~ 0.2 dex. The Ni, Ca and Si abundances for most of the clusters also agree with other studies within ~ 0.1 dex, but with a tendency of being slightly

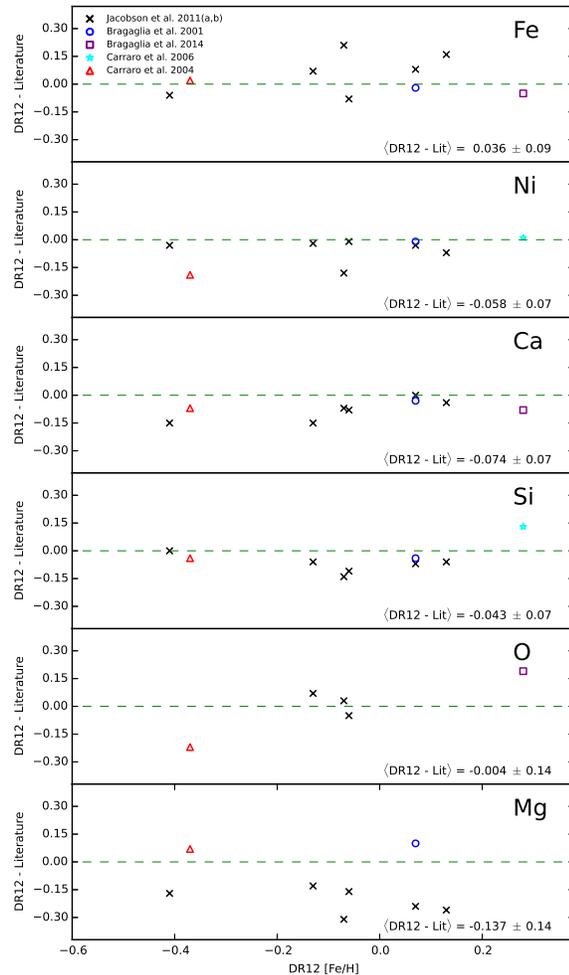


Fig. 1 A comparison of the ASPCAP/DR12 results with results from other optical high-resolution studies in the literature. The selected clusters are calibration clusters for the APOGEE survey (Mészáros et al. 2103). The abundance differences shown in the y axis are the average abundances per cluster and defined relative to the solar value as $[\text{el}/\text{Fe}]_{\text{DR12}} - [\text{el}/\text{Fe}]_{\text{Literature}}$. Typical uncertainties in the DR12 abundance averages are $\sim \pm 0.05$ dex (internal cluster abundance dispersions; Holtzman et al. 2015) and in the differences 'DR12 - Literature' are estimated to be $\sim \pm 0.07$ dex.

lower in DR12 than in the literature. We note, however, that Carraro et al. (2006) find a higher Si abundance than ours for the very metal rich cluster NGC 6791. For oxygen, there are fewer open clusters for comparison, but our results agree with those in Jacobson et al. (2011b), while there is +0.2 dex offset with the oxygen abundance in Bragaglia et al. (2014) for NGC 6791, and an opposite offset of -0.2 dex for Be 29, when compared to Carraro et al. (2004). The DR12 Mg abundances are systematically lower than those in Jacobson et al. (2011a,b), but are slightly higher than in Bragaglia et al. (2001, 2014).

¹ available at <https://www.sdss.org/dr12/>

The overall conclusion of the comparison above is that the DR12 abundances do not seem to show significant systematic offsets when compared to these literature studies. Certainly, the abundance differences found are typical of what is generally seen in other comparisons of different abundance studies in the literature. In addition, it is important to note that, since our goal is to investigate abundance gradients across the Galactic disk, it is an advantage to have observational data and abundance analysis methods which are homogenous, minimizing the possibility of having spurious trends that could be due to systematics.

3.2 Abundance gradients

An initial assessment of the metallicity (iron) and overall $[\alpha/\text{Fe}]$ abundance gradients from the APOGEE OCCAM survey has been presented in Frinchaboy et al. (2013). This previous study was based on abundances in SDSS-III Data Release 10 (DR10; Ahn et al. 2013). Other relevant studies of abundance gradients from open clusters in the literature include, e.g., Donati et al. (2015); Yong et al. (2012); Pancino et al. (2010); Magrini et al. (2015).

Figure 2 summarizes our results and abundance gradients obtained for Fe and Ni (products of Type Ia SN) and the α -elements O, Ca, Si and Mg (products of Type II SN). In all panels of Figure 2 the green open triangles represent the average abundances obtained per open cluster. The typical internal abundance dispersions are <0.05 dex. The horizontal and vertical dashed lines indicate, respectively, the solar abundance values and the galactocentric distance of the Sun (R_{GC}). Overall, the abundance results for all elements, except Si, are roughly solar at close to solar galactocentric distances. In addition, the abundance scatter at roughly solar R_{GC} is relatively small, but the open cluster NGC 6791 deviates from the average ($[\text{O}/\text{H}]$ and $[\text{Mg}/\text{H}] \sim +0.4$ dex; see also Cunha et al. 2015). The open cluster NGC 6791, however, is one of the most metal rich open clusters in the Galaxy and is known to have some special characteristics such as being very old, very massive, lying at ~ 1 kpc from the galactic plane. As previously mentioned, for Si, our results are systematically higher than the solar Si abundance at roughly solar galactocentric distances. This would be an indication that our Si abundances are overestimated, but the comparison with the open clusters in Figure 1 indicates that our Si results are slightly lower than the literature. We note, however, that DR12 results for $[\text{Si}/\text{Fe}]$ are systematically higher than the results in Bensby et al. (2014) by ~ 0.1 dex.

Concerning the abundance gradients, best fit slopes and uncertainties are also presented in Figure 2. These were computed from least squares fits to the cluster average elemental abundances. When considering the entire sample the gradients obtained for $[\text{Fe}/\text{H}]$ and $[\text{Ni}/\text{H}]$ (mostly products of SN Type Ia) are -0.035 ± 0.007 dex kpc^{-1} and -0.040 ± 0.007 dex kpc^{-1} , respectively, while the gradients for the α -elements are slightly flatter with an average slope of -0.029 ± 0.004 dex kpc^{-1} . Previous studies have found evidence for a possible break in the metallicity gradients at $R_{GC} \sim$

10–12 kpc (e.g., Frinchaboy et al. 2013, Yong et al. 2012; Magrini et al. 2010), with a flatter gradient in the outer disk when compared to the inner disk. When dividing our sample into clusters with $R_{GC} < 12$ kpc and those with $R_{GC} > 12$ kpc we also find that the metallicity gradient is flatter in the outer disk: -0.030 ± 0.009 dex kpc^{-1} , while for the inner disk ($R_{GC} \sim 7\text{--}12$ kpc) it is steeper: -0.068 ± 0.017 dex kpc^{-1} .

Radial metallicity gradients from field stars in the APOGEE survey with distances from the Galactic plane between $0.00 < z < 0.25$ kpc, are found to be flat in the inner disk ($R_{GC} < 6$ kpc) and quite steep (-0.087 ± 0.002 dex kpc^{-1}) between $R_{GC} \sim 6\text{--}12$ kpc, with a significant abundance scatter (Hayden et al. 2014). In the overlapping region from $R_{GC} \sim 7\text{--}12$ kpc, the metallicity gradient obtained for the cluster sample (-0.068 ± 0.017) is somewhat flatter than for the field stars based on DR10 results (these results should be revisited using DR12). We note, however, that the most distant cluster, Be 29, has $z=2$ kpc and its metallicity is in line with the median metallicity found by Hayden et al. (2014) for their sample of field stars with $1.00 < z < 2.00$ kpc. (See also Cheng et al. 2012; Boeche et al. 2014)

The open clusters in our sample have considerable age spread (~ 200 Myr – 10 Gyr) and it is possible that the derived metallicity gradient, which was obtained from open clusters of all ages, carries also the signature of its evolution as the Galaxy evolves. In addition, there is also the effect of radial migration. In order to investigate the possible time evolution of metallicity gradients, we break our open cluster sample into three arbitrary age bins. The top and middle panels of Figure 3 show, respectively, the young ($\log \text{age} < 8.7$) and intermediate age ($8.7 < \log \text{age} < 9.0$) clusters, and the bottom panel shows the oldest clusters, with ages over ~ 1 Gyr. The latter includes the only open cluster in our sample beyond $R_{GC} \sim 16$ kpc (Be 29). Best fit slopes are: -0.025 ± 0.017 and -0.037 ± 0.018 for the young and intermediate age populations, respectively. For the oldest clusters, we derive a steeper gradient of -0.049 ± 0.017 when considering the range $R_{GC} \sim 7\text{--}16$ kpc, which is covered in all 3 age bins and flatter when including Be 29 (-0.036 ± 0.010). These preliminary results indicate that the radial metallicity gradients are flatter for the younger open clusters.

Acknowledgements. PMF, BT, and JO are supported by NSF AST-1311835. Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is <http://www.sdss3.org/>. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the Univ. of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State Uni-

versity, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

References

- Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2014, *ApJS*, 211, 17
- Bensby, T., Feltzing, S., & Oey, M. S. 2014, *A&A*, 562, A71
- Boeche, C., Siebert, A., Piffl, T. et al. 2014, *A&A*, 568, A71
- Bragaglia, A., Carretta, E., Gratton, R. G., et al. 2001, *AJ*, 121, 327
- Bragaglia, A., Sneden, C., Carretta, E. et al. 2014, *ApJ*, 796, 68
- Carraro, G., Bresolin, F., Villanova, S., et al. 2004, *AJ*, 128, 1676
- Carraro, G., Villanova, S., Demarque, P., et al. 2006, *ApJ*, 643, 1151
- Cheng, J., Rockosi, C. M., Morrison, H. L., et al. 2012, *ApJ*, 746, 149
- Chiappini, C. 2002, *Ap&SS*, 281, 253
- Cunha, K., Smith, V. V., Johnson, J. A., et al. 2015, *ApJ*, 798, L41
- Frinchaboy, P. M., Thompson, B., Jackson, K. M., et al. 2013, *ApJ*, 777, L1
- Frinchaboy, P. M. et al. 2016, in preparation
- Garcia Perez, A. E., Allende Prieto, C., Holtzman, J. A., et al. 2015, preprint, arXiv:1510.07635
- Hayden, M. R., Holtzman, J. A., Bovy, J., et al. 2014, *AJ*, 147, 116
- Holtzman, J. A., Shetrone, M., Allende Prieto, C., Y., et al. 2015, *AJ*, 150, 148
- Jacobson, H. R., Friel, E. D., & Pilachowski, C. A. 2011a, *AJ*, 141, 58
- Jacobson, H. R., Pilachowski, C. A., & Friel, E. D. 2011b, *AJ*, 142, 59
- Kubryk, M., Prantzos, N., Athanassoula, E. 2015, *A&A*, 580, 126
- Magrini, L., Randich, S., Zoccali, M. et al. 2010, *A&A*, 523, 11
- Magrini, L., Randich, S., Donati, A. 2015, *A&A*, 580, 85
- Majewski, S. R., Schiavon, R. P., Frinchaboy, P. M., et al. 2015, preprint, arXiv:1509.05420
- Meszáros, Sz., Holtzman, J., Garcia Perez, A.E., et al. 2013, *AJ*, 146, 133
- Minchev, I., Chiappini, C., & Martig, M. 2014, *A&A*, 572, 19
- Pancino, E.; Carrera, R.; Rossetti, E.; Gallart, C. 2010, *A&A*, 511, 19
- Stanghellini, L., Magrini, L. & Casasola, V. 2015, *ApJ*, 812, 39
- Yong, D., Carney, B. W., Friel, E. D. 2012, *AJ*, 144, 95

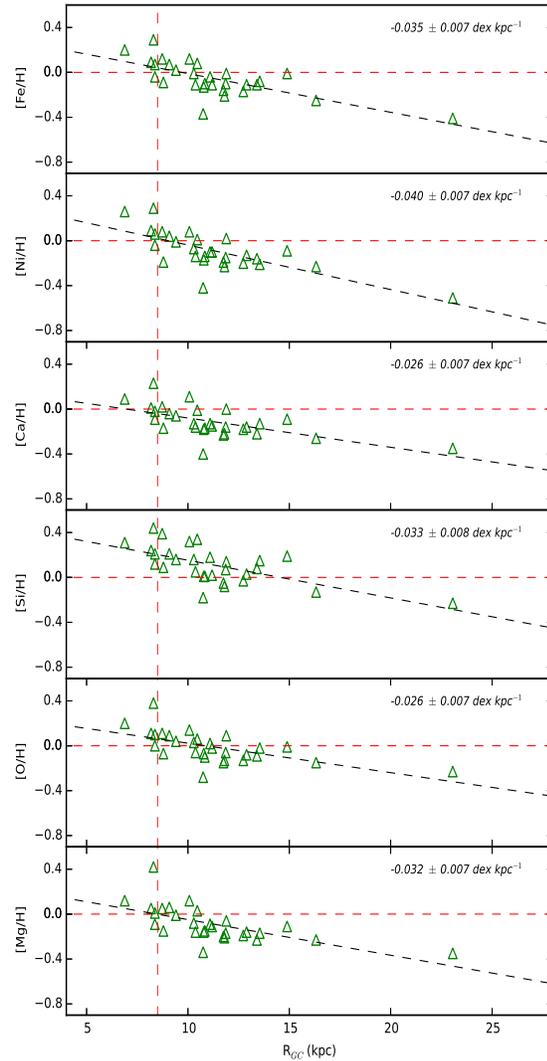


Fig. 2 Chemical Abundance gradients (best fit slopes) for a sample of open clusters observed by the APOGEE survey. The triangles represent average abundances for each cluster computed from individual stellar abundances from cluster members in SDSS-III/ DR12. The galactocentric distances adopted for the open clusters are from the Dias et al. (2002) catalog.

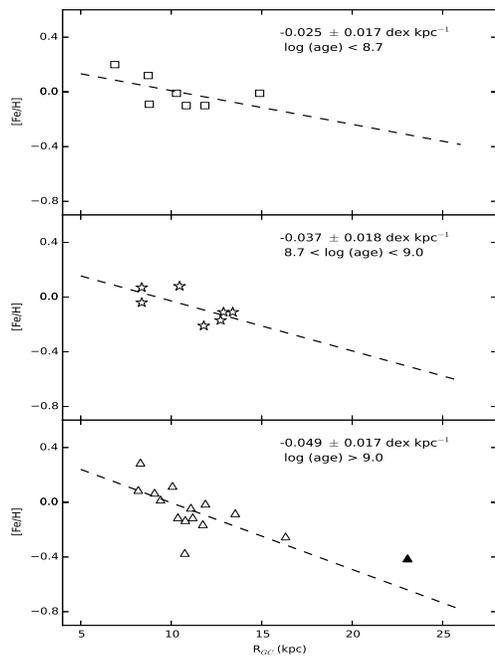


Fig. 3 The time evolution of gradients for the studied sample. The open clusters in our sample are divided in 3 age bins: $\log \text{age} < 8.7$; $8.7 < \log \text{age} < 9.0$ and $\log \text{age} > 9.0$. The best fit slope for the old population did not include Be 29 (filled triangle). The derived gradients are flatter for the youngest populations.