Two Sequences in the Age–Metallicity Relation as Seen from [C/N] Abundances in APOGEE

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Abstract

The age–metallicity relation (AMR) is fundamental to study the formation and evolution of the disk. Observations have shown that this relation has a large scatter, which cannot be explained by observational errors only. That scatter is hence attributed to the effects of radial migration in which stars tracing different chemical evolution histories in the disk get mixed. However, the recent study of Nissen et al., using high-precision observational data of solar-type stars, found two relatively tight AMRs. One sequence of older and metal-richer stars probably traces the chemical enrichment history of the inner disk while the other sequence of younger and metal-poorer stars traces the chemical enrichment history of the outer disk. If uncertainties in age measurements increase, these sequences mix, explaining the scatter of the one relation observed in other studies. This work follows up on these results by analyzing an independent sample of red clump giants observed by APOGEE. Because ages for red giants are significantly more uncertain, the [C/N] ratios are considered as a proxy for age. This larger data set is used to investigate these relations at different Galactic radii, finding that these distinct sequences exist only in the solar neighborhood. The APOGEE data set is further used to explore different abundance and kinematical planes to shed light on the nature of these populations.

Unified Astronomy Thesaurus concepts: Chemical abundances (224); Milky Way disk (1050)

1. Introduction

The age–metallicity relation (AMR) in the solar neighborhood has been a fundamental diagram to understand how the Milky Way disk has formed. Considering that stars pollute star-forming regions with metals after exploding, younger stars need to be more metal rich than older stars. Hence, in a closed-box scenario, it is expected that the AMR is tight, with a trend of metallicity increasing with time. However, even early works on the AMR, either using smaller spectroscopic samples (Edvardsson et al. 1993) or larger photometric samples (Casagrande et al. 2011), have shown the contrary: the relation has a scatter much larger than the uncertainties in determined metallicities or ages.

Explaining the scatter of the AMR has used the fact that stars migrate and that chemical enrichment is not constant across the disk (e.g., Silva Aguirre et al. 2018). Therefore, the variety of ages and metallicities with apparently no relation in the solar neighborhood can be attributed to stars tracing the chemical enrichment history from different birthplaces (Minchev & Famaey 2010). Recently, Feuillet et al. (2019) attempted to unveil the true structure of the AMR in an extended region of the disk, taking advantage of large spectroscopic data sets. By calculating means in the age distribution at a given metallicity, they found that the relation is not flat, but has a turnaround at solar metallicities, i.e., that metal-poor and metal-rich stars are older than solar-metallicity stars. This can be interpreted as the effect of stellar migration, that is, older stars born in inner regions of the Galaxy have moved outwards (e.g., Miglio et al. 2021).

Yet, quantifying the importance of migration and the net difference in chemical enrichment rates in the disk has remained an open question. The recent work of Johnson et al. (2021) used the observed AMR of Feuillet et al. (2019) to constrain not only the amount of migration of the fossil stars but also the migration of the intermediate-mass stars, which will become white dwarfs and then explode as Type Ia supernovae (SNe Ia). Because the latter are long lived, they are able to explode far from their birthplaces. This enriches a different region of the Galaxy with metals. A precise AMR is thus of paramount importance to constrain the different processes that affect disk formation and structure.

If the precision of measured ages and metallicities improves, we could unveil the details of the AMR and thus the formation of the disk. Nissen & Gustafsson (2018) extensively illustrated the power of using high-precision abundances of stars in several astrophysical applications. In particular, using high-precision solar-twin abundances, it has been possible to study tight relationships between chemical abundance ratios and ages, such as [Y/Mg] and [Ba/Mg] (e.g., Nissen 2015; Spina et al. 2018; Jofré et al. 2020). These relations are attributed to a strong dependency of chemical enrichment on time. These abundances have been dubbed as “chemical clocks” and offer interesting perspectives of using certain abundance ratios as an alternative for stellar ages.

With the intention of testing the applicability of these chemical clocks, which have been shown to vary with metallicity (Delgado Mena et al. 2019) and Galactic region because the star formation efficiency is not constant across the Galaxy (e.g., Casali et al. 2020; Casamiquela et al. 2021), Nissen et al. (2020, hereafter N20) extended the metallicity range of solar-type stars from the solar-twin regime (−0.1 < [Fe/H] < 0.1) to −0.3 < [Fe/H] < 0.3. To their surprise, they found two notable separate sequences in the AMR of their sample. The stars from both relations showed different chemical abundance ratios of a few other elements, as well as the overall kinematical distributions. They concluded that if the AMR in the solar neighborhood is truly composed of two sequences, it should be seen in larger samples as well. They stressed, however, that such a study is not straightforward due
to the typical large uncertainties in ages of stars very different from the Sun.

Fortunately, there is a way to avoid using ages and still test N20’s results in larger data sets. If ages do not reach the needed precision, we need to consider an alternative proxy for age that is precise. Masseron & Gilmore (2015) demonstrated the power of using [C/N] abundances of red giants as a proxy for ages to show how the thick disk and the thin disk had very different evolutionary histories. This abundance ratio differs from the chemical clocks because it does not follow a chemical enrichment rate but is the product of processes happening inside red giant stars. Masseron & Gilmore (2015) revived the fundamental principle that red giants change their C/N atmospheric abundance ratio after experiencing their first dredge-up because they bring new material synthesized in their cores toward the atmosphere. This is a consequence of the CNO cycle for hydrogen burning and applied it to Galactic archeology. Because the change in the C/N ratio largely depends on the stellar mass, a distribution of [C/N] abundances of a large sample of red giants of similar evolutionary stages can be related to their masses, hence their ages.

APOGEE has very precise atmospheric parameters and stellar abundances, in particular, metallicities and [C/N] abundance ratios, for a very large number of red giants distributed in the entire Galactic disk (Jönsson et al. 2020). Indeed, Hasselquist et al. (2019) studied the [C/N]-[Fe/H] relation in the disk as an alternative for the AMR. They used large samples of stars in APOGEE, spanning a wide range in parameter space and abundances. That allowed them to include the thin and thick disks in order to study the difference in the [C/N]-[Fe/H] relations and distributions at different Galactic radii and heights. They commented that the solar neighborhood had a larger scatter in the [C/N]-[Fe/H] relation than the majority of the Galactic regions, but no two separate sequences were identified.

The present work attempts to focus the discussion on a possible dual AMR in the solar neighborhood by selecting from APOGEE only stars that have a restricted range parameter space to avoid scatter in the [C/N]-age relation as much as possible. The main motivation is to focus on the Galactic plane and stars close to solar metallicities, following N20’s results. Such stars are then further studied by taking advantage of the multidimensional information available for the APOGEE stars today, namely kinematics from Gaia and the several elemental abundances beyond α, C, and N. With this focused analysis two separate [C/N]-[Fe/H] relations are found, sharing similar properties to those of N20.

2. Data and Methods

Two valued-added catalogs from the 16th Data Release of SDSS (Ahumada et al. 2020) were considered. The first one is the APOGEE Red-Clump (RC) catalog,1 which includes the identification of RC stars using spectrophotometric data applied then to APOGEE. It has 95% certainty that the star is an RC star. Details of this selection can be found in Bovy et al. (2014). The second catalog is the astroNN catalog of abundances, distances, and ages for APOGEE DR16 stars,2 which consists of applying a deep-learning neural network to APOGEE spectra in order to derive, among other properties, distances as described in Leung & Bovy (2019). That method is model free because it is based on the spectra and the parallax of stars and applied to spectra of stars with an unknown parallax (see Jofré et al. 2015; Jofré et al. 2017) for further discussions. The catalog also includes ages and dynamical and kinematical properties such as actions, eccentricities, and velocities, following the description of Macketh et al. (2019). Both samples cross-matched gives approximately 40,000 RC stars with abundances, distances, ages, and dynamical parameters.

The atmospheric parameters and stellar abundances considered are those of APOGEE DR16, that is, from the APSCAP pipeline (García Pérez et al. 2016). They are based on fitting synthetic spectra computed considering LTE and 1D to the observed spectra using the FERRE code (Allende Prieto et al. 2006). The spectra from which abundances are derived are in the infrared and have a resolution of about 20,000. Spectra normally have a signal-to-noise ratio of 100, which is sufficient to have abundance precisions normally below 0.05 dex (Jönsson et al. 2020). Extended discussion on APOGEE accuracy and precision in context with other optical spectroscopic surveys can be also found in Jofré et al. (2019).

Further cuts were applied to the data. As a quality cut, only stars with spectral parameters determined with confidence were considered. This means taking only stars with parameter APSCAPFLAG = 0. In addition, only stars in the metallicity range of $-0.35 < [\text{Fe/H}] < 0.35$ were selected with the intention of having a similar metallicity range to N20. In order to remove thick-disk (high-α) stars from the sample, further chemical and spatial cuts were applied by requesting $[\alpha/M] < 0.1$, Galactic height $|z| < 0.8$ kpc, and a positive parallax measured with better confidence than 20%. All of these cuts reduce the sample to about 18,000 stars. The atmospheric parameters of the sample have a distribution of mean temperature of 4800 K and a standard deviation of 130 K and mean surface gravity of 2.44 and a standard deviation of 0.1 dex. Abundance ratio precisions have mean and standard deviation indicated in Table 1.

\begin{table}[h]
\centering
\caption{Mean and Standard Deviation of the Error Distributions in the Abundance Ratios Considered in This Work}
\begin{tabular}{|c|c|c|}
\hline
\text{Element} & \text{Mean} & \text{Standard Deviation} \\
\hline
C & 0.012 & 0.004 \\
N & 0.018 & 0.005 \\
O & 0.015 & 0.005 \\
Mg & 0.011 & 0.002 \\
Al & 0.02 & 0.005 \\
Si & 0.011 & 0.002 \\
Ca & 0.013 & 0.004 \\
Ti & 0.018 & 0.0058 \\
Cr & 0.035 & 0.010 \\
Mn & 0.016 & 0.005 \\
Fe & 0.008 & 0.0002 \\
Ni & 0.013 & 0.007 \\
\hline
\end{tabular}
\end{table}

1 https://www.sdss.org/dr16/data_access/value-added-catalogs/?vac_id=apogee-red-clump-(rc)-catalog

2 https://www.sdss.org/dr16/data_access/value-added-catalogs/?vac_id=the-astromn-catalog-of-abundances,-distances,-and-ages-for-apogee-dr16-stars
2.1. [C/N] as a Proxy for Age

Masseron & Gilmore (2015) took upon the work of Iben (1965) to demonstrate that [C/N] abundances could indeed be used to study the mass, hence age, distribution of red giant populations. Since then, there has been rich literature on the relation of [C/N] abundances and ages for red giant stars. Some works derive empirical relations of measured [C/N] abundances from the spectra with independent measurements of ages from, e.g., asteroseismology (Martig et al. 2016) or open clusters (Casali et al. 2019). Other works derive ages using The Cannon directly from the spectra (Ness et al. 2016). The latter, however, indirectly uses [C/N] as an important input for ages (see also discussions in Das & Sanders 2019).

Figure 1 shows the relation of the [C/N] abundance ratios and ages of the stars used here. The ages considered for this plot are those from AstroNN, which were derived by Mackereth et al. (2019). They discuss the dependency of [C/N] on the derived ages; therefore, this relation is expected. To guide the eye, the empirical relationship determined by Casali et al. (2019) is plotted with lines. They used [C/N] abundances of red giants in open clusters observed with the APOGEE and the Gaia-ESO (Gilmore et al. 2012; Randich et al. 2013) surveys and independent ages derived from isochrone fitting to the CMD of the clusters to find an empirical relation. Their results have a generous uncertainty in the zero point and slope of the relation, allowing for a range of options between [C/N] abundances and ages. Here, the relations log Age (yr) = 10.64 + 2.61 [C/N] and log Age (yr) = 11.20 + 2.51 [C/N] are plotted in red and blue, respectively.

The figure intends to show that the [C/N] abundances in this sample can be used as an age proxy. This is an important step considering that RC stars are avoided in some studies of [C/N] abundances with age (e.g., Masseron & Gilmore 2015; Hasselquist et al. 2019). RC stars might have experienced extra mixing processes during the red giant branch through the helium flash or thermohaline mixing, which might have altered the [C/N] abundances after the first dredge-up (Lagarde et al. 2017; Masseron et al. 2017). The figure shows that this sample, which is restricted to a tight space in stellar parameters, still leads to a correlation with age, but transforming [C/N] abundances into ages can imply uncertain ages, especially because these mixing processes are poorly understood.

3. Results

3.1. [C/N]–Metallicity as a Function of Galactic Radius

Figure 2 shows density maps in the [C/N]–[Fe/H] plane for stars located in different Galactocentric radii R. The panels show the [C/N]–[Fe/H] for stars located from the inner to the outer disk, in R bins of 2 kpc starting at 3 kpc on the left-hand panel and finishing at 13 kpc on the right-hand panel.

It is possible to notice the stark difference of the [C/N]–[Fe/H] relations between the different panels. The first panel (3 < R < 5 kpc), containing 62 stars only, shows two separate groups of stars, with different metallicities and [C/N], which could be attributed to the overlap between the inner disk and the bulge. The second panel (5 < R < 7 kpc), containing 1488 stars, shows another sequence of stars, relatively metal rich and high in [C/N] abundances. The stars follow a tight relation between [C/N] and [Fe/H], suggesting they experienced rapid chemical enrichment in the past, probably like a closed box. The panel further shows a large number of stars in the background that are not part of this relation and shows indication of a secondary sequence at lower metallicities, but there are not enough stars to confirm this.

The third panel (7 < R < 9 kpc), containing 7016 stars, corresponds to the solar neighborhood. This region shows there are two separated groups of stars. The first one is a sequence that has similar properties to the sequence seen in the adjacent left panel, namely its stars are rather metal rich and [C/N] enhanced, and have a steep slope. The second sequence, which could be a continuation of the background population of the previous panel, shows a tight relation between [C/N] and [Fe/H], reaching more metal-poor stars and higher [C/N] values. The groups are separated, agreeing with N20’s results about the two sequences in the solar neighborhood. These sequences were not seen in Hasselquist et al. (2019), probably because they used stars covering a wider range in stellar parameters, which might have blurred the distributions. In fact, that same panel was commented to have a larger scatter in the [C/N]–[Fe/H] relation with respect to the rest of the panels.

The fourth panel (9 < R < 11 kpc) contains 7322 stars and presents one main sequence of stars that are rather metal poor as well as [C/N] poor. This suggests that the outer disk has had a slower star formation history, with stars being rather young. There is however a tight relation between [C/N] and [Fe/H], similar to the solar neighborhood lower sequence. Like in the (5 < R < 7 kpc) panel, there is a significant background of stars that do not follow the relation. Here, however, they are rather metal rich and could be attributed to the tail of the upper sequence seen in the solar neighborhood panel. The last panel (11 < R < 13 kpc) contains 1764 stars of almost only metal-poor stars with low [C/N], suggesting these stars are probably rather young. This is in agreement with previous studies, which have found a dominance of younger stars in the outer disk (Xiang et al. 2017; Huang et al. 2020). The relation between [C/N] and metallicities in this panel is rather loose.

Feuillet et al. (2019) also plotted the AMR at different Galactic radii and heights. Comparing with their results for the Galactic plane, it is possible that their turnaround in the AMR leading to a C shape is attributed to the appearance of the second sequence, which, as extensively discussed by N20, could produce a large scatter for typical uncertainties in stellar ages. The C shape in the AMR appears in the outer disk panels as well, but in Figure 2 the secondary sequence tends to
disappear. This might be a selection effect, because here only RC stars are considered, while Feuillet et al. (2019) include a wider range of surface gravities and hence luminosities.

It is worth commenting on the selection effects of these distributions due to the bias induced by selecting only metallicities that are above $-0.3$ dex. Because the star formation efficiency is different across the disk, the stars of the same metallicity in the inner and outer parts of the disk do not necessarily reflect the same timescales and epochs of formation and hence, they cannot be interpreted in a total evolutionary framework. Adding however a wider range in metallicity might induce further scatter in the C/N−age relation (Das et al. 2020) and other systematics that this work is trying to avoid.

3.2. Two Populations in the Solar Neighborhood

In order to see if the two sequences of AMRs found by N20 are also present in this larger and independent data set, the density map of [C/N] and [Fe/H] for the stars located in the solar neighborhood is shown again in Figure 3. If these sequences are produced due to two different populations tracing different chemical enrichment histories, investigating more chemical patterns as well as kinematics is useful. Therefore, only stars located at the maxima of the distributions were selected considering the clustering algorithm Shift Mean, which is designed to find local bumps in a density estimate of data (see Chapter 6.4 of Ivezić et al. 2014). The data of the solar neighborhood supports 3 main groups. which are located in the main two populations. One is more metal-rich (reaching [Fe/H] of 0.3 dex) and can be considered to be older because the [C/N] ratios are higher (see e.g., Figure 1) and the other one has a more extended range in metallicity reaching lower [Fe/H] values of $-0.2$ as well as a more extended range in [C/N] suggesting a larger range in ages reaching younger ages than the more metal-rich and older population.

The groups are shown as colored contours in Figure 3. The stars from the upper population are given a red color, while the stars from the lower population groups are given blue colors. These are studied in terms of their kinematics and other elemental abundances.

3.2.1. Kinematics

Figure 4 shows the distributions of different dynamical quantities for the stars enclosed in the red and blue groups of Figure 3.

The left-hand panels show the distributions of the stars in the classical Toomre diagram, which was also plotted by N20. While there is a large overlap between both groups, the red group has a tendency to have lower tangential velocities but slightly higher vertical and radial velocities than the blue group. This result agrees with N20, who also found that their red (old) group had a larger velocity dispersion and a larger rotational lag than the blue (younger) group, which is encouraging. Differences in kinematics are in any case minimal, here and in N20, making it difficult to add more about the origin of these two groups from the velocities alone.

The middle panels plot the relation of the stellar orbits angular momenta $L_z$ and the eccentricities $e$. As in the left-hand panel, the overlap between both groups is large, and only slight differences can be identified from the histograms. Both groups have relative circular orbits, with a range of eccentricities comparable to and below $e < 0.4$. The red group presents, however, a tendency to have stars slightly more eccentric at $0.3 < e < 0.4$ than the blue group, indicating that more stars in the red group have been kinematically heated. This makes sense because the red group has overall higher [C/N]
abundance ratios than the blue group, hence the red group has stars that are generally older, and old stars are kinematically hotter than young stars (e.g., Soubiran et al. 2008; Mackereth et al. 2019; Sharma et al. 2020; Bird et al. 2021).

While the overlap in $L_z$ is large, the red group has overall lower angular momenta than the blue group. If the red group is associated with a sequence of stars tracing the chemical enrichment history of the inner disk, then they could have radially migrated. The “churning” effect of radial migration moves stars outwards by keeping eccentricities fixed but losing angular momenta (Feltzing et al. 2020), which is consistent with the behavior of the distributions of the red group compared to the blue group. However, having two distributions with different $L_z$ does not necessarily mean one population has lost angular momentum, because eccentric orbits might also be an indicator of just visitors. In fact, the right-hand panels show the radial and vertical actions $j_r$ and $j_z$, respectively. Again, both groups heavily overlap in the scatter plot, but the distributions allow for a better inspection of possible differences. While the radial action distribution is very similar for both groups, there is a difference in the vertical actions $j_z$.

The difference in $L_z$ and $j_z$ between the red and the blue sequences might thus be interpreted as stars being born in different regions. More specifically, the red sequence might show stars formed at smaller Galactic radii that due to their higher eccentric orbits compared to the blue sequence reach the solar neighborhood.

3.2.2. Elemental Abundances as a Function of Metallicity

The red and the blue groups are also studied in other abundance planes, which are shown in Figure 5. In each panel, a scatter plot of stars colored by red and blue for different abundance ratios as a function of metallicity is shown. Linear regression fits to the corresponding distributions of the respective groups as a function of metallicity have been performed and are indicated with solid lines of the same color. The slope and the error of the regressions are indicated in each panel.

In all panels, the abundance trends have a smooth transition between one and the other sequence. For most of the elements both sequences merge into one sequence, behaving as the classical low-$\alpha$ chemical sequence found in the APOGEE data (Jönsson et al. 2020). The slope of the regression fits of the abundances as a function of metallicity, however, can differ between the red and blue group for some cases, such as $[\text{C+N}/\text{Fe}]$, $[\text{O}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, and $[\text{Ni}/\text{Fe}]$.

As discussed in Masseron & Gilmore (2015), while the $[\text{C}/\text{N}]$ abundance changes in giants after they experience dredge-up, the total amount of C and N stays the same, reflecting the composition of the birth cloud, which, like many other chemical abundances, will change as stars die (see also Figure 2 of Martig et al. 2016). Hence, $[\text{C+N}/\text{Fe}]$ ratios have been used to study the differences of star formation histories in the disk (Masseron & Gilmore 2015; Hasselquist et al. 2019) as well as metal-poor stars that might have formed in dwarf galaxies and accreted later on in the Milky Way (Hawkins et al. 2015; Das et al. 2020; Horta et al. 2021). Around solar metallicities, C is made by He burning in both the core of stars and in AGB stars, while N is made mostly in AGB stars (Kobayashi et al. 2020a); therefore $[\text{C+N}/\text{Fe}]$ traces the contribution of AGB stars. The fact that the red group has overall higher $[\text{C+N}/\text{Fe}]$ abundances than the blue group might be attributed to the difference in metallicity, because both C and N have a metallicity dependency, and the red group has mostly metal-rich stars while the blue group has a wider range in metallicities. It is noted that the $[\text{C+N}/\text{Fe}]$ are above zero even for the blue sequence. This might be related to a systematic uncertainty in the N abundances of APOGEE, which obtain a value of 0.2 for the solar N abundance (Jönsson et al. 2020). Indeed, the recent study of nitrogen abundances in the Sun of Amarsi et al. (2020a) points toward a systematic difference between N measured from molecular features and atomic features. It is not the aim of this paper to correct for systematic effects but to illustrate the trends in both populations and look for differences. This is another argument of why this work does not attempt to relate $[\text{C}/\text{N}]$ directly with an age value.

Oxygen and magnesium are $\alpha$-capture elements that are produced inside massive stars and are ejected into the interstellar medium via core-collapse SN (SN II). Both oxygen and magnesium belong to the few primary elements, e.g., the yields are not affected by the metal content of the progenitor star. Iron, on the other hand, is mostly produced by thermonuclear supernova (SN Ia), whose progenitors are lower-mass stars. Therefore, there is a time delay in the enrichment of oxygen (or magnesium) and iron (Matteucci & Greggio 1986). There is extensive literature in using in particular $[\text{O}/\text{Fe}]$–$[\text{Fe}/\text{H}]$ planes to constrain chemical evolution models, both of the Milky Way (Johnson et al. 2021) and other galaxies (Maiolino & Mannucci 2019). The mass of the progenitor galaxy as well as the star formation history can be addressed from the relation between $[\alpha/\text{Fe}]$ and $[\text{Fe}/\text{H}]$ for a given stellar population.
(Tinsley 1979). The $\alpha$/[Fe/H]—hereafter Tinsley–Wallerstein (TW)—diagram on the top right-hand panel of Figure 5 shows how the blue group has lower [O/Fe] ratios than the red group for the same metallicity. It further shows that while the red stars seem to have reached a plateau at solar metallicities, the blue stars still are in the decreasing part of the TW diagram, suggesting that star formation efficiency is lower for the blue group. A similar behavior is seen for Mg, shown in the left-hand side panel of the middle row of Figure 5. It is interesting to note that these abundance planes in the APOGEE data show a turnaround in the abundances around solar metallicities (Jönsson et al. 2020), which might also be seen in the [Mg/Fe]–[Fe/H] trends with optical spectroscopy (Adibekyan et al. 2012).

Silicon is another $\alpha$-capture element that presents a slight change of slope in the regression fits between the blue and red populations. This element is believed to be produced by both SNe II and SNe Ia, hence it does not correlate directly with Mg which is mostly produced by SNe II. Furthermore, the production mechanism in SNe II is different from Mg which translates to a dependency on the progenitor’s mass (Blancato et al. 2019). In the populations of this study, the Si abundance is a combination of the many SNe II of lower mass, in addition to SNe Ia. The fact that the red and the blue groups have a slight difference can be an effect of the different metallicities.

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Figure 5. Abundance ratios as a function of metallicity of selected groups from the $\text{[C}/\text{N]}$–$\text{[Fe}/\text{H]}$ diagram. Linear regression fits to the data of the corresponding groups are displayed for guidance.

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5 This is motivated after discussions among astronomers on social media in 2020 about calling this important diagram after Tinsley and Wallerstein, who used and explained it. Many fundamental diagrams are named after scientists who have first explained them.
between the groups (SN Ia contribution) as well as age (SN II contribution).

Nickel is an iron-peak element that is synthesized in SNe Ia as well as inside massive stars and expelled into the interstellar medium via explosions in essentially the same way as Fe. It is therefore expected that [Ni/Fe] has an overall flat and solar value for an extended range in metallicity. But as recently discussed by Kobayashi et al. (2020b), the large variety of possible progenitors of SNe Ia makes it hard to reproduce and interpret the observed [Ni/Fe] abundance ratios, especially at high metallicities (see also Palla 2021, for the effect of yields of different SN Ia prescriptions). Because the yields differ between the different white dwarf progenitors of the SNe, the elemental abundance ratios will be affected when changing the contribution of such progenitors. While the metal production of SN Ia is independent of metallicity, its production rate can be affected by metallicity, because the lifetime of the secondary star of the binary depends on the progenitor metallicity.

The red sequence shows a steeper trend of [Ni/Fe] with metallicity than the blue sequence. This could be attributed to a different metallicity effect for the progenitor (hence timescale) of the SN Ia, affecting in a different way the [Ni/Fe] abundance ratios. It would be the difference in environments leading to different contributions from SN Ia subclasses (Palla 2021). The slight increase at metallicities above solar has been seen in the literature (Adibekyan et al. 2012; Bensby et al. 2014) as well as when considering the bulk of the APOGEE data (Jösson et al. 2020). Considering the break in the slope between both sequences, it is interesting to associate this increase with an overlap between two stellar populations coexisting in the solar neighborhood that trace different star formation histories.

### 3.2.3. Elemental Abundances as a Function of [C/N]

Figure 6 presents the same abundance planes as in Figure 5 but here as a function of [C/N]. This allows for an alternative to study the temporal evolution of the elements in each sequence and thus chemical enrichment rates. Following the previous section, linear regression fits to the data have been performed to help interpreting the results. When studying the abundance ratios in the [C/N] plane, most of the merged sequences seen in Figure 5 break down in two separate sequences.

Interestingly, the α-capture elements O and Mg, which showed a sequence in the TW diagram of Figure 5 with different slopes, merge into one sequence in Figure 6. This might be due to the primary nature of this element, which is produced by massive stars regardless of the initial metallicity of the stars. Silicon, on the other hand, has different slopes for the blue and the red sequence, providing evidence of the SN Ia production of this element, in addition to SN II. Tight [O/Fe] or [Mg/Fe] relations with age have been discussed in the literature (Silva Aguirre et al. 2018; Delgado Mena et al. 2019; Haywood et al. 2019; Hayden et al. 2020). That the relation between [O/Fe] or [Mg/Fe] with [C/N] is tight reinforces the postulation of using [C/N] as a proxy for precise ages in RC stars.

[C+–Ni]/Fe) abundances present a large scatter, with a slight negative trend as a function of [C/N] for both groups. Because at these metallicities AGBs produce C and N, the abundance ratio is expected to increase with time, hence showing a negative trend with [C/N]. Both sequences have an offset, suggesting that the red stars have had more pollution from AGB stars than the blue sequence at a given time. That could happen if star formation is fast, reaching higher metallicities at a given time. The higher metallicities serve as seeds for higher C and N production in AGB.

While no significant offset between the [Al/Fe] mean abundances of the blue and red groups is found, the overall trends show opposite slopes, with the blue sequence increasing with [C/N] while the red sequence decreasing with [C/N]. The regression fits are however uncertain, because the abundances have high scatter. Aluminum is an odd-z element that is produced inside stars and is expelled into the interstellar medium via core-collapse SNe. More specifically, its production yields from nuclear reactions that use Ne and Na as seeds. While these are also produced generally inside stars, higher-metallicity stars have a larger Al production because some seeds are already available (Kobayashi et al. 2020a). This metallicity dependency shows as a stronger effect in the different sequences.

Calcium shows a stark discontinuity between the red and the blue sequence in the [Ca/Fe]–[C/N] plane, breaking down from the TW diagram shown in Figure 5. The abundances follow tight relations that have opposite trends, in which the blue sequence is positive and the red sequence is negative. This is very similar to the case of [Al/Fe], which can be understood from the same arguments. Calcium is an α-capture element produced in massive stars but is a secondary element whose yields depend on metallicity. Abundances of Ca are in general well measured; there are many clean lines with accurate atomic data for calcium in the APOGEE spectra, as well as in optical spectra (Jofré et al. 2019), therefore the trends here are more accurate than in the case of aluminum.

The bottom panels of Figure 6 show the abundances of titanium, manganese, and nickel. All of the abundance ratios show similar behavior in their differences between the blue and the red stars, in which the trends as a function of [C/N] have similar direction but a systematic difference, with the red stars being overall more enhanced. Both [Ti/Fe] and [Mn/Fe] have large scatter in their abundances, but [Ni/Fe] is tight. Titanium is a difficult element because it behaves like an α-capture element and therefore commonly associated with that family, even if its production mechanism is not like the rest of the α-capture elements. Modern theoretical yields of Ti do not match the observations (Kobayashi et al. 2020a), making it difficult to interpret why both sequences have an offset in the [Ti/Fe]–[C/N] plane. This offset is also seen in N20.

Mn and Ni on the other hand are produced in SNe Ia, and given the variety of progenitors for SNe Ia, including the binary companion of exploding white dwarfs, both elements have a dependency on metallicity (Kobayashi et al. 2020b) and on the explosion mechanism (Palla 2021). Manganese, while difficult to measure because of the strong hyperfine structure splitting in their lines, is one of the best-suited elements to test chemical evolution caused by SNe Ia. The stark differences seen in both sequences in the [Mn/Fe]–[C/N] plane hint toward two populations having formed in different environments, leading to different types of SNe Ia. Two stars of the same [C/N] (e.g., age) have quite different [Mn/Fe]. This is reinforced by the [Ni/Fe]–[C/N] panel. The differences in [Ni/Fe] are smaller for coeval stars as in the case of manganese, but still significant given the overall scatter in [Ni/Fe] abundances is much tighter.
It is worth commenting on the abundance planes that are in tension with N20, namely [O/Fe], [Mg/Fe], [Al/Fe], and [Ca/Fe]. N20 found that [O/Fe] had a large difference between sequences, while Mg had a change in its trend. In addition, the red sequences of N20 for [Al/Fe] and [Ca/Fe] were positive and steeper compared to the blue sequences. Here we obtain negative trends. There are some possible explanations that can help in understanding this difference. First, there is a selection effect in which an [$\alpha$/M] cut has been applied to select the thin disk only. This means that here it is not possible to reach high values of Mg, O, and Ca of N20. Second, the abundances might have significant offsets between both samples, because they are determined from very different methods and spectral signatures (fitting molecules in the case of APOGEE and determining equivalent widths of atomic lines in the case of N20). This can lead to large differences in final abundances (Jofré et al., 2017b). Third, the ages of the stars from the N20 red sequence can be up to 10 Gyr, whereas here the sequence might reach 6 Gyr at most (see Figure 1). Furthermore, the [C/N] range of the red sequence (~0.1 dex) implies a range in age of a few Gyr, which makes the “age trend” for the red group based on the [C/N] abundances not directly comparable with N20’s age sequences.

3.3. Uncertainties

3.3.1. 3D and Non-LTE Effects

While the different trends might be interpreted as an overlap of populations tracing different star formation histories, it is important to consider possible systematics caused by 3D and non-LTE effects. For example, Amarsi et al. (2019) discussed how O abundances are affected by 3D and non-LTE effects at
high metallicities. When an accurate prescription of the O triplet lines is considered for the determination of O, the apparent plateau of [O/Fe] observed at high metallicities is not seen. APOGEE results are obtained from molecular features, under the prescription of 1D and LTE, and present a plateau. The separation between the sequences in the [C/N]–[Fe/H] relation occurs at that metallicity range, and might be responsible for part of the differences found in the TW diagram in Figure 5 for both sequences.

Other elements might also be affected by this. The recent work of Amarsi et al. (2020b) illustrates the differences between LTE and non-LTE abundances for dwarfs and giants in the GALAH survey (Buder et al. 2020). While it is not possible to directly compare the effects of giants in optical and IR spectra, one can expect differences of the same order of magnitude. In that work, abundances that have a metallicity dependence on this effect at solar metallicities in giants are C, Mg, Al, and Mn. Indeed, Jönsson et al. (2020) attributed some of the Mg features at solar and supersolar metallicities in the APOGEE data to this effect. As commented in Jönsson et al. (2020), the next data releases of APOGEE will include non-LTE corrections. It will be interesting to see if the breaks found between the red and blue sequence remain after these effects have been considered.

3.3.2. Contaminations and Biases in RC Stars

The results presented here are based on the assumption that [C/N] correlates with age. In order to minimize systematic effects in this correlation, only the RC stars have been considered. This allows us to have a sample of well-determined distances (Leung & Bovy 2019) as well as stars with very similar stellar parameters. The latter is necessary to relate differences in abundances with some astrophysical reason and not because of systematic uncertainties in the spectral analysis (Nissen & Gustafsson 2018).

Still, restricting the parameter space does not ensure that [C/N] is affected by other inner processes inside red giants, for example, rotation (Salaris et al. 2015) or thermohaline mixing (Lagarde et al. 2017). Other fundamental problems in our understanding of stellar evolution theory still imply uncertainties in ages, which make a direct estimate of [C/N] and age in red giants difficult, such as possible dependencies of metallicity on the mixing length theory (Tayar et al. 2017), or simply the stellar evolution code employed (Silva Aguirre et al. 2020; Tayar et al. 2020). Binary evolution and mass transfer can also induce scatter in the [C/N]–age relation. If stars transfer mass from a binary, the [C/N] could be affected, and hence cannot be directly used as a mass (or age) proxy. Some such stars might not show signatures in the spectra that could hint toward a binary evolution, because the binaries could have merged and now be a single star (Jofré et al. 2016; Izzard et al. 2018).

Distinguishing a star that is younger from one that has experienced mass transfer from the [C/N] abundances is still not obvious (Hekker & Johnson 2019).

Using RC stars can further induce biases in the [C/N]–age correlation. Actually, Masseron & Gilmore (2015) avoided using RC stars in their discussions, because from their spectral parameters alone, it is difficult to disentangle them from lower red giants branch (RGB) stars, which are at an earlier evolutionary phase (see also Masseron & Hawkins 2017). Hasselquist et al. (2019) also avoided the parameter space of the RC in their [C/N]–[Fe/H] relations. Using RC stars can be a problem because low-mass stars experience further mixing and mass loss while at the tip of the RGB, e.g., before settling in the red clump. Stars of higher mass do not experience this as the phase at the tip of the RGB is very short. This issue was investigated in Martig et al. (2016), who studied an empirical relation between ages and [C/N] abundances using the first APOCASK catalog (Pinsonneault et al. 2014). That sample has stars with APOGEE spectra (determining same C and N abundances as here) but also with astroseismic observations from Kepler. The latter allows us to know from the power spectrum of such observations the evolutionary phase of the stars. Martig et al. (2016) benefited from the seismic analysis and distinguish stars in the RC and the RGB, deriving two different age–[C/N] relations, yet both with comparable accuracies (see also Lagarde et al. 2017). They further applied the age–[C/N] relation derived for the RC in APOKASC to the entire RC catalog of Bovy et al. (2014) stars and found consistent results as when applied to APOKASC only.

Masseron et al. (2017) also studied the effect of extra mixing in RC stars by comparing nitrogen abundances of APOGEE (and APOKASC) stars with different RGB models considering extra mixing such as thermohaline mixing. While theoretical predictions hinted at an increase in N along the RGB because of extra mixing, the observations of thin-disk solar-metallicity stars did not support the predictions. In fact, only observations of metal-poor stars showed an increase of N along the RGB. They explained this by a mass effect, namely that their thin-disk solar-metallicity sample was in general more massive than the metal-poor sample. The higher the mass of the star, the shorter its RGB phase, hence the smaller the effects of extra mixing. The stars used here are selected to be solar-metallicity thin-disk stars, hence the effects of extra mixing altering the [C/N] abundances as a proxy for age should be small.

It is finally worth commenting that by selecting the RC in the thin disk at solar metallicities there is a bias induced toward young stars. Bovy et al. (2014) discussed how these biases are increased in their RC catalog because of the selection cuts, stressing that the RC does not randomly sample the underlying age distribution of stars, but instead the distribution is skewed toward younger ages. Further noise can be due to contamination in the RC selection, because the RC catalog has a 95% purity (Bovy et al. 2014). These outliers, however, while present, still allow us to see that there is an overall trend of [C/N] and [Fe/H], which results from different chemical enrichment histories in the disk, the main focus of this work.

4. Discussion

4.1. The Evolutionary History of the Galactic Disk

A interesting prospect of taking the chemical abundances to study the evolution of stellar populations is interpreting phylogenetic trees (Jofré et al. 2017a; Jackson et al. 2021). As explained in these papers, using phylogenetic trees in this context is possible because there is heredity between stars through the chemical abundances, in addition to descent with modification, i.e., each stellar generation is more metal rich than the previous one, hence modifying the chemistry of the ISM. Because understanding and quantifying these two processes are at the core of phylogenetic studies, trees are a suitable tool that can be applied in Galactic chemical evolution studies.
Jackson et al. (2021) used abundances of solar twins that are very similar to those used by N20 to build such a tree. It showed two main stellar populations (branches), which were attributed to the thin and the thick disk. Jackson et al. (2021) found that the root of the thin-disk branch contained a group of stars whose branching pattern was poorly supported. This group had stars of very similar abundances and ages. Their kinematics suggest their origins spread out the disk. The authors concluded this population could be part of the old thin disk and perhaps product of a star formation burst. The blue sequence in fact has two bumps (see Figure 3), in particular one at lower metallicities and higher \(\text{[C/N]}\). It could be that this bump is the possible product of the star formation burst seen in the phylogenetic tree of Jackson et al. (2021). This bump could also be simply a selection effect, therefore concluding on its nature requires addressing the selection function of this sample.

The two main branches found in the tree might be attributed to the two AMRs that trace two different stellar populations. Perhaps the red group here is in fact the tail of the thick disk, as the red group traces a faster chemical enrichment history, an older population, and a hotter dynamics overall. The ages of the red group here and in Jackson et al. (2021) are not comparable as already discussed above. It is however difficult to be certain about this interpretation when looking at the sequences of panels outside the solar neighborhood (Figure 2), in which one of the two sequences seems to disappear. It would be interesting to see the branching pattern of phylogenetic trees outside the solar neighborhood, but that is a subject for another study.

As extensively discussed by N20, two sequences of age and metallicity in the solar neighborhood can be explained considering the two-infall model for chemical evolution (Chiappini et al. 1997). In such a model, there are two main episodes of star formation in the disk, which are different from each other. In the two-infall model, the first episode was fast, quickly enriching the interstellar medium with metals and forming the stars now belonging to the thick disk. Later on, a second episode that is going on to date, has been forming the thin-disk stars. Both episodes are driven by some inflow of metal-poor gas from the outside. In the thin disk, however, the enrichment of gas higher in the inner regions translates into a negative metallicity gradient with Galactic radii. The ages of the red group here and in Jackson et al. (2021) are not comparable as already discussed above. It is however difficult to be certain about this interpretation when looking at the sequences of panels outside the solar neighborhood (Figure 2), in which one of the two sequences seems to disappear. It would be interesting to see the branching pattern of phylogenetic trees outside the solar neighborhood, but that is a subject for another study.

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4.2. Age–Metallicity Relation, Radial Migration

As more accurate and precise data are available for stars in the Galaxy, the AMR is still a fundamental tool to study the formation of the disk (Silva Aguirre et al. 2018). It particularly helps to constrain the effects of radial migration. Johnson et al. (2021) present an interesting recent discussion about the effect of the dual AMR. The chemical evolution models discussed by Johnson et al. (2021) study the effect on the AMR using different star formation rates. In particular, a star formation rate that they call “Late Burst,” accounting for a later star formation burst produced by perhaps a galaxy merger, can create a bimodal AMR, especially at inner Galactic radii. They were however unable to confirm the duality of the AMR when comparing with data of Feuillet et al. (2019), which is their benchmark sample for observations, but perhaps considering a subset of stars would allow for higher precision in the data.

The dual AMR here can also be the product of radial migration caused by resonances in the disk (Minchev & Famaey 2010). As shown in that work, moving perturbers such as the rotation of the bar or the spiral structure in the disk can change the motions of the stars, inducing radial migration inwards and outwards in the disk. As long as two perturbers act simultaneously, it is possible to obtain a bimodality in the change of angular momentum of the stars, regardless of the details of the past history of the Milky Way and the pattern speed or strength of such perturbers. This bimodality might cause an effect in the metallicity distribution of the stars. The dual AMR seen only in the solar neighborhood panel of Figure 2 could thus be a signature of a spiral-bar resonance overlap, because it does not need to have the same effect everywhere in the disk.

4.3. The Sun’s Birthplace

It is interesting to comment further on the statement made by Haywood et al. (2019) about the solar birthplace. From radial migration arguments, it is expected that the Sun formed at inner Galactic radii because its metallicity is higher than the metallicity of the ISM in the solar neighborhood 4.5 Gyr ago. They argue, however, that when considering the TW diagrams at different Galactic radii, such as those displayed by Hayden et al. (2015), the solar \([\alpha/\text{Fe}]\) abundance ratios do not fall in the bulk of the abundance distributions of the stars in the inner regions, which have generally higher \([\alpha/\text{Fe}]\) abundances, but rather with the bulk of stars in outer regions.

In Figure 5, the solar abundances lie in the blue groups for all panels. If the red group in Figure 5 corresponds to the tail of the inner disk population and the blue group corresponds to the tail of the outer disk population, then it is possible that indeed the Sun migrated inwards from outer regions in the disk as noted by Haywood et al. (2019).

5. Conclusion

Inspired by the latest results of Nissen et al. (2020) about the two age–metallicity sequences in the solar neighborhood using high-precision analysis of solar-type stars, this work presented an alternative relation of \([\text{C}/\text{N}]\) and metallicity of RC stars to test if the two sequences are present in larger and independent data sets. In red giants, \([\text{C}/\text{N}]\) abundances can have a direct dependence on the stellar mass, hence ages. The advantage to using \([\text{C}/\text{N}]\) instead of ages arises from the fact that measuring precise C and N abundances is more plausible than deriving
ages. As concluded by N20, the two sequences were never seen before because stellar ages are still too uncertain.

For this work, about 18,000 red clump stars were selected from the APOGEE DR16 catalog with precise measurements of [Fe/H], C, and N, in addition to Galactic heights below 800 pc and solar scaled α abundances. The density maps of [C/N] versus [Fe/H] for different Galactic radii revealed that indeed in the solar neighborhood two separate sequences of [C/N] and age are present. Inner and outer regions in the disk, however, show just one dominant group.

By analyzing other elemental abundance ratios and dynamical distributions of stars belonging to each sequence, it was possible to see that the sequences are different. One is composed of stars that are more metal rich and [C/N] rich, suggesting an old population. The other is composed by stars that cover a wider range in both metallicity and [C/N], reaching lower values and suggesting that it contains younger stars. The old and metal-rich population was shown to be kinematically hotter with more eccentric orbits than the younger population. This is consistent with current expectations of metal-rich and old stars formed at inner parts of the disk moving to the solar vicinity through radial migration or simply passing by due to their eccentric orbits. A dual AMR might also be predicted by discrete episodes of star formation, which is predicted in some models.

The [C/N]–[Fe/H] sequence that covers a wider range in [Fe/H] showed two bumps of stars at slightly different [C/N] abundances (heights). This bump ages could be related to the group found in the phylogenetic tree by Jackson et al. (2021), which was attributed to the product of a star formation burst. To conclude on this hypothesis, however, counting stars should take selection effects into account.

If the two populations are attributed to one being the tail of the inner disk and the other one the tail of the outer disk, each experiencing different chemical enrichment histories, the solar abundances match better the outer sequence than the inner sequence. This supports Haywood et al.’s (2019) claims about the Sun forming in outer regions migrating toward the inner regions and not the other way around, as proposed in most studies.

Modern survey data enable us to find structure in the disk in several ways, allowing us to make progress in the understanding of how our home galaxy formed. This work shows the power of high-resolution spectra of a large number of stars, which give us not only information on metallicity and the classical [α/Fe] ratio, but on other abundances, too. This increases our chances of finding structure in the Milky Way. Here [C/N] was used as a key alternative to age, and other abundances such as Mn, Al, Ni, and Ca were used to evaluate how the formation histories of the structures could be different provided the systematic uncertainties in elemental abundance measurements are properly addressed. The revolution of combining multidimensional chemodynamical information in order to reveal the shared history of the stars in our Milky Way is just starting.

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