On the metallicity dependance of the \([Y/Mg]\) – age relation for solar type stars

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ABSTRACT
Several recent studies of Solar twins in the Solar neighbourhood have shown a tight correlation between various elemental abundances and age, in particular \([Y/Mg]\). If this relation is real and valid for other types of stars as well as elsewhere in the Galaxy it would provide a very powerful tool to derive ages of stars without the need to resort to determining their masses (evolutionary stage) very precisely. The method would also likely work if the stellar parameters have relatively large errors. The studies presented in the recent literature span a narrow range of \([Fe/H]\). By studying a larger sample of Solar neighbourhood dwarfs with a much larger range in \([Fe/H]\), we find that the relation between \([Y/Mg]\) and age depends on the \([Fe/H]\) of the stars. Hence, it appears that the \([Y/Mg]\) – age relation is unique to Solar analogues.

Key words: Stars: abundances, fundamental parameters, solar-type – Galaxy: disc

1 INTRODUCTION
To build a full picture of how a galaxy like our own Milky Way formed and evolved we can make use of the properties of the stars (e.g., age and elemental abundances) as tracers of past events (e.g., the star formation history). Until recently the study of elemental abundances and ages for stars was limited to the direct Solar neighbourhood or special places in the Milky Way such as globular clusters or the bulge. This situation is now rapidly changing with large spectroscopic data-sets (e.g., Majewski et al. 2015) coming on-line and the first data-release from ESA’s Gaia satellite (Gaia Collaboration et al. 2016; Lindegren et al. 2016).

Determining elemental abundances is in principle straightforward, but not necessarily simple. See, for example Meléndez (2014) for a comprehensive summary of difficulties in the analysis of the Sun and solar analogues. Methods to enhance the precision in the abundance determinations have been identified and resulted in some very interesting findings, such as the inhomogeneity in elemental abundances found in the open cluster Hyades by Liu et al. (2016). Determining ages of stars is, on the other hand, truly difficult. The most commonly used method is to compare the absolute luminosity (or magnitude) and effective temperature (or colour) of the star with theoretical models, isochrones or stellar evolutionary tracks. This requires that we have good measurements of the apparent luminosity of the star, the distance to the star, and either the temperature or the colour. In addition we need a measure of the metallicity (or the iron content \([Fe/H]\)) as the isochrones and evolutionary tracks change as the metallicity changes (e.g., Salasnich et al. 2000). In principle this method should be applicable to many types of stars – however, in practise, it is currently limited to turn-off stars and stars on the sub-giant branch, as the isochrones are most sensitive to age in these regions of the Hertzsprung-Russell diagram. If we also have the mass we can place the star in the \(T_{\text{eff}} - \log g\) diagram together with the relevant isochrones and read off its age with much higher precision for many more evolutionary stages. Recently, asteroseismic data have made it possible to derive masses for stars on the red giant branch (Chaplin & Miglio 2013). Regardless of the method used to place the star in the Hertzsprung-Russell diagram the uncertainty in the age always depends strongly on the errors in the measurements needed to place the star accurately on the correct stellar track.

The difficulties in obtaining good ages for all types of stars from isochrones and evolutionary tracks have fuelled an interest in alternative methods. We will not discuss all of them here but refer to the comprehensive review by Soderblom (2010). One new example includes studies that explore mass indicators in stellar spectra. Using results from APOGEE Masseron & Gilmore (2015) show that the ratio of carbon to nitrogen (\([C/N]\)) is an age indicator for red giant branch stars. Similarly, Ness et al. (2016) and Martig et al. (2016), using different methods, find that NIR red giant spectra show features (mainly carbon lines) that are
sensitive to mass. Other lines may also show a dependance on mass. This has been little explored so far (mainly due to the lack of good mass determinations). Bergemann et al. (2016) show that the Hα-line in K giants is sensitive to mass. Their finding is (so far) purely empirical.

Studies of elemental abundances in the Solar neighbourhood have shown some interesting correlations. Bensby et al. (2014) found that [Ti/Fe] correlates relatively well with age. Battistini & Bensby (2016) found several interesting correlations between neutron capture elements, e.g., [Sr/Fe] and [Zr/Fe], and age.

The first evidence of a linear correlation between the ratio of yttrium to magnesium ([Y/Mg]) and stellar age was presented by da Silva et al. (2012) for a sample of 25 solar-type stars. Recently, Nissen (2015) found a strong correlation between [Y/Mg] and age for a small sample of solar twin stars. This result has been reproduced by Spina et al. (2016) and Tucci Maia et al. (2016). The total spread in [Fe/H] for the solar twins reported in these studies is about 0.3 dex (about ±0.15 above and below solar). In all three studies the very high precision is achieved thanks to a strictly differential analysis focusing on stars with very similar parameters. In most studies of elemental abundances in the Solar neighbourhood or elsewhere, this is not the case. Instead large ranges of stellar parameters are included in order to obtain larger samples (e.g., Edvardsson et al. 1993).

This is an intriguing result pointing to the possibility of using measurements of [Y/Mg] to derive the age of solar-like stars. The questions then naturally arise: How universal is this correlation? Does it hold for a larger range of [Fe/H]? Does it hold for stars not in the Solar neighbourhood? Does it hold for stars with different kinematics (i.e., thin vs. thick disc)? In this paper we aim to answer some of these questions.

2 INVESTIGATING THE METALLICITY DEPENDENCE OF THE [Y/MG]–AGE RELATION

The main dataset used in this study is taken from Bensby et al. (2014). Briefly, Bensby et al. (2014) analysed high-resolution, high signal-to-noise ratio spectra for 714 dwarf stars in the Solar neighbourhood. The stellar parameters are based on an analysis of the spectra, taking the stellar parallaxes from Hipparcos (Perryman et al. 1997) into account. Elemental abundances were obtained for several elements, including Mg. Additional elemental abundances for iron peak elements and some r- and s-process elements have been presented in Battistini & Bensby (2015) and Battistini & Bensby (2016) (but note that the Y-abundances are from Bensby et al. 2014). We refer the reader to the papers describing the full analysis for a discussion of how stellar parameters were derived and the analysis of lines with, e.g., hyperfine structure was done.

The left panel of Fig. 1 shows the [Y/Mg] trend with age for all stars in Bensby et al. (2014) that have \( \sigma_{\text{age}} < 1 \) Gyr. As in Nissen (2015) (their Fig. 10) we see a downward trend such that older stars have lower [Y/Mg]. The spread at a given age is significant and this spread results from stars with lower [Fe/H] on average having lower [Y/Mg] at a given age. The right panel of the figure shows the same plot but now only for stars that have \( T_{\text{eff}} \pm 100 \) K of that of the Sun, i.e., solar analogues. Solar twins are stars with \( T_{\text{eff}} \) and \( \log g \) very close to those of the Sun (Hardorp 1978; Cayrel de Strobel et al. 1981), whilst solar analogues is a more loose definition with stars being ‘very similar to the sun’ but not necessarily a twin to the sun. The solar analogues in Fig. 1 show the same downward trend of [Y/Mg] as age is increasing as found for the full sample. Also here we see that at a given age stars with higher [Fe/H] also have higher [Y/Mg]. This is particularly present for ages 4–8 Gyr. For the oldest stars the change of [Y/Mg] as a function of [Fe/H] is less obvious, but still noticeable.

We have done the same analysis for the dataset by Brewer et al. (2016) of ∼1600 dwarf stars in the Solar neighbourhood. This sample consists of stars being monitored for radial velocity variations and hence potentially harbouring planets. The stars exhibit very similar trends in the [Y/Mg] versus age diagram as the stars in the Bensby et al. (2014) sample, but as the sample stars are centered on solar metallicity and have very few stars even at –0.5 dex in [Fe/H] the resulting trend with [Fe/H] is less obvious, although still present, giving further weight to our findings.

Are the trends we see in Fig. 1 influenced by the mixture of stellar populations present in the Solar neighbourhood (e.g., the thin and the thick disc) or are the findings universal? In the samples from Nissen (2015) and Spina et al.
(2016) almost all the stars have kinematics very similar to that of the sun, what we refer to as thin disc kinematics and only a few stars in each sample have the enhanced α-abundances typical of the thick disk or thick disc kinematics. In Nissen (2016) three stars with α-enhanced abundances fit the thin disc trend for [Y/Mg] – age well. This is also the case for the ten stars with thick disk kinematics studied in Tucci Maia et al. (2016). The sample by Bensby et al. (2014) was chosen to probe the abundance trends in stars with typical thin and thick disc kinematics. When we divide the sample according to their kinematics into thin and thick disc stars (following the probabilistic division used in Bensby et al. 2014) we find that the trends are a little less obvious but overall they persist.

The influence of ‘radial migration’ in the Milky Way means that the stars in the Solar neighbourhood come from a variety of birthplaces, in a way that can not be simply determined from their kinematics (e.g. Roskar et al. 2008; Schönrich & Binney 2009). This implies that the [Y/Mg] trend observed locally does not necessarily apply to stars with a single birthplace, but to stars born across much of the Milky Way. It would therefore be valuable to determine observationally that the trend is seen elsewhere. Whilst waiting for such samples we can only resort to using the kinematics of the stars today to infer their birth places by using, e.g., their mean distance to the Galactic centre as a proxy for their birth place (compare, e.g., Edvardsson et al. 1993). Recently, Adibekyan et al. (2016) used this for stars with solar like properties. In relation to the [Y/Mg] – age relation they found no difference between stars from the inner disk and the solar neighbourhood, which is agreement with the results from Bensby et al. (2014).

As a check we have re-derived ages for the Bensby sample using a version of the Bayesian method described by Binney et al. (2014) with the Parsec isochrones (Bressan et al. 2012). Our method differs from that of Binney et al. (2014) in that we have chosen to take a flat prior in both age and metallicity. We also take isochrones with a wider spread of metallicity and do not allow as wide a spacing in Z between isochrones. We exclude the pre-main sequence phase from the isochrones, because there are no indications from the spectra that these stars are pre-main sequence. All trends with age persist with both methods.

3 DISCUSSION

3.1 Potential effects of target selection

When we select stars for spectroscopic studies with high resolution and high signal-to-noise ratios there can be a tendency to select the brightest stars in the catalogue, as they will be the fastest to observe and we can thus get more stars in our sample. How this might affect the types of stars that make it into an ‘FGK-turn-off’ sample has been explored, e.g., in Feltzing et al. (2001) and Bergemann et al. (2014), where it is shown that old and metal-rich stars are preferentially disfavoured when a magnitude cut is imposed onto the sample. This is natural as old and metal-rich stars are both fainter and redder than young and metal-poor stars.

Can this type of selection effect have influenced the trend shown in Fig. 1? It is possible, in so much as the trend of [Y/Mg] as a function of age for solar metallicity stars should be flatter (i.e., old and metal-rich stars should occupy high [Y/Mg] and old age, where there currently are no stars present). Do these types of stars exist? Several studies in the Solar neighbourhood have shown such stars but the evidence is not robust (see, e.g., Feltzing et al. 2001; Casagrande et al. 2011).

We have also considered the possibility that the trends we see in this dataset are affected by the choice of [Fe/H]. At all but the oldest ages we have stars covering the full range of [Fe/H] seen in the discs of the Milky Way. Hence, we may conclude that this particular selection bias likely has not influenced our results.

3.2 Origin of the [Y/Mg] – age trend for solar twins

The link between the star formation history of the Milky Way and the resultant Galactic chemical evolution has been well known for some time now (Tinsley 1979; Matteucci 2003), and the [Y/Mg] clock is a natural consequence of this. Y is a neutron-capture element produced through the s-process (or slow neutron capture process), which occurs in asymptotic giant branch stars (AGB stars, for a summary of nuclear reactions in AGB stars see Karakas & Lattanzio 2014). All stars with masses between 1 and 8 $M_\odot$ evolve to become AGB stars in their final phases. Due to this restricted mass range, the enrichment of the ISM with s-process material only begins roughly 500 Myr after the formation of the first population of stars (e.g., Sneden et al. 2008). Lower mass AGB stars (1 – 4 $M_\odot$) in particular produce large amounts of Y, meaning that the enrichment of the ISM with Y gradually increases with time (Travaglio et al. 2004; Fishlock et al. 2014), and therefore younger stars will have larger Y abundances (compare Fig. 2).

Magnesium, in contrast, is an α-element, and is mostly produced in Type II supernovae. These take place in the final stages of the evolution of massive stars (greater than 10 $M_\odot$), and so typically occur quickly after the stars formed. Therefore the ISM is almost immediately enriched in α-elements, and becomes over-abundant in these compared to other elements. As time progresses and with the advent of Type Ia su-
Figure 3. [Ti/Fe] as a function of age (in Gyr) for all stars with $\sigma_{\text{Age}} < 1$ Gyr from Bensby et al. (2014). The stars are colour coded according to their [Fe/H] (as indicated in the colour bar). A typical error bar is shown.

We conclude that although it is relatively easy to find various abundance ratios that appear to vary in lock-step with age the interpretation of such relations is not obvious. There can often be an underlying explanation from the point of view of nucleosynthesis or from selection biases. A thorough understanding of both of these issues is required for a correct interpretation of the observations.

3.3 Other relations between elemental abundances and age

The usefulness of the $\alpha$-abundance ‘cosmic clock’ as a proxy for age has been the subject of discussion in the literature (Fuhrmann 1998; Ramírez et al. 2013; Recio-Blanco et al. 2014), and underpins the main argument for the [Y/Mg] clock as examined in this paper. Looking more specifically at this trend, Figure 3 shows the relation between [Ti/Fe] and age. Similar figures have been presented in Bensby et al. (2014) and Haywood et al. (2013). Here we explicitly indicate the [Fe/H] values for the stars as well as the Ti abundances and age and find that the trend is not so straightforward, due to a large amount of [Fe/H]-related scatter in the plot. Figure 7 in Haywood et al. (2013) in fact shows a similar pattern, although perhaps less obvious thanks to the colour coding scheme they use. We find that also the Brewer et al. (2016) sample shows exactly the same pattern. At young ages, there are a wide range of [Ti/Fe] values seen, and in particular a significant group of more metal-poor stars with [Ti/Fe] $> 0.1$. A star with [Ti/Fe] = 0.2 and [Fe/H] = −0.5, for example, could have an age anywhere in the range of approximately 3 to 14 Gyr. Stars with very different [$\alpha$/Fe] can have the same age, but hardly varying [Fe/H]. Not only an observational effect, this is also seen in chemical evolution models such as that of Schönrich & McMillan (2016).

The wide scatter in the trend, and the significant number of outliers, in the [$\alpha$/Fe] ratios cast some doubts on the usage of these ratios as indicators of age (e.g., as applied in Bovy et al. 2012).

4 CONCLUSIONS

We confirm the downward trend in [Y/Mg] with age first noted in da Silva et al. (2012) and thereafter explored further by Nissen (2015). Our sample is fully independent in all aspects (spectra, spectral analysis, and age determination). Our sample has lower precision in the measurements (lower signal-to-noise ratios) but covers a wider range of types of stars and, crucially, a much larger range in [Fe/H].

We find that the downward trend strongly depends on the [Fe/H] of the stars. For solar [Fe/H] the trend is clear but for stars with [Fe/H] $\approx$ −0.5 dex, the trend is almost flat and has no predictive power on age. Our conclusion is thus that there exists clear a correlation between [Y/Mg] and age, but it depends on [Fe/H] too. We find that independent samples show similar results and we have also tested our age determination and found that regardless of the method used the results persist.

We would propose the following investigations to fully conclude on the relation between [Y/Mg], age and [Fe/H]: The first ‘obvious’ study would be a dedicated observing
programme targeting stars with very similar stellar parameters as in, e.g., Nissen (2015), but with [Fe/H] = −0.5 dex. This should then be compared with the results from Nissen (2015), Spina et al. (2016) and Tucci Maia et al. (2016). The best would be to select stars with effective temperature and surface gravities close to solar for a study that is as differential as possible between these studies and the new study. It would be exciting to perform similar studies also for stars not in the solar neighbourhood. Selection of suitable samples should be possible already with the upcoming TGAS data from the first Gaia release (Michalik et al. 2015).

Another ‘obvious’ study would be to go after stars on the red giant branch with asteroseismically determined stellar mass for which thus good ages can be derived and do a highly differential study of their elemental abundances both at solar metallicity and −0.5 dex. This should show if the trends are also persistent for more evolved stars or not. Atomic diffusion might play a role when comparing turn-off stars and red giant stars, but it is expected that the differences would be smaller for higher metallicities (see, e.g., Gruyters et al. 2013).

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