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High-precision abundances of elements in stars with asteroseismic ages

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Abstract. High-precision abundances of elements have been derived from HARPS-N spectra of F and G main-sequence stars having ages determined from oscillation frequencies delivered by the *Kepler* mission. The tight relations between abundance ratios of refractory elements, e.g., [Mg/Fe] and [Y/Mg], and stellar age previously found for solar twin stars are confirmed. These relations provide new information on nucleosynthesis and Galactic evolution. Abundance ratios between volatile and refractory elements, e.g., [C/Fe] and [O/Fe], show on the other hand a significant scatter at a given age, which may be related to planet-star interactions. This is a potential problem for chemical tagging studies.

Keywords. Stars: abundances, Stars: oscillations, Planet-star interaction, Galaxy: disk, Galaxy: evolution

1. Introduction

Recent high-precision determinations of abundances of elements in solar twin stars have revealed the existence of tight correlations between some abundance ratios and stellar age (Nissen 2015, 2016; Spina *et al.* 2016). Thus, [Mg/Fe] decreases by ~ 0.1 dex over the lifetime of the Galactic disk, whereas [Y/Mg] increases by ~ 0.3 dex. These results are based on ages derived from isochrones using spectroscopic values of effective temperature and surface gravity, which could introduce spurious trends if errors in age and abundances are correlated. As a check, high-precision abundances have therefore been derived from high S/N spectra for a sample of *Kepler* LEGACY stars (Silva Aguirre *et al.* 2017) for which ages are available from asteroseismology. Here, we summarize the results and briefly discuss implications for studies of Galactic chemical evolution. More details may be found in Nissen *et al.* (A&A, submitted).

2. Observations and analysis

The high-resolution ($R \simeq 115\,000$) HARPS-N spectrograph (Cosentino *et al.* 2012) at the 3.6 m TNG telescope on La Palma was used to obtain spectra with $S/N > 250$ of ten *Kepler* LEGACY stars (see Fig. 1) selected to have effective temperatures, surface gravities and metallicities in the ranges $5700 < T_{\rm eff} < 6400$ K, $3.9 < \log g < 4.5$, and $-0.15 <$ [Fe/H] < 0.15. The ages of these stars derived from oscillation frequencies range from 1 Gyr to 7 Gyr with uncertainties from 0.3 Gyr to 0.8 Gyr, which estimate takes into account both the errors of the frequencies and differences of ages derived by different analysis methods.

MARCS model atmospheres (Gustafsson *et al.* 2008) were used to obtain abundances of elements from equivalent widths of weak to medium-strong spectral lines (see Table 2 in Nissen 2015). Using recent statistical equilibrium calculations based in some cases

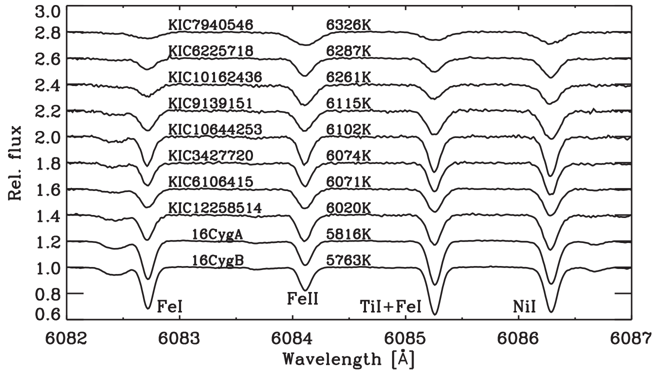

Figure 1. HARPS-N spectra in the 6082 - 6087 Å region arranged in order of $T_{\rm eff}$ and offset in successive steps of 0.2 units relative to the spectrum of 16 Cyg B.

on quantum-mechanical hydrogen collisional rates (see review by Barklem 2016), the derived LTE abundances were corrected for non-LTE effects. The differential corrections relative to those for the Sun are quite small, i.e., in the range -0.03 to $+0.03$ dex, but are not negligible compared to the errors of the abundances, σ[X/H] ~ 0.02, as estimated from the line-to-line scatter of the derived abundances and the uncertainties of stellar atmospheric parameters.

Apart from stellar ages, asteroseismology also provides very precise values of stellar gravities, $\sigma(\log g) < 0.01$. This makes it possible to determine $T_{\rm eff}$ by requesting that the average Fe abundances derived from Fe I and Fe II lines should be the same; as seen from Fig. 1, the ratio of the strength of Fe II and Fe I lines is a sensitive measure of $T_{\rm eff}$. In doing so, we applied non-LTE corrections for Fe I lines from Lind *et al.* (2012). The estimated precision of $T_{\rm eff}$ is 15 K to 25 K.

3. Results and discussion

Figure 2 shows [Fe/H] and [Mg/Fe] as a function of age for the *Kepler* stars and 18 solar twins from Nissen (2015), excluding three old α-enhanced stars. As seen the data for the *Kepler* stars confirm the tight relation between [Mg/Fe] and age. In contrast there is no correlation between [Fe/H] and age, but a scatter of 0.10 dex at a given age. Often this scatter in the age-metallicity relation is explained as due to orbital mixing of stars in a Galactic disk formed inside-out causing a radial gradient in [Fe/H] (e.g., Minchev *et al.* 2013), but it remains to be seen if such models are compatible with the very small scatter in [Mg/Fe] at a given age, σ[Mg/Fe] $\simeq 0.01$, for solar metallicity stars. As an alternative explanation of the scatter in the age-metallicity relation, Edvardsson *et al.* (1993) discuss infall of metal-poor gas triggering star formation, which may cause a scatter of 0.1 dex in [Fe/H], but less than 0.01 dex in [Mg/Fe] if the infalling gas has [Fe/H] and [Mg/H] less than -1.

Various abundance ratios between refractory elements, e.g., [Al/Fe], [Si/Fe], [Ti/Fe], and [Zn/Fe], also show a tight correlation with stellar age, and like [Mg/Fe] these ratios decrease with decreasing age. Given that Fe is mainly contributed by Type Ia supernovae, whereas the other elements are primarily made in massive stars exploding as Type II supernovae, the trends can be explained by an increasing ratio between the number of Type Ia and Type II supernovae in the course of time.

As seen from Fig. 3, the *Kepler* stars also confirm the tight relation between [Y/Mg] and stellar age previously found for solar twins (Nissen 2015; Tucci Maia *et al.* 2016).

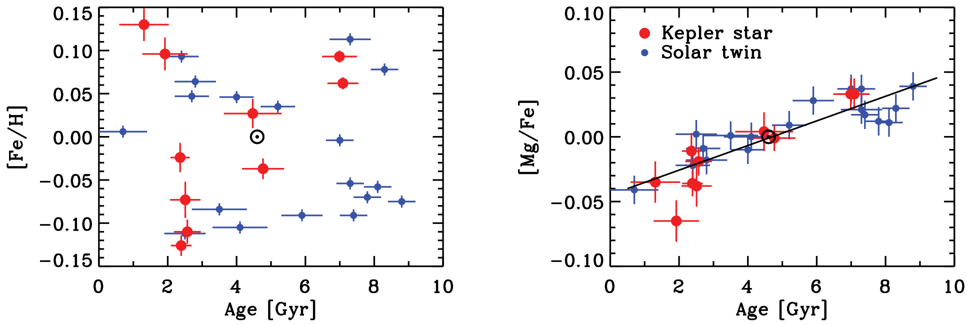

Figure 2. [Fe/H] and [Mg/Fe] versus stellar age.

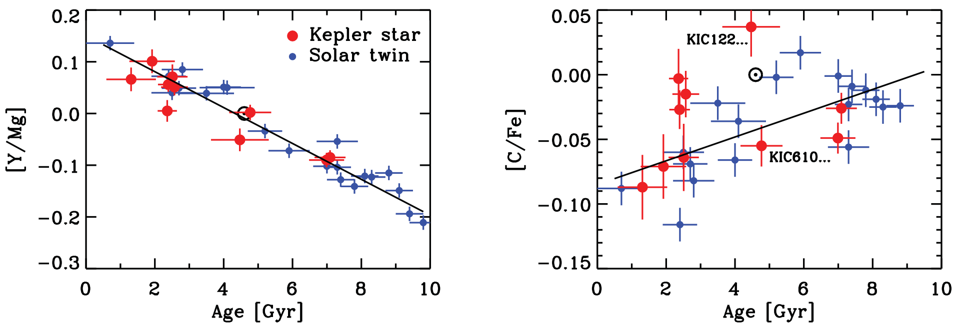

Figure 3. [Y/Mg] and [C/Fe] versus stellar age.

The steep increase of [Y/Mg] over the lifetime of the Galactic disk may be explained by an increasing contribution of *s*-process elements from low-mass AGB stars relative to the contribution of Mg from Type II supernovae. It should, however, be emphasized that the tight relation is only valid for solar metallicity stars. According to Feltzing *et al.* (2017), [Y/Mg] decreases with [Fe/H] at a given age, so a metallicity term has to be included in the calibration, if [Y/Mg] is to be used as a "clock" of stellar ages.

Abundance ratios between volatile and refractory elements have, on the other hand, a rather poor correlation with stellar age. Thus, the scatter of [C/Fe] at a given age cannot be explained by the estimated errors as seen from Fig. 3. In particular, we note that the two stars marked on the figure, KIC 6106415 and KIC 12258514 with about the same age as the Sun, have a difference in [C/Fe] of 0.092 ± 0.028 dex. Significant differences in [X/Fe] between the two stars are also present for other volatile elements. Furthermore, there is a correlation between [X/H] and the condensation temperature, T_c, of the elements in a solar composition gas (Lodders 2003) with different slopes for the two stars as seen from Fig. 4. This may be connected to different degrees of dust-gas separation in the molecular clouds out of which the stars formed (Önehag *et al.* 2014; Gaidos 2015) or to sequestration of refractory elements in planets (Meléndez *et al.* 2009).

Another example of systematic changes of stellar abundances as a function of condensation temperature is shown in Fig. 4 for the two components in the binary system 16 Cyg, which has an asteroseismic age of 7.0 ± 0.5 Gyr. As seen both stars have a positive slope of [X/H] versus T_c indicating that they have lower volatile-to-refractory ratios than the Sun. Furthermore, 16 Cyg A is on average 0.03 dex more abundant in elements than 16 Cyg B and has a slightly steeper dependence of [X/H] on T_c. Given that the stars are members of a binary system, it is unlikely that these abundance differences are due to dust-gas separation in star-forming gas clouds, but the differences may be

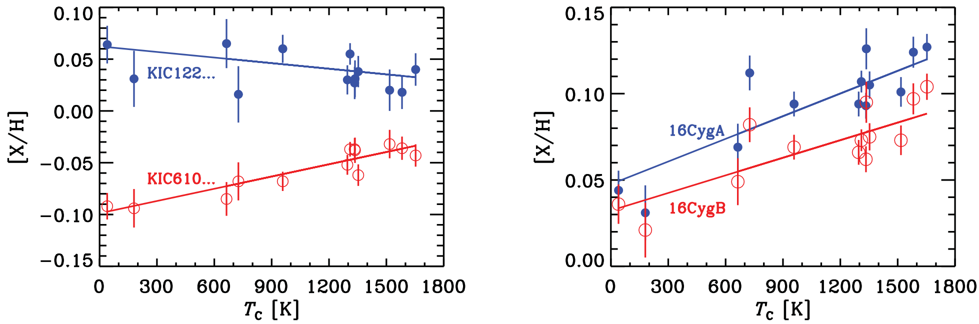

Figure 4. Abundances as a function of condensation temperature of the elements for two stars with the same age as the Sun (left panel) and for the components in the 16 Cyg binary star (right panel).

due to planet-star interactions, because 16 Cyg B has a Jupiter-sized planet (Cochran *et al.* 1997), whereas no planets have been detected around 16 Cyg A. Other cases of abundances differences between stars in binary systems have been found, most notable HAT-P-4 (Saffe *et al.* 2017) for which the components have an abundance difference of 0.1 dex! Whatever the explanation is, such differences are a potential problem in chemical tagging studies aiming at finding stars with a common origin based on their abundances.

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