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[Y/Mg] as a Stellar Chronometer: Combining Asteroseismic and Chemical Data

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Abstract

The determination of stellar ages remains one of the greatest challenges in astrophysics, as age cannot be directly measured. Advances over the last decade highlight a great potential of chemical clocks, particularly abundance ratios involving *s*-process and *α*-elements to estimate stellar ages with improved precision. For a sample of 205 stars observed with the high-resolution spectrograph and 1.65 m telescope at the Molėtai Astronomical Observatory in Lithuania, we determined Y and Mg abundances and derived new asteroseismic ages from TESS observations. Our results reveal the dependence of the [Y/Mg]–age relationship on the Galactic birthplaces of thin-disc stars, while confirming previous results on negligible correlations for thick-disc stars. This study highlights the importance of integrating chemical compositions, asteroseismic data, and precise astrometric measurements from *Gaia* to refine the applicability of chemical clocks and enhance our understanding of Galactic chemical evolution.

Keywords: galaxy evolution; asteroseismic stellar ages; low-mass stars

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1. Introduction

Stellar ages cannot be directly measured, making indirect indicators such as abundances of chemical elements essential. The ratios between *s*-process and *α*-elements, particularly [Y/Mg] and [Y/Al], have proven effective tracers of stellar age since the pioneering studies by [1,2] applied them to solar-type stars. These ratios decrease with age, as yttrium enrichment from asymptotic giant branch (AGB) stars occurs later than magnesium production by Type II supernovae.

However, recent studies have revealed that the [Y/Mg]–age relation is environment-dependent, varying with metallicity [3] and Galactic location [4]. The inclusion of open clusters has made it possible to extend these investigations to more distant regions of the Galactic disc [5–8]. The [Y/Mg]–age relation in the thin disc shows a clear negative slope, reflecting prolonged star formation and a gradual AGB enrichment, while the thick disc displays a flat trend [9], consistent with rapid early formation. Spatial variations across the Galactic disc, flatter in the inner regions and steeper in the outer regions [6], further indicate that this relation encodes information about the local star formation history. Magnetic-buoyancy-induced mixing in AGB stars has been proposed to reduce Y yields at high metallicity [10], providing a theoretical explanation for the lower [Y/Mg] ratios observed in the inner Galactic disc. However, the most recent multi-zone chemical clocks models [11], which adopt a three-infall scenario for disc formation, reproduce the [*s*-/*α*] increase with age in the outer regions but still fail to match the observed [Y/Mg] behaviour in the inner disc, highlighting the complexity of the problem.

Recent advances combining high-precision spectroscopy and asteroseismology, such as the detailed calibration of chemical ages of *Kepler* red giants [12], demonstrate the potential of these techniques to refine empirical relations and anchor theoretical models. Integrating chemical abundances, asteroseismic constraints, and *Gaia* astrometry is therefore essential to recalibrate chemical clocks and improve stellar age determinations across the Milky Way.

2. Methods

We analysed a sample of 205 stars observed with the Vilnius University Echelle Spectrograph (VUES) [13] mounted on the 1.65 m Ritchey–Chrétien telescope at the Molėtai Astronomical Observatory (Lithuania). We used the abundances of yttrium and magnesium determined in [9,14,15]. Additionally, for this work, abundances of yttrium were determined for 110 new FGK stars from archival high-resolution spectra using the same standard LTE analysis techniques. The separation into Galactic thin- and thick-disc components was carried out according to the chemical and kinematic criteria established in those studies.

Asteroseismic ages were derived from the 60 min and 2 min cadence TESS light curves processed with the Lightkurve package [16]. Using asteroseismic parameters $\nu_{\max}$ and $\Delta\nu$ for stars with solar-type pulsations, and spectroscopic effective temperature $T_{\rm eff}$, we calculated stellar mass, radius, $\log g$, and luminosity based on classical scaling relations [17]. Then, we used an online interface PARAM (v.1.5) for the Bayesian estimation of stellar parameters [18–20].

We assumed the solar seismic parameters $\nu_{\max,\odot} = 3141$ μHz and $\Delta\nu_\odot = 134.98$ μHz [21], a solar metal content of $Z_\odot = 0.01756$ [22], an exponential initial mass function [23], and an unknown prior of the evolutionary stage. To account for the mass loss in our calculations, we applied a Reimers-type mass-loss efficiency coefficient, $\eta_R = 0.4$.

The ages were determined using a grid of MESA isochrones [20] for stars with $M/M_\odot < 2.5$, and with PARSEC isochrones [24] for stars with larger masses.

3. Results and Discussion

Our results (Figure 1) confirm a clear and statistically significant correlation between [Y/Mg] and stellar age for thin-disc stars, consistent with earlier works that established this ratio as one of the most reliable chemical clocks [2]. The observed relation follows a negative slope, with younger stars showing higher [Y/Mg] values, reflecting the progressive enrichment of *s*-process elements from AGB stars over time. However, the slope of this relation is not uniform across the Galactic disc: stars located at different Galactocentric radii display distinct behaviours, indicating that the efficiency of chemical enrichment and the contribution of various nucleosynthetic channels vary spatially within the disc [6]. In particular, stars in the inner regions tend to show flatter trends, whereas those in the outer disc exhibit steeper correlations, consistent with differences in star formation timescales and gas accretion histories, in the context of the inside-out formation of the Galactic disc.

In contrast, thick-disc stars show no significant dependence of [Y/Mg] on age, suggesting that this ratio cannot be reliably used as an age indicator for this older population (cf. [9]). This lack of correlation likely reflects the rapid and intense star formation history of the early Galaxy, during which Type II supernova dominated the chemical enrichment, leaving little time for *s*-process contributions to build up. The clear dichotomy between thin- and thick-disc behaviours thus reinforces the idea that chemical clocks such as [Y/Mg] are sensitive not only to stellar age but also to the star formation and enrichment history of the environment where stars were born. We also note that the few thick-disc stars that appear at young ages in our sample are α-enhanced, indicating that they are likely rejuvenated objects, young α-rich stars [25,26], that preserve the chemical signature of an old thick-disc population.

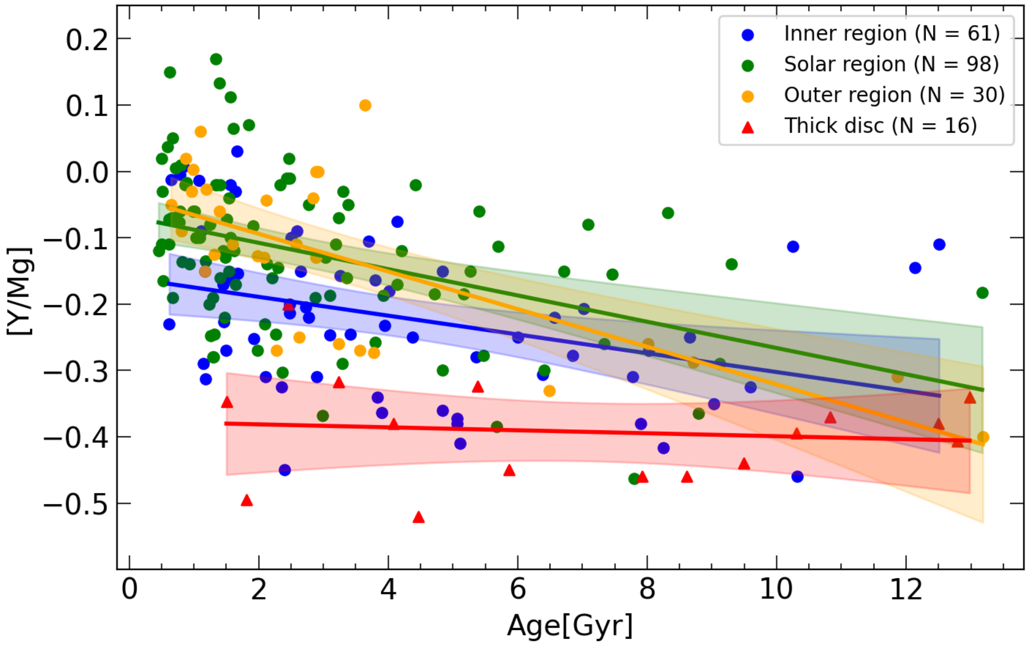

Figure 1. [Y/Mg] as a function of stellar age for thin- and thick-disc stars. Linear fits for different Galactic regions and their 95% confidence intervals are shown. Stars with $R_{\text{mean}} < 7.5$ kpc are attributed to the inner Galactic region, the Solar region is at $7.5 \leq R_{\text{mean}} \leq 8.5$ kpc, and the outer region is at $R_{\text{mean}} > 8.5$ kpc.

To quantify the trends visible in Figure 1, we present below the relations between [Y/Mg] and stellar age for each Galactic region:

$$[\text{Y/Mg}]_{\text{Inner}} = -0.161 - 0.014 \cdot \text{age [Gyr]}, \tag{1}$$

$$\text{age [Gyr]}_{\text{Inner}} = -71.43 \cdot [\text{Y/Mg}]_{\text{Inner}} - 11.5, \tag{2}$$

for the inner disc ($N = 61$, $PCC = -0.35$);

$$[\text{Y/Mg}]_{\text{Solar}} = -0.068 - 0.020 \cdot \text{age [Gyr]}, \tag{3}$$

$$\text{age [Gyr]}_{\text{Solar}} = -50 \cdot [\text{Y/Mg}]_{\text{Solar}} - 3.4, \tag{4}$$

for the Solar region ($N = 98$, $PCC = -0.41$);

$$[\text{Y/Mg}]_{\text{Outer}} = -0.037 - 0.028 \cdot \text{age [Gyr]}, \tag{5}$$

$$\text{age [Gyr]}_{\text{Outer}} = -35.71 \cdot [\text{Y/Mg}]_{\text{Outer}} - 1.32, \tag{6}$$

for the outer disc ($N = 30$, $PCC = -0.69$);

$$[\text{Y/Mg}]_{\text{Thick}} = -0.377 - 0.002 \cdot \text{age [Gyr]}. \tag{7}$$

$$\text{age [Gyr]}_{\text{Thick}} = -500 \cdot [\text{Y/Mg}]_{\text{Thick}} - 188.5, \tag{8}$$

for the thick-disc sample ($N = 16$, $PCC = -0.11$).

The flatter [Y/Mg]–age slopes found for both the inner and thick discs suggest rapid chemical evolution in these regions. However, the systematically lower [Y/Mg] ratios in the thick disc indicate that it formed earlier, from gas enriched primarily by Type II supernovae, before significant contributions from AGB stars had occurred. In contrast, the inner thin disc likely formed from already partially enriched material, leading to a similar slope but at a higher [Y/Mg] level. This behaviour is consistent with recent findings showing that the [*s*-/Mg]–age relation is strongly dependent on the birth radius of stars, with the weakest correlations found in the inner disc [27]. The scenario proposed by [28], in which the inner thin disc is formed from the gas left after the thick-disc phase without further accretion, provides a natural explanation for our results. Both components exhibit shallow [Y/Mg]–age slopes due to their rapid early evolution, but the higher [Y/Mg] ratios in the inner disc suggest continued enrichment of the residual gas by AGB stars in a closed-box regime, whereas the thick disc formed earlier, before such enrichment became significant.

4. Conclusions

Using asteroseismic ages, our analysis confirms previous results regarding the distinct behaviours of thin- and thick-disc stars in the [Y/Mg]–age plane [9]. Our full sample consists of 205 stars: 61 in the inner disc, 98 in the solar neighbourhood, 30 in the outer disc, and 16 thick-disc stars, of which 110 have yttrium abundances newly derived in this work. The strong correlation found for thin-disc stars contrasts with the nearly age-independent [Y/Mg] ratios observed in the thick disc [9], consistent with its rapid early formation history. Furthermore, we confirm that the slope of the [Y/Mg]–age relation varies with Galactocentric distance, becoming flatter in the inner regions and steeper toward the outer disc [6,27]. These findings strengthen the evidence that chemical clocks are sensitive not only to stellar age but also to the local star formation history. Overall, this study demonstrates the power of combining asteroseismology, astrospectroscopy, and *Gaia* astrometry to recalibrate chemical clocks and refine our understanding of the temporal and spatial evolution of the Milky Way. This study presents results that form part of a broader analysis, and the future work will include NLTE abundances and an expanded dataset.

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