Atomic Diffusion: Constraints from Open Clusters in Gaia-ESO and GALAH

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Abstract

As stars begin to die, their surface chemistry changes over time. This is due to the combined effect of two competing processes: (1) gravitational settling that causes heavier elements to sink below the stellar surface and (2) radiative acceleration from photons that push gas upward. Although diffusion is a primary physical process in stellar interiors, its impact on surface chemical abundances is often overlooked in large-scale spectroscopic surveys, leading to systematic biases in stellar age estimates. This project investigates the onset ('turn-on') and suppression ('turn-off') signatures of atomic diffusion as dying stars transition into giants. Using high-resolution optical spectra, we will analyse open-cluster stars across various evolutionary stages to identify the age (or mass) threshold at which diffusion becomes detectable and shuts off. The resulting measurements will constrain the magnitude of diffusion-driven abundance changes, the stellar age (or mass) at which diffusion becomes observable, and the efficiency of abundance restoration during the first dredge-up. It will improve stellar age determinations and enhance the precision of Galactic archaeology and chemical-tagging studies.

1. Introduction

Atomic diffusion operates within stars over billions of years, causing heavy elements to sink below the photosphere, resulting in a surface metallicity lower than the birth composition.

- **The Age Bias:** Neglecting diffusion and assuming a constant-metallicity isochrone leads to systematic age overestimates of up to 20% (Dotter et al., 2017).
- **The Turn-Off Point:** As stars evolve into giants, the first dredge-up deepens the convective envelope, restoring surface abundances to primordial levels (Souto et al., 2025).

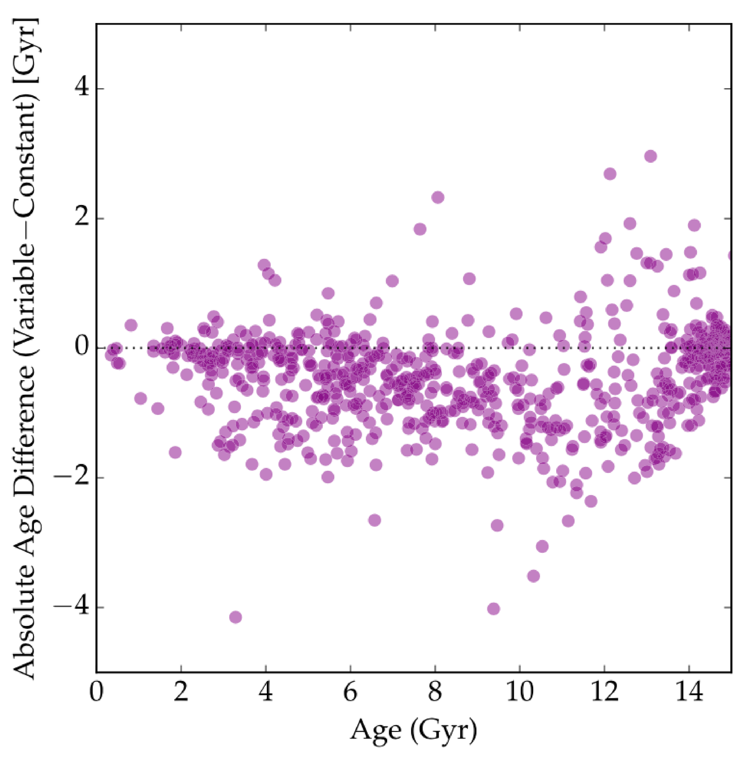

Figure 1. Age differences arising from neglecting atomic diffusion (Dotter et al., 2017).

2. High-Precision Analysis with BACCHUS

- We utilize the Brussels Automatic Code for Characterizing High-accuracy Spectra (BACCHUS), which synthesizes lines individually (Hayes et al., 2022).
- By anchoring fits to the precise wavelength of a feature, BACCHUS bypasses the biases that arise from strong blending in metal-rich populations.
- Systematic gravity offsets are mitigated by supplying physically motivated $\log g$ values from cluster isochrone fits (Souto et al., 2025).

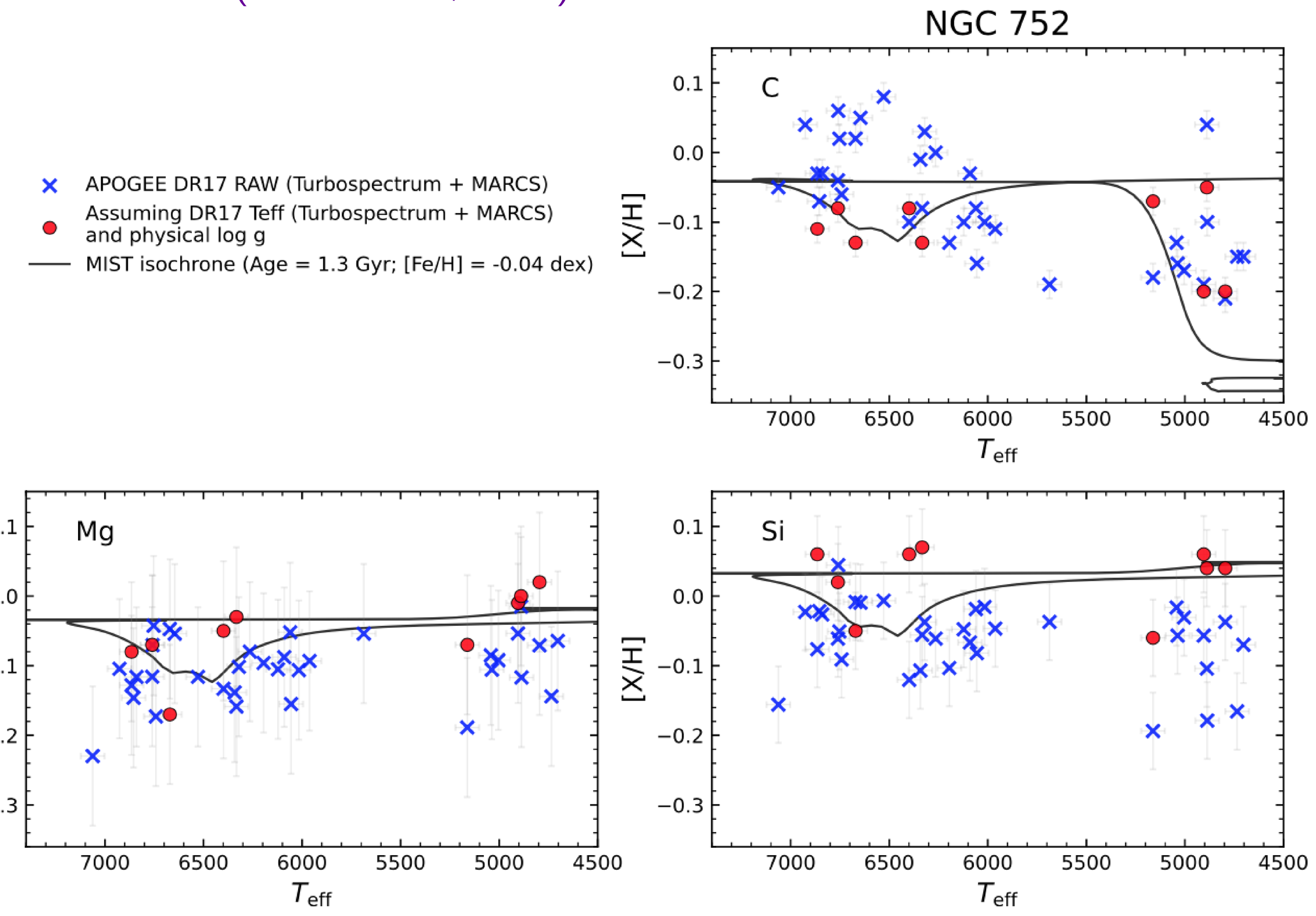

Figure 2. Multi-element abundance patterns in NGC 752. The 0.05–0.15 dex chemical dip at the turnoff is resolved through line-by-line synthesis (Souto et al., 2025).

3. Data Sources

- **Gaia-ESO survey:** Analyzes open clusters using the high-resolution spectrograph, providing a baseline for high-precision turn-on detection.
- **GALAH survey:** A massive release providing data for 917,588 stars and incorporating NLTE modeling for 14 elements, essential for proving observed depletions are physical rather than modeling artifacts (Buder et al., 2025).

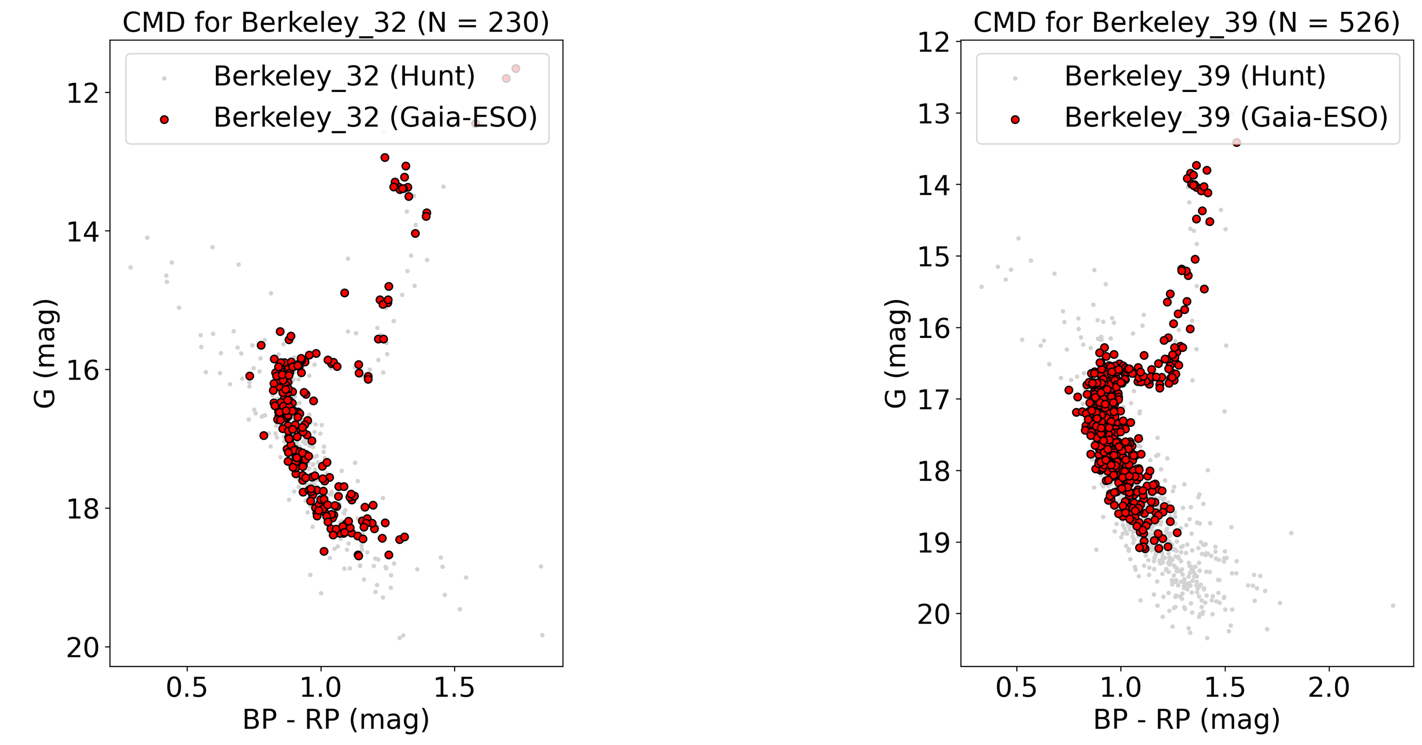

Figure 3. Sample clusters from Gaia-ESO survey.

4. Three-Year Research Plan

Year 1: Map Gaia-ESO iDR6 cluster data to determine the universal age threshold where gravitational settling overcomes mixing.

Year 2: Utilize the [C/N] ratio and $^{12}C/^{13}C$ isotopic ratio from GALAH DR4 to pinpoint exactly where the first dredge-up resets abundances (Buder et al., 2025).

Year 3: Create a unified corrective framework to resolve pipeline offsets and map birth abundances across the Milky Way disc (Magrini et al., 2023).

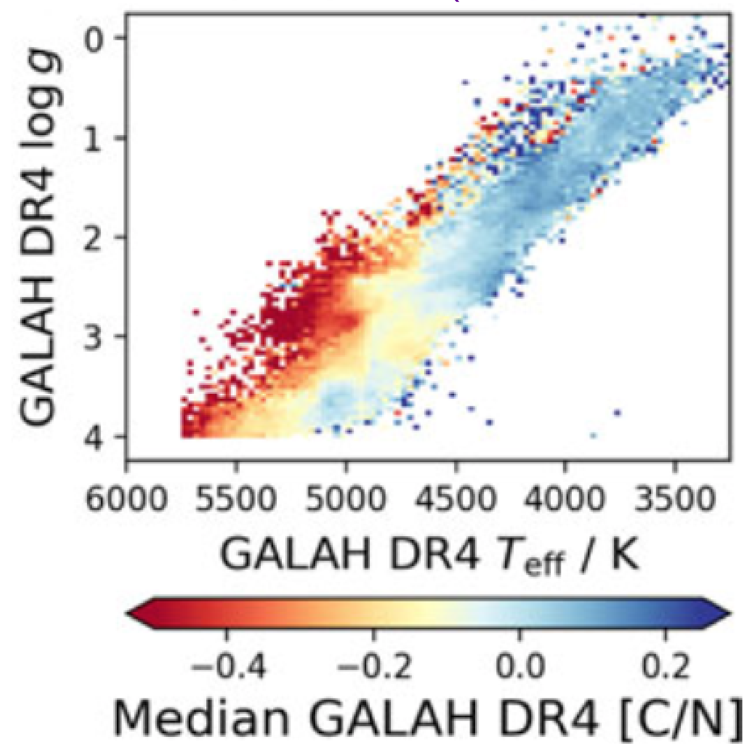

Figure 4. Kiel diagram. The sharp drop marks the mixing phase where diffusion signatures are suppressed and composition is restored (Buder et al., 2025).

5. Summary and Impact

By shifting from isolated cluster studies to comprehensive Galactic mapping, this work will:

1. Establish the universal turn-on thresholds for diffusion.
2. Eliminate the current 20% age bias in Galactic archaeology.
3. Provide primordial chemical tags for field stars, allowing us to reconstruct the formation history of the Milky Way using accurate birth values rather than biased surface measurements.

References

Buder, Sven et al. (May 2025). "The GALAH survey: Data release 4". In: *Publications of the Astronomical Society of Australia* 42, e051. eprint: 2409.19858.

Dotter, Aaron et al. (2017). "The Influence of Atomic Diffusion on Stellar Ages and Chemical Tagging". In: *The Astrophysical Journal* 840.2, p. 99.

Hayes, Christian R. et al. (Sept. 2022). "BACCHUS Analysis of Weak Lines in APOGEE Spectra (BAWLAS)". In: *Astrophysical Journal Supplement Series* 262.1, p. 34. eprint: 2208.00071.

Magrini, L. et al. (2023). "The Gaia-ESO survey: Mapping the shape and evolution of the radial abundance gradients with open clusters". In: *Astronomy & Astrophysics* 669, A119.

Souto, Diogo et al. (2025). "The Open Cluster Chemical Abundances and Mapping Survey: IX. Measuring the Effects of Stellar Diffusion in the open Clusters NGC 752 and Ruprecht 147 using APOGEE". In: *The Astrophysical Journal*. Draft version November 11, 2025.

Student Research Symposium (17th April, 2026), Davis College of Science & Engineering, Texas Christian University, Fort Worth, Texas, USA