

The Sodium Challenge: New Insights into Disc Separation and Nucleosynthetic Yields

Novel Tracers and Chemical Evolution Models for Understanding Milky Way Formation

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Sodium as an Effective Tracer for Disc Sequences

GALAH DR3 Application – Key Take Aways

Owusu et al. (2024) pioneers the use of sodium's unique chemical behavior as a precision tracer for stellar populations.

Introducing a novel method to cleanly separate young and old Milky Way disc sequences using $[\text{Na}/\text{Fe}]$ abundance patterns, significantly advancing beyond traditional methods.

Leveraging high-precision spectroscopic data from 4,037 solar-type stars in the GALAH DR3 survey for unparalleled accuracy.

Demonstrating sodium's superior utility over standard alpha-elements in the high-metallicity regime, critical for understanding disc chemical evolution.

Key Innovation: Sodium Abundance Patterns

Shows pronounced $[\text{Na}/\text{Fe}]$ enrichment at super-solar metallicities in older disc stars, enabling cleaner population separation and tighter constraints on chemical evolution models.

Background and Scientific Context

Foundation for Sodium as a Galactic Tracer

Milky Way Structure & Nucleosynthesis



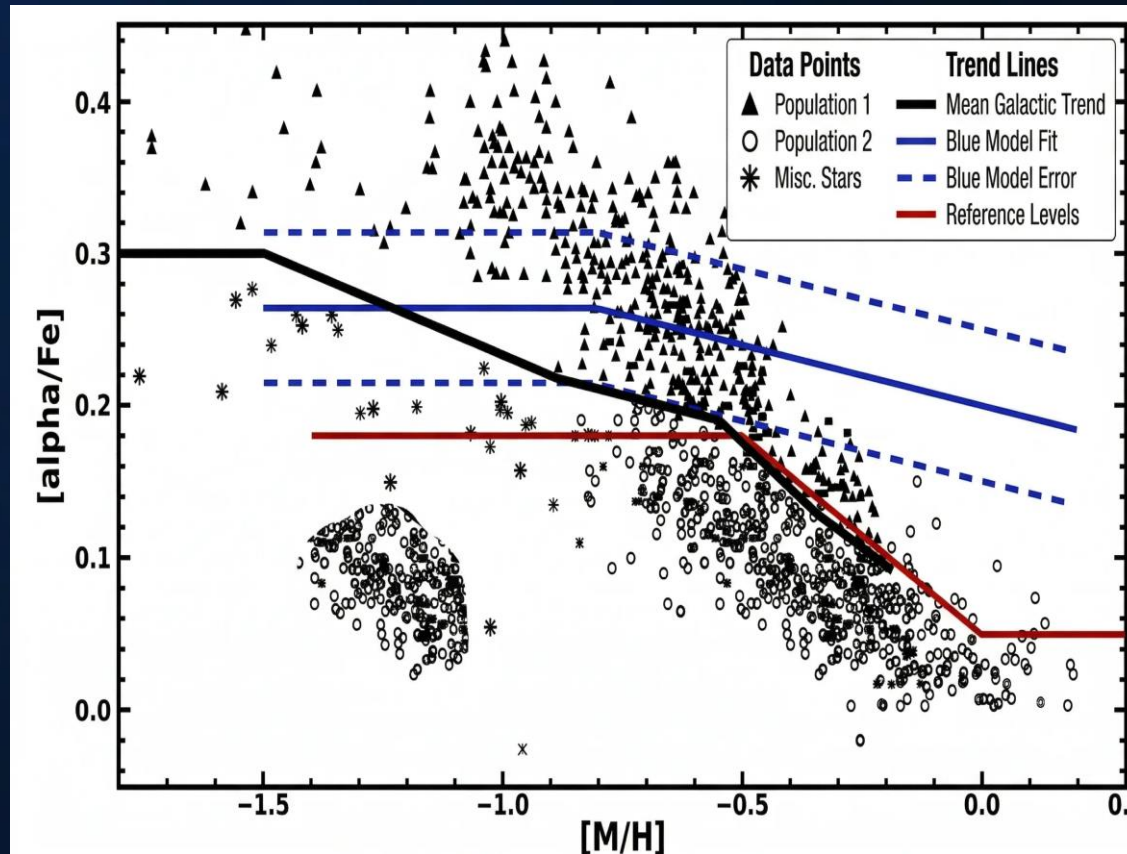
Milky Way Disc (Thin & Thick): Comprises 'thin' (young, low- q , dynamically cold) and 'thick' (old, high- q , dynamically hot) stellar populations. Structure is key to understanding formation.



Sodium (Na) Synthesis: An odd-Z element produced in massive stars during core-collapse (CCSNe) and in asymptotic giant branch (AGB) stars via the NeNa cycle.



GALAH DR3 Survey: Provides high-precision chemical abundances for hundreds of thousands of stars, enabling detailed chemo-dynamical analysis.



$[\alpha/Fe]$ versus $[Fe/H]$ relation reveals distinct chemical evolution tracks for thin and thick disc stars. Fig. credit: *Recio-Blanco et al. 2014*

Scientific Context: The Sodium Anomaly

Peculiar $[Na/Fe]$ Enrichment: Sodium exhibits unexpected enrichment at super-solar metallicities ($[Fe/H] > 0$) in older disc populations.

Crucial for Galactic Tracing: Understanding these abundance Trends are essential for tracing galactic formation history and chemical evolution pathways.

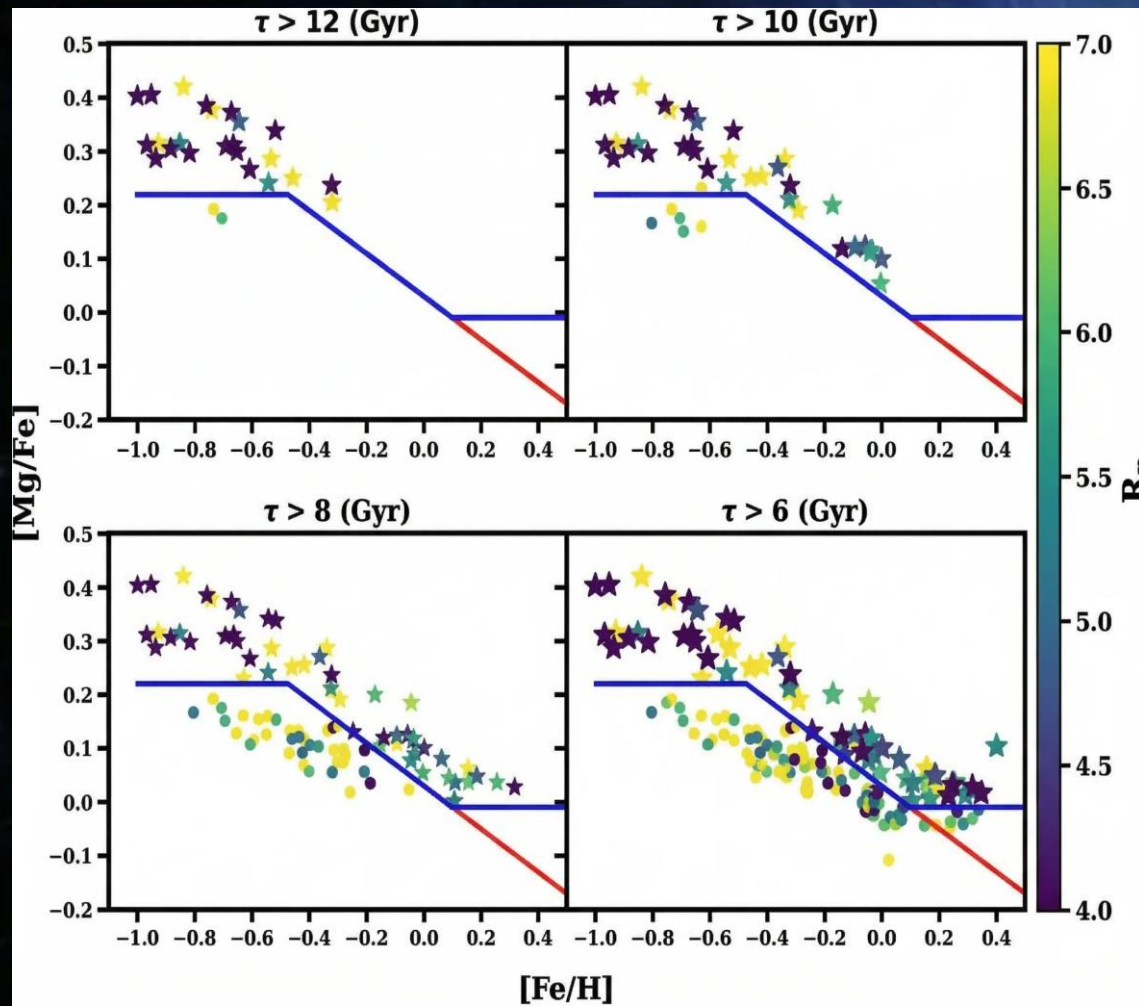
— resolution SEGUE

— *Recio-Blanco et al. 2014*

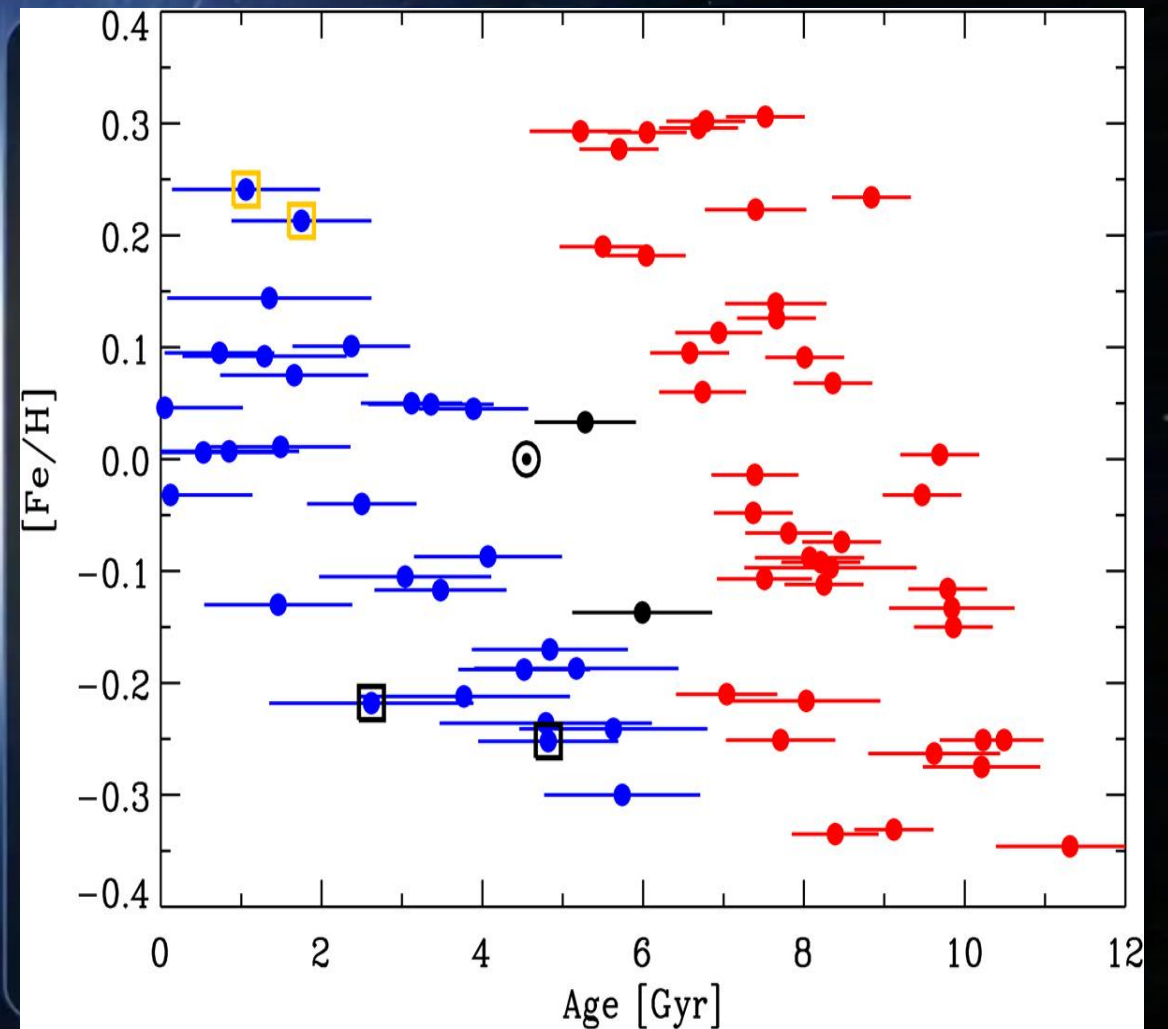
— Adibekyan et al. (2012) for the solar neighbourhood

Background Continued

Hayden et al. (2017)



Nissen et al. (2020)



Existing Limitations & Gaps



Ambiguity in Traditional Separation

Conventional [Mg/Fe] vs. [Fe/H] methods fail to cleanly distinguish thin & thick disc populations, especially at intermediate ages (5–8 Gyr), obscuring their distinct evolutionary histories.

[Mg/Fe] (alpha-enhancement) is a key tracer of rapid star formation.



Confounding at High Metallicity

Significant population overlap occurs at super-solar metallicities ($[Fe/H] > 0$), where traditional alpha-enhancement tracers lose their diagnostic power, leading to misidentification.



Population Assignment Conflict

A staggering 59% of stars exhibit conflicting classifications when comparing traditional [Mg/Fe]-based and innovative Na-based selection criteria, highlighting a critical need for more reliable tracers.



Limited Kinematic Resolution

Current methods result in substantial overlap in galactocentric pericenter distances (the closest point of an orbit to the Galactic center), severely restricting their utility for precise **disc archaeology** (uncovering the Milky Way's formation history).

These critical limitations necessitated the development of Sodium as a novel, high-precision tracer, a cornerstone of this award-winning work.

METHODOLOGY: RIGOROUS DATA SELECTION & QUALITY CONTROL

GALAH DR3 High-Resolution Spectroscopic Survey

Utilizes GALACTIC ARCHAEOLOGY with HERMES (GALAH) DR3, a massive survey from the Anglo-Australian Telescope, providing atmospheric parameters and chemical abundances for ~30 elements.

Includes isochrone-interpolated stellar ages critical for temporal evolution studies.

Stringent Quality Criteria & Selection

Age uncertainties restricted to $< 20\%$ or < 2 Gyr for high precision.

Solar-Type Star & Abundance Precision

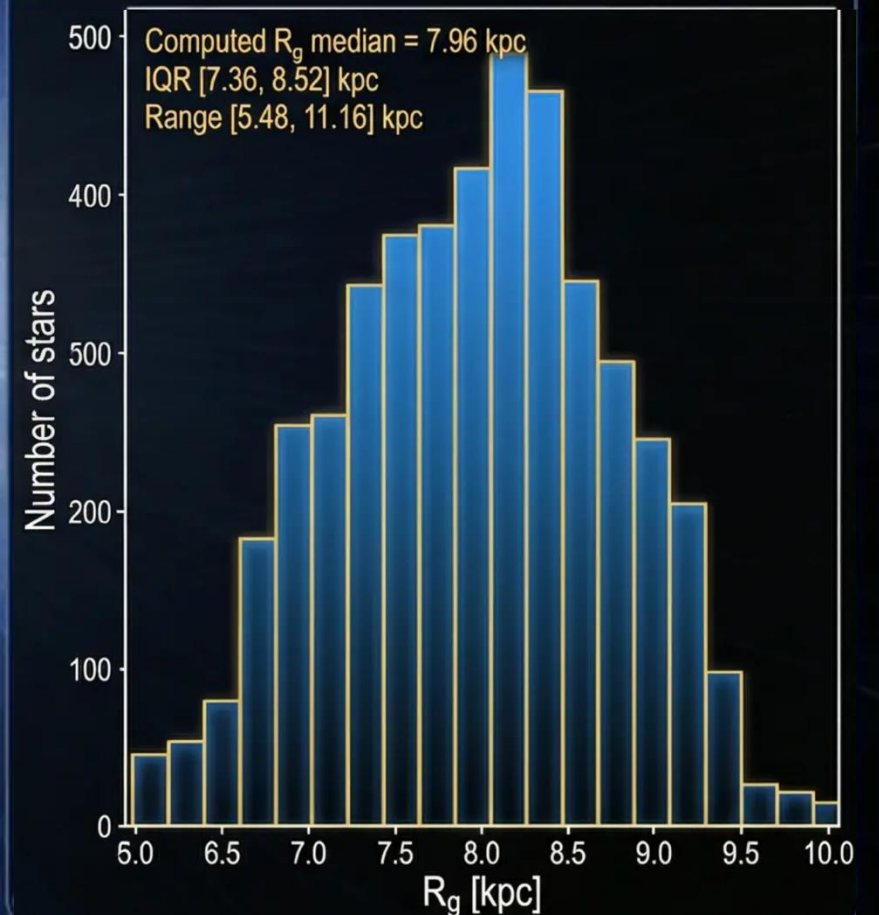
Focus on solar-type stars ($5600 \text{ K} < T_{\text{eff}} < 5950 \text{ K}$; $\log g > 4.15$) for accurate differential analysis.

Metallicity range: $-0.3 < [\text{Fe}/\text{H}] < 0.3$.

Non-Local Thermodynamic Equilibrium (NLTE) corrections applied for sodium abundances, crucial for accurate chemical analysis.

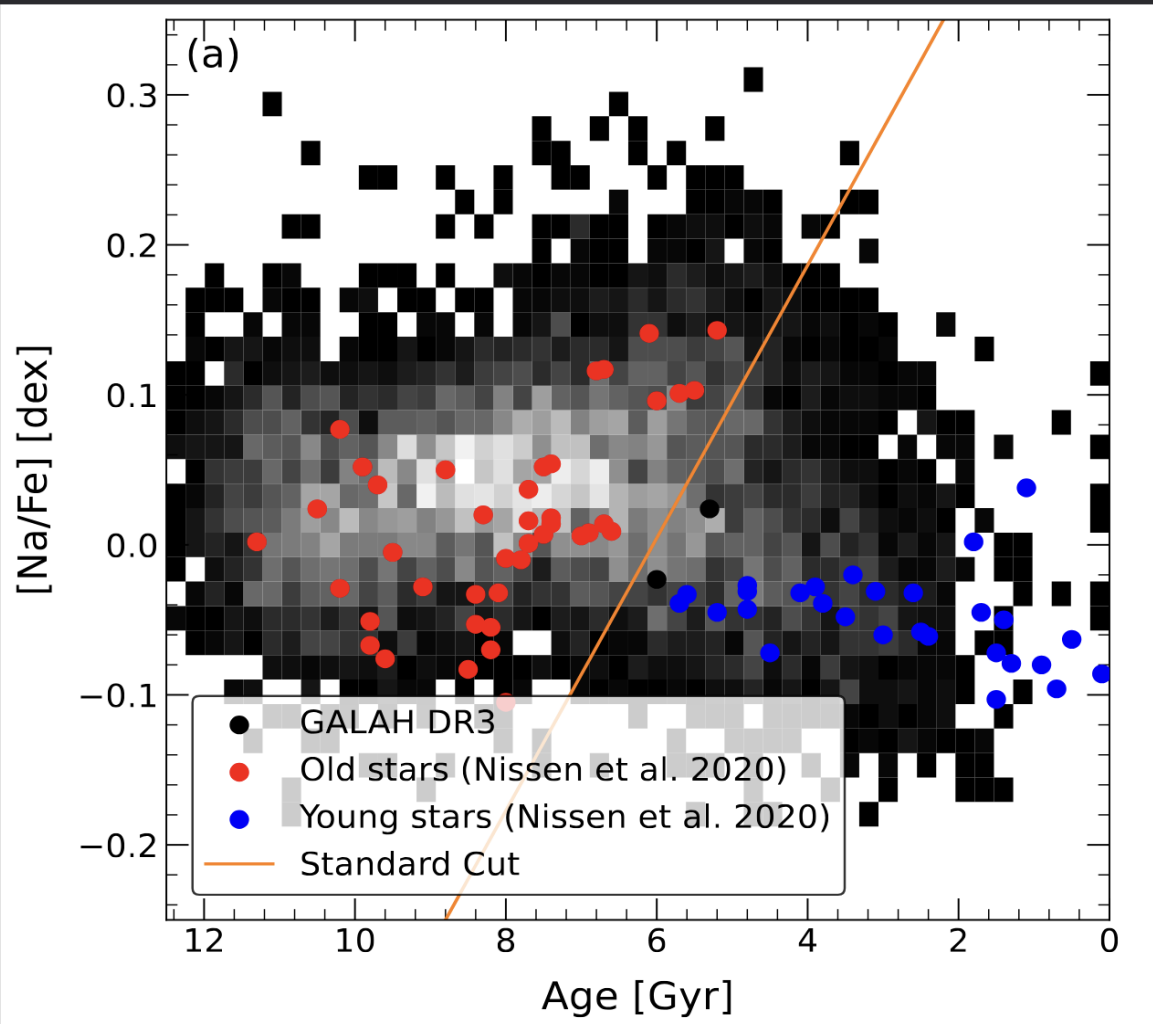
Emphasizes the robust methodology underpinning the award-winning thesis work.

Stellar Sample Distribution by Galactocentric Radius (R_g)

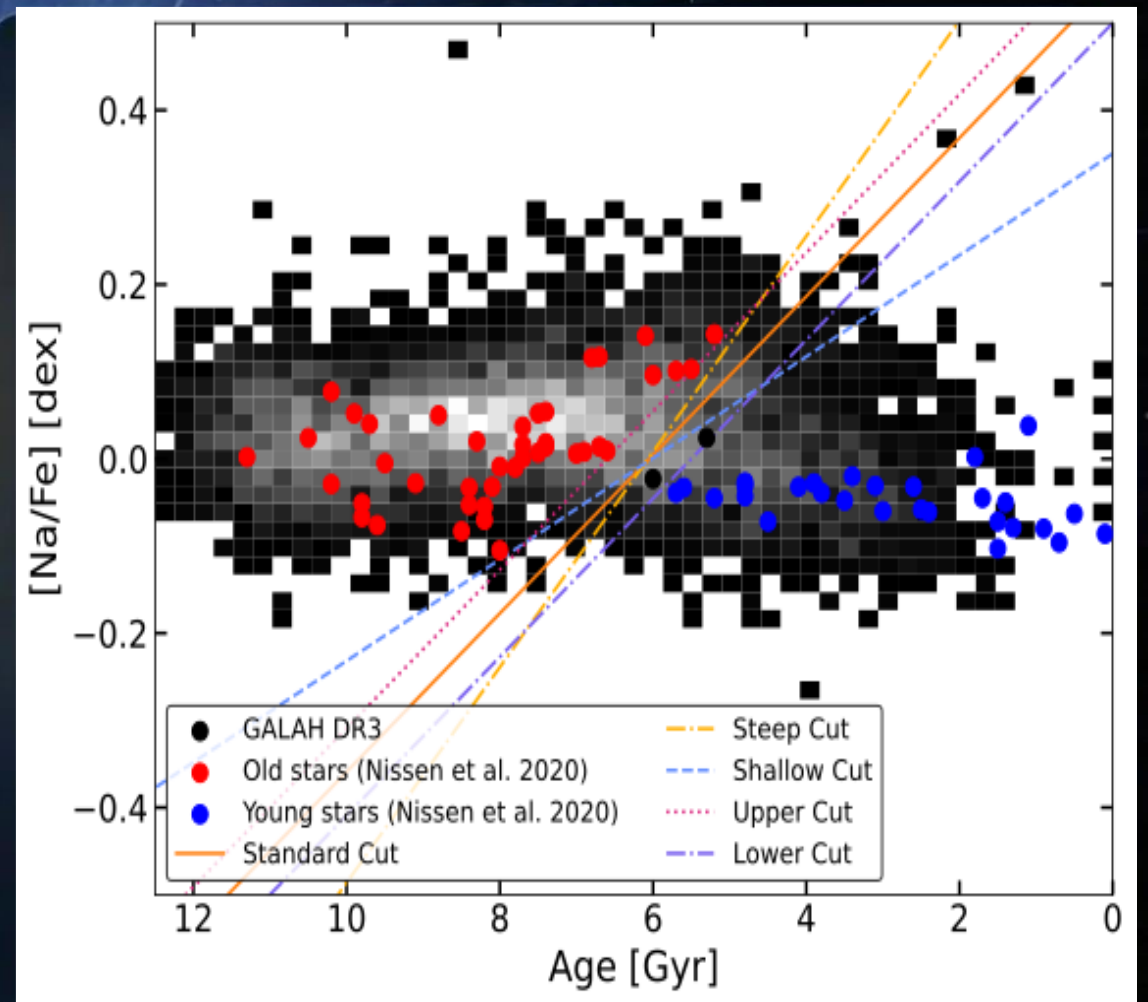


Background Continued

Owusu et al. (2024)



Nissen et al. (2020)



Methodology: Novel [Na/Fe]-Age Disc Separation Technique

A key innovation for precise chemical tagging of stellar populations, outperforming traditional methods.

Technique & Validation

Introduced a novel, physics-based selection criterion leveraging the [Na/Fe]-age plane to cleanly separate stellar disc populations.

Developed a robust mathematical classification for distinct stellar sequences:

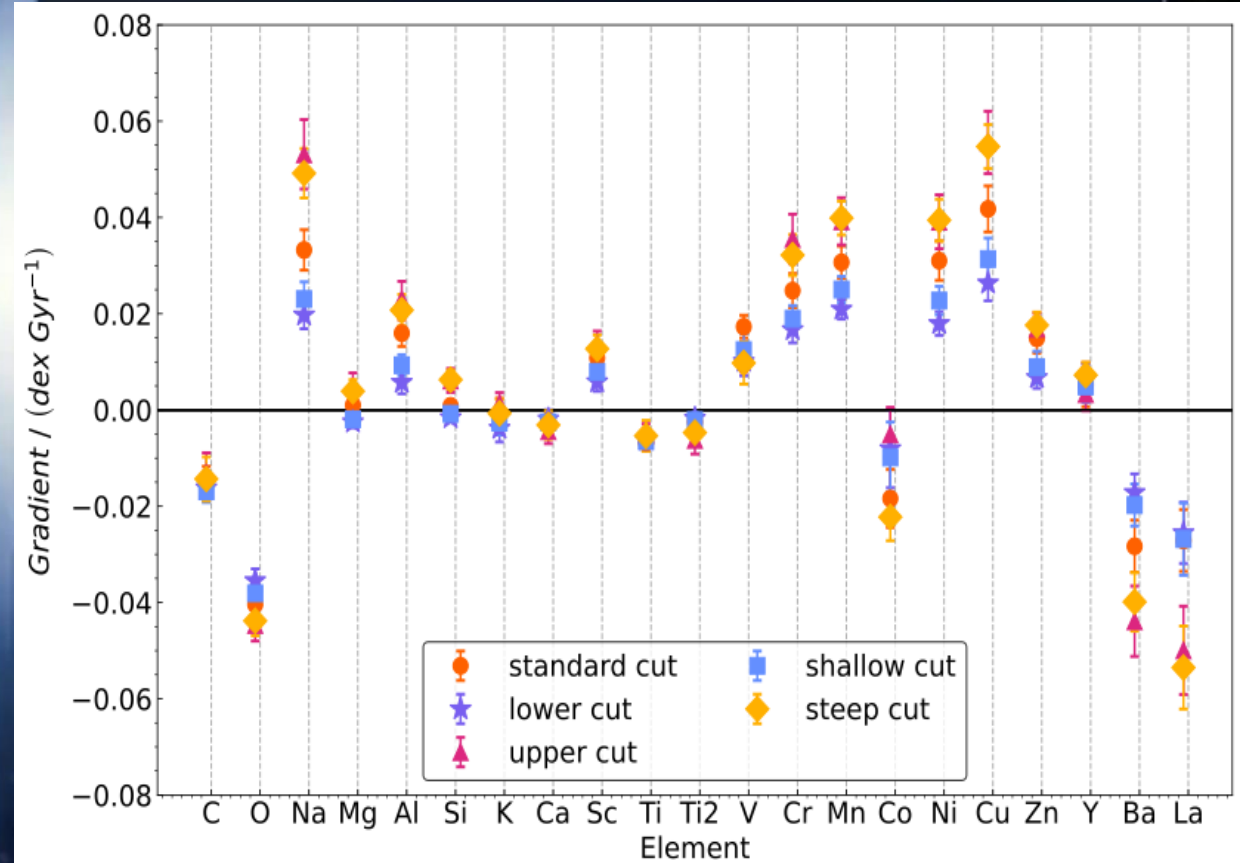
- Old sequence: $[Na/Fe] > 0.55 - 0.5/5.5 \times \tau$ (age in Gyr)
- Young sequence: $[Na/Fe] < 0.55 - 0.5/5.5 \times \tau$ (age in Gyr)

Rigorous Method Validation: Confirmed technique's stability through extensive robustness testing, systematically varying slope and intercept parameters to ensure reliability.

Benchmarking & Superiority: Quantified performance against traditional [Mg/Fe]-based selection using confusion matrix analysis, demonstrating superior classification accuracy.

Significance: The [Na/Fe]-age plane offers a more direct tracer of chemical evolution timescales than traditional α -elements.

Visualizing the Separation



Improved Population Separation: Demonstrating the Power of Sodium Tracing in Disc Archaeology

Key Findings in Disc Archaeology

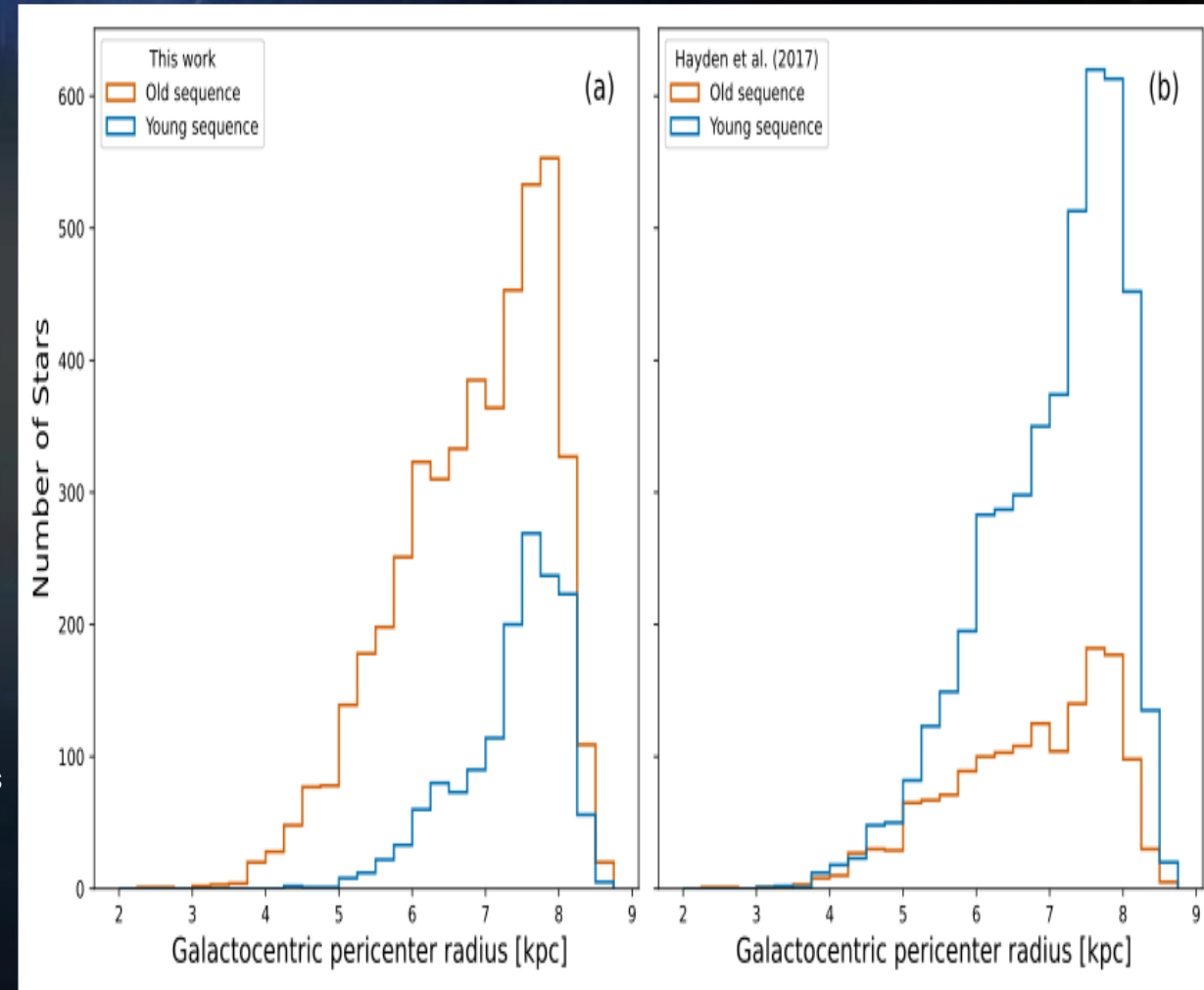
Quantitative Analysis (Confusion Matrix): 59% of stars are misclassified when relying on traditional Magnesium (Mg) methods compared to the novel Sodium (Na) selection, highlighting significant discrepancies in population assignment.

Enhanced Spatial Resolution (Pericenter Distances): The Na-based approach reveals a much clearer separation between populations. This is particularly critical in the 3-5 kpc range from the Galactic center, a region where stellar orbits are tightly packed, demonstrating its efficacy as a high-precision tool for disc archaeology (the study of the Milky Way's formation history).

Refined Population Properties: Old sequence stars are consistently and accurately mapped to orbits closer to the Galactic center. This method significantly reduces cross-contamination from younger populations, providing a purer sample for studying the early Galaxy.

Limitations of Traditional Methods: In contrast, the Mg-based method suffers from significant overlap, obscuring the distinct orbital characteristics of different stellar populations and limiting its utility for detailed evolutionary studies.

Conclusion: These results definitively establish sodium tracer approach for achieving the high-fidelity population separation required for advanced Galactic archaeology.



Discussion: Nucleosynthetic Implications

Unveiling Galactic Chemical History via Sodium Tracers

Metallicity Effect & Core-Collapse Supernovae (CCSN):

High-progenitor metallicity enables more efficient neutron capture, enhancing synthesis of neutron-rich odd-Z isotopes like ^{23}Na in CCSN environments.

This challenges conventional primary nucleosynthetic models for observed $[\text{Na}/\text{Fe}]$ enhancement trends, suggesting metallicity-dependent yields.

CCSN: Explosive deaths of massive stars, key sources of many heavy elements)

Asymptotic Giant Branch (AGB) Star Contributions:

AGB stars, particularly those at super-solar metallicity, are crucial sources for rising sodium abundance, largely through proton-capture nucleosynthesis (NeNa cycle) and deep mixing.

Mass-loss efficiency in metal-rich AGB stars profoundly impacts Na yields, a critical factor highlighted in the thesis analysis.

AGB Stars: Advanced stage of low-to-intermediate mass stars, significant contributors to chemical enrichment via stellar winds)

The 6.3 Gyr Knee Effect & Galactic Evolution:

Indicates a major transition in star formation and enrichment, marked by a steeper rise in $[\text{Na}/\text{Fe}]$ and other elements.

Upward trends in Fe-peak and odd-Z elements (like Na) signal the increasing, delayed contribution of Type Ia supernovae, reshaping the chemical landscape.

Type Ia SN: Thermonuclear explosions of white dwarfs, main source of iron and related elements, acting on longer timescales)

Thesis Conclusion: High-precision sodium tracer analysis provides critical constraints on nucleosynthetic yields and galactic chemical evolution models, challenging existing paradigms.

Major Contributions: Sodium Enrichment, Galactic Evolution & Future Directions

Award-Winning Thesis Findings and Forward-Looking Research Pathways

Key Findings (Award-Winning Thesis Contributions)

- ★ **Superior Population Separation:** $[Na/Fe]$ provides superior separation of young and old disc sequences compared to traditional $[Mg/Fe]$ methods, particularly at super-solar metallicities.

Explanation: $[Na/Fe]$ offers a more distinct chemical signature for identifying different stellar populations than magnesium, crucial for understanding high-metallicity environments.

- ★ **Significant Knee Effect (6.3 Gyr):** The 'knee' effect around 6.3 Gyr indicates significant changes in star formation rates and chemical enrichment processes.

Explanation: The steepening of the abundance trend (knee) reveals a pivotal moment in galactic history where the relative contributions of different supernovae types shifted, indicating a change in star formation activity.

- ★ **Improved Galactocentric Classification:** Improved galactocentric pericenter distance distinction demonstrates cleaner population classification.

Explanation: Using the closest point a star reaches to the Galactic center as a classifier allows for a more accurate grouping of stars based on their orbital properties and origins.

Future Research Directions (Forward-Looking & Contextualised)

Nucleosynthetic Channels: Investigate nucleosynthetic channels responsible for Na enrichment, particularly metallicity effects in core-collapse supernovae.

Explanation: Determine the exact stellar processes creating sodium, focusing on how metal-rich core-collapse supernovae contribute, as current models lack detail.

Galactic Chemical Evolution Models: Integrate Na-based selection method into galactic chemical evolution models.

Explanation: Incorporate the new Na-based classification into computational models of the Milky Way's chemical history to refine our understanding of how elements build up over time.

Radial Migration & Dynamics: Explore impacts of radial migration and dynamical processes on observed abundance trends.

Explanation: Study how stars move from their birthplaces (radial migration) and other gravitational interactions influence the observed distribution of chemical elements across the Galaxy, complicating simple trends.

Young Disc

Knee (6.3 Gyr)

Old Disc

High-precision GALAH DR3 data enables unprecedented insights into Galactic chemical evolution.

Concluding Remarks & Impact of Research

Major Contributions to Galactic Archaeology

Sodium ([Na/Fe]) identified as a premier chemical clock and diagnostic tool for distinguishing Milky Way disc populations.

Revealed critical gaps in understanding stellar nucleosynthesis at super-solar metallicities, challenging current yield models.

Pioneered new pathways for high-precision galactic archaeology using large-scale surveys like GALAH.

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Website: [research.website/sodium-tracers]

Questions & Collaboration Welcome

Acknowledgments and Facilities

We acknowledge the traditional owners of the land on which the Anglo-Australian Telescope stands, the Gamilaraay people.

Collaborators

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- ◆ Alex Kemp, Benoit Côté,
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- ◆ Philipp Eitner,
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- ◆ Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australian Research Council
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Australian Research Council Future Fellowship and DECRA Fellowship programs, Australia-Germany Joint Research Cooperation Scheme

Key Facilities

- ◆ Anglo-Australian Telescope with 2df-HERMES (GALAH Survey), Gaia Mission (European Space Agency), Two Micron
- ◆ All-Sky Survey (2MASS) and CDS VizieR

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KEY SCIENCE GOALS

FOUNDATION



INVESTIGATE [Na/Fe] ENRICHMENT AT SUPER-SOLAR METALLICITY

- Utilising high-precision stellar abundances from the GALAH DR3 survey (Galactic Archaeology with HERMES, Data Release 3) to Probe Sodium enrichment trends in the Milky Way disc's oldest, metal-rich stars.
- Context: [Na/Fe] serves as a critical chemical clock and tracer of specific nucleosynthetic processes, particularly from asymptotic giant branch (AGB) stars, helping to unravel the Milky Way's formation history.



DEVELOP NOVEL SELECTION TECHNIQUE FOR DISC POPULATIONS

- Pioneering a new classification method to cleanly separate thick and thin disc stellar populations based on unique observed [Na/Fe] enrichment patterns.
- Context: This approach offers a complementary and potentially superior method to traditional kinematic or [Mg/Fe] selections, refining our understanding of the disc's structural evolution.



ASSESS EFFECTIVENESS OF NA-BASED SELECTION METHOD

- Rigorously evaluating the new [Na/Fe]-based technique against established conventional approaches, such as [Mg/Fe] vs. [Fe/H] diagrams.
- Context: Demonstrating the method's robustness and improvements in identifying distinct stellar generations, providing a more precise tool for Galactic archaeology.



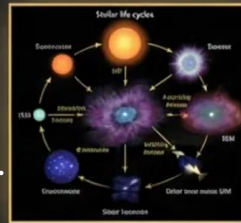
INFER NUCLEOSYNTHETIC ORIGINS & IMPLICATIONS FOR GALACTIC ENRICHMENT

- Synthesizing observed elemental age-abundance trends to constrain the sites of sodium production (e.g., AGB stars, supernovae) and refine models of Galactic chemical enrichment.
- Context: Connecting detailed elemental data to the broader narrative of how the Milky Way galaxy assembled and enriched its interstellar medium over cosmic time.

Background: Galactic Chemical Evolution (GCE)

Foundations: Stellar Nucleosynthesis & GCE

Galactic Chemical Evolution models trace the cosmic build-up of elements through stellar nucleosynthesis, explaining abundance patterns over time.

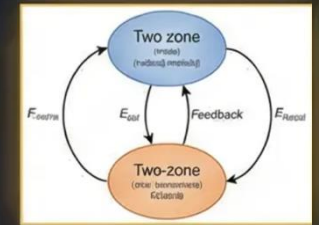


Driven by element production in stars and their remnants (supernovae, AGB stars), which enrich the interstellar medium (ISM).

Accurate stellar nucleosynthetic yields are crucial input parameters, directly determining model predictions for elemental abundance patterns.

Theoretical Framework: The OMEGA+ Code

OMEGA+ provides a flexible, two-zone framework for exploring feedback-regulated star formation and metal recycling processes.




Allows detailed modeling of element exchange between star-forming regions and the surrounding galactic medium.

Crucial for understanding how feedback mechanisms shape galactic chemical enrichment and structure.

Key Science Goals for Model Evaluation


Pioneering Galactic Chemical Evolution Research (Award-Winning Thesis)

Systematic Evaluation of Stellar Yield Prescriptions

 Rigorous testing of varied nucleosynthetic yield tables from Core-Collapse Supernovae (CCSN), Asymptotic Giant Branch (AGB) stars, and Type Ia Supernovae.


- Yield tables are fundamental libraries detailing element production in stellar life and death cycles, crucial inputs for models.

Investigate Sodium Enrichment at Super-Solar Metallicities

 Explore the underlying drivers of observed [Na/Fe] enhancement in young, metal-rich thick disc stellar populations.


- Understanding this trend probes unique nucleosynthetic environments and stellar migration in the Milky Way.

Assess Current Galactic Chemical Evolution Models

 GCE models simulate the chemical history of galaxies, linking star formation, stellar yields, and gas flows.

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Identify Critical Gaps in Nucleosynthetic Understanding

 Pinpoint specific discrepancies where theoretical models and high-precision observational data diverge.

- Highlighting these divergences provides a roadmap for future improvements in stellar physics and yield calculations.

CURRENT CHALLENGES & LIMITATIONS IN GCE MODELING

Technical Barriers & Uncertainties



Reproducing the Super-Solar [Na/Fe] Upturn



Limited Sub-Chandrasekhar Mass SNe Ia Yields

*Context: SNe Ia are primary iron factories; 'sub-Chandrasekhar' models are a vital class whose chemical output depends on the progenitor's initial composition.



Uncertain Metallicity-Dependent AGB Star Yields

*Context: Asymptotic Giant Branch (AGB) stars are late-stage stars that enrich the ISM with elements like C, N, and Na through strong stellar winds; accurate mass-loss modeling is essential.



Incomplete Nucleosynthesis for Odd-Z Elements

Motivation for Comprehensive Thesis Approach

Identified GCE Limitations (Left Panel)



Requirement for Advanced, Multi-Zone Modeling

Necessitates a framework integrating metallicity-dependent yields, new nucleosynthetic channels, and spatially-resolved evolution.






Thesis Goal: A Holistic, Data-Driven GCE Framework

To resolve abundance discrepancies by building a comprehensive model that addresses these specific limitations, as detailed in the subsequent results.

Methodology: Sophisticated OMEGA+ Two-Zone Model

Award-Winning Thesis Work: Advanced Galactic Chemical Evolution Framework

OMEGA+ Code Features (Sophisticated Approach)

-  **Two-zone galactic chemical evolution framework:** Models the intricate interplay between the galaxy's star-forming disk and the surrounding halo.
-  **Self-consistent star formation rates and metal recycling:** Physically-motivated processes driven by gas supply and stellar feedback.
-  **Metal exchange between galaxy and circumgalactic medium (CGM):** Tracks inflows of pristine gas and outflows of enriched material to/from the extended gas reservoir.

Key Parameter Modifications for Metal-Rich Regime



Initial Mass Function (IMF)

Standard: $1-30 M_{\odot}$

Modified: $1-130 M_{\odot}$

Top-heavy IMF enables more massive stars and metal production.



Star Formation Efficiency (SFE)

Standard: 3.0×10^{-9}

Modified: 3.0×10^{-10}

Reduced efficiency slows gas consumption, allowing enrichment.



Initial Gas Mass

Standard: $1.0 \times 10^{10} M_{\odot}$

Modified: $2.0 \times 10^{11} M_{\odot}$

Higher initial gas reservoir sustains prolonged star formation.

Adjustments enable precise simulation of higher metallicity ($[Fe/H] > 0$) stellar populations, crucial for understanding complex chemical pathways.

MAIN RESULTS: MODEL-DATA DISCREPANCIES

KEY FINDINGS & CONTEXT

[Na/Fe] UPTURN MISMATCH: All tested Galactic Chemical Evolution (GCE) models fail to reproduce the pronounced [Na/Fe] upturn observed at super-solar metallicities ($[\text{Fe}/\text{H}] > 0$). GCE models trace element abundance over time and metallicity.

CONTRADICTIONARY PREDICTIONS: Models predict a decline in [Na/Fe] for $[\text{Fe}/\text{H}] > 0$, directly contradicting the empirical data from the high-precision GALAH DR3 survey. GALAH DR3 provides detailed abundances for >500k stars.

BEST FIT LIMITATIONS: The K10WW95 model, while providing the best fit at lower metallicities, still shows an incorrect decline at higher $[\text{Fe}/\text{H}]$, highlighting the universality of the discrepancy.

SNe Ia IMPACT: The choice between Chandrasekhar-mass and sub-Chandrasekhar-mass Type Ia Supernovae (SNe Ia) progenitors had minimal impact on the [Na/Fe] predictions, indicating the issue lies elsewhere in the nucleosynthesis physics. SNe Ia are major iron contributors.

THESIS IMPACT: This significant discrepancy reveals a fundamental gap in our current understanding of nucleosynthesis, representing a major finding of the award-winning thesis work.

MODEL PREDICTIONS VS. GALAH DR3 OBSERVATIONS

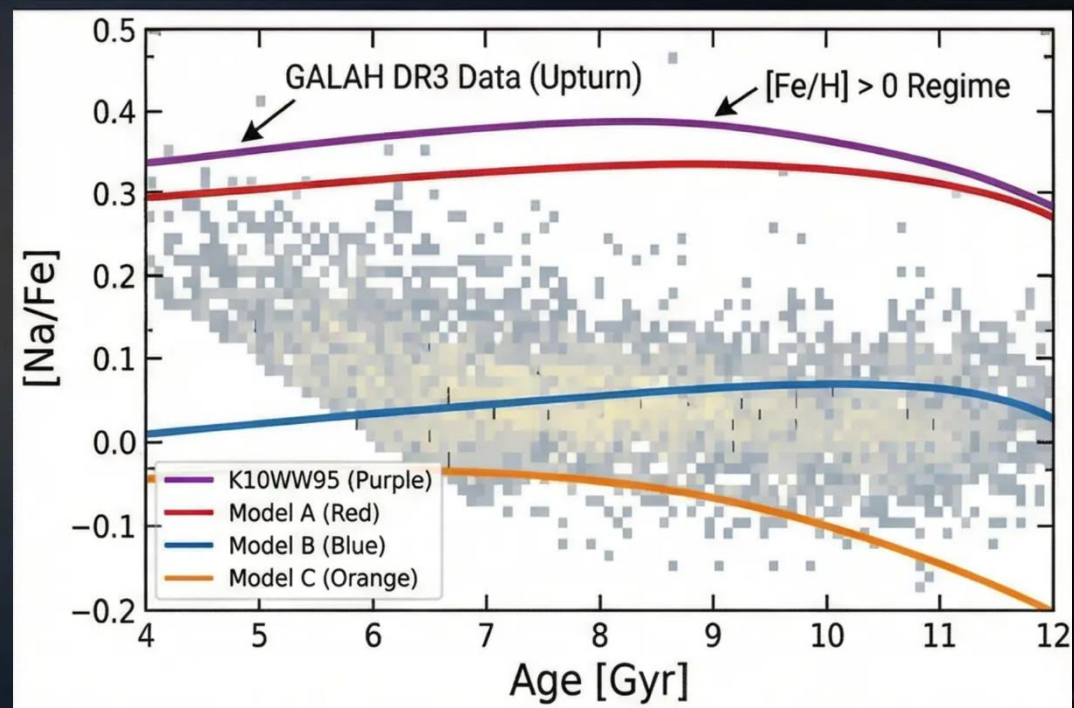


Figure: Comparison of various GCE model predictions (colored lines) with GALAH DR3 observational data (grey points). The observed upturn at young ages is not captured by any model.

Discussion: The Iron Over-Enrichment Problem

A Significant Theoretical Insight from the Award-Winning Thesis Work

GCE Models vs. Observations: Discrepancy in [Na/Fe] Ratios

- GCE models consistently predict declining [Na/Fe] ratios at super-solar metallicities ($[Fe/H] > 0$).
 - Observed enrichment trends show a pronounced upturn in [Na/Fe], indicating a limitation in current models.
- This discrepancy challenges standard chemical evolution pathways.

Iron Over-Enrichment and Sodium Trends

Abstract of the thesis work discussing the iron over-enrichment problem and sodium trends in the context of Galactic Chemical Evolution (GCE) models and observations.

Progenitor Clouds and Type Ia Supernovae Role

- Progenitor clouds for high-metallicity stars may have been underabundant in Type Ia supernova-expelled pollutants (e.g., iron).
 - Current metallicity-dependent CCSN and AGB yields might not fully capture complex Na production at high metallicities.
- Suggests a potential delay or dilution in Type Ia SN contributions or alternative Na sources.

Challenges in Stellar Physics: AGB and CCSN

- Mass-loss efficiency in AGB stars and proton-capture reaction rates in CCSN environments require urgent re-evaluation.
 - Complex Na production processes at high metallicities involve intricate nucleosynthesis pathways.
- Implies a need for updated nuclear reaction rates and stellar evolution models to resolve the iron over-enrichment problem.

Discussion: Addressing Key Uncertainties and Advancing Galactic Archaeology Models

Key Contributions: Identifying Critical Gaps in Physics and Modeling for Future Research

Nucleosynthetic Uncertainties & Yields

Uncertain proton-capture reaction rates (creating elements by adding protons) in core-collapse Supernovae hinder accurate yield predictions for light elements.

Mass-loss rates in Asymptotic Giant Branch (AGB) stars, which depend on metallicity, remain poorly constrained, affecting s-process yields.

Theoretical yields for sub-Chandrasekhar Type Ia Supernovae are largely restricted to solar metallicity, limiting models at lower $[Fe/H]$.

Galactic Dynamics & Evolution Processes

Radial migration (stars moving significant distances from their birth orbits) transports metal-rich stars from the inner Galaxy, blurring local metallicity trends.

Simplified two-zone models fail to capture the complexity of gas infall and turbulent mixing, oversimplifying the interstellar medium's chemical evolution.

Significant spatial and temporal variations in star formation efficiency and feedback mechanisms across the Galaxy are difficult to model accurately.

Modeling Framework & Methodological Challenges

Assuming a single evolutionary sequence oversimplifies the Milky Way's complex, multi-component disc structure.

Next-generation 3D spatially-resolved hydrodynamic simulations are necessary to accurately model the intricate interplay of dynamics and chemistry.

Development of refined, metallicity-dependent theoretical yield prescriptions for all nucleosynthetic channels is a critical future need.

Conclusions & Future Research: Culmination of Award-Winning Thesis Work



The Current Nucleosynthetic Challenge

Current GCE models with diverse stellar yield prescriptions fail to reproduce the observed [Na/Fe] upturn at super-solar metallicities in young thick disc stars.

The persistent nucleosynthetic puzzle highlights critical gaps in our understanding of metallicity-dependent stellar yields and element production pathways.

Context: This is especially true for "odd-Z elements" (like Sodium), which have unique nucleosynthesis origins distinct from α -elements.



Future Pathways & Essential Advancements

Future research requires enhanced theoretical stellar evolution models incorporating refined nucleosynthetic prescriptions for odd-Z elements like sodium.

Multidimensional GCE simulations beyond two-zone models are essential to capture complex galactic processes, including radial migration and spatially-resolved chemical evolution.

Context: Advanced simulations are needed to fully represent the 3D structure and dynamic mixing of elements across the galaxy, moving beyond simplified models.

Interdisciplinary collaboration is crucial to bridge these theoretical and observational gaps.

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