Galactic Archaeology: Constraining the Origin of the Elements with Empirical and Theoretical Supernova Yields

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Recent large scale spectroscopic surveys have enabled us to measure the abundances of over 15 elements for $\sim 5 \times 10^5$ stars in our Galaxy. Coupled with advancements in computing power that have improved the mass/metallicity sampling and nucleosynthesis networks of supernova models, we are in the prime time to study the origin of the elements through an observational and theoretical lens and address the questions: What are the relative contributions from core-collapse and Type Ia supernova to the elements on the periodic table? What are the characteristics of these explosive events? How is elemental production impacted by aspects of Galactic evolution? To answer these questions we need precise abundances for many stellar populations with varying evolutionary histories as well as supernova yields for a range of explosion scenarios and progenitors. As an NSF postdoctoral fellow at The University of Colorado Boulder, I will study the abundance trends of Galactic populations and dissect their different enrichment sources with APOGEE-2 and Milky Way Mapper data. I will explore the accessible parameter space of supernova yields, identify abundance ratios that distinguish enrichment pathways, and constrain the characteristics of supernovae in the Milky Way and Local Group through a comparison of observational and theoretical data.

1 Astronomical Context

Stellar abundance surveys & Galactic archaeology: The photospheres of stars preserve a snapshot of the ISM at the time of their birth and contain metals formed by previous generations of stars and their explosive deaths (e.g., Johnson, 2019). Spectroscopic stellar observations reveal absorption features from which we measure the stars' elemental and molecular abundances. These photospheric measurements vary from star to star, as the chemical makeup of the ISM evolves with time due to metallicity dependent supernovae (SN) yields and time dependent contributions of Type Ia supernovae (SNIa) and asymptotic giant branch (AGB) stars (e.g., Andrews et al., 2017). Because of the strong production of Fe-peak elements from SNIa (e.g., Iwamoto et al., 1999) and the pure core-collapse supernovae (CCSN) origin of Mg, stars formed after CCSN enrichment but before SNIa explosions have larger ratios of Mg/Fe, while stars formed after SNIa enrichment show increased Fe, and thus lower Mg/Fe ratios. This, in part, contributes to a bimodal distribution of stars in [Mg/Fe] vs. [Fe/H][1] space (Wallerstein, 1962; Tinsley, 1979). The two observed populations are traditionally referred to as high and low-α, but the respective terms low-Ia and high-Ia better capture their enrichment origin. High resolution spectra for hundreds of thousands of stars from APOGEE[2] (Majewski et al., 2017) and GALAH[3] (De Silva et al., 2015; Martell et al., 2017), coupled with spatial and kinematic information from *Gaia* (Gaia Collaboration et al., 2018, 2021), reveal this chemical bimodality throughout the Galactic disk (e.g., Hayden et al., 2015; Weinberg et al., 2019) and bulge (e.g., Rojas-Arriagada et al., 2019; Griffith et al., 2021a, Figure 1).

Together, APOGEE and GALAH observe 30 elements for stars in the disk, bulge, halo, and Magellanic clouds (Buder et al., 2020; Jönsson et al., 2020). Both surveys report abundances of α, light odd-Z, Fe-peak, and neutron capture elements, spanning multiple enrichment channels. Within both collaborations, I have analyzed the abundance patterns of the high-Ia and low-Ia stars (Griffith et al., 2019, 2021a,c). I empirically derived the CCSN and SNIa contributions to over

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[1] Where $[\mathrm{X/Y}] = \log_{10}(\mathrm{X/Y}) - \log_{10}(\mathrm{X/Y})_\odot$

[2] Apache Point Observatory Galactic Evolution Experiment, conducted as a part of the Sloan Digital Sky Survey III (SDSS-III Eisenstein et al., 2011) and IV (Blanton et al., 2017)

[3] GALactic Archaeology with HERMES

20 elements with the two-process model (Weinberg et al., 2019, 2021), which leverages the pure CCSN origin of Mg (Andrews et al., 2017) to infer the relative CCSN and SNIa contribution to the elements from their median [X/Mg] vs. [Mg/H] trends. We have fit this model to stars across the disk (Weinberg et al., 2019) and bulge (Griffith et al., 2021a) and found that though the density of the high-Ia and low-Ia populations varies with spatial location, the median sequences do not. The median abundance trends, and therefore the relative CCSN and SNIa enrichment, are insensitive to most aspects of chemical evolution. This conclusion allows us to constrain potential differences in the star formation history of the Galactic components, such as the initial mass function (IMF) that might drive location dependent abundance trend (Griffith et al., 2021a).

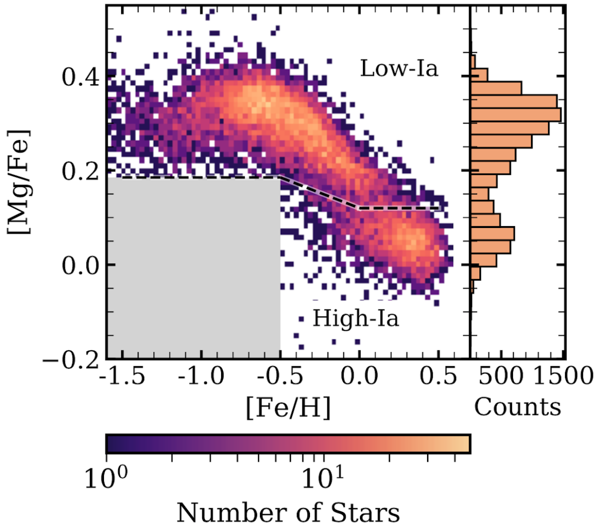

Figure 1: *Number density plot of APOGEE stars in the Galactic bulge. The dashed line denotes the division between the high-Ia and low-Ia populations. We include a histogram of the [Mg/Fe] distribution in the right hand panel. Figure adapted from Griffith et al. (2021a).*

Nucleosynthetic yield sets: As a theoretical complement to observational yield constraints, stellar models of CCSN (e.g., Woosley and Weaver, 1995), SNIa (e.g., Iwamoto et al., 1999), and AGB stars (e.g., Gallino et al., 1998) track the production and destruction of hundreds of isotopes through the end stages of stars' lives. Models of massive stars track progenitors of many masses through collapse, calculating yields of material synthesized in the progenitor, stellar winds, and explosive nucleosynthesis (e.g., Sukhbold et al., 2016). While some models force stellar explosions with thermal pistons or bombs (e.g., Woosley and Weaver, 1995; Limongi and Chieffi, 2018), neutrino-driven explosions provide a more physically motivated view of CCSN (e.g., Ugliano et al., 2012; Sukhbold et al., 2016; Curtis et al., 2019). They reveal a complex black hole explosion landscape (the masses of stars that successfully explode vs. collapse to black holes) that is strongly tied to core structure, in contrast with thermal bombs that force the explosion of all stars. However, the effects of many aspects of massive star evolution on nucleosynthetic yields remain unexplored, such as binary evolution (Patton and Sukhbold, 2020; Laplace et al., 2021) and uncertainties in key reaction rates (Kibédi et al., 2020). A synthesis of CCSN properties and potential yields is necessary to form a more realistic picture of their Galactic enrichment.

Yield models of SNIa span a wide parameter space because their progenitors are less constrained. While it is widely accepted that SNIa result from the thermonuclear explosions of white dwarfs (WD, Hoyle and Fowler, 1960), the core structures, combustion processes, WD masses and metallicities, as well as binary interactions are debated (e.g., Lach et al., 2020). To distinguish Chandrasekhar mass ($M_{\rm Ch}$) from sub-$M_{\rm Ch}$ explosions, many studies have compared the SNIa models' Fe-peak yields to Galactic abundances, often focusing on Mn (Seitenzahl et al., 2013a; Eitner et al., 2020), an element dominantly produced in SNIa (Weinberg et al., 2019). Lach et al. (2020) analyze the Mn yields of over 10 SNIa models and combinations of near-$M_{\rm Ch}$ and sub-$M_{\rm Ch}$ scenarios. They conclude that many progenitors can produce sufficient Mn yields and that a detailed comparison of SNIa yields to observations is necessary in order to distinguish WD explosion channels.

Theoretical CCSN and SNIa yields are traditionally compared to and evaluated against the solar mixture. The sun, however, holds material produced from a variety of processes, including

CCSN, SNIa, and AGB stars. **We must compare empirical and theoretical CCSN and SNIa yields independently to determine the processes that create the elements and to constrain the characteristics of SN.** Such a comparison separates yield components and improves our understanding of elements with multiple nucleosynthetic sources. With the two-process model, we can derive empirical CCSN and SNIa yields for metallicities spanned by an observational sample. In essence, this method uses the correlation of [X/Mg] with [Fe/Mg] to infer the fraction of element X in the sun that is associated with SNIa enrichment and the fraction that originates in CCSN. In Griffith et al. (2021b), for example, we compare empirical CCSN yields from GALAH (Griffith et al., 2019) to CCSN yields from Sukhbold et al. (2016) for a variety of black hole landscapes at solar metallicity (Figure 2). For plausible choices, we find 0.05 to 0.3 dex variations in the [X/Mg] values for different black hole landscapes. These variations are larger than typical APOGEE abundance uncertainties and much larger than the errors on the median abundances from which we derive empirical CCSN yields. Though no landscape produces yields in agreement with all empirical elemental constraints, we critique CCSN models and propose changes to reaction rates and winds that might bring them into better agreement with observations. Comparisons of theoretical and empirical nucleosynthesis yields have just begun and must continue with current and upcoming yields sets to answer questions about our Galactic enrichment history.

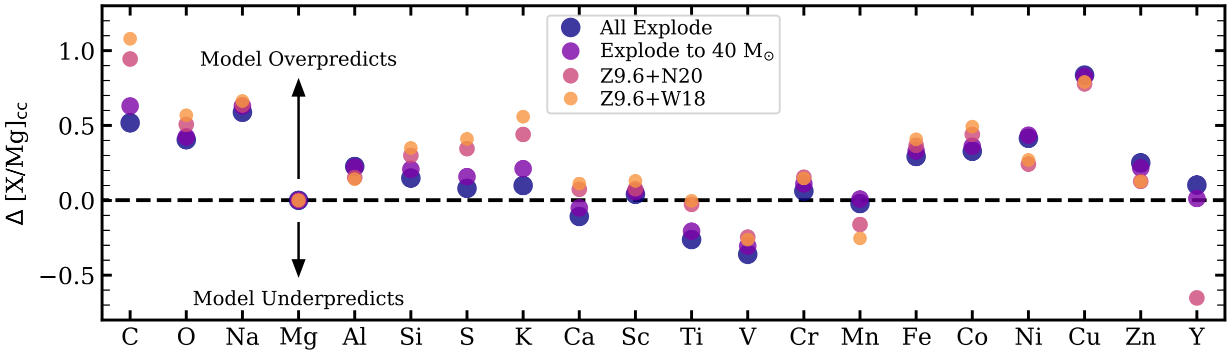

Figure 2: *Offset by which the explodability landscapes from Sukhbold et al. (2016) over/underpredicts the CCSN contribution to [X/Mg] for engines Z9.6+W18 (yellow), Z9.6+N20 (orange), Explode to* $40 M_\odot$ *(purple), and All Explode (dark blue). The dashed line at 0.0 represents the point where theoretical and empirical results agree. Observational constraints are taken from solar abundances (Asplund et al., 2009) and corrected for SNIa contributions using the results of Griffith et al. (2019) and Weinberg et al. (2019). Figure adapted from Griffith et al. (2021b).*

2 Intellectual Merit

2.1 Plan for Research

My goal as an NSF fellow is to build upon prior comparisons of yield models and observed abundances to deepen our understanding of the origin of the elements. As an NSF fellow, I will conduct an in depth analysis of empirical and theoretical supernova yields, studying CCSN and SNIa enrichment independently. My work will take advantage of state of the art CCSN and SNIa yield models as well as observational data from SDSS-V's Milky Way Mapper program–a spectroscopic survey that will revolutionize the field of Galactic archaeology over the next three years. Completing this research at CU Boulder will not only provide proprietary access to the Milky Way Mapper abundances, but will also allow me to become leader in observational and theoretical abundance research in the SDSS collaboration and the broader field. Over the course of my fellowship I will combine observations and theory to (1) investigate the black hole landscape in the Galactic bulge, LMC, and SMC; (2) constrain the relative delayed enrichment from $M_{\rm Ch}$ and sub-$M_{\rm Ch}$ white dwarfs; and (3) test my methodology on simulated stellar populations to understand the imprint of non-CCSN and SNIa sources.

2.2 Project 1: How do stellar evolution and explosion properties impact IMF averaged CCSN abundances?

Goals: *(1) To understand the variations of CCSN enrichment and the black hole landscape in the disk, bulge, and Magellanic clouds and (2) explore the effects of binarity on CCSN yields.*

Constraining the Galactic black hole landscape: Neutrino-driven CCSN models reveal an explodability mass function, or landscape, with islands of black hole formation that are strongly tied to core properties such as compactness (e.g., Ertl et al., 2016; Sukhbold et al., 2016; Curtis et al., 2019). Lower metallicity models show more black hole formation than solar metallicity models, especially at high masses ($M_* \gtrsim 40 M_\odot$), though to date the metallicity sampling is sparse (Pejcha and Thompson, 2015; Ebinger et al., 2020). The true CCSN black hole landscape remains unknown. To observationally constrain it, we must identify abundance ratios diagnostic of CCSN explodability at many metallicities. This requires neutrino-driven CCSN models with explosive nucleosynthesis calculations that are finely sample in mass and metallicity, such as those from Curtis et al. (2019) and Ebinger et al. (2020). With these explosive yields in hand for > 150 models of massive stars with $10.8 M_\odot \leq M \leq 120 M_\odot$ at $Z = 0$, $10^{-4} Z_\odot$, and $Z_\odot$, I will calculated the IMF averaged yields and [X/Mg] abundance ratios of their models. The published yields will only provide a prediction of abundance ratios for the complex black hole landscapes their models produce. To compare yields from complex black hole landscapes with more explosive landscapes, I will collaborate with Dr. Sanjana Curtis (University of Amsterdam) to calculate explosive yields for the stars that collapse to black holes in her prior work. We will construct an artificial yield set at three metallicities where all massive stars explode. With a fully exploding yield set, I can "mask" regions to calculate IMF averaged yields for any black hole landscape. I will compare results to Griffith et al. (2021b), extending my past work with CCSN yields from Sukhbold et al. (2016) to a new neutrino-driven explosion mechanism and lower metallicity models. With predicted abundance ratios from plausible choices of black hole landscapes at from $Z = 0$ to $Z_\odot$, I will create a list of stellar abundances that vary by > 0.15 dex and are thus diagnostic of CCSN explodability.

Comparing with observations: The next step to constrain the black hole landscape is to compare theoretical yields with observations. This requires empirical estimates of CCSN contributed abundances in stellar populations that are not contaminated by other enrichment sources. Past works by my group have produced robust constraints of the CCSN yield in the disk (Weinberg et al., 2019; Griffith et al., 2019, 2021b) and bulge (Griffith et al., 2021a). I am interested in extending this work to determining if the empirical CCSN yields and inferred black hole landscapes vary between stellar populations with different chemical enrichment histories. Rather than focus on the absolute agreement of theoretical and empirical CCSN yields, I will compare the Δ [X/Mg] spanned by IMF averaged yield sets with different BH landscapes to the range in empirical CCSN yields between stellar populations with unique chemical enrichment histories. I will focus on difference between the Galactic disk, bulge, and Magellanic clouds, as past works have suggested IMF variations between these populations (e.g., Grieco et al., 2012, 2015; Hasselquist et al., 2021).

To separate out the CCSN enrichment to stars in the bulge and Magellanic clouds, we need high quality abundances for 1000s of stars in each population. At CU Boulder, I will join the SDSS-V and Milky Way Mapper teams, who are expanding spectroscopic observations and abundance determinations to $\sim 6 \times 10^6$ stars across the Galaxy and Local Group. Milky Way Mapper will produce densely sampled maps of the disk and bulge, with unparalleled coverage of the low-latitude inner galaxy (Kollmeier et al., 2017). Combined with spatial and kinematic data from *Gaia*, we will be able to disentangle the meso-structure of the inner Galaxy and study the abundances of large populations of stars in the bar and bulge separately for the first time. Further, Milky Way Mapper will expand coverage of the nearby dwarf galaxies, shown to have unique chemical abundances trends that differ from the low metallicity disk (Hasselquist et al., 2021). I will fit the bulge, LMC, and SMC populations with the two-process model to quantify the relative CCSN and SNIa enrichment and empirically derive CCSN yields. I will compare their median abundance trends and CCSN components with those of the Galactic disk to assess the enrichment differences and with the range of yields produced by a variety of black hole landscapes. This comparison will determine if CCSN contribute differently in stellar populations with unique chemical enrichment history and if these differences can be explained by a changing black hole landscape.

The impact of binary interactions: Over half of the massive stars in our Galaxy live in multi-star systems and experience mass transfer during their lifetime (Sana et al., 2012). Recent pre-supernova models find that massive stars undergoing binary interactions have lower core compactness and greater amounts of ^{12}C than single massive stars of the same initial mass (Patton and Sukhbold, 2020; Laplace et al., 2021). As core structure is intimately tied to stellar explodability, binary interactions will likely impact the resulting explosive nucleosynthesis and black hole landscape. However, all available CCSN models with nucleosynthetic calculations evolve single progenitors stars. I will collaborate with Dr. Santana Curtis to explode the existing binary progenitors (Laplace et al., 2021) with the neutrino-driven engine, PUSH (Perego et al., 2015), calculating the first explosive nucleosynthesis yields for the binary progenitors. I will compare the resulting yields and black hole landscapes to those from single progenitors and evaluate the impact of binarity on CCSN. If we observe significant yield differences between binary and single progenitors, I will repeat my comparison with empirical CCSN abundances of the Galactic disk and identify elements with improved/worsened agreement.

Beyond my proposed exploration of the black hole landscape and binary interaction, I am interested in the impact of rotation and reaction rate uncertainty on CCSN yields as well as the development of massive star progenitor models for metallicities closer to those of the observed population (e.g., 1/10 $Z_\odot$ and 2× $Z_\odot$). I will seek out collaborations with massive star modelers to develop such progenitors. As all of these factors may impact IMF averaged CCSN yields, it is important to quantify their impact in order to understand or rule out potential model degeneracies.

Documentation: This project will result in at least two publications: (1) A paper comparing the IMF averaged yields for a range of black hole landscapes at three metallicities to empirical CCSN yields of the disk, bulge and Magellanic clouds and (2) a paper presenting yields for massive stars with binary interaction. All yields from these projects will be integrated into the publicly available package VICE[4], the Versatile Integrator for Chemical Evolution (Johnson and Weinberg, 2020), for which I am a contributing author.

2.3 Project 2: What elemental yields are diagnostic of SNIa progenitors?

Goals: *(1) To identify yield ratios that vary with SNIa progenitor mass & metalliicty and (2) constrain the SNIa component of the delayed enrichment to Cu and Zn.*

Compiling SNIa yields: The specific stellar progenitors of SNIa have remained elusive for decades, as astronomers have debated their single vs. double degenerate origin. The final mass, density, and metallicity of the progenitor WD will impact the material produced through its explosive nucleosynthesis. With recent yields from Gronow et al. (2021) for 44 sub-$M_{\rm Ch}$ SNIa with

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[4] https://github.com/giganano/VICE.git

metallicity from 0.01 to $3Z_\odot$ and Leung and Nomoto (2018) for 41 near-$M_{\rm Ch}$ SNIa with metallicity between 0 and $5Z_\odot$ (along with many other smaller yield sets, e.g., Iwamoto et al., 1999; Seitenzahl et al., 2013b; Lach et al., 2020), it is the prime time to compare the nucleosynthetic implications of mass and metallicity dependent SNIa. I will compile SNIa yields from the works referenced above and update the SNIa yield library of VICE (Johnson and Weinberg, 2020). Using a $t^{-1.1}$ delay time distribution with an SNIa rate from Maoz et al. (2012), I will calculate the predicted total yields and [X/Fe] abundances for a range of models with varying WD masses, densities, and metallicities.

Comparing with observations: To evaluate the ability of SNIa models to reproduce the observed abundance trends, I will compare theoretical yields to empirical constraints on the SNIa enrichment. While I leverage the two-process model to isolate the Galactic CCSN enrichment in Griffith et al. (2021b) and Project 1, the remaining non-CCSN component has delayed production. For Fe-peak elements, this material is entirely produced by SNIa (Andrews et al., 2017). I will derive empirical SNIa yields from two-process fits to the Galactic disk (Griffith et al., 2019; Weinberg et al., 2021) and compare the empirical and theoretical yields for a range of SNIa model spanning many masses and metallicities. Through this comparison I will identify yield ratios that are sensitive to the progenitor properties. I will focus on Mn, whose use to distinguish $M_{\rm Ch}$ and sub-$M_{\rm Ch}$ is debated (Seitenzahl et al., 2013a; Eitner et al., 2020; Lach et al., 2020). My work will improve upon the traditional comparison with Galactic chemical evolution models, from which it is difficult to evaluate the success of SNIa models in reproducing abundances of elements with multiple enrichment sources.

In addition to evaluating and comparing yields for single WD models, I will also calculate and compare yields for combinations of progenitors. SNIa likely result from a mix of $M_{\rm Ch}$ and sub-$M_{\rm Ch}$ explosions that each contribute different Fe-peak yields. I will review the six model combinations from Lach et al. (2020) and determine the relative fraction of $M_{\rm Ch}$ and sub-$M_{\rm Ch}$ SNIa needed to best reproduce empirical SNIa yields at solar metalicity.

Disentangling delayed contributions: While my initial analysis of SNIa yields will focus on elements produced entirely by CCSN and SNIa (α, light odd-Z, Fe-peak), a wealth of enrichment information remains in heavier elements with multiple delayed enrichment sources (e.g., SNIa, AGB, neutron star mergers). For elements such as Cu and Zn (observed by GALAH+ DR3; Buder et al., 2020), the two-process model is only able to separate out the delayed enrichment and cannot distinguish between SNIa and AGB enrichment (Griffith et al., 2021c). I will compare empirical delayed abundances of Cu and Zn with theoretical SNIa yields to determine if SNIa models can reproduce their full delayed component. The failure of models to reproduce the empirical delayed abundance could point to alternative delayed enrichment sources. I am particularly interested understanding the delayed contributions to Cu and Zn, as Lach et al. (2020) identify both elements as potential diagnostics of the SNIa progenitor mass, density, and metallicity.

With two-process fits to the disk and SNIa yields in hand, this project can bring with the start of my NSF fellowship. The project does not require the creation of new yield sets, only the integration of current yields into existing software. Future data releases from GALAH or Milky Way Mapper may expand upon the number of heavy element for which we have trustworthy abundances and increase the scope of my investigation into elements with multiple delayed sources.

Documentation: This project will be documented through a paper comparing SNIa yields to empirical delayed abundances. I will add all publicly available yields that I use to VICE.

2.4 Project 3: How well can the two-process model isolate enrichment channels?

Goals: *To test the underpinnings of the two-process model's methodology and identify the imprint of AGB contribution on the residual abundances.*

Projects 1 and 2 focus on α, light odd-Z and Fe-peak elements and rely on the ability of the two-process model to separate out the prompt and delayed Galactic enrichment. By the model's definition, this would work perfectly for stellar abundances with metallicity independent enrichment from only CCSN and SNIa with no observational error. The inclusion of metallicity dependent yields, additional enrichment sources, and observational errors create multiple pathways to the same abundance point, introducing scatter and complicating the separation of empirical CCSN and SNIa components. For my final project as an NSF postdoc, I will test the two-process model on a sample with known nucleosynthetic yields to understand its behavior in realistic enrichment scenarios and extend its functionality to elements produced by AGB stars.

Constructing stellar sample: I will employ the multi-zone and radial migration features of the galactic chemical evolution modeler VICE to create a solar neighborhood stellar population with CCSN and SNIa enrichment, using the yield sets identified in the previous projects and the chemical evolution history from (Johnson et al., 2021). I will add a random observational error term to each [X/H] abundance for each star, such that the elemental error distribution matches that of the Milky Way Mapper solar neighborhood sample to replicate observing conditions. Finally, I will fit the two-process model to the faux observational data and compare the predicted fractional contribution from CCSN and SNIa to the true contribution. This analysis will reveal how robust the two-process model is to observational errors and metallicity dependent yields.

Identifying signatures of multiple delayed enrichment channels: After understanding the signatures of CCSN and SNIa enrichment on the α, light odd-Z and Fe-peak elements in the simulated stellar population, I will turn on VICE's AGB enrichment, repeat the two-process fit, and re-evaluate the model's ability to predicted the observed abundances for elements with AGB enrichment, such as C, N, Sr, and Ba. Because the two-process model assumes only prompt CCSN enrichment and delayed enrichment on the timescale of SNIa, the addition of an AGB enrichment will likely cause the model to poorly fit stellar abundances for these elements. I will analyze the residual abundances (the differences between the "observed" and two-process predicted values) and identify element groups with correlated residuals. This work will reveal if AGB enrichment skews the two-process fits and will develop strategies for empirically separating AGB and SNIa enrichment through studies of residual abundance correlations, outlier stars, and additional model components (Griffith et al., 2021c), extending our model to elements produced by AGB stars.

Documentation: This project will be documented through the creation of a mock abundance catalog and a paper on the model's success in separating its CCSN, SNIa, and AGB components.

3 Broader Impacts

As scientists, we have a responsibility to make science accessible to and welcoming for all. Mentorship and science communication efforts are necessary now to improve the retention of students in STEM at all levels and increase science literacy. At Ohio State, I have been a leader in undergraduate student mentoring as well as in the planetarium presenter training and show design, and my contributions have been recognized with the Astronomy Department's Anne S. Tuttle Citizenship Award. My involvement in both activities has grown my passion for outreach and taught me communication and management skills, enabling me to lead impactful work as an NSF fellow. The Astronomy and Physics departments at CU Boulder have a strong commitment to outreach initiatives, and my broader impact plans compliment their current programming. Here, I will (1) develop near-peer mentor training for the STEM mentorship initiative CU Prime to help improve the retention and sense of belonging of first year students and (2) create an SDSS Milky Way Mapper planetarium show to share the collaboration's science with the broader community.

3.1 Project 1: Mentor Training

Background: Physics and astronomy departments across the United States suffer from poor representation of minorities on the basis of gender, race, and ability at all levels (e.g., James et al., 2020). This stems from the historic exclusion of minority students as well as the lack of recruitment and support for them now. To improve students' STEM experience and representation, we must implement programming that develops their science identify (Trujillo and Tanner, 2014), sense of belonging (Freeman et al., 2007), and self efficacy (Fencl and Scheel, 2004). At the undergradaute level, mentorship programs have been shown to improve retention among STEM students and improve student experience (Zaniewski and Reinholtz, 2016). Recent reports from national organizations such as AAS (Rudolph et al., 2019) and AIP (James et al., 2020) have highlighted the need for mentorship at many academic levels.

At Ohio State, I have worked with Polaris, a partnership between undergraduate and graduate physics and astronomy students dedicated to fostering a more equitable and inclusive undergraduate experience in the Ohio State Departments of Physics and Astronomy. I have organized and taught a mentorship course for the program for three years. The course pairs lower level undergraduate students from underrepresented backgrounds with graduate student mentors, initiates discussions about diversity in STEM, and aids students' professional development. Polaris is a part of the Access Network[5], a NSF funded organization of STEM mentorship programs at twelve universities, including CU Prime at Boulder. CU Prime offers similar programming to Polaris, including a class on authentic science and a paired mentorship program. One of the largest challenges we've faced in Polaris is the ability to supply sufficient mentor training. Beyond program expectations, potential mentors need guidance on supporting students through difficult situations and recognizing how demographics impact the STEM experience.

Goal: *To provide participants at CU Prime and across the Access Network with skills needed to be successful, empathetic mentors.*

Project Outline: I will support the programming of CU Prime and work with the current leaders to identify the successes and shortcomings of the current mentor training. Over the first year of my fellowship I will meet monthly with CU Prime mentors to check in and create a forum for them to share experiences and resources. Through conversations with current and past mentors, I will compile a list of situations that they felt underprepared to handle. Examples from my work with Polaris include student roommate disputes, mental health concerns, academic hardships, and misconduct by TAs or professors. Informed by the common student struggles, I will consult with undergraduate academic advisors and CU Boulder's Student Support and Case Management office to compile a list of resources that mentors should be aware of.

In addition to instruction on institution specific resources, mentors need guidance on how to be compassionate, empathetic supporters to students of all backgrounds. Mentors across the Access Network are undergraduate and graduate students in STEM whose education is dominated by science and research. Though some universities have begun to host college wide research mentor trainings, in-house socially conscious near-peer mentoring workshops are not available. Using my annual fellowship allowance, I will collaborate with and hire Dr. Nicole Salazar from the STEM equity consulting firm *Movement Consulting*[6] to develop a four-hour workshop on near-peer mentoring of minority students. The workshop will be open to all Access Network leaders and will "train the trainer," allowing myself and others to integrate what we learn into the mentor training protocols at multiple universities. I have contacted *Movement Consulting* and confirmed that this

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[5] https://accessnetwork.org/about/

[6] https://www.movebold.ly/

is inside the scope of their services and that the cost could be covered by my fellowship allowance.

I will combine the resources from this workshop with those from campus services and develop lesson plans for a series of mentor trainings. I will implement this new training during the second and third year of my fellowship, revising content based on mentor feedback. By redesigning the training at CU Prime and providing mentoring resources across the Access Network, mentors will be more equip to help and support their mentees. This will directly lead to an increased sense of belonging, supporting students to STEM degree completion.

Documentation: I will document this project by (1) taking notes on the *Movement Consulting* workshop (2) creating detailed lesson plans and materials for mentor training sessions.

3.2 Project 2: Milky Way Mapper Planetarium Show

Figure 3: *APOGEE stars overlaid on a model of the Milky Way in the Arne Sletteback Planetarium.*

Background: Around the world, planetariums engage audience members of all ages from all levels of scientific backgrounds. Their visuals encapsulate audiences with the beauty of our universe and teach astronomical concepts through imagery and simulations (e.g., Plummer, 2009; Zimmerman et al., 2014; Yu et al., 2015). Over the last four years, I have worked in the Arne Sletteback Planetarium at Ohio State where I have given over 75 planetarium shows and developed planetarium content, I have also trained student presenter on the planetarium software and guided students to a complete understanding of the astronomical concepts they strove to present. While planetarium shows traditionally focus on the planets, constellations, and seasons, I've begun integrating data onto the dome to explore the ways we can communicate current research to the public. Digital Sky Dark Matter, the planetarium software licensed by both Ohio State and the Fiske Planetarium at CU Boulder, includes a few astronomical data set (e.g., known exoplanets) and telescope models, but gives the user the opportunity import their own 3D models and data. The ability to show real astronomical data in three dimensions on a planetarium dome opens the doors to new mediums of data analysis and aids astronomers in communicating current and ongoing science to the public.

Goal: *To create a publicly accessible planetarium show and undergraduate level presenter's guide that give a tour of the SDSS survey and its data products.*

Project Outline: At CU Boulder I will collaborate with Planetarium Director, Dr. John Keller, and Theatre Manager, Nick Conant, to import SDSS Milky Way Mapper data into the planetarium and develop a show to communicate the survey goals, observing methods, and results to the public. My planetarium show will discuss our Galactic structure, evolution, and chemical enrichment, incorporating the research products from this NSF proposal. At CU Boulder, as at many other universities, undergraduate 'navigators' present most live public shows and answer questions from the audience. Because it is crucial for the show presenter to have a thorough understanding of the content they are discussing, the most important piece of this project will be the construction of a presenter's guide. In this guide, I will explain each component of the planetarium show and explicitly state the learning objects we strive to communicate. I will workshop the planetarium show and guide with current undergraduate navigators at CU Boulder to ensure the that the content is accessible and interesting.

Documentation: A Dark Matter planetarium show script and a corresponding presenter's guide. The planetarium show will be made publicly available to other universities with compatible software through SDSS's Education and Public Engagement group.

4 Justification For Host Institution

My proposed research will directly benefit from proprietary access to Milky Way Mapper's spectroscopic observations and working group collaborations available at a SDSS-V member institution, such as CU Boulder. Here I will be sponsored by Dr. Jeremy Darling, an expert in galaxy evolution with interests in heavy element detection. Conversations with him will broaden my understanding of the cosmological context of my work. At CU Boulder I will also have the opportunity to collaborate with exoplanet faculty (Meredith MacGregor, Kevin France, Zach Berta-Thompson) who are interested in characterization of host stars. In addition to its academic resources, CU Boulder is the ideal location to engage in outreach. I will join CU Prime, a STEM mentorship program, and continue my involvement with the Access Network. At CU Boulder I will also have access to the Fiske Planetarium and Digital Sky Dark Matter software. I will collaborate the planetarium staff (Dr. John Keller, Nick Conant, and undergraduate navigators) to bring current research to the dome. I hope to extend the products of my work in the planetarium to the larger community by joining the SDSS Education and Public Engagement group. These opportunities for research and broader impact collaborations make CU Boulder the ideal location for my NSF fellowship.

5 Career Goals

I plan to pursue a career as a faculty member at a smaller liberal arts university or as a planetarium or museum-based educator. Through either route I will be able to continue research, but also focus on teaching, undergraduate involvement, and community engagement. As an NSF fellow at CU Boulder, I will pursue my research and outreach passions, gaining the necessary skills to be a successful faculty/staff member. In my postdoctoral studies and future career I will strive to contribute to the field of Galactic archaeology, provide a welcoming and supportive environment for all students, and engage the public in scientific discussions.

6 Timeline

Year 1 (2022-2023:)

- Project 1: Analyze explosive CCSN yields and create a fully exploding yield set.
- Project 2: Compare predicted SNIa abundances from a variety of mass and metallicity models.
- Broader Impacts 1: Discuss mentor training needs with CU Prime mentors. Host a workshop with *Movement Consulting*.

Year 2 (2023-2024:)

- Project 1: Identify bulge, LMC, and SMC stellar samples. Calculate empirical CCSN yields.
- Project 2: Calculate empirical SNIa yields for the Galactic disk and constrain the SNIa progenitors. Study the delayed enrichment to Cu and Zn.
- Broader Impact 1: Hold mentor training sessions. Solicit feedback from mentors.
- Broader Impacts 2: Begin planetarium show development and set learning objectives.

Year 3 (2024-2025:)

- Project 1: Acquire, explode, and analyze pre-SN models of stars with binary interactions.
- Project 3: Create a stellar population with CCSN, SNIa, and AGB enrichment. Evaluate the two-process model's ability to separate enrichment sources.
- Broader Impact 1: Revise and document mentor training. Hold mentor training sessions.
- Broader Impact 2: Workshop planetarium materials with undergraduates and premier show.