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Chemically Self-Consistant Modeling of the Globular Cluster NGC 2808 and its Effects on the Inferred Helium abundance of Multiple Stellar Populations.

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ABSTRACT

Over its approximately 100 year history stellar modeling has become an essential tool for understanding certain astrophysical phenomena which are not directly observable. Modeling allows for empirical constraints — such as elemental abundances, luminosities, and effective temperatures — to strongly inform non-observables such as a star's age, mass, and radius. Here we propose a thesis in five parts, related through their use of both modeling and the Dartmouth Stellar Evolution Program (DSEP) to conduct this modeling. In two of the parts of this thesis we will use DSEP, in conjunction with atmospheric boundary conditions generated by collaborators, to build chemically self-consistent models of multiple populations (MPs) in the globular clusters NGC 2808, 47 Tuc, and NGC 6752. We will infer helium abundances across MPs and compare these inferred abundances to those from models which do not consider as careful a handling of a star's chemistry. PLACEHOLDER

1. INTRODUCTION

Globular clusters (GCs) are among the oldest observable objects in the universe (Peng et al. 2011). They are characterized by high densities with typical half-light radii of ≤10 pc (van den Bergh 2010), and typical masses ranging from 10^4–10^5 $M_\odot$ (Brodie & Strader 2006) — though some GCs are signifigantly larger than these typical values EXAMPLE. GCs provide a unique way to probe stellar evolution (Baumgardt & Makino 2003), galaxy formation models (Boylan-Kolchin 2018; Kravtsov & Gnedin 2005), and dark matter halo structure (Hudson & Robison 2018). BRING IN SOME MORE RECENT CITATIONS.

Whereas, people have have often tried to categorized objects as GCs through relations between half-light radius, density, and surface brightness profile, in fact many objects which are generally thought of as GCs don't cleanly fit into these cuts EXAMPLE + CITATION. Consequently, Carretta et al. (2010) proposed a definition of GC based on observed chemical inhomogeneities in their stellar populations. The modern understanding of GCs then is not simply one of a dense cluster of stars which may have chemical inhomogeneities and multiple populations; rather, it is one where those chemical inhomogeneities and multiple populations themselves are the defining element of a GC.

All Milky Way globular clusters older than 2 Gyr studied in detail show populations enriched in He, N, and Na while also being deplete in O and C (Piotto et al. 2015; Bastian & Lardo 2018). These light element abundance patterns also are not strongly correlated with variations in heavy element abundance, resulting in spectroscopically uniform Fe abundances between populations. Further, high-resolution spectral studies reveal anti-correlations between N-C abundances, Na-O abundances, and potentially Al-Mg (Sneden et al. 1992; Gratton et al. 2012). Typical stellar fusion reactions can deplete core oxygen; however, the observed abundances of Na, Al, and Mg cannot be explained by the likes of the CNO cycle (Prantzos et al. 2007).

Formation channels for these multiple populations remain a point of debate among astronomers. Most proposed formation channels consist of some older, more massive, population of stars polluting the pristine cluster media before a second population forms, now enriched in heavier elements which they themselves could not have generated (for a detailed review see Gratton et al. 2012). The four primary candidates for these polluters are asymptotic giant branch stars (AGBs, Ventura et al. 2001; D'Ercole et al. 2010), fast rotating massive stars (FRMSs, Decressin et al. 2007), super massive stars (SMSs, Denissenkov & Hartwick 2014), and

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massive interacing binaries (MIBs, de Mink et al. 2009; Bastian & Lardo 2018).

Hot hydrogen burning (proton capture), material transport to the surface, and material ejection into the intra-cluster media are features of each of these models and consequently they can all be made to *qualitatively* agree with the observed elemental abundances. However, none of the standard models can currently account for all specific abundances (Gratton et al. 2012). AGB and FRMS models are the most promising; however, both models have difficulty reproducing severe O depletion (Ventura & D'Antona 2009; Decressin et al. 2007). Moreover, AGB and FRMS models require signifigant mass loss ($\sim$ 90%) between cluster formation and the current epoch — implying that a signifigant fraction of halo stars formed in GCs (Renzini 2008; D'Ercole et al. 2008; Bastian & Lardo 2015).

In addition to the light-element anti-correlations observed it is also known that younger populations are signifigantly enhanced in Helium (Piotto et al. 2007, 2015; Latour et al. 2019). Depending on the cluster, Helium mass fractions as high as $Y = 0.4$ have been inferred (e.g Milone et al. 2015). However, due to the relatively high and tight temperature range of partial ionization for He it cannot be observed in globular clusters; consequently, the evidence for enhanced He in GCs originates from comparison of theoretical stellar isochrones to the observed color-magnitude-diagrams of globular clusters. Therefore, a careful handling of chemistry is essential when modeling with the aim of discriminating between MPs; yet, only a very limited number of GCs have yet been studied with chemically self-consistent (structure and atmosphere) isochrones (e.g. Dotter et al. 2015, NGC 6752).

This thesis will contain chapters where we expand the number of clusters which have been self-consistently modeled. In this chapter we will focus on chemically self-consistent modeling of the two extreme population of NGC 2808 identified by (Milone et al. 2015), A and E.

One key element of NGC 2808 modeling is the incorporation of new atmospheric models, generated from the `MARCS` grid of model atmospheres (Plez 2008), which match interior elemental abundances. `MARCS` provides one-dimensional, hydrostatic, plane-parallel and spherical LTE atmopsheric models (Gustafsson et al. 2008). Members of our collaboration have generated atmospheric models for populations A and E. Integration of these new model atmospheres into DSEP is ongoing.

1.0.1. *Population Opacities*

For similar reasons as discussed in §**??** we conduct this research with OPLIB high-temperature opacity tables as opposed to OPAL tables. We will also generate low temperature opacity tables using the `MARCS`. Moreover, we confirm that the atmosphere and structure meet in an optically thick region of the star by shifting the atmospheric fitting point from an optical depth of $\tau = 2/3$ (used by DSEP currently for `PHOENIX` model atmospheres) to some higher τ. We will experiment to identify the best optical depth to fit at..

These population have been studied in depth by Feiden and their chemical compositions were determined in Milone et al. (2015) (see Table 2 in that paper). While we cannot yet evolve DSEP models with these new boundary conditions, we can make a first pass investigation of the affect of OPLIB opacities (Figure **??**). Note how the models generated using OPLIB opacity tables have a systematically lower luminosity. This discrepancy is consistent with the overall lower opacities of the OPLIB tables.

1.0.2. *Additional Consistency*

The isochrones generally used to infer the degree of helium enhancements assume that convection operates in the same manner in metal-poor stars as it does in the Sun. However, observations from *Kepler* of metal-poor red giants (Bonaca et al. 2012; Tayar et al. 2017), in concert with interferometric radius determination of the metal-poor sub-giant HD 140283 (Creevey et al. 2015), have shown that the efficiency of convection changes with iron content. As the final portion of our work to more carefully handle a star's chemistry, we will modify DSEP to capture this variation in convective efficiency.

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