Models of Low Mass Stars in the Local Solar Neighborhood and in Globular Clusters

A Thesis Proposal

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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 a core temperature and pressure. 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 stars chemistry. The remaining three parts of this thesis will address a recently discovered feature in the Gaia $G_{BP} - G_{RP}$ color-magnitude-diagram (colloquially the Jao Gap). Throughout this series we will update DSEP's opacity tables to the most modern available (OPLIB from Los Alamos) and show how this change affects the theoretical location of the Jao Gap. Subsequently, we will use synthetic color-magnitude-diagrams (CMDs) — covering the Jao Gap regime — in conjunction with gyro-kinematically derived age distributions to test the feasibility of population age-dating by measuring the Jao Gap's location in a CMD. Finally, we will apply techniques developed in our theoretical testing of Jao Gap based age-dating to the solar neighborhood, attempting to identify coeval groups and roughly age-date them. These five parts will compose the scientific chapters of a thesis to be submitted to the faculty and advising committee no latter than the summer term of 2024.

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1. INTRODUCTION

Throughout last half of the 19th and first decade of the 20th centuries Lane, Ritter, and Emden codified the earliest mathematical model of stellar structure, the polytrope (Equation 1), in *Gaskugeln* (Gas Balls) (Emden 1907).

$$\frac{d}{d\xi}\left(\xi^2\frac{d\theta}{d\xi}\right) = -\xi^2\theta^n \tag{1}$$

Where ξ and θ are dimensionless parameterizations of radius and temperature respectively, and n is known as the polytropic index. Despite this early work, it wasn't until the late 1930s and early 1940s that the full set of equations needed to describe the structure of a steady state, radially-symmetric, star (known as the equations of stellar structure) began to take shape as proton-proton chains and the Carbon-Nitrogen-Oxygen cycle were, for the first time, seriously considered as energy generation mechanisms (Cowling 1966). Since then, and especially with the proliferation of computers in astronomy, the equations of stellar structure have proven themselves an incredibly predictive set of models.

There are currently many stellar structure codes (e.g. Dotter et al. 2008; Kovetz et al. 2009; Paxton et al. 2011) which integrate the equations of stellar structure — in addition to equations of state and lattices of nuclear reaction rates — over time to track the evolution of an individual star. The Dartmouth Stellar Evolution Program (DSEP) (Chaboyer et al. 2001; Bjork & Chaboyer 2006; Dotter et al. 2008) is one such, well tested, stellar evolution program.

Here we propose to model low-mass stars in both the local solar neighborhood and in globular clusters using DSEP. This work will primarily extend our understanding of stellar physics in two areas: the effects of chemical self-consistency on stellar models (e.g. Dotter et al. 2015) and the time evolution of the core-convective instabilities which ultimately are believed to result in the observed paucity of stars at a Gaia G magnitude of $\sim$10 (Jao et al. 2018; Feiden et al. 2021).

1.1. *Globular Clusters*

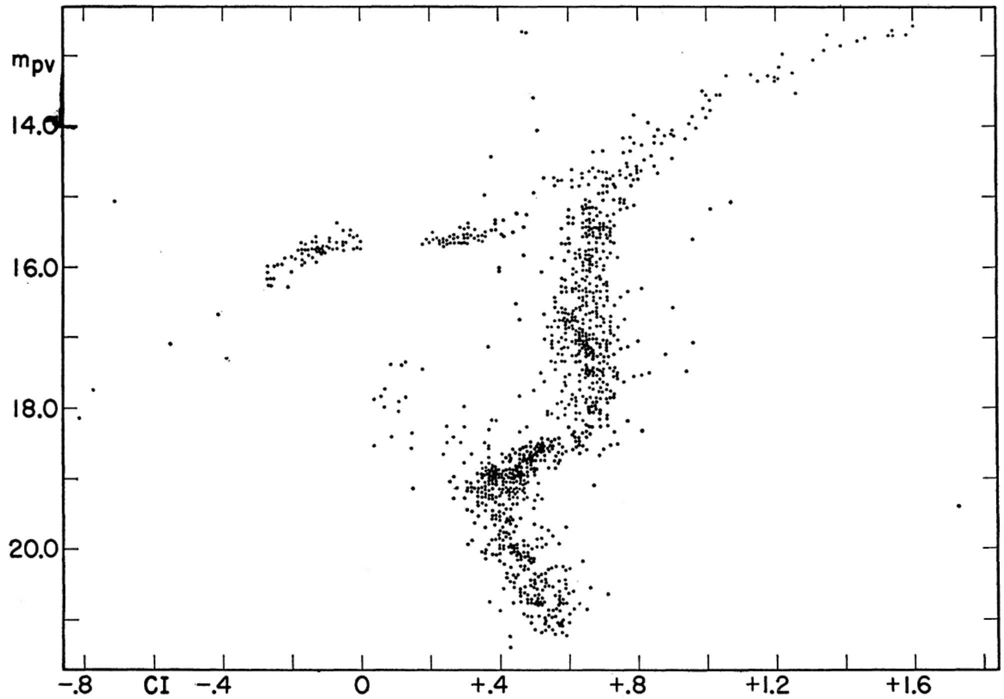

Figure 1. m_{pg} - m_{pv} color-magnitude diagram for the globular cluster M3.

Globular clusters (GC, Herschel 1814) are among the oldest groupings of stars in the Universe, with typical ages greater than 10 Gyr. They are characterized by their compact size — typical half-light radius < 10 pc but up to 10s of pc — and high surface brightness — $M_V \sim -7$. For decades, prevailing thought had it globular clusters were composed of a single stellar population born from a pristine interstellar media. Single stellar populations had been assumed — as opposed to multiple stellar population (MPs) due to spectroscopically uniform iron abundances (Gratton et al. 2012) and very narrow principal sequences (e.g. Figure 1 taken from Sandage 1953; Stetson & Harris 1988), both of which are indicative of a single stellar population.

These early studies either did not handle or had very large photometric uncertainties masking subtly distinguished features within the CMD. Moreover, given these studies were ground based they were limited to optical bands where colors do not respond strongly to all chemical changes within a star's atmosphere.

Despite the canonical view of single populations composing GCs, there has been spectroscopic evidence for chemical inhomogeneities in GCs since the early 1970s (e.g. Osborn 1971) and by the late 1980s, as higher resolution photometry became available, multiple clusters were known which exhibited features in their CMDs consistent with either bimodal or multimodal stellar populations (e.g. Norris 1987).

The first conclusive evidence for MPs came with Hubble Space Telescope (HST) high precision crowded field photometry in which three distinct main sequences in NGC 2808 were identified (Piotto et al. 2007). Since this discovery, split main sequences have been found in nearly all Milky Way globular clusters studied by HST (Anderson et al. 2009; Milone et al. 2012). Split stellar populations are believed to be due to enhanced helium abundances in the stellar populations formed after the primordial population of stars (D'Antona et al. 2005; Piotto et al. 2007). When compared to primordial helium mass fractions (Y) of $Y \sim 0.25$ (Collaboration et al. 2016) or solar helium abundances $Y \sim 0.27$ (Vinyoles et al. 2017) these populations have mass fractions as high as $Y \sim 0.4$. Helium enhancement is strongly suspected to be the result of an earlier, more massive population dying off, enriching the interstellar medium (Gratton et al. 2001, 2004, 2012); however, precise formation channels for split stellar populations remain contentious. The primary open question then is not why some populations are enhanced in helium; rather, it is to what extent they are enhanced.

Two chapters of this thesis will further constrain the helium enhancement of MPs within globular clusters by modeling their stellar populations in a fully chemically self-consistent manner. Sections **??** and **??** address the details of these projects in more detail.

1.2. *Local Solar Neighborhood*

Jao et al. (2018) discovered a novel feature in the Gaia $G_{BP} - G_{RP}$ color-magnitude-diagram. Around $M_G = 10$ there is an approximately 17% decrease in stellar density of the sample of stars Jao et al. considered. Subsequently, this has become known as either the Jao Gap, or Gaia M dwarf Gap. Section **??** will go into more detail regarding the physics underpinning this feature; however, in brief convective instabilities in the core are believed to form for stars straddling the fully convective transition mass. These instabilities result in star's luminosities preferentially evolving either slightly brighter or dimmer than the mass-luminosity relation around the convective transition mass would naively indicate (Jao & Feiden 2020).

The Jao Gap, inherently a feature of M dwarf populations, provides an enticing and unique view into the interior physics of these stars (Feiden et al. 2021). This is especially important as, unlike more massive stars, M dwarf seismology is currently infeasible due to the short periods and extremely small magnitude's which both radial and low-order low-degree non-radial seismic waves are predicted to have in such low mass stars (Rodríguez-López 2019). The Jao Gap therefore provides one of the only current methods to probe the interior physics of M dwarfs.

Stellar modeling has been successful in reproducing the Jao Gap (e.g. Feiden et al. 2021; Mansfield & Kroupa 2021) and, with these models, we have begun to understand which parameters constrain the Jao gap's location. For example, it is now well documented that metallicity affect the Jao gap's color, with higher metallicity stellar populations showing the Jao Gap at consistently higher masses (Mansfield & Kroupa 2021).

Initial testing we have done using DSEP along with articles from both Feiden et al. and Mansfield & Kroupa indicated the Jao Gap's location sensitivity to age, evolving to higher mass regions of the mass-luminosity relation with population age. Per Mansfield & Kroupa (2021) this location evolution also does not seem to be strongly sensitive to metallicity. Sections **??** and **??** of this proposal lay out a plan to use this observed age-dependence to age-date gyro-kinematically separated populations in the solar neighborhood.

1.3. *OPAL (move?)*

Here we will present work transitioning DSEP from OPAL opacities to opacities based on measurements from Los Alamos national Labs T-1 group (OPLIB Colgan et al. 2016). Moreover, we will present two projects which are in large part reliant on these updated opacities. For the first project we investigate the affects of chemically self consistent modeling of multiple populations within the globular cluster NGC 2808, and for the second project we present the effects of the OPLIB opacities on the location of the recently discovered Gaia M-dwarf gap.

2. DSEP

DSEP solves the equations of stellar structure using the Henyey method (Henyey et al. 1964). This is a relaxation technique making use of a Newton–Raphson root finder and therefore requires some initial guess to relax towards a solution. This guess will be either some initial, polytropic, model or the solution from the previous timestep. In order to evolve a model through time DSEP alternates between solving for reaction rates and the structure equations. At a given temperature and pressure from the solution to the structure equations DSEP finds the energy generation rate due to proton-proton chains, the CNO cycle, and the tripe-alpha process from known nuclear cross sections. These reaction rates yield both photon and neutrino luminosities as well as chemical changes over some small time step. Thermodynamic variables are calculated using an equation of state routine which is dependent on the initial model mass. All the updated physical quantities (pressure, luminosity, mean molecular mass, temperature) are then used to solve the structure equations again. This process of using a solution to the structure equations to calculate reaction rates which then inform the next structure solution continues until DSEP can no longer find a solution. This can happen as the stellar structure equations are extremely stiff. In addition, for finite radial mesh sizes, discontinuities can occur.

As DSEP pushes a star along its evolutionary track the radiative opacity must be known for a wide range of temperatures, pressures, and compositions. Specifically, opacity is a key parameter in the equation of energy transport. With current computational tools it's infeasible to compute opacities on the fly; rather, Rossland Mean opacity (κ_R) for individual elements must be pre-tabulated over a wide range of temperatures and densities. These opacities can then be somewhat arbitrarily mixed together and interpolated to form opacity lookup-tables. Multiple groups have preformed these calculations and subsequently made tables available to the wider community, these include the Opacity Project (OP Seaton et al. 1994), Laurence Livermore National Labs OPAL opacity tables (Iglesias & Rogers 1996), and Los Alamos National Labs OPLIB opacity tables (Colgan et al. 2016).

3. THESIS

The thesis here proposed will be split into 5 chapters. Each chapter will consist of work focusing on models low mass stars.

3.1. *Jao Gap & Updated High Temperature Opacities*

Due to initial mass requirements of the molecular clouds which collapse to form stars, star formation is strongly biased towards lower mass, later spectral class, stars when compared to higher mass stars. Partly as a result of this bias and partly as a result of their extremely long main-sequence lifetimes, M-dwarfs make up approximately 70 percent of all stars in the galaxy. Moreover, some planet search campaigns have focused on M-dwarfs due to the relative ease of detecting small planets in their habitable zones (e.g. Nutzman & Charbonneau 2008). M-dwarfs then represent both a key component of the galactic stellar population as well as the possible set of stars which may host habitable exo-planets. Given this key location M-dwarfs occupy in modern astronomy it is important to have a thorough understanding of their structure and evolution.

3.1.1. *Observations and Instability*

Gaia Data Release 2 (DR2) revealed a previously unknown structure in in the $G_{\mathrm{BP}} - G_{\mathrm{RP}}$, M_G color-magnitude diagram (Figure 2) corresponding to stars with a mass near that where a star transitions from fully convective to having both convective and radiative regions within (the fully convective transition mass) (Jao et al. 2018). The so called Gaia M-dwarf gap, or Jao gap, represents a decrease in luminosity and commensurately a decrease in stellar density — by approximately 17% — over this mass range. Jao et al. (2018); Baraffe & Chabrier (2018) suggest that this density deficiency is due to stars between a mass of 0.3 to 0.35 $\mathrm{M}_{\odot}$ transitioning into full convectivity.

A theoretical explanation for such a density deficiency comes from van Saders & Pinsonneault (2012), who propose that directly above the transition mass between a star with a radiative core and convective envelope and a fully convective star, due to asymmetric production and destruction of He^3 during the proton-proton I chain (ppI), periodic luminosity variations can be induced. This process is known as convective-kissing instability. Take for example a star with a mass right on the

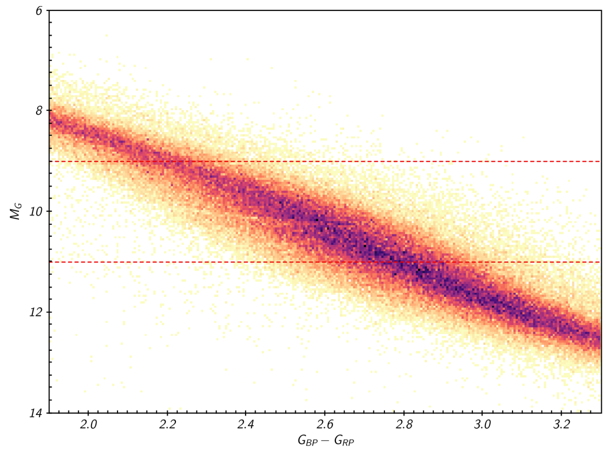

Figure 2. Figure 1 from Jao et al. (2018) showing the so called "Jao Gap" at $M_G \approx 10$

fully convective transition. Such a star will descent the pre-MS with a radiative core; however, as the star reaches the zero age main sequence (ZAMS) and as the core temperature exceeds 7×10^6 K, enough energy will be produced by the ppI chain that the core becomes convective. At this point the star exists with both a convective core and envelope, in addition to a thin, radiative, layer separating the two. At this Point asymmetries in ppI affect the evolution of the stars convective core.

The proton-proton I chain constitutes three reactions

1. $p + p \longrightarrow d + e^{+} + \nu_e$
2. $p + d \longrightarrow \ ^3\text{He} + \gamma$
3. $^3\text{He} +^3\text{He} \longrightarrow \ ^3\text{He} + 2p$

Because reaction 3 of ppI consumes ^{3}He at a slower rate than it is produced by reaction 2, ^{3}He abundance increases in the core increasing energy generation. The core convective zone will therefore expand as more of the star becomes unstable to convection. This expansion will continue until the core connects with the convective envelope. At this point convective mixing can transport material throughout the entire radius of the star and the high concentration of ^{3}He will rapidly diffuse outward, away from the core, again decreasing energy generation as reaction 3 slows Down. Ultimately, this leads to the convective region around the core pulling back away from the convective envelope, leaving in place the radiative transition zone, at which point ^{3}He concentrations build up in the until it once again expands to meet the envelope. This process repeats until chemical equilibrium is reached throughout the star and the core can sustain high enough nuclear reaction rates to maintain contact with the envelope, resulting in a fully convective star.

3.1.2. *Modeling the Gap*

Since the identification of the Gaia M-dwarf gap, stellar modeling has been conducted to better constrain its location, effects, and exact cause. Both Mansfield & Kroupa (2021) and Feiden et al. (2021) identify that the gap's mass location is correlated with model metallicity — the mass-luminosity discontinuity in lower metallicity models being at a commensurately lower mass. Feiden et al. (2021) suggests this dependence is due to the steep relation of the radiative temperature gradient, ∇_{rad}, on temperature and in turn, on stellar mass.

$$\nabla_{rad} \propto \frac{L\kappa}{T^4} \tag{2}$$

As metallicity decreases so does opacity, which, by Equation 2, dramatically lowers the temperature where radiation will dominate energy transport (Chabrier & Baraffe 1997). Since main sequence stars are virialized the core temperature is proportional to the core density and total mass (Equation 3). Therefore, if the core temperature where convective-kissing instability is expected decreases with metallicity, so to will the mass of stars which experience such instabilities.

$$T_c \propto \rho_c M^2 \tag{3}$$

This strong opacity dependence presents a slight problem where modeling is concerned. With current computational tools it's infeasible to compute opacities on the fly; rather, Rossland Mean opacity (κ_R) for individual elements must be pre-tabulated over a wide range of temperatures and densities. These opacities can then be somewhat arbitrarily mixed together and interpolated to form opacity lookup-tables. Multiple groups have preformed these calculations and subsequently

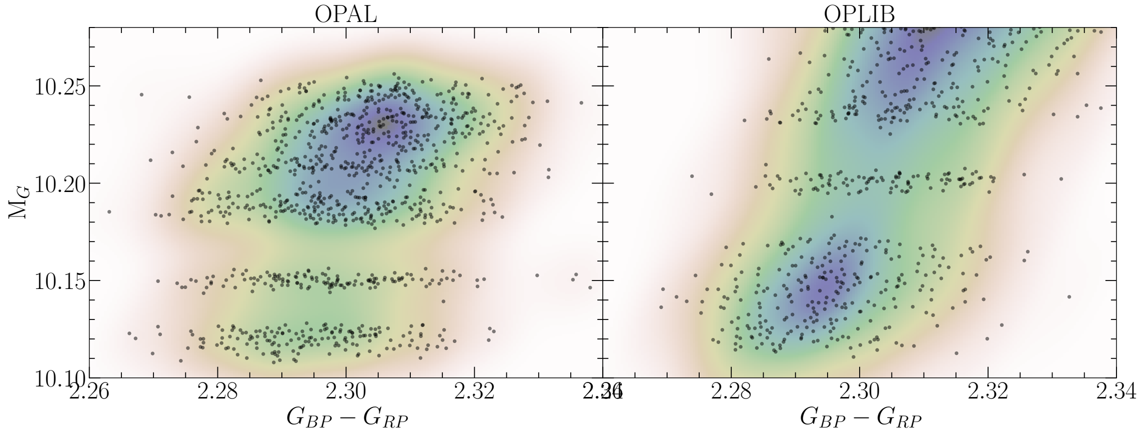

Figure 3. Synthetic CMDs derived from simple population synthesis code. (Left) CMD showing the Jao Gap for a GS98 composition stellar population generate from models evolved using OPAL opacity tables. (Right) CMD showing the Jao Gap for a GS98 stellar population generated from models evolved using the OPLIB opacity tables. Note how the OPLIB derived Jao Gap is slightly brighter than the OPAL Jao Gap.

made tables available to the wider community, these include the Opacity Project (OP Seaton et al. 1994), Laurence Livermore National Labs OPAL opacity tables (Iglesias & Rogers 1996), and Los Alamos National Labs OPLIB opacity tables (Colgan et al. 2016).

The OPAL opacity tables in particular are very widely used by current generation stellar evolution programs (in addition to current generation stellar model and isochrone grids). However, they are no longer the most up date elemental opacities. Moreover, the generation mechanism for these tables, a webform, is no longer reliably online.

Given the strong theories opacity dependence of the Jao Gap it is reasonable to expect updated opacity tables to affect the Jao Gap. Therefore, as part of this project we have transitioned DSEP from OPAL opacities to opacities based on measurements from Los Alamos national Labs T-1 group (OPLIB Colgan et al. 2016). Detailed, statistical, comparisons between the Jao Gap's from the two models will be included as a portion of a paper to be published on this work; however, a visual comparison is provided here (Figure 3 and Table 1).

3.2. *Jao Gap Ageing - 1*

$Z =$	$Z_\odot$	0.01	0.001	0.0001
OPAL	0.3803 - 0.384	0.3583 - 0.3631	0.34 - 0.3448	0.362 - 0.3663
OPLIB	0.374 - 0.3767	0.3526 - 0.3567	0.3358 - 0.3406	0.3577 - 0.3621

Table 1. Mass ranges for the discontinuity in OPAL and OPLIB models. Masses are given in solar masses.

Following the integration of updated high temperature opacities detiled in §3.1 we will investigate using the Jao-Gap color to age the local solar neighboorhood.

Preilimiary modeling we have done, along with past literature [CITE] demonstrates that the Jao Gap is expected to migrate along the main sequence as a population of stars age. Stellar populations younger than $\sim 3Gyr$ do not show a gap. Once the gap forms it will migrate towrds brighter portions of the CMD.

For this proposal we do not preform any rigorous statistical testing of whether the differences in theoretical Jao Gap location could be discrimated between in observational data; instead, choosing to save that element of the research for thesis work proper. However, we do preform a qualitative test of the visual distinguisability of the Jao Gap location for two sample sizes — 500 and 1000 stars (Figure 4).

$$\xi(m) = \xi_0 \left(\frac{m}{M_\odot}\right)^{-2.68\pm0.09} \tag{4}$$

We evolve models over an extremely finley sampled mass grid centered at the theoretical Jao Gap location for a GS98 solar composition population of stars. We then adopt the (Sollima 2019) IMF between 0.1 and 1 $M_\odot$ (Equation 4) to sample these evolved models. Model surface gravities, effective temperatures, and luminosities are transformed into Gaia magnitudes using bolometric correction tables provided by ESA[1]. Uncertainty is injected by first transforming G, BP, and RP flux and flux uncertaninty measurments for all stars Gaia observed within 10pc to magnitude and

[1] FOOTNOTE HERE

magnitude uncertaninties. Flux errors do not transform into symetric magnitude errors; however, for small uncertaninties the transformation may be approximated as symetric (Equations 5 & 6).

$$M_x = -2.5\log_{10}(I_x) + ZP_x \tag{5}$$

$$\sigma_x = \left(\frac{1.086\sigma_{I_x}}{I_x}\right)^2 + ZP^2_{\sigma_{I_x}} \tag{6}$$

Where x is the band of interest, I_x is the measured flux in that band, and ZP_x is the zero point offset in `VEGAMAG`. Following this transformation, we fit a second-order polynominal to the magnitude error v.s. magnitude for each band. This polynominal gives an approximation of the mean uncertaninty for a given magnitude. For each point sampled from the IMF and set of evolved models we add a sample from a normal distributions centered at 0 and with a standard deviation equal to the evaluation of the optimized quadradic at that points magnitude.

Figure 4 Panels A and B show (1 Gyr) do not show any visible Jao Gap; whereas, Panels C, D, E, and F all do. Moreover, the location of the Gap visible shiftes to lower magnitudes from 3 Gyr to 6 Gyrs. Note that this shift is apparent in CMDs with both 1000s stars and those with 500 stars. In fact, visually, this shift is clear with CMDs containing as few as 100 stars within this mass range. Obviously, a simple visual identification is prone to confirmation bias; however, we belive that these results are sufficent to warrent a future, more rigorus, study.

Models predict that the location of the Jap Gap will shift with population age [CITATION]; in fact, we see this behavior, gap colors reddening as populations age, in populations evolved with DSEP [FIGURE] which span the mass range of the gap.

[DETAILS ON KINEMATIC AGEING]

We propose to model a population of stars of various ages and mettalicities sampled from the local stellar neighboorhood. Each of these stars will be assigned kinematics — again sampled from empirical distributions. We will then extract kinematically derived ages from this population and

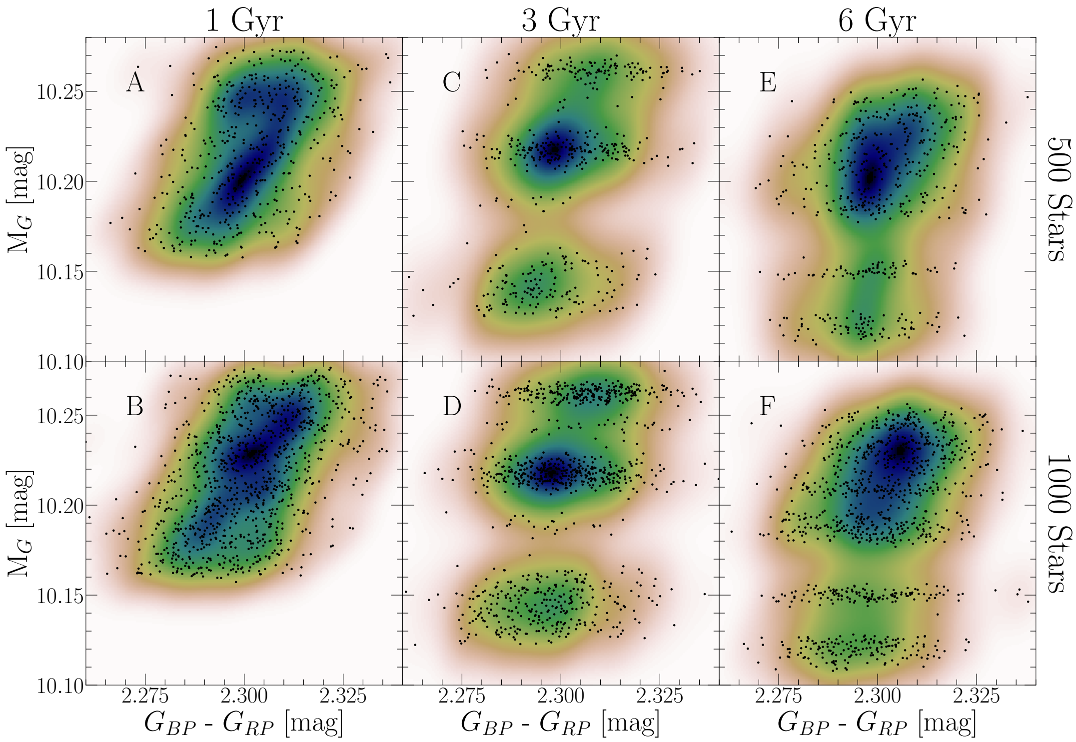

Figure 4. Populations synthetis results for a mass range surrounding the theoretical location of the Jao Gap at 3 population ages and with different sample sizes. The superimposed color map is derived from a gaussian kernel-density-estimation run on the displayed points. This is included to better illustrate the gap location.

use these to segregate stars into rough age bins. Finally, we will measure if difference in Jao gap locations are statistically distinquishable between these rough age bins.

3.3. *Jao Gap Ageing - 2*

Where the project laied out in §3.2 study the feasibility of using the Jao Gap to date stellar populations; this project will apply this tequnique to observational data. Specifically, we measure the Jao Gap location in populations seperated by gyro-kinematic dataing in the solar neighboorhood.

3.4. *NGC 2808*

Whereas, people have have often tried to categorized objects as GCs by making cuts along 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. Consequently, Carretta et al. (2010) proposed a defini-

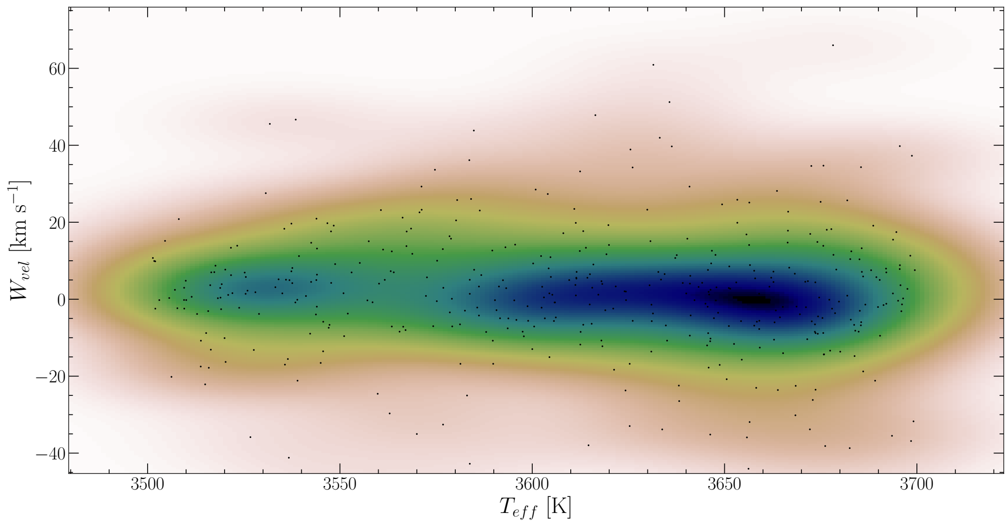

Figure 5. Kernel Density Estimation function of the gyro-kinematically infered velocity vs. effetive temperature. This sample is selected from Lu et al. (2021) and cut between $T_{eff} < 3800$ K and $T_{eff} > 3500$ K.

tion 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.

Variations in observed abundances were initially attributed to evolutionary mixing (Denisenkov & Denisenkova 1990). However, enhanced abundances are still observed in scarcely evolved main sequence stars, ruling out evolutionary mixing as the primary mechanism (Gratton et al. 2004; Briley et al. 2004). Moreover, mixing of a degree high enough to explain the observed anomaly in cyanogen abundances would result in extended lifetimes and a broadened main sequence turn off region in the CMD of ancient GCs, which is not observationally supported. More recently, precision Hubble photometry revealed that almost every cluster in orbit of the milky way comprises multiple main sequences (Piotto et al. 2007; Roh et al. 2011; Milone et al. 2012) (MP) as opposed to a single stellar population (SP).

Due to the relatively high and tight temperature range of partial ionization for helium it cannot be observed in globular clusters; consequently, the evidence for these enhanced helium abundances

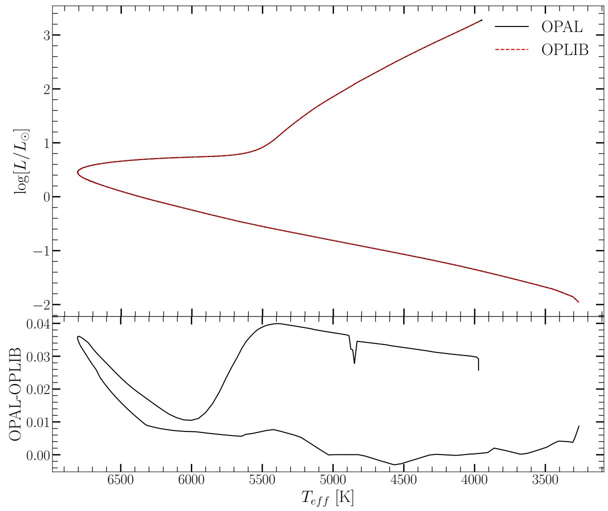

Figure 6. 10 Gyr & Y=0.33 isochrones for models generated with OPAL and OPLIB opacities tables (top). Residuals between isochrones (bottom).

originates from comparison of theoretical stellar isochrones to the observed color magnitude diagrams of globular clusters. None of the isochrones used to date in these comparison have been generated from models with self consistent chemistries.

3.5. *Population Opacities*

Given the relative historic difficulty in generating new opacity tables, stellar models have tended to use opacity tables whos range of compositions is derived from simple rescaling of the some solar composition. Here we use our OPLIB web scraper to generate opacity tables with compositions specific to each population in NGC 2808.

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 currently make fully self-consistent models due to still ongoing atmospheric modeling, we can make a first pass investigation of the affect of OPLIB opacities (Figure 6). Note how the models generated using OPLIB opacity tables have a systematically lower luminosity. Recall, that this is consistent with the overall lower opacities of the OPLIB tables.

3.6. *Additional Consistency*

The lack of self consistency presents problems at other stages of stellar evolution codes. Perhaps most importantly, where the interior of a stellar model meets the atmosphere. Atmospheric models such as a grey (Eddington 1916), Krishna Swamy (Krishna Swamy 1966), or Phoenix (Husser et al. 2013) model atmosphere provide one pressure boundary conditions to solve the two-point boundary value problem that is the equations of stellar structure. Once again however, models tend to use atmospheres with non consistent chemistries. Therefore, 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. Members of our collaboration are currently working on such atmospheric modeling.

Finally, The isochrones 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. We will additionally modify DSEP to capture this variation in convective efficiency. While we wait for atmospheric modeling to be completed it makes sense to investigate other locations where opacity differences on the order of 5% may affect results.”s

3.7. *47 Tuc & NGC 6752*

In addition to NGC 2808, Feiden has generated MARCS atmospheric models for the clusters NGC 6752 and 47 Tuc. We will conduct the same, self-consistent, modeling for these clusters as we do for NGC 2808.

4. THESIS TIMELINE

We propose a thesis in five parts. Hereafter, the papers which will form the chapters of the thesis will be refered to P1, P2, P3, P4, and P5. These are enumerate in chronological order of submission.

The first paper, P1, detailing work already done to update DSEP to OPLIB opacity tables and the affects those new opacity tables have on the Jao Gap location will be submited in the Summer

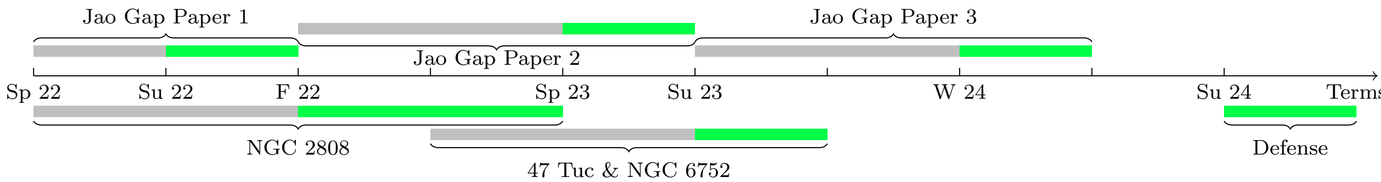

Figure 7. Proposed timeline for thesis work. Terms where a paper is expected to be submited are marked with green, terms where work on a project is intended to take place are marked in grey.

of 2022. The primary outstanding work for P1 is to run population synthetis models as, observationally, the Jao Gap is observed in populations of stars.

P2 covering self consistent modeling of NGC 2808, will be submited sometime between the start of the fall 2022 term and the spring 2023 term. Per Section **??** much of the background work for this paper has been completed and we are currently ramping up modeling efforts now that we have atmospheric models in hand. P4, consistent modeling of both 47 Tuc and NGC 6752 will follow directly from this work. Given P4's similarity to P2 we anticipate it will only take three terms to submit, with an expected submission term of summer 2023.

P3 will be submitted in the spring of 2023. This paper will focus on modeling populations of low mass stars in the local solar neighborhood in order to determin if the location of the Jao Gap in the CMD may be used to date these populations. Work on this paper has not yet begun. Finally, P5 will follow up on the theoretical work from the P3; gathering archival photometric data from low-mass stars in the local solar neighborhood and comparing Jao Gap derived ages to ages derived from the age-velocity-dispersion relation.

These five papers, in addition to an introductory chapter, will comprise a thesis to be defended sometime in the Summer 2024 term.

This research has made use of NASA's astrophysical data system (ADS). We acknowledge the support of an NASA grant (No. 80NSSC18K0634). Additionally, we would like to thank James Colgan for his assistance with the OPLIB opacity tables. We would like to thank Aaron Dotter, and Elisabeth Newton for their assistance. Finally, we thank our colleagues and peers in for their continuing and appreciated support.

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