Research Program: Observational Tests of Stellar Physics

Overview
My research has focused on using Hubble Space Telescope (HST) observations of individually resolved stars in other galaxies to place observational constraints on stellar evolution models. My approach is distinguished by how I compare stellar evolution models to observational data. Using a probabilistic framework, I create synthetic stellar populations based on a large grid of models, and obtain, given the data, the most likely stellar model parameters, their uncertainties, and degeneracies between model parameters.

Stellar evolution models are critical to nearly all astrophysical studies. Interpreting the colors and luminosities of stars is the foundation to understanding topics ranging from galaxy formation at early times, to the physical characteristics of exoplanets, and to the nature of interstellar dust grains. Despite their importance, most stellar evolutionists overlook model uncertainties and seldom account for degeneracies between uncertain model parameters. My research provides a much-needed overhaul to the field of stellar evolution by incorporating large stellar databases as calibration sets and Bayesian parameter inference to determine the most likely models that describe the data.

In the near future, I will use data beyond HST, to JWST, LSST, WFIRST, GAIA, and other observatories. These data will help me and my students to advance the state-of-the-art in stellar evolution modeling by better describing the physics of stars born in varying environments. I will also complete my shift to using MESA (Paxton, 2011, 2013, 2015), a fully open source stellar evolution code, which will allow researchers across all of astrophysics to use and reproduce my models.

I would bring an active independent research program with a large, international network of collaborators to [*school*]. *[statement of what I would bring/expand upon and potentially ask for in a start up package]*

In what follows, I build upon my previous research program to make scientific advances in a diverse range of stellar physics: the core Helium burning phases of stellar evolution, which can affect the interpretation of distant star forming galaxies; the asymptotic giant branch phase of stellar evolution, which can dominate the infrared light of distant galaxies; and old, low mass, UV emitting stars found in the center of M31, our nearest proxy to the centers of large spiral and dormant elliptical galaxies. For each program, I briefly describe sample related undergraduate research projects. Research project details, including planned outcomes are outlined in Appendix R.

1. Core Helium Burning Stars

Overview
Massive stars dominate the flux of star forming galaxies. Consequently, derived parameters such as star formation rates, stellar masses, and metallicities depend on how well we model them (e.g., Kennicutt & Evans, 2012). Despite their clear importance, current models remain flawed. They over-predict the observed UV flux of nearby galaxies (Johnson et al., 2013), they overestimate the lifetimes of observed massive stars (e.g., Drout et al., 2009), and they are unable to accurately predict the colors, luminosities, and number densities of evolved massive stars on color-magnitude diagrams (CMDs) for dozens of nearby galaxies (McQuinn et al., 2011; see Fig. 1 below). These inadequacies are largely due to the complex nature of massive star physics, which is known to be strongly dependent on the treatment of convection, mass loss, and metallicity. Calibrations of massive stars

have historically been limited to a relatively small number of stars in the Magellanic Clouds (e.g, Bertelli et al., 1994), whereas models of massive stars in other environments are mostly extrapolations from these limited sets of models. Consequently, uncertainties in the physical modeling of massive stars propagate directly to errors in the earliest epochs of galaxy formation and evolution. Accurate massive star models are critical to interpreting current and next generation (e.g., JWST, LSST) observations of the early universe.

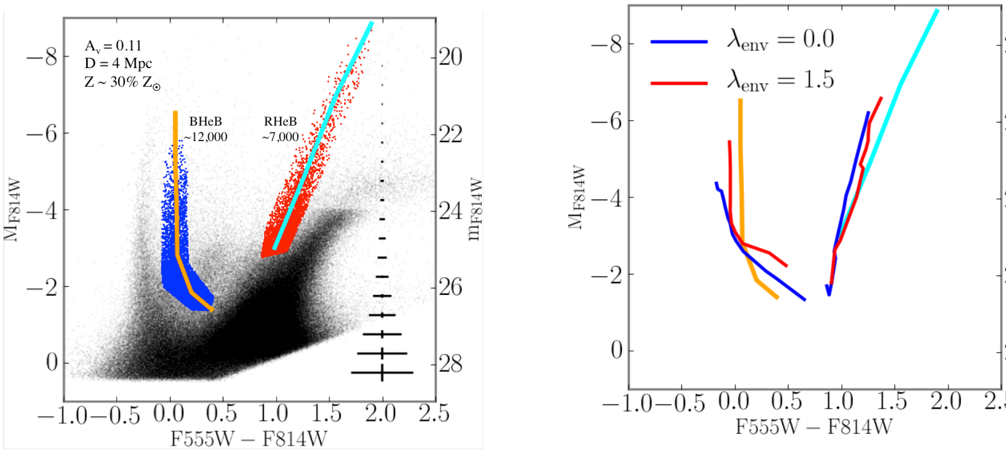


Figure 1. *Using CMD features to constrain Helium burning models: Left*: An HST-based optical CMD of a field in the dwarf galaxy IC 2574. Located at ~4 Mpc with a moderate metallicity and low interstellar extinction. Blue Helium burning (BHeB) and red Helium burning (RHeB) populations are highlighted. *Right*: The theoretical BHeB and RHeB sequences based on Padova models with different values of convective envelope overshooting (blue: none, red: 1.5 times the local pressure scale height) plotted against the empirical BHeB (orange) and RHeB (cyan) locations. Adjustments in the amount of envelope overshooting varies the expected location of the BHeB on the CMD. In addition, both the slopes and colors of the theoretical vs. the empirical RHeB tracks differ over the entire magnitude and color range. The shape of these tracks is governed by stellar physics, e.g., convection, rotation, mass loss, which are all dependent upon metallicity (a galactic metallicity spread is negligible, since the mixing time scales are much longer than these stellar lifetimes).

My research exploits the power of CMD-fitting of resolved stellar populations to constrain massive star models. In CMD-fitting, one models the luminosities and colors of a population of stars and derives the best combination of model parameters that reproduces the CMD of the data (Dolphin, 2002). I have been part of five large surveys of resolved stellar populations: the ACS Nearby Galaxy Survey Treasury; Archival Nearby Galaxy: Reduce, Reuse, Recycle; The Panchromatic Hubble Andromeda Treasury, (Dalcanton et al., 2009, 2012, 2012b); planned HST/Multicycle observations of M33; and I am a co-PI of an HST legacy program to uniformly reduce the HST archive of Magellanic Cloud clusters. These surveys provide the necessary data to significantly improve stellar models through direct calibration. My aim is to first constrain the evolution of low mass Helium burning stars (<4 Msun) using Magellanic Could clusters, and then further refine the models using nearby galaxies to access higher stellar masses (up to ~20 Msun).

Looking Forward

My team is nearing completion of the first major paper from the Magellanic Clouds HST archival legacy program. We have, for the first time, implemented a Bayesian framework to simultaneously fit model stellar populations varying 7 uncertain parameters in the data and models: distance, interstellar extinction, binary fraction, initial mass function slope, age, metallicity, and the strength of convective core overshooting. We then successfully applied this framework to 9 stellar clusters. I would be excited to continue this program at UR, where with the help of undergraduates, we will add stellar rotation, differential extinction, and explore the ~120 stellar clusters from the HST archive at a range of ages and cluster mass. These constraints will provide the necessary footing needed to model higher mass stars in ~70 nearby galaxies.

Sample Related Undergraduate Research Projects (see Appendix R.1-3)

1) The B/R Ratio in Nearby Galaxies, M31and M33
   Students will determine the empirical ratio of blue to red Helium burning stars, study which uncertain model parameters can improve model predictions, and apply the best models to reinterpret the integrated light of galaxies.
2) Blue Helium Burning Stars or Massive Main Sequence, Should Anyone Care?
   Massive Main Sequence stars and older, lower mass blue Helium burning stars can overlap in optical colors and luminosities. Students will work to understand when this occurs, and to what extent it affects our understanding of a galaxy's history.

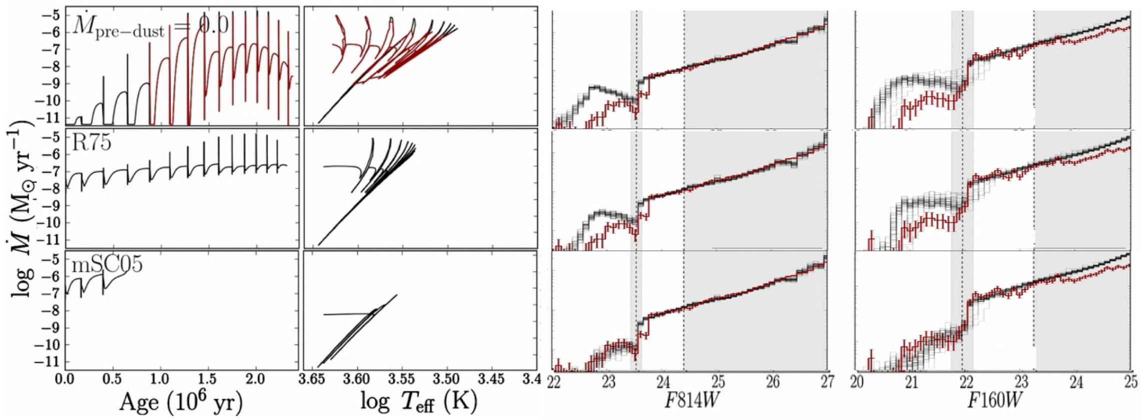
2. Asymptotic Giant Branch Stars

Overview

The Asymptotic Giant Branch (AGB) phase of stellar evolution is the most uncertain evolutionary phase of low and intermediate mass stars (1-8 Msun). AGB stars affect the origin of cosmic dust and the chemical enrichment of the interstellar medium. Although AGB lifetimes are short, their high luminosities may contribute significantly to the integrated light of galaxies, particularly at redder wavelengths (e.g., Conroy et al. 2009).

AGB stars are fascinating because of a myriad of interesting physical processes happening together: a Carbon-Oxygen core becomes degenerate; two shell fusion phases alternate as the main source of energy production, triggered by Helium shell-flashes (called thermal pulses); deep convection dredges up nuclear processed material to the surface and dramatically changes the composition of the dust around the star; and AGB stars shed their outer layers at a rate that can be more than a mass of Earth per year. While the AGB phase lasts less than a few million years, nearly all low and intermediate-mass stars are expected to pass through it. Thus, the ubiquity of AGB stars makes them responsible for about 75% of the mass loss from stars in our galaxy (Sedlmayr 1994) and may contribute up to 70% of the infrared light of distant galaxies (Melbourne et al., 2012).

My research has focused on using nearby galaxies to constrain the lifetimes of AGB stars using models calculated by the Padova group and as part of the "Solving the TP-AGB Star Conundrum: A Key to Galaxy Evolution[1]" international collaboration (Girardi 2010, Rosenfield et al., 2014, and 2016). We showed the lifetimes of AGB stars best match those derived from populations within nearby galaxies when an early phase of AGB winds are included (before the winds are driven by



dust; see Fig. 2 below). Our work was unprecedented in that we used a statistically significant sample of AGB stars from diverse environments, as opposed to the usual calibration using individual AGB stars or an aggregated sample from several Magellanic Cloud star clusters. Using a diverse and statistically significant sample of AGB stars is critical for this work. For example, in Girardi et al. (2013), we showed that the Magellanic Cloud clusters primarily used for calibration happen to be at an age that boosts the number of AGB stars, causing researchers to over-predict AGB lifetimes, which propagates to mischaracterizing the integrated light from distant galaxies.

Figure 2: *Improving AGB Models using luminosity functions (LFs). Left grid:* Mass-loss as a function of age and surface temperature for 1 Msun AGB star models with varying treatments of mass-loss. *Left Top*: no mass-loss before dust-driven winds, *left middle*: cannonical mass-loss law (Reimers, 1975), *left bottom:* modification of Schröder & Cuntz (2005), presented in Rosenfield et al., 2014. *Right grid*: HST optical (left) and near infrared (right) LFs of dwarf galaxy KKH37 (red lines) and ~100 simulated LFs based on most likely star formation history and AGB mass-loss prescriptons from the left. (Figure adapted from Rosenfield et al., 2014.)

Looking Forward

With all the complexities of the AGB phase, it is no wonder we still do not have a complete understanding of their most basic qualities. My students and I will search for answers to pressing questions fundamental to our understanding of AGB stars: How long do AGB stars last as a function of mass and metallicity? How do AGB stars lose their mass? How efficiently does an AGB star dredge material to its surface? And what effects do AGB stars have on their environment?

My future research plans are to continue to constrain uncertain aspects of AGB models including mass-loss, convection, and the efficiency of the dredge up of nuclear-enriched material. I will also use MESA models and incorporate AGB stars from M31, M33, and nearby galaxies with archival infrared observations and to-be-proposed JWST and WFIRST observations.

Sample Related Undergraduate Research Projects (see Appendix R.4-5)

3) Understanding Low Metallicity AGB Stars: Nearby Galaxies from Optical to Infrared
4) Understanding High Metallicity AGB Stars: Andromeda and M33 from Optical to Infrared

[1] http://starkey.astro.unipd.it

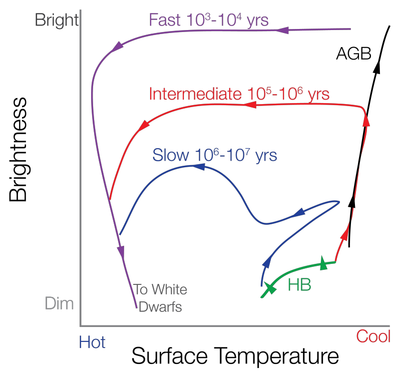
Students will model the observed luminosity functions and CMDs of AGB populations varying interesting AGB parameters in multiple wavelengths and comparing their models to data.

3. Old, Low Mass, UV Emitting Stars

Overview

The ability to correctly model UV stellar populations is critical for interpreting galaxy observations from the optical through the far-IR, due to their impact on the production of emission lines and on the heating of dust. Although massive main sequence stars are the most widely known source of UV emission, older stellar populations also host UV-emitting stars that produce significant flux (detectable as a "UV-excess") in dormant elliptical galaxies or spiral galaxy bulges.

The detection of UV-excess is a direct probe of early galaxy evolution. In old stellar populations, the UV flux is emitted by low mass (<1 Msun) horizontal branch (HB) stars and their hot luminous descendants. Because post-HB stars are the evolved progeny of long-lived, low-mass main sequence stars, they directly probe the earliest epochs of star formation.



These UV-bright stars have HB and post-HB evolution that depends on their initial envelope mass. Three different evolutionary channels are sketched in Fig. 3: in the canonical path, stars populate the HB at the red clump; later, while climbing the AGB, they lose their large convective envelope to become UV-bright post-AGB stars. Stars with thinner envelopes leave the AGB before the thermally pulsing phase, and become UV-emitting post-early AGB stars. Stars with the very thin envelopes become UV emitters during their extreme HB phase; these hot stars evolve to hotter temperatures and brighter luminosities as AGB manqué stars.

Figure 3. *HR schematic diagram of old, low-mass, UV emitting stars.* The usual path for low mass stars begins Helium burning on the cooler side of HB (green line) and upon core Helium exhaustion, travel up the AGB (black) to the rapid UV emitting post-AGB track (purple). In rare cases, stars that have lost much of their atmospheres occupy the hotter edge of the HB and leave the AGB early (post-early AGB; red), or in extreme cases (EHB), do not reach the AGB track at all (AGB-manqué, blue). EHB and AGB-manqué stars emit in the UV and are the source of "UV-excess" observed in the centers of many elliptical galaxies. (Figure adapted from Rosenfield et al., 2012.)

As part of the PHAT collaboration, we have detected the brightest post-AGB and post-early AGB stars in the near UV, and a small fraction of the fainter AGB manqué population in the central 800 pc of M31 (Rosenfield et al., 2012). The data reveal a strong radial gradient, which must arise from a gradient in the properties of M31's bulge.

Looking Forward

I am now the PI of an HST survey of the center of the M31 where we are producing the first UV catalog of these hot evolved stars as a function of galaxy radius, with the quality required to constrain their evolution. My team has obtained radial UV imaging of the M31 bulge and we are making stellar models to derive the observationally constrained lifetimes of the post-AGB and post-early AGB stars. This will lead to understanding which of several plausible mechanisms sets the fraction of stars that pass through these rare stages for galaxy stellar populations. The revised models will have important implications for each of the following, which I plan to study in depth:

the preceding evolution, especially for the extreme HB phase, for interpreting the UV flux from old stellar populations, and understanding the origin of LINER emission (Singh et al., 2013).

Sample Related Undergraduate Research Projects (see Appendix R.6-7)

5) Are all of the UV Bright Stars in the Center of M31 Binary Stars?
Students will investigate the radial distribution of UV-bright stars in the center of M31 and compare it to the radial distribution of X-ray binaries and the underlying stellar population.
6) The Characteristics of Planetary Nebulae in the Central Regions of M31
Students will discover new planetary nebulae, characterize them, and compare them to published catalogues.

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