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RESOURCES & ACTIVITIES

MESA-Web: A cloud resource for stellar evolution in astronomy curricula

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Abstract

We present `MESA-Web`, a cloud resource with an online interface to the Modules for Experiments in Stellar Astrophysics (`MESA`) software instrument. `MESA-Web` allows learners to evolve stellar models without the need to download and install `MESA`. Since being released in 2015, `MESA-Web` has delivered over 17,000 calculations to over 2,200 unique learners and currently performs about 11 jobs per day. `MESA-Web` can be used as an educational tool for stars in the classroom or for scientific investigations. We report on new capabilities of `MESA-Web` introduced since its 2015 release including learner-supplied nuclear reaction rates, custom stopping conditions, and an expanded selection of input parameters. To foster collaboration we have created a Zenodo `MESA-Web` community hub where instructors can openly share examples of using `MESA-Web` in the classroom. We discuss two examples in the current community hub. The first example is a lesson module on Red Giant Branch stars that includes a suite of exercises designed to fit a range of learners and a `Jupyter` workbook for additional analysis. The second example is lesson materials for an upper-level Astronomy majors course in Stars and Radiation that includes an assignment verifying some of the expected trends that are presented in a popular stellar physics textbook.

Keywords: Stellar Astrophysics; Astronomy Education; Computational Models

1 Introduction

One of the cornerstones underpinning modern astrophysics is the fundamental properties of stars throughout their evolution. Transformative capabilities in space- and ground-based hardware instruments are providing an unprecedented volume of high-quality measurements of stars, significantly strengthening and extending the observational data upon which stellar astrophysics ultimately depends. Revolutionary advances in software infrastructure, computer processing power, and data storage capability are enabling exploration of gravitational waves from the mergers of neutron stars and black holes, revolutionary new sky surveys that probe ever-larger areas of the dynamic sky and ever-fainter sources, the oscillation modes of stars across the Hertzsprung-Russel (HR) diagram, and more.

The standard computational tool of anyone interested in understanding stars is a stellar evolution code - a piece of software that can construct a model for the interior of a star, and then evolve it over time. Evolution codes allow us to check and refine the various physical theories that together compose stellar astrophysics (e.g., atomic physics, nuclear physics, fluid dynamics, thermodynamics); they provide laboratories for performing experiments on stars (e..g, discovering what factors contribute to the formation of red giants); and, they shed light on stages of stellar evolution that may be too fleeting to observe directly in the Universe.

While a number of stellar evolution tools exist, many are proprietary and unavailable outside restricted research settings. The past decade has seen the rise of sophisticated, open-source (anyone can freely download), open-knowledge (best practices are freely shared), community-driven software instruments that model stars throughout their evolution (e.g., Modules for Experiments in Stellar Evolution, MESA, Paxton et al., 2011, 2013, 2015, 2018, 2019; Jermyn et al., 2023). Moreover, the MESA Project supports a vibrant global community of learners and researchers (1000+ registered users), with active mailing lists, distributed version control, summer schools, and other learning activities.

Ubiquitous usage of a stellar evolution instrument in classrooms worldwide remains a rich site of fascinating challenges. For example, stellar evolution software instruments can be complicated to install. They require comfort using the Unix command line, setting up compilers and other required software elements, and installing the software instrument. The hardware must also be capable enough to calculate the evolution in a reasonable amount of wall-clock time. These can be barriers, especially in under-resourced communities and/or when a course objective is aimed at a pedagogical survey of the evolution of stars. Our goal is to lower these barriers to entry and to provide open educational resources for learning about stellar evolution.

MESA-Web[1] is a cloud resource featuring a point-and-click web interface that lowers the barrier to entry of using MESA for education. MESA-Web supports a variety of options for evolving a stellar model. Upon completion, MESA-Web delivers to the learner an MP4 movie containing numerous model diagnostics and plain text output files for use in many common plotting package. Through hands-on exercises, learners can gain new knowledge about the properties of stars that are not possible with traditional textbook-only approaches. MESA-Web offers unique opportunities to dynamically illustrate the evolution of stars by following a golden rule of learning: involve don't tell.

This article is organized as follows. In § 2, we discuss major improvements and milestones since the creation of MESA-Web. In § 3 we discuss aspects of our MESA-Web implementation for educators who may want to adopt it for their own software instruments. In § 4 we discuss the current capabilities of MESA-Web, in § 5 we discuss working with the stellar model output, and in § 6 we highlight learner exercises and describe resources for instructors to share their MESA-Web exercises.

2 Origins to the Present

MESA-Web launched in June 2015 on a 2 core, 4 GB RAM, 10 GB disk server hosted by Arizona State University. Responding to community demand for increased throughput, the platform was upgraded in 2017 for a modest additional cost to a 4 core, 8 GB RAM, 50 GB disk configuration. Still under-powered relative to average community demand, in August 2021 MESA-Web was re-factored and ported to a 48 core, 192 GB RAM, 2 TB disk cluster at the University of Wisconsin-Madison. This new cluster supports 12 concurrent jobs, meets current peak demand during traditional semesters, and substantially enhances the computational resources focused on education.

Figure 1 shows the cumulative growth of MESA-Web usage over a 8 year period. To date, MESA-Web has provided more than

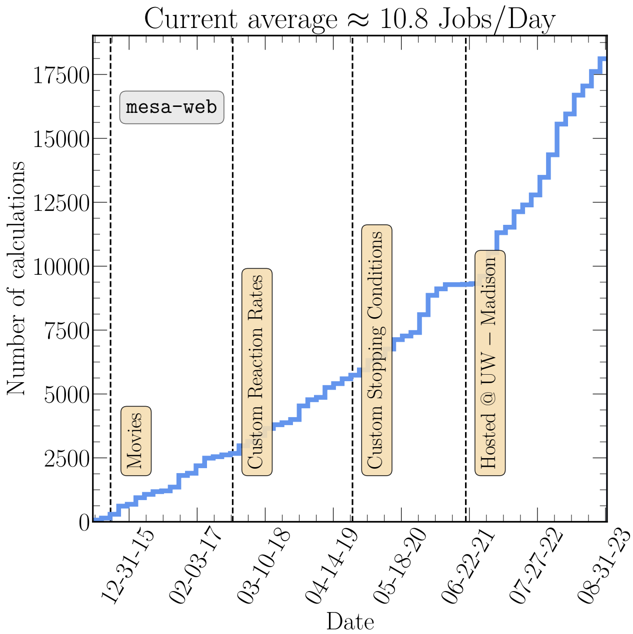


Figure 1. MESA-Web usage to date. Dashed vertical lines and labels indicate the dates when a new capability was released.

17,000 calculations to an international community of learners in courses at more than 50 institutions worldwide. The University of Chicago, Stony Brook University, the University of California, Santa Cruz, University of Pittsburgh, Texas A&M University Commerce are among the institutions that have most utilized MESA-Web since its first release. These metrics suggest that MESA-Web is having a growing impact in astronomy education.

Figure 1 shows an MP4 movie file included with the output was introduced early in the evolution of MESA-Web. Following this development, we introduced examples of the Test Suite that come included with a standard MESA distribution. Because of the complex nature of some of the Test Suites (multiple inlists, high computational demand, or others) pre-computing the examples provided is the most efficient means of delivering these data to learners.

Figure 1 also shows addition in mid-2017 of the option for a learner to choose a specific nuclear reaction from a list of eight key nuclear reactions and provide their own custom reaction rate. This option is also visible in the submission form shown in Figure 2. The eight key reactions are the H-burning CNO cycle reactions $^{12}C(p,\gamma)^{13}N$, $^{13}C(p,\gamma)^{14}N$, $^{14}N(p,\gamma)^{15}O$; the He-burning reactions $\alpha(\alpha\alpha,\gamma)^{12}C$, $^{12}C(\alpha,\gamma)^{16}O$, $^{16}O(\alpha,\gamma)^{20}Ne$; and the C-burning reactions $^{12}C(^{1}2C,\alpha)^{12}Ne$, and $^{24}Mg(\alpha,^{12}C)^{16}O$. These eight are chosen as they have demonstrated significant impact on stellar properties across a range of stellar environments including massive stars (deBoer et al., 2017; Fields et al., 2018) and stars that produce white dwarfs (LUNA Collaboration et al., 2006; Fields et al., 2016). If this option is chosen, a learner uploads a file containing the customized reaction rate data. This file must have (a) zero or more lines beginning with a hash (#) mark; these are treated as comments and ignored; (b) exactly one line consisting of a single integer, giving the number of subsequent lines. (c) one or more lines containing a space-separated T8/rate pair, where T8 is the temperature in units of 10^8 K and rate is the reaction rate in units of per second. Interpolation is used to evaluate the rate between the tabulated values. A learner may use experimental or theory vales for the rates, including zero.

This capability also expanded MESA-Web's impact to being a viable means of scientific investigation for the nuclear astrophysics community without significant prior experience with MESA.

Finally, Figure 1 shows the impact of providing a custom

1 http://user.astro.wisc.edu/ townsend/static.php?ref=mesa-web-submit

stopping condition in mid-2019. This option is also visible in the submission form shown in Figure 2. Learners can specify a limit to different stellar quantities as condition for which the model will complete. This new capability provides learners an increase in throughput especially if investigating a particular evolutionary epoch. `MESA-Web` can currently use `MESA` versions 11701 or 12115 and is continually updated to reflect a modern version.

3 Technical Implementation

To provide an overview of the technical implementation of `MESA-Web`, here we narrate the series of steps involved in a typical calculation. The interface to `MESA-Web` is presented as web form (Fig. 2), in which a learner can enter calculation parameters (e.g., initial mass, composition, stopping condition, nuclear reaction network). A link to explanatory text is provided for each parameter, indicating semantics, units and acceptable values. Sensible default values are provided for all parameters save for the email address to which results will be sent; taken together, these defaults result in a simulation of the Sun's evolution.

When a learner submits the web form, a PHP script transmits the form data from the web server to a separate computation server, using a TCP socket. (The separation of web and calculation servers is both for security and for computational efficiency). The computation server validates the form data, checking each parameter lies within acceptable bounds. If the data are valid, then it schedules a calculation request and transmits a confirmation message back to the web server; otherwise, it transmits an error message back that indicates which parameters are invalid.

Calculation requests are fulfilled by a cluster comprising the computation server (2 Intel Xeon E-2660 8-core CPUs, 64 GB RAM) and two identical peer nodes, together with shared disk storage. The cluster is managed using `SLURM` (Yoo et al., 2003), an open-source job scheduling system. Each calculation request is comprised of a pair of jobs:

star — running `MESA` with the supplied parameters (assigned 2 CPUs and a maximum runtime of 2 hours).

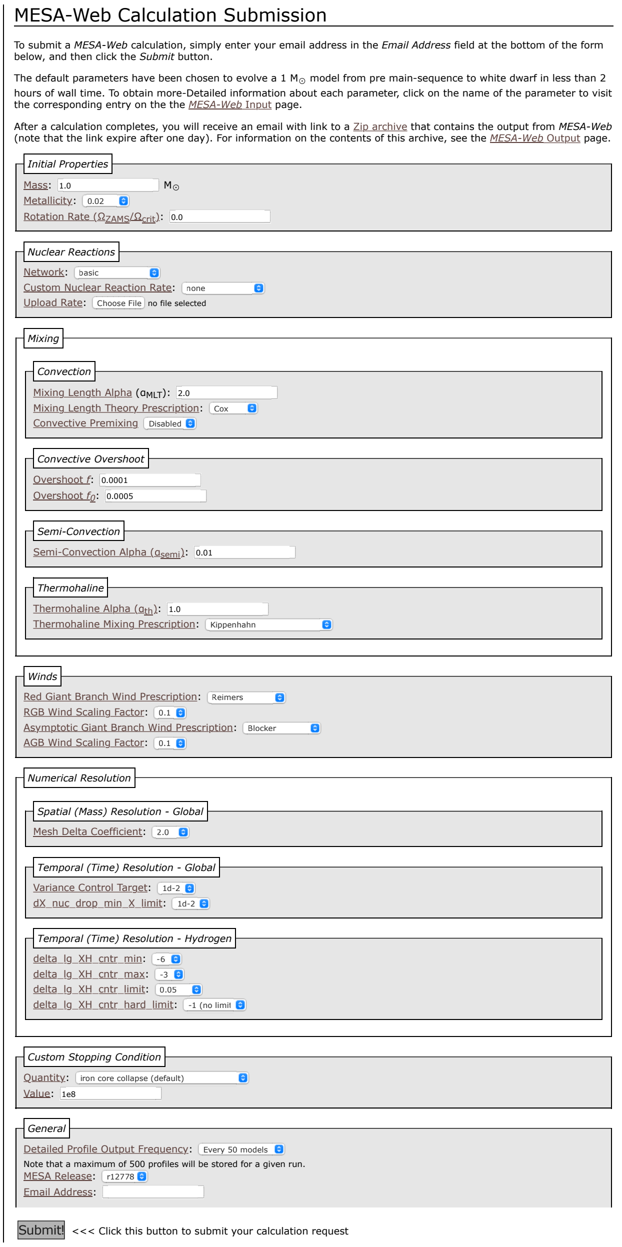
proc — post-processing the `MESA` output (assigned 1 CPU) and emailing the learner.

Completion of the *star* job is a pre-requisite for the corresponding *proc* job to run. The resources (CPU and time limit) assigned to *star* jobs is chosen to strike a balance between how far a single calculation request is allowed to proceed, and how many separate calculation requests can be completed within a given time period; with these resources, `MESA` can follow the evolution of a solar model from the pre-main sequence to the tip of the asymptotic giant branch.

The *proc* job assembles the plot images written out by `MESA` into an MP4 movie, and then packages this movie into a Zip archive. This archive also includes a `MESA` 'history' file, which tabulates variables (e.g., surface radius and luminosity; central elemental abundances) as a function of stellar age; and a series of 'profile' files, which tabulate variables (e.g., pressure, temperature, density) as a function of position at selected instants during the star's evolution. To facilitate analysis of these files, we provide a Python module `mesaweb.py` on the `MESA-Web` site. This module includes routines that read profile and history data into Python dict data structures.

On completion of the *proc* job, the Zip archive is copied back to the web server, and an email is sent to the learner providing a download link. This link remains valid for 24 hours, after which the archive is deleted to free up space on the server.

As the functionality of the underlying `MESA` code grows and changes, it is desirable to expose these improvements in `MESA-Web`. However, this has to be balanced against the pedagogical need to offer a stable and predictable service; a calculation request re-submitted to `MESA-Web`, with the same parameters as before, should provide exactly the same results no matter how much time has elapsed between the two submissions. To strike this balance, `MESA-Web` offers the ability to dynamically select which release of `MESA` is used to service each calculation request.


MESA-Web Calculation Submission

To submit a *MESA-Web* calculation, simply enter your email address in the *Email Address* field at the bottom of the form below, and then click the *Submit* button.

The default parameters have been chosen to evolve a 1 $M_\odot$ model from pre main-sequence to white dwarf in less than 2 hours of wall time. To obtain more-Detailed information about each parameter, click on the name of the parameter to visit the corresponding entry on the the *MESA-Web* Input page.

After a calculation completes, you will receive an email with link to a Zip archive that contains the output from *MESA-Web* (note that the link expire after one day). For information on the contents of this archive, see the *MESA-Web* Output page.

Initial Properties
Mass: 1.0 $M_\odot$
Metallicity: 0.02
Rotation Rate ($\Omega_{ZAMS}/\Omega_{crit}$): 0.0

Nuclear Reactions
Network: basic
Custom Nuclear Reaction Rate: none
Upload Rate: Choose File no file selected

Mixing

Convection
Mixing Length Alpha (α_{MLT}): 2.0
Mixing Length Theory Prescription: Cox
Convective Premixing Disabled

Convective Overshoot
Overshoot *f*: 0.0001
Overshoot f_0: 0.0005

Semi-Convection
Semi-Convection Alpha (α_{semi}): 0.01

Thermohaline
Thermohaline Alpha (α_{th}): 1.0
Thermohaline Mixing Prescription: Kippenhahn

Winds
Red Giant Branch Wind Prescription: Reimers
RGB Wind Scaling Factor: 0.1
Asymptotic Giant Branch Wind Prescription: Blocker
AGB Wind Scaling Factor: 0.1

Numerical Resolution

Spatial (Mass) Resolution - Global
Mesh Delta Coefficient: 2.0

Temporal (Time) Resolution - Global
Variance Control Target: 1d-2
dX_nuc_drop_min_X_limit: 1d-2

Temporal (Time) Resolution - Hydrogen
delta_lg_XH_cntr_min: -6
delta_lg_XH_cntr_max: -3
delta_lg_XH_cntr_limit: 0.05
delta_lg_XH_cntr_hard_limit: -1 (no limit

Custom Stopping Condition
Quantity: iron core collapse (default)
Value: 1e8

General
Detailed Profile Output Frequency: Every 50 models
Note that a maximum of 500 profiles will be stored for a given run.
MESA Release: r12778
Email Address:

Submit! <<< Click this button to submit your calculation request

Figure 2. `MESA-Web` submission page.

4 Learning with `MESA-Web` Capabilities

Figure 2 shows the `MESA-Web` submission webpage as of September 27, 2023. Learners can specify different physical parameters of the stellar model including initial mass, metallicity, and mixing values. Learners can also change the mass or temporal resolution, stopping conditions, and frequency of the returned data output. With these options learners can target specific stellar phenomena within the available computing resources.

The default values in the calculation submission page will evolve a 1 $M_\odot$ stellar model from the pre main-sequence to

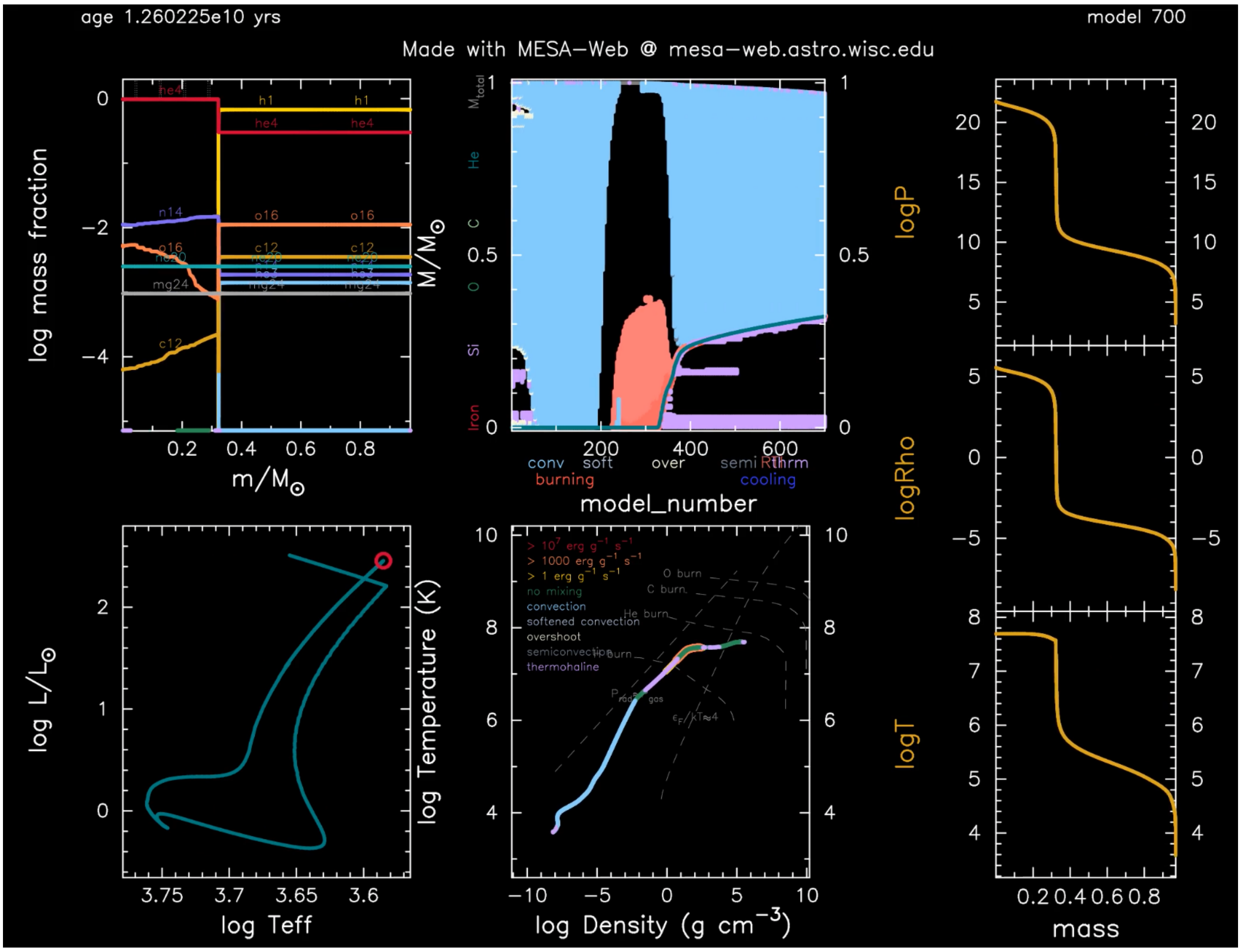


Figure 3. Snapshot showing grid plot of profile and history data for `MESA-Web` calculation of a 1 $M_\odot$ rotating stellar model. At this model number, the star is on the red giant branch. The data shown in the movie are divided into five panels: *upper-left* – abundance profiles, plotting the mass fractions of selected nuclides as a function of mass coordinate within the star; *upper-mid* – a Kippenhahn (convective and burning profile history) diagram; *lower-left* – a Hertzsprung-Russell Diagram; *lower-mid* – a density-temperature profile plot; *right* – thermodynamic state profiles, plotting the total pressure (upper), density (mid), and temperature (lower) as a function of mass coordinate within the star.

the tip of the asymptotic giant branch within the walltime limit. For other unique evolutionary epochs, learners can consult the `MESA-Web` Input page where they can experiment with the input parameters that help build the stellar model and some details of their implementation in `MESA`.

Some advanced evolutionary epochs may require the use of a larger nuclear reaction network. Learners can explore optional choices for a reaction network using the guidance at `MESA-Web Nets`. Larger networks take walltime to take a timestep and could potentially require reduced mass resolution to reach the phenomena within walltime limits. Advanced learners can consult the `MESA` instrument papers for guidance in these choices (Paxton et al., 2011, 2013, 2015, 2018, 2019; Jermyn et al., 2023).

`MESA-Web` reduces barriers to accessing the core capabilities of `MESA` for any community. One example is serving as a lightweight tool for researchers to produce stellar tracks to model the observational data of the eclipsing binary IT Librae (Wysocki et al., 2022). Another example is enabling the experimental low-energy nuclear astrophysics community with a key scientific tool by providing the capability to utilize custom nuclear reaction rates for a list of key nuclear reactions common to many stellar phenomena.

5 Learning with `MESA-Web` Output

As a part of the output data, learners receive an MP4 movie showing profile and history quantities of their stellar model. The movie is a time series of grid plots created using `MESA`'s internal `pgstar` plotting routines to showcase general structure and surface properties. For example, a frame from the movie for a non-rotating 1 $M_\odot$ stellar model is shown in Figure 3.

The output also includes numbered `profileX.data` where `X` corresponds to an integer profile number. The profiles are produced at a learner specified interval and the `profiles.index` file is provided as a key to their correspondence. The profile data contains stellar structure information for 56 quantities as a function of mass coordinate. These data are useful for learning assignments which require information about cell-specific properties.

The output also includes a `trimmed_history.data` file containing the traditional "evolutionary track" data for total or cell-specific information at all timesteps. For example, this file would include the surface luminosity for the stellar model as a function of timestep. The history file currently contains information about 57 different quantities recorded at every timestep taken by the stellar model. In Figure 4, we further highlight the utility of data provided by `MESA-Web` showing the time evolution of a subset of the quantities depicted in Figure 3. These history values and specific structure profiles are plotted at various evolutionary epochs: during the main-sequence, the red giant branch, and the white dwarf cooling phase.

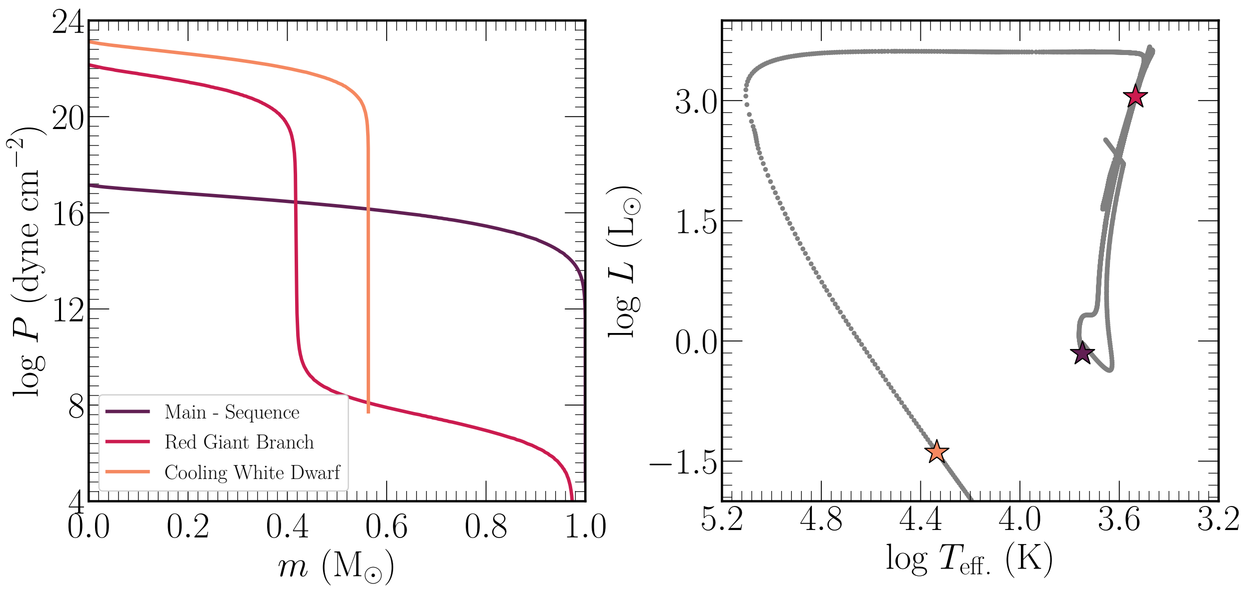


Figure 4. MESA-Web history and profile data for a 1 $M_\odot$ stellar evolutionary model at three approximate epochs: the main-sequence, red giant branch, and during the white dwarf cooling phase.

6 MESA-Web in the classroom

Our goal is to provide open access educational materials for learning about stars. A step towards implementing this goal is developing and aggregating a prototype series of lesson modules that address educational needs ranging from high school to graduate school. Each module will include real-world cases and MESA-Web exercises addressing a specific topic: essential principles, a listing of MESA-Web settings, interpreting the results returned by MESA-Web in relation to the essential principles, and providing assignments for a learner's current and future studies. Through hands-on exercises, learners gain new knowledge about stars that are not possible with traditional textbook centric material.

Open-ended computational projects, such as those in many stellar courses, can have a positive impact on learning (Odden, 2019). The importance of computational literacy in astrophysics has also been highlighted (Zingale et al., 2016).

An anonymous survey suggests that an approximately equal number of undergraduate and graduate courses have utilized MESA-Web and that the majority of these courses are taught once per academic year. In 62% of these courses, MESA-Web is used repeatedly during the term while the remainder (38%) used it once. About 55% of the respondents said their courses had no more than 20 learners and 45% said their courses had more than 20 learners. The survey also solicited suggestions for future expansion and the two most requested features are the ability to run giant planet models and the ability to compute pulsation modes with GYRE (Townsend and Teitler, 2013; Townsend et al., 2018). Both capabilities already exist in MESA.

6.1 Sustained collaboration and integration of MESA-Web in the classroom

A goal of MESA-Web is to foster collaboration for educators around the globe and increase the efficacy of technology in astronomy courses at large. To this end, we have created a Zenodo MESA-Web community hub where educators can search or share examples of MESA-Web use in the classroom. We encourage educators to share the following

- Markdown ('.md') file describing Lesson:
    Instructor information and contact
    Course description
    Lesson learning objective and plan
    Information regarding textbooks/materials utilized
- Assignment(s)
- Analysis workbooks (Jupyter, GoogleColab)
- Data Analysis Scripts (Instructor Version)
- Lecture Notes

as part of their upload. Our next step is to develop prototypes, leveraging a decade's worth of guiding learner experiences during the successful MESA Summer Schools. A MESA Summer School offers participants a week of extensive hands-on labs to gain familiarity with MESA and learn how to use in their own education and research activities. About 20% of the time is spent in a lecture format; participants spent most of their time setting up, running, and interpreting MESA models in small groups. One teaching assistant at each table of three learners ensures hands-on participation and energetic interactions among the participants, teaching assistants, and lecturers. Topics vary from year-to-year, highlighting MESA's flexible education and science capability, and were led by experts in their respective fields. The cohort of instructors, teaching assistants, and participants (amateurs, undergraduates, graduates, postdocs, and faculty) now number over 500. They are creating their own MESA infrastructures at ≃100 institutions around the world, which accelerates education and discovery. MESA Summer School material from the past decade is stored on Zenodo and aggregated chronologically at this URL.

6.2 Example: The Red Giant Branch

The following example is part of the instructor submitted collection of MESA-Web learning materials available publicly at our Zenodo MESA-Web community hub.

Learning Objective

- Explain what happens when a Sun-like star runs out of hydrogen fuel in its core.

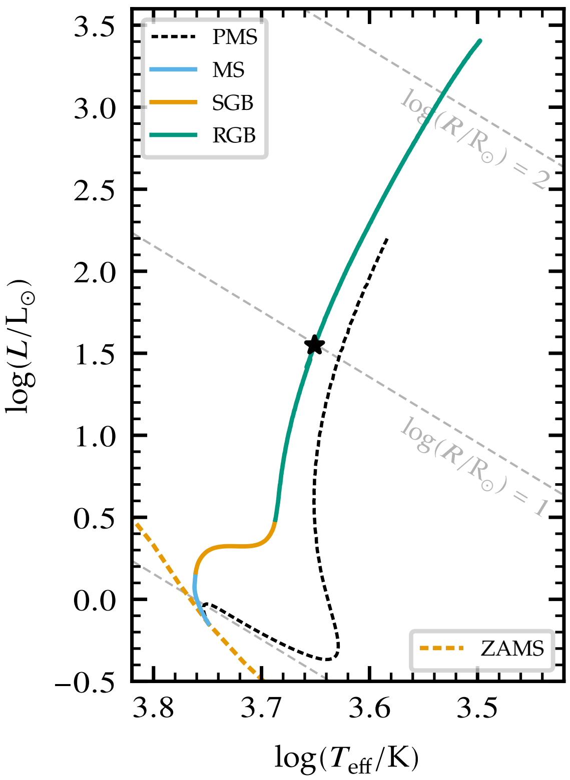


Figure 5. MESA-Web evolutionary track in the Hertzsprung-Russell diagram for a for a 1 $M_\odot$ MESA-Web model, spanning the pre-main sequence (black dashed), main sequence (blue), sub giant branch (gold), and red giant branch (RGB; green) phases The asterisk marks the case plotted in Figure 6, and the gold dashed line marks the zero-age main sequence.

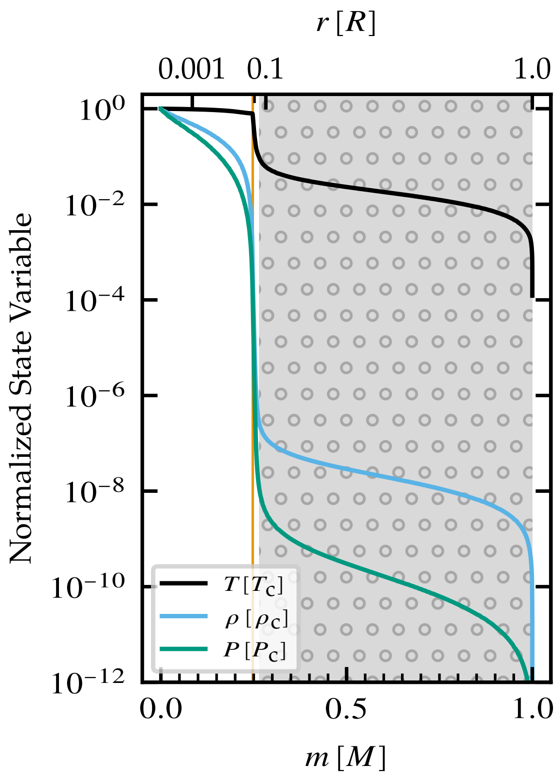


Figure 6. The state variables temperature T, density ρ and pressure P (in units of their central values $T_c = 3.65\times 10^7$ K, $\rho_c = 1.90\times10^5$ g cm^{-2}, $P_c = 2.00\times10^{21}$ Ba), plotted as a function of interior mass m for the 1 $M_\odot$ model at $R = 10\,R_\odot$ (marked by the asterisk in Figure 5). The ticks at the top mark the position of layers with radial coordinates $r =$ 0.001, 0.01, 0.1 and 1 R. The gold-shaded region indicates the (very narrow) hydrogen-burning shell; the gray-shaded/dotted region indicates the extended convective envelope.

Concept: Evolution onto the Red Giant Branch

When a star runs out of hydrogen at its center, its time on the main sequence has reached an end, and it embarks on a series of dramatic changes. For low- and intermediate-mass stars like the Sun, hydrogen burning continues in a shell around the core (now composed predominantly of helium), and the star evolves to the right in the Hertzsprung-Russell diagram. This phase is known as the sub giant branch (see Figure 5).

Eventually, the star becomes mostly convective and the curve transitions to more-vertical evolution in the HR diagram. This phase is known as the red giant branch (RGB), because the star becomes very large ($R \geq 100R_\odot$) and appears red due to its low effective temperature.

Concept: Core-Envelope Dichotomy on the RGB

A characteristic property of stars on the RGB is the division of the star into two dichotomous regions. One, a high-density radiative core composed primarily of helium (plus a small amount of metals). The core can encompass a significant fraction of the star's mass, but spans only a small fraction of the star's radius. Two, a surrounding low-density convective envelope composed of hydrogen-rich material. The envelope contains the remainder of the star's mass, and spans almost all of the star's radius.

Figure 6 illustrates the marked contrast between the core and the envelope, for a 1 $M_\odot$ MESA-Web model at R=10$R_\odot$ on the RGB. Note how the density at the top of the core is 5 orders of magnitude larger than the density at the bottom of the envelope. For this MESA-Web model, the core contains around 25% of the star's mass, but spans only about 0.3% of its radius. The envelope encompasses almost all of the remaining mass and radius. Because 95% by radius of the star is convective, its evolution in the Hertzsprung-Russell diagram (Figure 6) has a steeper slope.

Exercises:

- Enter the inlist of Figure 2 (all default values) on MESA-Web. Click submit. Explore the returned movies, plots, and plain text data files from which additional analysis can be performed. Explore the documentation of the MESA-Web output.
- Using the provided Jupyter notebook, reproduce Figures 5 and 6.
- Make drawings and annotations such that you can use it to be able to tell someone else how a star goes from the Main Sequence to the Red Giant Branch stage, describing the logic of how the core contracts/expands, how the star moves in the HR diagram, the means of energy transport, and the relevant nuclear reactions. Bring your drawings to class and use it (and nothing else) to tell the story of this phase of stellar evolution to another learner – then exchange your roles.
- The history file, named `trimmed_history.data`, provides general information about the entire stellar model as a function of time. The file consists of a few header lines giving global data, followed by a sequence of rows correspond to individual timesteps. The columns of each row contain physical characteristics of the model. In a plot, compare the dynamical, Kelvin-Helmholtz, and nuclear timescales as a function of time in the history file with analytical approximations for these timescales as the stellar model goes from the Main Sequence to the Red Giant Branch stage. Additional columns in the history file may be useful for evaluating the analytical approximations.

Figure 7 shows two learner's submissions in response to the third bulleted homework exercise suggested above. The first example was created with a digital illustration software instrument. Highlights of this assignment submission include showing stellar evolution tracks for three different initial masses, identifying the means of energy transport in the core region, defining the axis labels, and marking the starting and ending locations with fuel ignition events. The second example was created with colored pens on paper, which was subsequently digitally imaged. Highlights of this assignment submission include showing an analysis of changes in the thermodynamics and stellar structure due to nuclear burning, distingushing the global means of energy transport, and identifying astronomy names for groups of stars at different points along the evolution's trajectory. Both submissions were adjudicated to have met the learning objective listed in this Red Giant Branch Example.

6.3 Example: Stellar Structure and Evolution

The following describes an example that is part of the instructor submitted collection of `MESA-Web` learning materials available publicly at our Zenodo `MESA-Web` community hub. The lesson materials are part of a Stony Brook University's AST 341 *Stars and Radiation* course.

Stony Brook's AST 341 *Stars and Radiation* class is an upper-level Astronomy class for majors. Until recently, students were not required to have any computing prerequisite, so having the students install and run `MESA` is not appropriate for the class. Instead, they were given `MESA-Web` models to explore (the instructor generated a few, just to ensure that there was some data without overloading `MESA-Web`, but the students were also encouraged to run their own). Since the students may not have python experience, the `MESA` output was converted to columnar data with `py_mesa_reader` (scripts were available for students to do this on their own as well). The assignment had them verify some of the trends that we explored in class in our discussion of stellar structure and evolution, and referred to the discussion in the class text, Prialnik's *An Introduction to the Theory of Stellar Structure and Evolution* (Prialnik, 2009). For the graduate version of this class, students were given a final project where they could explore some aspect of stars. Several students chose `MESA` projects, and most used `MESA-Web`, exploring, for example, the effect of metallicity on stellar structure, the dependence of WD mass on initial progenitor or wind model.

7 Summary

We have presented `MESA-Web`, a cloud resource with an online interface to the Modules for Experiments in Stellar Astrophysics (`MESA`) software instrument. The goal of `MESA-Web` is to remove barriers to access and to provide open educational resources for learning about the evolution of stars. Since its inception in 2015, `MESA-Web` has evolved over 10,000 models to over 2,200 unique learners and currently performs about 11 jobs per day. `MESA-Web` has had several major improvements in capabilities and available resources over the years, making it a powerful tool for education and scientific investigations.

To help facilitate a community of educators and access to materials that have leveraged `MESA-Web` in the classroom, we created a Zenodo `MESA-Web` community hub. This community hub serves as a central repository for sharing materials and fostering collaboration among the `MESA-Web` community. We encourage educators to help contribute to and support this hub to help aide in the continued success of `MESA-Web` as an educational resource for years to come.

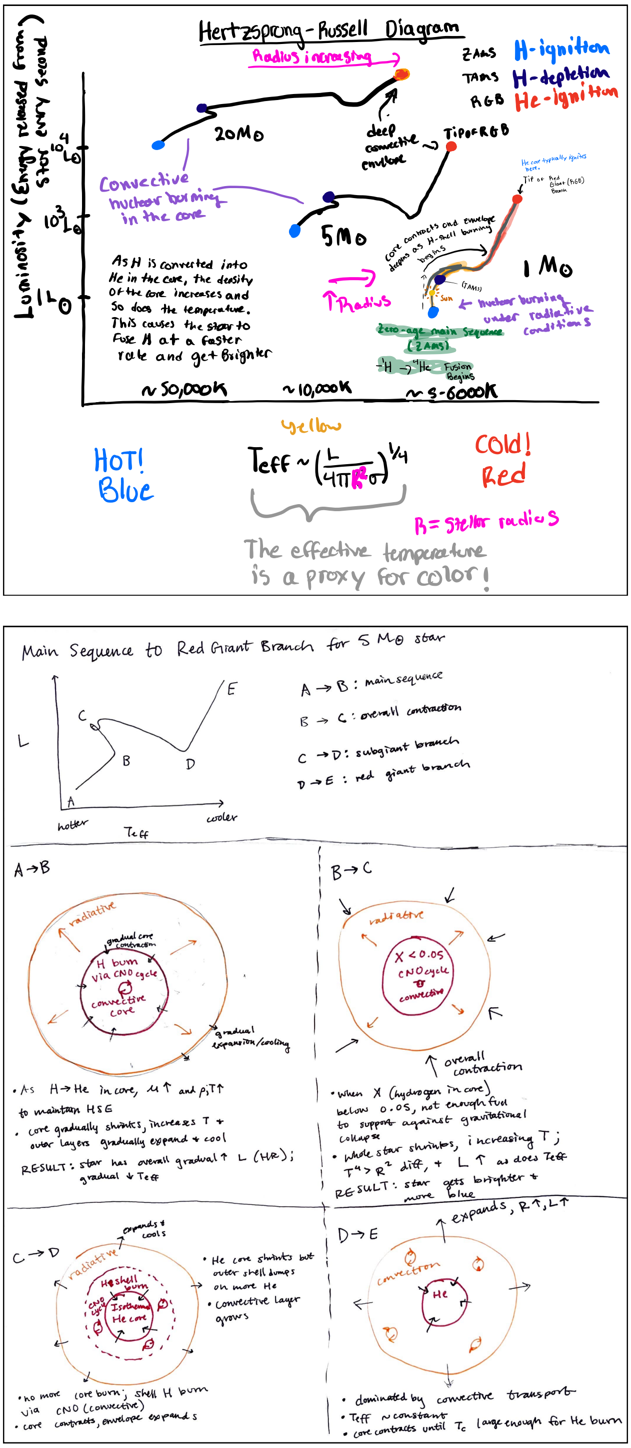


Figure 7. Two learner's responses to the drawing exercise in The Red Giant Branch Example.

8 Declarations

8.1 List of abbreviations

- `MESA` - Modules for Experiments in Stellar Astrophysics
- HR - Hertzsprung-Russell
- RGB - red giant branch
- WD - White Dwarf

8.2 Competing Interests

The authors declare that they have no competing interests.

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8.4 Author's Contributions

All the authors contributed equally to this article.

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