



MESA

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Watch embedded movies at

<https://docs.google.com/presentation/d/1IjEH2uWfr2MzW8XYTN-ZaozT0mo3h4OsVKqiKAS0fBg/edit#slide=id.p>

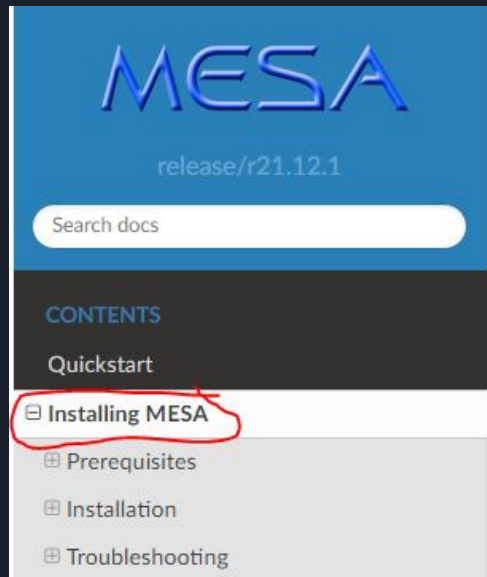


Introduction

- MESA (Modules for Experiments in Stellar Astrophysics)
 - Open source Fortran 90 software for modeling stellar evolution
 - How does MESA model stars?
 - Numerical evolution based on various analytic and differential equations (ex: hydrostatic equilibrium, Saha equation)
 - Limitations of MESA
 - Many approximations
 - High angular momentum states such as neutron stars are difficult to model correctly
 - Documentation: <https://docs.mesastar.org/en/release-r21.12.1/quickstart.html>
- We present the evolution of a 10 solar mass star with low initial metallicity ($1e-4$), no angular momentum, and implemented without mass loss

MESA Prerequisites

- Install MESA SDK (prebuilt set of required compilers/libraries)
- Everything documented well on MESA website



Package	Fedora / CentOS	Ubuntu	Mint	Gentoo	Arch
Binutils	binutils	binutils	binutils	sys-devel/binutils	binutils
Make	make	make	make	sys-devel/make	make
Perl	perl	perl	perl	dev-lang/perl	perl
X11 library	libX11, libX11-devel	libx11-6, libx11-dev	libx11-dev	x11-libs/libX11	libx11
Z library	zlib, zlib-devel	zlib1g, zlib1g-dev	zlib-dev	sys-libs/zlib	zlib
C shell	tcsh	tcsh	tcsh	sys-shells/tcsh	tcsh
Other			libc6-dev		glibc

MESA Installation/Setup

- Install MESA (zip file)
- Set environment variables in .bashrc (or similar file for your shell)
- Compile code in command line (./install)

The screenshot shows the Zenodo website interface. At the top, there's a blue header with the Zenodo logo, a search bar, and links for 'Upload' and 'Communities'. Below the header, the main content area displays the release information for 'Modules for Experiments in Stellar Astrophysics (MESA)' by Paxton, Bill. The release date is December 17, 2021. It shows 4,712 views and 4,690 downloads. A file list is visible, including 'mesa-r21.12.1.zip' (2.1 GB) and 'mesa-r21.12.1.tar.gz' (2.1 GB). The file list is currently empty, with a message 'The previewer is not showing all the files'. On the right side, there's a section for 'OpenAIRE' and a 'Publication date' of December 17, 2021. Below that, there's a 'DOI' section with the DOI '10.5281/zenodo.578640'. The 'Conversions' section lists 'Modules for Experiments in Stellar Astrophysics (MESA)'. The 'License (for files)' section states 'CC-BY General Public License v3.0 or later'. At the bottom, there's a 'Versions' section with a table of releases.

Version	File Size	Download Count	Release Date
Version 01.12.1	10.5 MB	4,690	Dec 17, 2021
Version 01.12.0	10.5 MB	4,690	Dec 17, 2021
Version 01.11.0	10.5 MB	4,690	Dec 17, 2021
Version 01.10.0	10.5 MB	4,690	Dec 17, 2021

```
# set MESA_DIR to be the directory to which you downloaded MESA
# The directory shown is only an example and must be modified for your particular system.
export MESA_DIR=/Users/jschwab/Software/mesa-r21.12.1

# set OMP_NUM_THREADS to be the number of cores on your machine
export OMP_NUM_THREADS=2

# you should have done this when you set up the MESA SDK
# The directory shown is only an example and must be modified for your particular system.
export MESASDK_ROOT=/Applications/mesasdk
source $MESASDK_ROOT/bin/mesasdk_init.sh
```



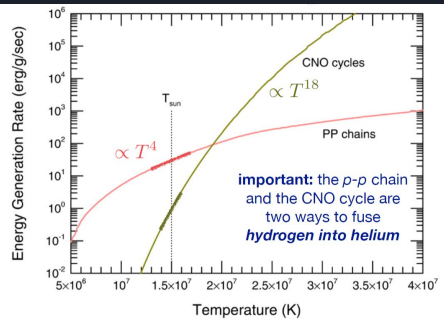
Running MESA

- Compile star/work directory (./mk)
- Edit model parameter file (inlist_project)
- Edit PGSTAR parameters (inlist_pgstar)
- Run in terminal (./rn)
- Watch your star evolve

```
36      inlist_project
37      / ! end of rep namelist
38
39      &controls
40      ! see star/defaults/controls.defaults
41
42      ! starting specifications
43      initial_mass = 10 ! in Msun units
44      initial_z = 1d-4
45
46      ! when to stop
47
48      ! stop when the star nears ZAMS (Lnuc/L > 0.99)
49      ! nuc_div_l_zams_limit = 0.99d0
50      ! stop_near_zams = .true.
51      stop_at_phase_WDCS = .true.
52
53      ! stop when the center mass fraction of h1 drops below this limit
54      ! xa_central_lower_limit_species(1) = 'h1'
55      ! xa_central_lower_limit(1) = 1d-3
56
57      ! wind
58
59      ! atmosphere
60
61      ! rotation
62
63      ! element diffusion
64
65      ! mlt
66
67      ! mixing
68
69      ! timesteps
70
71      ! mesh
72
73      ! solver
74      ! options for energy conservation (see MESA V, Section 3)
75      energy_eqn_option = 'dedt'
76      use_gold_tolerances = .true.
77
78      ! output
79
80      / ! end of controls namelist
```

Nuclear Reactions

- Efficiency
 - $\epsilon = \Delta m / m_{\text{start}}$
- $E = \epsilon M c^2$
- pp-chain
 - ${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + e^+ + \nu_e$
 - ${}^1_2\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$
- CNO cycle
 - ${}^1_1\text{H} + {}^{12}_6\text{C} \rightarrow {}^{13}_7\text{N} + \gamma$
 - ${}^{13}_7\text{N} \rightarrow {}^{13}_6\text{C} + e^+ + \nu_e$
 - ${}^1_1\text{H} + {}^{13}_6\text{C} \rightarrow {}^{14}_7\text{N} + \gamma$
 - ${}^1_1\text{H} + {}^{14}_7\text{N} \rightarrow {}^{15}_8\text{O} + \gamma$
 - ${}^{15}_8\text{O} \rightarrow {}^{15}_7\text{N} + e^+ + \nu_e$
 - ${}^1_1\text{H} + {}^{15}_7\text{N} \rightarrow {}^{12}_6\text{C} + {}^4_2\text{He}$



• Helium

- ${}^4_2\text{He} + {}^4_2\text{He} \rightarrow {}^8_4\text{Be}$
- ${}^8_4\text{Be} + {}^4_2\text{He} \rightarrow {}^{12}_6\text{C} + 2\gamma$
- ${}^{12}_6\text{C} + {}^4_2\text{He} \rightarrow {}^{16}_8\text{O} + \gamma$

• Carbon

- ${}^{12}_6\text{C} + {}^{12}_6\text{C} \rightarrow {}^{20}_{10}\text{Ne} + {}^4_2\text{He}$
- ${}^{12}_6\text{C} + {}^{12}_6\text{C} \rightarrow {}^{23}_{11}\text{Na} + {}^1_1\text{H}$

• Oxygen

- ${}^{16}_8\text{O} + {}^{16}_8\text{O} \rightarrow {}^{28}_{14}\text{Si} + {}^4_2\text{He}$
- ${}^{16}_8\text{O} + {}^{16}_8\text{O} \rightarrow {}^{31}_{15}\text{P} + {}^1_1\text{H}$
- ${}^{16}_8\text{O} + {}^{16}_8\text{O} \rightarrow {}^{31}_{16}\text{S} + n$



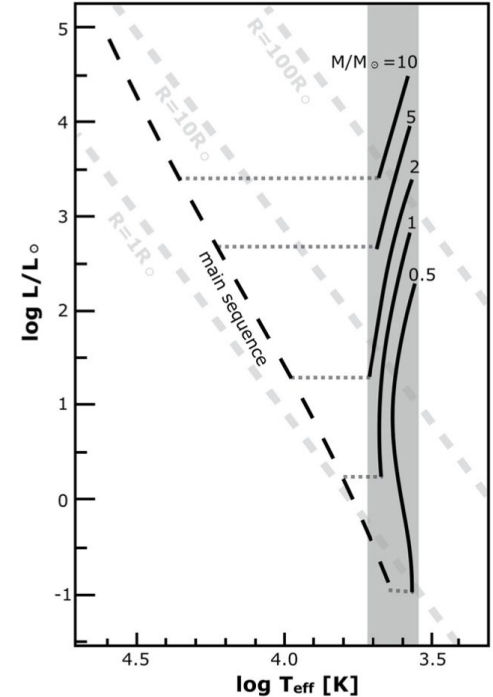
Convection

- Schwarzschild Criterion
 - Convection at high temperature gradient or low gravitational acceleration
 - Cores of high mass stars, outer regions of low mass stars

$$\left| \frac{dT}{dz} \right| > \frac{\gamma - 1}{\gamma} \frac{\mu m_p}{k} g$$

Pre-MS (LL Ch. 12)

- Star collapses until it reaches hydrostatic equilibrium
- If molecular cloud is massive enough, hydrogen molecules dissociate and ionize
- Hayashi track at $T_{\text{eff}} \sim 3000$ K
 - No fusion, but star loses energy from temperature gradient radiation as star contracts
- Horizontal to main sequence
 - No fusion, but in radiative + hydrostatic equilibrium
 - $L \sim M^3$ so constant L





Main Sequence

- Star spends the majority of its lifetime on the main sequence burning hydrogen
- Hydrostatic equilibrium
- Mass-luminosity relation

$$\frac{L}{L_{\odot}} \approx 1.4 \left(\frac{M}{M_{\odot}} \right)^{3.5} \quad (2M_{\odot} < M < 55M_{\odot})$$

- Hydrogen burning
 - MESA can struggle when transitioning fuel type on small timeframes
 - Note graph spikes between 11-12s and spontaneous generation of H in bar graph





Main Sequence

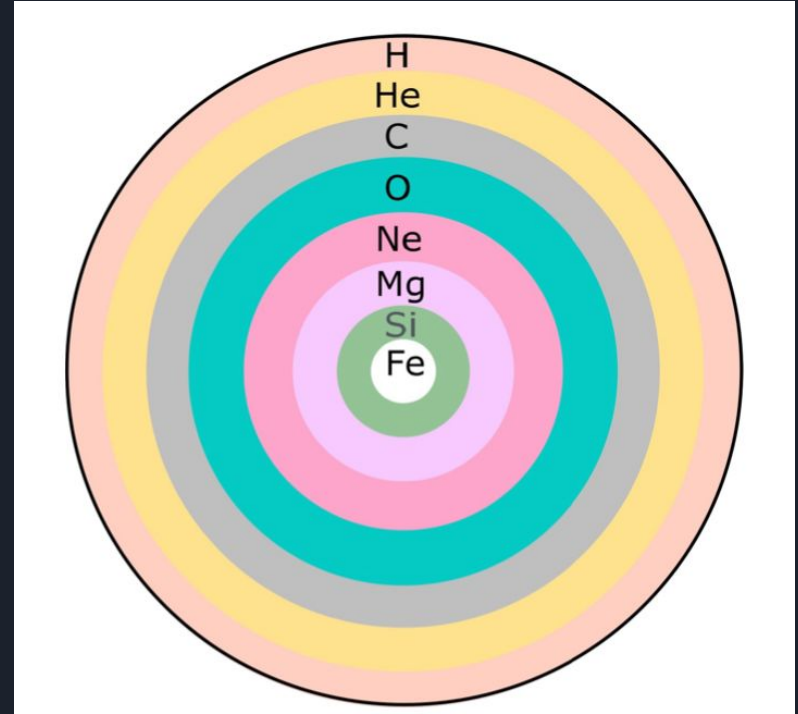
Energy

equations of state

X=hydrogen Y=helium
composition

Post-MS Evolution

1. At TAMS, hydrogen in the core is depleted
 - Hydrogen shell burning begins
 - Helium core collapses and star expands
2. Once the core reaches a high enough temperature, helium fusion begins
3. Eventually, the outer layers of the expanding star cool down and hydrogen fusion stops
4. Hydrogen fusion reignites
5. Cycle continues with various stages of core burning (C, O, Si) and shell burning





Full Evolution of a 10 Solar Mass Star

1. Hayashi vertical track on HR diagram
2. Pre-main sequence horizontal track on HR diagram
3. Hydrogen burning (main-sequence)
4. Hydrogen shell burning (giant branch)
5. Helium core burning (horizontal branch)
6. Hydrogen shell stops fusing (pre-AGB)
7. Hydrogen shell reignites (AGB)
8. Helium shell burning
9. Carbon core burning, etc.

