MESA

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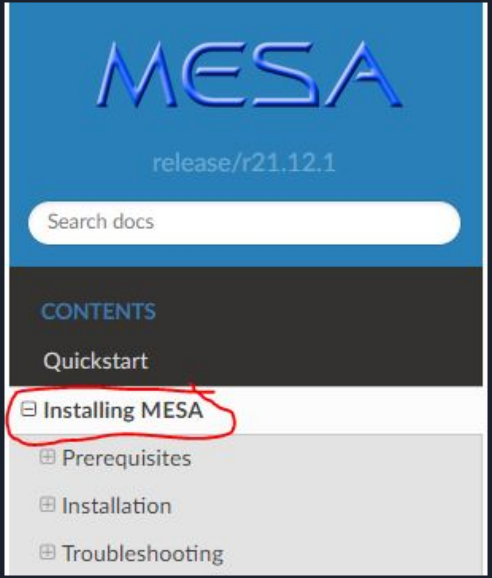
Watch embedded movies at
https://docs.google.com/presentation/d/1IjEH2uWfr2MzW8XYTN-ZaozT0mo3h4OsVKqiKAS0fBg/edit#slide=id.p

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

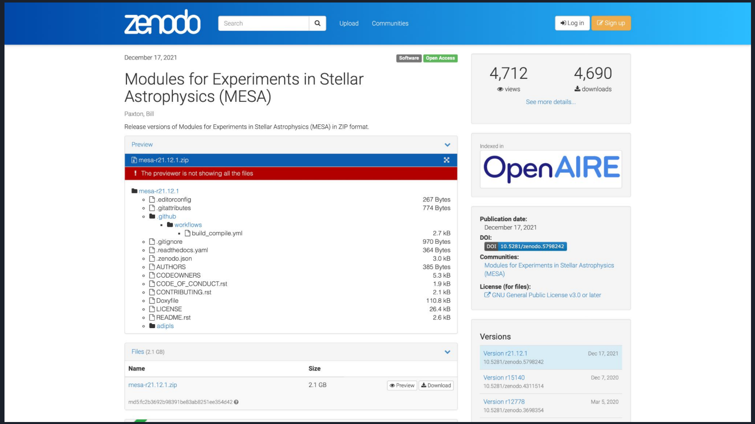
- Install MESA SDK (prebuilt set of required compilers/libraries)
- Everything documented well on MESA website



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)




```
# 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

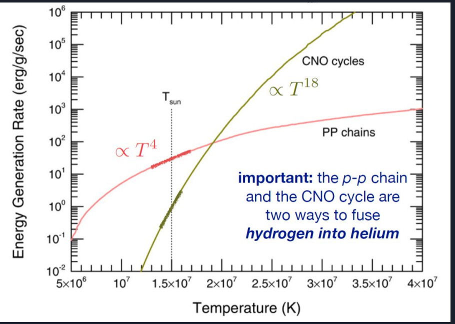
- Compile star/work directory (./mk)
- Edit model parameter file (inlist_project)
- Edit PGSTAR parameters (inlist_pgstar)
- Run in terminal (./rn)
- Watch your star evolve

inlist_project

```
&controls
  ! see star/defaults/controls.defaults

  ! starting specifications
    initial_mass = 10 ! in Msun units
    initial_z = 1d-4

  ! when to stop

    ! stop when the star nears ZAMS (Lnuc/L > 0.99)
    ! nuc_div_L_zams_limit = 0.99d0
    ! stop_near_zams = .true.
    stop_at_phase_WDCS = .true.

    ! stop when the center mass fraction of h1 drops below this limit
    ! xa_central_lower_limit_species(1) = 'h1'
    ! xa_central_lower_limit(1) = 1d-3

  ! wind

  ! atmosphere

  ! rotation

  ! element diffusion

  ! mlt

  ! mixing

  ! timesteps

  ! mesh

  ! solver
     ! options for energy conservation (see MESA V, Section 3)
     energy_eqn_option = 'dedt'
     use_gold_tolerances = .true.

  ! output

/ ! end of controls namelist
```

Nuclear Reactions

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



- Helium
    - ${}^{4}_{2}He + {}^{4}_{2}He \rightarrow {}^{8}_{4}Be$
    - ${}^{8}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + 2\gamma$
    - ${}^{12}_{6}C + {}^{4}_{2}He \rightarrow {}^{16}_{8}O + \gamma$
- Carbon
    - ${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{20}_{10}Ne + {}^{4}_{2}He$
    - ${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{23}_{11}Na + {}^{1}_{1}H$
- Oxygen
    - ${}^{16}_{8}O + {}^{16}_{8}O \rightarrow {}^{28}_{14}Si + {}^{4}_{2}He$
    - ${}^{16}_{8}O + {}^{16}_{8}O \rightarrow {}^{31}_{15}P + {}^{1}_{1}H$
    - ${}^{16}_{8}O + {}^{16}_{8}O \rightarrow {}^{31}_{16}S + n$

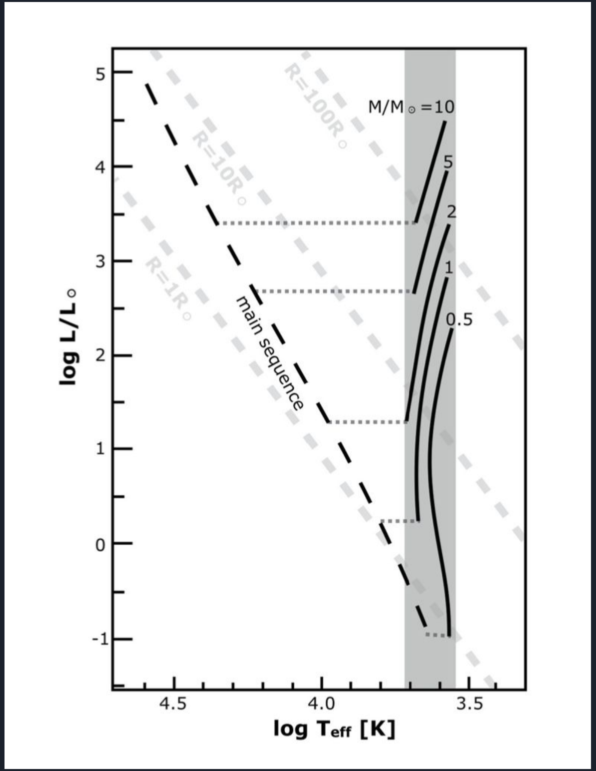
Convection

- 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_eff ~ 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 ~ 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

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

- 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

X=hydrogen Y=helium

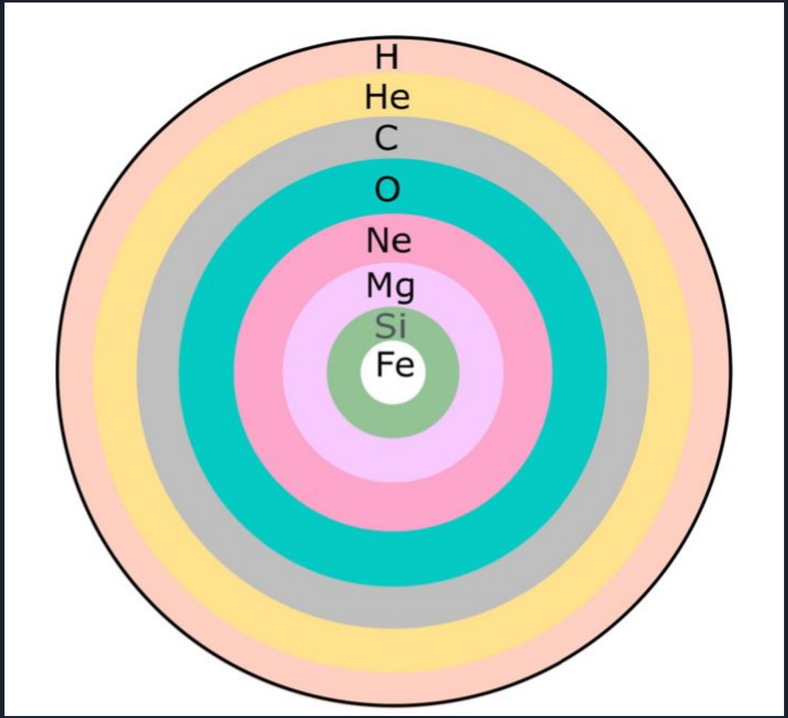
Energy

equations of state

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.