Simulating single and binary star systems using MESA

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Outline

Goal and relevancy

"Comparison of the evolution of single stars and stars part of a binary system."

Stellar evolution

- Fairly well understood
- Mass dependent

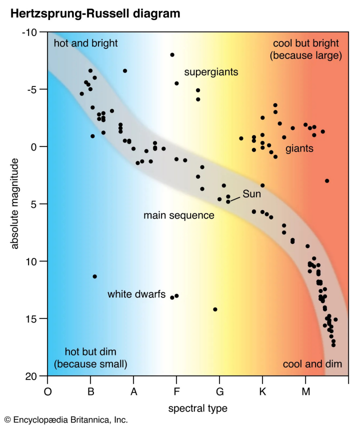

Figure 1: HR diagram

Algol paradox

Figure 2: Algol finding chart

Algol paradox

- Variable star
- Multiple system
  - Massive main sequence star
  - Less massive red giant
- Mass transfer
  - Stellar winds
  - Roche lobe overflow

Roche lobe overflow

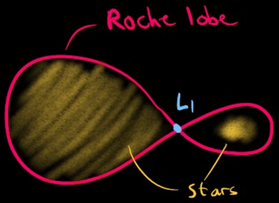

Figure 3: Semi-detached binary

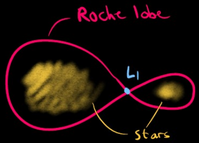

Figure 4: Detached binary

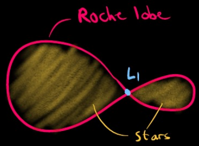

Figure 5: Contact binary

What is MESA?

- *MESA* stands for *Modules for Experiments in Stellar Astrophysics*.

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- It is a code library that is used to simulate stellar objects throughout their lifetimes.

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- In particular, we are interested in
  1. Comparing the HR-diagrams and T-ρ profiles of the stars in the binary system to the isolated stars.
  2. Obtaining information on the binary system, such as the mass transfer rate and state variables of the individual stars.

What does it look like?

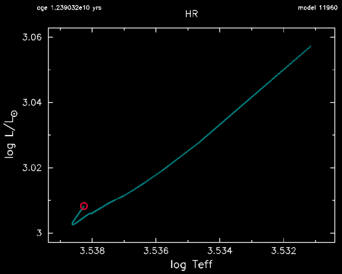

Figure 6: Simulated evolutionary track of a $1M_{\odot}$, $0.2Z$ star.

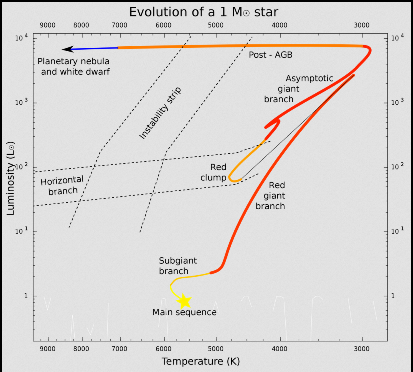

Figure 7: Example Evolutionary track of a $1M_{\odot}$ star. src: Wikimedia Commons, Lithopsian

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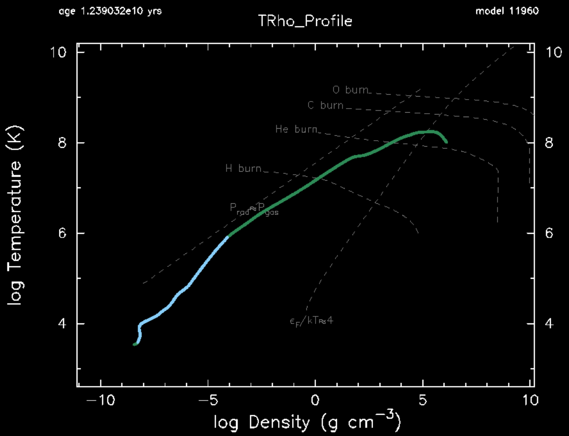

Figure 8: Temperature - density profile of a simulated $1M_\odot$ star throughout its lifetime.

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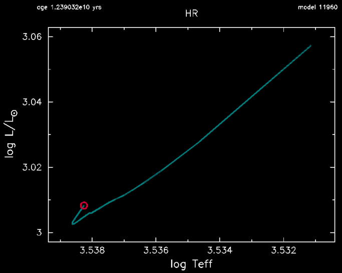

Figure 9: Hertzsprung-Russel diagram of $10M_\odot$, $0.4Z$ star

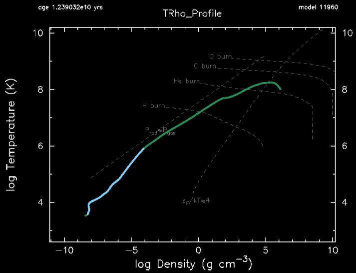

Figure 10: Temperature density profile of a $10M_\odot$, $0.4Z$ star

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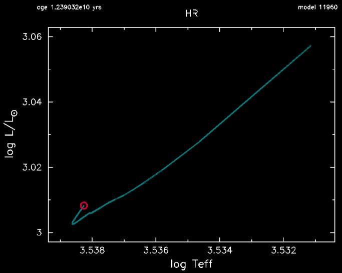

Figure 11: Hertzsprung-Russel diagram of a $50M_{\odot}$, $0.2Z$ star

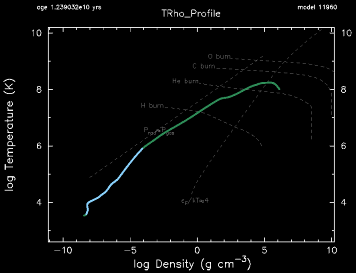

Figure 12: Temperature density profile of $50M_{\odot}$, $0.2Z$ star

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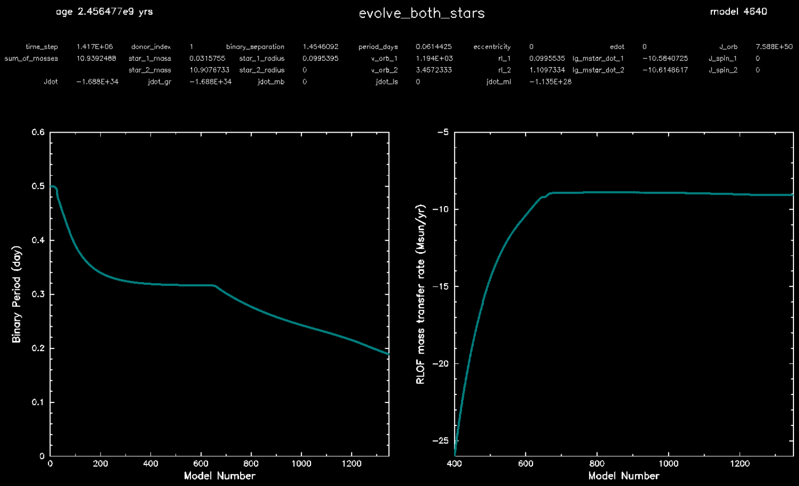

Figure 13: Binary system with increasingly smaller orbital period. Left: orbital period against model number. Right: Mass transfer rate against model number.

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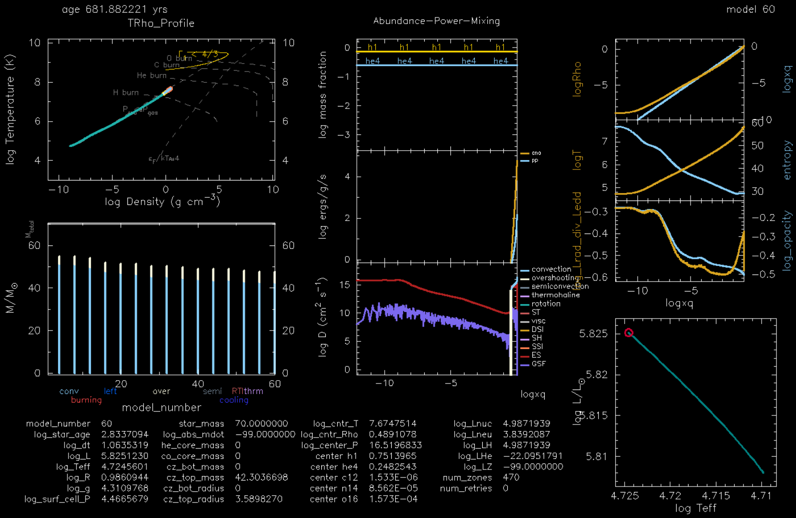

Figure 14: Test run with two stars that become black holes.

Configuring MESA

Structure of the library

- The library is written in Fortran and requires some basic knowledge of the language.

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- The library is written in Fortran and requires some basic knowledge of the language.
- The file in Fig. 15 contains some declarations and subroutines that initialize the model of the star.

```
logical :: have_initialized_star_handles = .false.
integer, parameter :: max_star_handles = 10 ! this can be increased as necessary
type (star_info), target, save :: star_handles(max_star_handles)
   ! gfortran seems to require "save" here.  at least it did once upon a time.


contains


subroutine star_ptr(id, s, ierr)
   integer, intent(in) :: id
   type (star_info), pointer, intent(inout) :: s
   integer, intent(out) :: ierr
   call get_star_ptr(id, s, ierr)
end subroutine star_ptr


subroutine get_star_ptr(id,s,ierr)
   integer, intent(in) :: id
   type (star_info), pointer :: s
   integer, intent(out) :: ierr
   if (id < 1 .or. id > max_star_handles) then
      ierr = -1
      return
   end if
   s => star_handles(id)
   ierr = 0
end subroutine get_star_ptr


subroutine result_reason_init
   result_reason_str(result_reason_normal) = 'normal'
   result_reason_str(dt_is_zero) = 'dt_is_zero'
   result_reason_str(nonzero_ierr) = 'nonzero_ierr'
   result_reason_str(hydro_failed_to_converge) = 'hydro_failed'
```

Figure 15: star_data/public/star_data_def.f90

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- Fig. 16 specifies a subset of settings for the binary system.

```
&binary_job

   inlist_names(1) = 'inlist1'
   inlist_names(2) = 'inlist2'

   evolve_both_stars = .true.

/ ! end of binary_job namelist


&binary_controls

   m1 = 5.0d0   ! donor mass in Msun
   m2 = 1.0d0 ! companion mass in Msun
   initial_period_in_days = 3650

   !transfer efficiency controls
   limit_retention_by_mdot_edd = .false.

!   max_model_number = 50000

/ ! end of binary_controls namelist
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- Fig. 16 specifies a subset of settings for the binary system.
- Individual settings for the stars, besides the initial mass and initial metallicity, are specified in separate inlists (not shown).

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- We then run simulations with respectively a $1M_\odot$, $2M_\odot$, $4M_\odot$, $5M_\odot$ and $8M_\odot$ star as the accretor, and a $5M_\odot$ as the donor in all the cases.
- We consider the mass transfer rate in the binaries and compare the HR-diagrams and $T\rho$-profiles of the accretor with that of the isolated stars.

What did it look like?

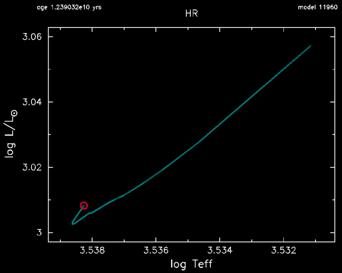

Figure 17: Hertzsprung-Russel diagram of $5M_\odot$ donor $4M_\odot$ accretor and 5 yr period

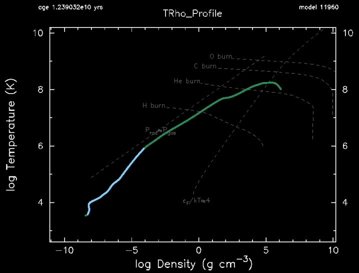

Figure 18: Temperature-Density profile of $5M_\odot$ donor $4M_\odot$ accretor and 5 yr period

Simulation Mishap

- Period set to 1 day

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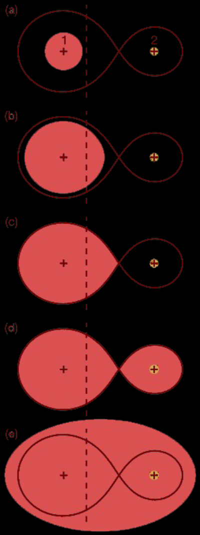

Figure 19: Formation of a common envelope, credits: Philip D. Hall

Simulation Mishap

- Period set to 1 day
- Simulation stops abruptly
- Decrease in period and mass transfer
- Common envelope
- Most common period: 100 yr
- Period of 2 yr

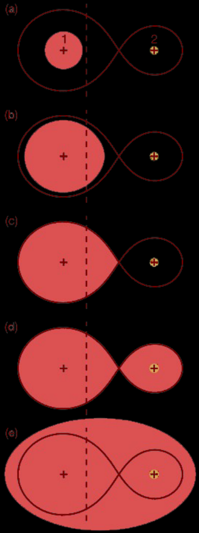

Figure 19: Formation of a common envelope, credits: Philip D. Hall

Simulation outcomes

$1M_\odot$ accretor

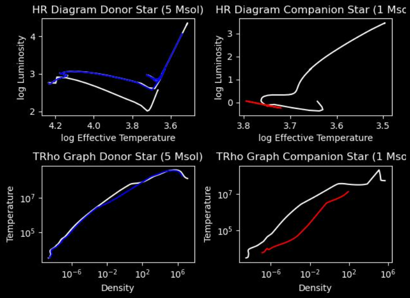

Figure 20: HR-Diagrams and T-ρ Graph of a $5M_\odot$ donor and $1M_\odot$ accretor.

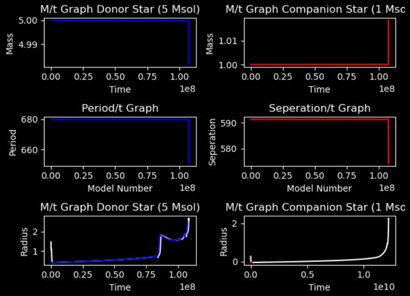

Figure 21: Mass, orbital period, separation and radius of a $5M_\odot$ donor and $1M_\odot$ accretor.

Simulation outcomes

$2M_\odot$ accretor

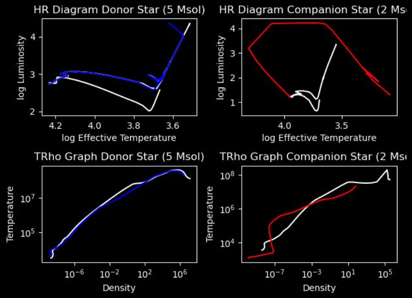

Figure 22: HR-Diagrams and T-ρ Graph of a $5M_\odot$ donor and $2M_\odot$ accretor.

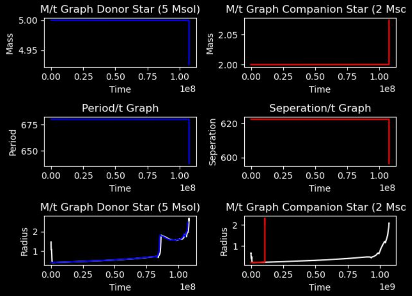

Figure 23: Mass, orbital period, separation and radius of a $5M_\odot$ donor and $2M_\odot$ accretor.

Simulation outcomes

$4M_\odot$ accretor

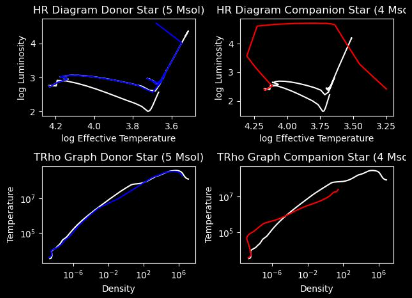

Figure 24: HR-Diagrams and T-ρ Graph of a $5M_\odot$ donor and $4M_\odot$ accretor.

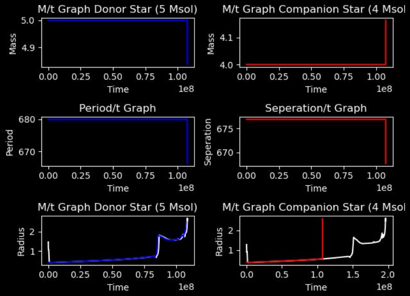

Figure 25: Mass, orbital period, separation and radius of a $5M_\odot$ donor and $4M_\odot$ accretor.

Simulation outcomes

$5M_\odot$ accretor

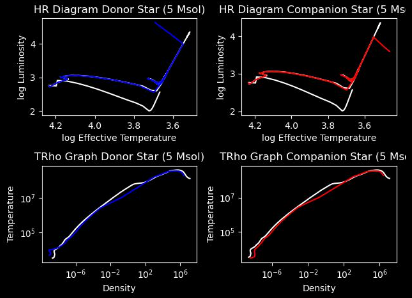

Figure 26: HR-Diagrams and T-ρ Graph of a $5M_\odot$ donor and $5M_\odot$ accretor.

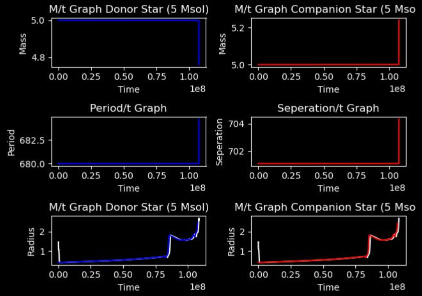

Figure 27: Mass, orbital period, separation and radius of a $5M_\odot$ donor and $5M_\odot$ accretor.

Simulation outcomes

$8M_{\odot}$ accretor

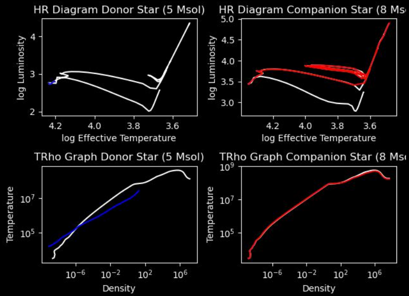

Figure 28: HR-Diagrams and T-ρ Graph of a $5M_{\odot}$ donor and $8M_{\odot}$ accretor.

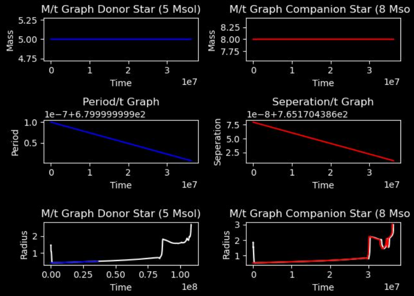

Figure 29: Mass, orbital period, separation and radius of a $5M_{\odot}$ donor and $8M_{\odot}$ accretor.

Takeaways

- Continuous mass transfer between the stars in the binaries results in vastly different HR-diagrams that are unrecognizable from the theory for the isolated case.

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- Stars will either merge and form a common envelope, or evolve separately within a binary system.
- In some cases, there will be mass transfer between stars and they will not immediately merge, but this will still be imminent.
- To examine the evolution in its entirety, longer periods of time to run simulations and a better understanding of MESA are needed.

Further research

Endless possibilities!

- General:
  1. Stellar winds
  2. Other types of objects
  3. Contact binaries
- Specific:
  1. Non-continuous mass transfer
  2. Changes in heat transfer mechanisms
  3. Higher multiple systems