PHY 474/374 **Spring 2021**

Week 8—Monday, May 17—Discussion Worksheet

High Mass Stars

High mass stars constitute a tiny fraction of the stellar mass spectrum, but they play a significant role in the Interstellar Medium. Therefore, it is important to learn about how they form and evolve.

1. Here, we will focus on evolution past the Main Sequence. Go to the website `Star in a Box` (https://starinabox.lco.global), move the button to `Advanced`, then `Open the lid`.

(a) Go ahead and evolve stars of different masses. Slow down the speed of the simulation using the radio button on the bottom right so you can see the steps more clearly. Write down your observations below regarding the differences that you observed between lower mass and high mass stars.

- Moves to a specific Lo and gains temp
- Reaches max temp and then begins to temp and luminocity

(b) Click on the `mass` icon on the bottom right of the screen so that you can see the mass of the star in the right panel. Evolve the stars to their end points and complete the table below regarding the nature and mass of the remnant. In the last column, find the % of mass lost (as a fraction of the original mass).

Mass	Name of Remnant	Remnant Mass	% Mass lost
0.2 $M_\odot$	Helium White Dwarf	0.183	8.5%
1 $M_\odot$	Carbon/oxygen White Dwarf	0.536	46%
10 $M_\odot$	Neutron Star	1.369	86%
40 $M_\odot$	Black hole	9.579	76%

Comment on the % of mass lost as a fraction of the original mass.

as mass increases mass loss increases. From there a maximum mass loss ratio will be created and the mass loss ratio levels out.

2. Carbon fusion cannot be initiated in stars like our Sun because the core temperature doesn't get high enough. Use the table below to answer the questions on this page.

Nuclear fuel	Nuclear products	Ignition temperature	Minimum main sequence mass	Period in $25M_\odot$ star
H	He	4×10^6 K	$0.1M_\odot$	7×10^6 years
He	C, O	1.2×10^8 K	$0.4M_\odot$	5×10^5 years
C	Ne, Na, Mg, O	6×10^8 K	$4M_\odot$	600 years
Ne	O, Mg	1.2×10^9 K	$\sim 8M_\odot$	1 years
O	Si, S, P	1.5×10^9 K	$\sim 8M_\odot$	~ 0.5 years
Si	Ni–Fe	2.7×10^9 K	$\sim 8M_\odot$	~ 1 day

(a) What is the minimum core temperature required to initiate fusion of carbon?

$T_c > 6 \times 10^8$ K

(b) Will carbon fusion take place in a 2 $M_\odot$ star? Does the simulation in `Star in a Box` support your answer?

NO, need at least 4 $M_\odot$ star

(c) What is the minimum mass of a star in which fusion stages beyond carbon can take place?

8 $M_\odot$, or large

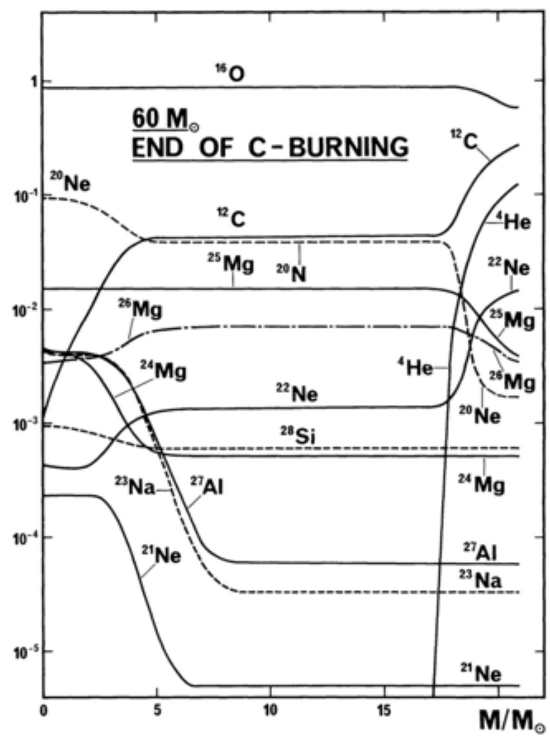
(d) What is the final product beyond which fusion will not take place in a star? Why is this?

Ni-Fe, due to the period it is in a star

(e) For stars that go through all of the stages listed in the table, what can you say about the time spent in each stage.

The period is shorter as the nuclear fuele increases

3. Let's look specifically at the products of carbon fusion in a high mass star. The figure below, taken from Maeder & Meynet (1987), shows the composition profile within a 60 $M_\odot$ star at the end of the carbon-fusion phase. The mass fraction of an element is shown along the y-axis, and the mass coordinate is shown along the x-axis; if it makes it easier, you can think of the x-axis as the radial distance, with zero being the center of the star.



(a) If the x-axis spans the helium core, then carbon fusion changes the chemical composition in what percentage of the mass of this He-core?

changes on Right of 5

$5/20 = 25\%$

(b) List the elements whose abundances have been enhanced in the inner part of the helium core during the carbon-fusion phase, and the elements that have been depleted.

Abundances enhanced	**Abundances depleted**
^{20}Ne, ^{21}Ne	^{22}Ne
^{23}Na	^{26}Mg
^{24}Mg, ^{25}Mg	^{12}C
^{27}Al, ^{28}Si	

(c) List the three most abundant elements at the end of the C-fusion stage in the 60 $M_\odot$ star.

^{16}O

^{20}Ne

^{25}Mg 97.8% in mass at center of 60 $M_\odot$ star

Stellar Remnants: White Dwarfs

The end products of low mass stars like our Sun are White Dwarfs.

4. A White Dwarf contains the mass of the Sun in a sphere about the size of our Earth.

(a) The nearest known white dwarf is Sirius B. It has a mass of 1.03 $M_\odot$ and a radius 5800 km. Calculate the density of Sirius B, and compare to our Sun, whose density is 1.4 g cm^{-3}.

$$\rho = \frac{M}{V} = \frac{(1.03\,M_\odot)(1.99\times10^{30}\,kg/M_\odot)}{4\pi/3\,[5860\times10^{3}\,m]^{3}} = 2.5\times10^{9}\,kg/m^{3}$$

$$\frac{\rho_{Sirius\,B}}{\rho_{sun}} = \frac{2.5\times10^{6}\,g/cm^{3}}{1.4\,g/cm^{3}} = 1.8\times10^{6} = 1.8 \text{ million times denser}$$

(b) Calculate the gravitational acceleration on the surface of Sirius B.

$$g = \frac{GM}{R^2} = \frac{(6.67\times10^{-11}\,m^3\,kg^{-1}\,s^{-2})(1.03\,M_\odot)(1.99\times10^{30}\,kg/M_\odot)}{[5800\times10^{3}\,m]^{2}}$$

$$= 4.1\times10^{6}\,m/s^{2}$$

(c) Compare the gravitational acceleration on the surface of Sirius B to that on the Earth's surface?

$$\frac{4.1\times10^{6}\,m/s^{2}}{9.8\,m/s^{2}} = 4.1\times10^{5}$$

(d) The luminosity of Sirius B is about 0.03 $L_\odot$, where 1 $L_\odot = 3.828\times10^{26}$ W. Assuming it to be a black body, calculate the surface temperature of Sirius B.
Note: The Stefan-Boltzmann constant is 5.67×10^{-8} W m^{-2} K^{-4}.

$$T_{eff} = \left[\frac{L}{4\pi\sigma R^2}\right]^{1/4}$$

$$= \left[\frac{0.03\,(3.828\times10^{26}\,W)}{4\pi(5.67\times10^{-8}\,W\,m^{-2}\,K^{-4})(5800\times10^{3}\,m)^{2}}\right]^{1/4} = 26{,}309\,K$$

Stellar Remnants: Neutron Stars

Neutron stars are the end products of stars with masses about 4 $M_\odot$ and larger; for much higher mass stars that leave behind remnants larger than 2-3 $M_\odot$, we get a Black Hole.

5. A neutron star packs the mass of the Sun into a sphere smaller than the size of Chicago!

(a) A neutron star of mass $\underbrace{1.4\ M_\odot}_{2.78\times10^{30}\,kg}$ has radius 11.4 km. Calculate its density, and compare to that of our Sun.

$$\rho = \frac{m}{V}$$

$$V_{sphere} = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi(11.4\times10^3 m)^3 = 6.04\times10^{12} m^3$$

$$= \frac{2.78\times10^{30}\,kg}{6.04\times10^{12}\,m^3} = 4.61\times10^{17}\,\frac{kg}{m^3}$$

$$R_\odot = 6.96\times10^8 m \qquad M_\odot = 1.99\times10^{30} kg$$

$$V_{sphere} = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi(6.96\times10^8 m)^3 = 1.42\times10^{27} m^3$$

$$\rho = \frac{1.99\times10^{30}\,kg}{1.42\times10^{27}\,m^3} = 1409\,\frac{kg}{m^3}$$

(b) Calculate the escape velocity from this neutron star. Express it in terms of c, and comment on whether you'd expect significant general relativistic deviations from Newtonian gravity on a neutron star.

Note: The escape velocity from an object of mass M and radius R is $v_{esc} = \sqrt{2GM/R}$, where $G = 6.68\times10^{-11}$ m^3 kg^{-1} s^{-2}.

$$v = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{2(6.68\times10^{-4} m^3 kg^{-1} s^{-2})(2.78\times10^{30} kg)}{11.4\times10^3 m}}$$

$$= \sqrt{3.25\times10^{16}\ m^2/s^2}$$

$$= 1.8\times10^8\ m/s$$

$$= 0.6\ c$$