PHY 474/374 Spring 2021

Class Summary—Week 8, Day 1—Monday, May 17

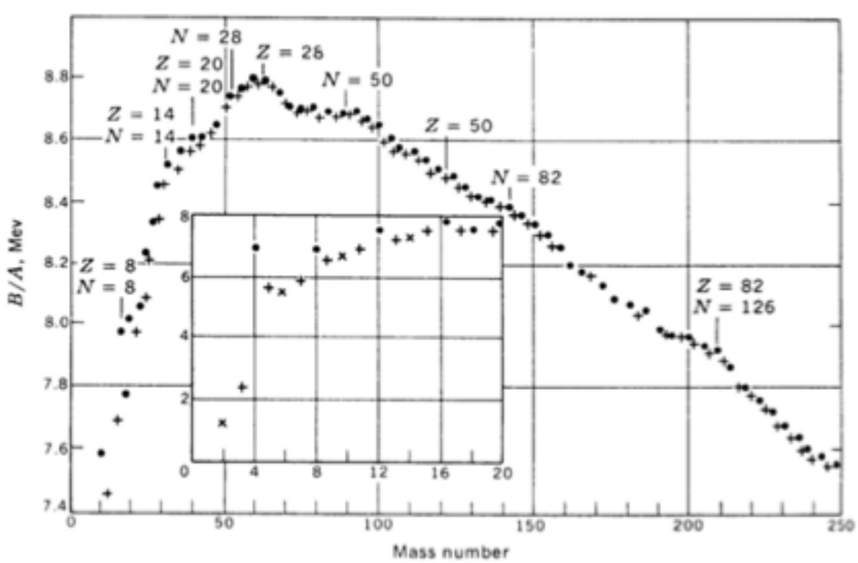
High Mass Stars

High mass stars constitute a tiny fraction of the stellar mass spectrum, but play a significant role in the Interstellar Medium. Significant mass loss via winds throughout lifetime seeds the Interstellar Medium with a variety of materials. Elements beyond carbon and oxygen up to iron are produced by fusion in cores of high mass stars. Many elements beyond iron are formed in supernovae of high mass stars.

We have learned in earlier class meetings that the fusion of lower mass stars like our Sun ends with a core comprised of carbon and oxygen. The next stage of fusion cannot be initiated in the cores of such stars because they become degenerate before their temperature becomes high enough to initiate fusion of carbon.

With increasing stellar mass, the tendency toward degeneracy in the core gets smaller. Thus, not only carbon, but elements with higher atomic number can also be created via fusion. Fusion of these elements alternates with gravitational contraction and heating, in the same manner as the post-Main Sequence stage. We end up with an onion-like structure, with the heaviest element at the center, along with shells in which fusion may also be taking place.

We will now discuss the stages of evolution of a high mass star. An important goal of learning about these stages is to understand the synthesis of elements, and their subsequent distribution in the Interstellar Medium. To understand nucleosynthesis, we must understand the energetics of fusion. Consider the graph shown below.



The graph shows the binding energy per nucleon plotted as a function of mass number. We see that the binding energy per nucleon increases up to about $Z = 26$ (iron) and $Z = 28$ (nickel), then decreases. To the left of this peak, fusion is exothermic. To the right of this peak, fusion is endothermic and needs energy to proceed, rather than creating energy. This has consequences for the nuclear fusion in the cores of stars.

We will now discuss the stages of fusion in high mass stars. An overview of each stage, including the fusing element, the products, the minimum ignition temperature, minimum main sequence mass, and duration in a 25 $M_\odot$ star is shown in the table in *Question 2 of today's worksheet.*

When the temperature exceeds about 5×10^8 K in the contracting core of a star, carbon fusion is initiated. This usually happens in stars with masses larger than about 4 $M_\odot$. The fusion takes place primarily through the reactions

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{24}\text{Mg} + \gamma$$

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{23}\text{Mg} + n$$

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{23}\text{Na} + p$$

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{20}\text{Ne} + {}^{4}\text{He}$$

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{16}\text{O} + 2{}^{4}\text{He}$$

Fusion stages beyond carbon require conditions that are realized only in stars with masses greater than about 8 $M_\odot$. After carbon-exhaustion in such cores, core contraction and heating lead to the initiation of neon fusion. At around 10^9 K, oxygen fusion sets in, and we get products like Si, S, and P.

At these high temperatures, another aspect of physics comes into play. A non-negligible fraction of photons now has energy in the MeV range, and can cause photodissociation of the nuclei (much like lower energy photons caused photodissociation of atoms). For example

$$^{32}\text{S} + \gamma \rightarrow {}^{28}\text{Si} + {}^{4}\text{He}$$

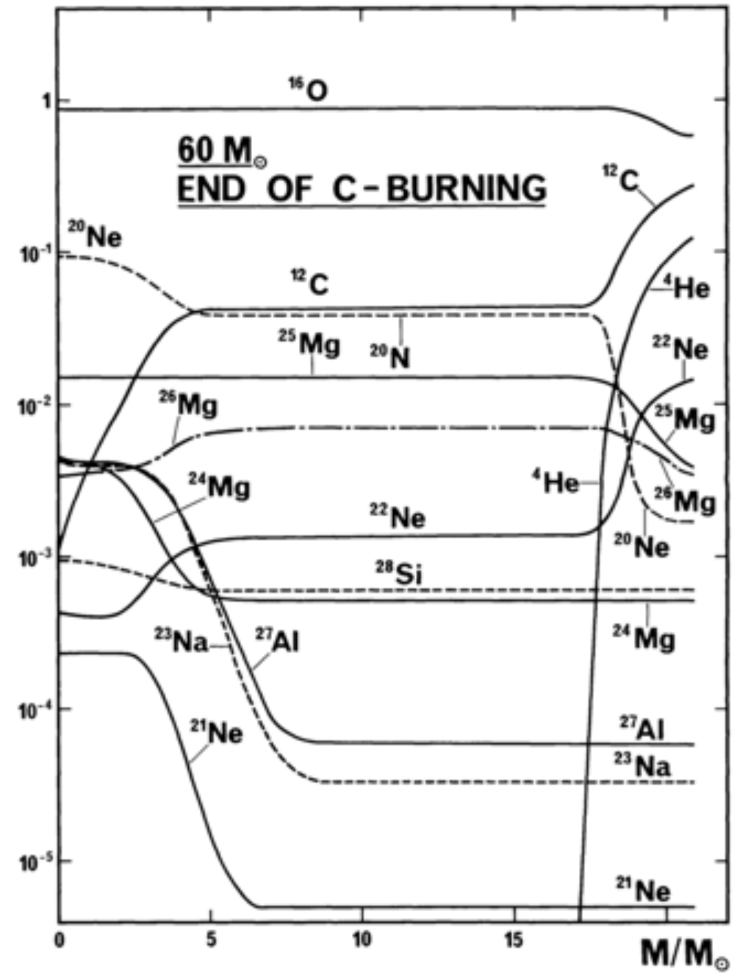
In essence, the reaction between ^{28}Si and ^{4}He becomes reversible, as do all reactions. Photons acquire the capability to disrupt the nuclei produced in the previous stages.

With all that goes on at these stages, we get an extremely complex network of reactions whose evolution must be followed numerically. In general, however, these processes occur almost in equilibrium, with nearly equal numbers of nuclei being created by fusion and disintegrated by high energy photons. The equilibrium isn't exact, however; the network evolves preferentially to nuclei with the largest binding energies.

We know from the binding energy curve shown on the previous page that the largest binding energies are for those in the iron group. At 3×10^9 K, silicon fusion is initiated. The products of silicon fusion, carried to completion under the equilibrium established by photodissociation, are nuclei in the iron group.

Since the nuclei in the iron group are the most stable in the Universe, silicon fusion represents the last step by which fusion reactions can build heavier elements under equilibrium conditions. It is worth asking why we can't produce heavier nuclei just by raising the temperature, so that the extra energy required for fusion can just be provided by the kinetic energy of the gas. However, the higher temperatures will lead to increased photodissociation, and it turns out that the equilibrium products are still the nuclei of the iron group. In the next class, we will learn how elements heavier than iron can be produced.

To get a feel for the complex networks that must be deployed to make sense of each fusion stage, we looked specifically at the products of carbon fusion in a high mass star *in Question 3 on today's worksheet.*



The figure above is taken from Maeder & Meynet (1987), and 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 we consider the x-axis to span the helium core (see the ^{4}He curve which climbs back up to post-Main Sequence values toward the right of the graph), then carbon fusion changes the chemical composition in about 25% of the mass of this helium core, as we can see from the changes in the elements slightly to the right of the 5 $M/M_\odot$ tick mark in the graph.

We can read off from the plot the elements whose abundances have been enhanced in the inner part of the helium core during the carbon-fusion phase; they are ^{20}Ne, ^{21}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{27}Al, and ^{28}Si. Elements that have been depleted during the C-fusion phase include ^{22}Ne and ^{26}Mg. Of course, ^{12}C has also been depleted since it is the main reactant, and Maeder and Meynet (1987) find that about 4.3% in mass fraction of ^{12}C is used up during this process.

At the end of the C-fusion stage in the 60 $M_\odot$ star, the three most abundant elements are ^{16}O, ^{20}Ne, and ^{25}Mg, and together they account for 97.8% in mass at the center of a 60 $M_\odot$ star. Maeder and Meynet (1987) point out that ^{16}O is the most abundant element at the end of the helium fusion stage, and remains largely unchanged during the carbon fusion stage. Only 2.2% in mass fraction is destroyed through the reaction ^{16}O (^{4}He, γ) ^{20}Ne.

Stellar Remnants

The remnant that is left as an end product of stellar evolution depends on the mass that the star had on the Main Sequence. *In Question 1 on today's worksheet*, you filled out a table on the nature and mass of the remnant. To do so, you used simulated data from the website Star in a Box.

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

You calculated the % mass lost by doing

$$\left(\frac{\text{original mass} - \text{remnant mass}}{\text{original mass}}\right) \times 100$$

The values written in the last column above are consistent with what we know about mass loss from stars. All stars suffer mass loss, but high mass stars lose an overwhelming fraction of their original mass compared to low mass stars. Also of interest is that lower mass stars undergo mass loss mainly in the Asymptotic Giant Branch (AGB) stage, but high mass stars lose mass throughout their lifetime.

White Dwarfs

After lower mass stars like our Sun shed most of their envelope mass while on the AGB and as a planetary nebula, their cores evolve into white dwarfs. These are remarkable objects. Since all nuclear fusion has long ceased in the core of the star, white dwarfs are held up against gravity by electron degeneracy pressure. Recall that electrons obey the Pauli exclusion principle, as a result of which no two electrons can be found in the same quantum state. This sets up a pressure, called degeneracy pressure, to counteract the gravitational force.

White dwarfs compress tremendously large amounts of matter into a very small volume. A rule of thumb is that in a typical white dwarf, the mass of the Sun is crammed into a space the size of the Earth. *In Question 4 on today's worksheet*, you calculated some parameters for Sirius B, the nearest known white dwarf (and companion to Sirius A, the brightest star in the night sky). You found that Sirius B is about 1.8 million times denser than our Sun! The gravitational acceleration on the surface of Sirius B is 4.1×10^6 m/s^2, 410,000 times stronger than the acceleration due to gravity on the Earth's surface. Yet, the surface temperature of Sirius B is over 25,000 K. Over time, white dwarfs will radiate away most of this leftover energy from their parent core, but since they are tiny objects, it will take time.

Neutron Stars

Neutron stars are the remnants of stars with masses larger than about 4 $M_\odot$, or more correctly, stars that suffer enough mass loss that their remnant cores are larger than 1.4 $M_\odot$ (the upper mass limit for a white dwarf, known as the Chandrasekhar Limit), and less than 2-3 $M_\odot$ (the actual upper limit isn't known to better than this spread in values). A neutron star is even denser than a white dwarf star; so high is its gravity that even electron degeneracy pressure cannot resist. The remnant core becomes a ball of neutrons, and it is only the neutron degeneracy pressure that is able to stabilize the remnant core against gravity.

Neutron stars pack the mass of our Sun into an object smaller than the size of Chicago. *In Question 5 on today's worksheet*, you found that density of a neutron star is 3×10^{17} times greater than that of our Sun. The escape velocity from the surface of a neutron star is 1.8×10^8 m/s. This is 60% of the speed of light, implying that neutron stars are general relativistic objects.