

## Chapter 21 Stellar Explosions

### Life After Death for White Dwarfs

Many stars will live out their lives years after year shining without change. Some stars though will change their brightness in a very short amount of time. Many of these stars are called a *nova*. They will brighten very rapidly and then take weeks or months to dim back down. Astronomers have found that these stars are actually a white dwarf. Many of these white dwarfs are *recurrent novae*, or stars that have undergone becoming a nova several times. Why does a faint, dead star brighten like this? There are a number of white dwarfs that are in a binary system. Material from the companion stars falls onto the surface of the white dwarf. Often times the disk of material from the companion will outshine the white dwarf itself. The gas becomes hotter and denser on the surface of the white dwarf until the temperature reaches 10 million K. At this point the hydrogen fuel ignites on the surface of the white dwarf. It brightens up rapidly and then fades away until the stolen hydrogen is gone. When the hydrogen builds up again, the white dwarf goes nova again.

### The End of a High Mass Star

A star with less than  $8 M_{\text{sun}}$  never gets hot enough to burn carbon. The bigger stars can burn elements including carbon, oxygen and others. The rate of burning accelerates as it continues to burn. How will all of this end? Let's see.

### Fusion of Heavy Elements

Figure 21.5 shows a highly evolved high mass star. You can see the numerous layers inside the star. As you move inside, the elements get heavier and heavier until you reach the iron ash in the core. A star that has  $20 M_{\text{sun}}$  will burn hydrogen for 10 million years, helium for 1 million years, carbon for 1000 years, oxygen for a year, and silicon for a week. The iron core grows for less than a day.

### Collapse of the Iron Core

Once the iron starts to form our high mass star is in serious trouble. Elements less massive will join together to form heavier elements (fusion). Elements heavier than iron will absorb energy when they join together. If you split these elements (fission) they will give off energy. Iron is in the middle between these 2 processes. With a substantial amount of iron in the core it effectively extinguishes the nuclear fire. The equilibrium is destroyed forever. Gravity wins! The star will implode on itself. The core temperature will reach 10 billion K and at that temperature the photons have enough energy to split the atoms into heavier elements. This will continue until there are only protons and neutrons left. This is called *photodisintegration*. In less than a second the collapsing core undoes everything that occurred during the last 10 million years. The energy being produced is absorbed by the photons and so the core cools somewhat, causing further instability and collapse. As it continues to collapse, the protons and electrons are squeezed together to form neutrinos and neutrons. This is called *neutronization*. Remember that the neutrino has basically no mass so they pass right through the core and escape into space. There is now nothing to stop the collapse to occur until the neutrons are touching. When this happens, the collapse will stop. This is due to what is called

*neutron degeneracy pressure*. Before the collapse stops, it has overshot its equilibrium point. It compresses, halts and then rebounds. Only about a second elapses from the start of the collapse to the rebound. An enormous shock wave pushes through the star blasting away the outer layers of the star. This is a *core-collapse supernova*.

### Novae and Supernovae

Just like a nova, a supernova will brighten dramatically and then dim slowly. The star that becomes a supernova is called the *progenitor*. A supernova and the nova were not well understood in the early 20<sup>th</sup> century. But there were obvious differences, such as a supernova is a million times brighter. The energy radiated away during the first few months is as much as our Sun will produce in its lifetime. (The energy radiated away in the form of neutrinos may be 100 times greater.) A nova may go off several times in its lifetime, but a supernova may only go off once in its life. This is because the supernova will destroy the star that formed it. There are 2 basic kinds of supernova: *Type I supernova* which shows very little hydrogen in its spectrum and the *Type II supernova* which shows lots of hydrogen in its spectrum.

### Carbon-Detonation Supernovae

The reason for these differences is that there is more than one way for a supernova to occur. We know that for a nova to occur a white dwarf accumulates the matter from a neighbor until it reaches a critical temperature and ignites the surface material. A white dwarf stops contracting due to electron degeneracy pressure. The maximum mass that a white dwarf may have is  $1.4 M_{\text{sun}}$ . This is called the *Chandrasekhar limit*. If the infalling material puts the white dwarf over the limit, gravity overcomes the degeneracy and collapse occurs. The temperature gets hot enough for carbon to start fusing. It occurs simultaneously everywhere in the white dwarf. The white dwarf explodes forming a carbon-detonation supernova. A different idea is that 2 white dwarfs collide for this to happen. Regardless the result is the same. This is a Type I supernova where there is little hydrogen present. The Type II supernova is from a massive star exploding.

### Supernova Remnants

Quite often when a star goes supernova you have something left over. The star does not blow itself up completely. It is called a *supernova remnant*. The fate of the remnant is again due to the mass left over. One of the most famous is found in the Crab Nebula from an exploded star in 1054 AD. For nearly a month this was seen during the day with the Sun out. This was a Type II supernova. It is still expanding at several thousand kilometers per second. There are many other examples of remnants in space. Figure 21.12 shows the Vela supernova remnant. This star exploded around 9000 BC. It is about 500 pc from the Earth. At this distance it must have been as bright as the full moon for months. We have seen hundreds of supernovae in other galaxies in the 20<sup>th</sup> century, but we have not seen any in the Milky Way during this time. The last one was in 1572 which was described by Tycho Brahe and in 1604 as seen by Johannes Kepler. These were both pre-telescopic. Every major galaxy seems to have a supernova every 100 years or so but it has been around 400 years for us. Even at several thousand parsecs the supernova would outshine Venus.

## The Formation of the Elements

Now we will discuss the results of these supernova explosions and what they meant to us as human beings.

### Types of Matter

We currently know of 113 different elements, from the simplest hydrogen to the most complex discovered in 1998 known as ununquadium. All elements exist as *isotopes* which have the same number of protons but different numbers of neutrons. Most of the universe is made up the same 81 naturally occurring elements found on the Earth. There are 10 radioactive elements found on Earth. We have produced 19 man-made radioactive elements which decay into other elements quite rapidly.

### Abundance of Matter

So where did all of these elements come from? We know that 98 %+ of the universe was hydrogen and helium. All of the other elements came from *stellar nucleosynthesis*. These elements were formed in the hearts of stars. The heavy elements are have a much lower abundance than the lighter elements.

### Hydrogen and Helium Burning

Stellar nucleosynthesis begins with the p-p chain.  $4\ ^1\text{H} \rightarrow\ ^4\text{He} + 2\ \text{positrons} + 2\ \text{neutrinos} + \text{energy}$

As the core's hydrogen is depleted, it shuts down, contracts, heats up to 100 million K and ignites the helium.  $3\ (^4\text{He}) \rightarrow\ ^{12}\text{C} + \text{energy}$

### Carbon Burning

At about 600 million K the carbon will ignite.  $^{12}\text{C} + ^{12}\text{C} \rightarrow\ ^{24}\text{Mg} + \text{energy}$

As you can see a new element is produced at each round of burning. At about 200 million K  $^{12}\text{C} + ^4\text{He} \rightarrow\ ^{16}\text{O}$

$^{16}\text{O} + ^{16}\text{O} \rightarrow\ ^{32}\text{S} + \text{energy}$  or  $^{16}\text{O} + 4\text{He} \rightarrow\ ^{20}\text{Ne} + \text{energy}$

It is more likely that new elements are produced by *helium capture* rather than fusion. As a result, elements with masses in multiples of 4 stand out as prominent peaks in our chart of cosmic abundances.

### Iron Formation

At about the time that silicon-28 is being produced in the core a competitive struggle begins in the core. We continue to produce heavier elements in the core, but as this happens heavier elements break down into simpler elements. The breakdown is caused by heat. By now the core temperature is about 3 billion K. this is called *photodisintegration*. The silicon-28 will break down into 7 helium-4's, providing a new source of material to grow bigger elements. Eventually you can have nickel-56 produced, but it is unstable and will become iron-56. It will have the greatest binding energy of all of the elements. This is why iron builds up in the core instead of breaking down.

### Making Elements Beyond Iron

There must have been some other process going on to produce the elements beyond iron. As the helium capture was going on, you also had *neutron capture* occurring. As we add neutrons to iron we don't change the iron atom. We just make an isotope of iron that is heavier than normal iron.  $^{56}\text{Fe} + n \rightarrow ^{57}\text{Fe}$  and so on. Iron-59 is unstable and in about a month it will decay into cobalt-59 which is stable. Cobalt-59 captures a neutron and becomes cobalt-60 which is unstable. It decays into nickel-60 and so on. This process takes about a year each time, so it is called the slow process or *s-process*.

### Making the Heaviest Elements

The s-process explains the synthesis up to and including bismuth-209. The heaviest elements are produced in the rapid process or r-process. This process occurs during the supernova explosion itself. During the blast there are huge numbers of free neutrons to be captured. Even the unstable elements can capture several neutrons before they have time to decay. The heaviest elements are born after their parent star has died. The amount of time for these elements to form is very short, so there is a lack of these elements in the universe.

### The Cycle of Stellar Evolution

All of the stars in the earliest universe were composed of mainly hydrogen and helium. As time has gone on and massive stars have lived and died (blazingly I might add) they have seeded the universe with heavier elements. The youngest stars that are out there contain larger amounts of the heavier material than the older stars do. The universe continues to recycle the material that it produces. So in our universe nothing is ever wasted.