The End of High Mass Stars

1. Supernovae
   1.1 The Process

As massive stars evolve, they go through as many fusion cycles as they are able to – which depends almost entirely on their mass. All of the successive fusion cycles in the core of a massive star (C, Ne, O, Si) results in a core that looks like an onion, since the highest density material would tend to sink towards the center. Only the most massive stars will have as the innermost layer of the core made up of iron, which is the last major fusion product produced during the silicon fusion phase. But what happens when silicon fusion finishes?

The iron will photo-disintegrate once the core becomes hot and dense enough for that to occur. This is really the only time the core of a massive star is degenerate. Since the mass is too massive for the Chandrasekhar limit, it will continue to contract. The temperature will also skyrocket. And that leads to iron “fusion”.

Technically it isn’t iron fusion, but is more like iron “destruction”. What happens is the following:
\[ ^{56}\text{Fe} + \gamma \rightarrow 13 \ ^{4}\text{He} + 4n \]
The iron nuclei breaks down into a lot of helium nuclei, and some neutrons through interactions with very high energy photons. Since this process absorbs energy it is an endothermic reaction. The loss of energy lead to further core collapse, actually the free–fall of the core occurs. The iron core at this time is only about 50 km in size. During the free-fall, the density of the core will increase by a factor of 1 million in about 1 second. The velocity of free-fall collapse at the outer edge of the core is close to 70,000 km/sec (=1/4 speed of light).

And since the rest of the star is pretty spread out at this time, it will take while for the rest of the star to react to the collapse of the relatively small iron core. So the core collapse really just impacts the core in a tiny fraction of a second. As the core collapses in a free-fall the helium nuclei will break down into protons and neutrons via a process similar to the iron photo-disintegration
\[ ^{4}\text{He} + \gamma \rightarrow 2p^+ + 2 n. \]
This process is also endothermic, so even more energy is absorbed which increases the collapse rate.

Eventually you get to the point where the following happens
\[ p^+ + e^- \rightarrow n + \nu \]
Protons get merged into electrons, and release neutrons and neutrinos. The core of the star is now comprised of a neutron gas. The density of this core is around \(10^{18}\) kg/m\(^3\), which is the same density of a proton or neutron. The mass of the core is less than \(1 \ M_\odot\) while the radius is only around 20 km. This is a neutron star, a neutron degenerate object. And just like electron degenerate objects, if you increase the mass, the radius decreases.
We’ll get back to the neutron star later, but we have to keep killing the star.

Once the neutron core forms in the collapse, it is very inert, sort of like an immovable brick wall to anything coming at it. The rest of the star will start to fall on to the core after it has collapsed. This mass motion of material will release a huge amount of energy. The collapse of the star releases about $3 \times 10^{46}$ joules of energy.

Where does the energy go and what form does the energy get converted into?
- About 1/10 goes into nuclear fusion ($2 \times 10^{45}$ J)
- About 1/100 goes into producing light - photons ($3 \times 10^{44}$ J)
- A similar amount goes into blasting off the outer layers ($5 \times 10^{44}$ J)
- And moving them away – kinetic energy ($10^{45}$ J)

If you add up the contributions of the things in the above list, you’ll see it doesn’t add up to the total energy that was produced. The majority of the energy went into something else, mainly into producing and charging up neutrinos! Approximately $10^{57}$ neutrinos are produced in a few seconds during the star’s collapse, and these carry off the majority of the energy of the collapse.

Some of the energy from the explosion in the form of neutrinos and light is transmitted into the material around the core – and it heats this layer up. When the neutrinos are created during the core collapse, the stars outer layers are very dense such that even the neutrinos have a hard time escaping – but only for a short time. There are a lot of neutrinos after all – you can’t block them all.

But neutrinos are slippery critters, and they do get out of the layers since they are able to pass through even very dense layers easily. After the layers become spread out to a distance of about 100 AU, the light from the explosion can travel freely through the material. This happens usually a few hours after the neutrinos have passed through.

There is always a lag between the neutrino escape and the light escape. But it isn’t until the light gets out that you can actually “see” what has happened.

And what has just happened is what is known as a **Supernova** (SN, SNe plural). Technically it is a Type II or core collapse supernovae (or Type II SN for short). The absolute magnitude of this event is around -16. Material from the explosion of the massive star will have an escape velocity close to 30,000 km/s (10% the speed of light).

The high temperatures (in the 10’s of billion K) and densities in the collapse lead to the production of radioactive nickel and other elements. Radioactive nickel decays into cobalt (with a half life of 6.1 days), and cobalt decays into iron (with a half life of 77.7 days). With each major decay event, there is another release of energy. This helps to keep the supernova lit up over a long period of time. You could almost think of these half life time scales like time-release medicine. So well after the initial event there is a re-energizing of the material that is measurable, so the rate of decay of the light isn’t
steady. In some cases the peak of brightness may not even occur immediately after the core collapse. SN1987A had its peak brightness occur 80 days after the initial collapse!

As the supernova cools, the outer ejected material will form into molecules and dust as they cool. This material will also block visible light from the supernova remnant and make it a very bright IR object later in the SN evolution.

It should be mentioned that SN are given very specific names. Generally SN is used to distinguish it from another event. Then the year of the discovery is given, followed by a letter or letter indicating the order of discovery, with the first SN of a year denoted as A. So you had SN2012A, SN2012B, …to SN2012Z, then SN2012aa, SN2012ab, …to SN2012az, then SN2012ba, …and so on. In 2012 this list ended with SN2012ih, though in 2007 we got to SN2007va. I’m not sure what will happen if we go beyond zz.

1.2 SN types

A Type II SN is what has been described so far. What is a Type I supernovae? Well that is a bit more complicated. Basically it is a star without much hydrogen, usually a white dwarf, that explodes. In the standard model for a Type I supernovae, you need a white dwarf that is in a close binary system which allows it to gain mass from the other star. Most white dwarfs are carbon and oxygen rich objects. When they are pushed over the Chandrasekhar limit, the carbon will ignite. Since it is electron degenerate, the ignition is in the form of a thermonuclear runaway.

In this case, since there aren’t all of the outer layers to the star like in a Type II SN progenitor, the energy from the explosion pretty much goes all into the blast. There is not much left behind, but after all there wasn’t that much to begin with. In this case, the luminosity is dominated by the decay of radioactive nickel, so there is a very quick peak in brightness and then a steady decline afterwards. It isn’t known about what is left behind by such an event, it is possible that nothing remains, or that a neutron star is left behind.

There are further subdivisions of distinguish Type I and Type II supernovae based upon spectral features and the possible scenario that caused the explosion. The spectral features provide clues concerning the conditions needed to produce the specific types of SN.

SN Type I Characteristics

⇒ Ia – The most common of the Type I SN and it is seen in all types of galaxies. They have Si II in the spectra, and could be the product of a white dwarf-red giant pair. The “non-standard” model for the Type I is the merger of two white dwarfs – an idea that has recently gained more observational support. In either case, the spectrum is depleted in hydrogen and all you are detecting is the white dwarf material. Type Ia SN are the brightest with \( M_V = -19.5 \) at peak brightness.

⇒ Ib – Found only in spiral galaxies, particularly near star forming regions. Comes from a massive star that has lost all of its outer layers of hydrogen, so when it
becomes a supernovae, it has He in the spectrum. This makes sense, because earlier mass loss phases (like Wolf-Rayet) would have blown off the hydrogen mainly from the outer layers. About 1.5-2 magnitudes fainter than Ia.

- Ic – Very similar to type Ib, also seen only in spiral galaxies. The main difference is that these have also lost pretty much all of their helium along with their hydrogen. There is no H or He in the spectrum, just heavy elements like calcium, oxygen, some silicon, iron, etc. Like Ib, they are 1.5-2 magnitudes fainter than Ia.

In a way, types Ib and Ic are sort of like the basic Type II except that they have lost all or part of their outer layers before the explosion. Type Ib and Ic are also fairly rare since they occur under unusual circumstance or in a rare population of stars (like very massive stars).

SN Type II Characteristics

- IIb – only a little hydrogen is seen in the spectrum, with most of the hydrogen likely lost before the SN even. Helium is dominant in the spectrum. In ways this is very similar to the Type Ib and Ic SN. Possible origin could be from a merger of stars, though it is still being debated.

- IIL – light curve is linear in decline, due to the loss of much of the star’s hydrogen before the supernova, possibly coming from stars with masses between 7-10 \( M_\odot \).

- IIP – light curve has a plateau, caused by the temporary increase in the opacity of the outer layers (which traps light). The longer this happens, the longer the plateau, possibly from stars with 10 \( M_\odot \) or more.

Usually SN Ia are the brightest of all SNe and have an absolute visual magnitude of -19.5 or thereabouts. Their light curve is also very well behaved and they are used as a distance indicator similar to how Cepheids are used (though they are brighter than Cepheids). Most major studies of the expansion of the Universe rely upon Type Ia supernovae since they are so bright and they have very consistent absolute magnitudes. Most major supernovae surveys are currently done to look for these objects in distant galaxies to help calibrate the Hubble Constant.

The early spectra of Type I SNe have no hydrogen in them but are instead full of helium, oxygen, carbon, etc. Type II SNe usually have a large amount of hydrogen present in their early spectra since these stars are still comprised mainly of hydrogen, or there is a lot of hydrogen still in the area of the supernova. As time goes on, the spectra will change appearance and hydrogen features may fade in or out of view depending upon the circumstances of the supernovae event. In any event, the initial spectrum classifies the star as a Type I or II SN.

Below is a flow-chart showing the classification process, which is usually done at maximum brightness.
Any H in the spectrum?  
No  
Any Si II in the spectrum?  
Yes  
Any He in the spectrum?  
No  
Type Ia  
Yes  
Type Ib  
No  
Type Ic  
Does the light curve have a plateau?  
Yes  
Type IIP  
No  
Type III
1.3 Historical Supernovae

A majority of the work that has been done to understand what actually happens with a supernova has occurred in only the past 50 or so years. However supernovae have been observed throughout history – though they were not recognized as such. Usually they are considered short term events, referred to by ancient Chinese astronomers as “guest stars”. There are a few very famous observed SNe over the centuries:

**SN1006** – (April 30) in Lupus (below Orion), observed by Arabic, Chinese, Japanese astronomers. Estimated $V = -9$ or $-10$, which makes it much brighter than Venus in the night sky, and comparable to the brightness of a quarter or gibbous phase moon (though concentrated into a point). The object was visible in the sky for 2 years. A supernova remnant is associated with this event, and currently it is thought to have been a Type Ia.

**SN1054** – (July 4) in Taurus, observed by Arabic, Chinese, Japanese astronomers, peak of $V = -6$, again brighter than Venus. Currently the supernova can be seen as the Crab Nebula (M1). This is a Type II supernova, though not enough information is available to classify it any more precisely.

**SN1572** – (November 6) in Cassiopeia – also referred to as “Tycho’s Supernova”, since he made many observations of its position and was able to show that it was a distant object. Estimated $V = -4$. Thanks to the observations of Tycho and others there is enough data to get a well defined light curve for this object and it is thought to be a type Ia object. Current observations show a well defined remnant.

**SN1604** – (October 9) – in Ophiuchus, this one is often called “Kepler’s supernova”, though he wasn’t the same level of observer as Tycho. It was also fainter than Tycho’s with a peak of only around $V = -2.5$ or $-3$. The well defined light curve indicates that it was a type Ia also and it has a relatively bright remnant.

The previously mentioned supernovae were all visible to the naked eye and were observed before the invention of the telescope. Also those supernovae all occurred in our galaxy, relatively close to us. Since 1604 astronomers have had to look outside of our galaxy to see supernovae – there hasn’t been one observed in the Milky Way since 1604! Frankly I think we are overdue, but that’s just me.

1.4 SN1987A

In spite of the scarcity of nearby supernova, we’ve been very lucky to have some relatively close extragalactic supernovae. The most famous was the one that occurred in the early morning of February 24, 1987. Since it was the first for that year, it is SN1987A. The object was seen to brighten by a factor of 100 in about 3 hours, and it became the first naked eye supernova visible since 1604. Even though you could see it with the naked eye, it did not happen in our galaxy, but in a neighboring galaxy, the Large Magellanic Cloud. And in case you were wondering why you have never heard of
that galaxy before, don’t be confused. You can only see the LMC in the sky if you are very far south of the equator.

Early spectra showed broad, shallow absorption features with velocities ~ 10% speed of light. And there was hydrogen in the spectrum, which indicated this to be a type II SN, actually a type IIP. The spectrum of SN1987A also showed relatively high amounts of helium, which indicate that it lost quite a bit of its hydrogen atmosphere before the supernova event. The temperature of the SN was also measured to change very rapidly (from 14,000 K initially then dropping to 5,500 K in 20 days).

This supernova was important due to the brightness of it, as well as its pre-SN history. This is one of the few instances where observations of the star that became the SN had been made and those could be compared to theoretical models. The star that became SN1987A was actually named Sanduleak -69 202. It was classified as a B3 I, or put simply a hot, blue supergiant. Its apparent magnitude before going “boom” was V=12.4, with a $B-V=0.04$. SN1987A’s light curve was also very unusual with a very late peak in the brightness, making it a type IIP, though the peak came much, much later than one would expect from a typical IIP. For that reason it sometimes considered a “peculiar” type. It is thought that the initial shock wave interacted a great deal with the material that had been lost by the star previously in its life and this kept the luminosity of the system high for an extended time.

One of the early problems with this supernova is that the star that blew up was BLUE. Previously astronomers thought that only RED stars became type II supernovae. It was now the job of stellar theoreticians to explain this unusual circumstance. One way to make a blue star would be if the progenitor actually formed from the merger of two stars. This would have also helped to explain the mass loss features that are seen in the area of the supernova (more on that later).

Regardless of how it formed, it was a biggie - the mass of the progenitor was estimated to be around $20 M_\odot$ with the core mass alone being near $10 M_\odot$. There were also several episodes of significant mass loss from the system prior to the SN, which resulted in the various ring structures currently seen around the supernovae location. The pre-supernova mass loss might be similar to the various mass loss episodes currently observed in eta Car, which is one of the reasons astronomers are so interested in that object. The unusual structure of the progenitor along with the mass loss made the progenitor a denser, bluer star than was predicted by previous models as a SN source. The end result was a fainter than normal supernova.

The light variation of SN1987A is divided into two parts. Early stages in the light output are dominated by shock events – the basic energy of the explosion. The later stage of the light curve is dominated by energy released by radioactive decay. Rapid cooling of the material also caused the ultraviolet output to drop and after that visible light became more dominant. The luminosity then reached a plateau as the temperature of the ejecta continued to drop but the radius of it increased.
Between approximately 110 and 500 days following the SN, the light drops off in a way that matches the radioactive decay of cobalt-56 into iron-56. After 500 days the drop in brightness was much faster than the previous span. There are a couple of causes of this. First, dust started to form around the object, which helped to effectively block the visible light or at least convert it to IR. Also the spread of the material allowed the higher energy photons (gamma-rays) to escape without converting to visible light.

Here’s one little fun fact: this was the first supernova that astronomers were able to directly link with neutrinos. And the neutrinos from SN1987A were observed 3 hours before the light of the supernova was observed. This confirmed the theory of neutrino production with a star’s core collapse. Actually it is sort of weird that at the time of the supernova, both neutrino detectors that caught the neutrinos were on the side of the earth opposite from the supernova. That means the neutrinos travelled thousands of light years, passed through the entire Earth and then were picked up by the detectors. The detectors were able to determine a couple of things from the neutrinos including the energy of the supernova (around $10^{47}$ Joules), and the temperature of the source that formed the neutrinos (around 40 billion K). These conditions are in line with the theory of the formation of neutron stars, so look out for one of those in the spot that still houses SN1987A.

As previously mentioned, there was a great deal of mass loss by the star before it became a supernova. This is seen in the extensive set of ring structures around the supernova. It is believed that while the star was still a red supergiant it had several mass loss episodes – especially around the equator. This probably happened about 20,000 years before the supernova. These mass losses would have resulted in relatively slow moving material leaving the star. Later the star became a blue supergiant. The winds from this type of star tend to be faster than the winds from a red star. It is likely that binary interactions caused the ejected material to be funneled up and down from the equatorial region and resulted in an hour glass shape around the star. Again, all of this happened before it became a SN.

So you had all of this junk from prior mass loss episodes just sitting out there in space, and then “KAPOW” the supernova happened. Energy from the blast (photons) would have heated up the slower, closer equatorial inner ring about 0.75 years after the supernova went off. Since that’s the amount of time for the light to get to the ring from...
the SN, it tells us the ring is 0.75 light years from the supernova. The outer rings (hourglass form) heated up much later.

Today if you check out the inner ring of material, it is again getting hit, though now it is being hit by the blast wave (shock wave) from the explosion and is lighting up again in a wide range of wavelengths (from visible to x-ray). This started in 1996 and the progression of the heating of this material is being monitored by various telescopes. It was predicted that this re-heating of the ring should occur at about this time based upon the velocity of the shockwave from the supernova.

After the shockwave finishes going through the ring, it will eventually fade away – but it may take decades for us to lose sight of it completely. We are also now observing material from the area of the supernova being ejected out as well in the hourglass direction. What is that? More outflow from the supernova? We’re not sure. You’ll just have to keep looking out for more information about this object in the years to come.

2. Supernova Remnants

The material that is ejected by a supernova will remain visible for a significant amount of time, primarily due to the high temperatures involved as well as the heating caused by the remnant (like a neutron star). Generally most supernova remnants will go through various stages of expansion based upon the environment that they are located in and their interaction with the environment. The initial expansion phase is that of free expansion. This is very fast, and unhindered, though the duration of this free-expansion will depend upon the density of the environment, but typically this phase lasts only a couple of hundred years. Very dense star forming regions will slow down the expansion significantly. The second phase is known as the Sedov phase, during which the material will start to slow down by a rate of \( r^{-3/2} \), while it also cools at a rate of \( r^{-3} \) (\( r=\text{distance} \)). The material in the SNR is very unstable and will mix with interstellar material that it ran into. This phase lasts about 10,000 – 20,000 years. The last phase is that of the “snowplow”. This begins once the material cools down to about 10^6 K. This lower temperature allows recombination of electrons with ions, which releases energy quickly – basically the interactions of the energy with the matter decreases and the energy is emitted away from the SNR very efficiently. As energy is lost from the shell of material, it cools down quickly and becomes denser. And of course this process accelerates as more and more energy is given off during the recombination of atoms – which is the snow-plowing of the material….it just piles up pretty quickly as it cools. This phase can last hundreds of thousands of years. Eventually the material from the initially high energy supernova will become part of the surrounding interstellar medium and will probably be incorporated into the next generation of stars.

Typically SNR can be viewed with visible, UV and x-ray telescopes depending upon which of the phases they are in. The expansion of these objects also allow us to age date the supernova event – simply determine the size of the object and its expansion rate and run the clock backwards. This works best for the very young SNR that are still in the
free-expansion phase. There are currently about 300 SNR in our galaxy, and several hundred in the nearby Large and Small Magellanic Cloud galaxies.

Probably one of the best studied SNR is that of the Crab Nebula (M1), which is linked with SN1054. This is a source of all sorts of light – x-rays, gamma-rays, visible, radio, infrared, etc. It is only about 2000 pc from the Earth, which allows careful study of its structure and evolution. Currently it is expanding at a rate of about 1,500 km/s. Most of the luminosity in Crab is currently in the form of synchrotron radiation, and it has a rather impressive energy output rate of about 100,000 $L_\odot$, though much of that is in wavelengths that we can’t see with our eyes.

3. Neutron Stars and Pulsars

What is left over from a supernova? The end product is either a neutron star or a black hole. We’ll cover the easier of these first, the neutron star.

A neutron star is basically a giant ball of neutrons. The only problem is that so many neutrons are not normally found in nature all together in a stable mass. Neutrons don’t like being by themselves – they tend to evaporate when at low densities, so the density of a neutron star must be at a level that will prevent this. In a neutron star the material is best described as being in a neutron degenerate “gas”. Once you get to such a high level of density, you also have such a strong concentration of mass such that you must also consider the impact of relativistic effects, like the warping of space-time. This limits the lower mass range to 0.18 $M_\odot$. Something that small would have a radius of 300 km. Remember, the smaller the mass, the larger the radius for degenerate material, and that means 300 km is a “large” radius for a neutron star. The highest stable mass is 1.11 $M_\odot$ or so (this value is not a certain value), with a corresponding radius is around 15 km. It isn’t too unreasonable to give the mass of most neutron star masses as being around 1 $M_\odot$ - only a few are known to exist in binary systems, and this is a typical mass for the stars in those systems.

Neutron star characteristics –

- Density around $6.65 \times 10^{17}$ kg/m$^3$
- Surface gravity around $2 \times 10^{11}$ g (200 billion times the Earth’s)
- Escape velocity around 64% c
- Maximum mass between 2.2 (for non-rotating) to 2.9 (rotating)
- Surface temperature: ~ few million K
- Magnetic Field = $10^8$ Tesla

While one may think that a neutron star is just a big ball of neutrons, it is more structured that that. Here is the current theory concerning the “structure” of a neutron star:

“Atmosphere” – not in the normal stellar sense since it is much denser than a normal star’s atmosphere. It is seems more like the core of a normal star in terms of temperature and density.

- Only a few cm thick
Densities of about 1 million kg/m$^3$
Comprised of electrons, protons, iron nuclei
Temperature of around 10 million K.

Surface layer (not the crust, that’s deeper)
density close to $10^9$ kg/m$^3$
closely packed solid atomic polymers of iron

Outer crust
About 200 m thick
Similar to a white dwarf, with relativistic degenerate electrons in a neutron lattice

Inner crust
About 1 km thick
Density close to $4.3 \times 10^{14}$ kg/m$^3$
Lattice loses structure further in, becomes a neutron gas

Liquid interior/Superfluid neutrons
About 9 km or so
Superfluids are basically the ultimate lubricant – it has no friction on any level
This occurs when you get to densities greater than $2 \times 10^{17}$ kg/m$^3$

Core?
3 or so km thick
Okay, we’re not sure if this exists, or what it is really like.
When you get to densities $> 3 \times 10^{18}$ kg/m$^3$, things are a bit uncertain and the rules of physics start to break down.
Possibly a quark rich region, or maybe not. At this point we’re not sure if there are limits on the density, since the physics just can’t currently define it very clearly.

Since neutron stars are not much larger than a large asteroid, it is quite unlikely that they would be visible through any normal observations. At least that would be the case if they didn’t have their own beacon system. Most often neutron stars are observed as pulsars. And as you might remember, pulsars don’t pulsate – they rotate. It is just that as part of their rotation, they give off energy that is observed as a pulse of light. So the name is a bit misleading. The vast majority of pulsars (99%) are detected by radio telescopes. This is due to the radiation produced in the form of synchrotron radiation, a non-thermal light caused by the presence of strong magnetic fields. Pulsation/rotation periods can be anywhere from a few seconds down to fractions of a second.

The period of pulsars tend to increase over time, with a decrease in the rate of rotation on the order of $10^{-8}$ second/year. This indicates they spin slower by a second after 100 million years. That’s a pretty good time keeper.

Pulsars have super fast rotation, and very strong magnetic fields (B=100 million tesla, with the Earth’s field = $10^{-5}$ T). How come it is spinning so fast and with such a strong magnetic field?

The high speed is pretty much due to the conservation of angular momentum. This produces the fast rotation via the following relation –
And the magnetic field strength follows a similar relation

\[ B_{\text{final}} = B_{\text{initial}} \left( \frac{R_{\text{initial}}}{R_{\text{final}}} \right)^2 \]  

So as the core of the star collapses to form the neutron star, both the angular momentum/rotation rate and the magnetic field strength increase drastically as the radius decreases. The strong magnetic field is also what will eventually kill the pulsar – it is radiating away energy. The loss of synchrotron energy decreases the kinetic energy of the system (decreases the rotational energy). There is also the effect of having the magnetic field drag through the surrounding interstellar medium which also slows the rotation rate. Like any type of spinning object, it eventually slows down.

The slow down rate can be related to the rate at which it is spinning (pulse frequency) and giving off energy (luminosity) by the following

\[ \frac{dP}{dt} = \frac{5}{8\pi^2} \frac{LP^3}{MR^2} \]  

The relation above indicates that as the pulsar emits more energy \( (L) \), it slows down faster. And as the period gets longer, it will slow down even faster. So even though the slow down rate isn’t really fast, they do eventually get slower and fade away. Pulsars don’t last forever. Around 2000 have been observed in our galaxy, though some estimate that over 30,000 should exist.

Pulsar Characteristics – (general characteristics are just like those of neutron stars)

- 2000 known
- Periods average 0.795 seconds.
- Longest period 11.779 seconds (PSR 1841-0456)
- Shortest period 0.001396 seconds (PSR J1748-2446ad)
- Typical slow down rate of \( 10^{-15} \)

4. Extreme Neutron Stars

While pulsars are fairly well established objects, other strange variations on a pulsar may exist. These include the magnetar and the quark star.

Magnetars may be best described as neutron stars on steroids. They are pretty much like a neutron star, except they have ultra high strength magnetic fields, perhaps up to 100 billion Tesla. The most likely way for this to happen during the collapse of a star’s core is to have a previously strong magnetic field collapse (a large value for \( B \) in equation 7-2 to begin with) so that the strength that is reached is beyond that for a normal neutron star. Another option is that as they formed, they were rotating at a much greater rate than regular stars. This rapid initial rotation can be combined with an effective dynamo in the star to create a much stronger magnetic field. Even though they may have had an initial
high rotation rate, all known magnetars have a very slow rotation rate, usually 5-8 seconds. This is not surprising since objects that are highly magnetic will give off their energy at a much greater rate and slow down faster (as was mentioned above). At this time there are only about 20 or so magnetars known to exist based upon how we classify them by their magnetic field strength.

The surfaces of magnetars are a bit unstable. They are prone to “starquakes”, basically an earthquake in the crust layers of the star. This can release large amounts of x-rays or gamma rays. Soft gamma rays (low energy) are often seen to come from these objects in a periodic manner, and such objects are referred to as soft gamma ray repeaters (SGR). The star quakes can disrupt the emissions of light from the repeaters; in particular any sort of pulses that come from them lose their rhythm. They are also seen to slow down their rotation (their pulses) as a result of the outbursts. It should be mentioned that regular pulsars also have glitches and those glitches may also be due to star quakes on the neutron stars. The star quakes just happen much more frequently in magnetars. At this point there are only 7 confirmed SGRs.

The star quakes can release not only energy but also matter from the star, and this will slow down the rotation rate and decrease the magnetic field strength, so more eruptions result in weaker magnetic fields. The SGR phase should not last very long (10,000 years?), since their slow down rates are very high. It is possible that after that phase, the star will then become an x-ray strong object (called an anomalous x-ray pulsars, AXP). The AXP phase won’t last very long, and the star will continue to weaken and after another 10,000 or so years the neutron star will be too faint/weak/quiet to be picked up with a telescope. There are only 9 confirmed AXPs known to exist.

While there are only about 20 magnetar known (this includes the SGRs and AXPs), there should be many more of them out there, but because they fade relatively “quickly” we can’t detect the majority of them. About one out of every 10 supernova should produce a magnetar.

The magnetic fields of a magnetar are deadly. Remember, these are objects that are only a few km in size. If you were about 1000 km away from one of these you would be killed due to the disruption of water molecules in human flesh by the magnetic field. If that doesn’t kill you then the tidal forces would be pretty nasty as well and would likely rip you apart (more on that effect later).

What is known is that even at great distances these objects can impact the Earth. On December 27, 2004 there was an outburst of gamma rays detected from an object which was labeled as SGR 1806-20. The corresponding absolute magnitude of the gamma-ray light was -29. That’s right, -29! Fortunately this object is located quite a distance from us, practically on the other side of the galaxy (15,000 pc from us). Even at that great distance the energy of this outburst SGR’s outburst interacted with our ionosphere and ionized our atmosphere enough to cause it to briefly expand.
If magnetars weren’t unusual enough, then we also have to consider the existence of quark stars, which are also called strange stars. This is just a star that is composed of quark or strange matter. The basic upshot is that it would be ultra-ultra-super-degenerate material.

You can get a quark star if you put the neutrons in a neutron star under enough pressure so that they break down into the individual quarks (there are 3 quarks per neutron). So rather than having the quarks bound together to make a neutron or proton, you have them bound together to make an entire star.

To get a neutron star to do this you really need to push it beyond the normal limits – take a rather massive neutron star (somewhere between 1.5 – 1.8 $M_\odot$), spin it really fast and that will cause the neutrons to break down. The resulting explosion (a quark nova) should be much more powerful than a supernova. The steps leading to the quark nova should start relatively soon after the creation of the neutron star itself from a regular supernova, perhaps only a few hours after the supernova. During this time the neutrons in the center of the neutron star would start to break down into quarks and this process would increase over time. It may take 1000 years before the star has enough free quarks to have a quark nova. It is also possible that quark nova explosions are currently being observed by astronomers as some of the strong gamma-ray bursts, though of course they may not be able to distinguish these events as being from this particular process.

How do you identify a quark star? It would be an object that is much denser than a neutron star. A few candidate objects are known to exist that might be quark stars based upon their mass and radius values.

One of these is RX J1856.5-3754. This object has a radius that is only 1.9-4.1 km, much too small for a neutron star. This is actually an interesting star since it is also a fairly close neutron star (or quark star), only 450 light years away (150 pc). The temperature of this thing is around 700,000 K.

Another is 3C58 which is a pulsar associated with a supernova event from 1181 AD. The surface temperature for this object is too cool for such a young neutron star. The low temperature might be explained if the object lost energy during its formation into a quark star, since that process would have led to a significant energy loss and corresponding temperature drop.

Finally there is the recently discovered XTE J1739-285. This beast apparently has a rotation rate of 1122 Hz (or 1122 rotations per second). Because it is not a steady light source its nature was not immediately known. It is also in a binary system where it accretes matter and that will flare up occasionally. For this thing to be spinning so fast and not to be ripped apart would require densities greater than that thought to exist in a regular neutron star – quark/strange star densities would be needed. But there is quite a bit of uncertainty about its rotation rate, and until that is resolved, it is not a slam-dunk for a quark/strange star.
These results may be interesting, but they are not conclusive. There is still a great deal of debate about the accuracy of the various measurements for these objects. New observations are needed to determine if these objects really are quark stars.

5. More on Gamma Ray Sources

Gamma rays have not been observed with a great deal of precision for very long due to their elusive nature. It has taken some time to understand the various sources that produce gamma rays and a few of these are from exotic stellar sources. One already mentioned is the soft gamma ray repeaters (SGRs). The other notable type of source is the Gamma Ray Burster (GRB). A typical GRB may release up to $10^{45}$ Joules of energy though they can go as high as $10^{47}$ Joules of energy.

General GRBs may not be produced by only one type of object. They can be associated with neutron stars or magnetars, or even black holes. While the amount of energy given off by a gamma-ray burst may be stronger and more powerful than anything we can see with our eyes, there is usually so much energy associated with the outburst that some of the energy also comes out at visible and other wavelengths. Typically about one GRB per day is detected with energies between 1 keV to many GeV, and durations between 0.01 to 1000 seconds during the burst. Some GRBs can have a very rapid rise in brightness, and then a very slow decay in brightness, which allows enough time for ground based telescopes to scan the sky for radio or optical sources that might accompany the GRB. Oddly enough GRBs were originally detected accidentally by scientists during the Cold War who were looking for signs of nuclear testing by other countries.

It is simplest to classify GRBs into two classes, those of short duration, and those of long duration. While this division may seem rather arbitrary, there are significant differences in the burst characteristics. In general,

Short-Hard GRB:
  Duration of 2 seconds or less (that’s the “short” part)
  Only one peak usually
  Dominated by high energy photons (that’s the “hard” part)

Long-Soft GRB:
  Duration of bursts longer than 2 seconds (which makes them “long”)
  Multiple peaks during outburst
  Dominated by lower energy photons (and “soft”)

Theories about how these different bursts are produced are still incomplete but there could be some sort of relationship such as between the long-soft gamma-ray sources and the formation of black holes.

GRB 980425 occurred in April of 1998 with an energy that was lower than that of typical GRBs – only $8 \times 10^{40}$ J. The duration of the GRB was about 30 seconds. This was followed about 3 days later by the detection of a supernova, SN1998bw, which was
classified as a type Ib or Ic SN due to the lack of hydrogen and Si II features in its spectrum. While the GRB was below normal levels, the SN was above normal in its energy output. This all happened in a galaxy about 40 Mpc away. The extremely bright nature of this supernova caused it to be classed as a hypernova. Models of hypernovae result in final masses which would have likely resulted in the production of a black hole rather than a neutron star. In addition to GRB 980425/SN1998bw, other links have been made between GRBs and SN, most notably GRB 030329/SN2003dh and GRB 031203/SN2003lw.

The formation of a GRB-SNe (hypernova) is also referred to as a collapsar, which is basically calling it a collapsing star. In this scenario a massive star reaches the end of its life and collapses to form a black hole. The key here is that the mass has to be too large for a neutron star and that there is rotation. The rotation of the forming black hole will cause the formation of a disk of debris around the black hole which will become superheated. Remember, all of this is occurring in the core of the star, under layers, and layers of material in a massive star. The super hot debris disk will become electrically charged and the resulting rotation produces a magnetic field that creates perpendicular relativistic jets. These jets will blast through (eat through) the outer layers of the star and this interaction of the jet with the outer layers results in a slow outburst of gamma-rays.

The short-hard GRB may be the result of cosmic collisions such as the collision of two neutron stars, or of a neutron star getting swallowed by a black hole. The merger of two stars is a much shorter event then the hypernovae collapse model for the longer duration GRBs, so this could be one way of explaining the shorter, but highly energetic GRBs.

The supernova light curves shown here include 1998bw, but the brightest is SN2006gy, which was likely a type II supernova, but one in which the gamma rays produced in the core led to its collapse. This type of supernova is quite rare, but is another indication that
there are strange objects out there that we have yet to understand. The size of the star that may have produced SN2006gy is uncertain, but could be as large as $140 \ M_\odot$.

Gamma-rays are the most deadly form of light, but can these extreme outbursts actually hurt us? Fortunately most GRBs are from sources that are very far away. However if they were a bit closer, we would be in big trouble. A relatively nearby GRB would be deadly, since it would cause the destruction of the ozone layer due to the heating of our atmosphere. Recently some astronomers have proposed that the Silurian/Ordovician mass extinction event (450 million years ago) may have resulted from a GRB. The destruction of the ozone layer would leave most land-based life forms without any protection from the UV light from the Sun. Marine life would be better off, but the mass destruction of creatures on land would severely disrupt the food chain. While this may be a possible scenario for this extinction even, at this point it is only just that – an idea. In general the scarcity of strong, nearby GRBs makes it unlikely that we have to worry about these events too much.