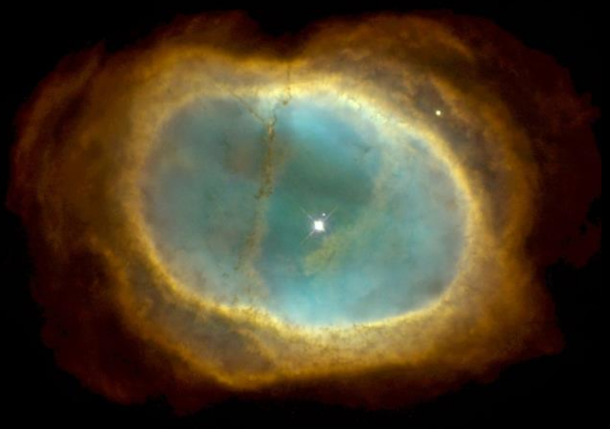
Upcoming Astronomy-themed Talks and Events

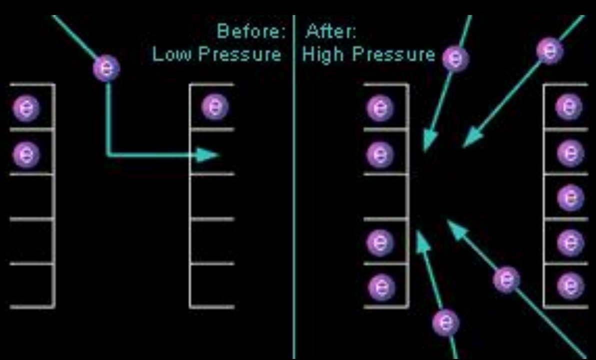
Thursday, 2/11, 3:45-5:00p Astronomy Colloquium – Phys-Astr A102 – Jason Dexter (UC Boulder) – “Imaging black holes: beyond the shadow”.

We focused last time on the final stages of the lives of low-mass and high-mass stars, including the formation of key elements to life – carbon in particular from the planetary nebulae of low-mass stars, and heavier elements like iron (and gold!) from the cloud of debris produced in the supernovae of high-mass stars.

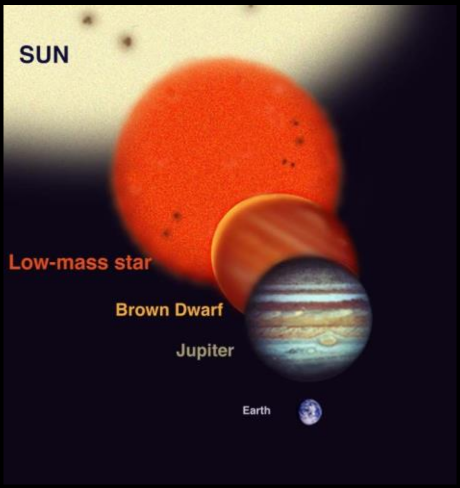
Planetary Nebulae NGC5189 (top), and the remnant from a supernova in Cassiopeia (bottom).



But what about those leftover carbon-rich and neutron-rich ‘cores’? What determines the fate of a stellar core that’s exhausted all its nuclear fuel? We’ll start there by looking at those stars that never even make it to the Main Sequence – so-called “Brown Dwarfs”…

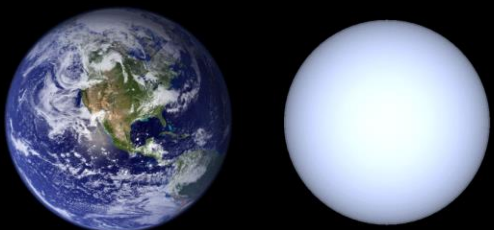


Recall that in the dense conditions at the cores of Brown Dwarfs, free electrons find very few available energy states that they can occupy – and since no two electrons can occupy the same energy states at once, electrons are forced into higher and higher energy states, generating a pressure called ***degeneracy pressure***.



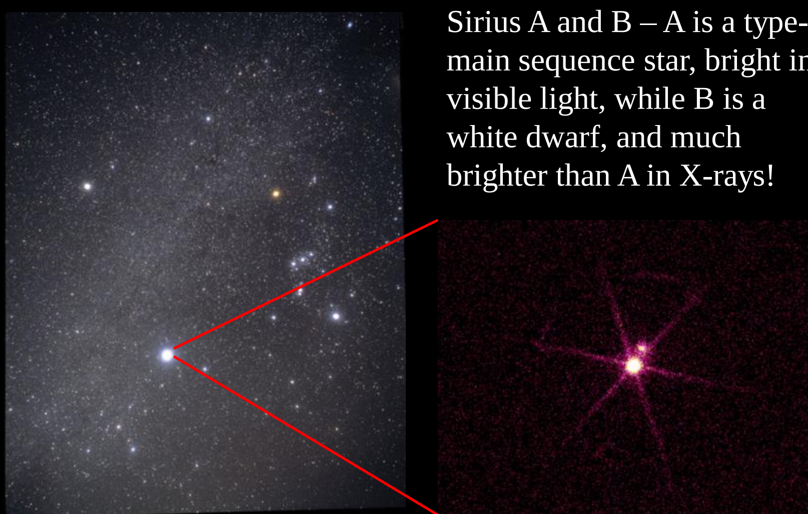
Relative sizes of the Sun, an M main sequence star, a brown dwarf, and Jupiter

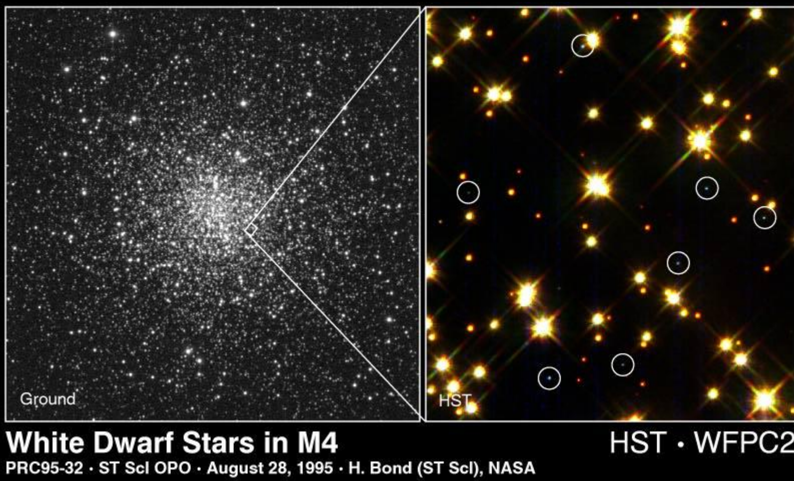
This pressure counters the crushing force of gravity, and keeps Brown Dwarfs stable against further compression, much like the cores of main sequence stars are stabilized by fusion. But since degeneracy pressure doesn't decay appreciably with time, or require input fuel (like fusion does) – objects supported by degeneracy pressure can maintain gravitational equilibrium for effectively unlimited amounts of time.

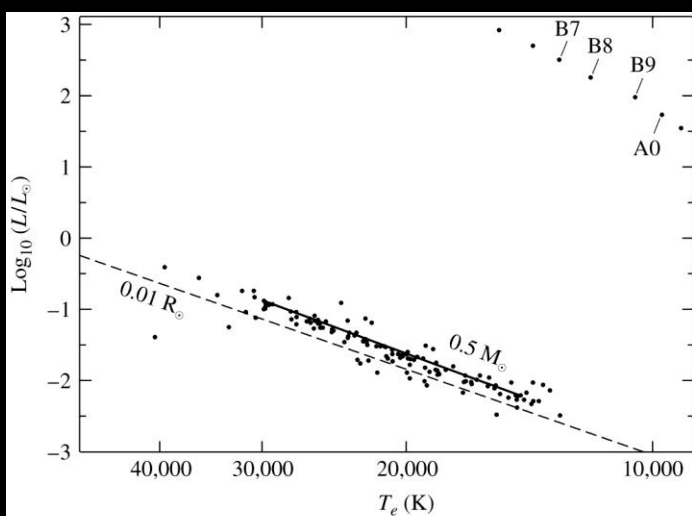


Degeneracy pressure is the support for the leftover cores of stars as well – with details set by the initial mass of the "dying" star. For example, ***white dwarfs*** are what we call the stable, primarily carbon cores (oxygen and helium are often in the mix too) left over after a low mass star's death. These are very dense, (~10^6 g cm^{-3}), and ***very*** hot (> 10^7 K) on their surfaces when they first emerge from their planetary nebulae.

Sirius A and B – A is a type-A main sequence star, bright in visible light, while B is a white dwarf, and much brighter than A in X-rays!

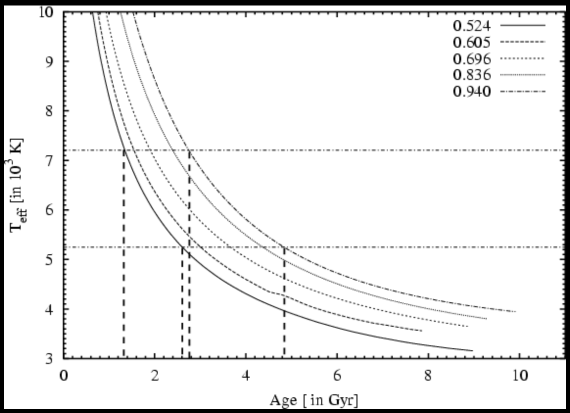






The location of WDs on an H-R diagram – note the very high temperatures, yet very low luminosities.

Models of the time evolution of the surface temperatures of white dwarfs. The different curves represent different initial masses (key in upper right, units of solar masses).



White dwarfs cool off over billions of years, however, steadily radiating away their remaining 'heat', like a dying ember of (very very dense!) coal in a (very very hot!) fire.

Pressure from gravity

Pressure from 'degenerate' electrons

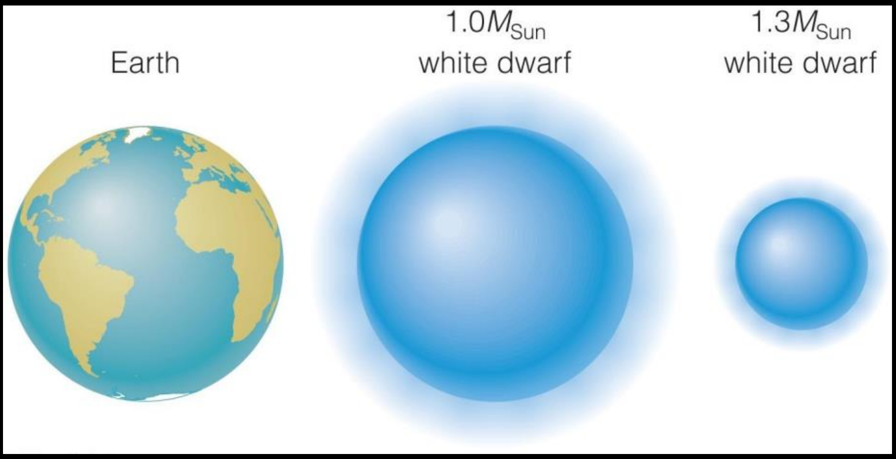
$$\frac{2}{3}\pi G\rho^2 R_{wd}^2 = \frac{\left(3\pi^2\right)^{2/3}}{5}\frac{\hbar^2}{m_e}\left[\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{5/3}$$

$$R_{wd}M_{wd}^{1/3} \approx \frac{\left(18\pi\right)^{2/3}}{10}\frac{\hbar^2}{Gm_e}\left[\left(\frac{Z}{A}\right)\frac{1}{m_H}\right]^{5/3}$$

$$M_{wd}V_{wd} = \text{Constant}$$

Please don't fret the math here – it won't be on a quiz! I just wanted to make the point in the 3rd line!

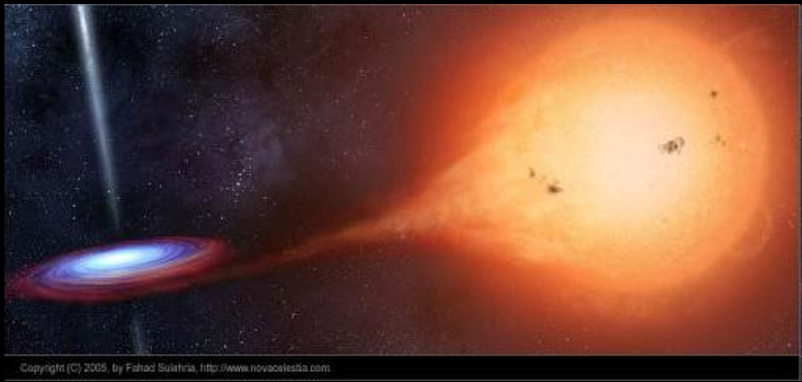
Since white dwarfs are stable in size, their electron degeneracy pressure must be equal to the gravitational pressure they face. We can use this fact to derive an expression for the radius of a white dwarf, and it reveals something very interesting – the product of the mass and the volume of a white dwarf is a constant. So more massive white dwarfs must be ***smaller*** than less massive ones!



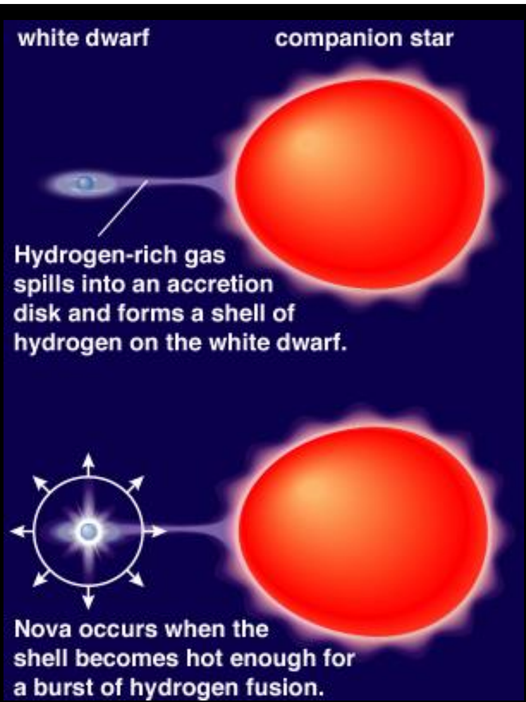
This is quite different from what we've been seeing so far – more massive stars and planets have been bigger in size – but with degenerate objects like white dwarfs, the opposite is true!

How small can a white dwarf get? Well, once the mass reaches 1.4 M_{Sun} (the ***Chandrasehkar Limit***) the electrons – forced into smaller and smaller volumes – have very large energies and velocities approaching the speed of light. At this point, the degeneracy pressure becomes unable to resist the force of gravity – no object larger than around 1.4 M_{Sun} can *possibly* be self-supported via electron degeneracy pressure.

Subrahmanyan Chandrasekhar, who worked this out when he was 20, on his way to Cambridge for Graduate School

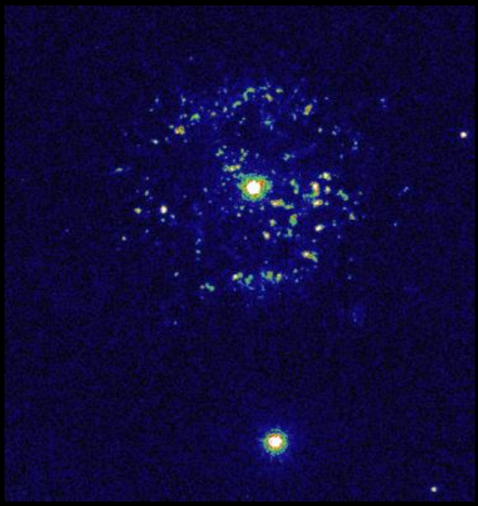


Of course, White Dwarfs *don't* exceed this mass when they are formed, but if a white dwarf is in a close binary – and many stars are – it can accrete matter from its companion when that (lower-mass star) finally begins to become a red giant. Gas from the companion is stripped away in a stream, forming an ***accretion disk*** as it falls onto the white dwarf.

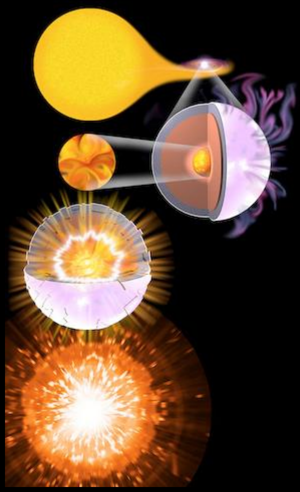


By the time the falling hydrogen reaches the white dwarf's surface it is ***very*** hot, and once sufficient pressure builds up, it can fuse explosively, causing the disk to brighten by a factor of 10,000 in just a few days. This event is called a ***nova***.

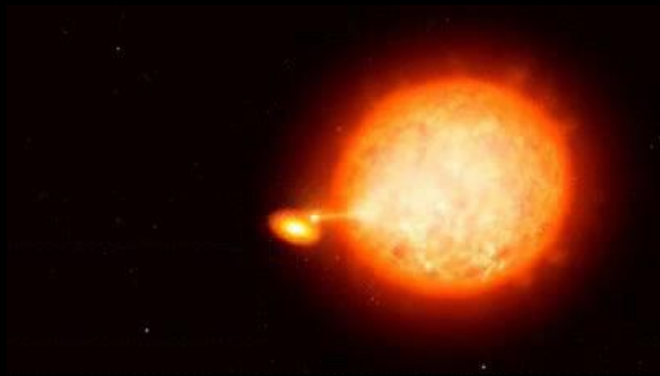
But very little mass – less than 0.0001 M_{Sun} – is consumed during a nova, so the explosion doesn't disrupt the binary, or the white dwarf itself, and the accretion process just continues on. Ignition of the infalling gas in these nova events can recur again and again, with periods ranging from months to many years.



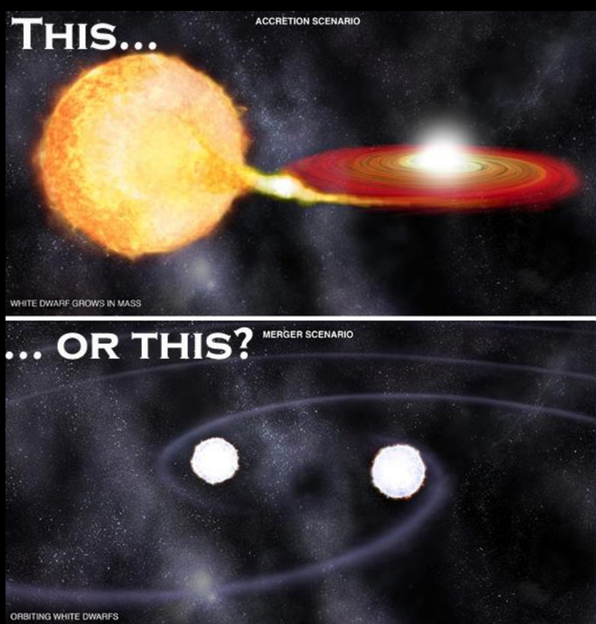
HST image of nova *T Pyxidis* in 2011; it had other outbursts in 1890, 1902, 1920, 1944, and 1966.



However, if by *any* means accretion does bring the mass of a white dwarf *above* the Chandrasekhar limit, electron degeneracy can no longer support the star, and so it starts to collapses. This collapse raises the temperature enough to start carbon fusion in a sudden, explosive burst that rips the white dwarf utterly and completely apart.

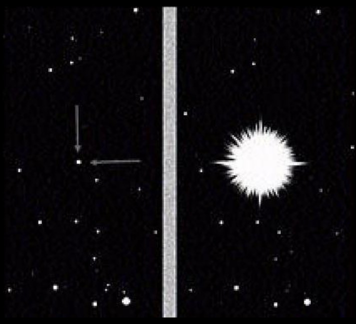


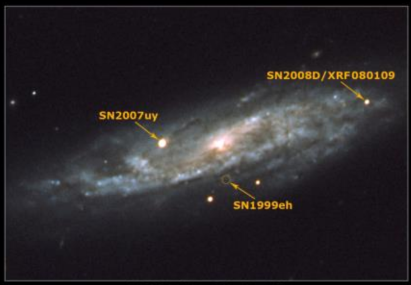
Such an exploding white dwarf is called a ***white dwarf supernova*** or ***Type Ia supernova***. Please note – this is ***not*** the same thing as the supernova phenomenon that happens at the end of a *high-mass* star's life (that's a ***Type II supernova***).



How this occurs is not clearly understood – can slow accretion build up the white dwarf's mass without igniting fusion?

Or is something more exotic required? The answer remains uncertain…





NGC 2770
Supernova factory

Regardless of their origin, these are very bright phenomena – a white dwarf supernova reaches a peak absolute brightness of over 10 billion Suns, and stays millions of times brighter than the Sun for many days after the event!

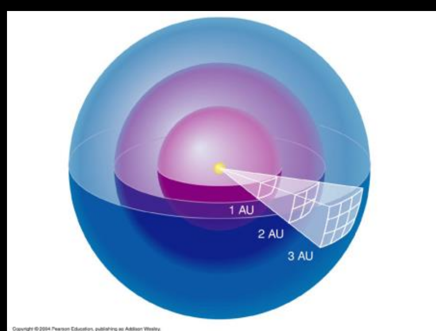
Now, as an aside – notice that all white dwarf supernovae happen to objects of basically the same mass: the Chandrasekhar limit.

Because of this inherent similarity, all white dwarf supernovae release about the *same amount of energy* when they explode. Since they all release about the same amount of energy, they all attain about the same peak luminosity.

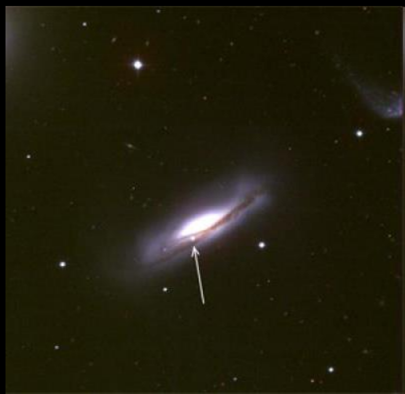
Every Type Ia supernova should be caused by a ~1.4 M_{Sun} white dwarf exploding.

Think about that… if all of these white-dwarf supernovae hit the same peak ***luminosity***, then determining the true luminosity of just one would tell you the luminosity of every white-dwarf supernova that happens (and there are many dozens observed every year!).

And recall the apparent brightness formula – if we know the luminosity of every white dwarf supernova – if they are true "standard candles" – then we could easily estimate the distance to each one that happens just by measuring its apparent brightness!



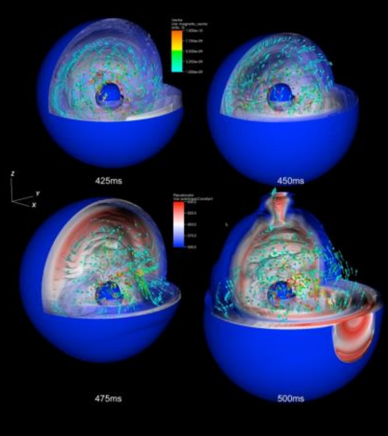
$$B = \frac{L}{4\pi d^2} \Rightarrow d_L = \sqrt{\frac{L}{4\pi B}}$$



A Type Ia Supernova in NGC3190

And it gets even better! Since white dwarf supernovae are very bright – more than 10 billion times brighter than the sun! – we can see them from ***billions*** of light years away! In fact, they're one of the best current tools we have for measuring distances to things outside of our galaxy, and will play a key role in our discussion of the larger universe later in the course.

For now, though, let's turn our attention to "Neutron Stars".

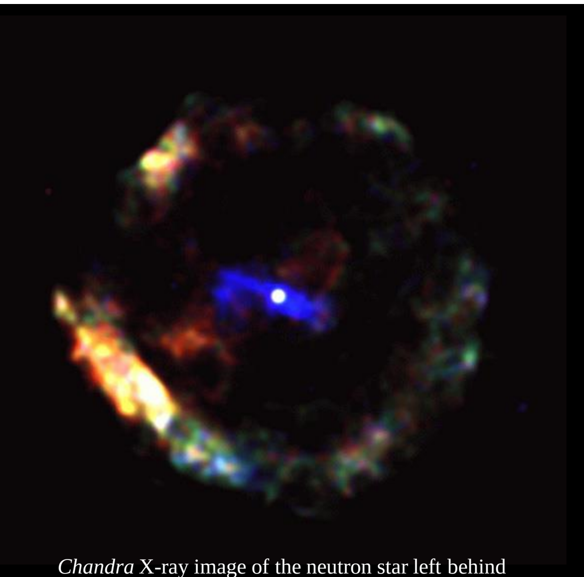


Model of the first half-second of a core-collapse supernova event.

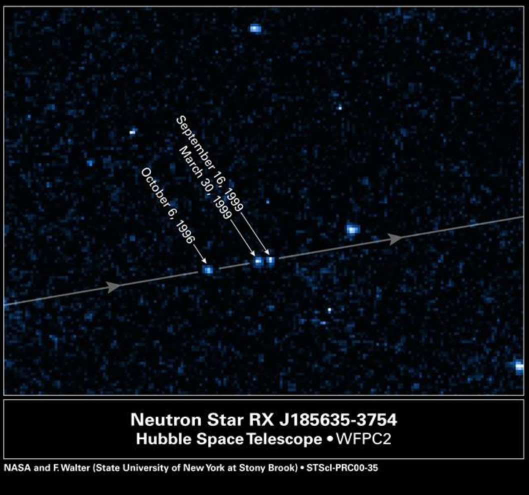
These objects are the leftover cores from the supernovae of high-mass stars ("Type II Supernovae"). Such explosions are triggered by the collapse of the electron degenerate, primarily Fe cores as they reach ~ 1.4 M_{Sun}. They stop collapsing with onset of ***neutron degeneracy pressure*** – similar to electron degeneracy pressure, but from fast-moving neutrons instead.

When these "neutron" stars are first formed, they have surface temperatures in excess of 10^{11}K.

At such high temperatures, they emit large amounts of high-energy radiation, such as UV and X-Rays.



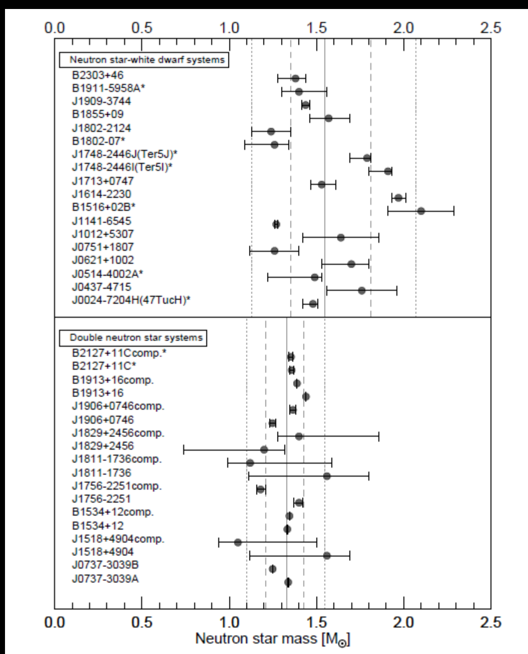
Chandra X-ray image of the neutron star left behind by a supernova observed in A.D. 386. The remnant is known as G11.2−0.3.



A single neutron star as imaged in the UV by the Hubble Space Telescope. Note how quickly the neutron star is moving – which is not unusual with these objects. They can acquire quite a significant velocity 'kick' during the supernova event!

$$M_{NS}V_{NS} \approx \text{Constant}$$

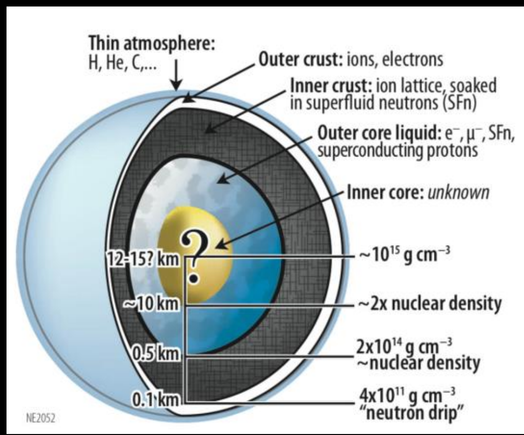
Neutron stars are quite small – less than 20km across – and like white dwarfs the product of their mass and volume is a constant. This means more massive neutron stars are smaller, and again there must be an upper limit to the amount of mass that could possibly be supported by neutron degeneracy pressure. For a non-rotating neutron star this would equal about 2.2 M_{Sun}, while for rotating neutron stars (the ones we find in nature!) it could reach ~ 2.9 M_{Sun}.



However, most neutron stars aren't nearly that massive. The neutron stars we see typically have masses between 1.3 and 1.5 Solar masses – just what you might expect, given how they formed!

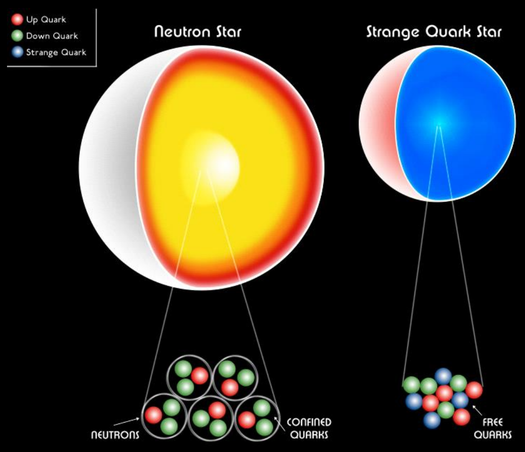
Kiziltan, et al., 2013

Neutron stars are very, very dense (> 10^{20}g cm^{-3}) – 1.5 times the mass of the Sun, but with a diameter of only 10-20 km! The resulting surface conditions are truly extraordinary – the acceleration due to gravity approaches 10^{11} times that of the Earth, and the escape velocities can exceed 64% of the speed of light!



Schematic of a Neutron Star's interior – notice that giant question mark!

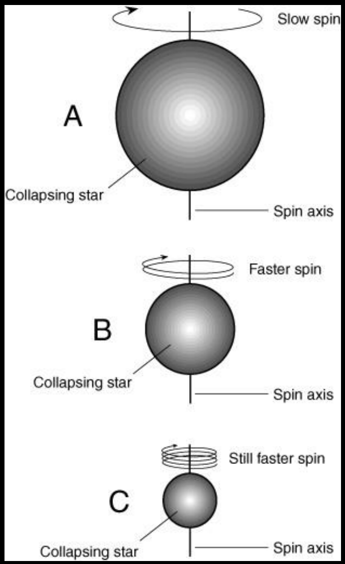
Determining the physics of how objects like this behave is far from trivial, and – at present – poorly constrained. The NICER experiment, installed last year aboard the International Space Station, is currently studying neutron stars to answer some of these questions.

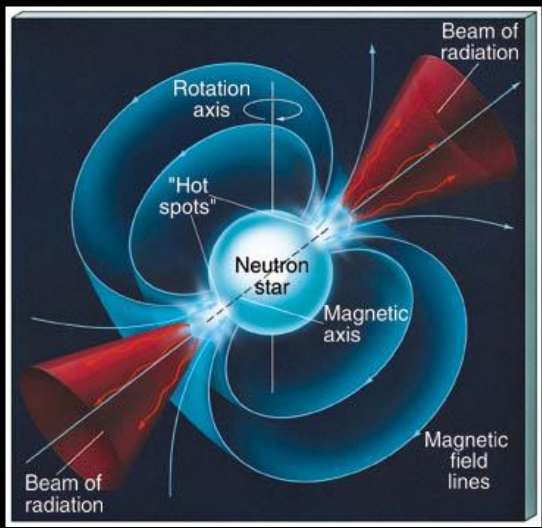


Many mysteries remain – some observations suggest that many neutron stars are smaller than they could possibly be – suggesting that their interiors are composed of very unusual forms of matter, perhaps even from free quarks – a ***strange*** star indeed!

Neutron stars are also observed to rotate – ***very*** rapidly. During the collapse that forms them, conservation of angular momentum requires them to rotate more and more rapidly as they shrink in radius.

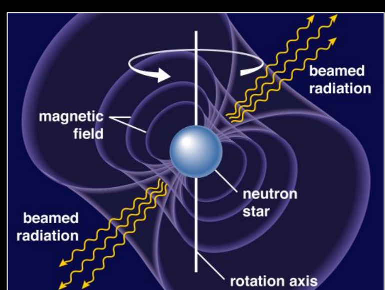
Neutron stars end up with rotational periods that range from a few seconds to a few ***milliseconds*** – making them amongst the fastest spinning objects in the Universe!



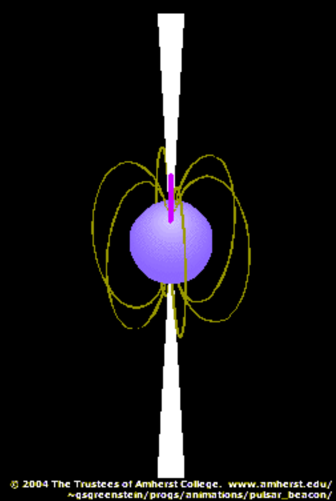


Schematic of a Neutron Star, showing Magnetic Field orientation.

Like their rotation, their magnetic fields are intensified during the collapse. Neutron stars end up with surface magnetic fields some 10^{13} times stronger than Earth's. Electrons trapped in these fields are accelerated, and produce a unique type of radiation called ***synchrotron*** radiation.

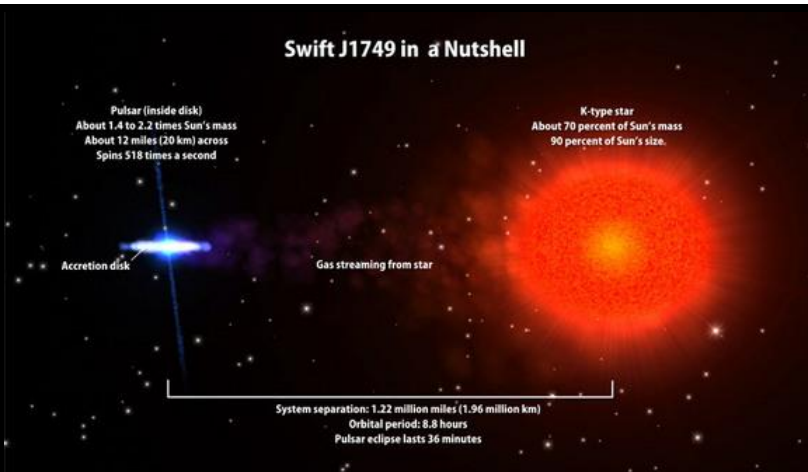


As a neutron star rotates, the beams of synchrotron radiation along its magnetic axis sweep across the sky. If you happen to be aligned so that the beams periodically shine right at you – or illuminate something else you can see – you observe a "pulse" of radiation from the neutron star.

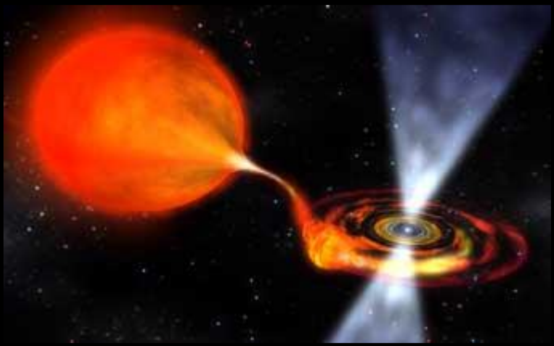


Animated X-ray images of the Crab Pulsar, by CHANDRA

The rotating magnetic fields also transfer kinetic energy from the neutron star into nearby material (primarily gas and dust from the supernova), producing the shock features and the radiation emitted by the nebular material surrounding the pulsar.



Like White Dwarfs, Neutron stars often have close companions which they can cannibalize during the lower-mass star's Red Giant phase. The transfer of this material can 'spin up' the Neutron Star, resulting in so-called "millisecond pulsars".



But notice that once again we're piling material onto a degenerate object – and we saw how that could fail catastrophically for white dwarfs. What happens if so much material accretes onto the Neutron Star that its self-gravity exceeds the strength of its neutron degeneracy pressure? What becomes of a Neutron Star if it's forced to collapse?

We'll pick up the story there next time, under the most extreme physical conditions imaginable and with the most bizarre of all astronomical objects – a Black Hole!