

Three Announcements

- *Before the lecture:*
 - Please turn in your homework#3 RIGHT NOW.
 - Don't forget to staple it!
- *After the lecture:*
 - Please pick up your quiz#3 as you leave the lecture hall.
- **Remember, the mid-term is not next week, but the following week!**
 - If you did not pick up the review questions for the mid-term, please see Elizabeth Jefferey (TA) for a copy.

Lecture 14

The Bizarre Stellar Graveyard

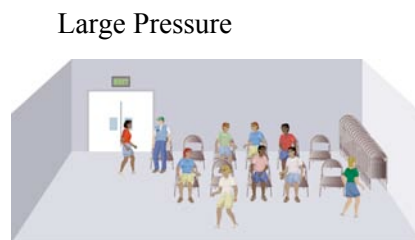
- Fate of Stars -
Reading: Chapter 18

Weird Q.M.: Degeneracy Pressure

- Two Fermions (particles having half-integer spins) cannot occupy the same space with the same energy/spin state.
- For **very** dense solids, the electrons cannot be in their ground states, they become very energetic---approaching the speed of light.
 - the electrons play a game of musical chairs
- The pressure holding up the star no longer depends on temperature.



Less Pressure



Large Pressure

Degenerate Objects: Review

- In the leftover core of a dead star...
 - degeneracy pressure supports the star against the crush of gravity:
 - Gravity vs Thermal Pressure → Gravity vs Degenerate Pressure.
- A degenerate star which is supported by:
 - electron degeneracy pressure is called a **white dwarf**
 - neutron degeneracy pressure is called a **neutron star**
- If the remnant core is so massive that the force of gravity is greater than neutron degeneracy pressure...
 - the star collapses out of existence and is called a **black hole**

Degenerate Core Leftover: Low Mass Stars

- The central star of a Planetary Nebula heats up as it collapses.



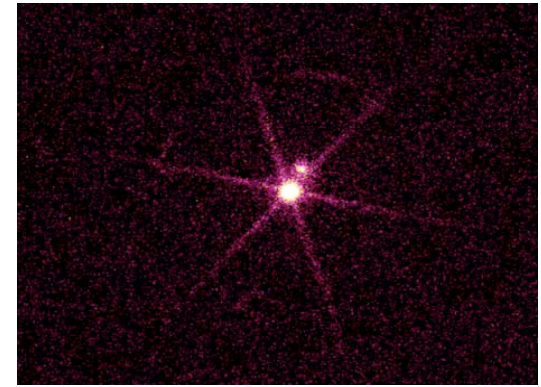
- The star has insufficient mass to get hot enough to fuse Carbon. Collapse, collapse, collapse...until
- Gravity is finally stopped by the force of **electron degeneracy pressure**.
- The star is now stable.....

White Dwarf
White Dwarf

White Dwarfs: Fading Away

Sirius B is the closest white dwarf to us

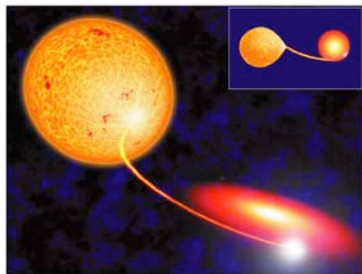
- They generate no *new* energy.
- They slide down the HR-diagram as they radiate their heat into space, getting cooler and fainter.
- They are very dense; 0.5 - 1.4 M_{\odot} packed into a sphere the size of the Earth!



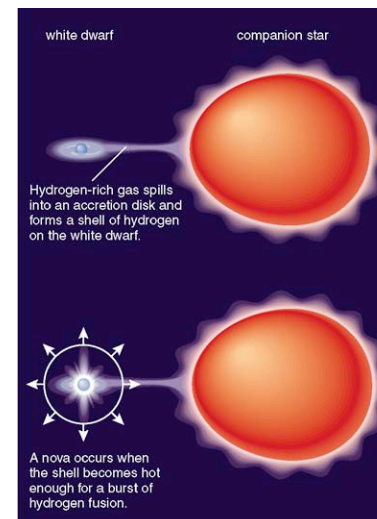
Sirius A + B in X-rays

Novae: A Lucky White Dwarf

- A binary white dwarf can get **brighter** sometimes.
 - Gas is supplied by a companion star, and the WD acquires more mass \rightarrow more gravitational energy \rightarrow heat up \rightarrow Fusion.
- They typically increase in brightness from 5 to 10 magnitudes for a few days, then fade.
- Some increase by up to 20 magnitudes and last for weeks, then fade slowly.



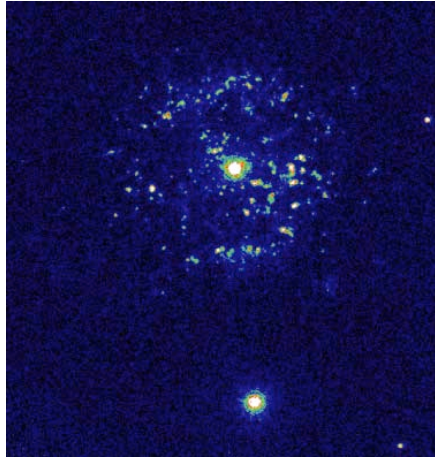
Novae



- Though this shell contains a tiny amount of mass ($0.0001 M_{\odot}$)...
- it can cause the white dwarf to brighten by 10 magnitudes (10,000 times) in a few days.

Novae

- Because so little mass is blown off during a nova, the explosion does not disrupt the binary system.
- Ignition of the infalling Hydrogen can recur again with periods ranging from months to thousands of years.

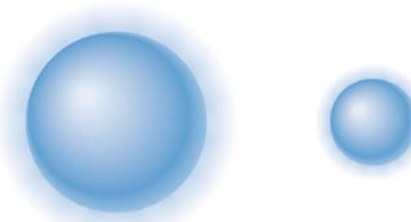


the nova *T Pyxidis*
viewed by Hubble Space Telescope

White Dwarfs: Size

- Degenerate matter obeys different laws of physics.
- The more mass the star has, the *smaller* the star becomes!
 - increased gravity makes the star denser
 - greater density increases degeneracy pressure to balance gravity

1.0 M_{Sun} white dwarf 1.3 M_{Sun} white dwarf



Limit on White Dwarf Mass

- Chandra formulated the laws of degenerate matter.
 - for this he won the Nobel Prize in Physics
- He also predicted that gravity will overcome the pressure of electron degeneracy if a white dwarf has a mass $> 1.4 M_{\odot}$
 - energetic electrons, which cause this pressure, reach the speed of light



Subrahmanyan Chandrasekhar
(1910-1995)

Chandrasekhar Limit

White Dwarf Supernovae: Oops, that's too much!

- If accretion brings the mass of a white dwarf above the Chandrasekhar limit, electron degeneracy can no longer support the star.
 - **TOO MUCH MASS!** the white dwarf collapses
- The collapse raises the core temperature and runaway carbon fusion begins, which ultimately leads to an explosion of the star.
- Such an exploding white dwarf is called a **white dwarf supernova**.

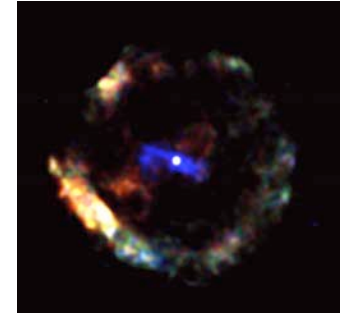
White Dwarf Supernovae: A standard candle

- A remarkable feature of white dwarf supernovae
 - They have more or less the same luminosity because they have more or less the same mass (~1.4 times the mass of the Sun, Chandrasekhar limit).
 - Inverse-square Law of the apparent brightness tells us **distances** to white dwarfs:
 - $(\text{Apparent Brightness}) = (\text{Luminosity})/(\text{Distance})^2$
 - A very important tool which has led to the discovery of **Dark Energy** (the Discovery of the Year for 1998)



Massive Star Supernovae

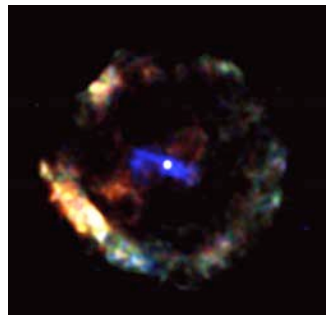
- Intermediate/High mass stars do not form white dwarfs:
 - Rather, they prefer to die by explosion.
 - Their high masses easily overcome electron degeneracy pressure.



Neutron Stars: After Explosion

- ...are the leftover cores from supernova explosions.
- If the core $< 3 M_{\odot}$, it will stop collapsing and be held up by neutron degeneracy pressure. (last resistance!)
- Neutron stars are very dense (10^{12} g/cm^3)
 - **$1.5 M_{\odot}$ with a diameter of 10 to 20 km**
- They rotate very rapidly: Period = 0.03 to 4 sec

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.

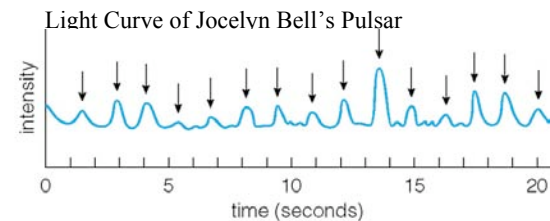


Pulsars

- In 1967, graduate student Jocelyn Bell and her advisor Anthony Hewish accidentally discovered a radio source in *Vulpecula*.
 - Hewish has received Nobel Prize for Physics in 1974
- It was a sharp pulse which recurred every 1.3 sec.
- They determined it was 300 pc away.
- They called it a **pulsar**, but what was it?
 - A beacon from aliens living on other planets?

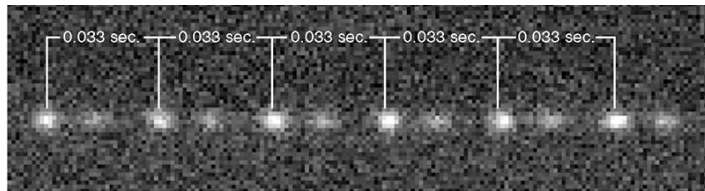


Jocelyn Bell

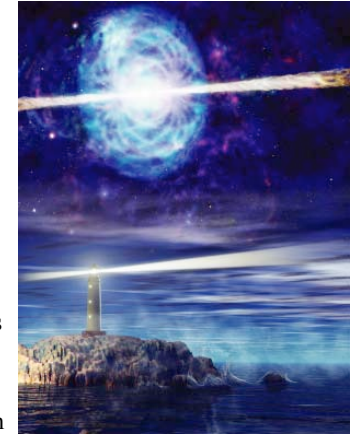
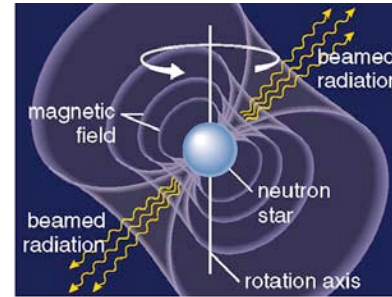


The mystery was solved when a pulsar was discovered in the heart of the Crab Nebula.

The Crab pulsar also pulses in visual light.



Pulsars are the lighthouses of Galaxy!



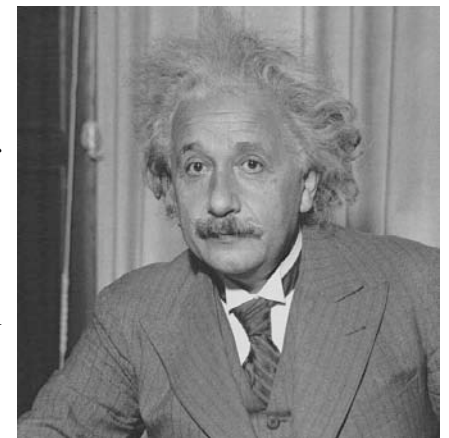
- All pulsars are neutron stars, but all neutron stars are *not* pulsars!!
- Whether we see a pulsar depends on geometry.
 - if the polar beam sweeps by Earth's direction once each rotation, the neutron star appears to be a pulsar
 - if the polar beam is always pointing toward or always pointing away from Earth, we do not see a pulsar

Black Holes: Sorry, can't stand it anymore...

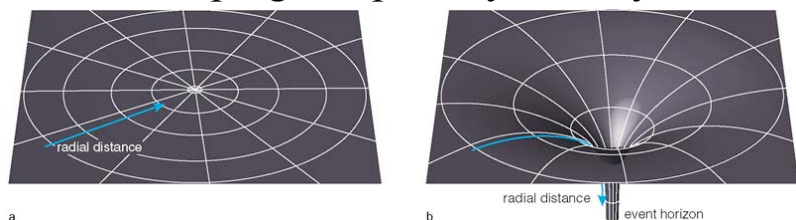
- After a massive star supernova, if the core has a mass $> 3 M_{\odot}$, the force of gravity will be too strong for even neutron degeneracy to stop.
- The star will collapse into oblivion.
 - **GRAVITY FINALLY WINS!!**
- This is what we call a **black hole**.
- The star becomes infinitely small.
 - it creates a "hole" in the Universe
- Since $3 M_{\odot}$ or more are compressed into an infinitely small space, the gravity of the star is HUGE!
- **WARNING!!**
 - **Newton's Law of Gravity is no longer valid !!**

Black Holes

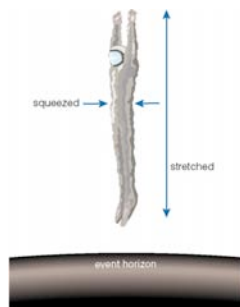
- According to Einstein's Theory of Relativity, gravity is really the warping of spacetime about an object with mass.
- This means that even light is affected by gravity.



Warping of Space by Gravity



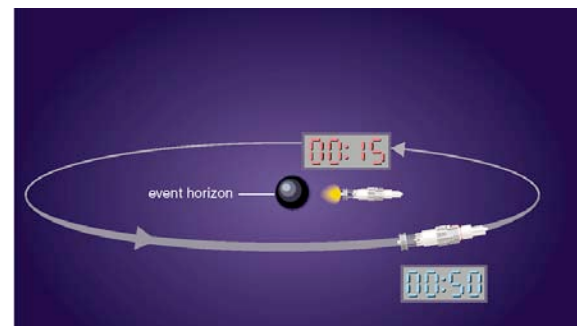
- Gravity imposes a curvature on space.
 - even though it has no mass, light will be affected by gravity
 - its path through space will be bent
 - within the event horizon, it can not climb out of the hole
- As matter approaches the event horizon...
 - the tidal forces are tremendous
 - the object would be “spaghettified”



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Warping of Time by Gravity

- In the vicinity of the black hole, time slows down.
- If we launched a probe to it, as it approached the event horizon:
 - e.g., it takes 50 min of time on mother ship for 15 min to elapse on probe
 - from the mother ship’s view, the probe takes forever to reach event horizon
 - light from the probe is red-shifted
 - probe would eventually disappear as light from it is red-shifted beyond radio



- From the probe’s view:
 - it heads straight into the black hole
 - light from the mother ship is blue-shifted

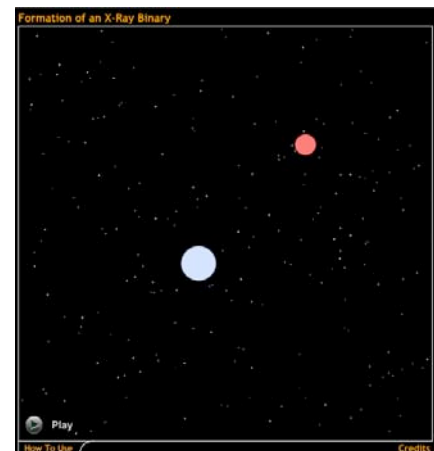
Do Black Holes Suck?

- At a distance, a black hole exerts gravitational force according to Newton’s Law.
 - just like any other star with the same mass
 - if our Sun was replaced by a $1-M_{\odot}$ black hole, the planet’s orbits would not change
- Only at a distance of 3 times the event horizon from the black hole will the gravity increase from what Newton’s Law predicts.
 - then one could eventually fall into the black hole

A black hole does not suck in everything around it!

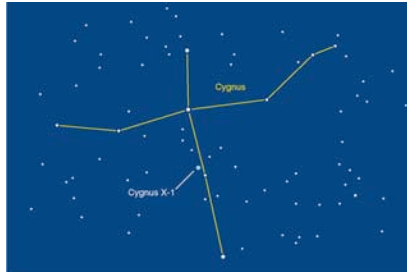
Finding Black Holes

- Then how do we know black holes exist?
 - we detect them in **X-RAY BINARY STARS**



Finding Black Holes

- We can see the effect that a black hole has on its stellar companion in an X-ray binary:
 - Cygnus X-1 was the first good candidate for a black hole
 - Kepler's 3rd Law gives a mass $> 3 M_{\odot}$ for unseen companion
 - it can not be a neutron star
 - the only thing that massive, yet small enough to be invisible is a black hole



Now you are familiar with Orion

•Betelgeuse is a red supergiant. (therefore, it's red and bright.) It may die anytime soon (or, it may have already died!) So watch out, IF it died 425 years ago, it would appear to explode as a brilliant supernova even tomorrow! (it can be seen in full day light.)

•Rigel is a blue supergiant, and is on its way to become a red supergiant. Still blue, but it will become as red as Betelgeuse as its surface expands and cools.

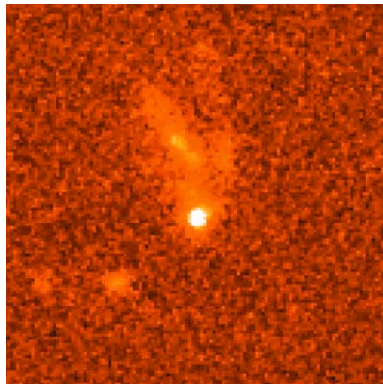
•Orion's belt (tristars): Main sequence O stars.

•Orion nebula (a.k.a. M42): new stars are born (star-forming region)



Gamma Ray Bursts (GRB): The Biggest Explosion in the Universe

- Mysterious Gamma Rays Detected
 - since the 1960s, satellites have detected strong bursts of γ -rays
 - U.S. Military satellites discovered them first: cheating! nuclear experiments somewhere?!
 - they occur daily, for a few minutes
 - γ -rays are hard to focus, so determining their direction is tough
 - After all, they came from deep in the Universe.
- Since 1997, we have detected the afterglows of GRBs at other wavelengths.
 - we can pinpoint their sources to distant galaxies
- What they are is still a mystery.
 - best theory: they are hypernovae ... gigantic supernovae which form black holes
 - most luminous events since the Big Bang



Hubble ST image of GRB afterglow in a distant galaxy

Enjoyed Stars? Let's Wrap It Up

- How stars are born
 - A cloud of gas collapsing gravitationally
 - Conservation of energy, conservation of angular momentum
 - Heat up, get denser, and finally turn-on fusion
- How stars shine
 - Balance between gravitational force and thermal pressure from fusion
 - Burn hydrogen. $E=mc^2$. Main sequence
- How stars evolve
 - Burn helium. Then Carbon. Then Nitrogen. Etc.
 - As stars exhaust their fuel, they become big and bright (giants, supergiants)
 - H-R diagram: Stars live on different evolution tracks depending on their masses
- How stars die
 - Low mass stars \rightarrow White Dwarfs
 - Only binary white dwarfs can then explode as supernovae, leaving nothing.
 - High mass stars \rightarrow Explode, leaving neutron stars or black holes
 - Maybe GRBs

Next Stop: The Milky Way

- Lecture 15 (Tuesday), Reading: Chapter 19
- Please pick up your quiz#3 as you leave the lecture hall.
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