18. The Bizarre Stellar Graveyard

Now, my suspicion is that the Universe is not only queerer than we suppose, but queerer than we can *suppose.*

J. B. S. Haldane (1892 – 1964)
from Possible Worlds, 1927

Agenda

- Announce:
  - Extra Credit presentations on April 18
  - H-R Tutorial due this week
- Ch. 18 – The Bizarre Stellar Graveyard
- Discuss Crab Nebula lab

18.1 A Star's Final Battle

Our goals for learning:

- What determines the fate of a stellar core that has exhausted all its nuclear fuel?

Degeneracy Pressure

- Two particles cannot occupy the same space with the same momentum (energy).
- 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.

Degenerate Objects

- In the leftover core of a dead star…
  - degeneracy pressure supports the star against the crush of gravity
- 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**

18.2 White Dwarfs

Our goals for learning:

- What is a white dwarf ?
- Why can't white dwarfs weigh more than 1.4 times the mass of the Sun?
- What is a nova?
- What are white dwarf supernovae (Type Ia) and why are they good for measuring gigantic distances?

Degenerate Core Leftover

- The central star of a Planetary Nebula heats up as it collapses.
- The star has insufficient mass to get hot enough to fuse Carbon.
- Gravity is finally stopped by the force of **electron degeneracy pressure**.
- The star is now stable……

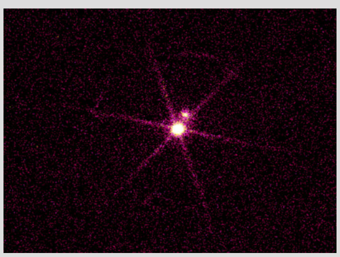
White Dwarf

White Dwarfs

- They are stable…
  - gravity vs. electron degeneracy *pressure*
- 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!

White Dwarfs

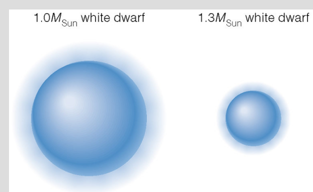
Sirius B is the closest white dwarf to us



Sirius A + B in X-rays

White Dwarfs

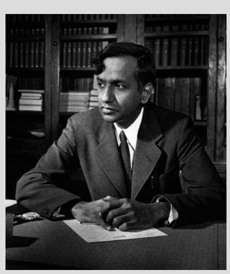
- Degenerate matter obeys different laws of physics.
- The more mass the star has, the *smaller* the star becomes!
  - increased gravity makes the star denser
  - greater density increases degeneracy pressure to balance gravity



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

Chandrasekhar Limit



Subrahmanyan Chandrasekhar (1910-1995)

White Dwarfs

- If a white dwarf is in a close binary:
  - Matter from its companion can be *accreted* onto the WD
  - The matter forms a disk around the WD
  - friction in the accretion disk heats it
    - it emits visible, UV, and even X-ray light
  - if matter falls onto the WD, H fusion begins
- The WD temporarily gets brighter.

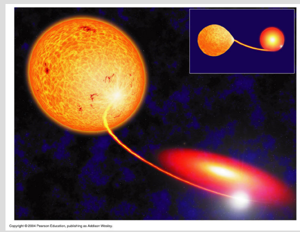
NOVA

Novae

- Term comes from the Latin *Stella Nova*.
  - meaning a new star
  - what the ancient Greeks & Romans called a star which suddenly appeared!
- In reality the star is not **new**, it just gets much brighter in a matter of days.
- Since they did not have telescopes, these stars were normally too faint to be seen – hence they suddenly appeared.

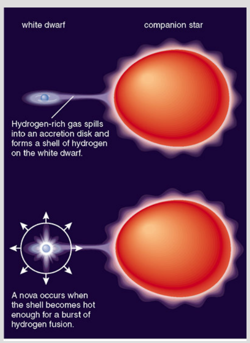
Novae

- 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.
  - we call these **supernovae**



- **Accretion disk** is a rotating disk of gas orbiting a star.
  - formed by matter falling onto the star.
- The hydrogen build-up on the surface of the white dwarf can ignite into an explosive fusion reaction that blows off a shell of gas.

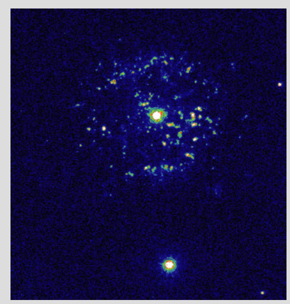
Novae



- 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

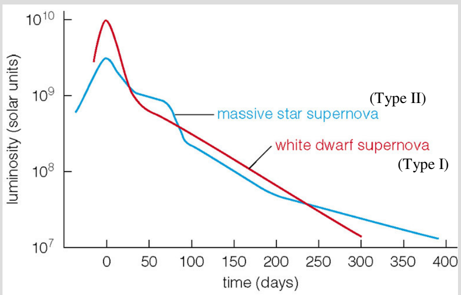
White Dwarf Supernovae

- If accretion brings the mass of a white dwarf above the Chandrasekhar limit, electron degeneracy can no longer support the star.
  - 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

- While a nova may reach an absolute magnitude of –8 (about 100,000 Suns)…
- a white dwarf supernova attains an absolute magnitude of –19 (10 billion Suns).
  - since they all attain the same peak luminosity (abs mag)
  - white dwarf supernovae make good distance indicators
  - they are more luminous than Cepheid variable stars
  - so they can be used to measure out to greater distances than Cepheid variables
- There are two types of supernova:
  - ***white dwarf***: no prominent lines of hydrogen seen; white dwarfs thought to be origin.
  - ***massive star***: contains prominent hydrogen lines; results from explosion of single star.

Supernova Light Curves



18.3 Neutron Stars

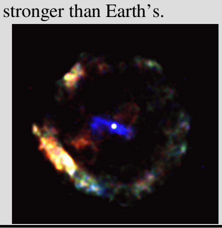
Our goals for learning:

- What is a neutron star?
- What is a pulsar?
- Why do X-ray binaries emit so much X-ray radiation?
- Contrast X-ray bursters with novae on white dwarfs.

Neutron Stars

- …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.
- 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
- Their magnetic fields are 10^{13} times stronger than Earth's.

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.

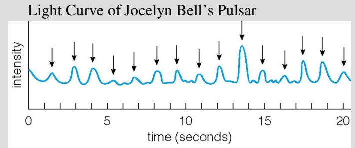


Pulsars

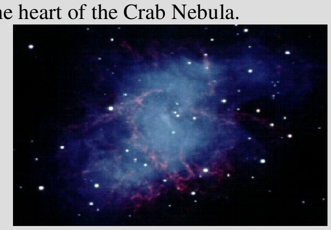
- In 1967, graduate student Jocelyn Bell and her advisor Anthony Hewish accidentally discovered a radio source in *Vulpecula*.
- It was a sharp pulse which recurred every 1.3 sec.
- They determined it was 300 pc away.
- They called it a **pulsar**, but what was it?

Jocelyn Bell

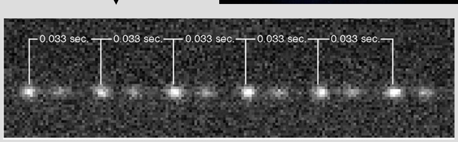
Light Curve of Jocelyn Bell's Pulsar



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



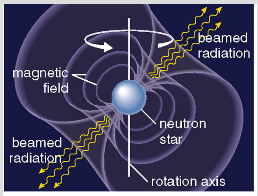
The Crab pulsar also pulses in visual light.



Pulsars and Neutron Stars

- All pulsars are neutron stars, but all neutron stars are *not* pulsars!!
- Synchrotron emission --- non-thermal process where light is emitted by charged particles moving close to the speed of light around magnetic fields.
- Emission (mostly radio) is concentrated at the magnetic poles and focused into a beam.
- Whether we see a pulsar depends on the 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

Pulsars and Neutron Stars



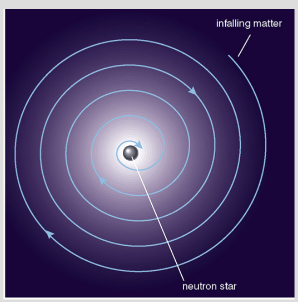
Pulsars are the lighthouses of Galaxy!

Rotation Periods of Neutron Stars

- As a neutron star ages, it spins down.
- The youngest pulsars have the shortest periods.
- Sometimes a pulsar will suddenly speed up.
  - This is called a **glitch**!
- There are some pulsars that have periods of several milliseconds.
  - they tend to be in binaries.

Birth of a Millisecond Pulsar

- Mass transfer onto a neutron star in a binary system will spin the pulsar up faster.
  - to almost 1,000 times per sec
- Like white dwarf binaries, an accretion disk will form around the neutron star.
  - the disk gets much hotter
  - hot enough to emit X-rays
- We refer to these objects as **X-ray binaries.**



Do X-ray Binaries go Nova?

- Just as is the case with novae, Hydrogen gas will accrete onto the surface of the neutron star.
  - a shell of Hydrogen, 1 meter thick, forms on the star
  - pressure is high enough for Hydrogen to fuse steadily on the neutron star surface
  - a layer of Helium forms underneath
  - when temperatures reach 10^8 K, the Helium fuses instantly and emits a burst of energy
- These neutron star "novae" are called **X-ray bursters**.
  - a burst of X-rays, lasting a few seconds, is emitted
  - each burst has the luminosity of 10^5 Suns
  - the bursts repeat every few hours to every few days

18.4 Black Holes

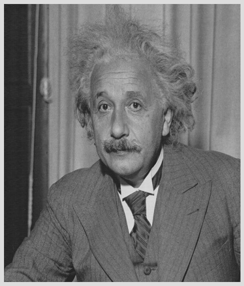
Our goals for learning:

- What is the maximum mass of a neutron star?
- What is a black hole?
- Do black holes suck?
- What property of a black hole determines its "size"?
- What would happen if you watched someone falling into a black hole?
- What observational evidence is there for the existence of black holes?

Black Holes

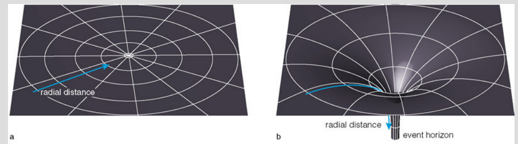
- After a massive star supernova, if the core has a mass > 3 $M_{\odot}$, the force of gravity will be too strong for even neutron degeneracy to stop.
- The star will collapse into oblivion.
  - GRAVITY FINALLY WINS!!
- This is what we call a **black hole**.
- The star becomes infinitely small.
  - it 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

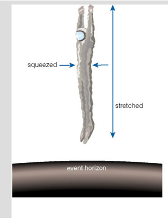


- According to Einstein's Theory of Relativity, gravity is really the warping of spacetime about an object with mass.
- This means that even light is affected by gravity.

Warping of Space by Gravity

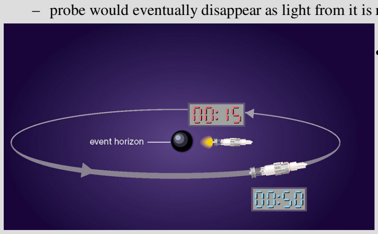


- Gravity imposes a curvature on space.
  - even though it has no mass, light will be affected by gravity
  - its path through space will be bent
  - within the event horizon, it can not climb out of the hole
- As matter approaches the event horizon…
  - the tidal forces are tremendous
  - the object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



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

"Size" of a Black Hole

- Spacetime is so highly warped around a black hole, even light can not escape.
- Schwarzchild Radius – the distance from a black hole where the escape velocity equals the speed of light.

  $R_s = 3\ M$ (R_s in km; M in $M_\odot$)

- A sphere of radius R_s around the black hole is called the **event horizon**.

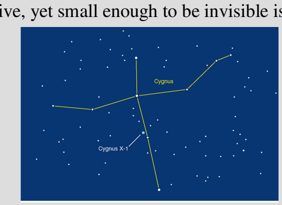
Do Black Holes Suck?

- 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 were replaced by a 1-$M_\odot$ black hole, the planet's orbits would not change
- Only at a distance of 3 R_s 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

- 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



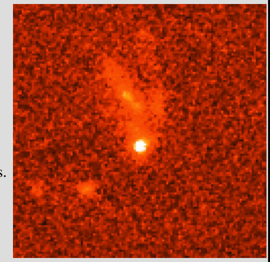
18.5 The Mystery of Gamma Ray Bursts

Our goals for learning:

- How are gamma-ray bursts detected?
- What do we know about gamma-ray bursts?

Gamma Ray Bursts (GRB)

- Cosmic γ-rays must be observed from above our atmosphere.
  - since the 1960s, satellites have detected strong bursts of γ-rays
  - they occur daily, for a few minutes
  - γ-rays are hard to focus, so determining their direction is tough
- 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

What have we learned?

- What determines the fate of a stellar core that has exhausted all its nuclear fuel?
  - A star's final state depends on whether degeneracy pressure can halt the crush of gravity. A white dwarf is supported by electron degeneracy pressure. A neutron star is supported by neutron degeneracy pressure. If neutron degeneracy pressure cannot halt the collapse, the core becomes black hole.

What have we learned?

- What is a white dwarf?
  - A white dwarf is the inert core left over from a low-mass star, supported by electron degeneracy pressure.
- Why can't white dwarfs weigh more than 1.4 times the mass of the Sun?
  - At masses greater than 1.4 M_{sun}, the white dwarf can no longer support its own weight with electron degeneracy pressure. The electrons would have to "move" faster than speed of light, which is physically impossible. So white dwarfs that become more massive than 1.4 M_{sun} must collapse.

What have we learned?

- What is a nova?
  - A white dwarf in a binary system can acquire hydrogen from its companion, which swirls toward the surface in an accretion disk. If enough hydrogen rains down on the white dwarf, the surface hydrogen layer will become so hot that it will ignite with nuclear fusion, essentially making a thermonuclear flash in which the star shines as brightly as 100,000 Suns for a few weeks.
- What are white dwarf supernovae (Type Ia) and why are they good for measuring gigantic distances?
  - A white dwarf supernova arises from the explosion of an entire white dwarf triggered by carbon fusion when it gains enough mass to approach the 1.4 M_{sun} limit. The peak luminosity of the explosion exceeds 10 billion times the Sun's. Because these supernovae have nearly identical light curves, and because they are so bright that they can be seen across the universe, we measure their distances from their apparent brightness in our sky.

What have we learned?

- What is a neutron star?
  - A neutron star is the ball of neutrons created by the collapse of the iron core in a massive star supernova. It is like a giant atomic nucleus 10 kilometers across but more massive than the Sun.
- What is a pulsar?
  - Pulsars are rotating neutron stars with magnetic fields. Hot spots at the magnetic poles of these neutron stars send out beams of radiation. If the magnetic poles do not align with the poles of the rotation, the beamed radiation from the hot spots sweeps through space like a lighthouse beam swings through the night. If this beam crosses the Earth, we see it periodically appear and disappear – in pulses.

What have we learned?

- Why do X-ray binaries emit so much X-ray radiation?
  - Neutron stars in binary systems can also accrete hydrogen from their companions, forming dense, hot accretion disks. Because the inner regions of these disks are so hot, they radiate X rays.
- Contrast X-ray bursters with novae on white dwarfs.
  - Novae occur when hydrogen fusion suddenly ignites on the surface of a white dwarf in a binary system. In contrast, hydrogen fusion is steady on the surface of a neutron star in a binary system. However, the steady hydrogen burning builds up a layer of helium beneath the surface shell of hydrogen. Every few days, enough helium can build up for it to ignite suddenly in a burst of helium fusion, which causes an X-ray burst. For about a minute during an X-ray burst, the star produces power equivalent to 100,000 Suns.

What have we learned?

- What is the maximum mass of a neutron star?
  - The maximum mass of a neutron star, about 3 M_{Sun}, is determined by the maximum amount of mass that neutron degeneracy pressure can support.
- What is a black hole?
  - A place where gravity has crushed matter into oblivion, creating a true hole in the universe from which nothing can ever escape.
- Do black holes suck?
  - Black holes don't suck in objects at large distances. If our Sun were instantly replaced by a solar-mass black hole, the Earth would not be sucked into the black hole. The planets would continue to orbit normally.

What have we learned?

- What property of a black hole determines its "size"?
  - A black hole's "size" depends on its mass, because the mass determines the size of the black hole's event horizon, the boundary of the region from which not even light can escape.
- What would happen if you watched someone falling into a black hole?
  - You'd see time slow down for them as they approached the black hole, and their light would be increasingly redshifted. They would never quite reach the event horizon, though they would soon disappear from view as their light became so redshifted that no instrument could detect it.

What have we learned?

- What observational evidence is there for the existence of black holes?
  - We cannot see black holes directly, but we can infer their presence by their influence on their surroundings. For example, the study of X-ray binaries shows that some of these binary systems may have black holes rather than neutron stars. The X-ray behavior of black hole systems differs from that of neutron stars because a neutron star has a surface and black holes do not. The most definitive evidence is obtained by measuring the orbit of the companion, from which one can infer the mass of the object with the accretion disk. If that object is more massive than 3 M_{Sun}, it is probably a black hole. Cygnus X-1 is one of the binary systems thought to contain a black hole.

What have we learned?

- How are gamma-ray bursts detected?
  - Gamma rays, since they do not penetrate the atmosphere, must be detected from high altitude or space. Gamma ray telescopes on satellites have detected gamma-ray bursts coming from every direction in the sky.
- What do we know about gamma-ray bursts?
  - They occur in distant galaxies, and they must be extremely large explosions – the most powerful bursts of energy since the Big Bang. We do not know their precise cause, although at least some appear to be the result of unusually powerful supernovae.

What would happen to the Earth's orbit if our Sun suddenly became a black hole?

1. The Earth would immediately vanish into the black hole.
2. The Earth would be sucked into the center of the black hole.
3. The Earth would be flung off in a tangent into outer space.
4. The Earth would gradually drift away from the black hole.
5. The Earth's orbit would not change.

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The radii of white dwarf stars in close binary systems gradually increases as they accrete matter.

1. Yes, their radii will slightly increase due to the extra material.
2. Yes, their radii will continue to increase up to a critical limit.
3. No, the radius of a white dwarf star is constant.
4. No, the matter will be ejected into a nova and their radii will remain unchanged.
5. No, the higher gravity of the more massive white dwarf star compresses it to a higher density and a smaller radius.

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Before pulsars were discovered, no one knew for sure whether neutron stars existed.

1. Yes, pulsars were the first evidence for the existence of objects more compact than a white dwarf.
2. Yes, neutron stars had been observed before at optical wavelengths but it was only after they were found to pulsate at radio wavelengths that astronomers realized their nature.
3. No, the existence of neutron stars was predicted by theory and it was widely accepted that they were common in the universe.
4. No, the existence of neutron stars is still debated and is a major reason why neutrino telescopes are being built.

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If a black hole ten times more massive than our Sun were lurking just beyond Pluto's orbit, we'd have no way of knowing it was there.

1. Correct. Black holes do not emit light so they cannot be detected.
2. Correct. Such a low mass black hole would have no influence on the solar system unless it impacted a planet.
3. Incorrect. Such a black hole would measurably affect the orbits of the planets.
4. Incorrect. X-ray observations would reveal its presence as it sucked in material around it.
5. Incorrect. It would be readily apparent as a pulsating radio source in the outer solar system.

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We can detect black holes with X-ray telescopes because matter falling into a black hole emits X-rays after it smashes into the event horizon.

1. Yes, the energy of matter smashing into the event horizon is very high and creates strong X-ray emission.
2. No, after matter smashes into the event horizon, its radiation cannot escape.
3. No, black holes do not have surfaces for material to smash into. The X-ray emission comes from gas as it falls toward the event horizon and heats up.
4. No, black holes are invisible and only apparent through their gravitational influence.

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Crab Nebula Lab

Crab Nebula Lab

- Calibrate pictures of astronomical events
- Measure expansion
- Calculate age of expansion
- Determine year of explosion

Was the lab a success?

- If we didn't have an accepted value, would you have believed the year you got?
- Did your results agree with the accepted value?
- If your neighbors submitted this as a paper, and you were a referee, what would you question?

How did you determine your confidence interval?