High-mass stars die violently by blowing themselves apart in supernova explosions.
Remnants of supernova explosions can be detected for millennia afterward.
What causes a Supernova?

• The force of gravity grows as the mass of the Fe core increases
  - Gravity overcomes electron degeneracy
  - Electrons are smashed into protons $\Rightarrow$ neutrons

• The neutron core collapses until abruptly stopped by neutron degeneracy pressure
  - this takes only seconds
  - The core recoils and sends the rest of the star flying into space
  - The amount of energy released is so great, that most of the elements heavier than Fe are instantly created
Supernova

In the last millennium, four supernovae have been observed in our part of the Milky Way Galaxy: in 1006, 1054, 1572, & 1604.

*Crab Nebula in Taurus*

supernova exploded in 1054
Supernovae

There are actually two different kinds...
Accreting White Dwarfs in close binary systems can also explode as supernovae if the White Dwarf exceeds 1.4 $\text{M}_\odot$ (Chandrasekhar limit). 

Called a TYPE I supernova
Limit on White Dwarf Mass

- Chandrasekhar 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 $> 1.4 M_{\odot}$

Chandrasekhar Limit

Subrahmanyan Chandrasekhar (1910-1995)
The White Dwarf Limit

Einstein’s theory of relativity says that nothing can move faster than light.

When electron speeds in White Dwarf approach speed of light, electron degeneracy pressure can no longer work since electrons cannot go faster than $c$ – the speed of light.

Chandrasekhar found that this happens when a white dwarf’s mass reaches $1.4 \, M_{\odot}$.
The most famous “before and after” picture
Supernova 1987 A
Supernova 1987A offers a close-up look at a massive star’s death.
Outer ring at edge of swept up gas from earlier mass loss.

Inner ring of swept up red-supergiant gas.

Supernova remnant. A dark, invisible outer portion surrounds the brighter inner region lit by radioactive decay.
What can happen to a white dwarf in a close binary system?
White dwarf’s gravity pulls matter off its giant companion, but angular momentum prevents the matter from falling straight in.

Infalling matter forms an *accretion disk* around the white dwarf.
Friction in disk makes it hot, causing it to glow.

Friction also removes angular momentum from inner regions of disk, allowing them to sink onto white dwarf.
Thought Question

What would gas in disk do if there were no friction?

A. It would orbit indefinitely.
B. It would eventually fall in.
C. It would blow away.
Thought Question

What would gas in disk do if there were no friction?

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Two Types of Supernova

**Massive star supernova:**

Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion. Contains prominent hydrogen lines

**White dwarf supernova:**

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion. No prominent lines of hydrogen seen.
Supernova Light Curves

- **massive star supernova** (Type II)
- **white dwarf supernova** (Type I)
1. A nearby star is found to have a parallax angle of 40 arcsec, How far away is it in meters?

\[ d = \frac{1}{p} = \frac{1}{40} \text{ pc} \quad m \]

2. The flux of radiation we detect here on Earth for this star is 7x10^10 W/m^2 What is its Luminosity?

\[ f = \frac{L}{4\pi d^2} \quad L = ? \]

3. Where would we have to put this star so that it would have the same Luminosity as the Sun?

\[ f = \frac{L}{4\pi d^2} \quad d = ? \]
To take the final or not... that is the Question

Suppose you have the following quiz grades:

5, 2, 6, 7, 7, 10, 8, 4, 3, 9, 9, 3, 7, 7, 8, 7 = average of 5.94

1) **Drop the lowest 2**
5, 6, 7, 7, 10, 8, 4, 9, 9, 3, 7, 7, 8, 7 = average of 6.43

2) **Examine the next lowest 4**
5, 6, 7, 7, 10, 8, 4, 9, 9, 3, 7, 7, 8, 7

3) **Add them** 5+6+3+4 = 18

Now suppose you were to get 60% on the final then I would replace those 4 scores with 6’s – and you gain 6 points overall bringing your average up to ~6.9

80% - 7.5; 90% - 7.8; 100% - 8.0

But, if the sum of the four lowest scores in step 3 is greater than 24 then maybe the final won’t help you.
The Bizarre Stellar Graveyard

The objects depend on which force is resisting the crush of gravity:

- Thermal pressure – main sequence stars and red giants
- Electron degeneracy pressure – white dwarfs
- Neutron degeneracy pressure – neutron stars
- Black holes – gravity wins!!!
Electron Degeneracy

- The central star collapses, heats up, and ejects a Planetary Nebula.
- 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☉ packed into a sphere the size of the Earth!
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.
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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☉ packed into a sphere the size of the Earth!
A white dwarf is about the same size as Earth
Neutron Stars

• ...are the leftover cores from supernova explosions.
• If the core < 3 M☉, it will stop collapsing and be held up by neutron degeneracy pressure.
• Neutron stars are very dense (10^{12} \text{ g/cm}^3 )
  - 1.5 M☉ 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.
Hydrogen that accretes onto a neutron star builds up in a shell on the surface. When base of shell gets hot enough, hydrogen fusion suddenly begins leading to a nova.
Nova explosion generates a burst of light lasting a few weeks and expels much of the accreted gas into space (H-bomb)
• While a nova may reach about 100,000 $L\odot$...

• A white dwarf supernova attains 10,000,000,000 $L\odot$ (10 billion $L\odot$)
  - Runaway carbon fusion in core – causes explosion
  - Since they all attain the same peak luminosity, 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
The cores of many Type II supernovae become neutron stars

- When stars between 4 and 9 times the mass of the Sun explode as supernovae, their remnant cores are highly compressed clumps of neutrons called *neutron stars*.
  - These tiny stars are much smaller than planet Earth - in fact, are about the diameter of a large city (about 20 km)!!
  - suggested in 1934
  - max. mass of 3 solar masses (otherwise, collapse)
  - LGM’s discovered
LGM

• 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.

• What was it?
A part of the LGM puzzle was solved when a pulsar was discovered in the heart of the Crab Nebula.

The Crab pulsar also pulses in visual light.
Pulsars

Areceibo Observatory
Areceibo, Puerto Rico

The observatory is part of the National Astronomy and Ionosphere Center, a national research center operated by Cornell University under contract with the National Science Foundation.
Some neutron stars in binary systems emit powerful jets of gas.
Pulsars and Neutron Stars

Pulsars are the lighthouses of Galaxy!
Lighthouse Model
Pulsars and Neutron Stars

Pulsars are the lighthouses of Galaxy!
Rotation Periods of Neutron Stars

- As a neutron star ages, it slows 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.
  - They are perhaps the most accurate clocks in the universe
Neutron Star
What Happens When a Super Massive Red Giant Is Too Massive and collapses?

We call it a 'Black Hole'.

A black hole is a tiny, spherical, collapsed stellar core that has enormous gravity, so much gravity that even photons of light cannot escape.
Black Holes

- first suggested in 1783!
- require a mass at least 3-5 solar masses
- evidence?
- A new Phenomena may point the way!!
Gamma Ray Bursts (GRB)

- Cosmic -rays must be observed from above our atmosphere.
  - since the 1960s, satellites have detected strong bursts of -rays
  - they occur daily, for a few minutes
  - -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.
  - most luminous events since the Big Bang
  - best theory: they are hypernovae … gigantic supernovae which form black holes

Hubble ST image of GRB afterglow in a distant galaxy
Gamma ray bursts may signal the births of new black holes
At least some gamma ray bursts come from supernovae in very distant galaxies
The star has collapsed into oblivion.

- **GRAVITY HAS FINALLY WON!!**

- The star becomes infinitely small.
  - it creates a “hole” in the Universe
  - ‘Size’ of a black hole – the Schwarzschild radius – is about 3km for each solar mass of material.

- Since 3 M⊙ 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

- first suggested in 1783!
- require a mass at least 3-5 solar masses
- evidence?
- A new Phenomena may point the way!!
The Metric = $ds^2$

A useful tool:

- A measure of distance in a spacetime
- For a flat spacetime it is given simply by the Pythagorean Theorem:

$$ds^2 = dx^2 + dy^2$$
\[ ds^2 = dx^2 + dy^2 \]

\[ ds^2 = \text{something more complicated!} \]

\[ \sim \frac{1}{r} (dx^2 + dy^2) \]
Black Hole Verification

• Need to measure mass
  ➞ Use orbital properties of companion
  ➞ Measure velocity and distance of orbiting gas

• It’s a black hole if it’s not a star and its mass exceeds the neutron star limit (~3 $M\odot$)
Some black hole candidates include:

- LMC X-3 in the Large Magallenic Cloud orbits its companion every 1.7 days and might be about 6 $M\odot$.
- Monoceros A0620-00 orbits an X-ray source every 7 hours and 45 minutes and might be more than 9 $M\odot$.
- V404 Cygnus has an orbital period of 6.47 days which causes Doppler shifts to vary more than 400 km/s. It is at least 6 $M\odot$. 
Cygnus X-1 must have a mass of about 7 times that of the Sun.
The best Black Hole candidate (thus far):
The Motion of a Star around the Central Black Hole in the Milky Way