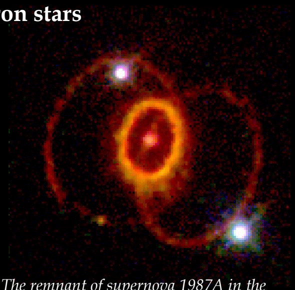
Today in Astronomy 102: violent stellar death and neutron stars

- ❑ White dwarfs, novae, and Type Ia supernovae.
- ❑ The relativity of mass.
- ❑ Neutron stars and the Oppenheimer maximum mass.
- ❑ Collapse of burned-out stars, the formation of neutron stars, and Type II supernovae.
- ❑ Pulsars are neutron stars.
- ❑ When is black-hole formation inevitable?

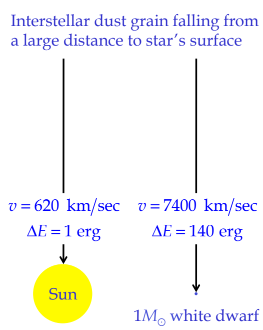


The remnant of supernova 1987A in the Large Magellanic Cloud, seen by the Hubble Space Telescope in 1995 (NASA/STScI).

Aside: huge, violent astrophysical explosions

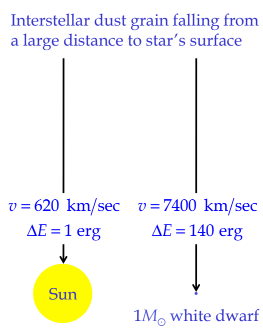
Small, massive objects like white dwarfs and other degenerate stars are very dangerous things to leave laying around.

- ❑ Material falling to the surface of such a star gains a lot more energy that the same stuff falling to the surface of a normal star of the same mass.



Huge, violent astrophysical explosions (continued)

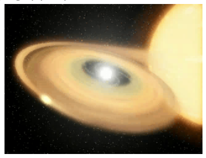
- ❑ This extra energy has to go somewhere, and winds up one way or other in the motion of the infalling material:
  - as heat (and extremely high temperatures and pressures), or
  - as organized motion: for instance, if the infalling material encounters a hard enough surface from which to bounce.
- ❑ Either way, this can produce gigantic explosions.



Aside: white dwarfs, novae, and Type Ia supernovae

Sometimes white dwarfs (WDs) are found in binary systems with ordinary stars, in orbits small enough for hydrogen-rich material to fall from the normal star to the WD.

- The material on the surface of the WD winds up hot and compressed to high densities.
- When it gets hot and dense enough it can undergo fusion again, which, lacking a stellar envelope around it, tends to be explosive. Two basic types of these explosions:
  - **Classical nova**: about 10^{45} erg released, stars brighten by a factor of 10^4-10^5, WD survives, process can repeat.



Artist's conception of classical nova Z Camelopardalis (GALEX/ Caltech/NASA)

White dwarfs, novae, and Type Ia supernovae (continued)

- **Type Ia supernova (SNIa)**: about 10^{51} erg released, stars brighten by factor of about 10^{10}, **WD destroyed**.
- SNIa happen when the "match" of fusion in material acquired from the normal star ignites fusion of carbon and oxygen nuclei throughout the entire WD.
- This in turn can happen when the additional material has pushed the mass of the WD up close to the maximum (Chandrasekhar) mass.
- Since the total fusion-fuel supply is thus about the same for all of them, the energy released (and luminosity) is too: SNIa are bright "standard bombs. "
- This makes SNIa very useful for measuring distances to galaxies, and we will meet them again in that context.

Special-relativity interlude: the relativity of mass, the speed-of-light limit, and maximum degeneracy pressure

Why is the speed of light the maximum speed that can be reached by electrons? (Remember, this was not part of the two original axioms from which Einstein started…)

- Because of the **relativity of mass**: if a body with rest mass m_0 moves at speed V with respect to an observer, the observer will measure a mass

$$m = \frac{m_0}{\sqrt{1 - V^2/c^2}}$$

  for the body. (Another result of the Special Theory.)
- Note similarity to the formula for time dilation: in particular, that the denominator approaches 0, and thus **m approaches infinity, if V approaches c.**

PRS interlude: relativity of mass

What is the mass of an object that has rest mass 1 gram, and flies by at $0.99c$?

A. 0.14 gram B. 0.53 gram C. 1 gram D. 7.1 gram
E. 14.2 gram

PRS interlude: relativity of mass

Take a guess: how fast would an object have to fly for its mass to be a factor of 2 larger than its rest mass?

A. $V = \frac{1}{2}c$ B. $V = \frac{\sqrt{3}}{2}c$ C. $V = \frac{\sqrt{5}}{6}c$ D. $V = \frac{99}{100}c$ E. $V = 2c$

The relativity of mass, the speed-of-light limit, and maximum degeneracy pressure (continued)

So, suppose you have a body moving at very nearly the speed of light, and you want it to exceed the speed of light. What can you do?

- It needs to **accelerate** for its speed to increase.
- You need to exert a force on it in order to make it accelerate.
- The force required is, essentially, proportional to the product of mass and acceleration in your reference frame. (Nonrelativistic version of this statement is Newton's second law: force = mass times acceleration.)
- But the mass approaches infinity as V approaches c, and thus an infinite force is required to accelerate it further. There's no such thing as an infinite force (or indeed an infinite anything), **so c is the ultimate speed limit.**

Final implosion of massive burned-out stars

Electron degeneracy pressure can hold up a star of mass $1.4M_\odot$ or less against its weight, and do so indefinitely. Stellar cores in this mass range at death become white dwarfs.

For heavier stars – $\geq 10M_\odot$ – gravity overwhelms electron degeneracy pressure, and the collapse doesn't stop with the star at planet size.

- As the star is crushed past a circumference of 10^4 cm or so, all the electrons and protons in the star are squeezed together so closely that they rapidly combine to form neutrons: $p + e^- + \text{energy} \rightarrow n + \nu_e$.
- Eventually, then, the collapse might be stopped by the onset of **neutron degeneracy pressure.**
- A star whose weight is held up by neutron degeneracy pressure is called a **neutron star**.

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Oppenheimer's theory of neutron stars

Neutron stars were first proposed to exist, and to cause supernovae by their formation, by Zwicky and Baade (1934).

- First calculations of their sizes: Landau (1938).
- Neutron stars are analogous to white dwarfs, but the calculation of their structure is much more difficult, since the strong nuclear force and general relativity must be taken into account.
  - For white dwarfs, special relativity suffices because the gravity of these stars is not strong enough to make general relativistic effects substantial.
- They may also be expected to have a maximum mass, as white dwarfs do. So neutron-star formation prevents black hole formation only up to that maximum mass.

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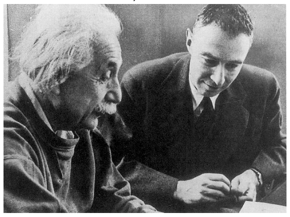
Oppenheimer's theory of neutron stars (cont'd)

- First calculation of maximum mass: Oppenheimer and Volkoff (1939). They got $0.7M_\odot$; more recent calculations, with improvements in the expression of the nuclear forces, give 1.5-3 $M_\odot$. (We will use $\mathbf{2M_\odot}$ in this course.)



Albert Einstein and J. Robert Oppenheimer at Caltech in 1939. They probably were, at that moment, discussing the prevention of black holes by neutron-star formation.

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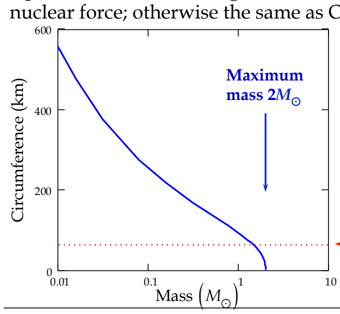
Oppenheimer's theory of neutron stars (cont'd)

Updated calculation using 1990s-vintage inputs for the strong nuclear force; otherwise the same as Oppenheimer and Volkoff.



The mass of a star, the size of a city!

Circumference of Rochester (outer loop)

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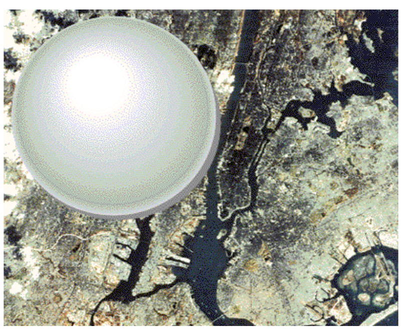
Oppenheimer's theory of neutron stars (cont'd)

A $1.4M_\odot$ neutron star and New York City, shown on the same scale. (From Chaisson and McMillan, *Astronomy today*.)



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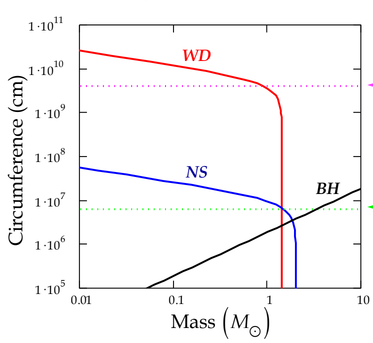
White dwarfs, neutron stars and black-hole horizons



Earth

Rochester

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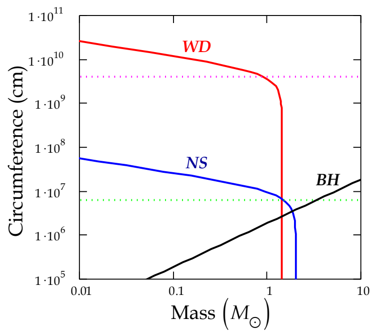
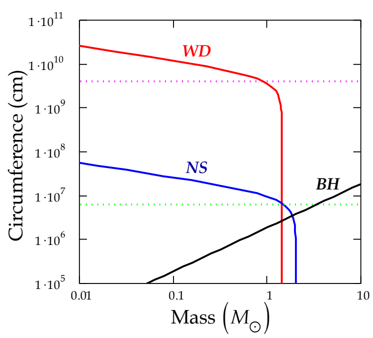
And now for some PRS problems using this graph



By what factor is a $1M_\odot$ white dwarf bigger around than a $1M_\odot$ neutron star?

A. 1 (they're the same size)
B. 10
C. 21
D. 100
E. 350

And now for some PRS problems using this graph



By what factor is a $1M_\odot$ neutron star bigger around than a $1M_\odot$ black hole?

A. 1 (they're the same size)
B. 5
C. 10
D. 50
E. 100

Mid-lecture break (4 min. 14 sec.)

- Homework #4 is due Monday, March 19, 8:30 AM.

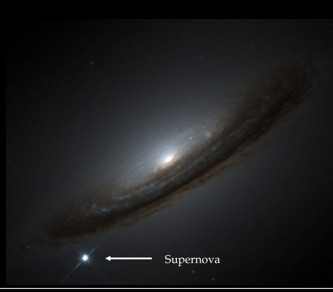


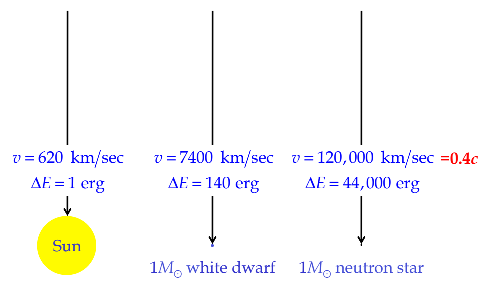
Image of Supernova 1994D (type Ia) in the galaxy NGC 4526, taken a few weeks after it was first discovered in March 1994, by the High-z Supernova Search Team, with the NASA Hubble Space Telescope.

Neutron star formation and Type II supernovae

- After electron degeneracy pressure is overpowered, and the electrons and protons combine to form neutrons, the star is free to collapse under its weight. Nothing can slow down this collapse until the neutrons are close enough together for their degeneracy pressure to become large.
  - Recall that this requires confinement of each particle to a space a factor of about 1836 smaller than for electron degeneracy pressure.
- This collapse takes very little time, and the collapsing material is moving very fast when neutron degeneracy pressure hits.
- A **neutron-degeneracy-pressure supported core** can form from the inner part of the collapsing material.

Neutron star formation and Type II supernovae (continued)

Interstellar dust grain falling from a large distance to star's surface



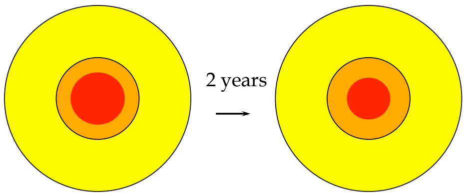
Neutron star formation and Type II supernovae (continued)

- The outer, collapsing material that didn't make it into the neutron core proceeds to **bounce** off this core, rebounding into the rest of the star and exploding it with great violence. This is called a **Type II supernova (SNII).**
- The bounce allows much of the energy gained in the collapse to be released, upwards of 10^{52} erg.

Artist's conception of the formation of a neutron star and a Type II supernova (CXO/CfA/NASA).

- Because this process will work for just about any star 8 solar masses and heavier, the released energy varies a lot more from SNII to SN II than from SNIa to SNIa.

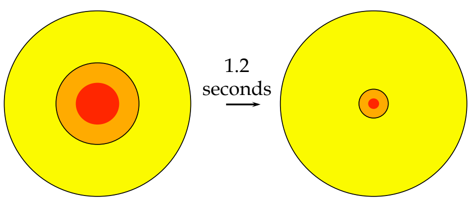
Type II supernova (SNII), not drawn to scale



Star: 6 $M_{\odot}$, 10^7 km circumference
Core: 1.4 $M_{\odot}$, 10^5 km circumference

Core: 10^4 km circum-ference. Electrons and protons begin combining to form neutrons.

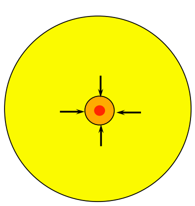
SNII (continued)



Core: 10^4 km circumference. Electrons and protons begin combining to form neutrons.

Core: 70 km circumference, neutron degeneracy pressure sets in.

SNII (continued)

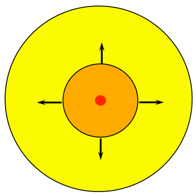


Core: 70 km circumference, neutron degeneracy pressure sets in. This makes the core very stiff.

Outside of core: still collapsing, moving inwards at about 10^{10} cm/s. (Near light speed!) Bounces off stiff core.

SNII (continued)

A few seconds →



Core: still 70 km circumference, it is now stable.

Outside of core: the rebounding outer-star material explodes the rest of the star. Energy comes from bounce, and from gravitational energy of core.

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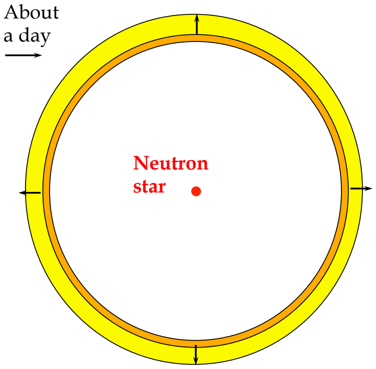
About a day →



SNII (continued)

Expanding supernova shell. Very, very bright for about a month after explosion (can outshine rest of galaxy!).

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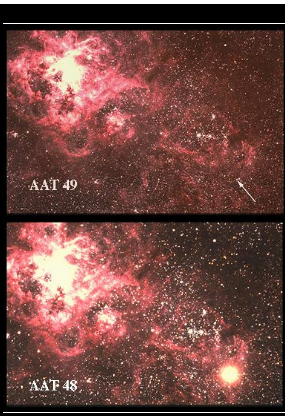

Supernova 1987A

Before: the Tarantula Nebula in the Large Magellanic Cloud, in 1984. The star that exploded is indicated by the white arrow.

After: the same field in 1987, two weeks after the supernova, a SNII, went off. It was still easily visible to the naked eye.

Images by David Malin, Anglo-Australian Observatory.

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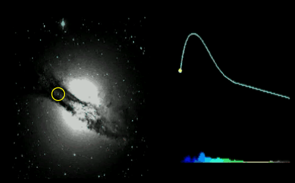
The appearance of a supernova as time passes

Here is an animated view of the first month after the explosion of a supernova (a SNIa), courtesy of UC Berkeley's Supernova Cosmology Project (Perlmutter, Nugent, Conley).



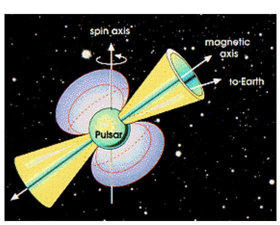
Neutron stars, SNII, and pulsars

Many hundreds of neutron stars are known today; they appear mostly as **pulsars**: starlike sources of radio and visible light whose light output pulsates rapidly.

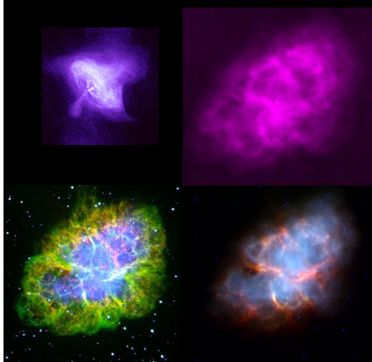
- Discovered in 1967 by Cambridge grad student Jocelyn Bell, they were almost immediately identified as rapidly-rotating neutron stars that emit "beams" of light by accelerating electrons and protons outward along their magnetic poles. (They pulse like a lighthouse does.)
- Many young supernova remnants contain pulsars.
- Several pulsars occur in binary systems, for which masses can be measured accurately; all turn out to be around 1.4-1.5$M_\odot$, comfortably less than 2$M_\odot$, and greater than the maximum white-dwarf mass.

Neutron stars and pulsars.

- One teaspoonful of a neutron star would weigh a billion tons.
- When a neutron star is formed, it in general spins.
- We can see the neutron stars because most of them have jets of particles bouncing off them, moving away with the speed of light along the magnetic axis of the neutron star.
- Since the star spins, we see this beam of light only when it is directed towards the Earth.
- The rate of the pulsar allows us to measure the spin rate.



http://imagine.gsfc.nasa.gov/science/objects/pulsars1.html



The archetype SNII remnant: the Crab Nebula (M1, SN1054)

Clockwise from upper left: X ray continuum (CXO/CfA/ NASA), visible spectral lines (Palomar Observatory/ Caltech), infrared continuum (Spitzer Space Telescope/NASA), radio continuum (VLA/NRAO)

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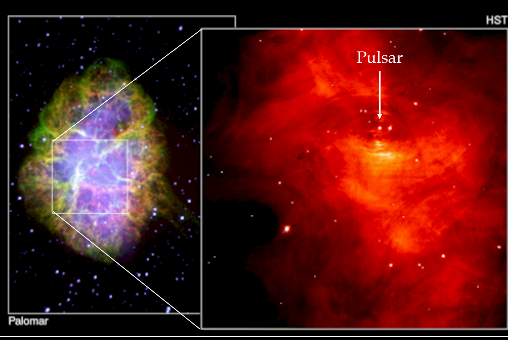
The Crab Nebula pulsar



Images by Jeff Hester, Arizona State U.

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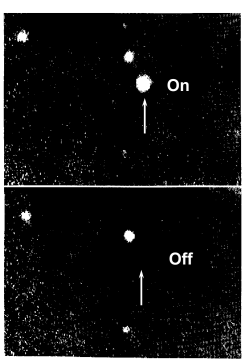
The Crab Nebula pulsar



The neutron star at the center of the Crab Nebula, seen as a pulsar in visible-light images taken 0.015 second apart.

- Note that the neutron star would be invisible, were it not for the pulsating emission. They're too small to appear as bright continuous sources of light. Not many non-pulsing neutron stars have ever been detected.

(Image oriented 100° counter-clockwise from the previous one.)

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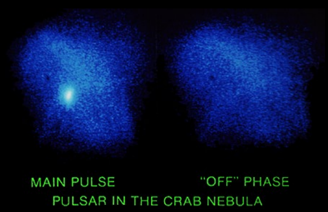
The Crab Nebula pulsar

Same again (i.e. images taken 0.015 sec apart) , but this time in X-rays, with the Chandra X-ray Observatory (CXO), and in the same orientation as page 31.



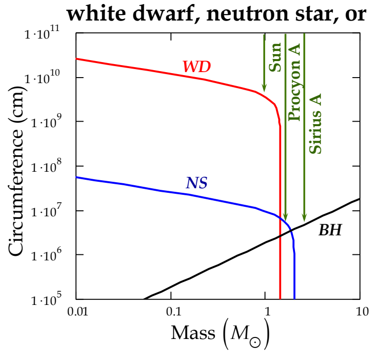
Summary: status of the Schwarzschild singularity and black holes

- Electron and neutron degeneracy pressure can prevent the formation of black holes from dead stars, but only for core masses below about $2M_\odot$.
- Stars with masses in excess of this must eject material during their final stages of life if they are to become white dwarfs or neutron stars.
- Judging from the large numbers of white dwarfs, neutron stars, planetary nebulae and supernova we see, the vast majority of stars do end their lives in this way.
- For core masses larger than this, a pressure stronger than the maximum neutron degeneracy pressure is required to prevent the formation of black holes.

Summary: status of the Schwarzschild singularity and black holes (continued)

- There aren't any elementary particles, heavier than neutrons and not radioactive at these high densities, that could provide a larger maximum degeneracy pressure.
- In fact, no force known to science exists that would prevent the collapse of a star with a core mass greater than $2M_\odot$ from proceeding to the formation of a black hole. **For very heavy stars, black hole formation is compulsory**. The Schwarzschild singularity is real!
- Einstein was very disappointed in this result, and never trusted it; but had he lived ten years longer, experiments and observational data would have compelled his acceptance.

Final collapse of burned-out stars: white dwarf, neutron star, or black hole?



If these stars do not eject mass while in their death throes, their fates are as follows: the Sun will become a white dwarf, Procyon A would become a neutron star, and Sirius A would become a black hole.

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Done on this beautiful day.

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