VIOLENT STELLAR DEATH & NEUTRON STARS

PROBLEM SET #4 ON WEBWORK – DUE TOMORROW AT MIDNIGHT

TI SURVEYS

VIOLENT STELLAR DEATH & NEUTRON STARS

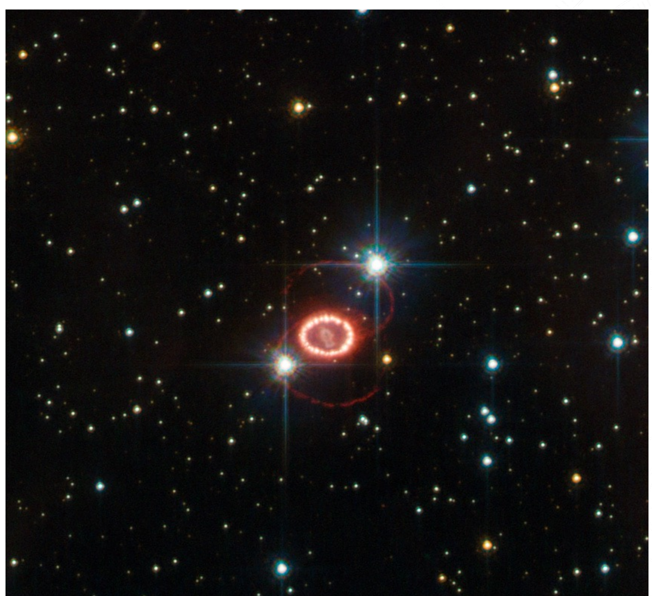
Type Ia supernovae

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?

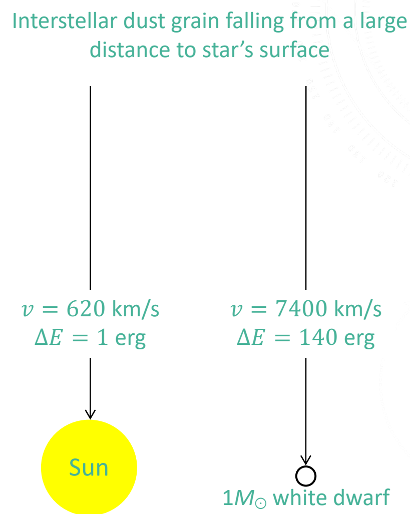


The remnant of supernova 1987A in the Large Magellanic Cloud, seen by the Hubble Space Telescope (ESA/Hubble, NASA)

HUGE, VIOLENT ASTROPHYSICAL EXPLOSIONS

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

- Material falling to the surface of such a star gains much more energy than the same stuff falling to the surface of a normal star of the same mass.
- This extra energy has to go somewhere, and eventually winds up 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 surface from which to bounce
- Either way, this can produce gigantic explosions.



WHITE DWARFS, NOVAE, AND TYPE IA SUPERNOVAE

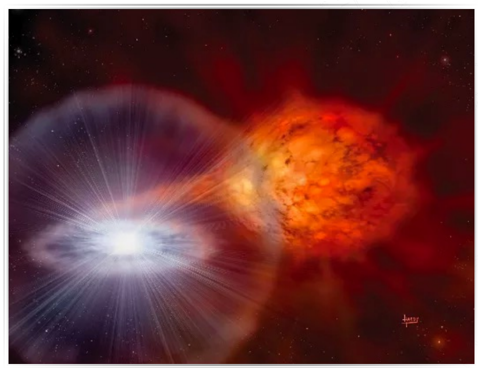
Artist's conception of classical nova Z Camelopardalis (GALEX/Caltech/NASA)

Sometimes, white dwarfs (WDs) are found in binary systems with ordinary stars in orbits that are 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.
  - **Type Ia supernova (SNIa):** about 10^{51} erg released, stars brighten by a factor of about 10^{10}, **WD destroyed.**

WHITE DWARFS, NOVAE, AND TYPE IA SUPERNOVAE

- SNIa happen when fusion in the material acquired from the normal star ignites fusion of carbon and oxygen nuclei throughout the entire WD.
- In turn, this 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 about the same for all of them, the energy released (and luminosity) is as well: SNIa are bright "standard explosions."
- This makes SNIa very useful for measuring distances to galaxies, and we will meet them again in that context.



Artist's conception of a WD accreting material and going supernova (David Hardy)

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TYPE IA SUPERNOVA

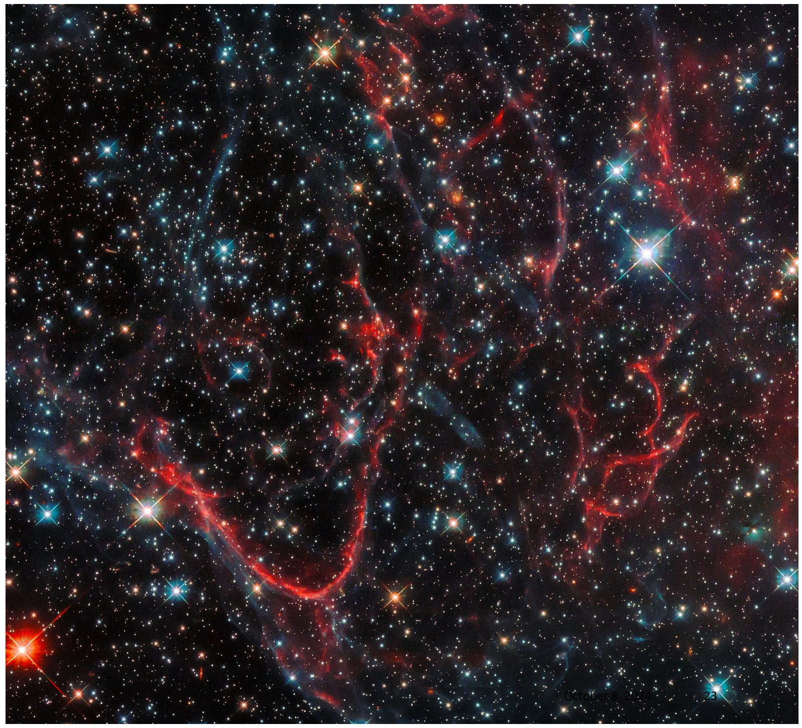
Similar in appearance to planetary nebulae, Type Ia supernova remnants are layered based on the material that the explosion expelled from the white dwarf.

G299, in the Milky Way (NASA/CXS/U. Texas)

TYPE IA SUPERNOVA

The material from a supernova continues to expand and move away from its original source. As it expands, it disperses into the interstellar medium, and eventually becomes the material for the next generation of stars and planets.

SNR 0454-67.2, in the Large Magellanic Cloud (NASA/ESA Hubble)



FINAL IMPLOSION OF MASSIVE BURNED-OUT STARS

Electron degeneracy pressure can hold up a star of mass $1.44M_{\odot}$ or less against its weight, and do so indefinitely. Stellar cores in this mass range at death become white dwarfs.

For heavier stars ($\geq 8M_{\odot}$), gravity overwhelms electron degeneracy pressure, and the collapse does not stop with the star at planet size.

- As the star is compressed 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:
$$p + e^- + \text{energy} \rightarrow n + v_e$$
- Eventually, 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**.

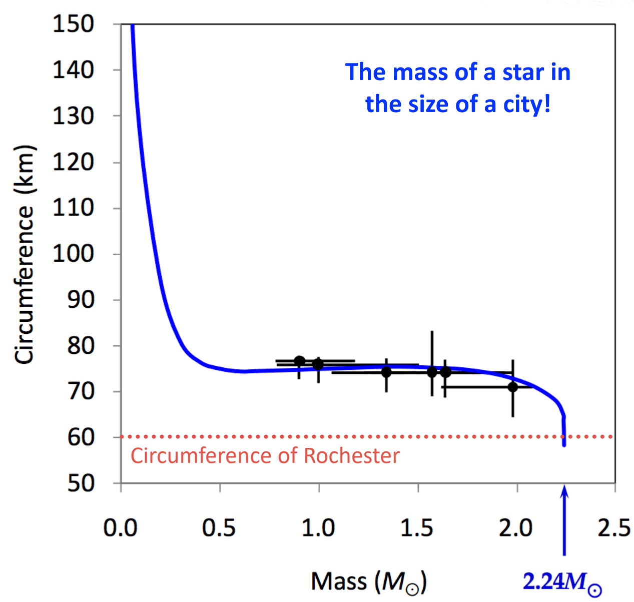
OPPENHEIMER'S THEORY OF NEUTRON STARS

Neutron stars were first proposed to exist, and to cause supernovae by their formation, by Zwicky & 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.
- First calculation of maximum mass: Oppenheimer & Volkoff (1939). They got $0.7M_\odot$; more recent calculations with improvements of the nuclear forces gives about $2.2M_\odot$.

OPPENHEIMER'S THEORY OF NEUTRON STARS

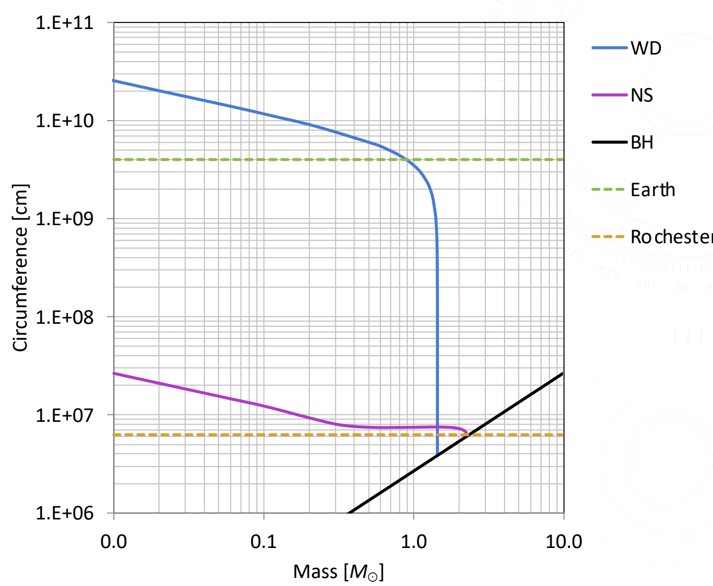
Same calculation as Oppenheimer and Volkoff, but with updated inputs for the strong nuclear force.



OPPENHEIMER'S THEORY OF NEUTRON STARS

A $1M_{\odot}$ neutron star and Rochester, NY (shown on the same scale)

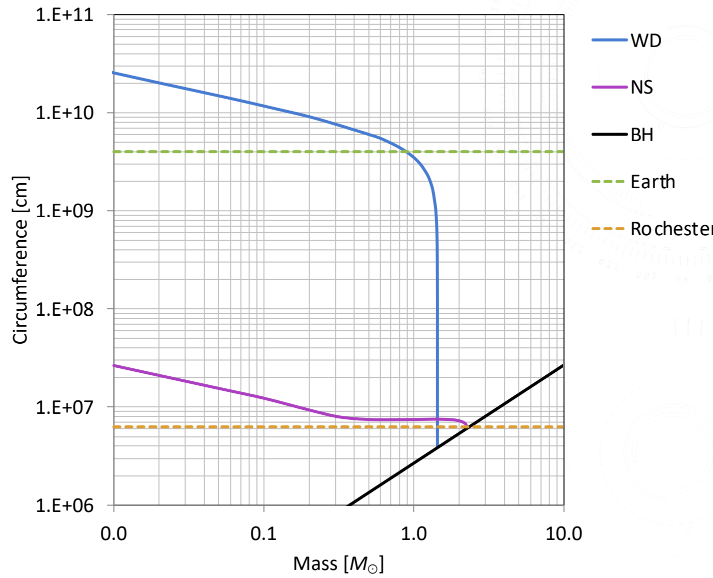
WHITE DWARFS, NEUTRON STARS, & BLACK HOLES



GRAPH PRACTICE

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

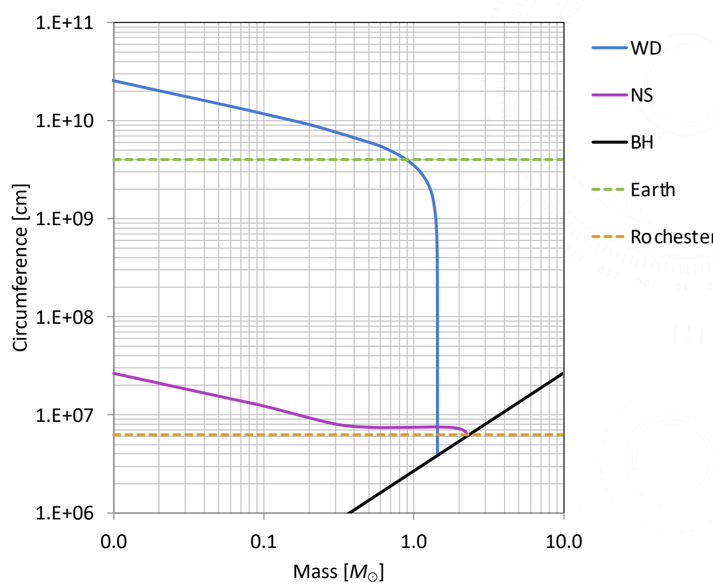
A. 1 (They are the same size.)
B. 10
C. 100
D. 1000



GRAPH PRACTICE

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

A. 1 (They are the same size.)
B. 5
C. 10
D. 50
E. 100

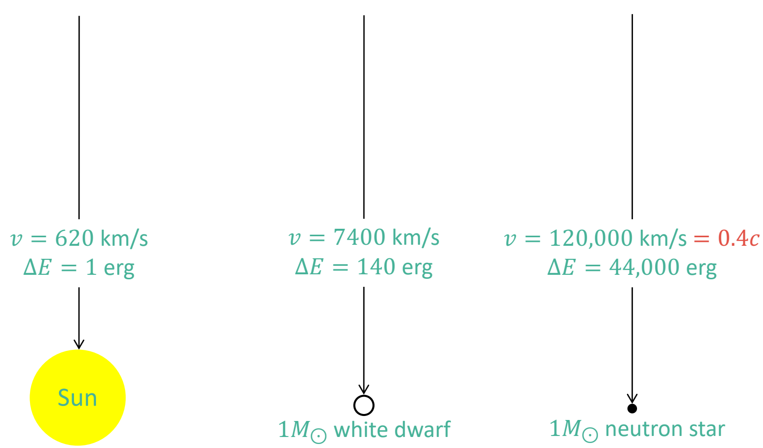


NEUTRON STAR FORMATION & TYPE II SUPERNOVAE

- 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 & TYPE II SUPERNOVAE

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

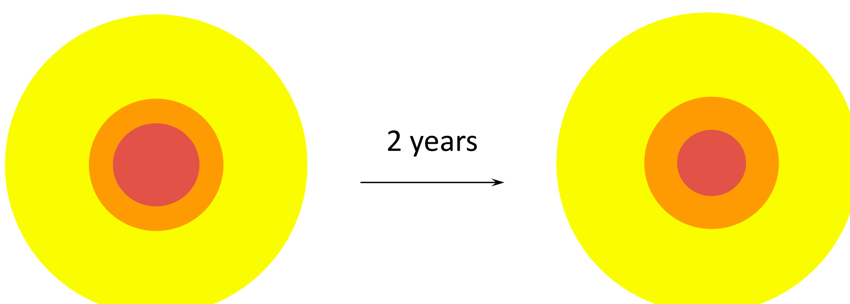


NEUTRON STAR FORMATION & TYPE II SUPERNOVAE

- The outer, collapsing material that did not 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.
- Because this process will work for just about any star $8M_{\odot}$ and heavier, the released energy varies much more from SNII to SNII than from SNIa to SNIa.

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

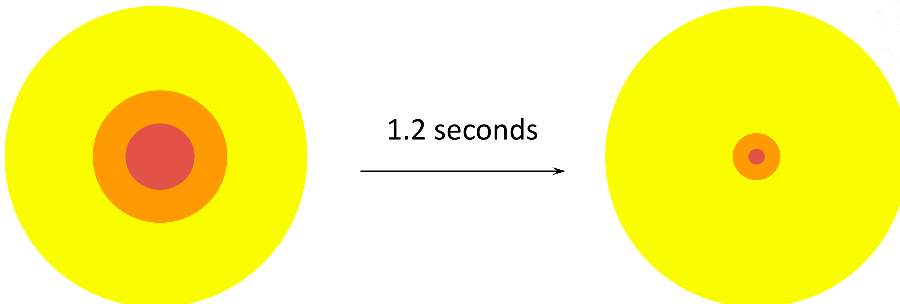
TYPE II SUPERNOVA (SNII), NOT DRAWN TO SCALE



Star: $8M_{\odot}$, 10^7 km circumference
Core: $1.5M_{\odot}$, 10^5 km circumference

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

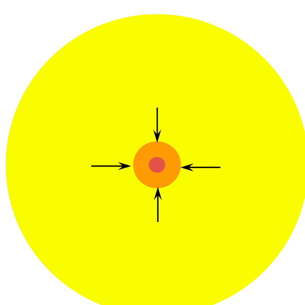
TYPE II SUPERNOVA (SNII), NOT DRAWN TO SCALE



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

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

TYPE II SUPERNOVA (SNII), NOT DRAWN TO SCALE

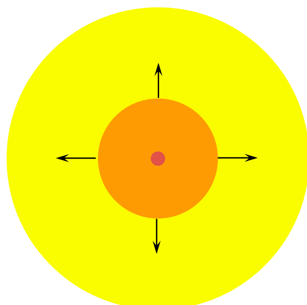


Core: 70 km circumference, neutron degeneracy pressure sets in. This makes the core very stiff.

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

TYPE II SUPERNOVA (SNII), NOT DRAWN TO SCALE

A few seconds

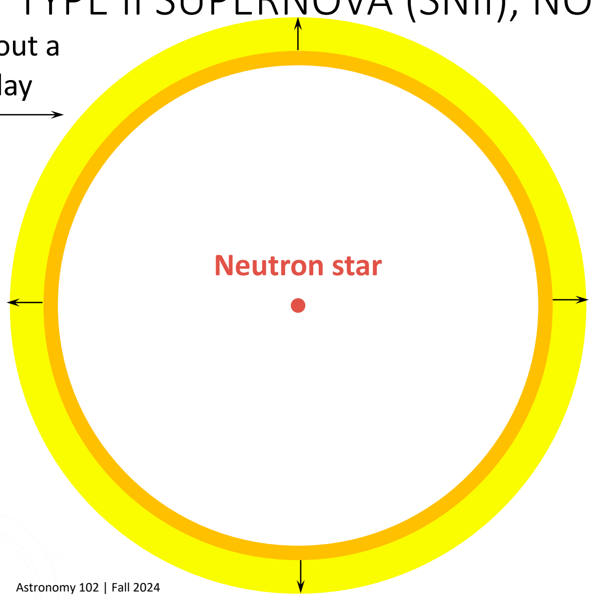


Core: still 70 km circumference; it is now stable.

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

TYPE II SUPERNOVA (SNII), NOT DRAWN TO SCALE

About a day



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

SUPERNOVA 1987A

Before

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

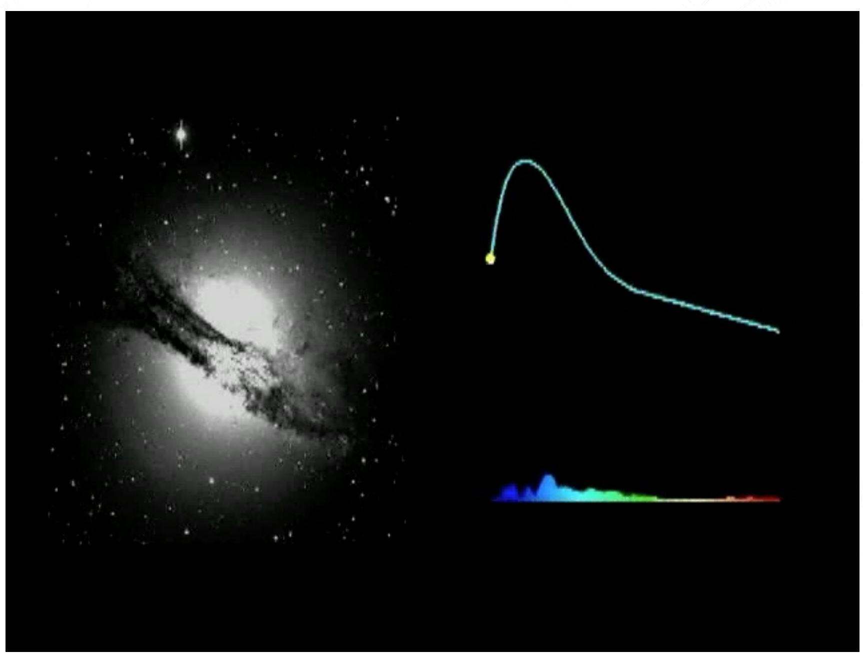
After

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

THE APPEARANCE OF A SUPERNOVA AS TIME PASSES

Animation of the first month after the explosion of a Type Ia supernova (Supernova Cosmology Project, UC Berkley)



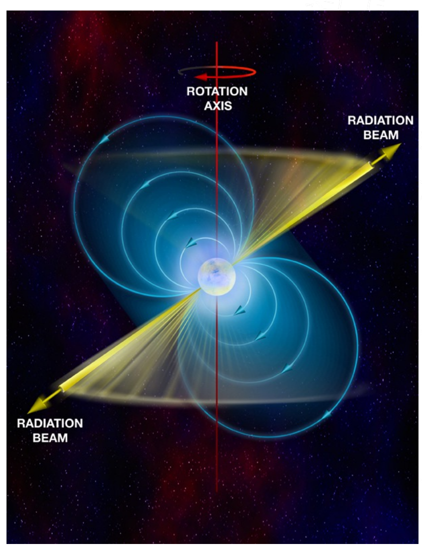
NEUTRON STARS, SNII, & PULSARS

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

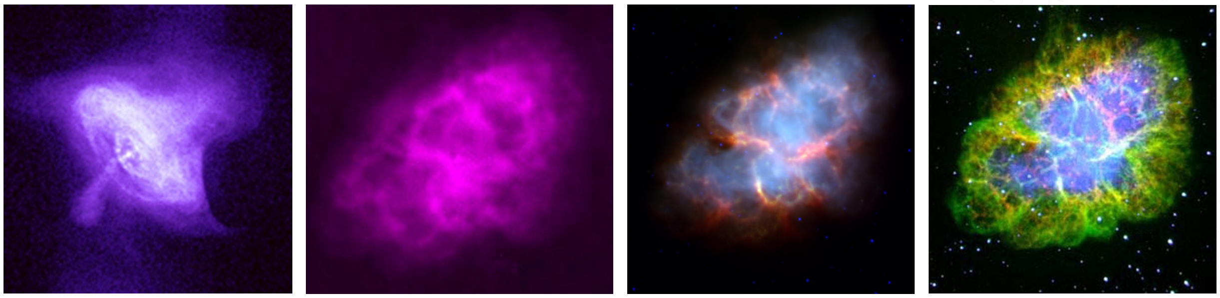
- Discovered in 1967 by Cambridge graduate student Jocelyn Bell, they were almost immediately identified as rotating neutron stars that emit “beams” of light by accelerating electrons and protons outward along their magnetic poles. (They pulse like a lighthouse does.)
- Many young supernova remnants contain pulsars.
- Several pulsars occur in binary systems, for which masses can be accurately measured; all turn out to be around $1.4 - 1.5M_{\odot}$, comfortably less than $2.2M_{\odot}$ and greater than the maximum white-dwarf mass.

NEUTRON STARS & PULSARS

- One teaspoonful of a neutron star would weigh a billion tons.
- When a neutron star forms, it is generally spinning.
- We can see the neutron stars because most of them have jets of particles bouncing off of them, moving away with speeds close to 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.



https://www.nrao.edu/pr/2006/mspulsar/



THE CRAB NEBULA (M1, SN1054) – THE ARCHETYPE SNII REMNANT

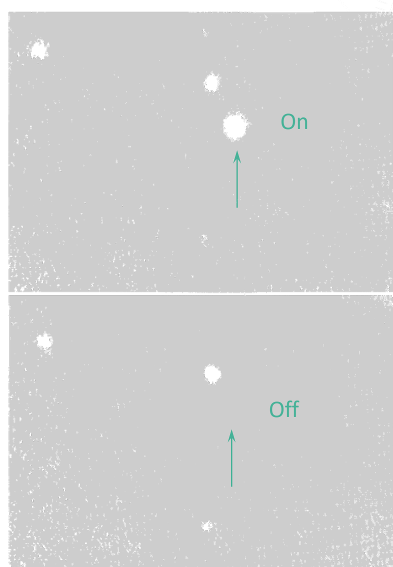
Left to right: X-ray continuum (CXO/CfA/NASA), visible spectral lines (Palomar Observatory/Caltech), infrared continuum (Spitzer/NASA), radio continuum (VLA/NRAO)

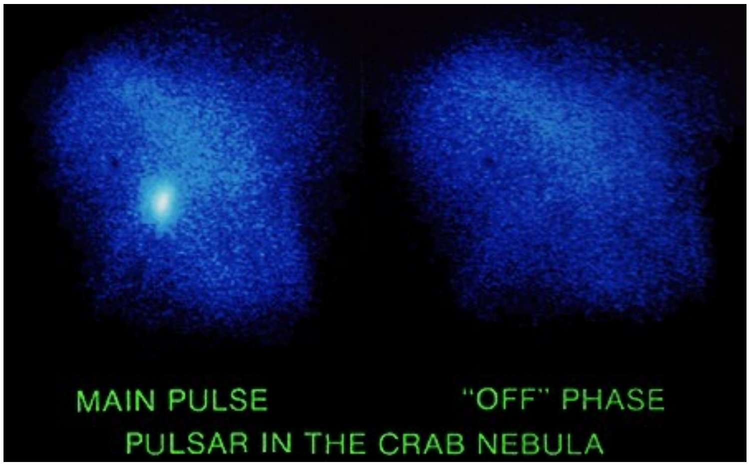
THE CRAB NEBULA PULSAR

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

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

Image rotated 100° counterclockwise from the previous slide.





THE CRAB NEBULA PULSAR

Again, images taken 0.015 seconds apart in the X-ray (Chandra); same orientation as original.

SUMMARY – SCHWARZSCHILD SINGULARITY & 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 number of white dwarfs, neutron stars, planetary nebulae, and supernovae that we see, the vast majority of stars 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.
- There are not 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. Had he lived 10 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 Canopus would become a black hole.