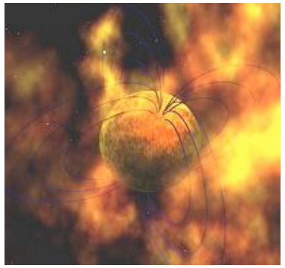
Lecture 11: Neutron stars, pulsars and black holes

- Neutron stars
- Pulsars
- X-ray binaries and novae
- Black holes
- Supermassive black holes and active galaxies

Neutron stars

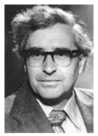


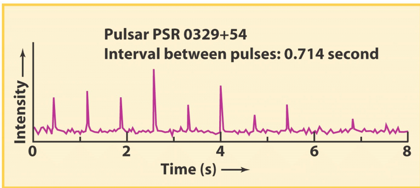
Artist's impression of a magnetised neutron star

- A white dwarf more massive than the Chandrasekhar limit (1.44 $M_{\odot}$) cannot be supported by electron degeneracy pressure, and will collapse to a much denser state, forming a neutron star.
- Neutron stars are held up against their own intense gravity by neutron degeneracy pressure (neutrons are also fermions, and hence resist compression).
- Any rotation or magnetic field present in the progenitor star will be greatly magnified during this collapse.
- A 1.44 $M_{\odot}$ neutron star is only about 10 km in radius. The density of such a star is 10^{17}-10^{18} kg m^{-3}. (i.e. ~10^8 tonnes per teaspoonful!)
- How do we know that neutron stars exist? One powerful source of evidence is pulsars.

The discovery of pulsars

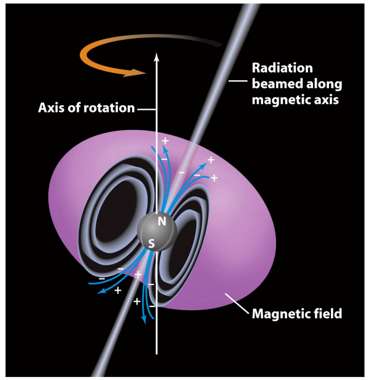
- Pulsars were first detected in 1967 by Cambridge University postgraduate student Jocelyn Bell, using a novel radiotelescope built by Anthony Hewish.
- Radio sources showing very regular pulsations with periods ~1 s.
- Could a star rotate this fast?



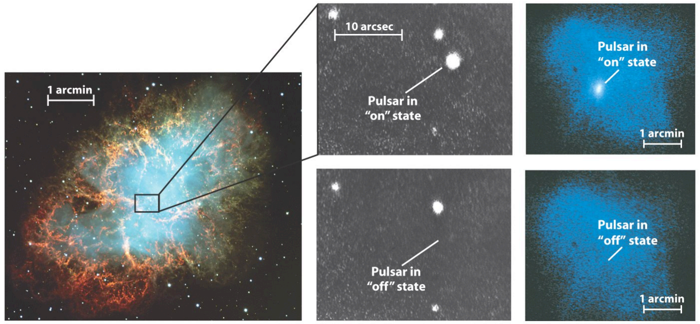


Pulsars are rapidly rotating neutron stars with intense magnetic fields

- The widely accepted model for pulsars is that they are rapidly rotating neutron stars.
- The pulses seen are produced as beams of radiation from a neutron star's magnetic poles sweep past the Earth.
- The beams are generated by charged particles trapped in the star's intense magnetic field.

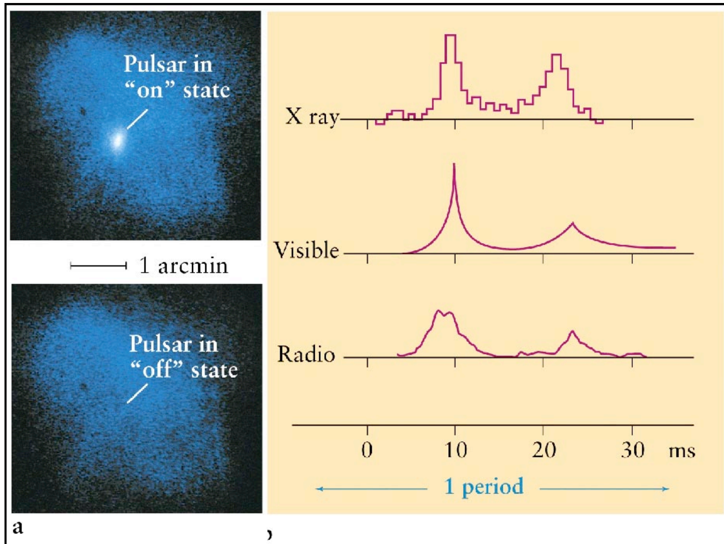


The Crab pulsar

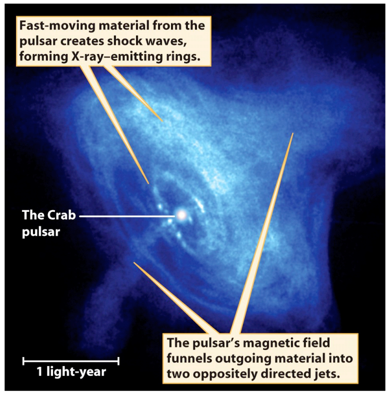


(a) The Crab Nebula (b) The Crab pulsar in visible light (c) The Crab pulsar in X rays

The pulsar in the Crab nebula supernova remnant pulsates at all wavelengths, with a period of only 33 ms.



Pulsars gradually slow down as they radiate energy

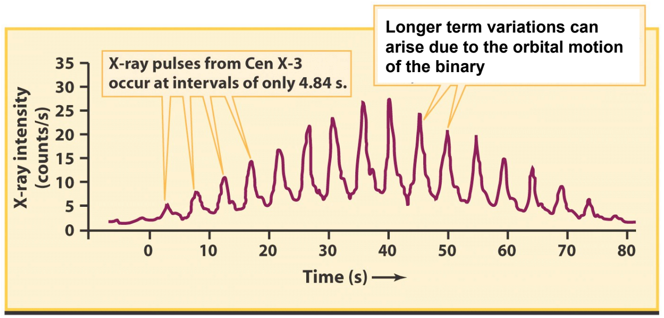


Chandra X-ray image of the Crab nebula

- The Crab pulsar is slowing down by $3x10^{-8}$ s per day.
- Electrons moving in a circular path at enormously high speed release energy in the form of synchrotron radiation.
- High energy particles also stream out into the surrounding nebula, and the loss of angular momentum slows the rotation.
- Hence older pulsars generally have longer pulse periods. The Crab is only ~1000 years old.

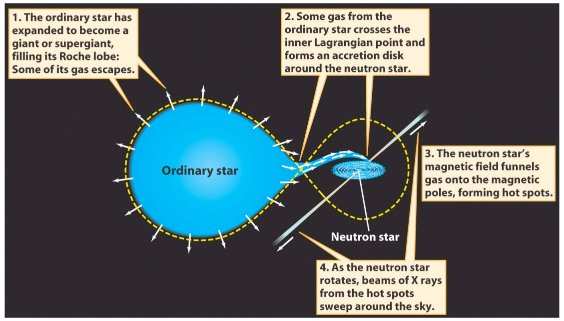
Some much more variable pulsating X-ray sources are neutron stars in close binaries

- Cen X-3 is an example of a bright pulsating X-ray source which also varies substantially on longer timescales.



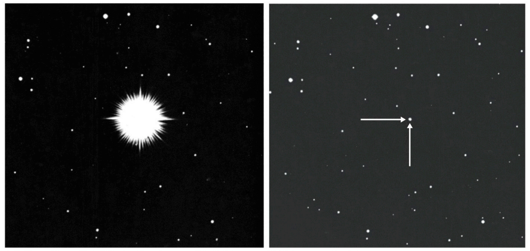
Some much more variable pulsating X-ray sources are neutron stars in close binaries

- Magnetic forces funnel gas accreting from a companion star onto the neutron star's magnetic poles, producing hot (~10^8 K) spots.
- These hot spots radiate intense beams of X rays.
- As the neutron star rotates, the X-ray beams appear to flash on and off.
- Periodic variations at the orbital period (typically days) may also be seen.

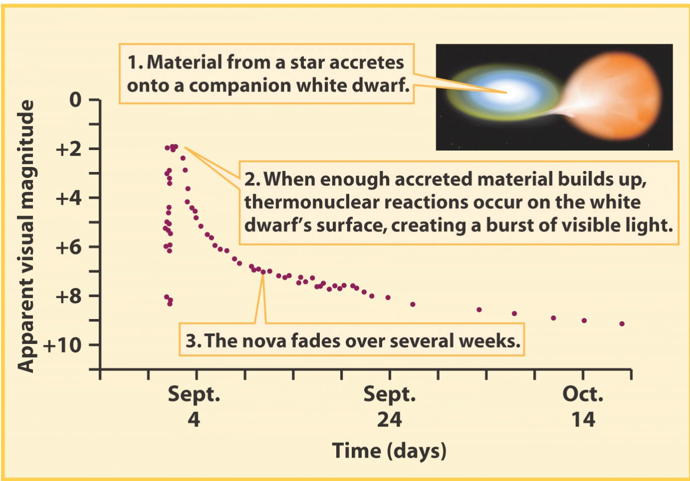


More binaries: novae and X-ray bursters

- Some stars which have high energy radiation (e.g. X-rays) also show remarkable outbursts.
- For example, novae exhibit a rise in optical brightness by a factor of 1000 or more, which then decays away on a timescale of weeks.
- The peak optical luminosity is ~10^{-4} of that observed in a supernova.
- Detailed studies have shown that a nova results from a thermonuclear explosion on the surface of a white dwarf, which is accreting material from a companion star in a close binary.



(a) Nova Herculis 1934 shortly after peak brightness (b) Two months later



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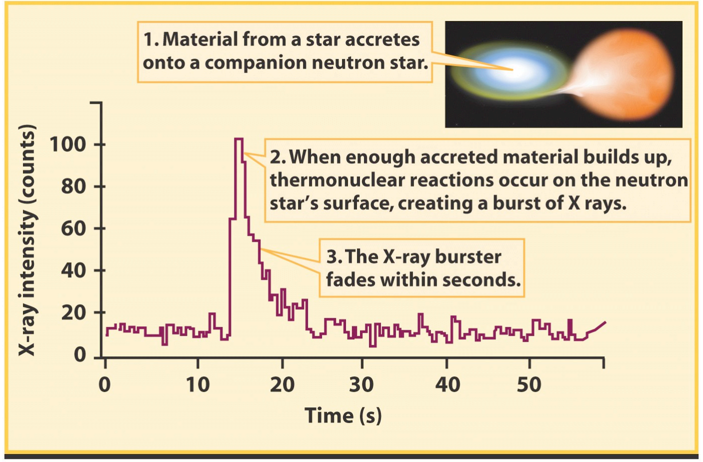
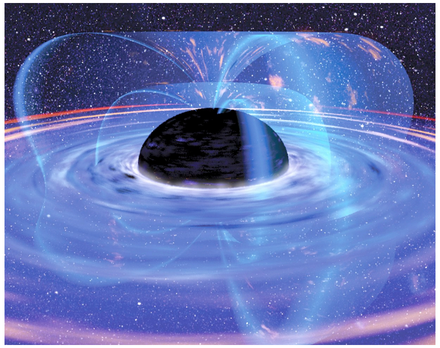
- A similar phenomenon, happening at higher energies and on shorter timescales, is seen the the X-ray burst sources.
- These emit flashes of bright X-ray emission lasting less than 1 minute.
- This is believed to occur due to a thermonuclear flash on the surface of an accreting neutron star.

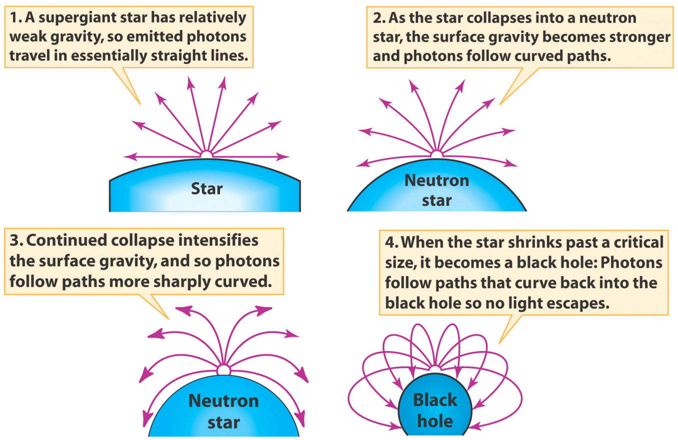


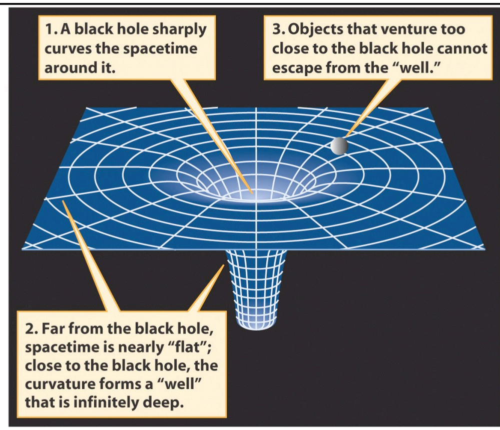
Black Holes

- Stellar cores that are more massive than about 3 $M_{\odot}$ have too strong a gravitational field to be supported by even neutron degeneracy pressure → collapse to a black hole



The general theory of relativity predicts black holes

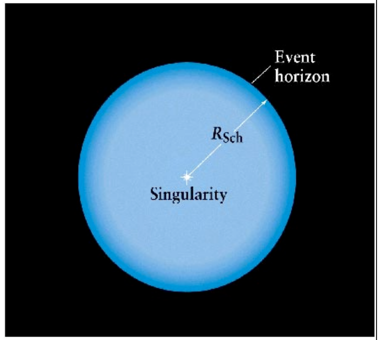




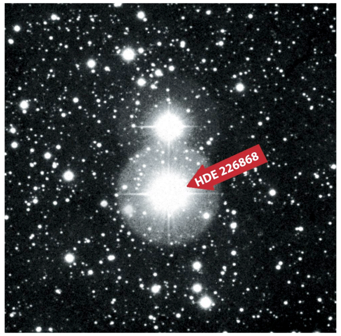
- General Relativity views gravity as resulting from curvature of spacetime
- In the vicinity of a black hole the spacetime is *very* strongly curved

A non-rotating black hole has only a "centre" and a "surface"

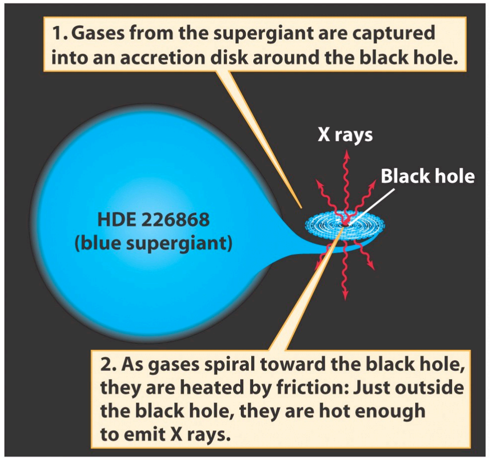
- The entire mass of a black hole is concentrated in an infinitely dense central singularity
- The black hole is surrounded by an event horizon where the escape speed equals the velocity of light
- No radiation can escape from within the event horizon
- The distance between the black hole and its event horizon is the Schwarzschild radius: $R_S = 2GM/c^2$



How do we know that black holes exist?

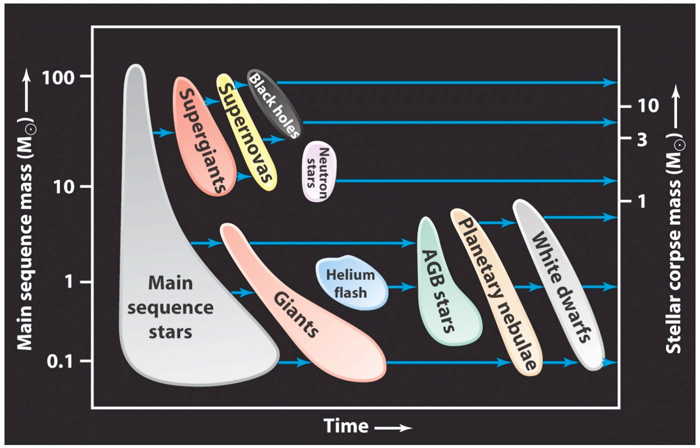


- Black holes have been detected using indirect methods
- A black hole in a binary star system can accrete material from a companion as in a neutron star binary
- Material in the accretion disk surrounding the black hole moves at speeds close to *c*, and friction heats it to T~10^8 K, so that it emits X-rays
- An X-ray binary, such as Cygnus X-1, which has an invisible compact component with mass >5 $M_{\odot}$, almost certainly indicates the presence of a black hole

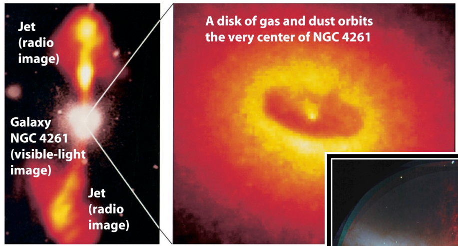


A schematic diagram of Cygnus X-1

Summary - pathways of stellar evolution

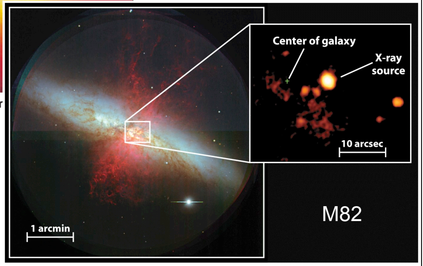


Supermassive black holes are believed to exist at the centres of most galaxies



(a) Galaxy NGC 4261 (b) Evidence for a superr NGC 4261

HST image of dust torus around central black hole



- SMBH are inferred by observing the motions of material around the black hole.
- Galaxies with large accreting black holes may emit energetic jets of material. These are known as Active Galaxies.