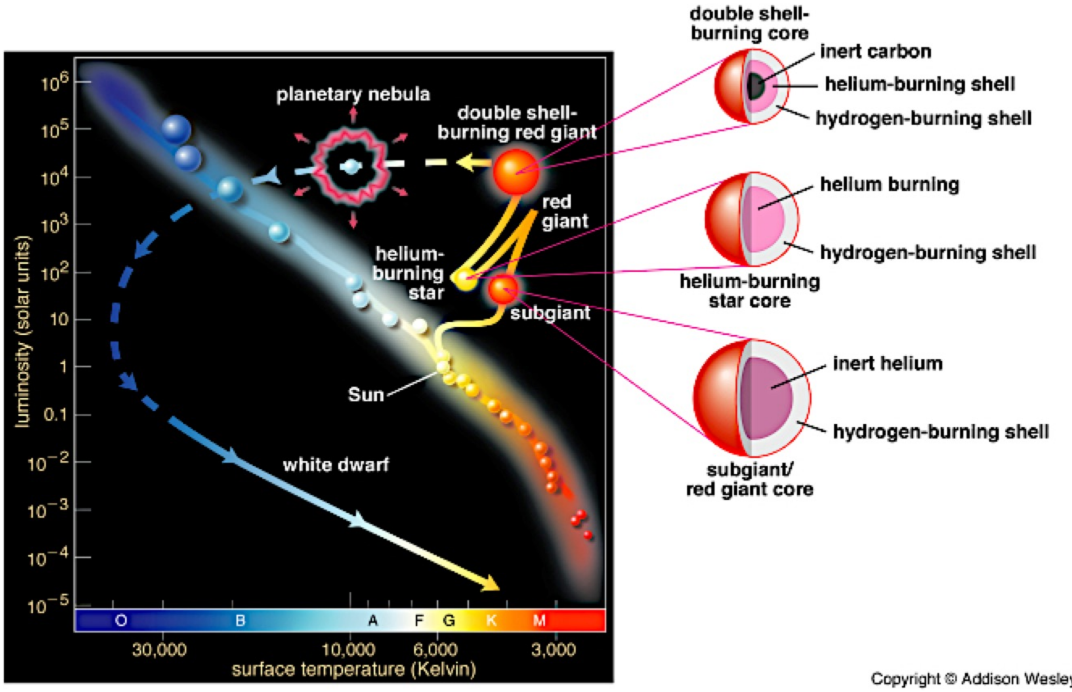
Class 11 : Neutron stars and pulsars

ASTR350 Black Holes (Spring 2020)
Prof. Richard Mushotzky

RECAP

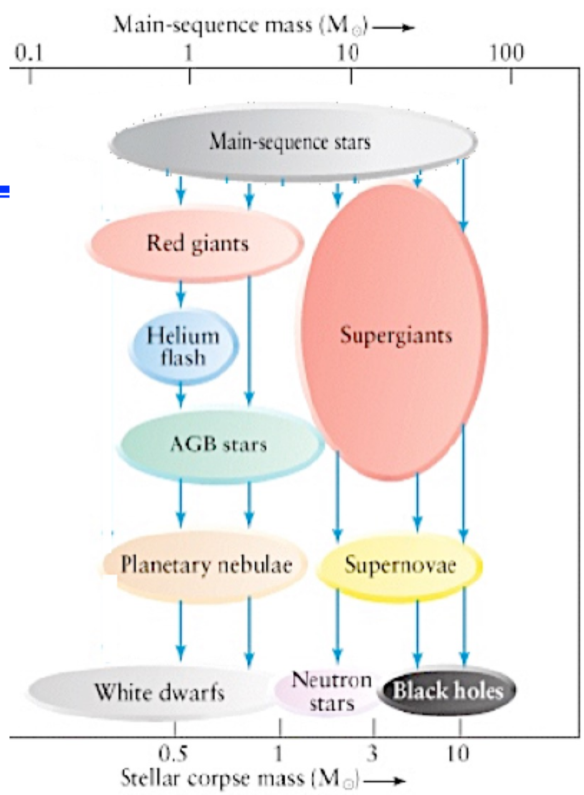
- Stellar life and death
- Low mass stars ($M<8M_{sun}$)
  - Most of long life on main sequence (H→He)
  - After exhausting hydrogen in core, enters complex post-MS evolution passing through Red Giant phase
  - End with a White Dwarf ($M>0.4M_{\odot}$)
- High mass stars ($M>8M_{sun}$)
  - Core temperatures are much hotter- short lives
  - Run through H more quickly, then start to burn other elements.
  - End up with shells of successively heavier elements, ending with an iron core
  - Collapse of iron core produces neutron star or black hole



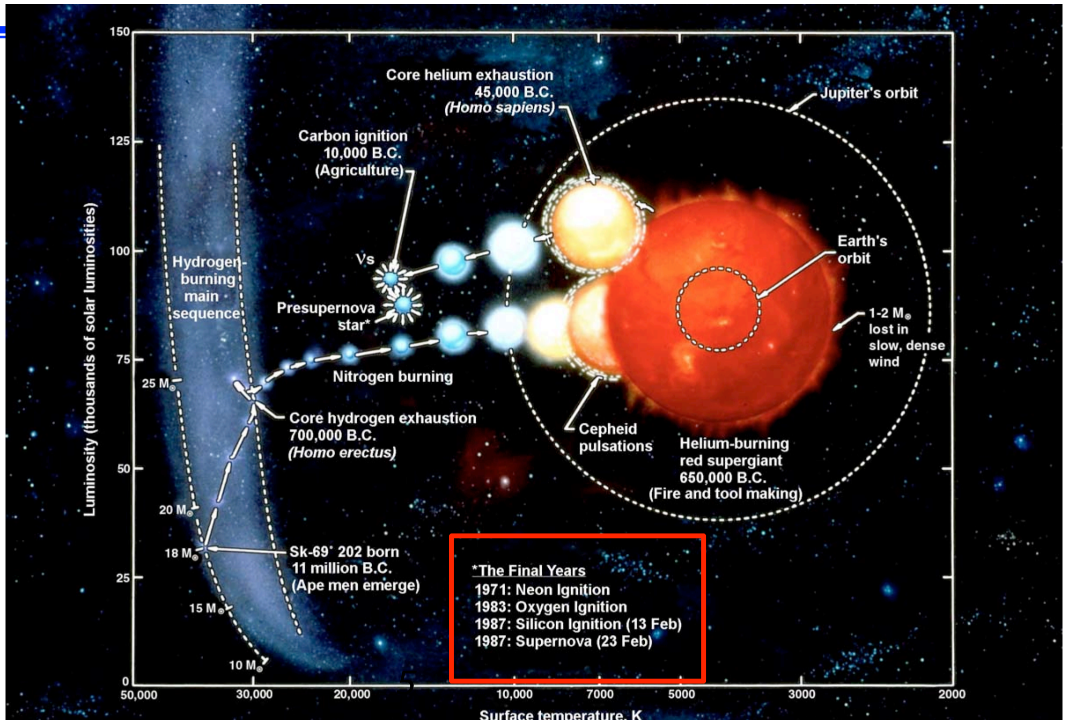
http://astronomyonline.org Copyright Addison Wesley

Recap-Progenitors of Compact Objects

- Main sequence stars evolve and at the end of their 'life' (period of nuclear burning) end up as compact objects
  - $t_{MS}/t_{sun} \sim (M/M_{sun})^{-2.5}$
- The most massive can end up as black holes or neutron stars.
- The least massive as white dwarfs (the main sequence lifetime of stars less than ~1/2 M_{sun} is greater than the Hubble time so they never get to be white dwarfs)



SN1987A- AKA SK-69-202 - Short But Exciting Life
Original Mass = 18 $M_{\odot}$



Recap-Origin and Basic Properties

- The collapse of massive stars can end when the degeneracy pressure of neutrons balances the gravitational forces of the matter (ignoring the strong force-baryonic interactions)-produces a neutron star.
  - The term neutron star refers to a star with a mass M on the order of 1.5 $M_{\odot}$, radius R of~8-16km, and a central density as high as 5 to 10 times the nuclear equilibrium density
- If the remnant is too massive- collapse to black hole (actually more complex)

Importance of Supernova

- Supernovae are the source of many of the elements of nature
- their blasts control the structure of the interstellar medium
- They are the origin of most cosmic-rays
- A majority of them give birth to neutron stars and black holes.
- can be seen across the Universe and have been used to determine cosmological parameters (modified from Burrows 2015)

This class

- Discovery of pulsars-first direct evidence of neutron stars
- Connection of neutron stars to pulsars
- Exotic nature of neutron stars

I : Discovery of pulsars

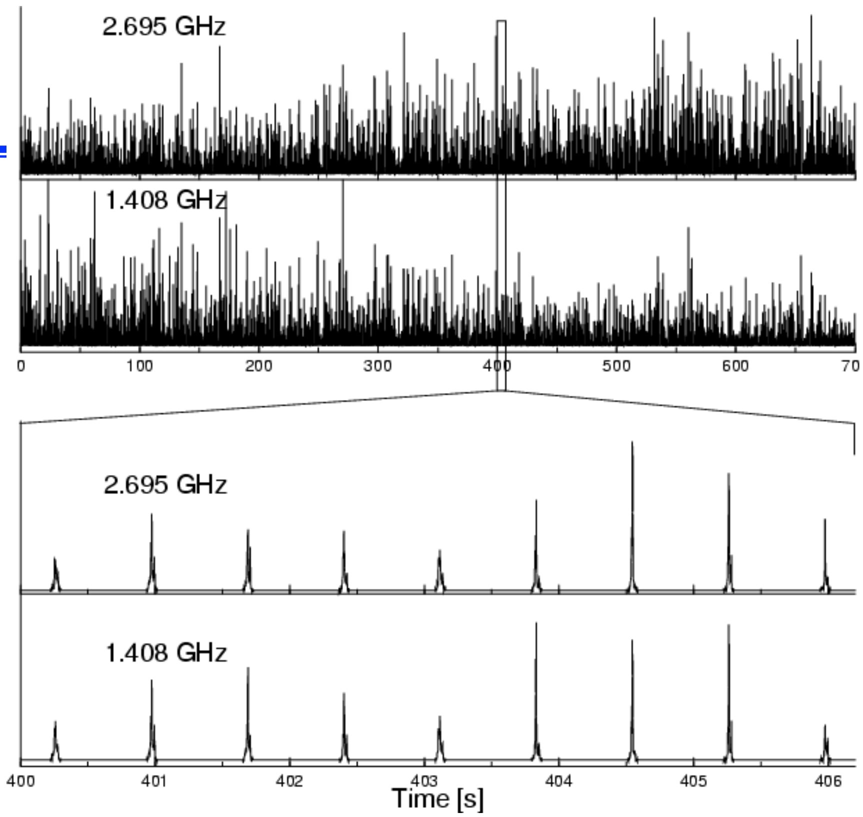
- Bell & Hewish (1967)
  - Constructed new type of radio telescope to study radio emission from quasars
  - Bell noticed a periodic signal… a blip/pulse every 1.33s
  - The pulse that lasted only 0.3 seconds. Its rapid rise and fall time meant the source had to be small, only a tenth of a light-second across.
  - the pulse repeated every 1.337 seconds with extreme regularity, and so tapped some constant large source of energy
  - This was termed a **pulsar**
  - What could this be?
    [Discussion!]
  - The Bell pulsar was just tip of the iceberg- over 2000 now known !

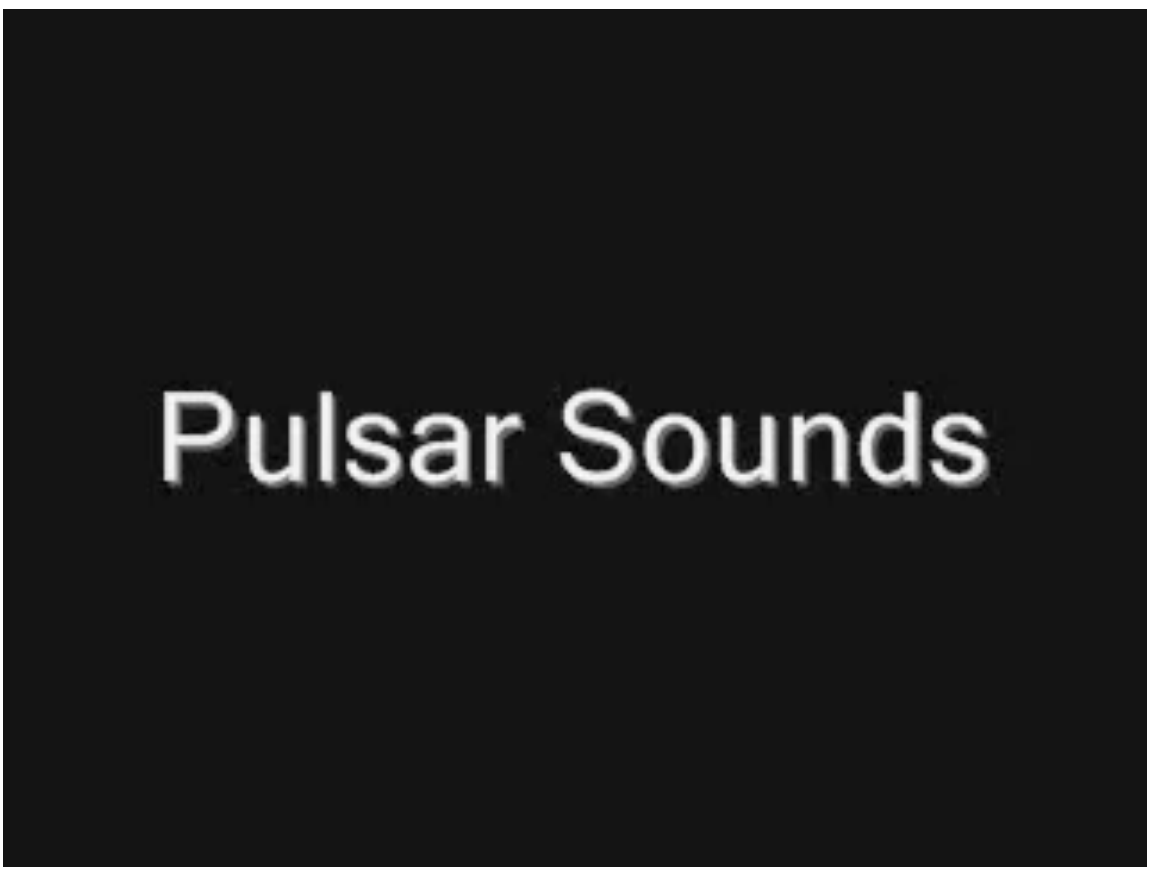
Discovery of pulsars

First 'discovered' by Hewish et al 1967 (Noble prize)

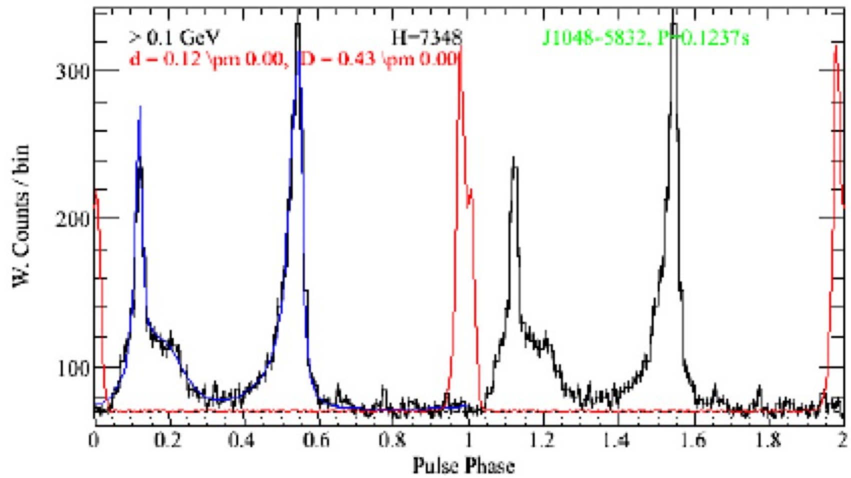
Rapidly realized that these were neutron stars- idea had been around since the 1930's

Two different radio frequencies (sound of pulsar)





Neutron Stars



Radio (black) and γ-ray (red)
pulse profiles from a neutron star

History: Baade and Zwicky

Walter Baade

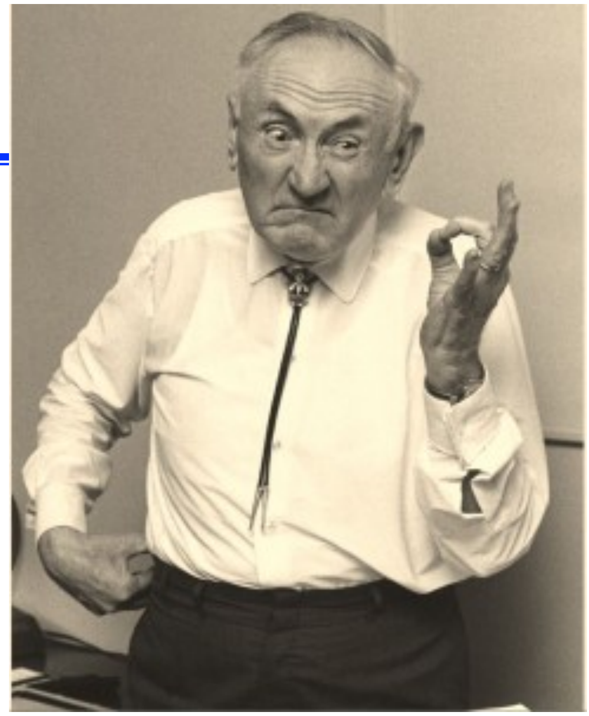
"With all reserve, we advance the view that a *supernova* represents the transition of an ordinary star into a *neutron star* consisting mainly of neutrons…

Baade & Zwicky (1934)

Just 2 yrs after the discovery of the neutron!

Fritz Zwicky

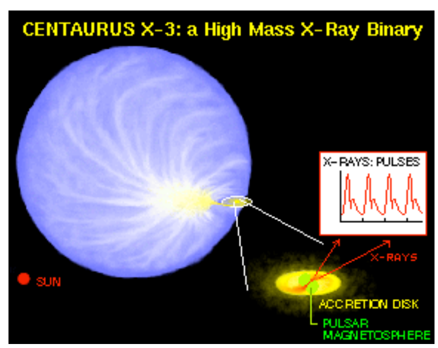
1934, Baade and Zwicky proposed the existence of the neutron star
- 2 years after Chadwick's discovery of the neutron !
- they proposed that the neutron star is formed in a supernova and *"consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density."*



Frits Zwicky (1998-1974)

Neutron Stars

- 1934, Baade and Zwicky proposed the existence of the neutron star a year after Chadwick's* discovery of the neutron - they proposed that the neutron star is formed in a **supernova**
- 1967, Shklovsky explained the X-ray and optical observations of Scorpius X-1 (the first non-solar) **x-ray** source as radiation coming from a neutron star v**ia accretion.**
- 1967, Jocelyn Bell and Antony Hewish** discovered regular **radio** pulses from the Crab-radiation from an isolated, rotating neutron star. The energy source of the pulsar is the **rotational energy** of the neutron star.
- 1971, Giacconi*** et al discovered 4.8 sec pulsations in an **X-ray** source in the constellation Centaurus, Cen X-3: Emission from a rotating hot neutron star. The energy source is the same as in Sco X-1



**Nobel laureate in physics awarded for his discovery of the neutron.*

*** Nobel laureate in physics 1974*

****Nobel laureate in physics 2002*

II : Pulsars are rotating neutron stars

- A rotating star will fly apart if the centrifugal force of rotation exceeds its gravitational force… it turns out to be the density of the star that matters.
  - Many pulsars rotate so rapidly that even a dense white dwarf would fly apart if it rotated that quickly… need something even higher density
  - This led people to seriously consider the idea of a neutron star

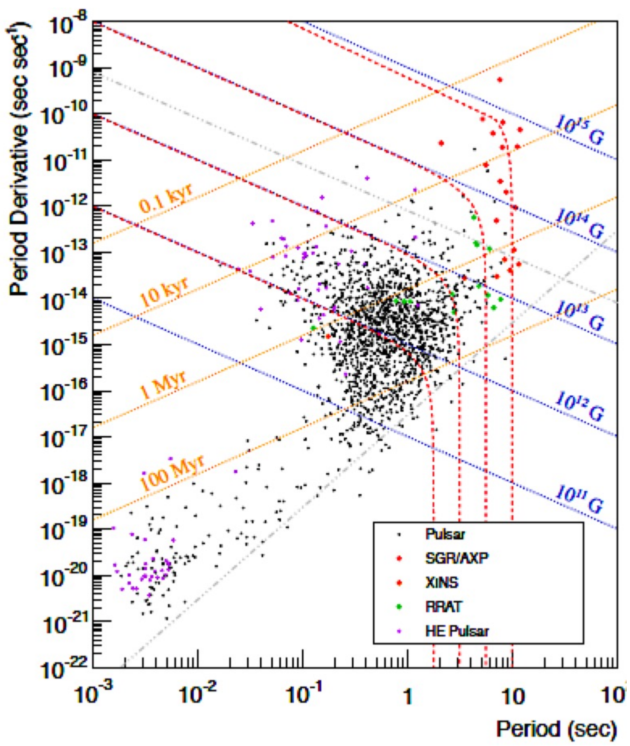
- So… **Pulsars are rotating neutron stars with intense magnetic fields**
  - The pulsed radiation is created by charged particles accelerated in the *spinning magnetic field* which is beamed along the magnetic axis
  - A lot of evidence for this idea now… e.g., can measure the moment of inertia of the central object and we find the expected value for a neutron star

Why Strong Magnetic Fields

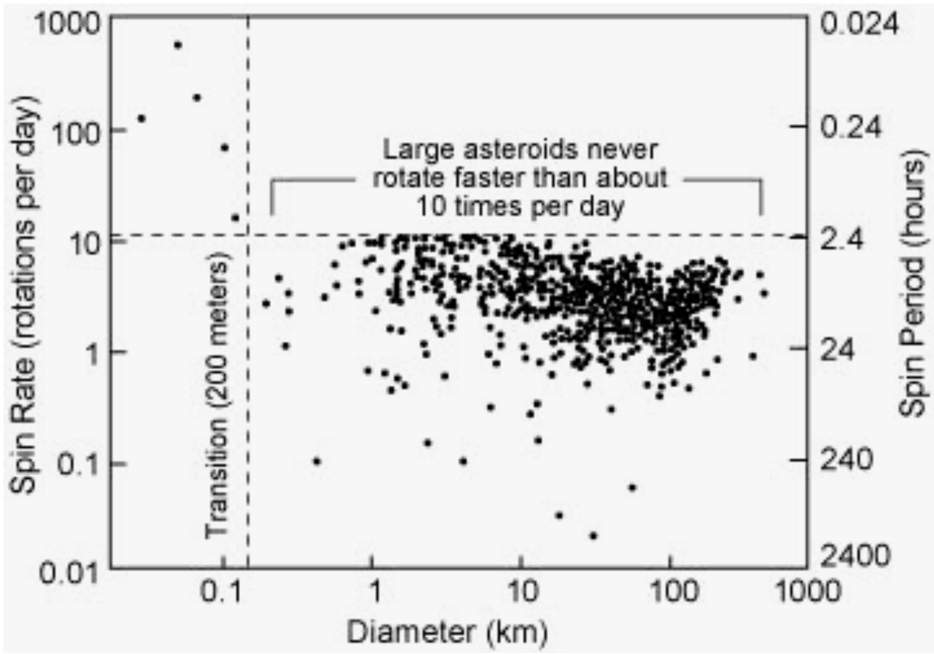
- The most 'common' observational population are non-accreting pulsars (>3000 known, https://www.atnf.csiro.au/people/pulsar/psrcat/)
- Periods (P) from 0.001-100 secs
- 22 orders of magnitude range in dP/dt
- dipole magnetic

$B_s \sim 10^{19}(P/dP/dt)^{1/2}$

P is in seconds, B in gauss



Spin Periods of Asteroids



Quick Quiz

A. Asteroids are not born rotating fast
B. There is no mechanism to spin up asteroids that fast
C. If asteroids rotate too fast they break-up
D. We cannot measure the rotation speed if the asteroid is rotating too fast.

The lack of objects rotating faster than 2.2 h period among asteroids, as well as the tendency to spheroidal shapes of fast rotators, is evidence that asteroids larger than a few hundred meters are mostly loosely bound, gravity-dominated aggregates with negligible tensile strength (“rubble piles”)

Icarus
Volume 148, Issue 1, November 2000, Pages 12-20
Fast and Slow Rotation of Asteroids
Petr Pravec & Alan W. Harris

Origin and Basic Properties

- Neutron stars are the very dense (denser than atomic nuclei) remnants of massive stars whose cores collapse during the supernova explosions at the end of their nuclear fusion lifetimes.
- Conservation of angular momentum and magnetic flux (?) of the progenitor star during the collapse gives the neutron star an extremely high spin rate and a high magnetic field.

Nuclear density $n=A/(4/3\pi R_0^3)= 3/4\pi(1.25\ \mathrm{fm})^3=0.122(\mathrm{fm})^{-3}$

A is the mean mass number ; $R_0 \sim 1.2\mathrm{fm}$

What Does Spinning Fast Tell Us

- The shortest period (*or angular velocity Ω*) which a star of mass M and radius R can have without being torn apart by centrifugal forces is (approximately)
- $\Omega^2 R \sim GM/R^2$
- Putting in the average density of the star ρ,
- $\Omega \sim (G\rho)^{1/2}$
- Putting in some numbers rotation periods of $P=2\pi/\Omega <1$ sec requires density of $>10^{11}\mathrm{kg/m^3}$
- fastest possible rotation frequency is

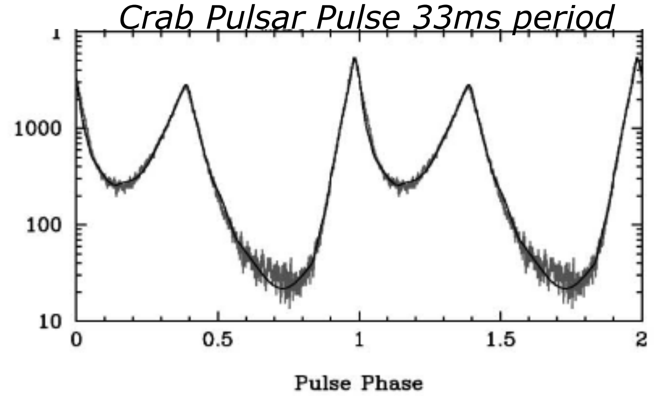
$$\tau=0.461\mathrm{ms}\ (R/10\mathrm{km})^{3/2}(M/1.4M_{\odot})^{-1/2}$$

.

Massive and Small

- The neutron star's density also gives it very high surface gravity, with typical values ranging from 10^{12} to 10^{13} m/s^2 (more than 10^{11} times that of Earth).
- With an escape velocity ~1/3 to ½ c

Crab Pulsar Pulse 33ms period



Simple dimensional analysis-
structure in pulse at 0.1 of period ~3ms
R<ct=1000km
Mass= $4/3\pi r^3 \rho$>~.1Msun
Better limits from fitting x-ray spectra of NS- later

- Predicted theoretically by Volkoff and Oppenheimer (1939) as a consequence of GR and quantum mechanics.

- Short period from radio pulsars (<1s) can only be obtained from a compact object via either rotation or oscillations;
  - the period derivatives are small and for radio pulsars periods always increase (slow down)

- **All characteristic timescales scale as $\rho^{-1/2}$ (ρ is density)**

$$\omega=1/\mathrm{sqrt}(GM/r^3) = 1/\mathrm{sqrt}(G\rho)$$

Observational Intro to Neutron Stars

- Neutron stars are a very diverse population, in their observational properties but narrow range in size and mass.
- Radiate over a broad band but most of their energy is emitted at X-ray and gamma-ray wavelengths

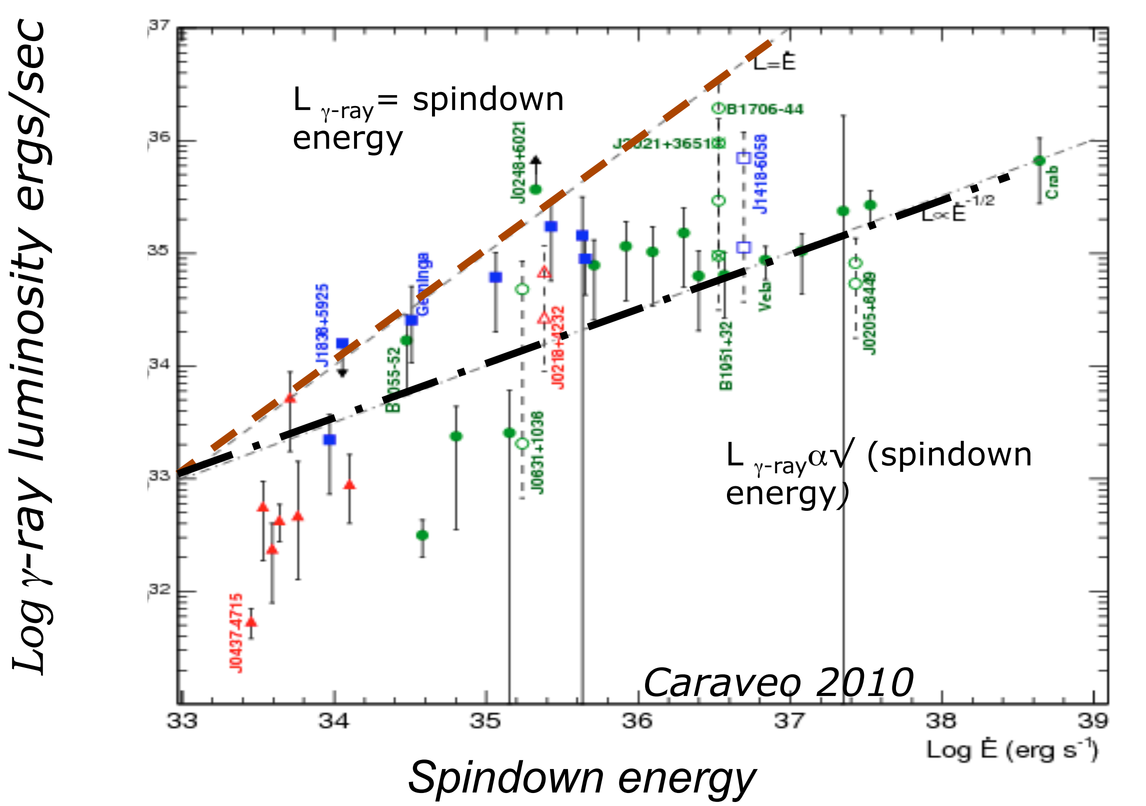
Their electromagnetic emission *can* be powered by

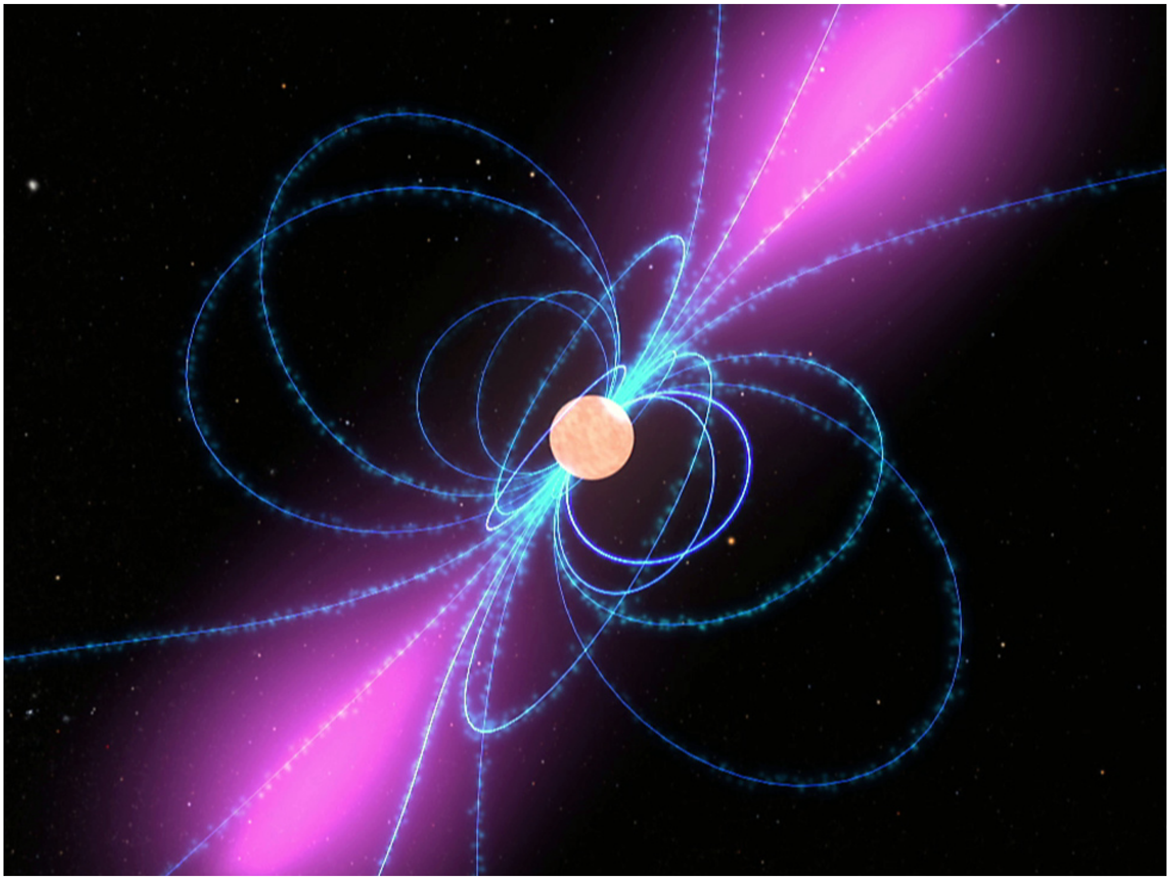
- rotation (spin down)
- accretion
- residual heat
- magnetic fields
- nuclear reactions

Vast number of names for these but all are a subset of the same sort of object

A. Harding 2013

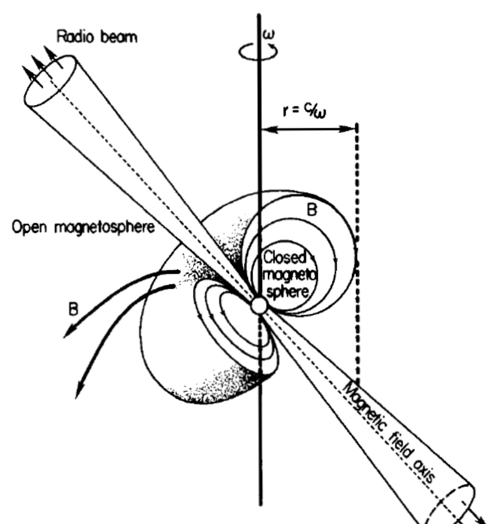
Comparison of Spin Down Energy and γ-ray Luminosity of Pulsar





Isolated Neutron Stars

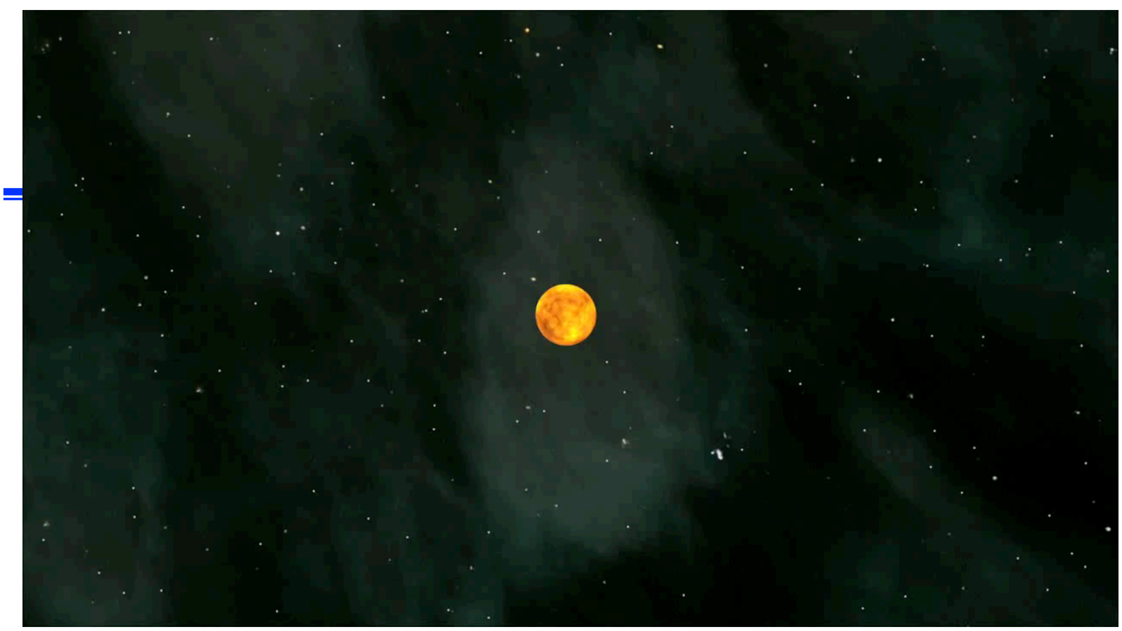
- In order to produce pulsed radiation from the magnetic poles, the magnetic dipole must be oriented at an angle with respect to the rotation axis and then the magnetic dipole displays a varying dipole moment
- **Energy loss goes as $\Omega^4 B^2$**
- As they radiate the star spins down- **visible for ~10^7 yrs**



Taylor 1991Proc. IEEE, 79, 1054

http://www.jb.man.ac.uk/~pulsar/Education/Tutorial/tut

What is a Pulsar-Animation



Pulsars emit relatively narrow radio beams, (green in this animation). If these beams don't sweep toward Earth, astronomers cannot detect the radio signals. Pulsar gamma-ray emission (**magenta**) form a broader fan of radiation -*NASA/Fermi/Cruz deWilde*

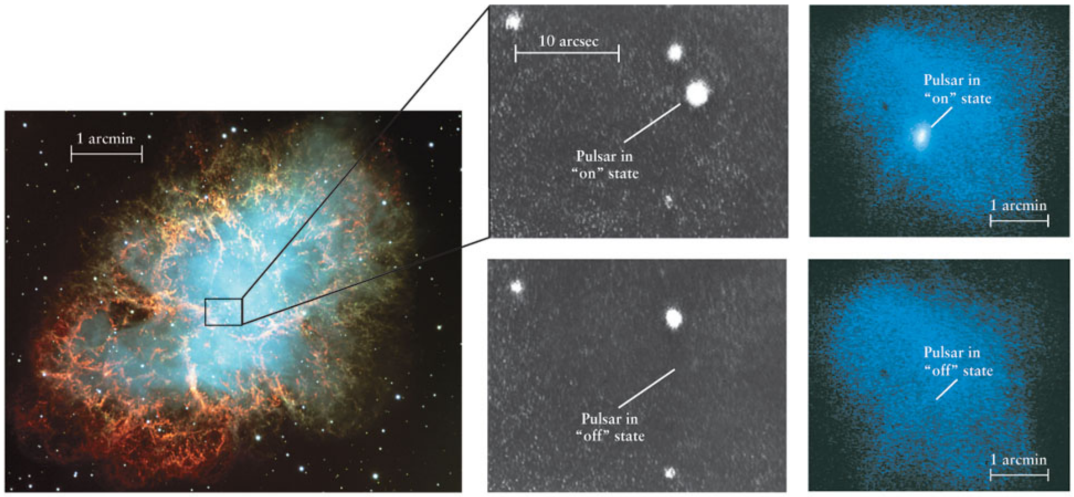
"Classes' of Neutron Stars

- Rotation-powered pulsars (RPP) derive their energy primarily from the rotation of the NS
- **Magnetars from magnetic field energy**
- Isolated NSs (INS) from the latent heat of the NS matter from the SN
- "X-ray" pulsars from accretion (next lecture)
- Bursters from nuclear burning of accreted material

Crab nebula
http://www.messier.seds.org/more/m001_sn.html

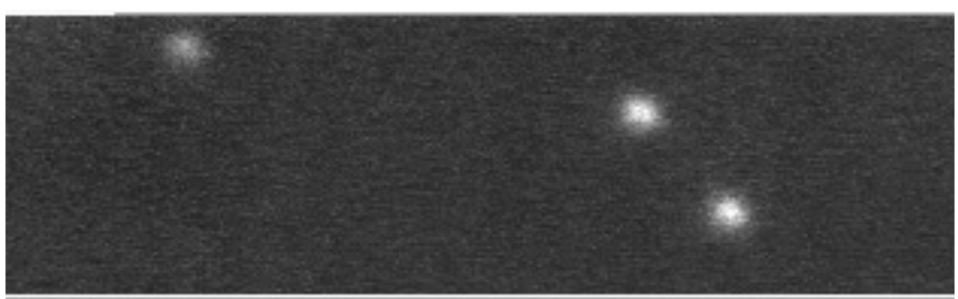
Result of a supernova detected by Chinese observers in July 1054 was ~4 times brighter than Venus at its brightest and was visible in daylight for 23 days.

The optical image shows hot gas moving at hot velocities (red) and x-ray emission (blue)



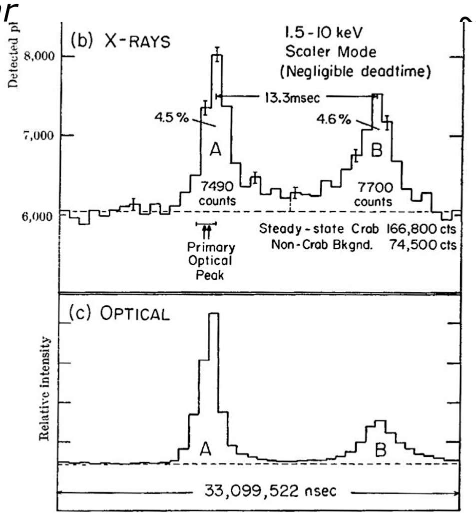
(a) The Crab Nebula (b) The Crab pulsar in visible light (c) The Crab pulsar in X rays

Crab Pulsar-Lucky Imaging

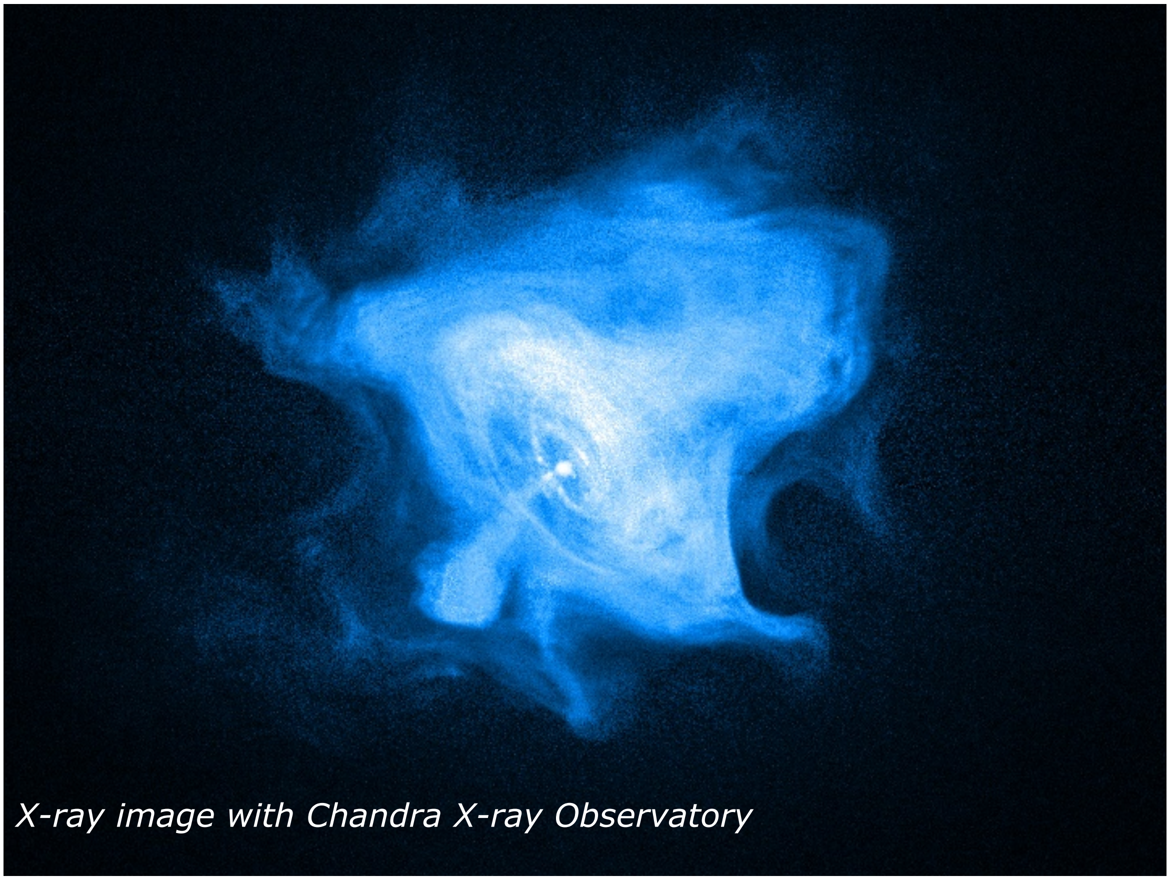


Optical image of pulsar

http://www.ast.cam.ac.uk/~optics/Lucky_Web_Site/



X-ray and radio pulses
33ms period, Bradt et al 1969



X-ray image with Chandra X-ray Observatory

Movie shows dynamic rings, wisps and jets of matter and antimatter around the pulsar in the Crab Nebula as observed in X-ray light by Chandra (left, blue) and optical light by Hubble (right, red).

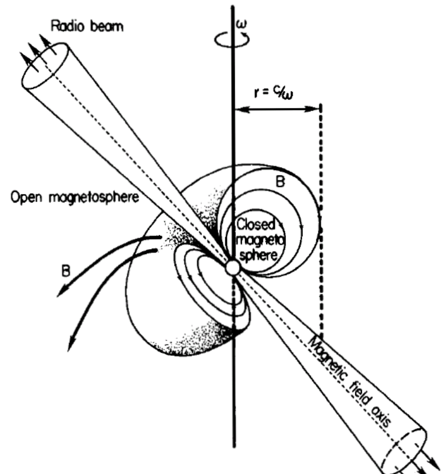
https://www.youtube.com/watch?v=O5u5nXZqYq0

Isolated Neutron Stars

- Most *isolated* neutron stars that are known are **radio and γ-ray pulsars** –

rapidly spinning neutron stars that emit relativistic particles that radiate in a strong magnetic field

- The pulses originate from beams of radio emission emitted along the magnetic axis-the pulsar loses energy by electromagnetic radiation which is extracted from the rotational energy of the neutron star.



Taylor 1991Proc. IEEE, 79, 1054

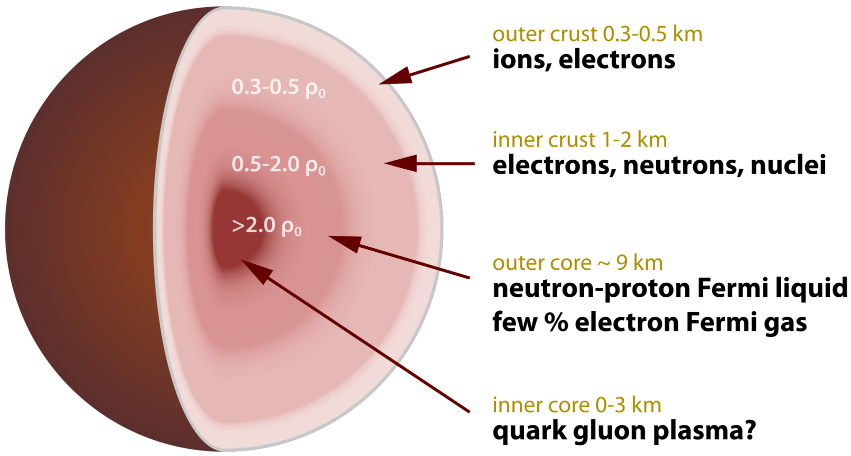
http://www.jb.man.ac.uk/~pulsar/Education/Tutorial/tut

III : Structure of neutron stars

- Neutron stars are exotic objects!
  - Average density is comparable to that of an atomic nucleus… center is even denser!
  - Surface gravity is so strong that any mountain higher than 1cm is squashed flat… any gas on surface quickly differentiates (H on top, then He, then C,…, heavy elements on bottom)

- Deeper down, neutron stars have matter in states that we can never obtain in a laboratory…
  - At the core of a neutron star, there may be "new" and exotic states of matter (new particles, quark soup etc.)

Internal structure of Neutron Stars



ρ_0=nuclear density- but an atomic nucleus is held together by the strong interaction, whereas a neutron star is held together by **gravity.**

IV : Magnetars

- In general, neutron stars possess the strongest magnetic fields of any known object
- But there’s a particular class of neutron stars (magnetars) than possess extremely strong fields (10^{15}G/10^{11}T)
  - Sometimes, these enormous magnetic fields “snap”, leading to very intense explosions
  - Dramatic example… the 27th December 2004 event
    - During a 0.2s period of time, it produced 100x the total luminosity of our galaxy
    - It produced a major disturbance of our upper atmosphere (despite being on the other side of our galaxy!)
    - Every X-ray/gamma-ray satellite detected it (even if it wasn’t looking!)
    - The blast probably ripped away the top 50m of the magnetar crust!
  - Good it wasn’t closer!!!

Magnetars

Have occasional huge outbursts of X-rays and soft-gamma rays, as well as luminosities in quiescence that are generally orders of magnitude greater than their spin-down luminosities.

Magnetars are thought to be young, isolated neutron stars powered by the decay of a very large magnetic field.

Their intense magnetic field inferred via spin-down to be in the range 10^{13}-10^{16}G

'quantum critical field' $B_{QED} \equiv m^2_e c^3/he = 4.4\times10^{13}$G.

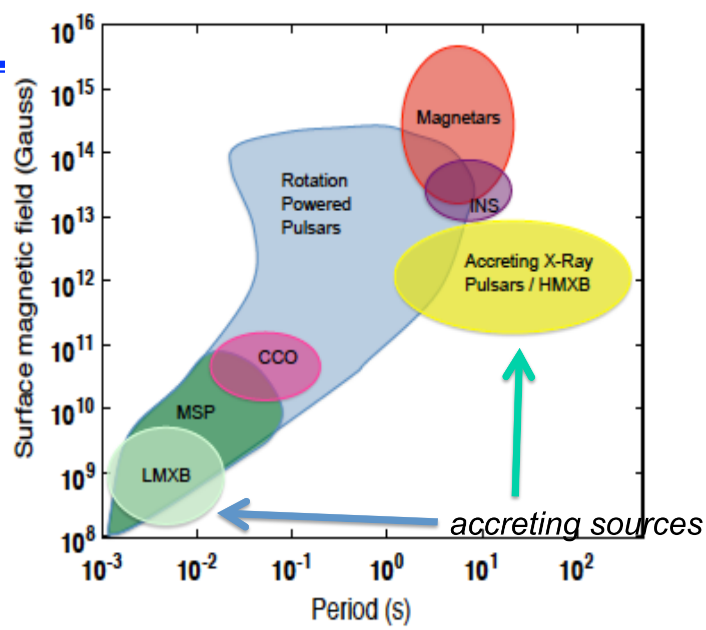
In their most luminous outburst magnetars can briefly out-shine all other cosmic soft-gamma-ray sources combined [Kaspi 2010]

Period and Magnetic Field

Notice enormous range of periods 10^{-3}-100 seconds

Magnetars- B~10^{14}-10^{16} Gauss

Above ~4×10^{13}Gauss quantum mechanical effects become important



CCO- central compact objects
MSP= millisecond pulsar
LMXBs- low mass x-ray binaries

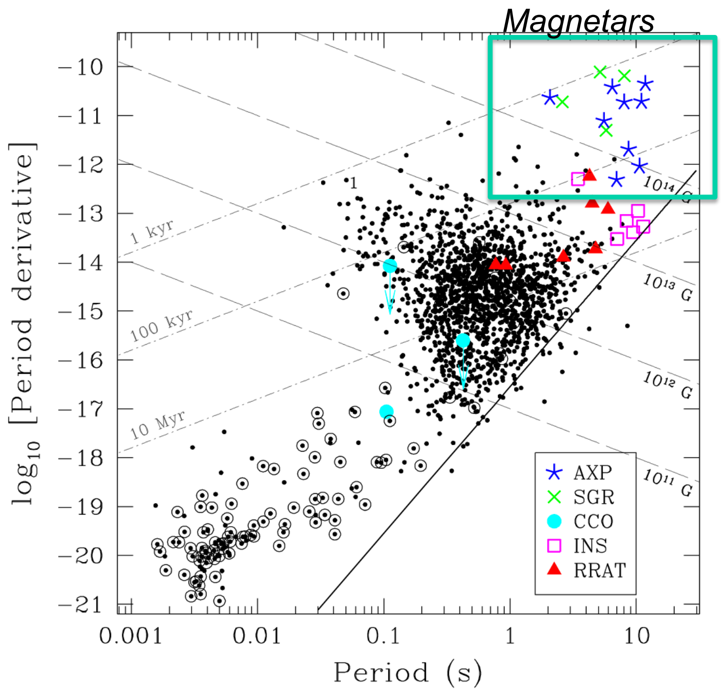
A. Harding 2013

Magnetars

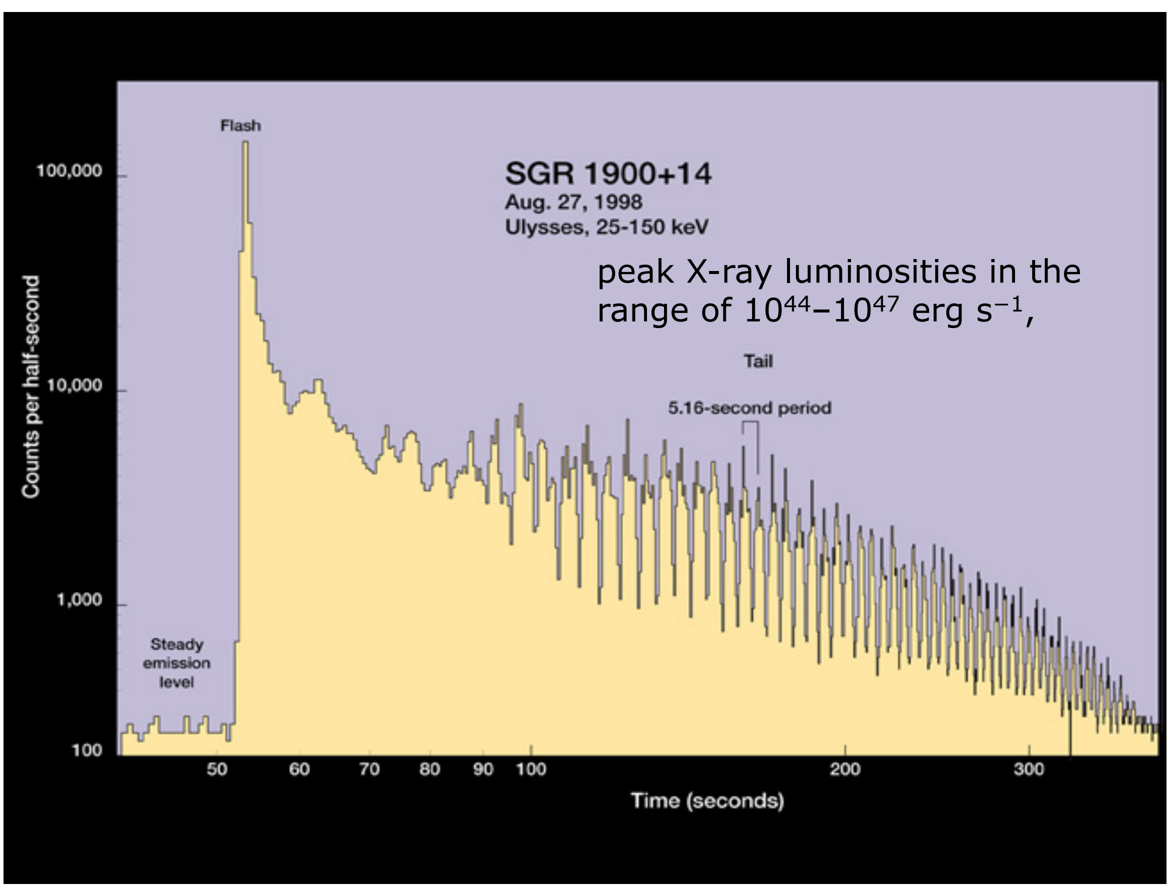
spinning down, with spin-down rates that imply spin-down timescales (~P/ dP/dt) of a *few thousand years*, suggesting great youth.

Confined to galactic plane

Lines of constant age, magnetic field.



Open circles are in binaries

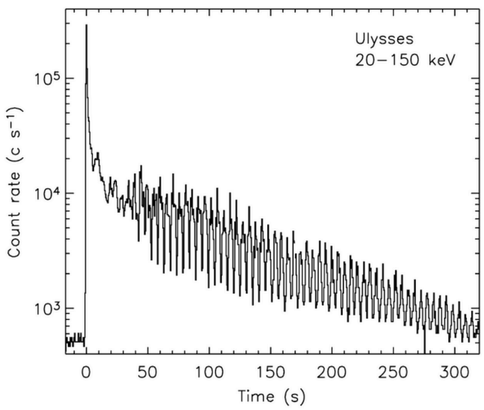


peak X-ray luminosities in the range of 10^{44}–10^{47} erg s^{-1},

Enormous Burst from Magnetar

A magnetar in the LMC on March 5,1979 was by a factor of 1000 the brightest source in the x-ray sky for a few seconds – the flux was strong enough to effect the ionosphere!

Total energy was 5×10^{44} ergs in x-rays equivalent 4000 years of solar luminosity



Position (obtained by triangulation) consistent with a supernova remnant in the LMC

Whats Happening??

- The behavior of magnetars on the timescales of 1–10 kyr is due to slow evolution of the magnetic field inside the star, which is capable of breaking the solid crust.
- The interior of a neutron star is an excellent conductor, and hence the magnetic field is practically "frozen" in the stellar material (Kaspi and Beloborodov 2017)
- But can have "starquakes"—sudden fractures and displacements of the crust, which shake the magnetosphere and trigger bursts.

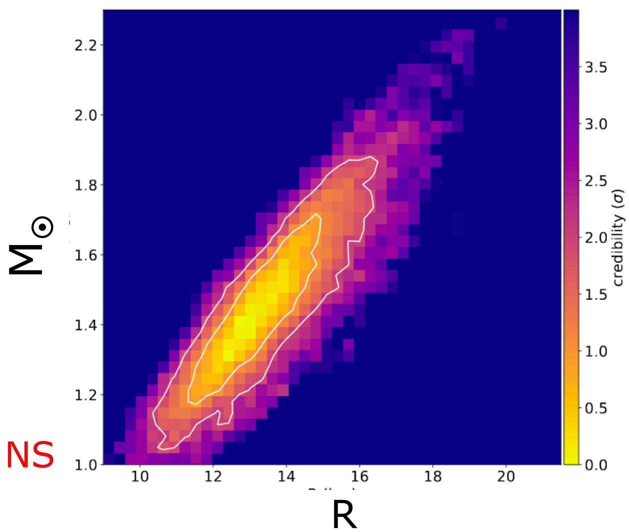
Neutron Stars are Relativistic Objects

- The gravitational field at the neutron star's surface is about 2×10^{11} times that of Earth.
- general relativistic correction to hydrostatic equilibrium within a neutron star is very significant

R_s=4kms for $M=1.4M_\odot$, radius of NS is ~14km-

e.g light bending, time dilation and gravitational redshift are large effects- allow estimate of mass and radius of NS.

Best estimate and size of a NS – Miller et al 2020



Neutron Stars are Relativistic Objects

- Space warping

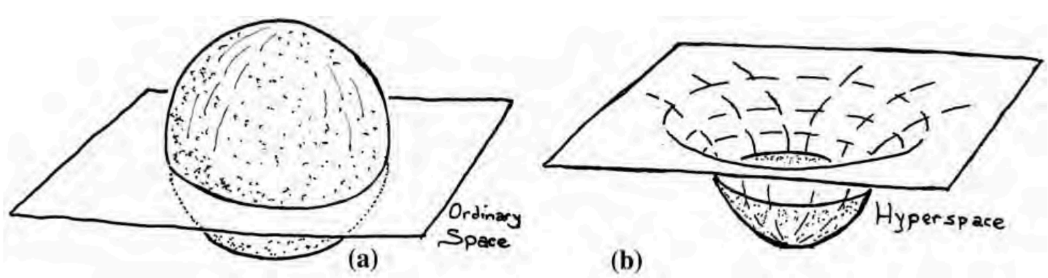


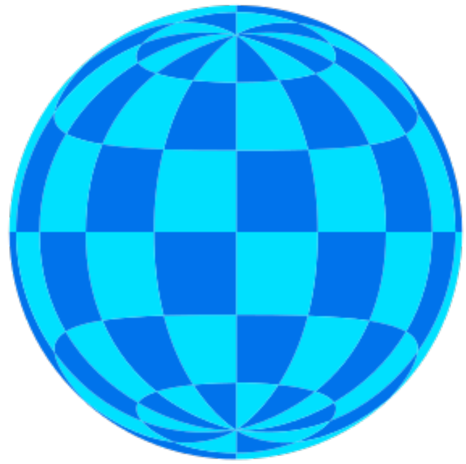
Figure 13: The warpage of space inside and around a neutron star: An equatorial slice through a star [diagram (a)], when osberved from a higher dimensional, flat hyperspace in which our universe is embedded, has the shape shown in diagram (b). The star's circumference may be about twice its diameter rather than π times its diameter.

Due to bending of space the stars circumference is ~4r rather than 2πr (K. Thorne*)*

R

Neutron Stars are Relativistic Objects

- Light bending



Gravitational light deflection by a neutron star.

Due to relativistic light bending more than half of the surface is visible to a distant observer- see both poles at same time ($R=2R_S$,M=1 solar mass)

R

So what is the actual size ?

$R_G \sim 1.5\ (M / M_\odot)$ km

So how close are neutron stars to being black holes ?

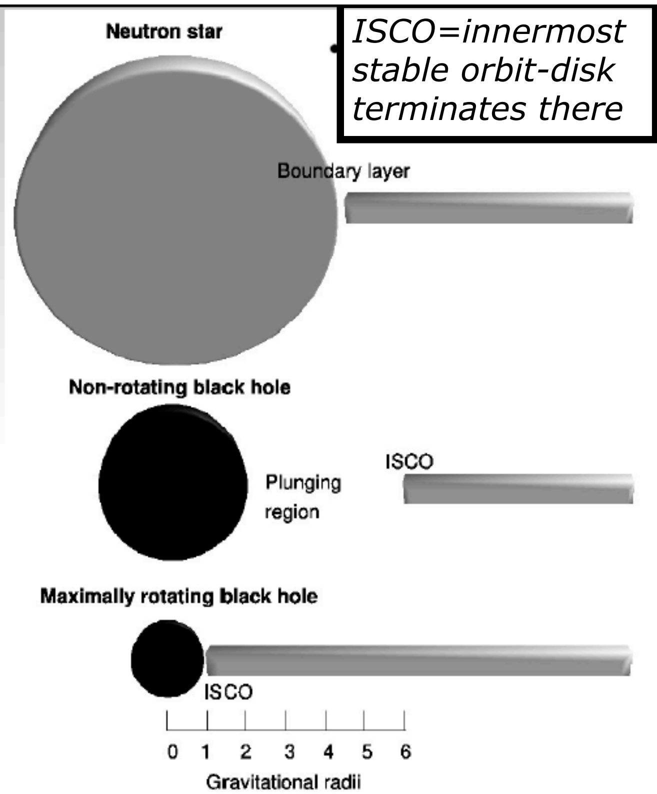
Neutron stars are only about a factor 2—3 larger than their event horizons

What about spin ?

A non-rotating (“Schwarzschild”) black hole has its event horizon at 2 R_G and its ISCO at 6 R_G

A maximally rotating (“Maximal Kerr”) black hole has both its event horizon and ISCO at R_G

→ Spinning black holes are more compact → potentially more radiatively efficient



R. Fender 2007

What Does Spinning Fast Tell Us

$$\frac{v_{\rm rot}^2}{R} < \frac{GM}{R^2}$$

To spin fast object must be dense
To show rapid changes must be small

$$\frac{4\pi^2 R}{P^2} < \frac{GM}{R^2}$$

$$\bar{\rho} \equiv \frac{3M}{4\pi R^3} > \frac{3\pi}{GP^2}$$

- $P = \text{sqrt}(3\pi/G\rho)$

P= period, ρ= density

$P=1\text{s} \Rightarrow \rho>1\times10^{11}\ \text{kg/m}^3$
$P=10^{-1}\text{s} \Rightarrow \rho>1\times10^{13}\ \text{kg/m}^3$
$P=10^{-2}\text{s} \Rightarrow \rho>1\times10^{15}\ \text{kg/m}^3$

Mass of object measured from Keplers Laws- **so pulsars must be small**