Dead Stars

- End of nuclear burning
- Supernova explosions
  - Formation of elements (R, S process)
- Chandrasekhar limit on white dwarf mass
- Neutron stars
- Pulsars

Nuclear Burning in Stars

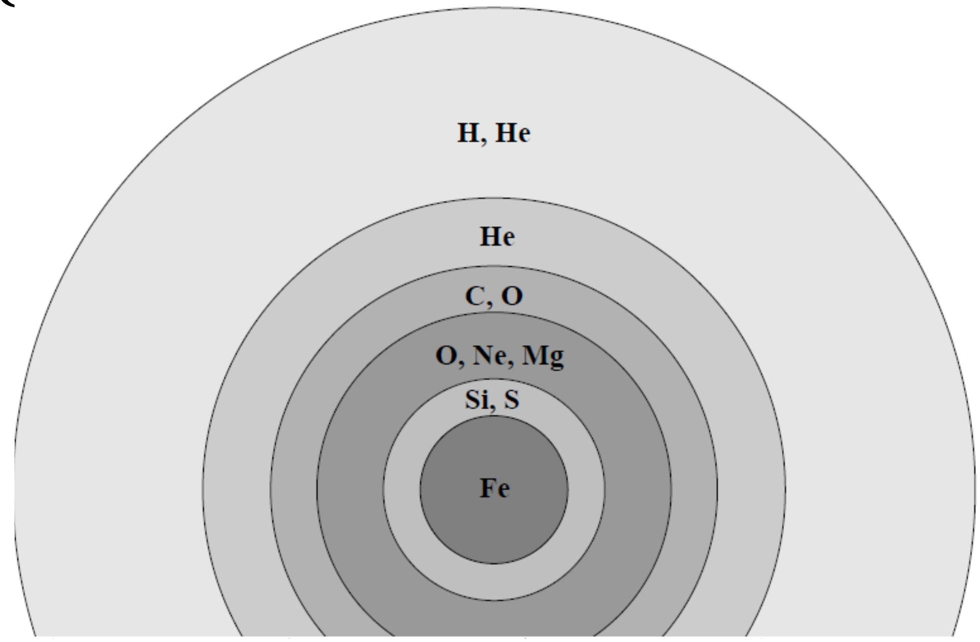
- Stars are powered by nuclear burning, which produces the energy needed to maintain pressure balance against gravity.
- Initial reaction is proton burning to He.
- At end of life for a solar mass star, final step is He burning.
- He burning: $^{4}He + {}^{4}He + {}^{4}He \rightarrow {}^{12}C + \gamma$ (7.275 MeV)
  - Reaction occurs through $^{4}He + {}^{4}He \rightarrow {}^{8}Be + \gamma$, but ^{8}Be has lifetime of only 10^{-16} seconds.
- He burning also produces O and N
  - $^{4}He + {}^{12}C \rightarrow {}^{16}O + \gamma$
  - $^{4}He + {}^{16}O \rightarrow {}^{20}N + \gamma$
- When conditions no longer allow He burning, nuclear fusion stops. Have a white dwarf – pressure support is from “electron degeneracy pressure” instead of pressure due to thermal motions.

End of Nuclear Burning

- There is a limit to the mass that electron degeneracy pressure can support, called the Chandrasekhar limit (1.4 solar masses).
- If gas is accreted onto a white dwarf, then this limit can be exceeded and the white dwarf collapses.
- This produces a supernova explosion.

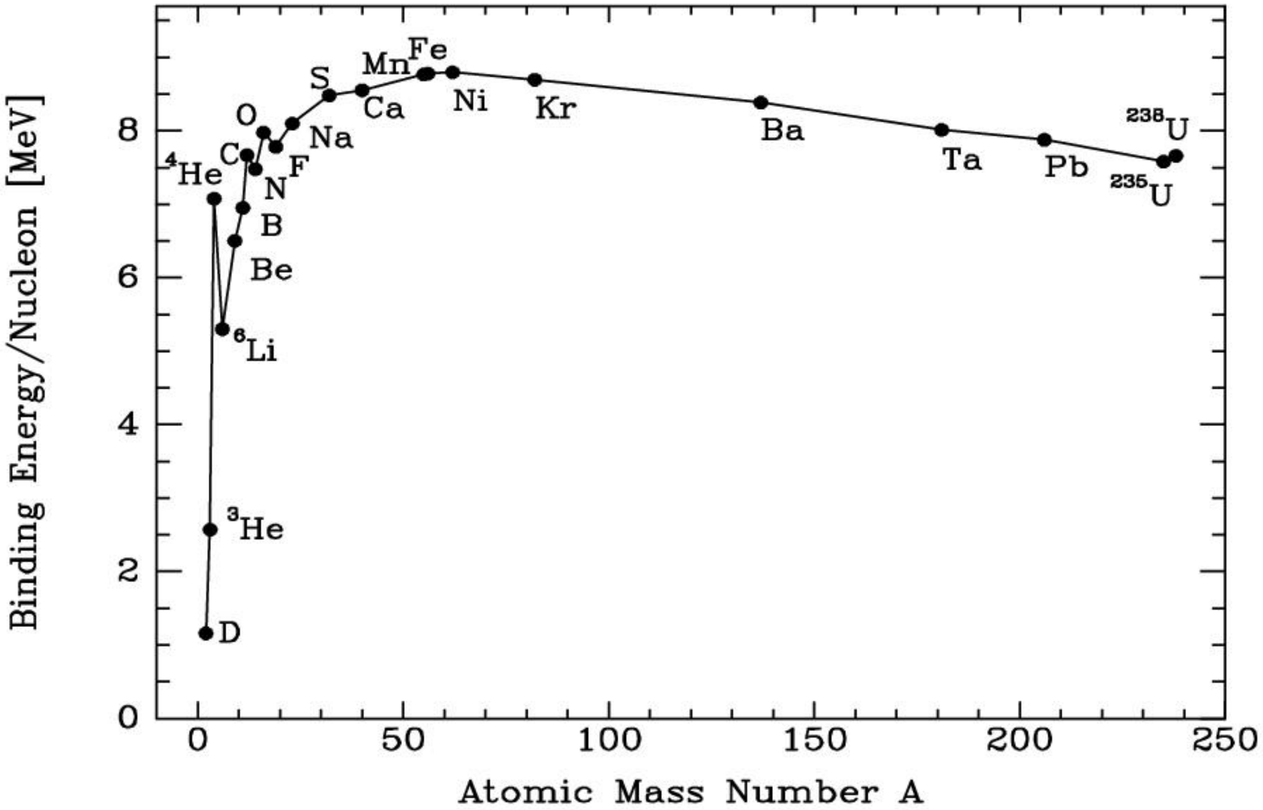
Nuclear Burning in Massive Stars

- Core temperature and density is higher in high mass stars
  - Nuclear burning can progress past CNO.
- ^{16}O + ^{4}He → ^{20}Ne + γ
- ^{12}C + ^{12}C produces mostly ^{20}Ne and ^{24}Mg.
- ^{16}C + ^{16}C produces mostly ^{28}Si and ^{32}S.
- Si burns to ^{56}Fe and some ^{52}Cr
- Leads to shell structure.
- Burning is very rapid
  - C ~ 500 years
  - Si ~ 1 day



Fusion

- Burning stops releasing energy with Fe because it is the most tightly bound nucleus.



Core Collapse

- Core can no longer support itself by nuclear burning.
- Core collapses, new energy source is gravitational contraction.
- High temperature and density lead to:
- Nuclear photodisintegration:
  - $\gamma + {}^{56}\mathrm{Fe} \rightarrow 13({}^{4}\mathrm{He}) + 4n$ (-124 MeV)
  - $\gamma + {}^{4}\mathrm{He} \rightarrow 2p + 2n$ (-28.3 MeV)
- Neutronization:
  - $e^{-} + p \rightarrow n + \nu_{\mathrm{e}}$
  - $e^{-} + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Mn} + \nu_{\mathrm{e}}$
  - $e^{-} + {}^{56}\mathrm{Mn} \rightarrow {}^{56}\mathrm{Cr} + \nu_{e}$

Core Collapse

- Energy loss ~ (124 + 13×28.3) MeV/56 ~ 8.8 MeV/nucleon.
- For Chandrasekhar mass of 10^{56} nucleons, release 10^{52} erg.
  - Compare with solar luminosity of 4×10^{33} erg/s.
- Energy is released as neutrinos, leaves the star.
- Core collapses on close to free-fall time scale
  - Core density at end of Si burning $\rho \sim 10^9$ g/cm^3.
  - Free-fall time scale $(3\pi/32G\rho)^{1/2} \sim 0.1$ s
- Most of nucleons (99.5%) are converted to neutrons.
  - Note free neutron lifetime ~ 886 seconds.
- Tremendous release of energy creates a **supernova explosion**.

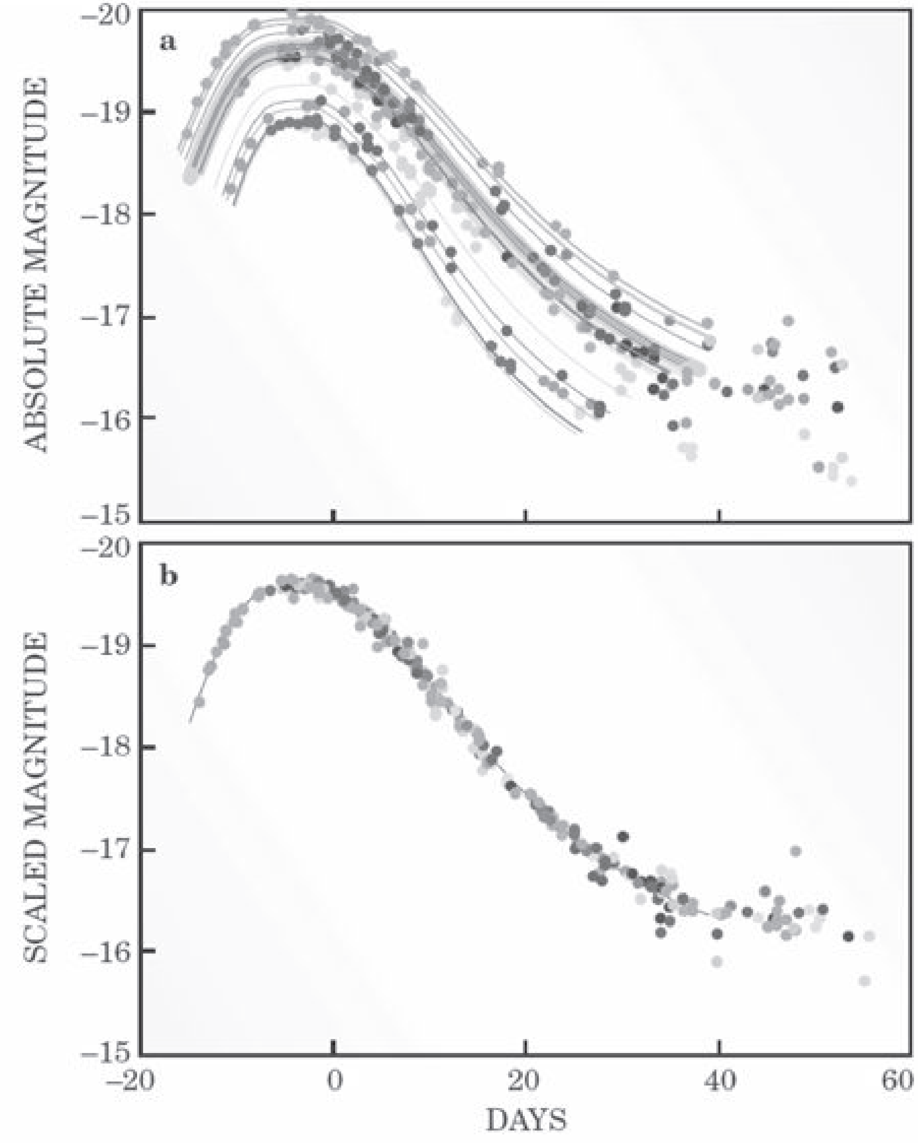
Types of Supernovae

- Type I – no hydrogen absorption lines
  - Ia – no hydrogen lines, no helium lines, late in decay strongest lines are iron
  - Ib, Ic – helium lines, still no hydrogen
- Type II – hydrogen absorption lines

- Collapse of massive stars leads to type II and Ib, only difference is whether or not star sheds outer hydrogen layer before exploding
- Type Ia is thought to be white dwarf exceeding Chandrashkar limit either via accretion or merger. Star is evaporated and no remnant remains.

Type Ia Supernovae

- Type Ia light curves reach the same maximum luminosity if scaled by width in time.
- Makes them useful for cosmology.



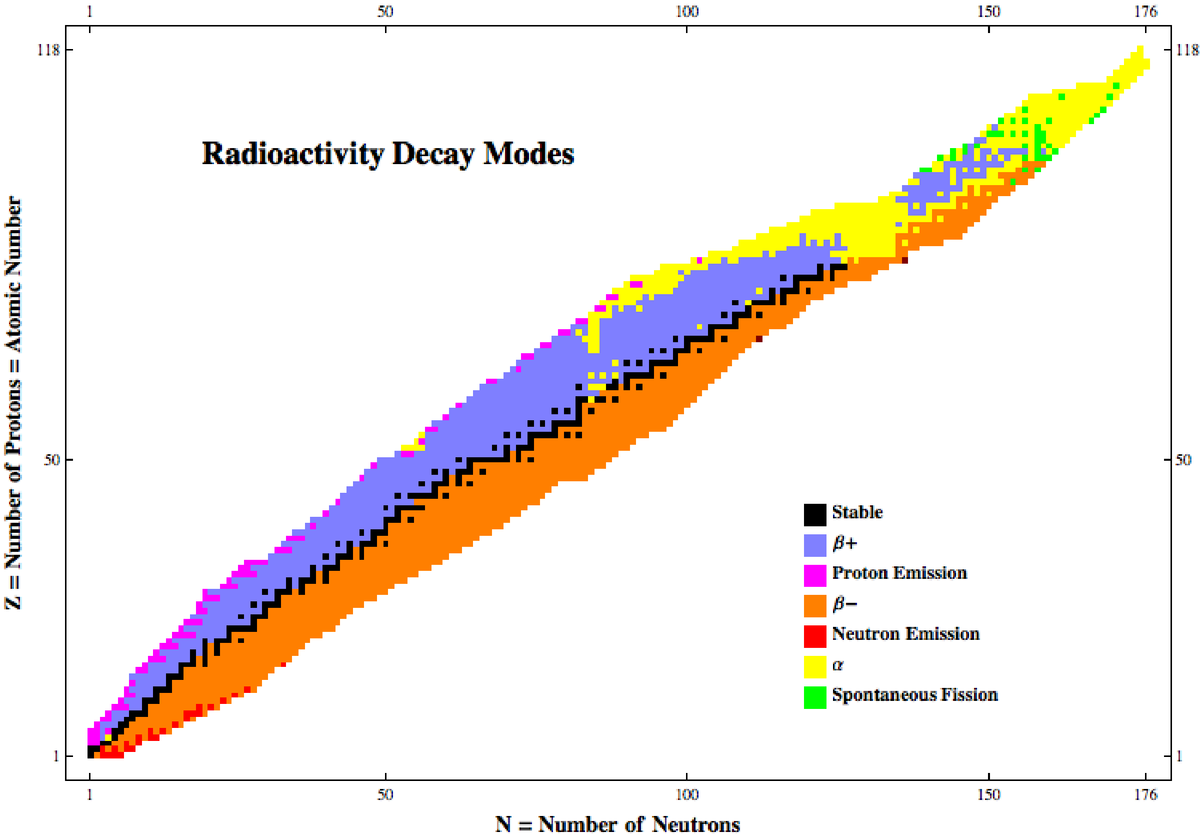
Nucleosynthesis

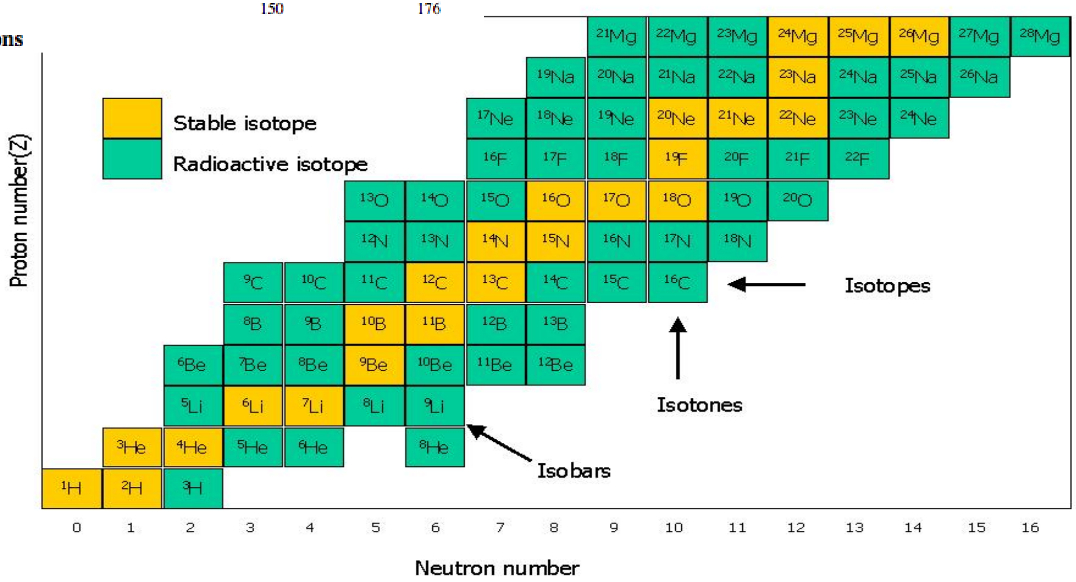
- Fusion (slow) – Nuclear burning in stars that is energetically favorable. Produces the abundant elements up to Fe.

- S-process (slow) - Rate of neutron capture by nuclei is slower than beta decay rate. Produces stable isotopes by moving along the valley of stability. Occurs in massive stars, particular AGB stars.

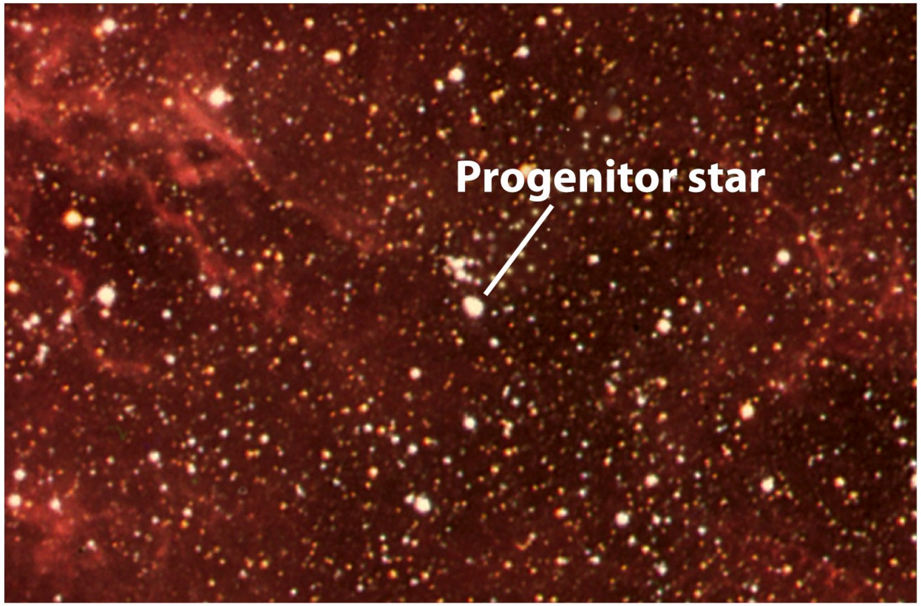
- R-process (Rapid) – Rate of neutron capture fast compared to beta decay. Forms unstable neutron rich nuclei which decay to stable nuclei.

Valley of Stability

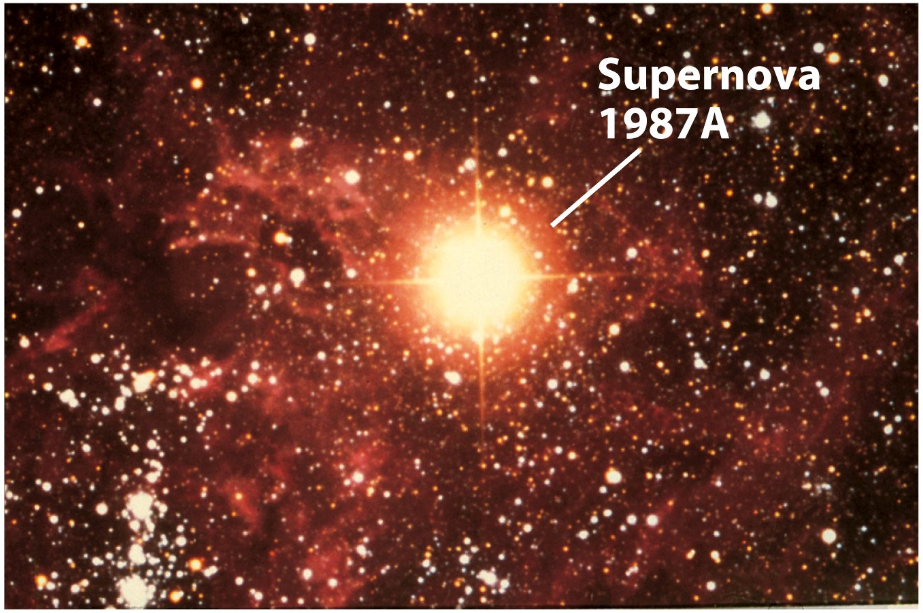




In 1987 a nearby supernova gave us a close-up look at the death of a massive star

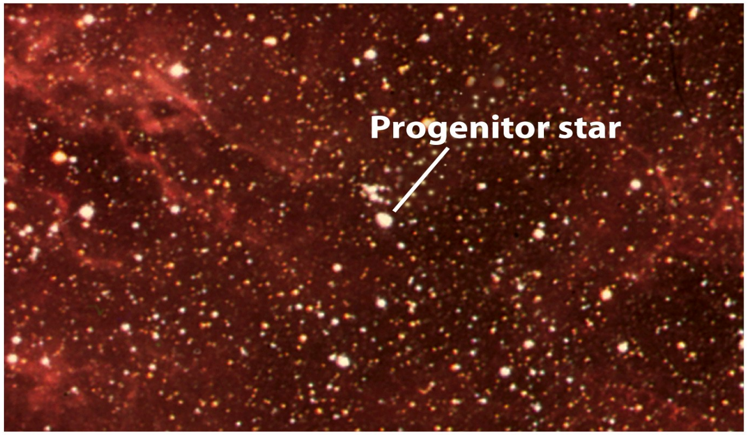


Before the star exploded

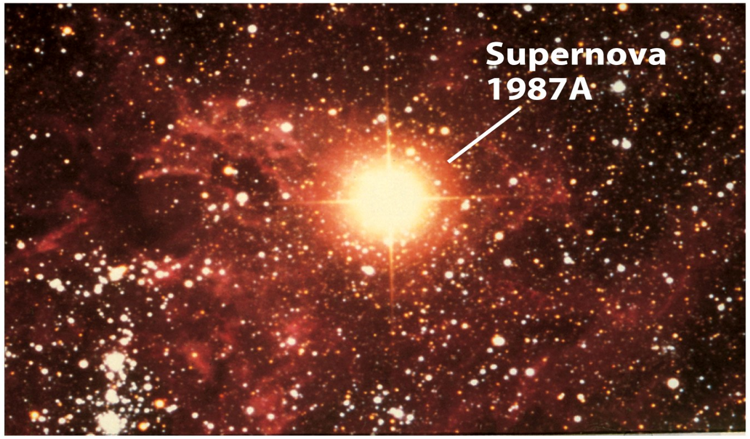


After the star exploded

Neutrinos from SN1987A

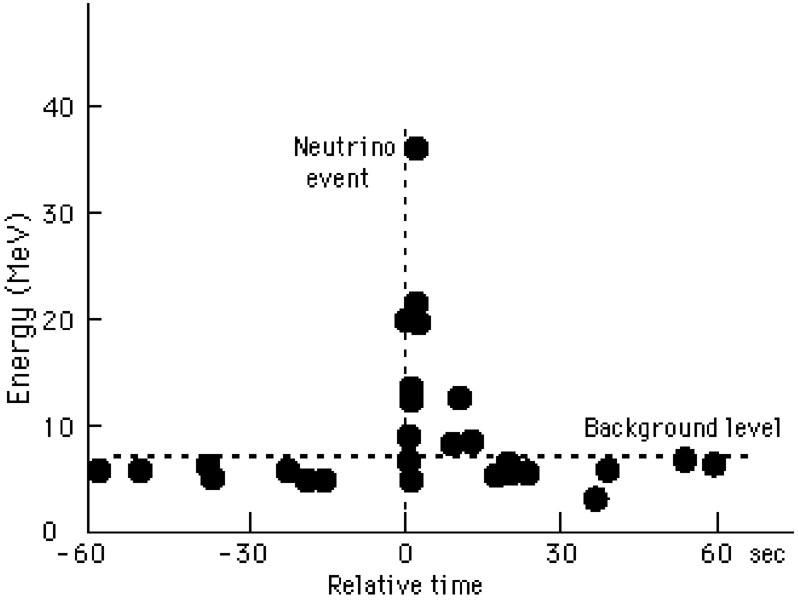


Before the star exploded

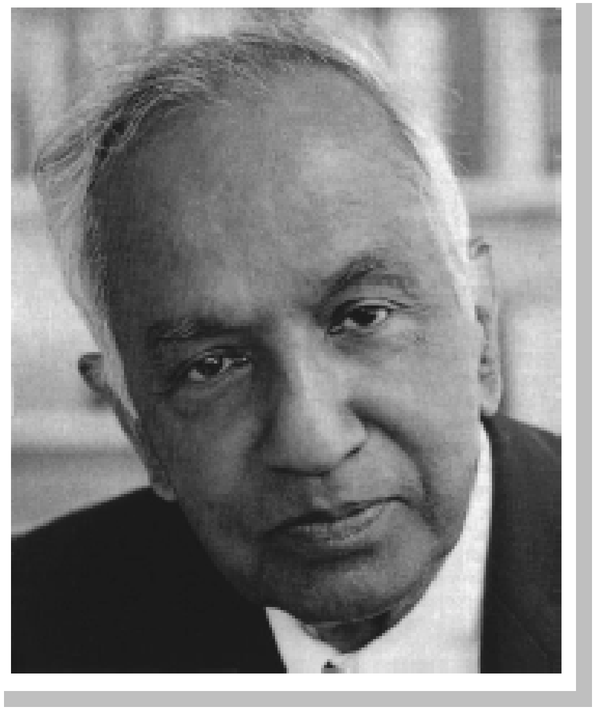


After the star exploded

- Supernova 1987A went off in the Magellanic Clouds.
- Neutrinos were detected on Earth.



Maximum white dwarf mass



Electron degeneracy cannot support a white dwarf heavier than 1.4 solar masses

This is the "Chandrasekhar limit"

Won Chandrasekhar the 1983 Nobel prize in Physics

How Dense is Quantum?

- Need to use quantum statistics when average separation between particles is comparable to the de Broglie wavelength $\lambda = h/p$.
- Thermal energy $E = p^2/2m = (3/2)\,kT$, find $\lambda = h(3mkT)^{-1/2}$.
  - Note λ is larger for electrons, since $m_e << m_p$.
  - Quantum statistics will become important first for electrons.
  - Electrons will “become degenerate” first.
- Density $\rho = m_p$/(volume per particle) $= m_p/(\lambda/2)^3 = 8m_p(3mkT/h^2)^{3/2}$
  - Note use m_p for density, but m_e for λ.
- As temperature decreases, gas becomes degenerate

Relativistic degenerate gas

- As the density increases, λ becomes smaller, and p increases.
- Eventually electrons are relativistic $E = pc = hc/\lambda^{-1/2}$.
- Let's find the equation of state...
- Pressure $P \sim$ energy density $\sim E/\lambda^{-3} \sim hc/\lambda^{-4}$.
- Still have mass density $\rho \sim m_p/\lambda^3$, therefore $P \sim hc\,(\rho/m_p)^{-4/3}$
- Can work out the correct numerical coefficients using the Fermi-Dirac distribution (result is in the book, not the derivation).

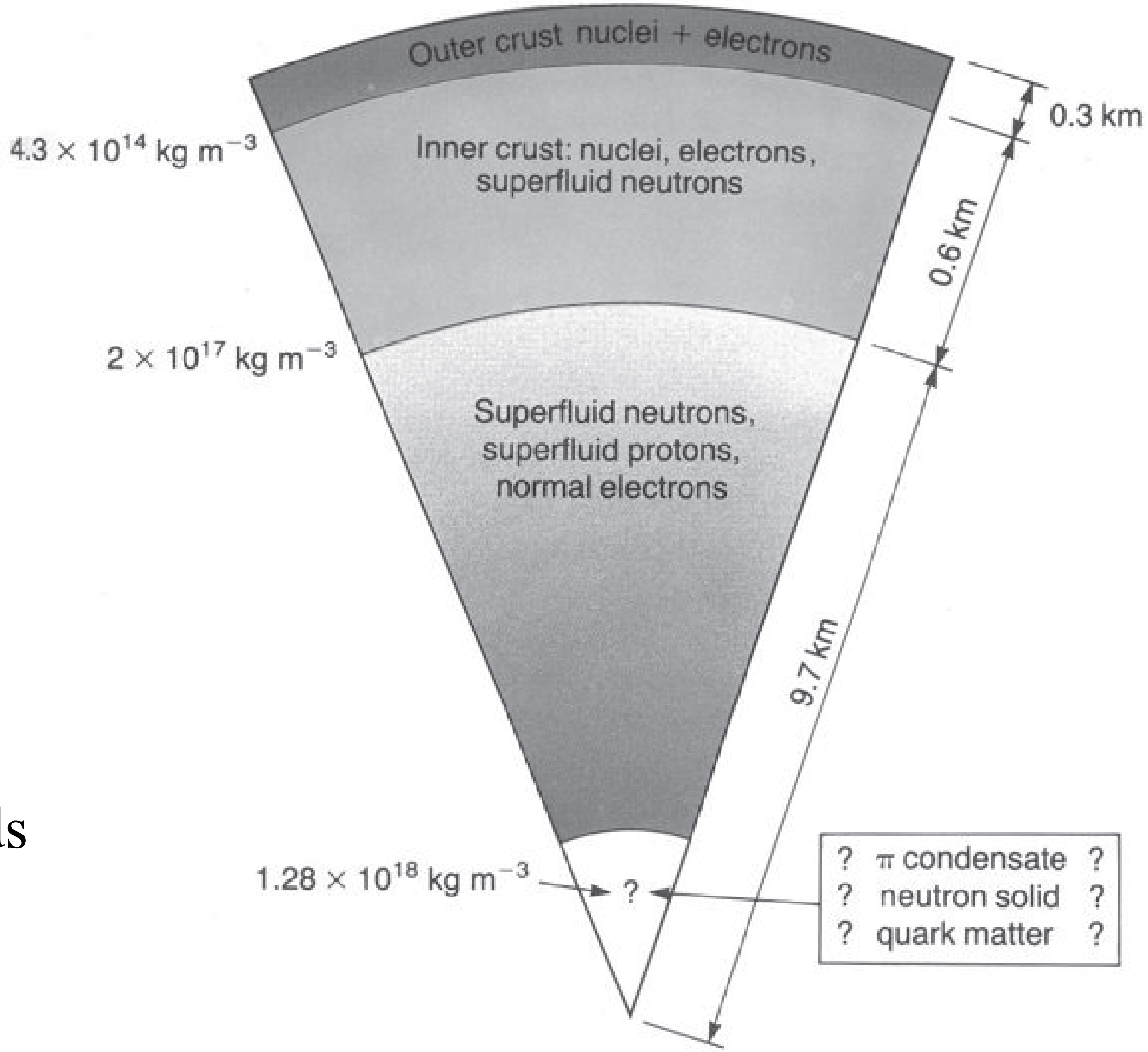
- Find Chandrasekhar mass on board.

Relativistic degenerate gas

- Chandrasekhar mass is 1.46 solar masses.

- Can do same calculation for neutron stars.
  - Need to use general relativity because object is so dense.
  - Need to extrapolate nuclear equation of state beyond what has been measured in the laboratory – makes estimates uncertain.
- Maximum neutron star mass is around 2-3 solar masses.

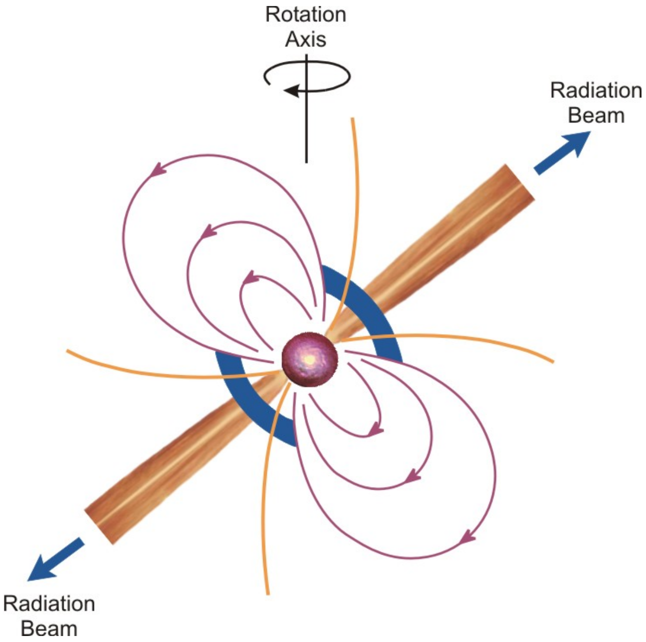
Neutron Stars



- Radius ~ 10-15 km
- Contains superfluids

Little Green Men

- First pulsar discovered in 1967 with pulse period of 1.33 s. Found by Jocelyn Bell, her advisor, Anthony Hewish, won the Nobel Prize in Physics for the discovery in 1974.
- What can make extremely regular pulsations?
- Discoverers named object "LGM-1" for "Little Green Men".
- Additional pulsars discovered within a year, periods 0.03 s to several seconds.



Crab Pulsar

Spinning Star?

For a rotating object to remain bound, the gravitational force at the surface must exceed the centripetal acceleration:

$$\frac{GMm}{r^2} > m\omega^2 r \Rightarrow \frac{GM}{r^3} > \frac{4\pi^2}{P^2} \Rightarrow \rho > \frac{3\pi}{P^2 G}$$

For the Crab pulsar, P = 33 ms so the density must be greater than 1.3×10^{11} g cm^{-3}.

This exceeds the maximum possible density for a white dwarf, requires a neutron star.

Magnetic Field

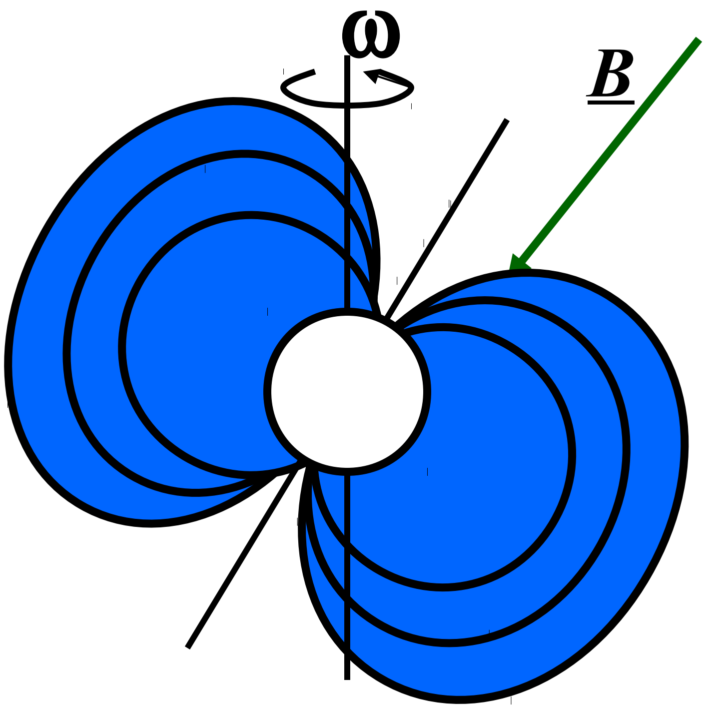
If a solar type star collapses to form a neutron star, while conserving magnetic flux, we would naively expect

$$R_{sun}^2 B_{sun} = R_{ns}^2 B_{ns} \quad \Rightarrow \quad \frac{B_{ns}}{B_{sun}} \approx 5 \times 10^9$$

For the sun, $B \sim 100\ G$, so the neutron star would have a field of magnitude $\sim 10^{12}\ G$.

Magnetosphere

Neutron star rotating in vacuum:



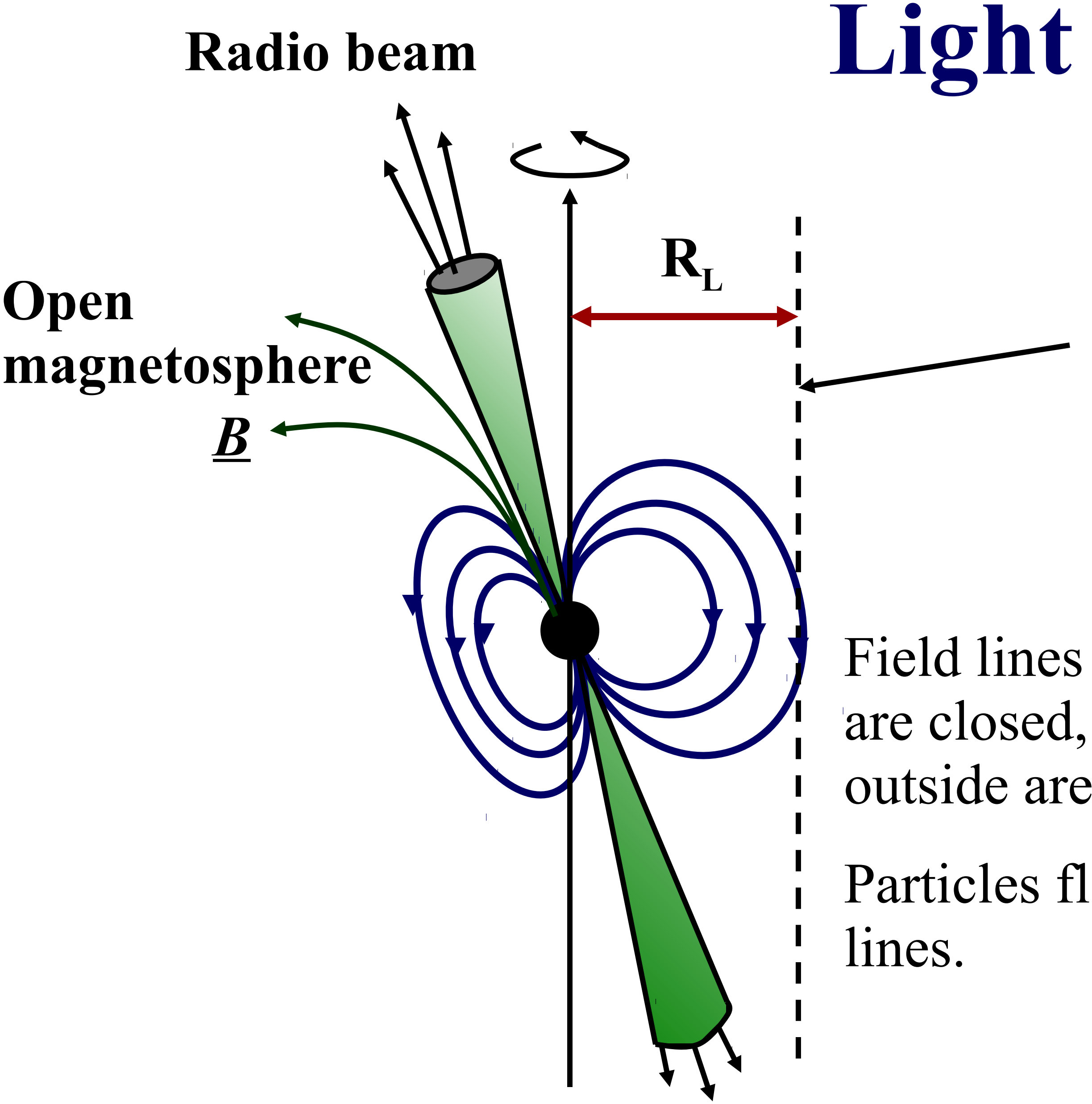
Electric field induced immediately outside NS surface.

$$E \simeq \frac{v}{c} B$$

The potential difference on the scale of the neutron star radius:

$$\Phi = ER \sim 10^{18} V$$

Light cylinder



$$\frac{2\pi R_L}{P} = c$$

Field lines inside light cylinder are closed, those passing outside are open.

Particles flow along open field lines.

Spin down of a pulsar

Energy $E = \frac{1}{2} I \left(2\pi\nu \right)^2$

Power $P = -\frac{dE}{dt} = 4\pi^2 I\nu \frac{d\nu}{dt}$

For Crab pulsar: $\nu = 30$/s, M = 1.4 solar masses, R = 12 km, and $d\nu/dt = -3.9\times10^{-10}\ \mathrm{s}^{-2}$.

Therefore, $P = 5\times10^{38}$ erg/s.

Over a year, the spin rate changes by 0.04%.

Dipole Radiation

Magnetic dipole, p_m, will radiate if rotated around misaligned axis.

$$\frac{dE}{dt} \propto \Omega^4 p_m^2$$

Equate this to loss of rotational energy:

$$\frac{d}{dt}\left(\frac{1}{2} I\,\Omega^2\right) = I\,\Omega^4 \frac{d\Omega}{dt} \propto \Omega^4 \rightarrow \frac{d\Omega}{dt} \propto \Omega^3$$

Braking Index

In general can write $\frac{d\Omega}{dt} \propto \Omega^n$

where *n* is the ‘braking index’.

Can estimate n from spin period P and its time derivatives:

$$n = 2 - \frac{P\ddot{P}}{\dot{P}^2}$$

“Characteristic” age of the pulsar is then $\tau = \frac{P}{(n-1)\dot{P}}$

Measurements of n range 1.8 to 3.0.

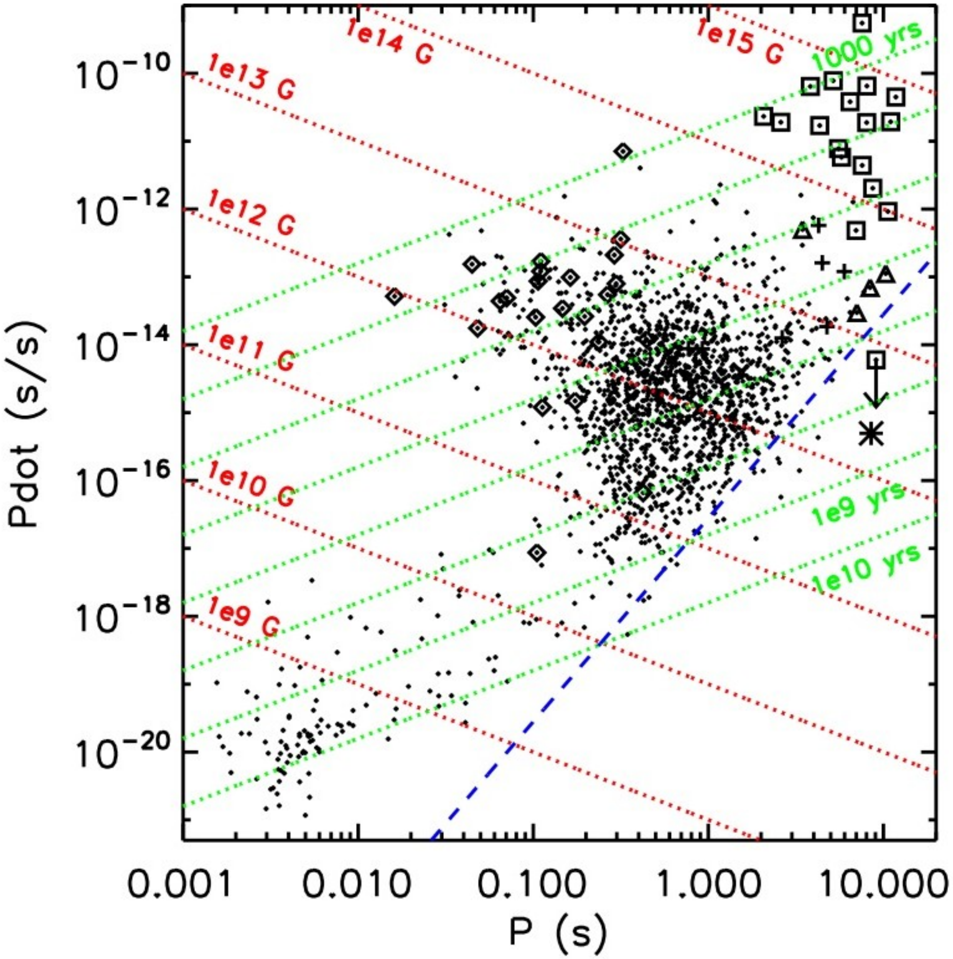
P P-dot Diagram

If neutron stars have the same radius, then $B \sim p_m$,

Using the dipole radiation formula, we can find

$$B_s \propto \left(P\dot{P}\right)^{1/2}$$

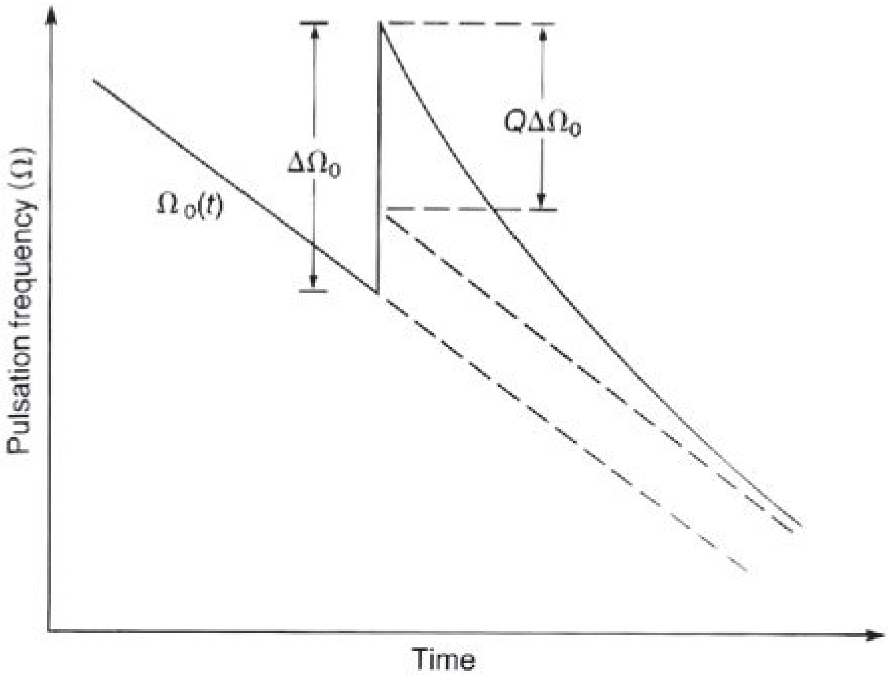
$$\tau = \frac{P}{2\dot{P}}$$



Pulsar Glitches

Short timescales - pulsar slow-down rate is **remarkably uniform**

Longer timescales - irregularities apparent, in particular, ‘glitches’

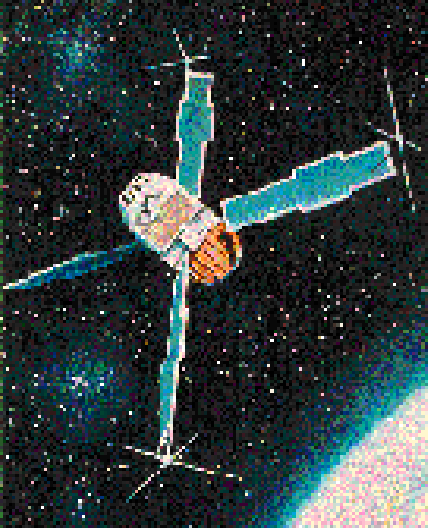


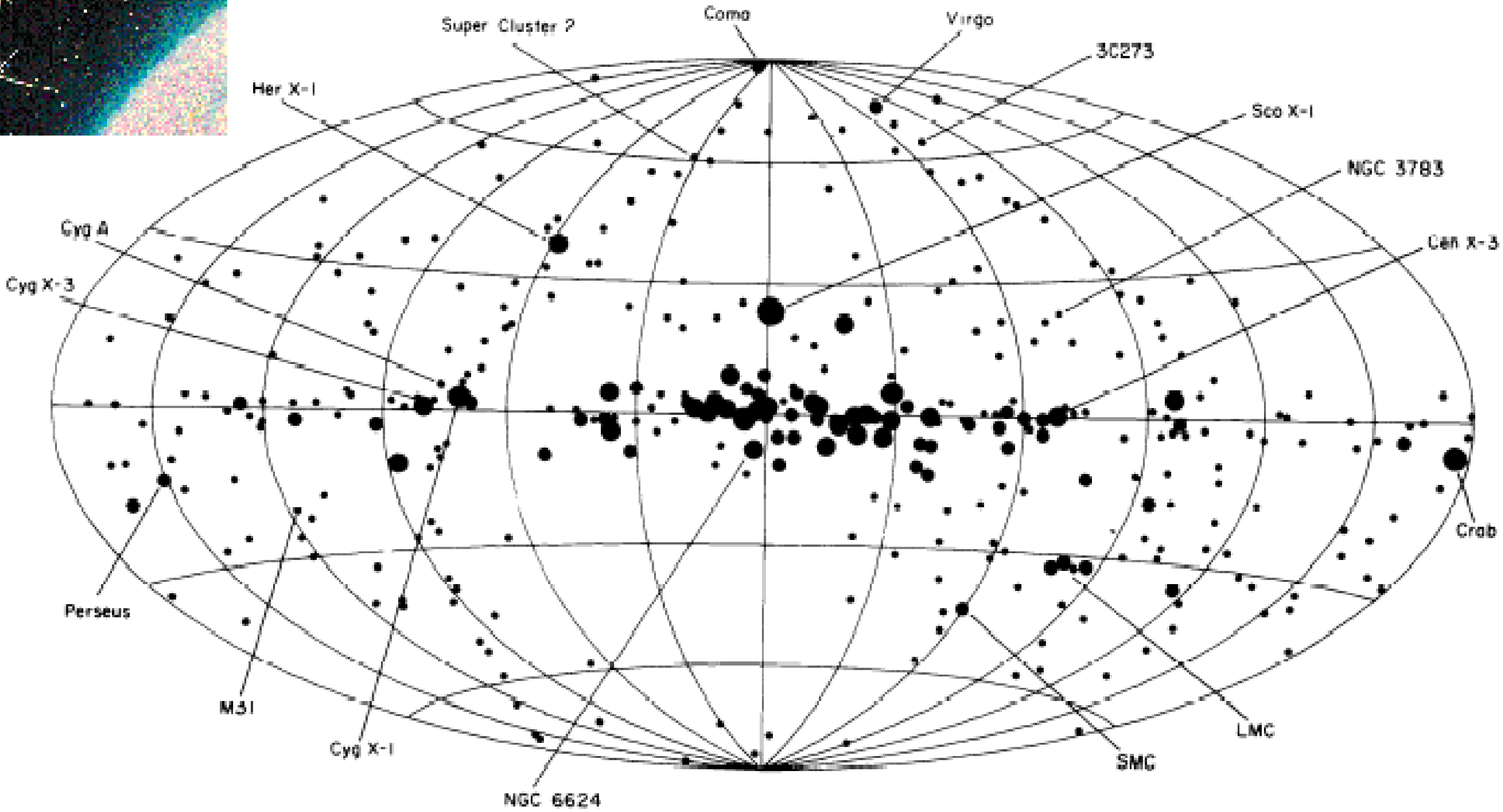
$$\frac{\Delta P}{P} \sim 10^{-10}$$

for Crab pulsar

Due to stresses and fractures in the crust?

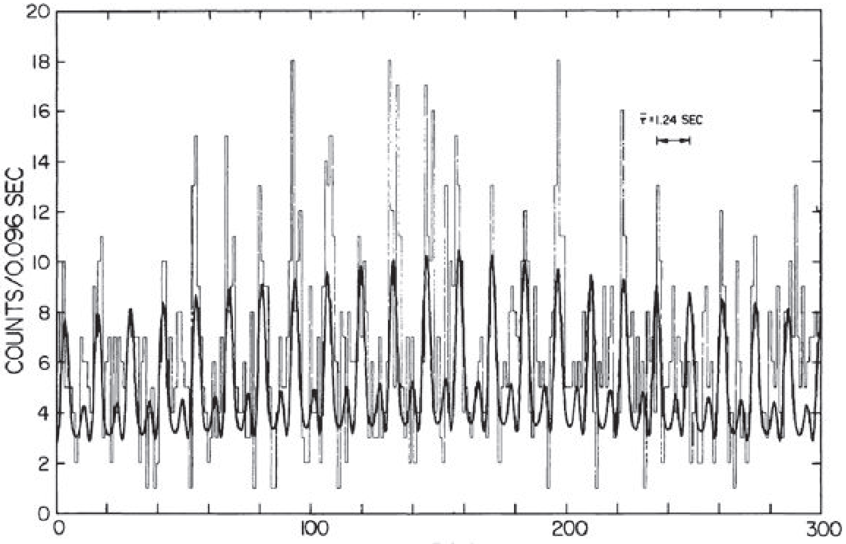
Uhuru (1970-1973)

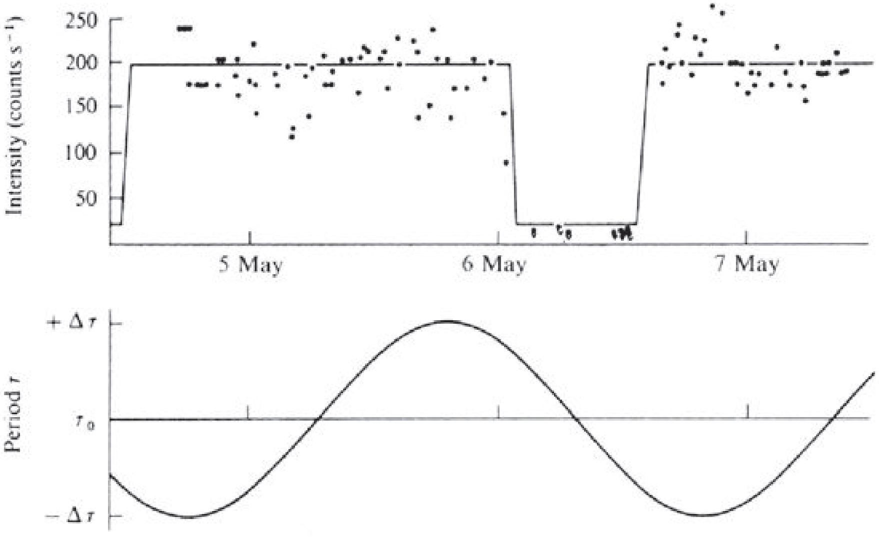




339 sources

X-Ray Pulsar Cen X-3





- Pulses occur at intervals of 4.84 seconds and are modulated at orbital period of 2.09 days.
- There is an eclipse when companion star blocks X-ray source.

Mass Function

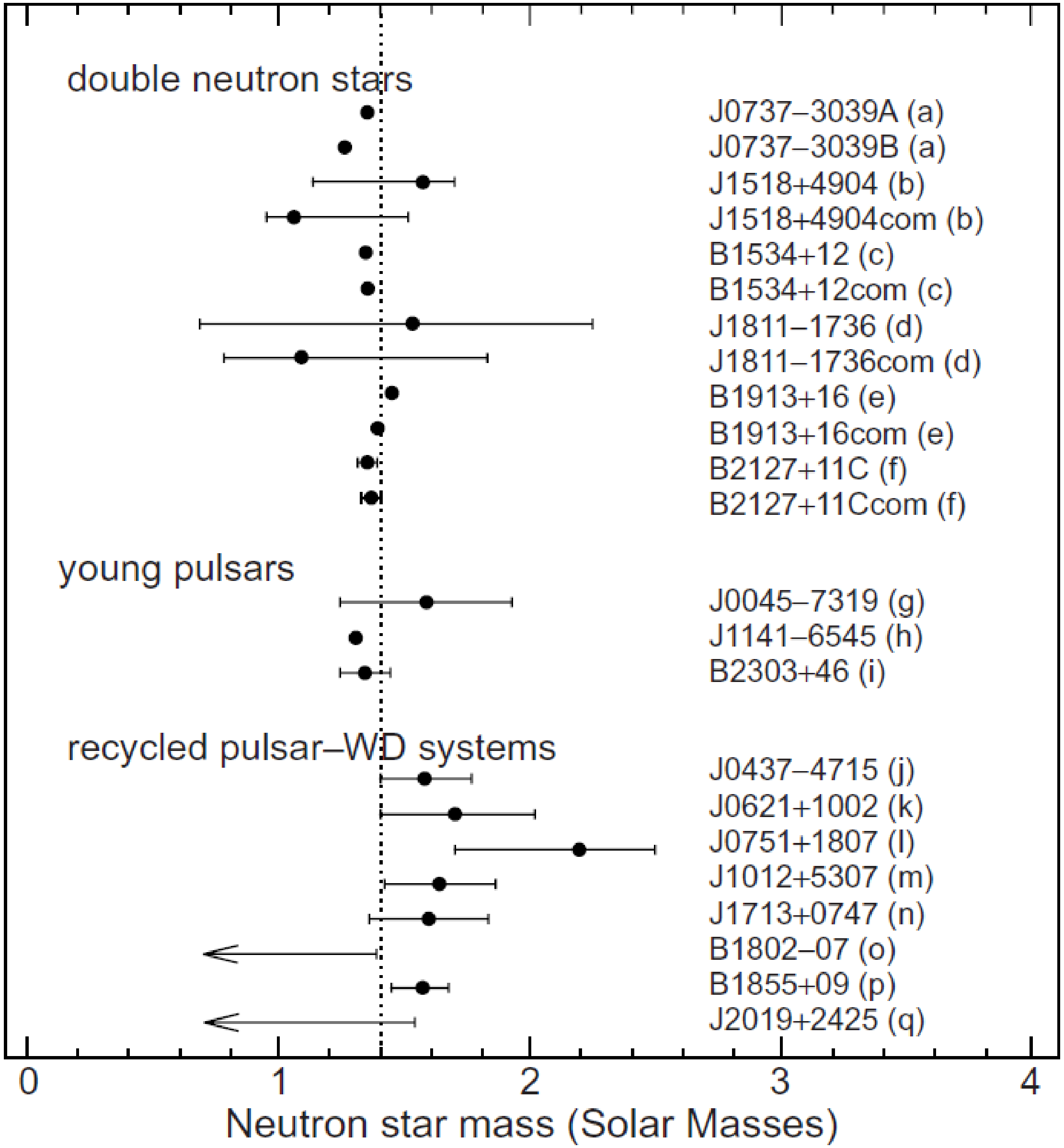
- If one can detect spectral lines from the companion, then one can measure the binary orbit and constrain the mass of the neutron star.
- K = peak velocity of companion, i = orbit inclination
- ‘Mass function’ is

$$f = \frac{M_X^3 \sin^3 i}{\left(M_0 + M_X\right)^2} = \frac{P_{orb} K^3}{2\pi G} < M_X$$

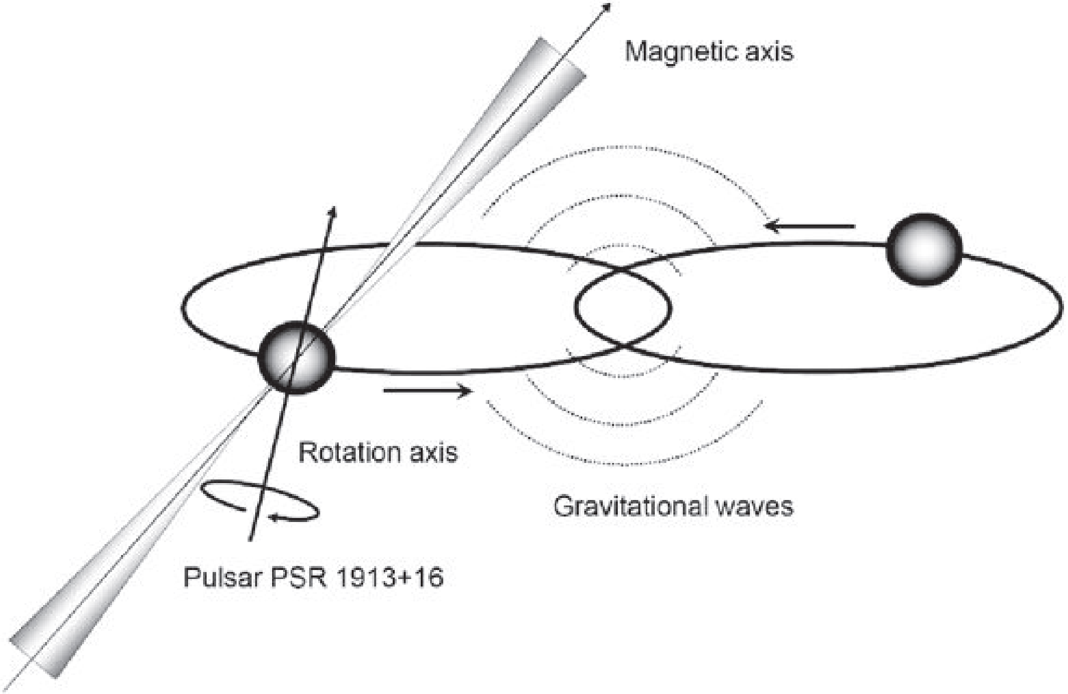
- Note that book has mass function measured using velocity shifts of X-ray source, which gives constraint on mass of companion star.

Binary Pulsars

- Systems with two neutron stars permit accurate mass measurements and tests of general relativity.
- First such binary was found by Hulse and Taylor in 1975; they won the Nobel prize. Double pulsar system found in 2006.



Binary Pulsars

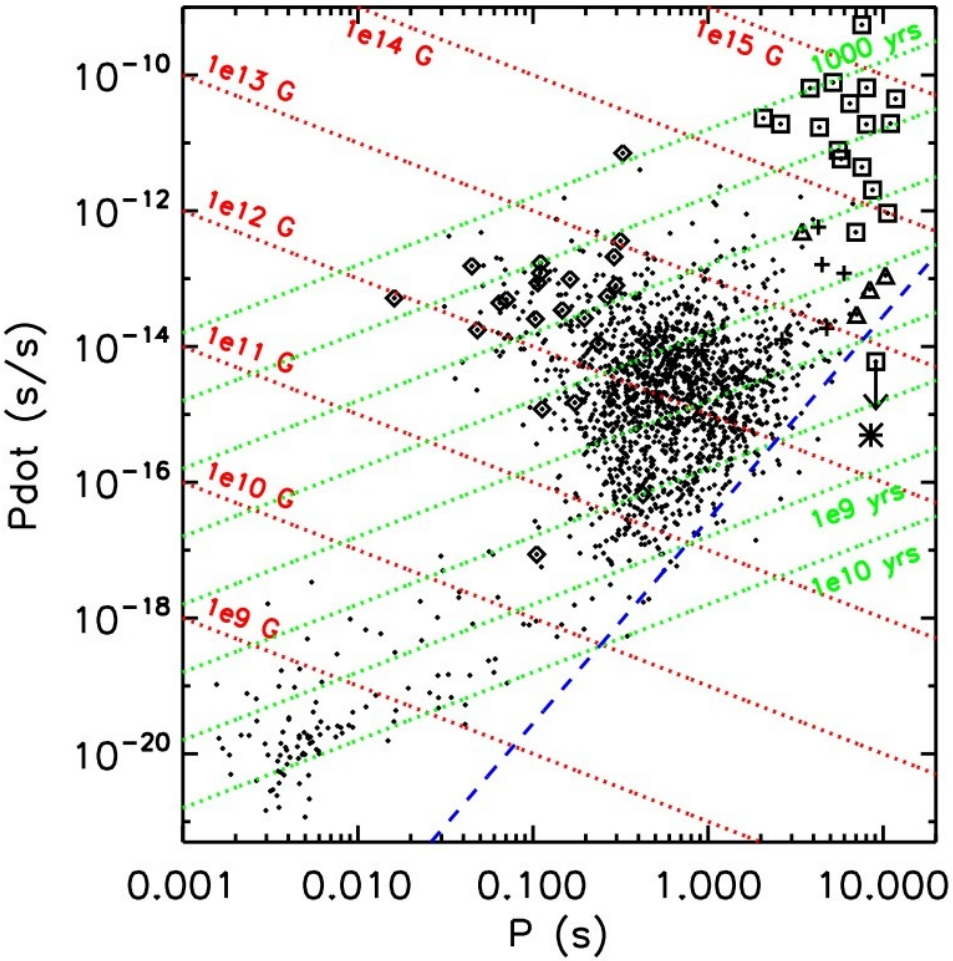


- Hulse and Taylor found that the binary orbit was gradually shrinking in a manor consistent with the binary losing energy to gravitational waves.
- Gravitational waves finally detected last year, but in a BH-BH binary.

Millisecond Pulsars

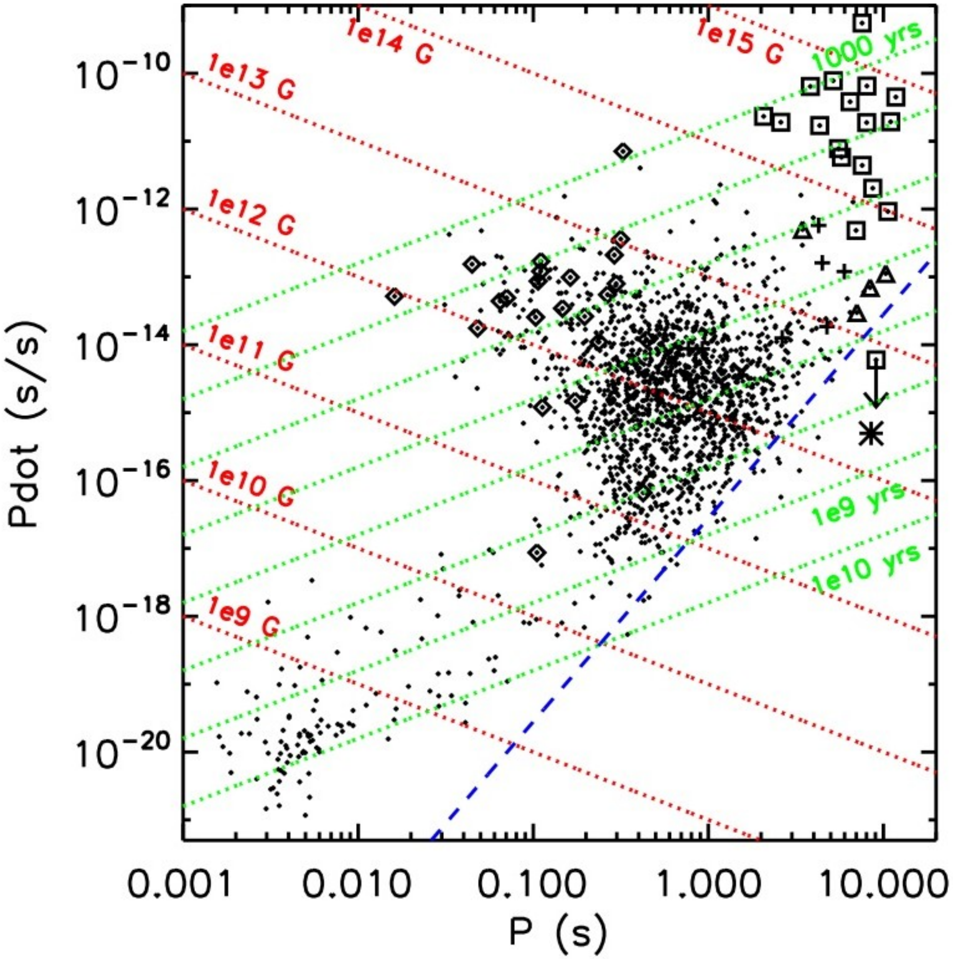
- There are pulsars with very short periods, milliseconds.
- How are they produced?

- Faster than the youngest pulsars. Also, have long characteristic ages and low magnetic fields. Often found in globular clusters.
- Millisecond pulsars are thought to be spun-up via accretion from a companion star.

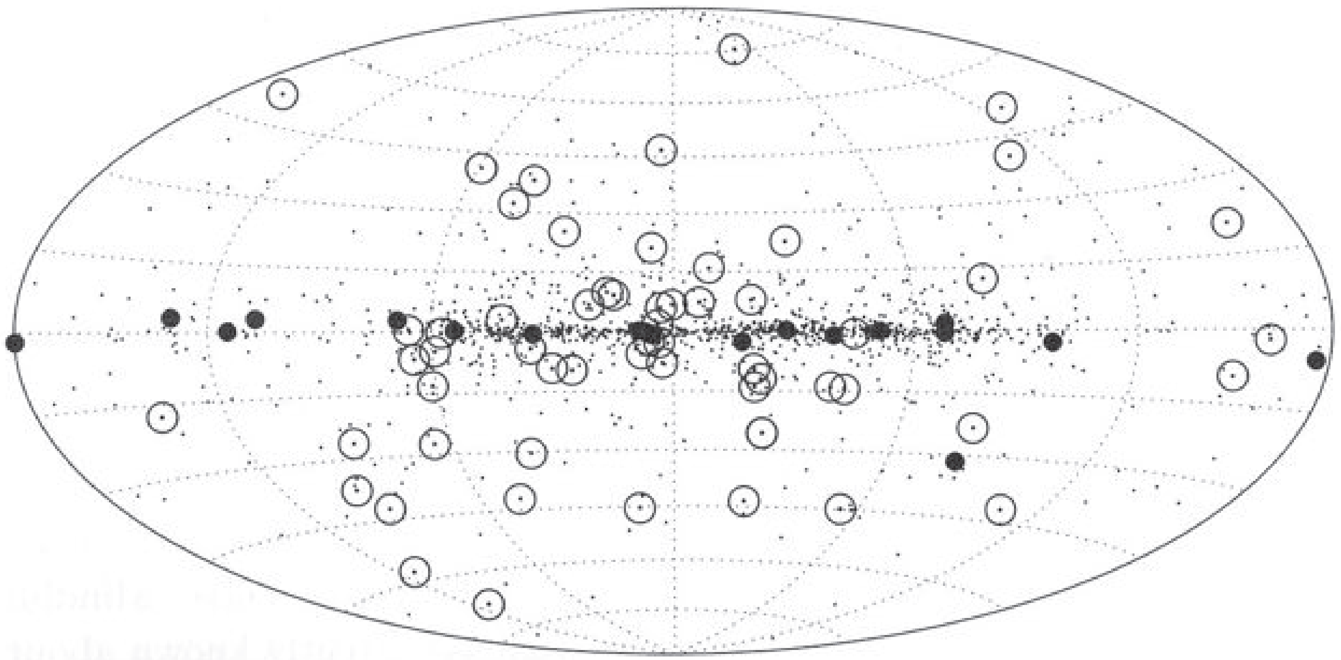


Magnetars

- There are pulsars with very high magnetic fields (squares) and few second periods.
- They also produce giant outbursts as ‘soft gamma repeaters’ and `anamalous X-ray pulsars’.
- Spinning down too slowly to power outbursts via spin.
- Outburst thought to be due to release of magnetic energy via starquakes.



Galactic Distribution of Pulsars



- Large dots are pulsars with SNR.
  - Why all in plane?
- Small dots are other regular pulsars.
  - Broader distribution due to velocities up to 1600 km/s.
- Dots in circles are millisecond pulsars.
  - Why wide distribution?