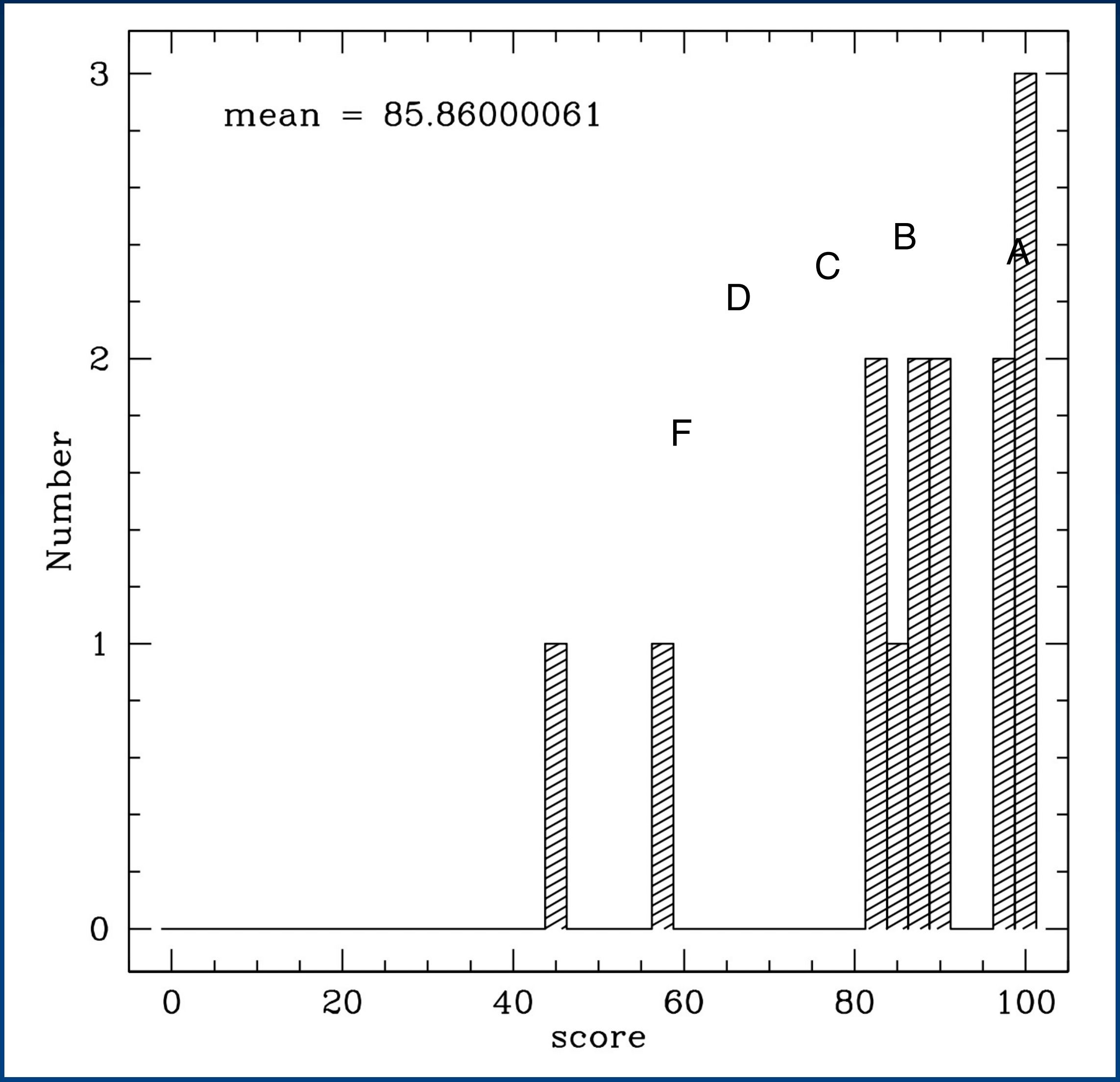
Test #3 Results

90 – 100: A
80 – 89: B
70 – 79: C
60 – 69: D
< 60 : F

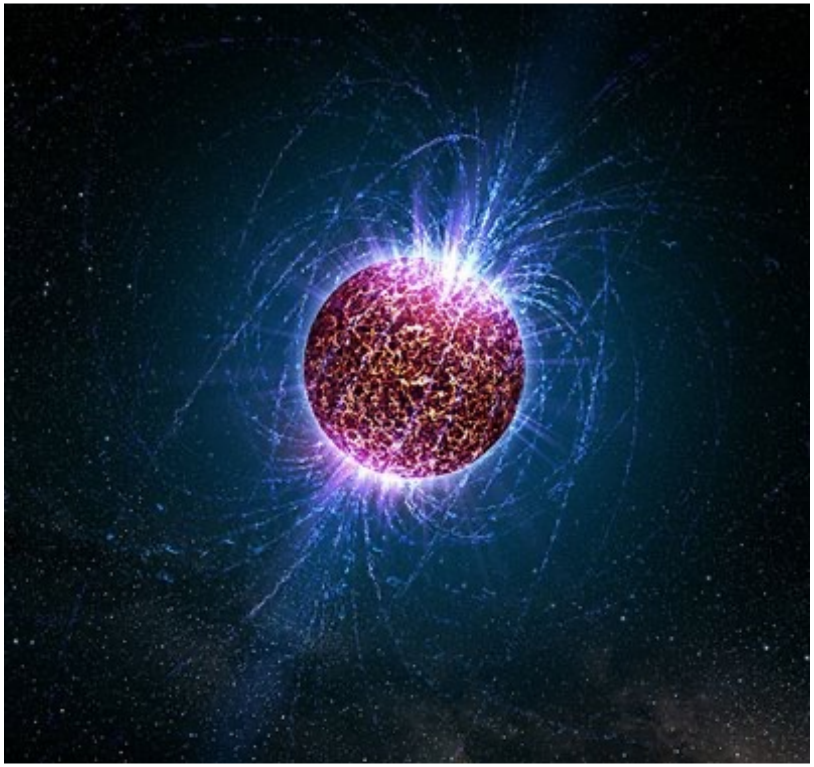


Announcements

- Instructor/Course Evaluations now available
- Term Paper presentations Dec 6: (10 min each)
    - Jesus, Christine, Talia, Sharleen, Joaquin, Jake, Soumyodipta
- Term Paper presentations Dec 8: (10 min each)
    - Will, Simon, Damen, Tousif, Matthew, Skylar, Prat
- Send powerpoint or pdf slides to Greg
- Aim for 7 min talk + 3 min Q&A + transition

- Written paper deadline Dec 12, at noon

Astronomy 421



Lecture 25: End states of stars - Neutron stars

Outline

Neutron stars

Pulsars

- properties
- distribution
- emission mechanism
- evolution

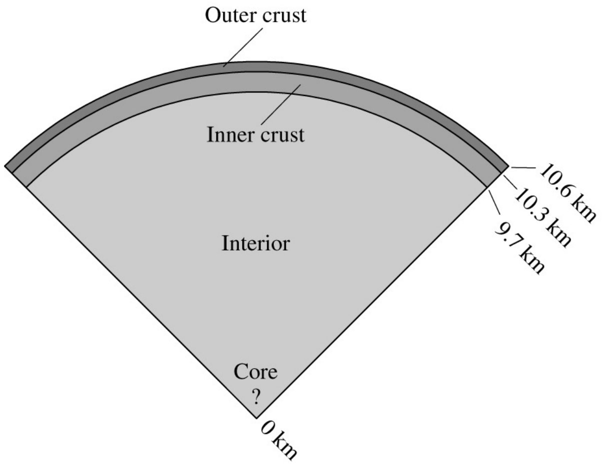
Neutron stars

Typical values:

- $M \sim 1.4 M_\odot$
- $R \sim 10$ km
- $\rho \sim 10^{18}$ kg m^{-3} (neutrons nearly “touch” each other)

The support is provided by *neutron degeneracy pressure.*

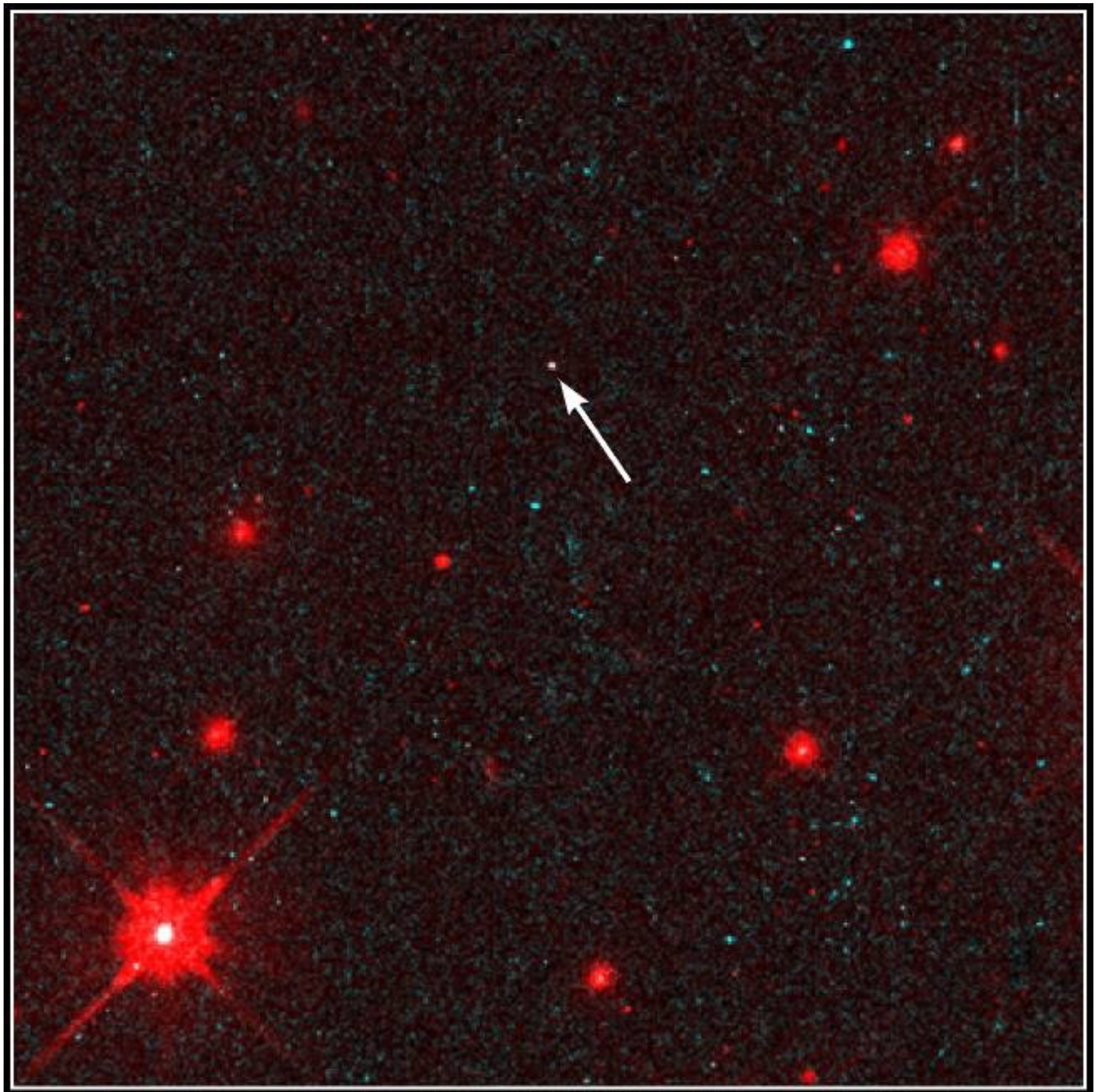
C&O describe a complex and uncertain structure.



The interior is mostly neutrons, with outer crust of some iron nuclei and charged particles. There may be a core of pions and other subatomic particles.

Predicted to exist in 1934 by Baade and Zwicky. Discovered as pulsars in 1967 by Bell.

An Isolated Neutron Star



Isolated Neutron Star RX J185635-3754 HST • WFPC2

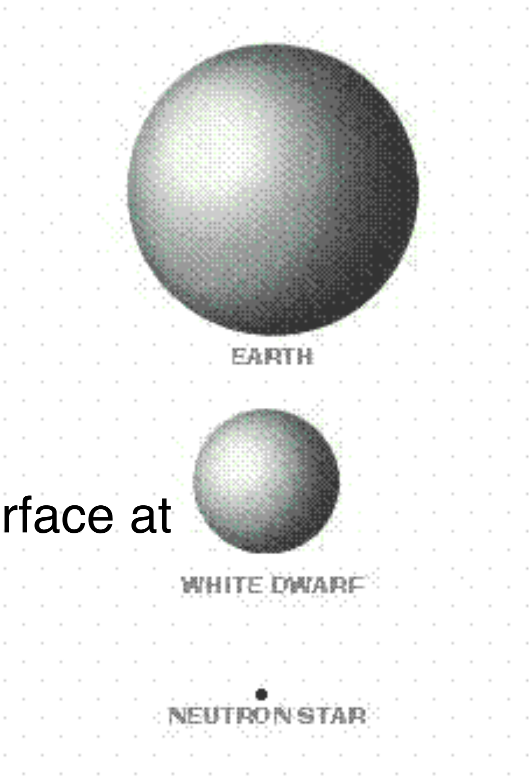
PRC97-32 • ST ScI OPO • September 25, 1997

F. Walter (State University of New York at Stony Brook) and NASA

T ~ 2 million K

Size ~ 30 km

The force of gravity at the surface is very strong:



$$F_G = \frac{GM_{NS}m}{R_{NS}^2} \Rightarrow \; a = \frac{GM_{NS}}{R_{NS}^2} = 1.9 \times 10^{12} \ \mathrm{m\,s^{-2}}$$

=> An object dropped from a height of 1m would hit the surface at a velocity 0.6% of the speed of light.

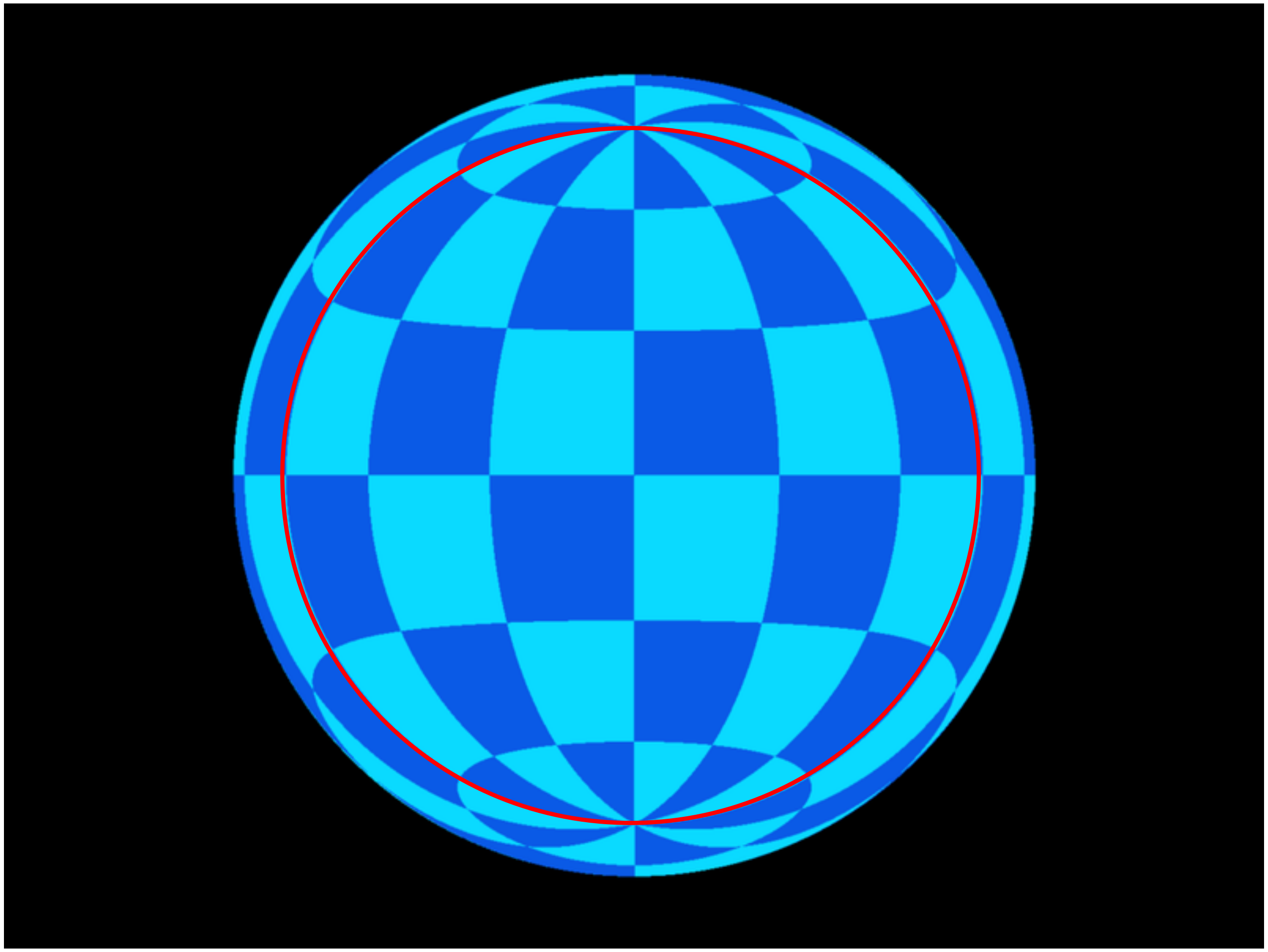
⇒ Must use general relativity to model correctly.

Radius can be calculated analogously to WD radius (see C+O):

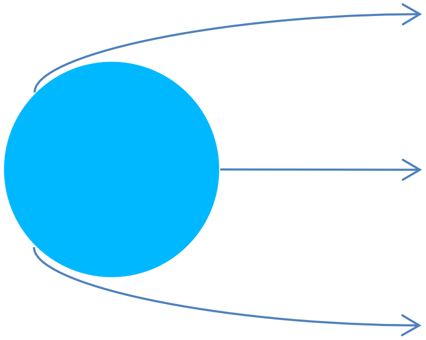
$$R_{NS} \approx \frac{(18\pi)^{\frac{2}{3}}}{10} \frac{\hbar^2}{GM_{NS}{}^{\frac{1}{3}}} (\frac{1}{m_H})^{8/3}$$

The maximum mass that can be supported by neutron degeneracy is uncertain, but can be no more than 2.2-2.9 $M_\odot$ (depending on rotation rate).

General Relativistic deflection of light



More than half the surface is visible at any one time!



Each square is 30 degrees x 30 degrees

Conservation of angular momentum:

A contraction of the core during the evolution means a very fast period *P* of rotation for neutron stars.

$$I_i \omega_i = I_f \omega_f \ \ \Rightarrow \ \ M_i R_i^2 \omega_i = M_f R_f^2 \omega_f$$

$$\Rightarrow \ \ \omega_f = \omega_i \left(\frac{R_i}{R_f} \right)^2$$

$$\Rightarrow \ \ P_f = P_i \left(\frac{R_f}{R_i} \right)^2$$

For an iron core, typical values give

$$P_{ns} \approx 4 \times 10^{-6} P_{core}$$

If, when core was Earth-sized, *P* was similar to observed WD values (1000 s), then P_{NS} 4 x 10^{-3} s. Neutron stars should be fast rotators.

Conservation of magnetic flux

Another prediction: magnetic field strength x area conserved as core shrinks

$$B_i 4\pi R_i^2 = B_f 4\pi R_f^2$$

Difficult to know what B of iron core is! Take value for WD, which can range from 10T to $5\text{x}10^4$ T (measured).

With these values, we find that B_{NS} could as high as 10^{10} T, but 10^8 T is probably more typical.

Compare this to the solar value, $B_\odot \sim 10^{-4}$ T.

Thus, neutron stars should have strong magnetic fields.

Pulsars

Periodic sources, discovered at radio wavelengths by Bell in 1967. Now over 2000 known.

Extremely regular, most have $P \sim 0.25\text{-}2$ sec. Some are measured to ~15 significant figures and rival the best atomic clocks on earth.

They slow down, but very slowly:

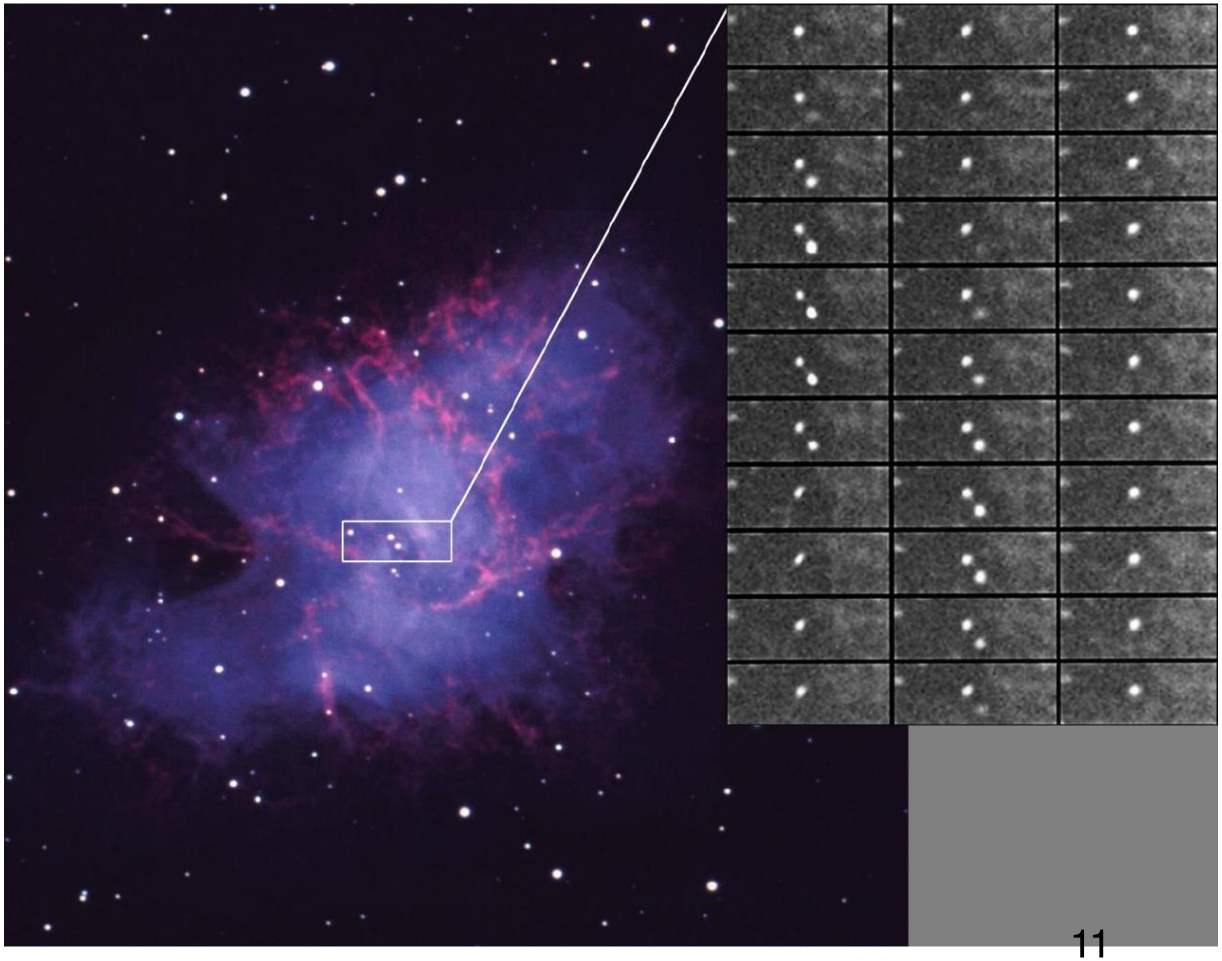
$$\frac{dP}{dt} = \dot{P} \approx 10^{-14} - 10^{-16}$$

for most.

Characteristic lifetime would correspond to $\sim 10^7$ years.

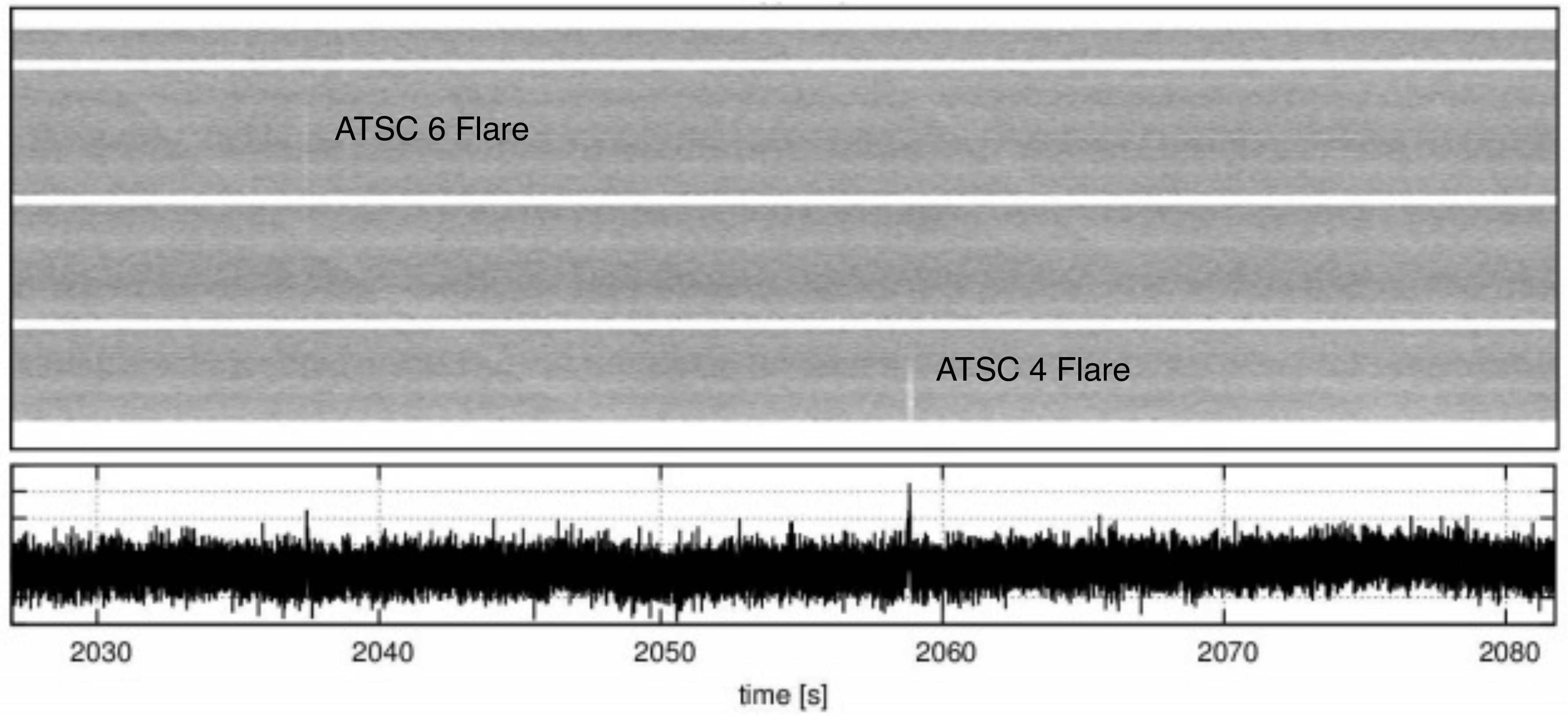
First explanation as NS by Pacini ’67, Gold ’68

(Gold predicted $\dot{P} > 0$)



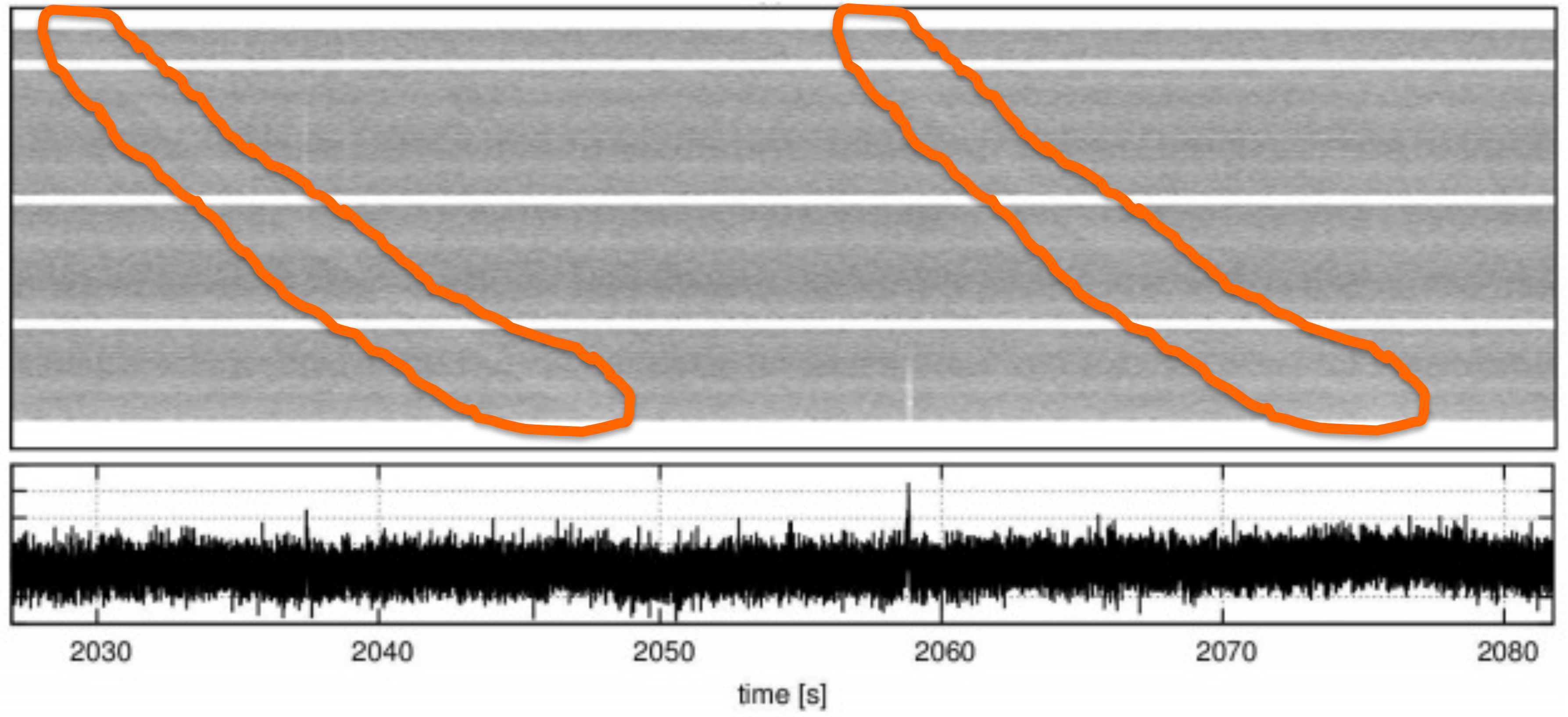
Science – Crab Giant Pulses

CGPs seen at a rate of ~10/hour



Science – Crab Giant Pulses

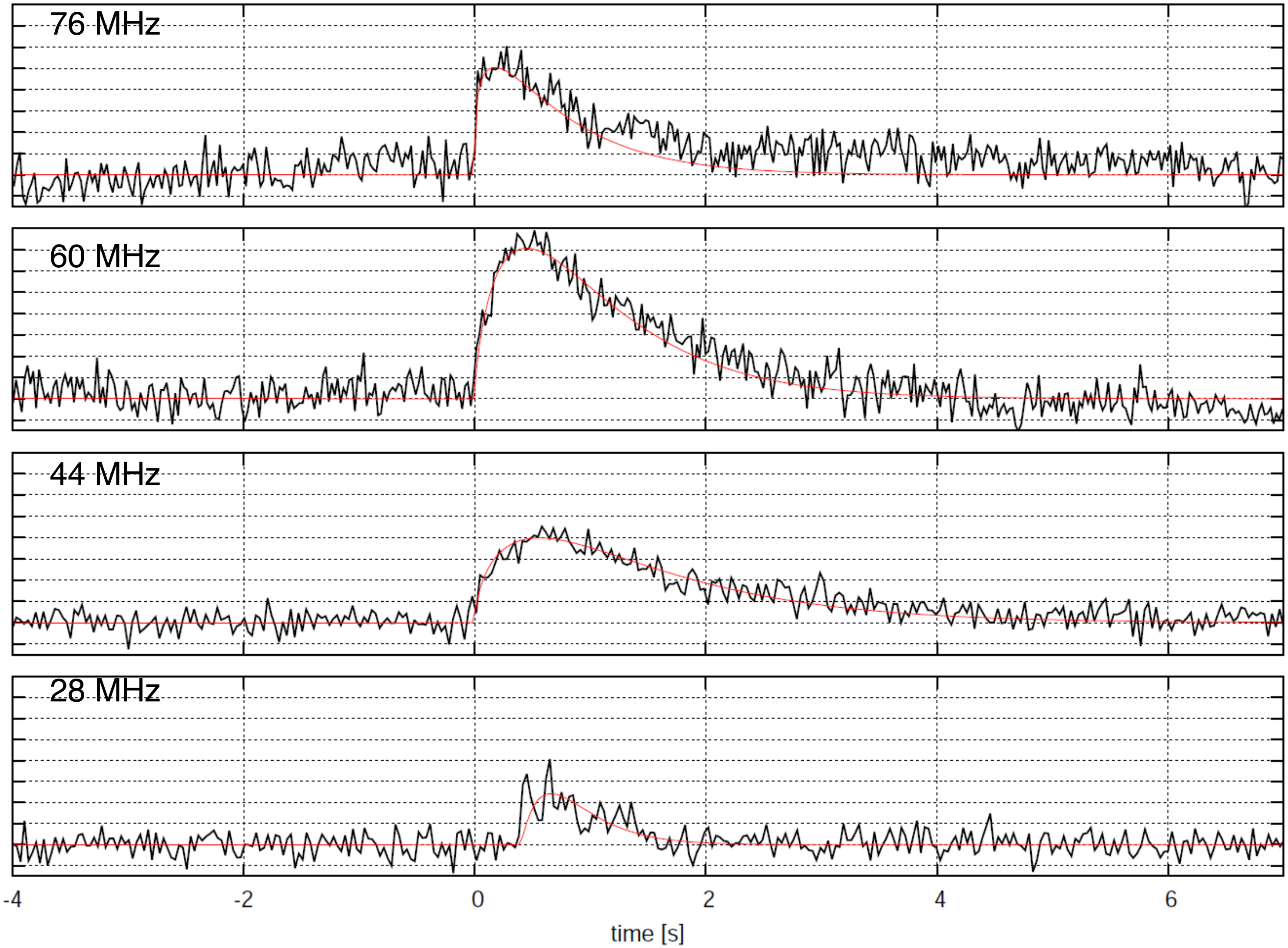
CGPs seen at a rate of ~10/hour



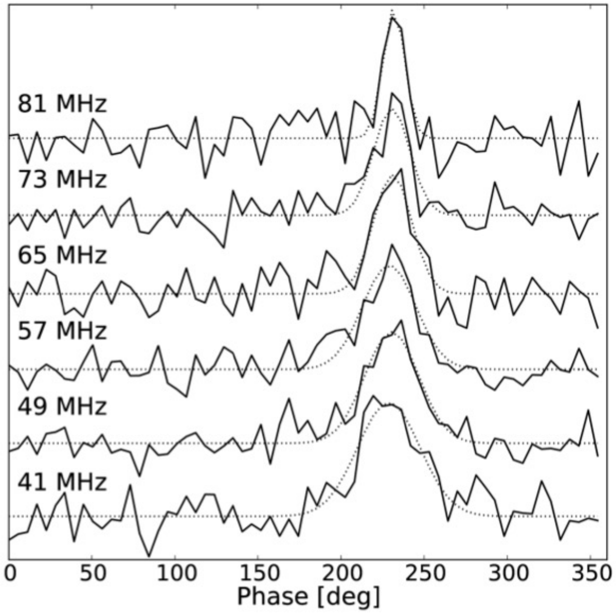
LWA Publication Highlights - 1

Crab Giant
Pulses

Ellingson et al.
2013, ApJ 768,
p. 136



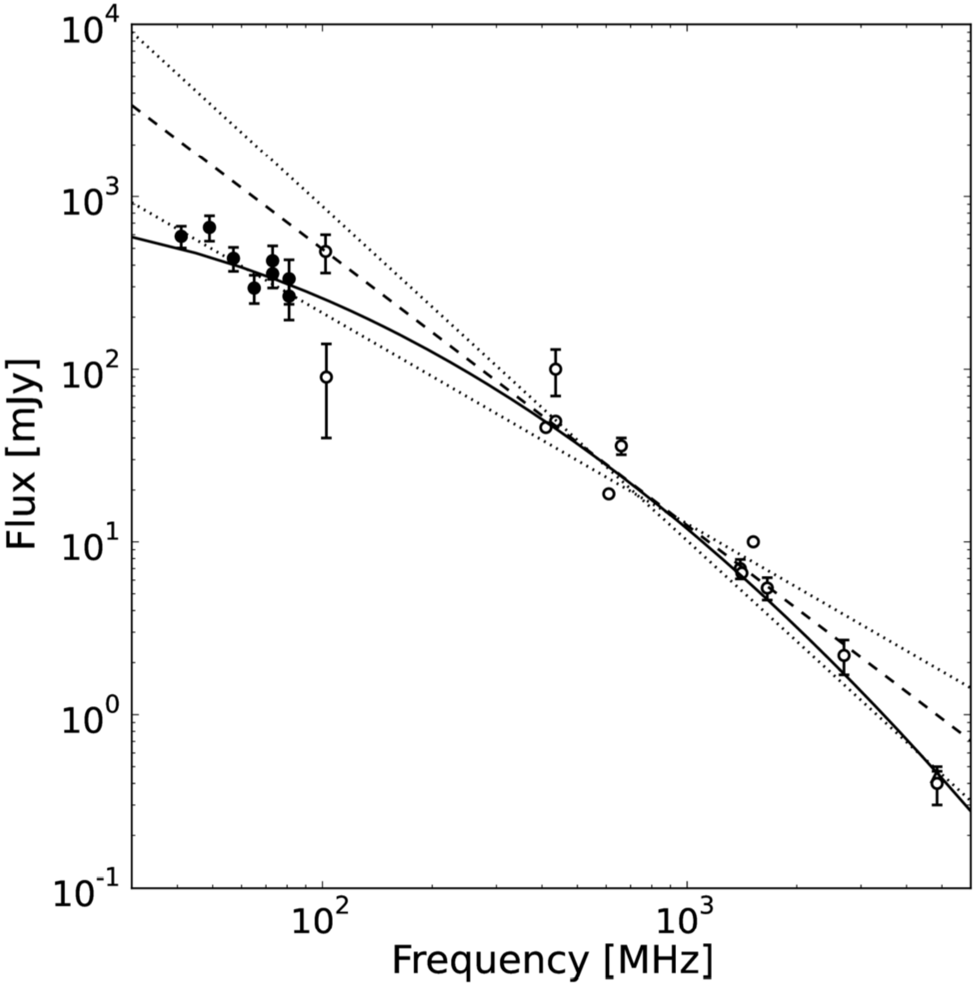
Millisecond Pulsars with LWA1



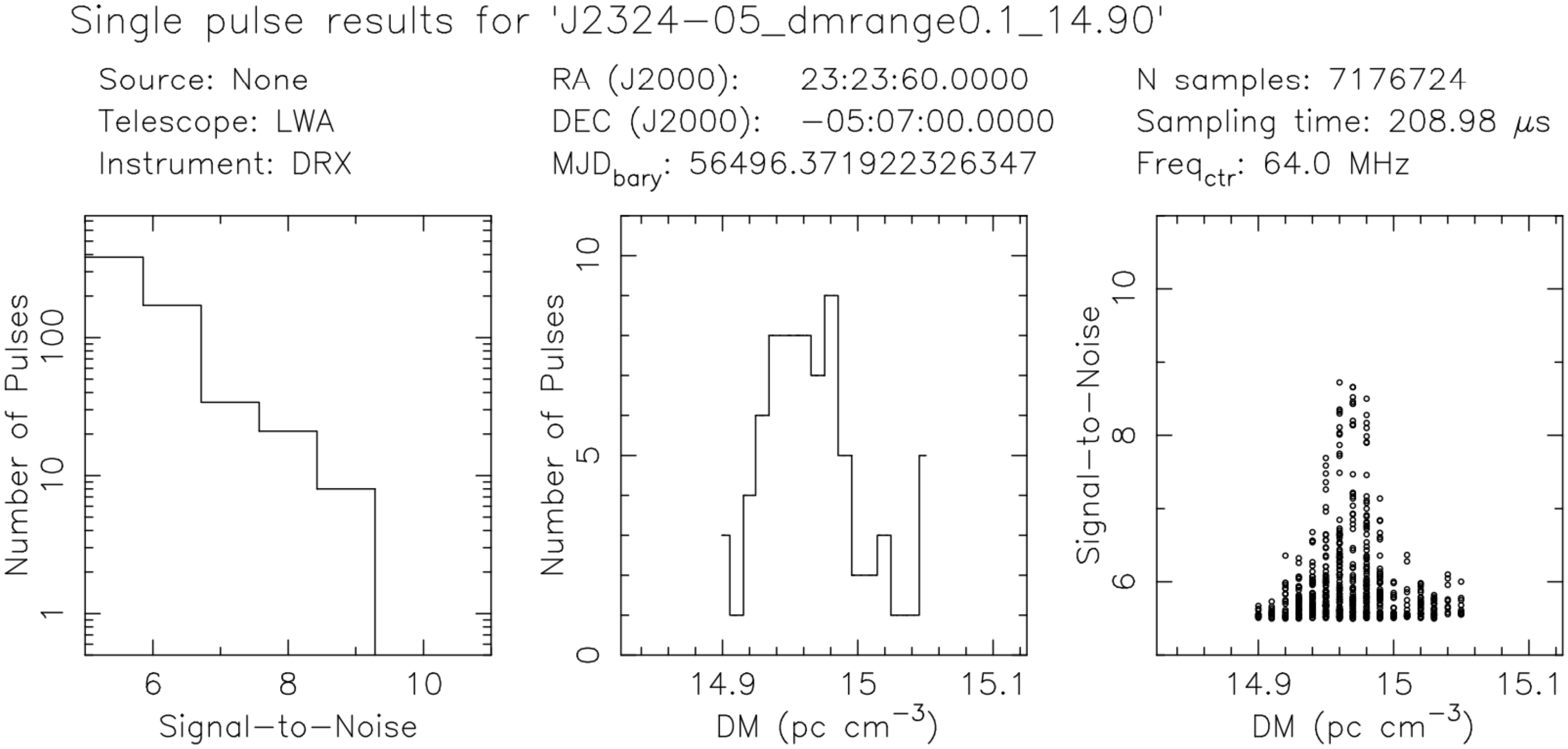
MSP J2145–0750

Dowell et al. 2013 ApJL, 775, L28

DM = 9.005 +/- 0.002 pc cm^{-3}



RRATS



Single pulse results for 'J2324−05_dmrange0.1_14.90'

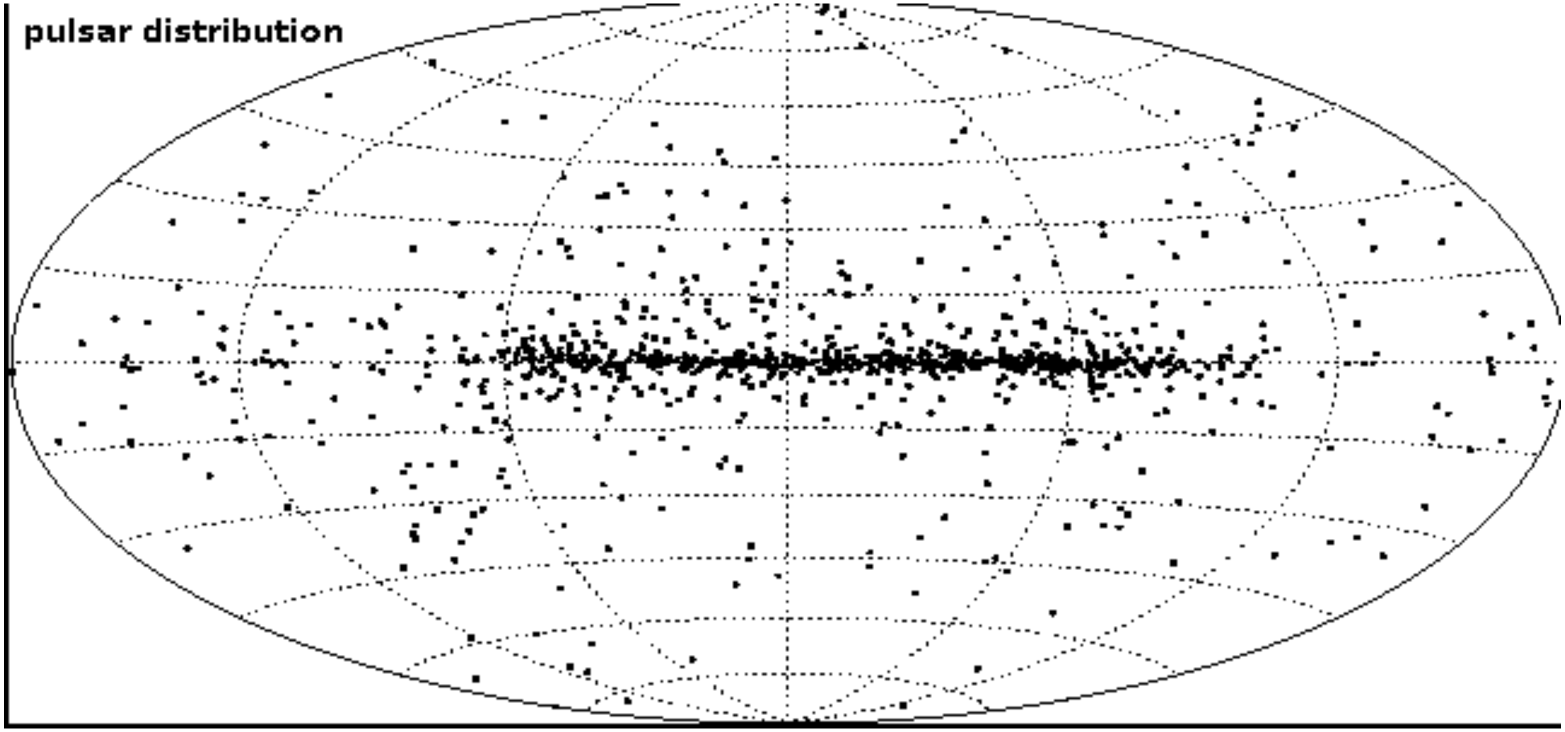
Source: None
Telescope: LWA
Instrument: DRX

RA (J2000): 23:23:60.0000
DEC (J2000): −05:07:00.0000
MJD_{bary}: 56496.371922326347

N samples: 7176724
Sampling time: 208.98 μs
$Freq_{ctr}$: 64.0 MHz

McLaughlin, Miller et al. 2013 in prep

Pulsar Distribution in Galactic Coordinates. Found mostly near the Galactic Plane.



Discovery of pulsar in the Crab nebula in 1968 confirmed it must be due to a neutron star, and these are a possible endpoint of massive star evolution. Several more associated with Supernova Remnants.

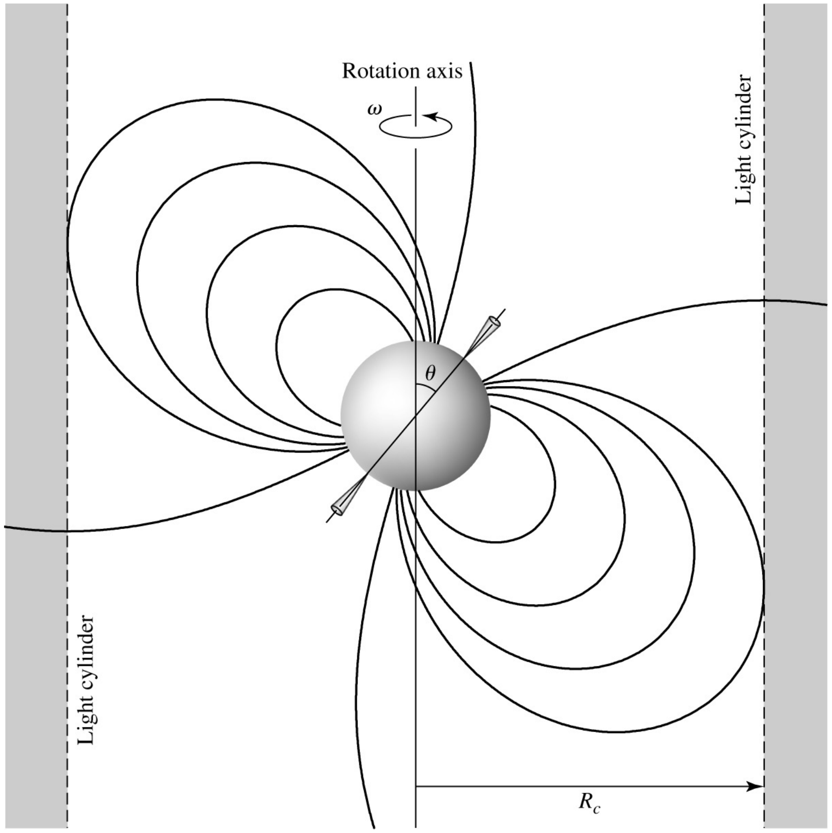
Many pulsars have high velocities (few 100 km/s vs. ~30 km/s for normal stars) as expected if ejected from a SN explosion which is not fully symmetric.

Pulsar model

Magnetic axis need not be aligned with rotation axis.

Rapidly changing magnetic field near rotating pulsar induces a huge electric field at the surface:

$$\epsilon = -\frac{d\Phi_B}{dt}$$

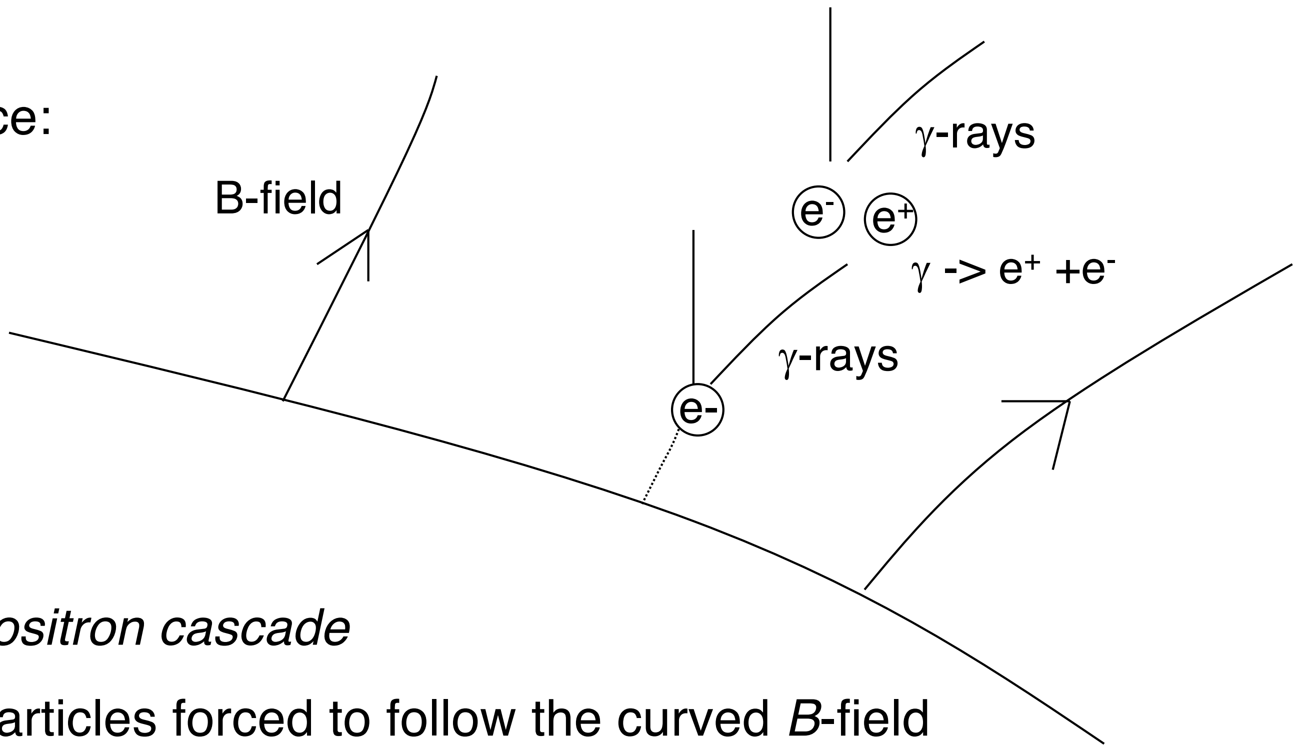


Φ_B is the magnetic flux through a given area.

The *B* field is strongest at the poles, thus the *E* field as well, about 10^{14} Volts/m.

=> Charged particles drawn off surface at the poles.

At the surface:



Electron-positron cascade

Charged particles forced to follow the curved *B*-field

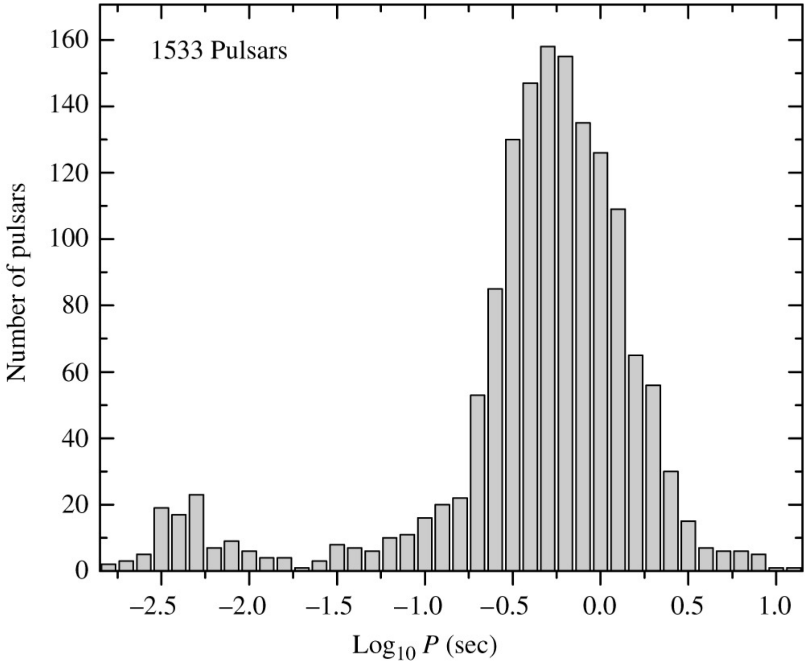
=> accelerated

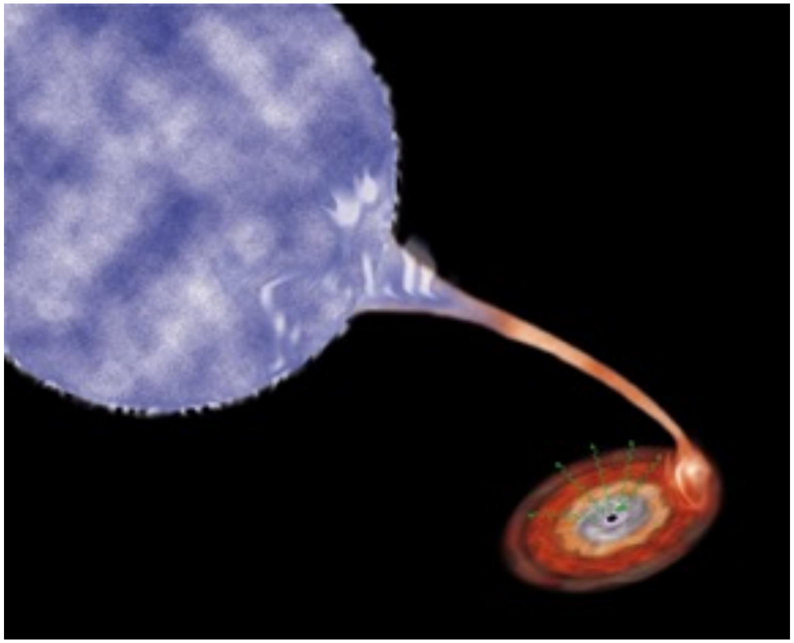
=> radiate photons (“curvature radiation”).

At first, there will be high energy γ-rays, which will interact and *pair-produce* more e^- and e^+. They will emit a continuous spectrum with a strong relativistic forward beaming effect into a narrow cone (e^+ accelerated back downward). Eventually particles lose energy and start to radiate brightly in radio waves.

Pulsar evolution

Since they slow down with age, they should lose energy to power the emission. Probably born with $P \sim$ several msec, die at ~ a few sec. Not clear how the emission mechanism turns off, but somehow associated with loss of rotational energy. Magnetic and electric fields may weaken, but highly uncertain.





Millisecond pulsars thought to be old neutron stars in binary systems. Many found in globular clusters.

Companion expanded, spills material onto slow neutron star.

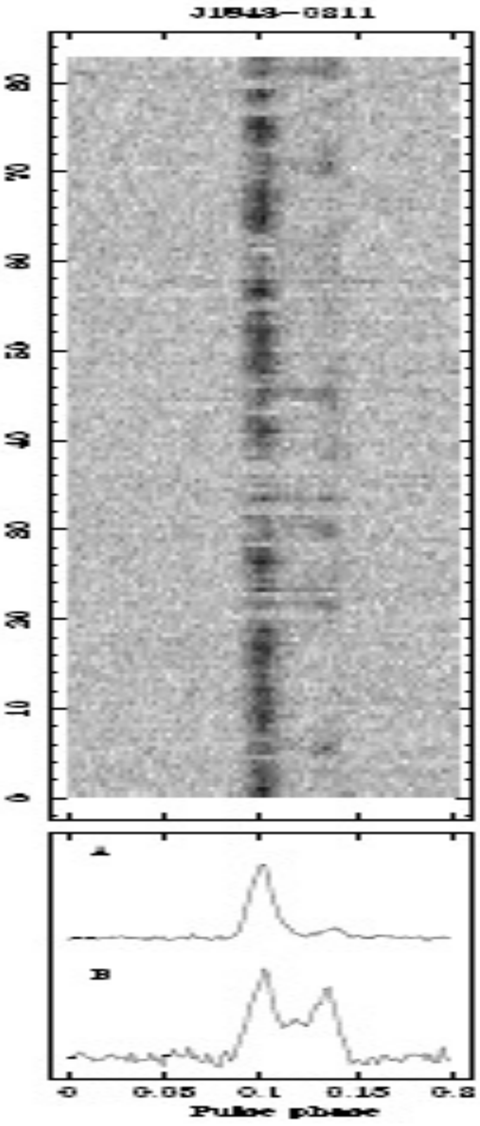
When material reaches NS surface, it is orbiting very rapidly. As it accretes, it adds to angular momentum of NS, spinning it up again.

The shape of each pulse shows substantial variation, though the average pulse shape is very stable.

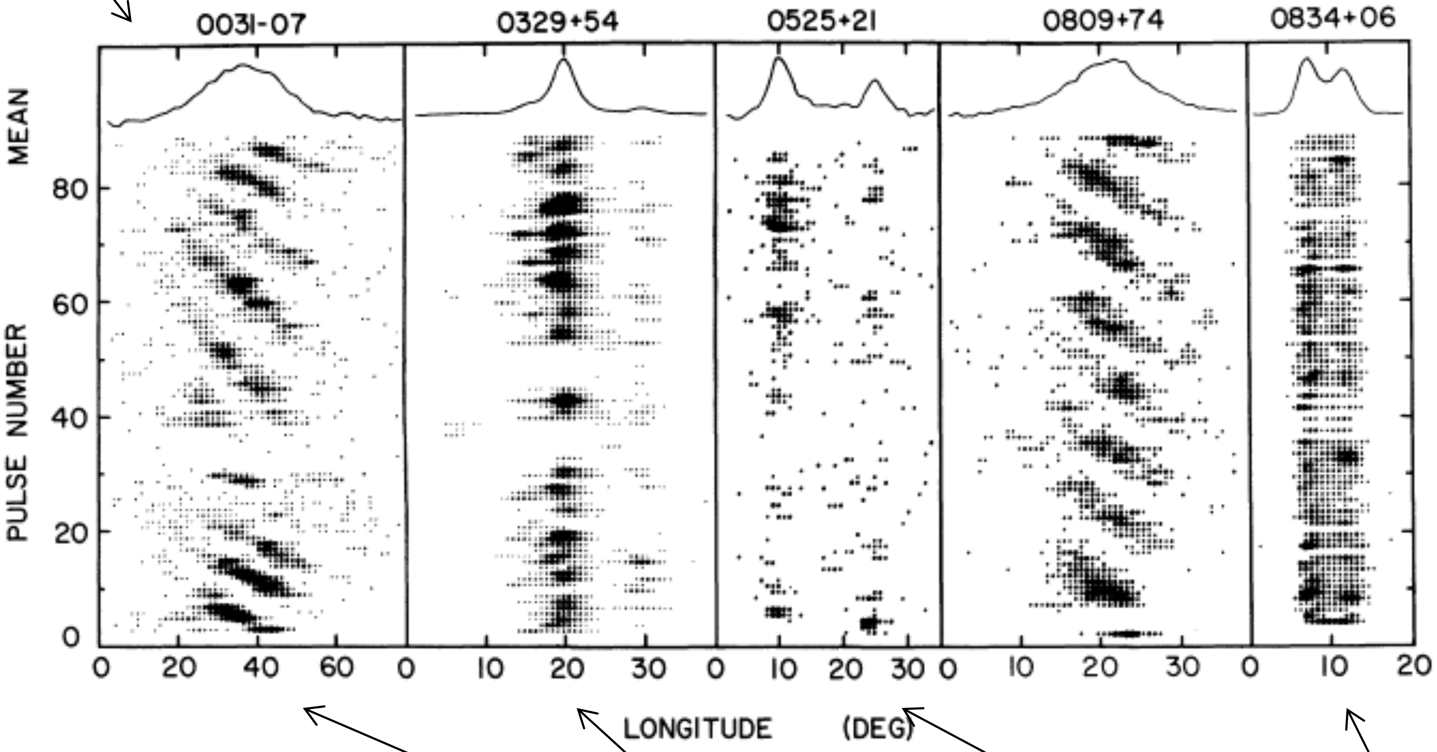
PSR1919+21
(first pulsar discovered)

(the pulse typically lasts several % of the period)

Several pulsars switch between two differently shaped average profiles – “mode switching”.



“Drifting subpulses”: seen in some longer period pulsars: region of emission must migrate around magnetic pole



“Nulling”: several longer period pulsars turn off for a few periods up to a few minutes. Seems connected to mode changing. Eventual turnoff this way?

Creation of neutrons

Neutronization: at high densities neutrons are created rather than destroyed.

Recall that neutron stars are remnants of Type II SN - massive stars.

During the last stages of a supergiant $T_{\text{core}} \sim 10^{10}$ K, at which point iron can photodisintegrate:

$$
\begin{aligned}
{}^{56}_{26}Fe + \gamma &\rightarrow 13\,{}^{4}_{2}He + 4n \\
{}^{4}_{2}He + \gamma &\rightarrow 2p^{+} + 2n
\end{aligned}
$$

Thus, γ-rays, protons and He nuclei are released.

These reactions absorb energy => core thermal pressure drops.

Core contracts very fast (tens of 1000 km/s)

=> degenerate core electrons eventually will have sufficient energy to react with the protons from the photodisintegration.

We will have electron capture:

$$p^+ + e^- \;\rightarrow\; n + \nu_e$$

All electrons from the core used up

=> no electron degeneracy pressure

=> core collapse continues

Once $T_{core} \sim 10^{12}$ K, the neutrons become degenerate.

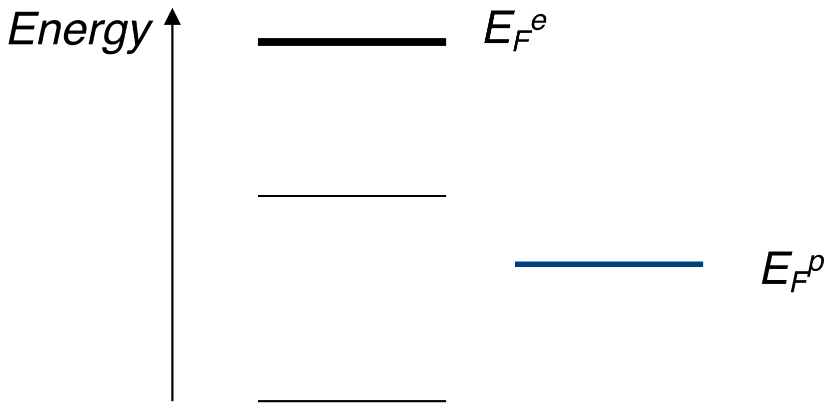
At what densities does electron capture occur?

Assume we start with a star made of e^-, p^+, and n.

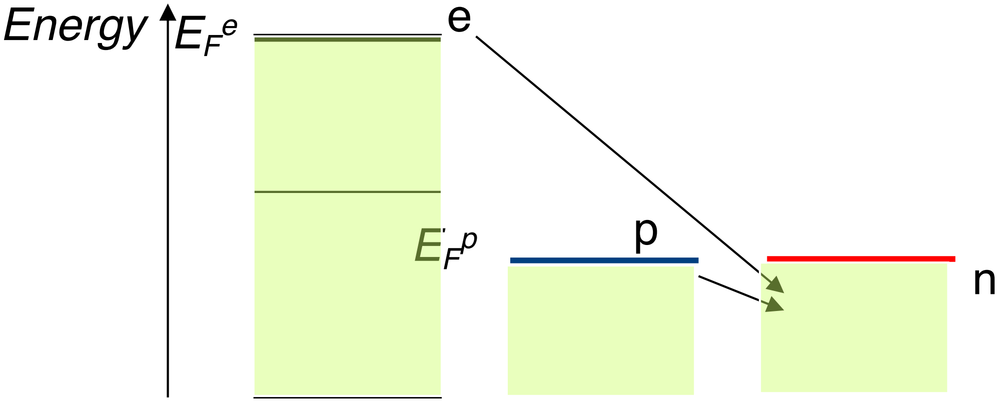
The Fermi energy varies depending on the particle mass, with the *lighter* particles having the *higher* energies:

$$E_F = \frac{\hbar^2}{2m}\left(3\pi^2 n\right)^{2/3}$$

Electrons have a Fermi energy which is 2000 times higher than that of protons. Energy levels will look like (not to scale):



When the difference between the Fermi energies is larger than the difference between the *p* and *n* mass energies mc^2, an e^- can be captured by a proton to create a *n.*



The amount of energy required for electron capture (with the release of a massless neutrino) is:

$$\Delta mc^2 = m_n c^2 - m_p c^2 - m_e c^2$$

Then:

$$m_n - m_p - m_e = (1.675 - 1.6726 - 0.00091) \times 10^{-27} = 1.5 \times 10^{-30} \text{ kg}$$

$$\Rightarrow \Delta mc^2 = 1.5 \times 10^{-30} c^2 = 1.34 \times 10^{-13} J$$

$$\text{Thus : } E_F^e - E_F^p \simeq E_F^e - \frac{E_F^e}{2000} \simeq E_F^e = \Delta mc^2 = 1.34 \times 10^{-13} \text{ J}$$

There is a density corresponding to this threshold, which we can find from the expression of the Fermi energy:

$$E_F = \frac{\hbar^2}{2m_e}\left[3\pi^2\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{2/3}$$

Thus, $$\rho = \left(\frac{E_F^e 2m_e}{\hbar^2}\right)^{3/2} \frac{m_H}{3\pi^2}\left(\frac{A}{Z}\right) \simeq 1.2 \times 10^{10}\ \mathrm{kg\,m^{-3}}$$

Compare to the density of the Sun, ~1400 kg m^{-3}.

This means that the threshold for electron capture in a $1M_\odot$ neutron star would occur at a radius of about 3400 km.

Caveats:

- We used non-relativistic expression for the kinetic energy of the electrons (see C&O)
- We have ignored nuclear binding effects (assumed H instead of Fe in core)
- We calculated the threshold of the formation of neutrons, not really the equilibrium density.

Taking that into account, the real threshold density is closer to 10^{12} kg m^{-3}.

Now, we have formed neutrons (or heavy nuclei rich in neutrons):

most stable arrangement is when neutrons and protons are found in a lattice of increasingly neutron rich nuclei

=> this reduces the Coulomb repulsion between protons.

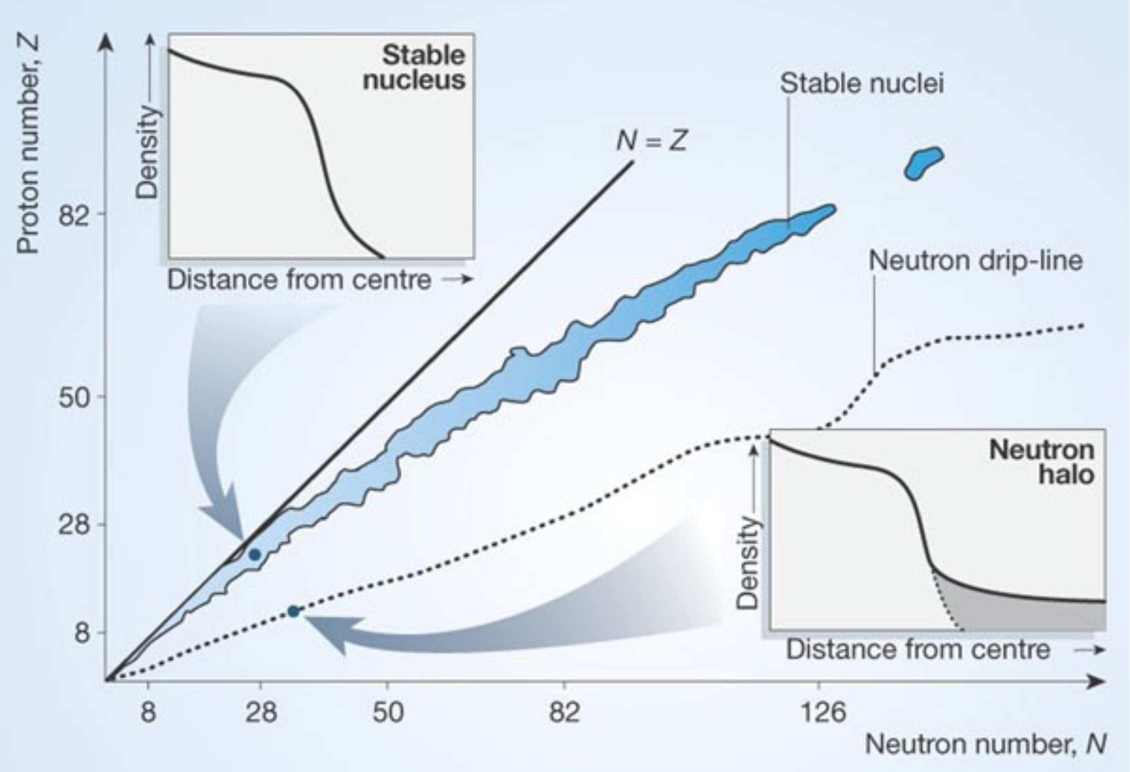
Normal beta-decay won't happen, since no allowed vacant spaces for electrons.

At yet higher densities, we will have a more stable arrangement forming with some neutrons outside lattice.

Neutron drip

Nuclei with too many neutrons are unstable: beyond the *neutron drip-line* nuclei become unbound.

These neutrons form a nuclear 'halo': neutron density extends to larger distances that in a well-bound, stable nucleus.

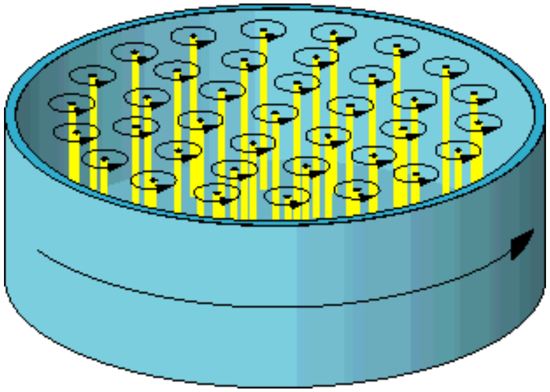


Now: lattice of neutron-rich nuclei, non-relativistic degenerate free neutrons, and relativistic degenerate electrons.

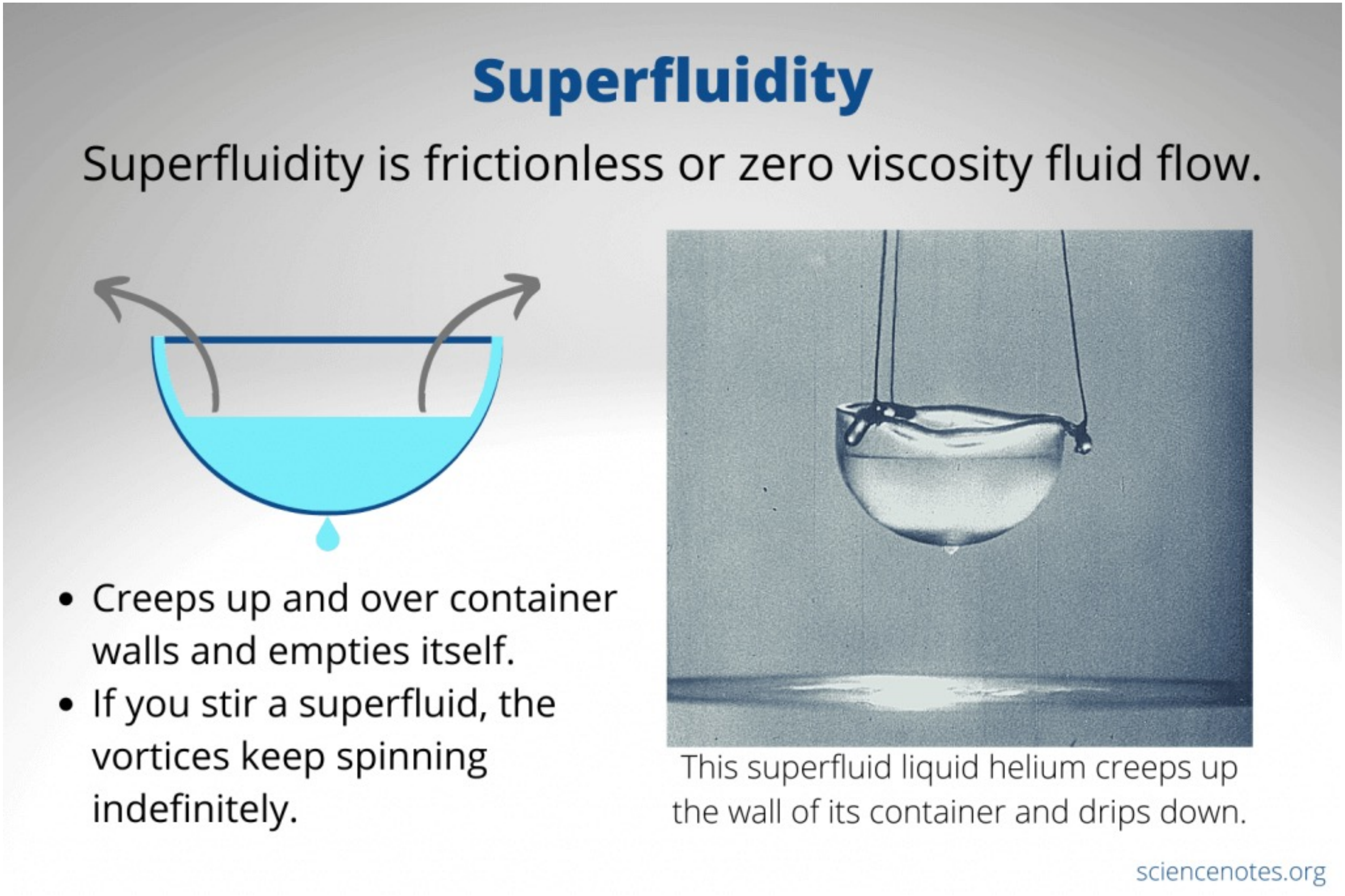
Superfluidity

Free neutrons pair up to form bosons => Pauli EP will not apply.

- Degenerate bosons can flow without viscosity (all bosons occupy lowest energy state, so no energy can be lost)
- A rotating container will form quantized vortices, spinning forever without resistance.



- At $\rho \sim 4 \times 10^{15}$ kg/m^3 neutron degeneracy pressure dominates.
- Nuclei dissolve and protons also form a *superconducting* superfluid.



Superfluidity

Superfluidity is frictionless or zero viscosity fluid flow.

- Creeps up and over container walls and empties itself.
- If you stir a superfluid, the vortices keep spinning indefinitely.

This superfluid liquid helium creeps up the wall of its container and drips down.

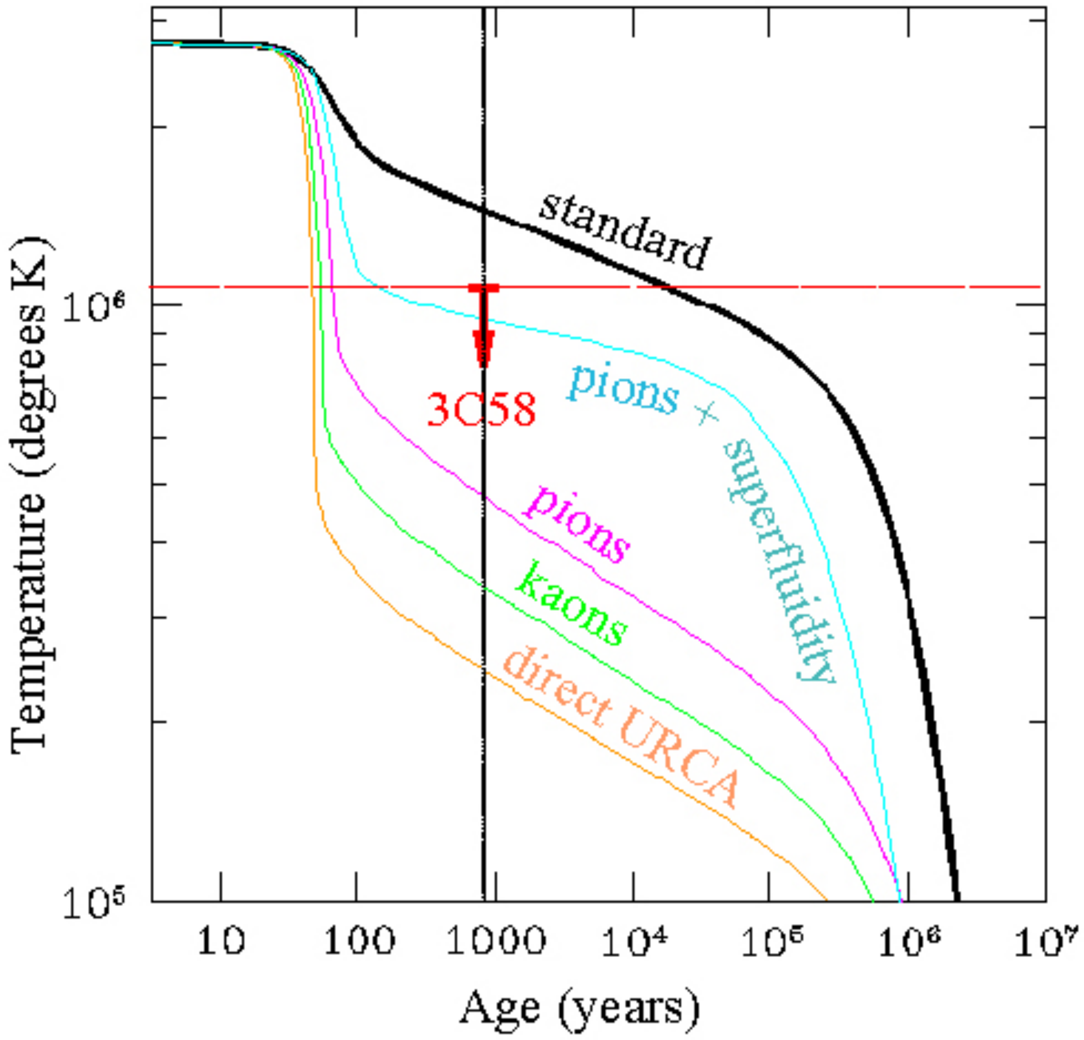
sciencenotes.org

Cooling

In the collapse (during the SN formation) the internal temperatures drop to 10^9 K within a few days.

This is due to neutrinos carrying energy away. Once degenerate, fewer neutrinos created, although still dominating the cooling.

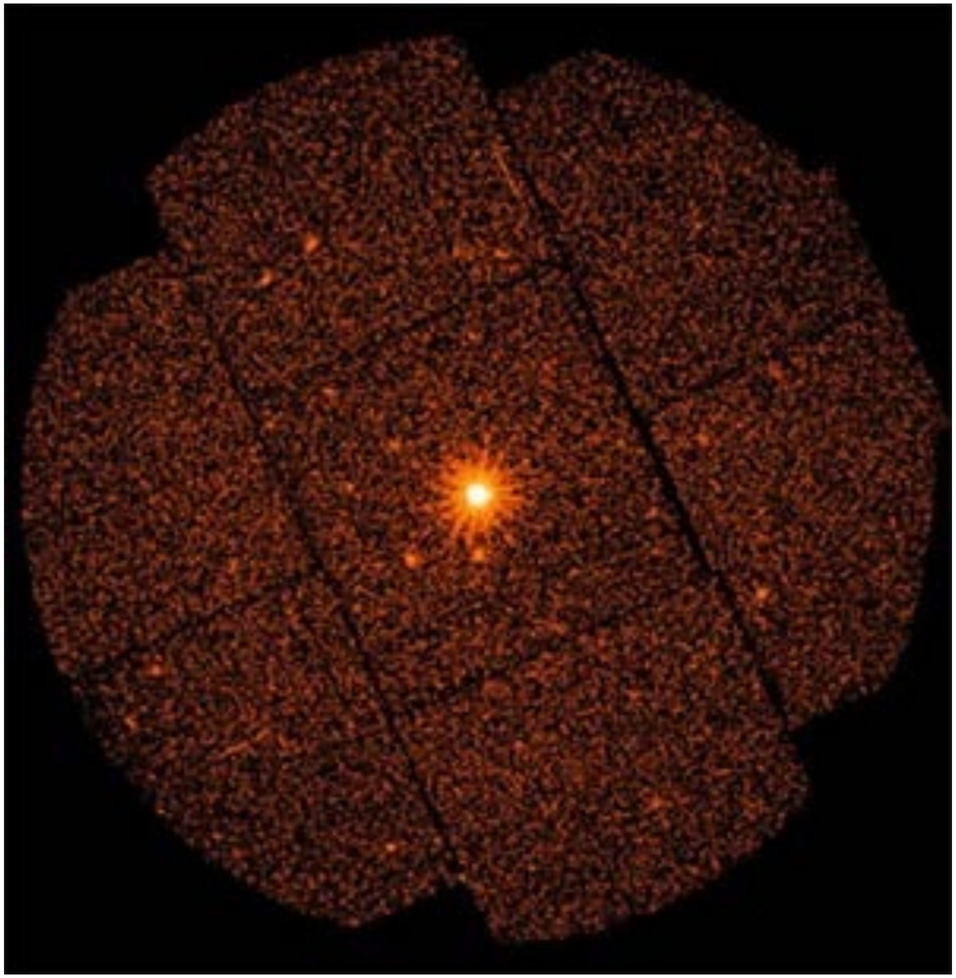
Surface temperature ~ 10^6 K for about 10,000 years.



Luminosity

Blackbody luminosity of $1.4M_{\odot}$ neutron star with a surface temperature of 10^6 K is given by Stefan-Boltzmann: 7.13×10^{25} W

Wien's displacement law shows the radiation peaks in the X-ray (2.9nm).



Chandra X-ray image
of a neutron star.