Neutron stars:

When WD's mass exceeds M_{ch}, it begins to collapse and $\rho\uparrow$. At some point, the e^- Fermi energy $E_F = \sqrt{p_F^2 + m_e^2}$ exceeds $(m_n - m_p)c^2 = 1.29$ MeV. This happens at density $\rho \simeq 1.2\times10^7\ g/cm^3$. At higher ρ, it becomes energetically favorable for e^-'s to inverse-beta decay (combine) with protons to form neutrons $\Rightarrow$ neutron star.

More realistically, WD contains CO, not free protons. What really happens is that e^-'s capture on nuclei to form increasingly n-rich nuclei. At density $\rho \gtrsim 4\times10^{11}\ g/cm^3$, neutrons begin to bleed from nuclei. This "ionization" of n's from nuclei softens the EOS, and star continues to collapse until $\rho \gtrsim 10^{14}\ g/cm^3$ at which point neutron degeneracy pressure becomes sufficient to support the star.

The density $\rho_{nuc} \simeq 2\times10^{14}\ g/cm^3$ is the density of ordinary nuclear matter. The EOS at higher densities is determined by nuclear theory, which is <u>highly</u> uncertain.

More quantitatively, there will be degenerate n, p, and e^- with Fermi energies $\epsilon_F(n)$, $\epsilon_F(p)$, $\epsilon_F(e)$. If $\epsilon_F(n) < \epsilon_F(p) + \epsilon_F(e)$, then neutrons cannot β decay. In thermal equilibrium, $\epsilon_F(n) = \epsilon_F(p) + \epsilon_F(e)$, and $p_F = (3n/8\pi)^{1/3} h$ for all. At ρ_{nuc},

$$\epsilon_F(n) \simeq m_n c^2 + \frac{[p_F(n)]^2}{2m_n} \qquad \epsilon_F(p) \simeq m_p c^2 + \frac{[p_F(p)]^2}{2m_p},$$

but $\epsilon_F(e) \simeq p_F(e)c$.

Using $n_e = n_p$, we find

$$\left(\frac{3n_p}{8\pi}\right)^{1/3} hc + \left(\frac{3n_p}{8\pi}\right)^{2/3}\frac{h^2}{2m_p} - \left(\frac{3n_n}{8\pi}\right)^{2/3}\frac{h^2}{2m_n} \simeq (m_n - m_p)c^2 = 1.3\ \text{MeV}$$

Can then solve this at any density noting that

$$(n_n + n_p) = \rho/m_p.$$

E.g., at ρ_{nuc} $(n_e/n_n) \simeq \frac{1}{200} \Rightarrow$ neutron star!

Mass-Radius relation for NSs:

The WD central density relation,

$$\rho_c = \frac{3.1}{Y_e^3}\left(\frac{M}{M_*}\right)^2 \frac{m_u}{(\hbar/m_e c)^3}\left(\frac{B}{0.39\ldots}\right)^3$$

is easily modified for NSs by $Y_e = 1$ $m_e \longrightarrow m_n$.

Likewise, the radius is (roughly)

$$R = \cancel{2}^{5/3}\ 0.77\ Y_e^{5/3}\left({M_*}/{M}\right)^{1/3} \alpha_G^{-1/2} \frac{h}{m_n c}$$

Y_e relative to WD

$$\simeq (0.0135)\, 2^{5/3} \frac{m_e}{m_n}\left({M_\odot}/{M}\right)^{1/3}$$

$$\simeq 2.1\times10^{-5} R_\odot \left({M}/{1.4 M_\odot}\right)^{-1/3} = 1.5\times10^{6}\ \mathrm{cm}\left({M}/{1.4 M_\odot}\right)^{1/3}$$

$$\simeq 15\ \mathrm{km}\left({M}/{1.4 M_\odot}\right)^{1/3}$$

A few comments/caveats:

① As will be seen below, the (Schwarzchild) radius of a $1.4 M_\odot$ BH is $R_{sh} \simeq 3$ km. Therefore, the NS is in the strong-field regime of GR. Alternatively, the redshift from the surface of the neutron star is

$$\frac{GM}{Rc^2}\ \frac{\Delta\lambda}{\lambda} \simeq 0.2.$$

Thus, GR corrections to the Newtonian eqn. of hydrostatic equil will give rise to $\mathcal{O}(20\%)$ correction.

This GR eqn of hydrostatic equilibrium is known as the Tolman-Oppenheimer-Volkoff (TOV) equation.

(2) The approximation $P \propto \rho^{5/3}$ used to derive $M \propto R^{-3}$ breaks down already for ~~M~~ $1.4\,M_\odot$; in fact $E_F \simeq m_n c^2$ there, and so ~~the~~ a more accurate EOS must be used.

(3) In our simple calculation, $\rho_c \simeq 3.3 \times 10^{17}\,g/cm^3 > \rho_{nuc}$.

Uncertainties in the nuclear EOS at these high densities give rise to additional uncertainties in the NS M-R reln.

E.g., nucleon-nucleon repulsion might stiffen EOS. But if new particles (e.g., π^0's, K^0's, hyperons) are produced at high ρ, this might soften the EOS.

(4) The gravitational binding energy$/c^2$ is

$$\frac{E_B}{c^2} = \frac{GM^2}{R} \simeq 0.1\,(1.4\,M_\odot).$$

Thus, the mass of a NS is smaller than might expect from Newtonian calculation.

~~Maximum Mass for NSs?~~

Incidentally, people now try to determine the nuclear EOS by measuring the M-R reln for NSs. E.g., GM/R can be obtained from redshifts of lines emitted from the NS surface. The surface gravity GM/R^2 can be measured through its effects on pressure broadening of lines. ~~Are~~ ~~A~~ Combined measurement of M/R and M/R^2 can be used to obtain M and R. Are difficult but ambitious people are trying.

Maximum Mass for NSs:

Naively scaling the WD result, we obtain

$$M_{ch} \simeq 6 M_\odot \quad \text{for NS.}$$

However, all complications above are important, and generally tend (especially GR) to reduce M_{ch}. State-of-the-art calculations for different EOSs give $M_{ch} \simeq 1.5-3 M_\odot$.

For fun, suppose we had a star consisting of incompressible matter of density ρ_0. In Newtonian gravity,

$$\frac{dP}{dr} = \frac{-Gm(r)\rho(r)}{r^2} \Rightarrow P(r) = \frac{2\pi}{3} G(R^2 - r^2), \text{ and}$$

$$P_c = P(r=0) = \frac{2\pi}{3} G \rho_0^2 R^2 = \left(\frac{\pi}{6}\right)^{1/3} G M^{2/3} \rho_0^{4/3}.$$

In GR, though the TOV eqn is

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2} \frac{(1+P/\rho c^2)(1+4\pi r^3 P/mc^2)}{(1-2Gm/rc^2)}$$

which integrates to

$$P = \rho_0 c^2 \left[\text{something complicated} \right]$$

and

$$P_c = \rho_0 c^2 \left[\frac{1-(1-2GM/rc^2)^{1/2}}{3(1-2GM/rc^2)^{1/2} - 1} \right].$$

Then, have $P_c < \infty$ only if $\frac{GM}{Rc^2} < \frac{4}{9}$,

which is a slightly stronger bound than $\frac{M}{Rc^2} < 2$ from the Schwarzschild radius.

For constant density ρ_0, this yields

$$M < \frac{8}{27}\left(\frac{c^2}{G}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

$$= 7.5 \left(\rho_0/\rho_{nuc}\right)^{1/2} M_\odot$$

A slightly stronger bound to M/R is obtained by considering causality, which requires $c_s^2 = (\partial P/\partial \rho) < c^2$, or $P = \rho c^2$. This results in $\frac{GM}{Rc^2} < \frac{1}{2.9}$

Pulsar spindown:

Pulsars are rapidly rotating NSs that ~~are~~ produce pulsating signals with periods ~msec—secs. E.g., the Crab pulsar in the Crab nebula from a SN in 1054 AD. It has period $P = 33$ ms and is slowing down with

$$\frac{dP}{dt} = \frac{ms}{90\ yrs}$$

The rapidity of the pulses identifies pulsars as NSs. A star has a max spin freq ω_{max} from

$$\frac{GM}{R^2} = R\omega_{max}^2 \quad \Rightarrow \quad P_{min} = \frac{2\pi}{\omega_{max}} = 2\pi\left(\frac{R^3}{GM}\right)^{1/2} \sim t_{ff}$$

or $$P_{min} = 10^4 \left(\frac{(R/R_\odot)^{3/2}}{(M/M_\odot)^{1/2}}\right) sec$$

$$\text{for } M \sim M_\odot \quad P \sim \overset{33\,msec}{P_{min}} \Rightarrow R \lesssim (33)^{2/3}(10^{-7})^{2/3} R_\odot \sim 10^{7} cm \sim 100\ km$$

If we approximate NS by uniform-density sphere, then the moment of inertia is

$$I = \frac{2}{5}MR^2 = 2.5\times10^{45}\left(\frac{M}{1.4M_\odot}\right)\left(\frac{R}{1.5\times10^6 cm}\right)^2 g\text{-}cm^2$$

The Crab pulsar slows down at a rate

$$\frac{d\omega}{dt} = -2.4\times10^{-9}\ sec^{-2},$$

implying a spin-energy loss rate

$$\frac{dE_{rot}}{dt} = I\omega\frac{d\omega}{dt} \simeq 4.6\times10^{38}\ \frac{erg}{sec}$$

which is comparable to the Crab-nebula luminosity, $5\times10^{38}\ \frac{erg}{sec}$

The canonical explanation for the spindown is magnetic-dipole radiation. If NS has (like Earth) a B dipole misaligned from [illegible] the spin axis by an angle θ, it radiates with

$$\frac{dE}{dt} = \frac{2}{3c^3} m^2 \omega^4 \sin^2\theta \qquad \left(= \frac{2}{3c^3} |\ddot{m}|^2 \right),$$

where $m \simeq BR^3$ is the magnetic dipole which is required for Crab to be ~~$m \sin\theta \simeq 3\times10^{20}$ G-cm^3~~ ~~or $B \approx$~~ $m \sin\theta \simeq 4\times10^{30}$ G-cm^{+3} or

$$B \sim 10^{12}\ \text{G}.$$

This seems large, but B-field can be enhanced by large factor if initially magnetized pre-collapse iron core contains the B field as it collapses.

If B-dipole radiation is at work in the Crab, then

$$\frac{dE}{dt} = I\omega \frac{d\omega}{dt} \propto \omega^4 \quad \text{or} \quad \frac{d\omega}{dt} = -C\omega^3$$

where $C = 3.5\times10^{-16}$ sec for $\omega = 190\ s^{-1}$, $\frac{d\omega}{dt} = -2.4\times10^{-9}\ s^{-2}$.

Integrating,

$$t = \frac{1}{2C}\left[\frac{1}{\omega^2} - \frac{1}{\omega_i^2}\right] \underset{\omega_i < \omega}{<} \frac{1}{2C\omega^2} = 1253 \text{ years},$$

as opposed to historical age ($\simeq 950$ yrs) since SN.

The <u>braking index</u> is defined to be

$$n \equiv \frac{-\omega\ddot{\omega}}{\dot{\omega}^2}.$$

It is $n=3$ for magnetic-dipole model and, e.g., 5 for emission of GWs. Measured to be 2.515 for Crab and 2.83 for PSR1509-58.

Goldreich-Julian current =

Suppose the NS has a $\vec{B}$ dipole *aligned* with spin axis:

$$\vec{B}^{(in)} = B_p R^3 \left(\frac{\cos\theta}{r^3} \hat{e}_r + \frac{\sin\theta}{2r^3} \hat{e}_\theta \right).$$

Inside NS, are enough free e^-'s so that MHD approximation holds; i.e., the e^-'s rearrange themselves so that they are not accelerated — they short out the fields. I.e.,

$$\vec{E}^{(in)} + \underbrace{\frac{\vec{\Omega} \times \vec{r}}{c}}_{\vec{v}} \times \vec{B}^{(in)} = 0.$$

Thus, just inside the surface, $\vec{E}^{(in)} = \frac{R\Omega B_p \sin\theta}{c} \left(\frac{\sin\theta}{2} e_r - \cos\theta \, e_{\hat{\theta}} \right)$

The $\hat{r}$ component of $\vec{E}$ ~~just outside~~ may jump at the NS surface if charges accumulate there, but the tangential component is const. Thus, just outside the star,

$$E_\theta^{(out)} = -\frac{\partial}{\partial\theta} \left(\frac{R\Omega B_p \sin^2\theta}{2c} \right) = \frac{\partial}{\partial\theta} \left[\frac{R\Omega B_p}{3c} P_2(\cos\theta) \right].$$

Outside the star, $\vec{E}^{(out)} = -\vec{\nabla}\Phi$ with $\nabla^2 \Phi = 0$, implying

$$\Phi = -\frac{\Omega B_p}{3c} \frac{R^5}{r^3} P_2(\cos\theta) \quad \text{to satisfy BC.}$$

i.e., a quadrupole electric field is induced.

Inside the star, there is a charge density $\rho_e = \frac{1}{4\pi} \vec{\nabla} \cdot \vec{E} = \frac{-1}{2\pi c} \vec{\Omega} \cdot \vec{B}$

or $n_e = 7 \times 10^{-2} \, B_{12} \, P^{-1} \, \text{cm}^{-3}$.

At the surface of the star, there is a surface charge density $\sigma = \frac{1}{4\pi} (\vec{E}_{out} - \vec{E}_{in})_r = -B_p \Omega R \cos^2\theta / 4\pi c$.

Inside, $\vec{E} \cdot \vec{B} = 0$, but outside (assuming vacuum outside),

$$\vec{E} \cdot \vec{B} = -\frac{R\Omega}{c} \left(\frac{R}{r} \right)^7 B_p^2 \cos^3\theta.$$

Thus,

Thus at the surface there is electric field $\vec{E} \sim \vec{B}$:

$$E_\phi \sim \frac{R\Omega}{c} B_p \sim 2\times 10^{8} P^{-1} B_{12} \text{ V/cm.}$$

This is much bigger than gravity; e.g., for protons,

$$\frac{\text{electric}}{\text{gravitational}} \sim \frac{eR\Omega B_p/c}{GMm_p/R^2} \sim 10^{9} \gg 1$$

and is $\sim 10^{12}$ for e^-'s.

$\Rightarrow$ Vacuum is unstable!

$\Rightarrow$ Particles are stripped from surface of NS, and NS is necessarily surrounded by plasma of charged particles tied to $\vec{B}$-field lines; <u>magnetosphere</u>.

Resulting picture is that $\vec{B}$-field and plasma co-rotate with NS (like an egg beater) out to <u>light cylinder</u> of radius $R_c \equiv c/\Omega = 5\times10^{9} P$ cm beyond which co-rotation would imply $v > c$ for plasma. What happens at larger radii is unclear, but probably involves bending back of field lines to toroidal component, and perhaps expulsion of highly relativistic particles.

Within light cylinder, $\vec{E}\cdot\vec{B} = 0$, and $\vec{E} = -\left(\frac{\vec{\Omega}\times\vec{r}}{c}\right)\times\vec{B}$. Thus $\vec{E}\times\vec{B}$ with $|\vec{E}| \simeq |\vec{B}|$ at light cylinder, thus driving <u>Poynting flux</u>

$$S \sim c\frac{\vec{E}\times\vec{B}}{4\pi} \sim \frac{cB^2}{4\pi} \quad \text{over area} \sim \pi R_c^2, \text{ or}$$

luminosity,

$$\frac{dE}{dt} \sim B_c^2 R_c^2 c \sim c\left(\frac{B_p R^3}{R_c^3}\right)^2 R_c^2$$

$$\sim \frac{B_p^2 R^6 \Omega^4}{c^3}$$

Therefore, get same spindown from pulsar magnetosphere as in ~~pure~~ magnetic-dipole model, even if ~~$\vec{B}\not\parallel\vec{\Omega}$~~ $\vec{m} \parallel \vec{\Omega}$.

If $\vec{B}$ field dominates particle energy [illegible] [illegible] [illegible] since $c\left(\frac{B^2}{8\pi}\right)4\pi r^2 \sim$ indep of r,

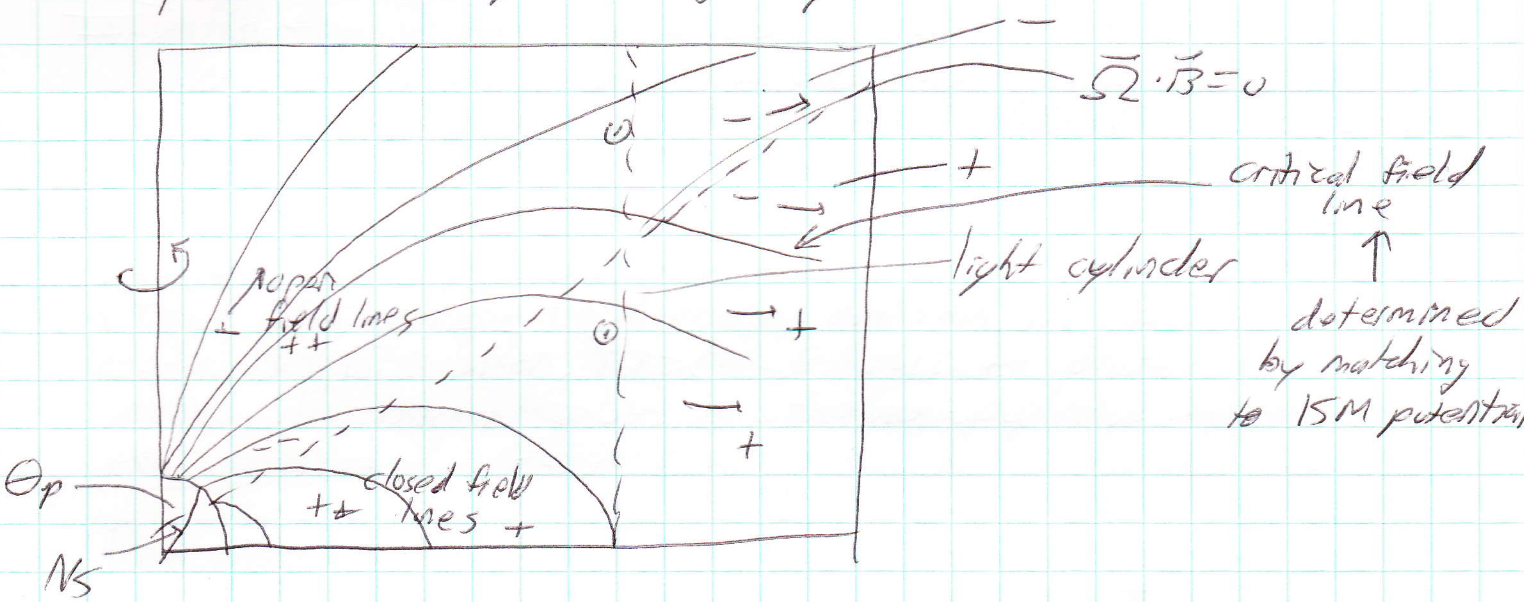
$$\Rightarrow B \sim \frac{10^{8}\,G}{(r/cm)} \quad \text{for} \quad r > R_c \Rightarrow B \sim 10^{-4}\,G \text{ @ pc}$$

as seen

If particle energy $\mathcal{E}_p >> \frac{B^2}{8\pi}$, then $B \propto 1/r$;

$B \sim 10^{-14}\,G$ @ $r \sim pc$; too small.

The picture of the pulsar magnetosphere is:



Angular size of polar cap is Θ_p determined by noting that $\sin^2\theta/R$ is const along ~~the~~ dipole field lines. Thus, ~~the~~ $\Theta_p \sim \sqrt{\Omega R/c}$, and the polar cap has area

$$A_p \sim \pi R^2 \Theta_p^2 \sim \pi \frac{\Omega R^3}{c}$$

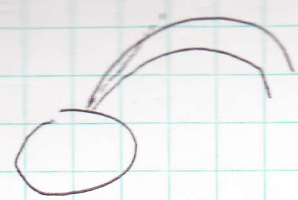
Pulsar emission mechanisms:

In spite of huge amount of detailed data, these are not well understood. In part this is because ~~rad~~ pulsed radio emission is "dirt" — constitutes $\lesssim 10^{-4}$ (e.g. in Crab) of total emission.

[illegible]

Implies $T_b \sim 10^{23}-10^{26}$ K $\quad 10^{19}-10^{22}$ eV

$\Rightarrow$ not synchrotron emission



One fairly universal ingredient:

Particles accelerated ~~there~~ by $\vec{E}$ field will ~~cross~~ become very energetic. E.g., ~~in polar cap, the voltage is~~ potential drop between pole and equator in pulsar is

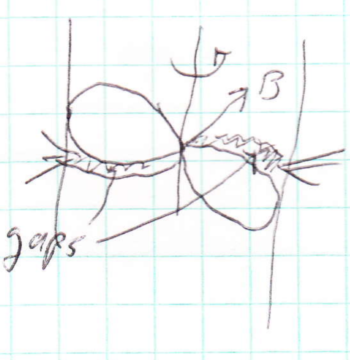
$$V \sim \frac{R\Omega}{c} B\Omega \sim 10^{16}\ V \quad \text{for } \Omega \sim 10^{2}\,\text{Hz}\ B \sim 10^{12}\,G$$
$$(\gg \text{MeV}/e)$$

Thus e^-'s attain $\gamma \gg 1$. They then produce <u>curvature radiation</u> as they cross $\vec{B}$-field lines. These γ-rays then escape (high-energy emission in <u>polar-cap models</u>)? and/or run into other γ's (or B field) to produce e^+e^- pairs. The magnetosphere is therefore populated by a <u>pair plasma</u>.

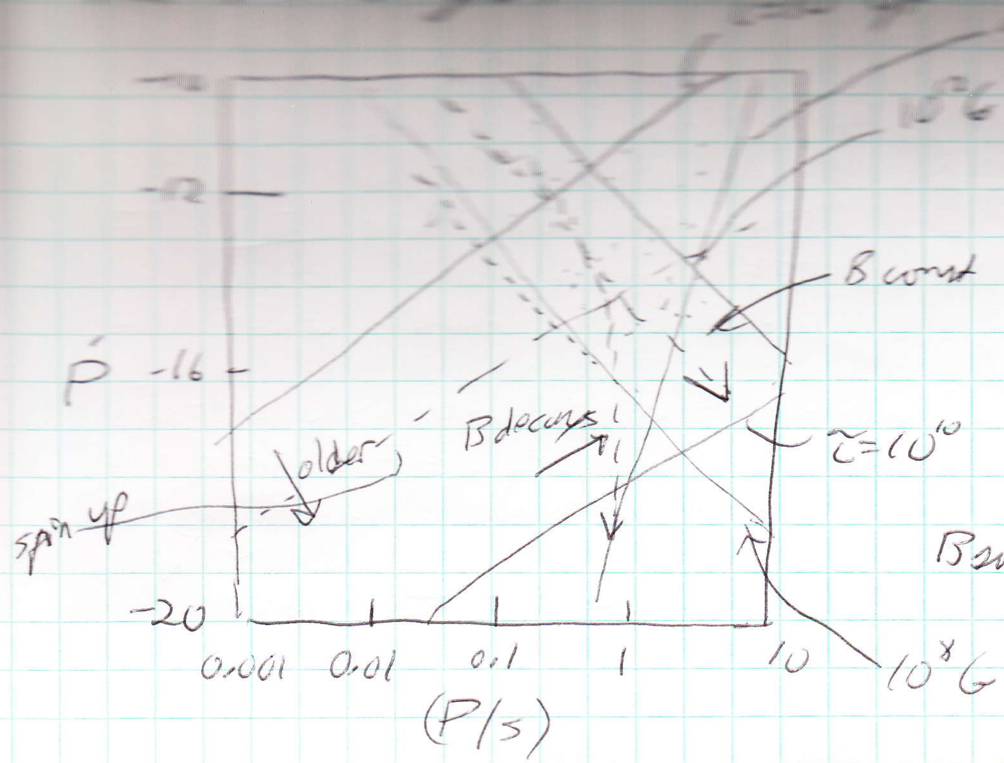
There may also be large-scale charge separation; this may then allow for coherent emission (where intensity scales as N^2, rather than N) which may explain $T_b \gg 10^{12}$ K.

In polar-cap models, all this takes place near poles, and emission is along axis of symmetry.

In <u>outer-gap</u> models (or light-cone models), emission occurs near light cone near equator in NSs with misaligned $\vec{B}$ fields.



The P-Ṗ diagram



Spindown time:

$$\tau = \frac{P}{2\dot{P}} \quad (1)$$

B-field (from $I\omega \frac{d\omega}{dt} = \frac{2}{3c^3} M^2 \Omega^4$) (2)

$$B \sin\theta \simeq 3\times 10^{19}\,G\,(P\dot{P})^{1/2}$$

(3) Evolutionary tracks.

(4) <u>Death line</u>: voltage drop $\propto B\Omega^2 \propto BP^{-2}$ (typo in Longair?)

expect e^+e^- pairs to be produced only for $BP^{-2} \gtrsim 10^{11}\,G\,s^{-2}$; & or $\dot{P} \gtrsim$ gives line $\dot{P} \propto P^3$ toward right. Expect all pulsars to be near left.

(5) <u>Spin-up limit.</u> Pulsars in binaries do not follow same rules nor occupy same regions of P-$\dot{P}$ space.

May be spun up by accretion from companion. Are expected to have

$$P \gtrsim 2\,(B/10^9 G)^{6/7}\ \text{ms}.$$

[illegible]

$M \simeq 1.4\, M_\odot \quad R \simeq 10$ km

$$E_{grav} \sim \frac{GM^2}{R} \sim 5 \times 10^{53} \text{ erg} \sim \frac{1}{5} M_\odot c^2$$

$$g \sim \frac{GM}{R^2} \sim 2 \times 10^{14} \frac{\text{cm}}{\text{sec}^2}$$

$$\bar{\rho} \sim \frac{3M}{4\pi R^3} \simeq 7 \times 10^{14} \text{ g/cm}^3 \simeq 2\text{–}3 \times \text{normal nuclear density.}$$

Structure: atmosphere/outer crust/inner crust/outer core/inner core

Atmosphere: ~10 cm for $T_s \sim 3 \times 10^6$ K
to ~mm for $T_s \sim 3 \times 10^5$ K
models not complete for $B \gtrsim 10^{11}$ G or $T_s \lesssim 10^6$ K
$\rho \lesssim 10^6$ g/cm^3; negligible mass; primarily ^{56}Fe
shapes emergent spectrum
plasma layer; highly ionized; atomic levels distorted by high B fields

Outer Crust: ("outer envelope")
from atmosphere to $\rho \sim 4 \times 10^{11}$ g/cm^3
100s m thick
ions + e^-'s (magnetic effects may be important)
top few m's is nondegenerate e^- gas
deeper → degenerate e^- gas, ultrarelativistic
solidifies at high depth
β capture in nuclei → n-rich nuclei
bottom of crust: n's start to drip, form n gas (@ $\rho \sim 4 \times 10^{11}$ g).
n gas is still background sea for nuclei

inner crust: ~km thick
from $\rho_{ND} \sim 4 \times 10^{11}$ g/cm^3 to $0.5\, \rho_0$ — magnetic effects not important
e^-'s, n-rich ions, n's
n fraction increases as $\rho \uparrow$
nuclei → 0 at crust/core boundary
nucleons can be superfluid if T low enough

Outer core: $0.5\rho_0 \lesssim \rho \lesssim 2\rho_0$ $\sim 10^{14}$ g/cm^3

[illegible] for [illegible], where nuclei cease to exist

$\frac{n}{p} \gtrsim 20$

n/p ratio in β equilibrium

manybody effects may be important

everything very degenerate

nucleon-nucleon interactions $\Rightarrow$ n's superfluid

p's superconducting

contains (with inner core) $\sim 99\%$ of mass

Inner core: $\rho \gtrsim 2\rho_0$ ρ up to $(10-15)\rho_0$?

$R \gtrsim$ few km

composition/EOS uncertain; nobody knows what nuclear matter at such high P, ρ does

hyperons? pions? kaons? quark matter?

may be probed in heavy-ion collisions

(e.g., RHIC @ Brookhaven)

<u>Superfluidity</u>: occurs for $T < T_c$ = critical temperature (uncertain)

does not affect EOS, M-R much

n's in inner crust should be superfluid

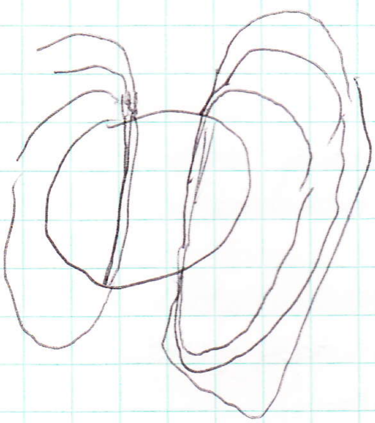
affects heat capacity and ν emission, and so is relevant for cooling of NS.

Spin of NS is quantized in discrete vortices

superfluid p's are <u>superconducting</u>

B fields quantized in flux tubes

B fields fix crust/core rotation to be same, but superfluid neutrons may have different spin.



Cooling of Neutron Stars

Are born with $T \sim 10^{11}$ K and radiate $\sim 10^{53}$ erg in few secs. $T \sim 10^{10}$ K after $\sim$day
ν emission dominates for first 10^5 yr to 10^6 K;
then γ radiation from surface takes over.
Observationally NS surface temperatures are $\sim 5 \times 10^5$ K
$\Rightarrow$ thermal emission in UV/soft-x-ray

ν's produced with $E_\nu \sim k_B T$ and scatter from N with

$$\sigma \sim 4.4 \times 10^{-45}\,\text{cm}^2 \left(E_\nu / m_e c^2\right)^2,$$

so their mean-free path is

$$l = \frac{1}{n\sigma} \simeq 2500\,\text{km} \left(\frac{R}{12\,\text{km}}\right)^3 \left(\frac{1.4 M_\odot}{M}\right) \left(\frac{10^9\,\text{K}}{T}\right)^2$$

so @ $T \sim 10^{11}$ K is opaque, but transparent for $T \lesssim 10^9$ K

Direct URCA process: $n \to p + e^- + \bar{\nu}_e \qquad p + e^- \to n + \nu_e$

is slow if p's are scarce; slowed also by Pauli blocking

Modified URCA process:

$$n + (n,p) \to p + (n,p) + e^- + \bar{\nu}_e$$

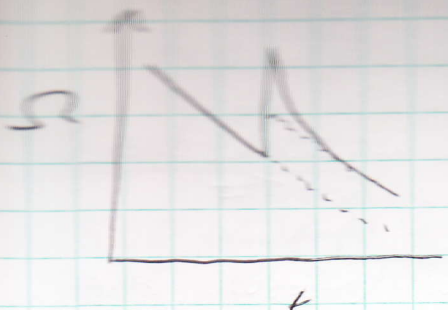
$$p + (n,p) \to n + (n,p) + e^+ + \nu_e$$

can increase rate by providing more energy-momentum combinations.

Measurements of t (e.g., from $P/\dot{P}$) and T_{eff} (from x-ray) suggest modified URCA is important.

Pulsar glitches

Some pulsars occasionally suddenly speed up and then slow down. This is explained by starquakes, cracks in the crystalline crust. Moment of inertia $I \downarrow$ sending $\Omega \uparrow$. E.g., $\Delta\Omega/\Omega \sim 10^{-2}$ once in Vela. More characteristically, $\Delta\Omega/\Omega \lesssim 10^{-6}$.



After glitch, pulsar spins down more rapidly. This is explained by the time it takes crust to spin superfluid-n component up. Then asymptotes to usual B-field spindown with slightly smaller I that results from quake.

Magnetars:

Typical NS B fields are $T \simeq 10^{12}$ G. But a few have $B \sim 10^{14}-10^{16}$ G $\Longrightarrow$ magnetars.

If B is large enough, then the Larmor radius $r_L = \frac{v m_e c}{eB}$ of an e^- becomes smaller than the deBroglie wavelength, $\lambda = \hbar/m_e v$. Thus, above a quantum-critical field

$$B_{QC} = \frac{m_e^2 c^3}{\hbar e} = 4.4 \times 10^{13}\,G,$$

QM effects become important

Example: Soft Gamma Repeaters (SGRs):

are x-ray sources that repeatedly emit γ-ray flashes; spectrum is softer than GRBs.

Have $P \sim 5-8$ s $\qquad \dot{P} \simeq 7 \times 10^{-11}$

Eg, SGR 0526-66 in SNR N49 in LMC

SNR has age $t \sim 10^4$ yr and $P \simeq 8$ s

setting $\frac{P}{2\dot{P}} = t \Rightarrow \dot{P} \cong 10^{-11} \Rightarrow B \sim 10^{14}$ G

<u>Giant flares:</u>

SGR 1806-20 ~~0526-66~~'s most energetic burst was 27 Dec '04 with $E \sim 2 \times 10^{46}$ erg; ~~(typical bursts are $\sim 10^{43}$ erg/sec)~~
most released in $\lesssim$ sec burst with 50 ms rise time
rest released in softer pulsating tail

From $P\dot{P}$, $B \simeq 1.6 \times 10^{15}$ G.

$$E_{mag} \sim \frac{B^2}{8\pi} \frac{4}{3} \pi R^3 \sim 10^{48} \text{ erg},$$

so burst is only small fraction of B-field reservoir.

Explanation for pulsed emission is that starquake rearranges B-field produced γ-e^+e^- fireball confined to magnetosphere.

<u>Anomalous X-ray Pulsars:</u> (AXPs)

Isolated pulsars emitting pulsed X-ray with $L \sim 10^{35-36} \frac{\text{erg}}{\text{sec}}$ and $P \sim 5$-12 sec.
L is too high for magnetic dipole; is assumed/guessed to be powered by dissipation of B field. Uncertain?