Neutron Stars

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Outline

- Neutron Stars
    - Observed Properties of Neutron Stars
    - Structure of Neutron Stars
    - Formation and Evolution of Neutron Stars
- Mass Measurements and Implications
    - How Masses of Neutron Stars Are Measured
    - Implications of a Large Maximum Mass
    - Neutron Star Radii, the Maximum Mass, and the EOS
    - Nuclear Physics Constraints

Observed Properties of Neutron Stars

- Over 1800 known as pulsars
- A few dozen accreting or quiescent sources in binary systems
- Less than a dozen isolated neutron stars

Pulsars: The Early History

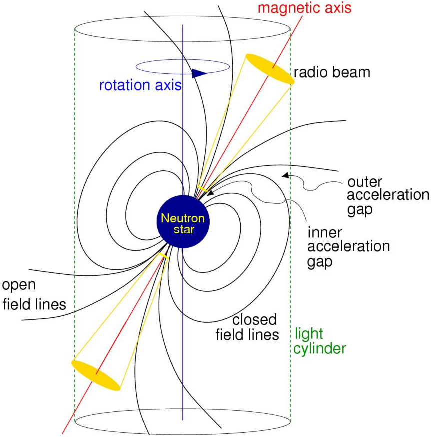
1932 - Chadwick discovers neutron.
1934 - W. Baade and F. Zwicky predict existence of neutron stars as end products of supernovae.
1939 - Oppenheimer and Volkoff predict mass limit of neutron stars.
1966 - Colgate and White simulate supernovae forming neutron stars.
1966 - Wheeler predicts Crab nebula powered by rotating neutron star.
1967 - C. Schisler discovers pulsing radio sources, including the Crab, with military radar.
1967 - Hewish, Bell, Pilkington, Scott and Collins discover the pulsar PSR 1919+21, Aug 6. Only Hewish awarded Nobel Prize (1974).
1968 - Crab pulsar discovered.
1968 - T. Gold identifies pulsars with magnetized, rotating neutron stars.
1968 - The term "pulsar" first appears in print, in the *Daily Telegraph*.
1969 - "Glitches" provide evidence for superfluidity in neutron star.
1971 - Accretion powered X-ray pulsar discovered by Uhuru (*not* Lt.).
1974 - Binary pulsar PSR 1913+16 discovered by Hulse and Taylor with orbital decay due to gravitational radiation. Nobel prize 1993.
1982 - First millisecond pulsar, PSR B1937+21, discovered by Backer et al.
1992 - Discovery of planets orbiting PSR B1257+12, Wolszczan and Frail.
1992 - Prediction of magnetars by Duncan & Thompson.

Amazing Facts About Neutron Stars

- Densest objects this side of an event horizon: 10^{15} g cm^{-3}
  Four teaspoons on the Earth would weigh as much as the Moon.
- Largest surface gravity: 10^{14} cm s^{-2}, about $10^{11}g$
- Fastest spinning massive objects known
  PSR J1748-2446ad, located in the globular cluster Terzan 5 28,000 light years away, spins at 716 Hz. (33 pulsars have been found in this cluster.) The velocity at this star's equator is $c/4$.
- Largest known magnetic field strengths: $B = 10^{15}$ G, Sun $= 1$ G.
- Highest temperature superconductor: $T_c = 10$ billion K
  The record superconductor on the Earth is mercury thallium barium calcium copper oxide ($Hg_{12}T_{l3}Ba_{30}Ca_{30}Cu_{45}O_{125}$), at 138 K.
- Highest temperature since Big Bang: $T = 700$ billion K
- Fastest velocity of a massive object in the Galaxy: > 1083 km/s
- Largest burst of energy in our Galaxy since SN 1604
  A burst from magnetar SGR 1806-20 was brighter than the full moon in gamma rays and released more energy in 0.1 s than Sun emits in 100,000 years. It ionized ionosphere to daytime levels.
- The only place in the universe except for the Big Bang where neutrinos become *trapped*.

Pulsars: Why do they pulse?

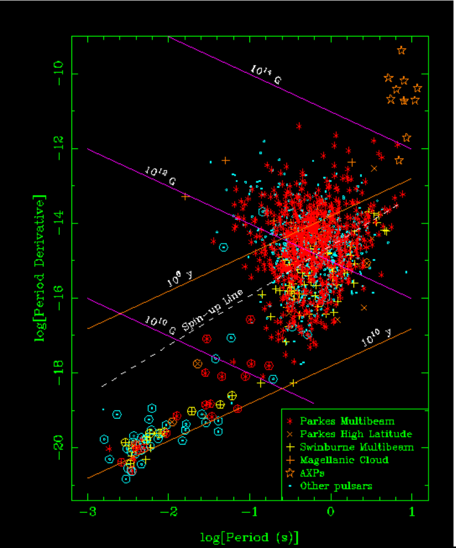
- All models involve the lighthouse effect, in which particles and light are emitted from magnetic poles that are misaligned with the orbital poles (magnetic dipole model). The beam widths are measured in some cases to be several degrees, so we are fortunate to see any given pulsar.
- It is known that spinning magnetic dipoles can emit energy.
- Nobody understands in detail how the beaming is accomplished.
- For the magnetic dipole model,
  $dE_{rot}/dt = \dot{E}_{rot} \propto B^2 R^6 P^{-4}$
  $E_{rot} \propto MR^2 P^{-2}$
  $\dot{E}_{rot} \propto MR^2 P^{-3} \dot{P}$
  $B \propto R^{-2}\sqrt{MP\dot{P}} > 10^{19}\sqrt{\frac{P\dot{P}}{\mathrm{s}}}\ \mathrm{G}$
  Characteristic age $\tau = P/(2\dot{P})$
- Neutron stars with too small B or ν can not pulse.

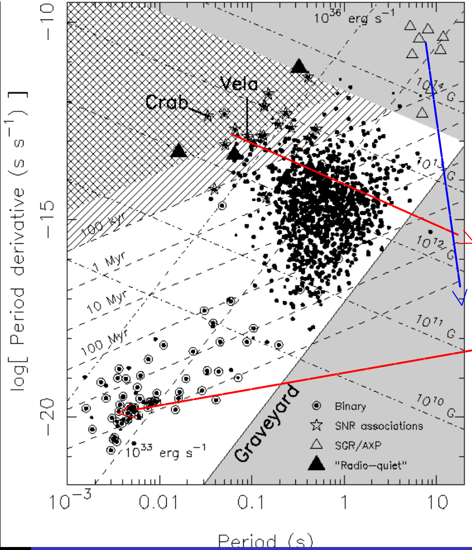


From *Handbook of Pulsar Astronomy* by Lorimer and Kramer

The $P - \dot{P}$ Diagram – The H-R Diagram for Pulsars

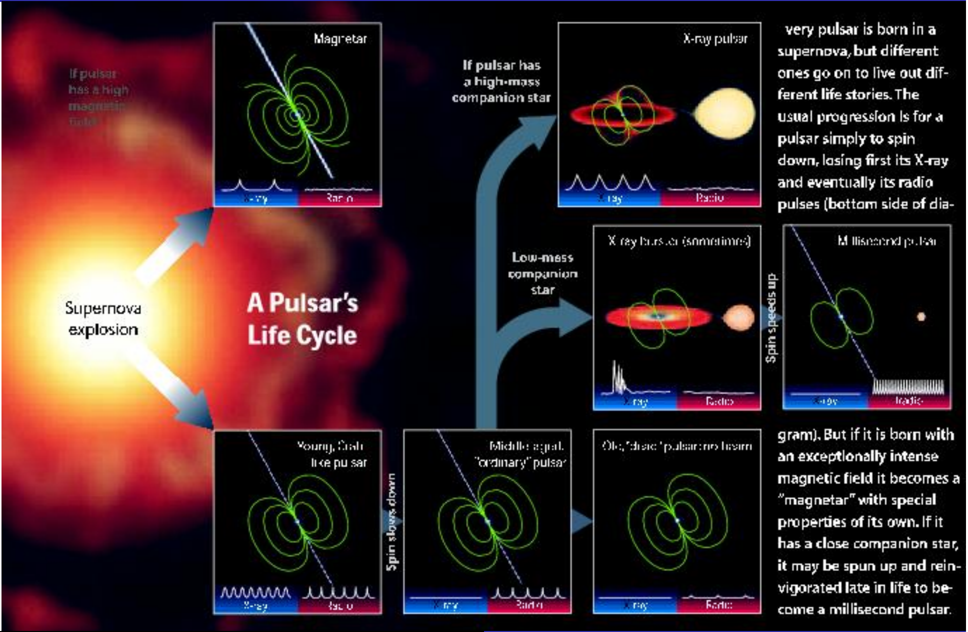
The magnetic field strength and age can be expressed in terms of the period P and the spin-down rate $\dot{P}$: $B \propto \sqrt{P\dot{P}}$, $\tau \propto P/\dot{P}$.





Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

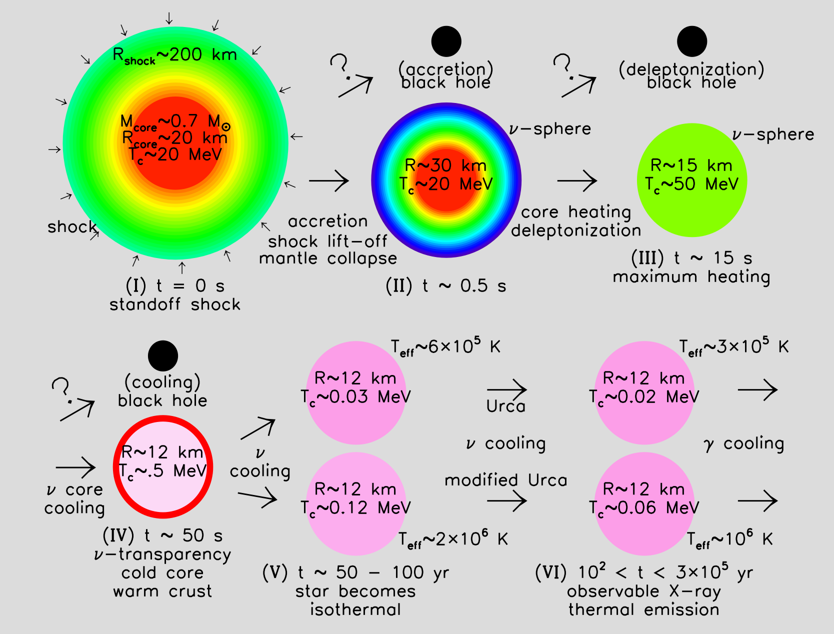
The Lives of Pulsars



very pulsar is born in a supernova, but different ones go on to live out different life stories. The usual progression is for a pulsar simply to spin down, losing first its X-ray and eventually its radio pulses (bottom side of diagram). But if it is born with an exceptionally intense magnetic field it becomes a "magnetar" with special properties of its own. If it has a close companion star, it may be spun up and reinvigorated late in life to become a millisecond pulsar.

Credit: Dany Page, UNAM

Proto-Neutron Stars and Neutron Star Evolution



R_{shock}~200 km

M_{core}~0.7 $M_\odot$

R_{core}~20 km

T_c~20 MeV

shock

(I) t = 0 s
standoff shock

accretion
shock lift−off
mantle collapse

(accretion)
black hole

ν−sphere

R~30 km

T_c~20 MeV

(II) t ~ 0.5 s

core heating
deleptonization

(deleptonization)
black hole

ν−sphere

R~15 km

T_c~50 MeV

(III) t ~ 15 s
maximum heating

(cooling)
black hole

ν core
cooling

R~12 km

T_c~.5 MeV

(IV) t ~ 50 s
ν−transparency
cold core
warm crust

ν
cooling

T_{eff}~6×10^5 K

R~12 km

T_c~0.03 MeV

Urca

ν cooling

modified Urca

R~12 km

T_c~0.12 MeV

T_{eff}~2×10^6 K

(V) t ~ 50 − 100 yr
star becomes
isothermal

T_{eff}~3×10^5 K

R~12 km

T_c~0.02 MeV

γ cooling

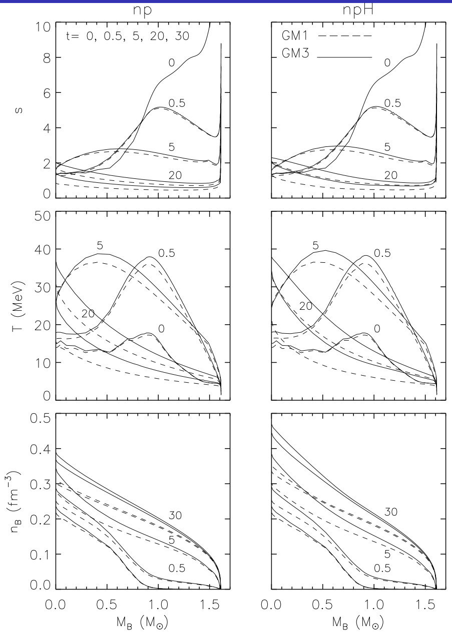
R~12 km

T_c~0.06 MeV

T_{eff}~10^6 K

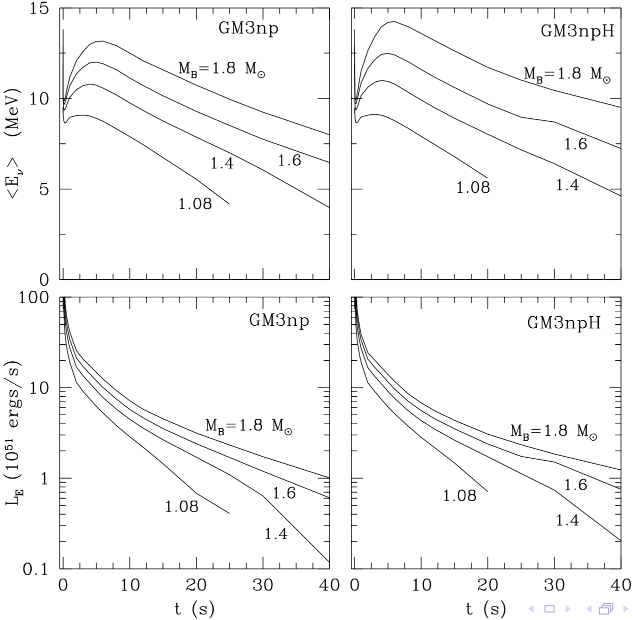
(VI) 10^2 < t < 3×10^5 yr
observable X−ray
thermal emission

Model Simulations of Proto-Neutron Stars

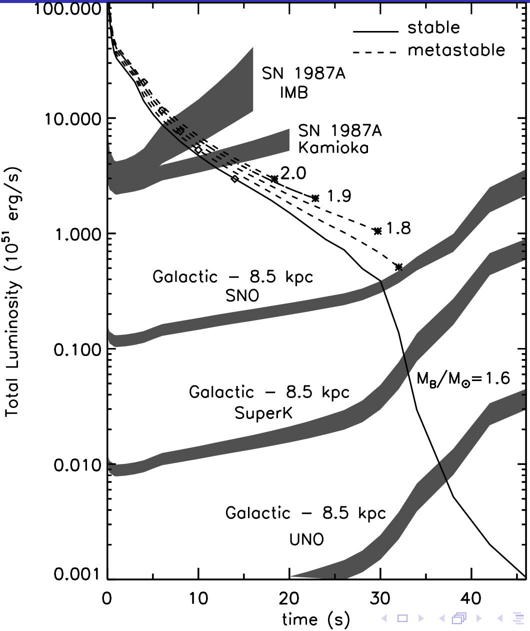


Pons et al. 2000

Model Simulations of Proto-Neutron Stars



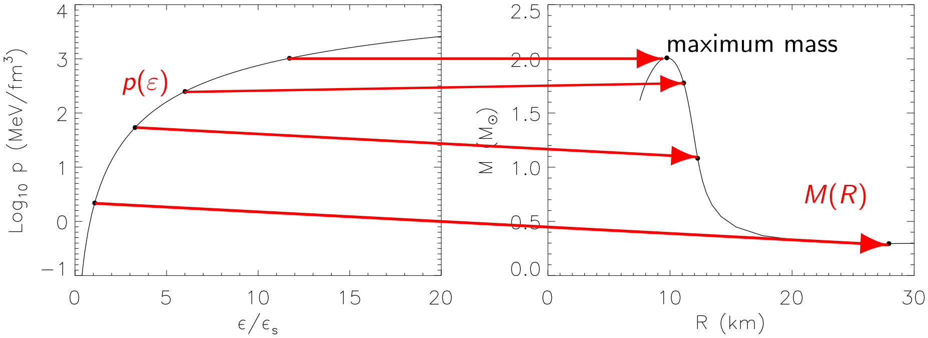
Model Signal From Proto-Neutron Stars



Neutron Star Structure

Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m+4\pi pr^3)(\varepsilon+p)}{r(r-2Gm/c^2)}$$
$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$

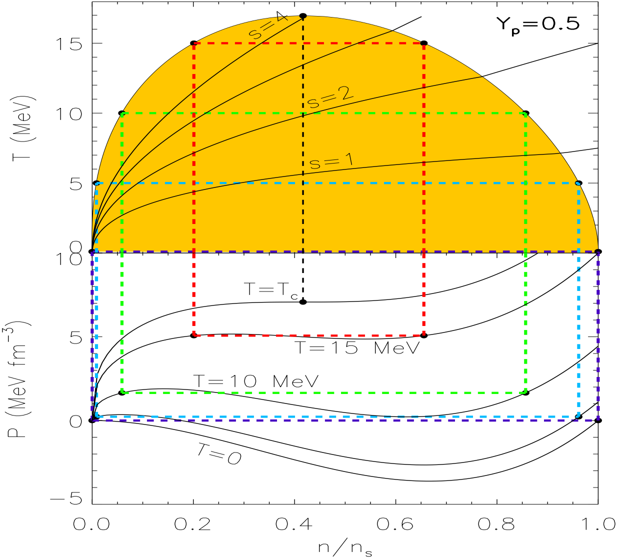


Schematic Nucleonic Energy Density

n: number density; x: proton fraction; T: temperature
$n_s \simeq 0.16 \pm 0.01$ fm^{-3}: nuclear saturation density
$B \simeq -16 \pm 1$ MeV: saturation binding energy
$K \simeq 220 \pm 15$ MeV: incompressibility parameter
$S_v \simeq 30 \pm 6$ MeV: bulk symmetry parameter
$a \simeq 0.065 \pm 0.010$ MeV^{-1}: bulk level density parameter

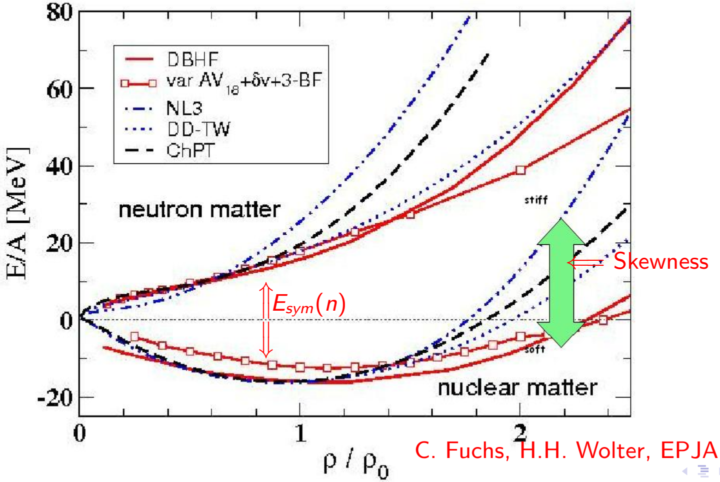
$$\begin{aligned}
\epsilon(n,x,T) &= n\left[B + \frac{K}{18}\left(1-\frac{n}{n_s}\right)^2 + S_v\frac{n}{n_s}(1-2x)^2 + a\left(\frac{n_s}{n}\right)^{2/3}T^2\right] \\
P &= n^2\frac{\partial(\epsilon/n)}{\partial n} = \frac{n^2}{n_s}\left[\frac{K}{9}\left(\frac{n}{n_s}-1\right) + S_v(1-2x)^2\right] + \frac{2an}{3}\left(\frac{n_s}{n}\right)^{2/3} T \\
\mu_n &= \frac{\partial\epsilon}{\partial n} - \frac{x}{n}\frac{\partial\epsilon}{\partial x} \\
&= B + \frac{K}{18}\left(1-\frac{n}{n_s}\right)\left(1-3\frac{n}{n_s}\right) + 2S_v\frac{n}{n_s}(1-4x^2) - \frac{a}{3}\left(\frac{n_s}{n}\right)^{2/3} T \\
\hat{\mu} &= -\frac{1}{n}\frac{\partial\epsilon}{\partial x} = \mu_n - \mu_p = 4S_v\frac{n}{n_s}(1-2x) \\
s &= \frac{1}{n}\frac{\partial\epsilon}{\partial T} = 2a\left(\frac{n_s}{n}\right)^{2/3} T
\end{aligned}$$

Phase Instabilities



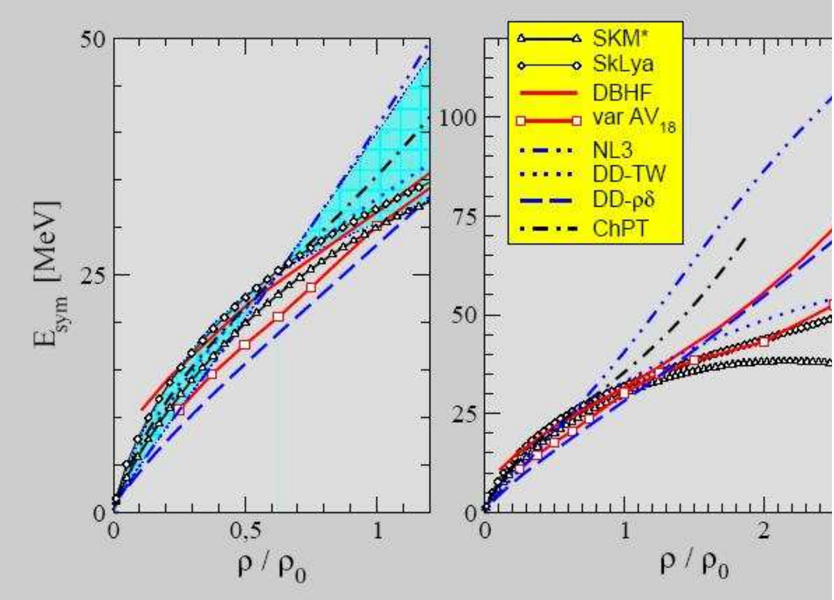
The Uncertain Nuclear Force

The density dependence of $E_{sym}(n) = E_{neutrons}(n) - E_{symmetric}(n)$ is crucial but poorly constrained. The skewness, $\partial^3 E/\partial n^3$, is also uncertain.



C. Fuchs, H.H. Wolter, EPJA 30(2006) 5

The Uncertain $E_{sym}(n)$



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