Neutron Stars

J.M. Lattimer

Department of Physics & Astronomy
Stony Brook University

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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.
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.).
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 ($\text{Hg}_{12}\text{Ta}_{3}\text{Ba}_{30}\text{Ca}_{30}\text{Cu}_{45}\text{O}_{125}$), 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,
  \[ \frac{dE_{\text{rot}}}{dt} = \dot{E}_{\text{rot}} \propto B^2 R^6 P^{-4} \]
  \[ E_{\text{rot}} \propto M R^2 P^{-2} \]
  \[ \dot{E}_{\text{rot}} \propto M R^2 P^{-3} \dot{P} \]
  \[ B \propto R^{-2} \sqrt{M P \dot{P}} > 10^{19} \sqrt{\frac{P \dot{P}}{\text{s}}} \text{ G} \]
  Characteristic age \( \tau = P/(2 \dot{P}) \)
- Neutron stars with too small \( B \) or \( \nu \) can not pulse.

From *Handbook of Pulsar Astronomy* by Lorimer and Kramer
The magnetic field strength and age can be expressed in terms of the period $P$ and the spin-down rate $\dot{P}$:

$$B \propto \sqrt{P\dot{P}}, \quad \tau \propto \frac{P}{\dot{P}}.$$
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 revigorated late in life to become a millisecond pulsar.
Proto-Neutron Stars and Neutron Star Evolution

(I) $t = 0 \text{ s}$ standoff shock

(II) $t \sim 0.5 \text{ s}$
- Core heating
- Deleptonization
- $R \sim 30 \text{ km}$
- $T_c \sim 20 \text{ MeV}$
- $\nu$-sphere

(III) $t \sim 15 \text{ s}$
- Maximum heating
- $R \sim 15 \text{ km}$
- $T_c \sim 50 \text{ MeV}$
- $\nu$-sphere

(IV) $t \sim 50 \text{ s}$
- $\nu$-transparency cold core warm crust
- $R \sim 12 \text{ km}$
- $T_c \sim 0.5 \text{ MeV}$
- $\nu$ cooling

(V) $t \sim 50 - 100 \text{ yr}$
- Star becomes isothermal
- $R \sim 12 \text{ km}$
- $T_c \sim 0.12 \text{ MeV}$
- $T_{\text{eff}} \sim 2 \times 10^6 \text{ K}$

(VI) $10^2 < t < 3 \times 10^5 \text{ yr}$
- Observable X-ray thermal emission
- $R \sim 12 \text{ km}$
- $T_c \sim 0.06 \text{ MeV}$
- $T_{\text{eff}} \sim 10^6 \text{ K}$

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Model Simulations of Proto-Neutron Stars

Pons et al. 2000
Model Simulations of Proto-Neutron Stars

$\langle E_v \rangle$ (MeV)

$M_b = 1.8 \, M_\odot$

$1.08$

$1.4$

$1.6$

$L_e (10^{51} \text{ ergs/s})$

$M_b = 1.8 \, M_\odot$

$1.08$

$1.4$

$1.6$
Model Signal From Proto-Neutron Stars

![Graph showing the total luminosity in erg/s over time for different neutron star scenarios. The graph includes lines for stable and metastable states, with markers for SN 1987A at IMB, Kamioka, and SN 1987A at SN 8, SNO, SuperK, and UNO. The y-axis represents total luminosity in $10^{51}$ erg/s, and the x-axis represents time in seconds.]
Neutron Star Structure

Tolman-Oppenheimer-Volkov equations

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

\[
\frac{dm}{dr} = 4\pi \frac{\varepsilon}{c^2} r^2
\]

\[p(\varepsilon)\]

\[M(R)\]

maximum mass
Schematic Nucleonic Energy Density

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

\[
\epsilon(n, x, T) = n \left[ B + \frac{K}{18} \left( 1 - \frac{n}{n_s} \right)^2 + S_v \frac{n}{n_s} (1 - 2x)^2 + a \left( \frac{n_s}{n} \right)^{2/3} T^2 \right]
\]

\[
P = n^2 \frac{\partial (\epsilon/n)}{\partial n} = \frac{n^2}{n_s} \left[ \frac{K}{9} \left( \frac{n}{n_s} - 1 \right) + S_v (1 - 2x)^2 \right] + \frac{2an}{3} \left( \frac{n_s}{n} \right)^{2/3} T^2
\]

\[
\mu_n = \frac{\partial \epsilon}{\partial n} - \frac{x}{n} \frac{\partial \epsilon}{\partial x} = B + \frac{K}{18} \left( 1 - \frac{n}{n_s} \right) \left( 1 - 3 \frac{n}{n_s} \right) + 2S_v \frac{n}{n_s} (1 - 4x^2) - \frac{a}{3} \left( \frac{n_s}{n} \right)^{2/3} T^2
\]

\[
\hat{\mu} = -\frac{1}{n} \frac{\partial \epsilon}{\partial x} = \mu_n - \mu_p = 4S_v \frac{n}{n_s} (1 - 2x)
\]

\[
s = \frac{1}{n} \frac{\partial \epsilon}{\partial T} = 2a \left( \frac{n_s}{n} \right)^{2/3} T
\]
The density dependence of $E_{\text{sym}}(n) = E_{\text{neutrons}}(n) - E_{\text{symmetric}}(n)$ is crucial but poorly constrained. The skewness, $\partial^3 E / \partial n^3$, is also uncertain.
The Uncertain $E_{\text{sym}}(n)$