In this talk ...

I will review the role of hyperons on:

- EoS & $M_{\text{max}}$ of Neutron Stars
- Properties of Proto-Neutron Stars
- Neutron Star Cooling
- R-mode Instability of Neutron Stars
Some known facts about Neutron Stars

- **Formed in:** type II, Ib or Ic SN
- **Mass:** $M \sim 1 - 2 M_\odot$
- **Radius:** $R \sim 10 - 12$ km
- **Density:** $\rho \sim 10^{14} - 10^{15}$ g/cm$^3$
  
  \[ \rho_{\text{universe}} \sim 10^{-30}$ g/cm$^3$
  \[ \rho_{\text{sun}} \sim 1.4$ g/cm$^3$
  \[ \rho_{\text{earth}} \sim 5.5$ g/cm$^3$

- **Baryonic number:** $N_b \sim 10^{57}$ ("giant nuclei")
- **Magnetic field:** $B \sim 10^{8...16}$ G ($10^4...12$ T)

0.3 – 0.5G  $10^3 – 10^4$ G  $10^5$ G  4.5x$10^5$G  2.8x$10^7$G

You are here!!

Earth  Magnet  Sunspots  Largest continuous field in lab. (FSU, USA)  Largest magnetic pulse in lab. (Russia)
- **Electric field**: $E \sim 10^{18} \text{ V/cm}$
- **Temperature**: $T \sim 10^6...11 \text{ K}$
- **Rotational period distribution** → two types of pulsars:
  - pulsars with $P \sim s$
  - pulsars with $P \sim \text{ms}$

  **Shortest rotational period**: $P_{\text{B1937+2}} = 1.58 \text{ ms}$ until the last discovery: PSR in Terzan 5: $P_{\text{J1748-2446ad}} = 1.39 \text{ ms}$

- **Accretion rates**: $10^{-10}$ to $10^{-8} \text{ M}_\odot/\text{year}$
Anatomy of a Neutron Star

Equilibrium composition determined by

✓ Charge neutrality

\[ \sum_i q_i \rho_i = 0 \]

✓ Equilibrium with respect to weak interacting processes

\[ b_1 \rightarrow b_2 + l + \bar{\nu}_l \]
\[ b_2 + l \rightarrow b_1 + \nu_l \]

\[ \mu_i = b_i \mu_n - q_i (\mu_e - \mu_{\nu_e}) \]
\[ \mu_i = \frac{\partial \epsilon}{\partial \rho_i} \]
Hyperons in NS considered by many authors since the pioneering work of Ambartsumyan & Saakyan (1960)

Phenomenological approaches

- Non-relativistic potential model: Balberg & Gal 1997
- Quark-meson coupling model: Pal et al. 1999, …
- Chiral Effective Lagrangians: Hanuske et al., 2000
- Density dependent hadron field models: Hofmann, Keil & Lenske 2001

Microscopic approaches

- $V_{\text{low }k}$: Djapo, Schaefer & Wambach, 2010

Sorry if I missed somebody
Hyperons are expected to appear in the core of neutron stars at \( \rho \sim (2-3) \rho_0 \) when \( \mu_N \) is large enough to make the conversion of N into Y energetically favorable.

\[
\begin{align*}
\mu_n + \mu_e - \mu_\nu & = \mu_\Sigma^- \\
\mu_\Lambda & = \mu_n
\end{align*}
\]

\[ n + n \rightarrow n + \Lambda \]
\[ p + e^- \rightarrow \Lambda + \nu e^- \]
\[ n + n \rightarrow p + \Sigma^- \]
\[ n + e^- \rightarrow \Sigma^- + \nu e^- \]

Relieve of Fermi pressure due to the appearance of hyperons \( \Rightarrow \) EoS softer \( \Rightarrow \) reduction of the mass
Measured NS Masses (up to 2006)

Phenomenological: $M_{\text{max}}$ compatible with 1.4-1.5 $M_\odot$

Microscopic: $M_{\text{max}} < 1.4-1.5 M_\odot$
Recent measurements of high masses → life of hyperons more difficult

- **PSR J1903+0327** (Freire et al. 2009)
  - Post-Kelplerian parameters:
    - binary system (P=95.17 d)
    - high eccentricity (ε=0.437)
    - companion mass: ~ 1$M_\odot$
    - pulsar mass: $M = 1.67 \pm 0.11 M_\odot$

- **PSR J164-2230** (Demorest et al. 2010)
  - Shapiro delay:
    - binary system (P=8.68 d)
    - eccentricity (ε=1.3 x 10^{-6})
    - companion mass: ~ 0.5$M_\odot$
    - pulsar mass: $M = 1.97 \pm 0.04 M_\odot$
The hyperon puzzle

“Hyperons $\Rightarrow$ “soft (or too soft) EoS” not compatible (mainly in microscopic approaches) with measured (high) masses. However, the presence of hyperons in the NS interior seems to be unavoidable.”

- can YN & YY interactions still solve it?
- or perhaps hyperonic three-body forces?
- what about quark matter?
Even hyperonic 3BF cannot solve the problem

\[ 1.27 < M_{\text{max}} < 1.6 M_{\odot} \]

See talks of D. Logoteta & K. Tsubakihara (parallel session VIII on Thursday)
Situation not much clear with phenomenological approaches

(Massot et al. 2012)

- $\chi$-LM & QMC
- Hartree-Fock
- $M_{\text{max}} = 1.6 - 1.66 M_\odot$

(Miyatsu et al. 2012)

- RHF & QMC
- $\pi$ & $f_{vB}$
- $M_{\text{max}}$ compatible with $1.97 M_\odot$

(Weissenborn et al. 2012)

- RMF
- $SU(6) \rightarrow SU(3)$
- Vary $z = g_\phi/g_\sigma$, $\alpha_v$
- $\phi$ mesons
- $M_{\text{max}}$ compatible with $1.97 M_\odot$

(Bednarek et al. 2012)

- RMF
- $\sigma^4$ terms
- $\sigma^*, \phi$ mesons
- $M_{\text{max}} > 2 M_\odot$

See talk of J. Schaffner-Bielich (parallel session VIII on Thursday)
Question is so open that …
Hyperon Stars at birth
Proto-Neutron Stars

New effects on PNS matter:

- **Thermal effects**
  
  \[ T \approx 30 - 40 \text{ MeV} \]
  
  \[ S / A \approx 1 - 2 \]

- **Neutrino trapping**
  
  \[ \mu_{\nu} \neq 0 \]
  
  \[ Y_e = \frac{\rho_e + \rho_{\nu_e}}{\rho_B} \approx 0.4 \]
  
  \[ Y_\mu = \frac{\rho_\mu + \rho_{\nu_\mu}}{\rho_B} \approx 0 \]

(Janka, Langanke, Marek, Martinez-Pinedo & Muller 2006)
Proto-Neutron Stars: Composition

- **Neutrino free** \( \mu_\nu = 0 \)
  - Large proton fraction
  - Small number of muons
  - Onset of \( \Sigma^- (\Lambda) \) shifted to higher (lower) density
  - Hyperon fraction lower in \( \nu \)-trapped matter

- **Neutrino trapped** \( \mu_\nu \neq 0 \)

(Burgio & Schulze 2011)
Proto-Neutron Stars: EoS

- **Nucleonic matter**
  - $\nu$-trapping + temperature $\rightarrow$ softer EoS

- **Hyperonic matter**
  - $\nu$-trapping + temperature $\rightarrow$ stiffer EoS
  - More hyperon softening in $\nu$-untrapped matter (larger hyperon fraction)
Proto-Neutron Stars: Structure

(Nucleonic matter)

$v$-trapping + $T$: reduction of $M_{\text{max}}$

(Burgio & Schulze 2011)

(Hyperonic matter)

$v$-trapping + $T$: increase of $M_{\text{max}}$

To BH

(delayed BH formation)

(I. V. et al. 2003)
Hyperons & Neutron Star Cooling
Neutron Star Cooling in a Nutshell

**Two cooling regimes**

**Slow**
Low NS mass

**Fast**
High NS mass

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Core cools by neutrino emission
Crust cools by conduction

Surface photon emission dominates at $t > 10^6$ yrs

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$I$. Core relaxation epoch
$II$. Neutrino cooling epoch
$III$. Photon cooling epoch

\[
\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\gamma - L_\nu + H
\]

- $C_v$: specific heat
- $L_\gamma$: photon luminosity
- $L_\nu$: neutrino luminosity
- $H$: “heating”
## Neutrino Emission in a Nutshell

<table>
<thead>
<tr>
<th>Name</th>
<th>Process</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct URCA</td>
<td>$n \rightarrow p + l + \bar{\nu}_l$</td>
<td>$\sim T^6$</td>
</tr>
<tr>
<td></td>
<td>$p + l \rightarrow n + \nu_l$</td>
<td></td>
</tr>
<tr>
<td>Modified URCA</td>
<td>$N + n \rightarrow N + p + l + \bar{\nu}_l$</td>
<td>$\sim T^8$</td>
</tr>
<tr>
<td></td>
<td>$N + p + l \rightarrow N + n + \nu_l$</td>
<td></td>
</tr>
<tr>
<td>Bremsstrah lung</td>
<td>$N + N \rightarrow N + N + \nu + \bar{\nu}$</td>
<td>$\sim T^8$</td>
</tr>
<tr>
<td>Cooper pair formation</td>
<td>$n + n \rightarrow [nn] + \nu + \bar{\nu}$</td>
<td>$\sim T^7$</td>
</tr>
<tr>
<td></td>
<td>$p + p \rightarrow [pp] + \nu + \bar{\nu}$</td>
<td></td>
</tr>
</tbody>
</table>
Hyperonic DURCA processes possible as soon as hyperons appear (nucleonic DURCA requires $x_p > 11-15\%$)

<table>
<thead>
<tr>
<th>Process</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda \rightarrow p + l + \bar{\nu}_l$</td>
<td>0.0394</td>
</tr>
<tr>
<td>$\Sigma^- \rightarrow n + l + \bar{\nu}_l$</td>
<td>0.0125</td>
</tr>
<tr>
<td>$\Sigma^- \rightarrow \Lambda + l + \bar{\nu}_l$</td>
<td>0.2055</td>
</tr>
<tr>
<td>$\Sigma^- \rightarrow \Sigma^0 + l + \bar{\nu}_l$</td>
<td>0.6052</td>
</tr>
<tr>
<td>$\Xi^- \rightarrow \Lambda + l + \bar{\nu}_l$</td>
<td>0.0175</td>
</tr>
<tr>
<td>$\Xi^- \rightarrow \Sigma^0 + l + \bar{\nu}_l$</td>
<td>0.0282</td>
</tr>
<tr>
<td>$\Xi^0 \rightarrow \Sigma^+ + l + \bar{\nu}_l$</td>
<td>0.0564</td>
</tr>
<tr>
<td>$\Xi^- \rightarrow \Xi^0 + l + \bar{\nu}_l$</td>
<td>0.2218</td>
</tr>
</tbody>
</table>

+ partner reactions generating neutrinos, Hyperonic MURCA, …

$R$: relative emissivity w.r.t. nucleonic DURCA

(Schaab, Shaffner-Bielich & Balberg 1998)
Pairing Gap $\Rightarrow$ suppression of $C_v \& \xi$ by $\sim e^{-\Delta/k_BT}$

- $^1S_0, ~^3SD_1 ~\Sigma N \& ~^1S_0 ~\Lambda N$ gap
  - $n\Sigma^- ~^3SD_1$
  - $n\Sigma^- ~^1S_0$
  - $n\Lambda ~^1S_0$
  
  (Zhou, Schulze, Pan & Draayer 2005)

- $^1S_0 ~\Lambda\Lambda$ gap
  - $(\text{Balberg} \& \text{Barnea 1998})$
  - $(\text{Wang} \& \text{Shen 2010})$

- $^1S_0 ~\Sigma\Sigma$ gap
  - $(\text{I. V.} \& \text{To l ó s 2004})$
  - NSC97e

 NSC97e
Hyperons & the R-mode instability of Neutron Stars
The R-mode Instability in a Napkin

\( \Omega_{\text{Kepler}} \): Absolute Upper Limit of Rot. Freq.

Instabilities prevent NS to reach \( \Omega_{\text{Kepler}} \)

R-mode Instability: toroidal mode of oscillation

- restoring force: Coriolis
- emission of GW in hot & rapidly rotating NS (CFS mechanism)
  - GW makes the mode unstable
  - Viscosity stabilizes the mode

\[
\frac{1}{\tau(\Omega, T)} = \frac{1}{\tau_{\text{GW}}(\Omega)} + \frac{1}{\tau_{\text{Viscosity}}(\Omega, T)}
\]

\[
A \propto A_0 e^{-i\omega(\Omega) - t/\tau(\Omega, T)}
\]

r-mode unstable due to GW emission

r-mode damped by shear viscosity

r-mode damped by bulk viscosity

\[ \tau(\Omega, T) = \tau_{\text{GW}}(\Omega) + \tau_{\text{Viscosity}}(\Omega, T) \]
Hyperon Bulk Viscosity $\xi_Y$


Sources of $\xi_Y$:

| Non-leptonic weak reactions | $N + N \leftrightarrow N + Y$
|                           | $N + Y \leftrightarrow Y + Y$
|                           | $Y \rightarrow B + l + \bar{\nu}_l$
| Direct & Modified URCA    | $B' + Y \rightarrow B' + B + l + \bar{\nu}_l$
|                           | $N + Y \leftrightarrow N + Y$
| Strong reactions          | $N + \Xi \leftrightarrow Y + Y$
|                           | $Y + Y \leftrightarrow Y + Y$

Reaction Rates & $\xi_Y$ reduced by Hyperon Superfluidity

(Haensel, Levenfish & Yakovlev 2002)
Critical Angular Velocity of Neutron Stars

- r-mode amplitude: \( A \propto A_o e^{-i\omega(\Omega)t-t/\tau(\Omega)} \)

\[
\frac{1}{\tau(\Omega,T)} = -\frac{1}{\tau_{GW}(\Omega)} + \frac{1}{\tau_\varphi(\Omega,T)} + \frac{1}{\tau_\eta(T)}
\]

\[\tau(\Omega_c,T) = 0 \quad \text{r-mode instability region} \]

\[\Omega < \Omega_c \quad \text{stable} \]
\[\Omega > \Omega_c \quad \text{unstable} \]

As expected:
smaller r-mode instability region
due to hyperons

BHF: NN (Av18)+NY (NSC89) (M=1.27M_\odot)
Take away message

Hyperons in Neutron Stars

✓ Strong softening of EoS & reduction of NS Mass
  ➞ Hyperons & Massive NS still an open question
  (Hyperons-NS-2012 Meeting)

✓ Modification of PNS properties (composition, EoS, Mass)

✓ Additional Fast Cooling Processes

✓ Reduction of r-mode instability region
MERCI!
THANK YOU!