Compressed baryonic matter of astrophysics

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http://vega.bac.pku.edu.cn/rxxu
Summary

- Introduction: What’s Compressed BM?
- What do we know about CBM?
- What don’t we know about CBM?
- What can observations teach us?
- Conclusions
Introduction: what’s compressed BM?

• What is *baryon*?

Our Universe is dominated by dark matter and dark energy. Nevertheless, the most familiar composition we know best is the atomic part, the *baryons* and *leptons*!
Introduction: what’s compressed BM?

**What is baryon:** the standard model of particle physics

<table>
<thead>
<tr>
<th>Baryon (a quark) = 1/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>color number</td>
</tr>
<tr>
<td>electricity</td>
</tr>
<tr>
<td>1st generation</td>
</tr>
<tr>
<td>2nd generation</td>
</tr>
<tr>
<td>3rd generation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Higgs Boson</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(July 2012, 5σ!)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gauge Boson</th>
<th>Strong</th>
<th>electro-magn.</th>
<th>Weak</th>
<th>gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>number</td>
<td>8</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Introduction: what’s compressed BM?

There is plenty of empty space between atoms…

• What if the space is squeezed out? —— high density, $> \rho_{\text{nucl}}$
• How can one squeeze space out of normal matter? —— gravity!
• Where could CBM be? —— in the heaven!

$\Rightarrow$ Supernova would make CBM from atoms!

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What do we know about CBM?

• Baryon number \( \sim 10^{57} \) → *medium effect significant*

• Density \( > \rho_{\text{nucl}} \) if *considering nuclei as gravity-free*

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What do we know about CBM?

- Energy scale $E_{\text{scale}} \sim 400\text{MeV}$ by either Heisenberg’s relation or Fermi energy

  \[ \left\{ \begin{array}{l}
  \text{Strangeness because of } E_{\text{scale}} > m_s \sim 100\text{MeV} \\
  \text{Strong } NQCD \text{ effects because of } E_{\text{scale}} < 1\text{GeV}
  \end{array} \right. \]

- $\sim 10^{57}$ quarks there and, by comparing with other forces, color interaction should play an important role in determining EoS,

  \textit{but … what’s more?}
Summary

- Introduction: What’s **Compressed BM**?
- What do we *know* about CBM?
  - What *don’t* we know about CBM?
- What can *observations* teach us?
- Conclusions

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What don’t we know about CBM?

• Confinement or de-confinement in CBM?
  A challenging problem!

Scenarios suggested?

- Hadron star: quarks confined
- Quark star: quarks de-confined
- Hybrid/mixed star
- Quark-cluster star: quarks grouped in clusters (> 6, rather than 3, grouped in a cluster of CBM possible?)
  - Gravity-bound
  - Self-bound on surface
What don’t we know about CBM?

- **3-flavor symmetry in CBM?**

<table>
<thead>
<tr>
<th></th>
<th>{u,d}</th>
<th>{u,d,s}</th>
</tr>
</thead>
<tbody>
<tr>
<td>nucleus</td>
<td>gigantic one</td>
<td>nucleus</td>
</tr>
<tr>
<td>electron outside</td>
<td>$E_e \ll \text{MeV}$</td>
<td>electron inside</td>
</tr>
<tr>
<td>electron inside</td>
<td>$E_e \ll \text{MeV}$</td>
<td>electron outside</td>
</tr>
<tr>
<td>stable</td>
<td>$e+p \rightarrow n+\nu_e$</td>
<td>unstable due to surface energy</td>
</tr>
<tr>
<td></td>
<td>$E_e$ decreases but $E_{\text{sym}}$ increases</td>
<td></td>
</tr>
</tbody>
</table>

$\Rightarrow \text{CBM: strange quark-cluster matter?}$
What don’t we know about CBM?

• What if CBM is made of quark-cluster matter?

Stiff EoS (NR clusters, repulsion, 3-body?)

\[ E = (c^2 p^2 + m^2 c^4)^{1/2} \sim p^2 \rightarrow P \sim \rho^\gamma (\gamma > 1!) \]

Self-bound by residual interaction between clusters

Global solid if \( kT < \) residual interaction energy

Free energy elastic and gravitational

and… \textbf{How to} model quark-cluster matter stars?

Very difficult from first principles,
but phenomenologically …

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What if CBM is made of quark-cluster matter?

• A realistic quark cluster: *H-star*?

Assuming *interaction* between H’s is mediated by $\sigma-\omega$ mesons,

\[
\begin{align*}
M_{\text{max}} - V_0 \\
M - R, M - \rho_c
\end{align*}
\]
What if CBM is made of quark-cluster matter?

- A corresponding-state approach to ... 

Wilczek (2007)

![Graph showing inter-nucleon potential](image)

- Dimensionless parameters:
  
  \[ P^* = P\sigma^3/\epsilon \]
  
  \[ V^* = V/(N\sigma^3) \]
  
  \[ T^* = kT/\epsilon \]
  
  \[ \Lambda^* = \hbar/(\sigma\sqrt{m\epsilon}) \]

- Corresponding state law EoS
  
  \[ P^* = f(V^*, T^*, \Lambda^*) \]

The results (Guo, Lai & Xu; arXiv1209.3688):

![Graphs and diagrams showing results](image)

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What can observations teach us?

Observational hints for the nature of CBM:

\* $2M_{\text{sun}} \text{ psr: Stiff EoS!}$

A mass gap?

$M_{\text{psr}}$ detected $< 2 M_{\text{sun}}$

$M_{\text{BH}}$ detected $> 5 M_{\text{sun}}$

$M_{\text{psr}}$ detected $< 2 M_{\text{sun}}$

$M_{\text{BH}}$ detected $> 5 M_{\text{sun}}$

$GRO J0422+32$

$4U1543-47$

Kreidberg et al. (2012)
What can observations teach us?

• Observational hints for the nature of CBM:
  * Self-bound surface

  _Subpulse drifting:_ strong B-field vs. self-bound on surface (Xu et al. 1999, Qiao et al. 2004)

  _Nonatomic spectra:_ strong B-field vs. self-bound (Xu. 2002)

  _Clean fireball_ for SNE & GRB? (Ouyed et al. 2005; Paczynski & Haensel 2005; Chen et al. 2007)

Linear $\text{poln}\% \ (B, \nabla T)$!
What can observations teach us?

• Observational hints for the nature of CBM:
  * Precession, free or forced

Eggs: *Raw* or *Cooked*?

Pulsars B1821-11: *precession* or even *free precession*?

(Stairs, Lyne & Shemar, 2000, Nature, 406, 484)

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What can observations teach us?

- Observational hints for the nature of CBM:
  - Huge free energy: B-field vs. quake? (Xu et al. 2006)

\[ E_{\text{stored}} \approx \frac{GM^2}{R} \sim 10^{53} \frac{\Delta R}{R} \text{ ergs} \]

for \( M \sim M_\odot \)

AXP/SGRs: bursts/glitches, flares, even superflares

\textit{magnetars vs. solid quark-cluster stars?}

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What can observations teach us?

- Observational hints for the nature of CBM:
  
  *Low-mass compact stars? (KRCS, PMCS)

![Graph showing age dependencies of BB radius and BB effective temperature for CCOs (filled circles), AXPs (open diamonds) and SGRs (filled diamonds). For objects with known SNR association, estimated SNR ages are used (solid horizontal error-bars) while for four magnetars (marked with horizontal dash lines) we use spin-down ages.](image)

- PSR J1719-1438 (Horvath 2012)
- PSR B1257+12 (Xu et al. 2003)
What can observations teach us?

• Observational hints for the nature of CBM:
  * X-ray bursts on surface: evidence for crust? Elaborate modeling in NS model!
  
  Can it be reproduced in quark-cluster star model? The key is to have unstable energy release during accretion: either thermal nuclear flash on crust formed above quark-cluster star or star-quake-induced burst.

  * Others: cooling, glitch and braking...?
  
What can observations teach us?

• To teach us more? by *radio* ...

  Five hundred meter *Aperture Spherical Telescope*

- To measure the mass of radio pulsars
- To measure the inertial of momentum of NS
- To find sub-ms radio pulsars

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A new answer: quark-cluster matter?

• To teach us more? by X-ray polarization …

X-ray Timing and Polarization

Lightweight Asymmetry and Magnetism Probe

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✓ Conclusions
Why study **Compressed Baryonic Matter**, or more generally strongly interacting matter at high densities and temperatures? Most obviously, *because it’s an important piece of Nature.* The whole universe, in the early moments of the *big bang*, was filled with the stuff. Today, highly compressed baryonic matter occurs in neutron stars and during crucial moments in the development of *supernovae*. Also, working to understand compressed baryonic matter gives us new perspectives on ordinary baryonic matter, i.e. the matter in *atomic nuclei*. But perhaps the best answer is a variation on the one George Mallory gave, when asked why he sought to scale Mount Everest: Because, as a prominent feature in the landscape of physics, it’s there. Compressed baryonic matter is a material we can *produce in novel, challenging experiments* that probe new extremes of temperature and density. On the theoretical side, *it is a mathematically well-defined domain* with a wealth of novel, challenging problems, as well as wide-ranging connections. Its challenges have already inspired a lot of very clever work, and revealed some wonderful surprises, as documented in this volume.

----- Frank Wilczek (2011)

“Prelude to compressed baryonic matter”

《The CBM Physics Book》
(Springer-Verlag Berlin Heidelberg)
Conclusions

Landau's Gigantic Nucleus

Normal Neutron Star

Quark-cluster Star

Top-down

Bottom-up

- nucleus
- proton
- neutron
- electron
- u-quark
- d-quark
- s-quark

~10^6 cm

~10^{11} cm