Nuclear Astrophysics in the new era of multi-messenger Astronomy

XIV International Workshop on Hadron Physics
18-23 March 2018
Florianópolis, SC, Brazil

LIGO Detects a Neutron Star Merger

Detailed analyses of the gravitational-wave data, together with observations of electromagnetic emissions, are providing new insights into the astrophysics of compact binary systems and γ-ray bursts, dense matter under extreme conditions, the nature of gravitation, and independent tests of cosmology.

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Astronomy.com

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From Tallahassee, Florida to Florianopolis, Brazil

Tallahassee to Florianopolis
7,500 km
Radius of the Earth
6,370 km
P.A.M Dirac
From Cambridge to Tallahassee

Florida State University Libraries invites you to honor
DR. PAUL A.M. DIRAC
October 20, 2015 | 4 pm
Roselawn Cemetery | 804 Piedmont Drive | Tallahassee

Please Join us as we honor Dr. Paul A.M. Dirac. As a symbol of our lasting relationship with the famed physicist and his family, FSU Libraries will groom his headstone, plant a flower and enjoy a sweet to honor his memory and his vast contribution to science.

*Dress in comfortable clothes and walking shoes

Paul A.M. Dirac was one of the most renowned physicists of the 20th including the Nobel Prize in 1933 for his work with Erwin Schrödinger on atomic theory. Dr. Dirac was a groundbreaking scientist in quantum mechanics and predicted the existence of antimatter. He worked at Florida State University from 1971 until his death in 1984.

Today, Florida State University Libraries is home to a vast and valuable collection of both his personal and professional papers. The Dirac Science Library also stands on FSU’s campus as a lasting legacy of his contributions to the university.

*Dr. Dirac was known for his long contemplative walks. He is also remembered by his daughter for enjoying sitting in the garden.

Wigner and Moshinsky
Outline

- Death of a massive star — birth of a pulsar
- An historical perspective (some of the main actors)
- Biography and anatomy of a neutron star
- Neutron stars as unique cosmic laboratories
- Heaven and Earth: Laboratory constraints on NS
- Earth and Heaven: NS constrains on laboratory observables
- It is all connected: a truly multidisciplinary journey …

The **BIG** questions?

- The creation of the heavy elements
- New states of matter at low and high densities
- The equation of state of neutron-rich matter
Lectures will attempt to provide an overall (personal) picture of the field

Main target audience are the students:
- Por favor faça perguntas
- Please ask questions
- Por favor haga preguntas
The Universe was created about 13.7 billion years ago (Big Bang!).

H, He, and traces of light elements formed 3 minutes after the Big Bang (BBN).

Stars and galaxies form from H and He clouds about 1 billion years after BB.

In stellar nurseries molecular clouds convert gravitational energy into thermal energy.

At about 10 million K protons overcome their Coulomb repulsion and fuse (pp chain):

\[
p + p \rightarrow d + e^+ + \nu_e \\
p + d \rightarrow ^3\text{He} + \gamma \\
^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + p + p
\]

ALL (gravity, strong, electroweak) interactions critical to achieve stardom.

Thermonuclear fusion halts the gravitational collapse.

Stellar evolution continues through several thermonuclear stages.
Death of a Star Birth of a Pulsar

- Big Bang creates H, He, and traces of light elements
- Massive stars create all chemical elements: from $^6$Li to $^{56}$Fe
- Once $^{56}$Fe is produced the stellar core collapses
- Core overshoots and rebounds: Core-Collapse Supernova!
- 99% of the gravitational energy radiated in neutrinos
- An incredibly dense object is left behind: A neutron star or a black hole

Neutron stars are solar mass objects with 10 km radii
Core collapse mechanism and r-process site remain uncertain!
S. Chandrashekar and X-Ray Chandra

- White-dwarf stars supported by electron degeneracy pressure (Dirac and Fowler 1926)

- For WD stars in excess of 1.4 solar masses electrons become relativistic and the pressure is insufficient to support the star against gravitational collapse (1931)

  \[ P \sim n^{5/3} \rightarrow n^{4/3} \]

- Arthur Eddington (1919 light bending) ridiculed Chandra

- James Chadwick discovers the neutron (1932)

- Chandra awarded the Nobel Prize with W.A. Fowler (1983)

- NASA launches the *Chandra* X-ray observatory (1999)
The Main Actors: Some Historical Facts

- Chandrasekhar shows that massive stars will collapse (1931)
- Chadwick discovers the neutron (1932)
  (... predicted earlier by Majorana but never published)
- Baade-Zwicky introduce the concept of a neutron star (1933)
  (... Landau mentions dense stars that look like giant nuclei)
- Oppenheimer-Volkoff use GR to compute the structure of neutron stars (1939)
  (predict 0.7 solar masses as maximum neutron star mass; as we will see later, this is a critical finding!!)
Neutron Stars: Dame Jocelyn Bell Burnell

Sounds of the 11 Hz (89 ms) Vela pulsar

Detected a bit of “scruff” (1967)

Discovers amazing regularity in the signal (P=1.33730119 seconds)

May the signal be from an alien civilization? (Little Green Man 1)

Paper announcing first pulsar published
[Observation of a Rapidly Pulsating Radio Source
A Hewish, SJ Bell, et al., Nature 217, 709 (1968)]

Nobel awarded to Hewish and Ryle (1974)

“No-Bell” roundly condemned (Hoyle)

“I believe it would demean Nobel Prizes if they were awarded to research students, except in very exceptional cases and I do not believe this is one of them”
Neutron Star Crust
Preface by Jocelyn Bell Burnell

I judge myself fortunate to be working in an exciting and fast moving area of science and at a time when the public has become fascinated by questions regarding the birth and evolution of stars, the nature of dark matter and dark energy, the formation of black holes and the origin and evolution of the universe.

The physics of neutron stars is one of these fascinating subjects. Neutron stars are formed in supernova explosions of massive stars or by accretion-induced collapse of smaller white dwarf stars. Their existence was confirmed through the discovery of radio pulsars during my thesis work in 1967. Since then this field has evolved enormously. Today we know of accretion-powered pulsars which are predominantly bright X-ray sources, rotation-powered pulsars observed throughout the electromagnetic spectrum, radio-quiet neutron stars, and highly magnetized neutron stars or magnetars. No wonder there has been an explosion in the research activity related to neutron stars!

It is now hard to collect in a single book what we already know about neutron stars along with some of the exciting new developments. In this volume experts have been asked to articulate what they believe are the critical, open questions in the field. In order for the book to be useful to a more general audience, the presentations also aim to be as pedagogical as possible.

This book is a collection of articles on the neutron stars themselves, written by well-known physicists. It is written with young researchers as the target audience, to help this new generation move the field forward. The invited authors summarize the current status of the field, both observational and theoretical, and identify which major progress may be expected in the next decade. I hope you agree with me, find the book enjoyable and fascinating.

Moreover, I expect that this book will become a useful resource for the many established practitioners. I believe that this book will have a wider readership. Most articles are accessible to a general audience, the presentations also aim to be as pedagogical as possible. This book should be useful to a more general audience, both graduate student, or to non-practitioner researchers, written by well-known physicists. It is written with young researchers as the target audience, to help this new generation move the field forward. The invited authors summarize the current status of the field, both observational and theoretical, and identify which major progress may be expected in the next decade.

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The Crab Pulsar

Biography of a Neutron Star: The Crab Pulsar

- SN 1054 first observed as a new “star” in the sky on July 4, 1054
- Event recorded in multiple Chinese and Japanese documents
- Event also recorded by Anasazi residents of Chaco Canyon, NM
- Crab nebula and pulsar became the SN remnants

Name: PSR B0531+21
POB: Taurus
Mass: 1.4 M☉
Radius: 10 km
Period: 33 ms
Distance: 6,500 ly
Temperature: 10^6 K
Density: 10^{14} g/cm^3
Pressure: 10^{29} atm
Magnetic Field: 10^{12} G
The Anatomy of a Neutron Star

Atmosphere (10 cm): Shapes Thermal Radiation \( L = 4\pi\sigma R^2 T^4 \)

Envelope (100 m): Huge Temperature Gradient \( (10^8 K \leftrightarrow 10^6 K) \)

Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)

Inner Crust (1 km): Coulomb Frustration ("Nuclear Pasta")

Outer Core (10 km): Uniform Neutron-Rich Matter \((n,p,e,\mu)\)

Inner Core (?): Exotic Matter (Hyperons, condensates, quark matter)
Neutron stars are the remnants of massive stellar explosions (CCSN)
- Bound by gravity — NOT by the strong force
- Satisfy the Tolman-Oppenheimer-Volkoff equation ($v_{\text{esc}}/c \sim 1/2$)

Only Physics that the TOV equation is sensitive to: Equation of State
- EOS must span about 11 orders of magnitude in baryon density

Increase from 0.7 → 2 Msun transfers ownership to Nuclear Physics!

Many nuclear models that accurately predict the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

What is missing?
A Grand Challenge: How does subatomic matter organize itself?
2010 Committee on the Assessment and Outlook for Nuclear Physics

Consider baryons and leptons in a fixed volume at $T=0$.

Enforce overall charge neutrality: $(e.g., \, p=e+\mu)$

Enforce conservation laws: (charge, baryon number, …)

Enforce full thermodynamical equilibrium $(T=0,P,\mu)$

<table>
<thead>
<tr>
<th>$p + e^- \leftrightarrow n + \nu$</th>
<th>(e-capture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \leftrightarrow p + e^- + \bar{\nu}$</td>
<td>(beta decay)</td>
</tr>
</tbody>
</table>

What is the ground state of cold, fully catalyzed matter?
Impossible to answer under normal laboratory conditions
Gravity is the catalyst for these exotic states of matter!!
How were the heavy elements from iron to uranium made?

Are there new states of matter at ultra-high densities? (Hyperons, meson condensates, quark matter, color superconductors, …)

How big(small) and heavy(light) can a neutron star be?

What is the role of multi-messenger astronomy? (EM, gravitational, and neutrino signals)

What are the critical laboratory experiments?

What are the critical astrophysical observations?

What are the critical theoretical insights? (To explain and predict with quantified uncertainties)
QCD is the fundamental theory of the strong interactions!

M: A theoretical MODEL with parameters and biases
D: A collection of experimental and observational DATA

The Prior $P(M)$: An insightful transformation in DFT

$$ (g_s, g_V, g_\rho, \kappa, \lambda, \Lambda_V) \leftrightarrow (\rho_0, \epsilon_0, M^*, K, J, L) $$

The Likelihood

$$ P(D|M) = \exp(-\chi^2/2) $$

$$ \chi^2(D, M) = \sum_{n=1}^{N} \frac{\left( O_n^{(th)}(M) - O_n^{(exp)}(D) \right)^2}{\Delta O_n^2} $$

The Marginal Likelihood; overall normalization factor
**Model Building: Relativistic DFT**

Building relativistic mean field models for finite nuclei and neutron stars

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\[ \mathcal{L}_{\text{Yukawa}} = \bar{\psi} \left[ g_s \phi - \left( g_V V_\mu + \frac{g_\rho}{2} \tau \cdot b_\mu + \frac{e}{2} (1 + \tau_3) A_\mu \right) \gamma^\mu \right] \psi \]

\[ \mathcal{L}_{\text{self}} = \frac{\kappa}{3!} (g_s \phi)^3 - \frac{\lambda}{4!} (g_s \phi)^4 + \frac{\zeta}{41!} g_\nu^4 (V_\mu V^\mu)^2 + \Lambda_\nu \left( g_\rho^2 b_\mu \cdot b^\mu \right) \left( g_\nu^2 V_\nu V^{\nu} \right) \]

**Nuclear Density Functional Theory (DFT)**

- Ab-initio calculations of heavy nuclei remains daunting task
- Search for energy functional valid over a large physics domain
- “From finite nuclei all the way to neutron stars”
- Incorporate physics insights into the construction of the functional
- Accurately calibrated to various properties of finite nuclei masses, charge radii, and giant monopole resonances
- Empirical constants encode physics beyond mean field
- Empirical constants obtained from the optimization of a quality measure

**Table III. Constrained energies (in MeV)**

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Observable</th>
<th>Experiment</th>
<th>NL3</th>
<th>FSU</th>
<th>FSU2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{16}\text{O})</td>
<td>(B/A)</td>
<td>7.98</td>
<td>8.06</td>
<td>7.98</td>
<td>8.00</td>
</tr>
<tr>
<td>(^{40}\text{Ca})</td>
<td>(R_n)</td>
<td>2.70</td>
<td>2.73</td>
<td>2.71</td>
<td>2.73</td>
</tr>
<tr>
<td>(^{48}\text{Ca})</td>
<td>(R_n)</td>
<td>3.48</td>
<td>3.49</td>
<td>3.45</td>
<td>3.47</td>
</tr>
<tr>
<td>(^{60}\text{Ni})</td>
<td>(R_n)</td>
<td>3.48</td>
<td>3.49</td>
<td>3.48</td>
<td>3.47</td>
</tr>
<tr>
<td>(^{80}\text{Sn})</td>
<td>(R_n)</td>
<td>3.48</td>
<td>3.49</td>
<td>3.48</td>
<td>3.47</td>
</tr>
<tr>
<td>(^{90}\text{Zr})</td>
<td>(R_n)</td>
<td>3.88</td>
<td>3.88</td>
<td>3.86</td>
<td></td>
</tr>
<tr>
<td>(^{100}\text{Sn})</td>
<td>(R_n)</td>
<td>3.88</td>
<td>3.88</td>
<td>3.86</td>
<td></td>
</tr>
<tr>
<td>(^{116}\text{Sn})</td>
<td>(R_n)</td>
<td>3.88</td>
<td>3.88</td>
<td>3.86</td>
<td></td>
</tr>
<tr>
<td>(^{132}\text{Sn})</td>
<td>(R_n)</td>
<td>3.88</td>
<td>3.88</td>
<td>3.86</td>
<td></td>
</tr>
<tr>
<td>(^{144}\text{Sm})</td>
<td>(R_n)</td>
<td>3.88</td>
<td>3.88</td>
<td>3.86</td>
<td></td>
</tr>
<tr>
<td>(^{208}\text{Pb})</td>
<td>(R_n)</td>
<td>3.88</td>
<td>3.88</td>
<td>3.86</td>
<td></td>
</tr>
</tbody>
</table>

**Table IV. Constrained giant monopole energies (in MeV)**

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>TAMU</th>
<th>RCNP</th>
<th>NL3</th>
<th>FSU</th>
<th>FSU2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{90}\text{Zr})</td>
<td>17.81 ± 0.35</td>
<td>—</td>
<td>18.76</td>
<td>17.86</td>
<td>17.93 ± 0.09</td>
</tr>
<tr>
<td>(^{116}\text{Sn})</td>
<td>15.90 ± 0.07</td>
<td>15.70 ± 0.10</td>
<td>17.19</td>
<td>16.30</td>
<td>16.47 ± 0.08</td>
</tr>
<tr>
<td>(^{144}\text{Sm})</td>
<td>15.25 ± 0.11</td>
<td>15.77 ± 0.17</td>
<td>16.29</td>
<td>15.55</td>
<td>15.59 ± 0.09</td>
</tr>
<tr>
<td>(^{208}\text{Pb})</td>
<td>14.18 ± 0.11</td>
<td>13.50 ± 0.10</td>
<td>14.32</td>
<td>13.72</td>
<td>13.76 ± 0.08</td>
</tr>
</tbody>
</table>