The Birth, Life, and Death of Stars

The Osher Lifelong Learning Institute
Florida State University

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Schedule: September 29 – November 3
Time: 11:30am – 1:30pm
Location: Pepper Center, Broad Auditorium
Ten Compelling Questions

- What is the raw material for making stars and where did it come from?
- What forces of nature contribute to energy generation in stars?
- How and where did the chemical elements form? ⭐
- How long do stars live?
- How will our Sun die?
- How do massive stars explode? ⭐
- What are the remnants of such stellar explosions?
- What prevents all stars from dying as black holes?
- What is the minimum mass of a black hole? ⭐
- What is role of FSU researchers in answering these questions?
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):

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

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

Thermonuclear fusion halts the gravitational collapse.

Stellar evolution continues through several thermonuclear stages.
Stellar Nucleosynthesis

Stars are incredibly efficient thermonuclear furnaces.
After H-burning terminates, the stellar core contracts.
Gravitational energy is transformed into thermal energy.
The heavier He-ashes (with a larger $Z$) can now fuse.

Thermonuclear fusion continues until the formation of an Iron core.
Thermonuclear fusion terminates abruptly: Supernova!
Every C in our cells, O in the air, and Fe in our blood was made in stars.
We all truly are “star stuff”...*Carl Sagan*
Massive stars create all chemical elements: from $^6\text{Li}$ to $^{56}\text{Fe}$

Once $^{56}\text{Fe}$ 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!
Some Historical Facts

- Chandrasekhar shows that massive stars will collapse (1931)
- Chadwick discovers the neutron (1932)
  ... predicted earlier by Ettore Majorana but never published!
- Baade and Zwicky introduce the concept of neutron stars (1933)
- Oppenheimer-Volkoff compute masses of neutron stars using GR (1939)
  Predict $M_* \simeq 0.7\, M_\odot$ as maximum NS mass or minimum black hole mass
- Jocelyn Bell discovers pulsars (1967)
- Gold and Pacini propose basic lighthouse model (1968)
  Pulsars are rapidly rotating Neutron Stars!

J. Piekarewicz (FSU-Physics)
S. Chandrasekhar and X-Ray Chandra

- White dwarfs resist gravitational collapse through electron degeneracy pressure rather than thermal pressure (Dirac and R.H. Fowler 1926)
- During his travel to graduate school at Cambridge under Fowler, Chandra works out the physics of the relativistic degenerate electron gas in white dwarf stars (at the age of 19!)
- For masses in excess of \( M = 1.4 M_\odot \) electrons becomes relativistic and the degeneracy pressure is insufficient to balance the star’s gravitational attraction \( (P \sim n^{5/3} \rightarrow n^{4/3}) \)
- “For a star of small mass the white-dwarf stage is an initial step towards complete extinction. A star of large mass cannot pass into the white-dwarf stage and one is left speculating on other possibilities” (S. Chandrasekhar 1931)
- Arthur Eddington (1919 bending of light) publicly ridiculed Chandra’s on his discovery
- Awarded the Nobel Prize in Physics (in 1983 with W.A. Fowler)
- In 1999, NASA lunches “Chandra” the premier USA X-ray observatory

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Jocelyn Bell

- Worked with Anthony Hewish on constructing a radio telescope to study quasars
- In 1967 as a graduate student (at the age of 24!) detected a bit of “scruff”

Jocelyn Bell discovers amazing regularity in the radio signals ($P = 1.33730119 \text{s}$)

- Speculated that the signal might be from another civilization (LGM-1)
- Paper announcing the first pulsar published in Nature (February 1968)
  A Hewish, S J Bell, J D H Pilkington, P F Scott, R A Collins
- Antony Hewish and Martin Ryle awarded the Nobel Prize in Physics in 1974
- The “No-Bell” roundly condemned by many astronomers (Fred 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”
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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 $M_\odot$
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
A Grand Challenge: How does subatomic matter organizes itself?

“Nuclear Physics: Exploring the Heart of Matter” (2010 Committee on the Assessment and Outlook for Nuclear Physics)

- Consider $A$ nucleons and $Z$ electrons in a fixed volume $V$ at $T = 0$
  
  ... cold fully catalyzed matter in thermal and chemical equilibrium

- Enforce charge neutrality $protons = electrons + muons$

- Enforce chemical (i.e., beta) equilibrium: $n \rightarrow p + e^- + \bar{\nu}$; $p + e^- \rightarrow n + \nu$

Impossible to answer such a question under normal laboratory conditions — as such a system is in general unbound!
Neutron Stars are bound by gravity \textbf{NOT} by the strong force

Neutron Stars satisfy the Tolman-Oppenheimer-Volkoff equation

GR extension of Newtonian gravity: $v_{\text{esc}}/c \sim 1/2$

Only Physics sensitive to is: \textbf{Equation of State}

EOS must span \textbf{10-11 orders of magnitude} in baryon density

Increase from $0.7 \rightarrow 2M_{\odot}$ must be explained by Nuclear Physics!

Gravitationally Bound Neutron Stars as Physics Gold Mines

\[ \frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r) \]

\[ \frac{dP}{dr} = -G \frac{\mathcal{E}(r)M(r)}{r^2} \left[ 1 + \frac{P(r)}{\mathcal{E}(r)} \right] \]

\[ \left[ 1 + \frac{4\pi r^3 P(r)}{M(r)} \right] \left[ 1 - \frac{2GM(r)}{r} \right]^{-1} \]

Need an EOS: $P = P(\mathcal{E})$ relation

\textbf{Nuclear Physics Critical}
The Anatomy of a Neutron Star

- **Atmosphere (10 cm):** Shape of 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 of exotic neutron-rich nuclei
- **Inner Crust (1 km):** Coulomb frustrated “Nuclear Pasta”
- **Outer Core (10 km):** Neutron-rich uniform matter \( (n, p, e, \mu) \)
- **Inner Core (?):** Exotic matter (Hyperons, condensates, quark matter, . . .)
The Outer Crust: $10^{-10} \rho_0 \lesssim \rho \lesssim 10^{-3} \rho_0 \ (\rho_0 \approx 2.4 \times 10^{14} \text{ g/cm}^3)$

- Uniform nuclear matter unstable against cluster formation
- Coulomb Crystal of neutron-rich nuclei immersed in $e^-$ Fermi gas
- Nuclear Crystallography: Dynamics driven by nuclear masses
  
  \[
  \frac{E}{A_{\text{tot}}} = \frac{M(N, Z)}{A} + 3/4 Y_e^{4/3} k_{\text{Fermi}} + \ldots
  \]
  
- bcc Crystal of neutron-rich nuclei immersed in a uniform $e^-$ gas
  
  \[
  ^{56}\text{Fe}, ^{62}\text{Ni} \rightarrow ^{86}\text{Kr}, \ldots, ^{78}\text{Ni}, \ldots \rightarrow ^{124}\text{Mo}, \ldots, ^{118}\text{Kr}_{82}(?)
  \]

- High-precision mass measurements of exotic unstable nuclei essential

**ISOLTRAP@CERN**: The case of $^{82}_{30}\text{Zn}_{52}$ with a 150 ns half-life!
The Inner Crust: “Coulomb Frustration and Nuclear Pasta”

- Frustration emerges from a dynamical (or geometrical) competition
- Impossibility to simultaneously minimize all elementary interactions
- Emergence of a multitude of competing (quasi) ground states
- Universal in complex systems (nuclei, $e^-$ systems, magnets, proteins,...)
- Emergence of fascinating topological shapes “Nuclear Pasta” or “Micro-emulsions”

“In 2D-electron systems with Coulomb interactions, a direct transition from a liquid to a crystalline state is forbidden” (Spivak-Kivelson)

How do we taste or smell the nuclear pasta?

Coulomb frustration is a fundamental problem in condensed-matter physics with widespread implications in nuclear physics and astrophysics!
The Outer/Inner Core: “Heaven and Earth”

- Structurally the most important component of the star
  90% of the size and all of the mass reside in the core
- Outer Core: Uniform neutron-rich matter in chemical equilibrium
  Neutrons, protons, electrons, and muons
- Inner Core(?): “QCD made simple (color-flavor locking)”
  Hyperons, meson condensates, color superconductors, ???
- Same pressure creates neutron skin and NStar radius
  Correlation among observables differing by 18 orders of magnitude!
Conclusions: Neutron Stars as Physics Gold Mines

- **Astrophysics**: What is the minimum mass of a black hole?
- **Atomic Physics**: Pure neutron matter as a unitary Fermi gas
- **Condensed-Matter Physics**: Insights into Coulomb frustration
- **General Relativity**: Neutron stars as a source of gravitational waves
- **Nuclear Physics**: What is the equation of state of dense matter?
- **Particle Physics**: Quark matter and color superconductors

It is all connected ...
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