The Birth, Life, and Death of Stars

The Osher Lifelong Learning Institute
Florida State University

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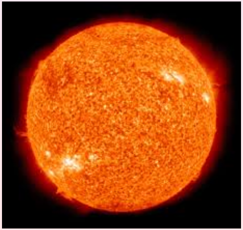
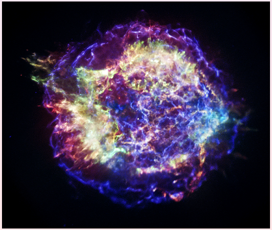
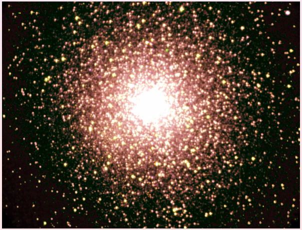
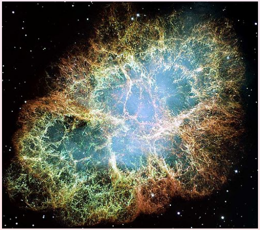
Schedule:	September 29 – November 3
Time:	11:30am – 1:30pm
Location:	Pepper Center, Broad Auditorium


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?



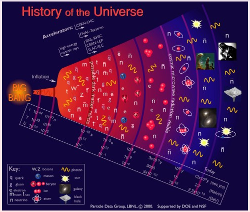


A Star is Born

- 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)

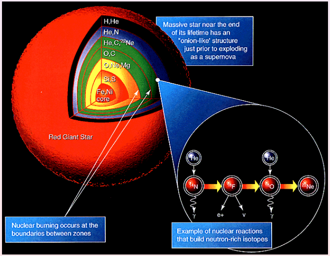
$$p + p \rightarrow d + e^{+} + \nu_e$$
$$p + d \rightarrow {}^3He + \gamma$$
$${}^3He + {}^3He \rightarrow {}^4He + p + p$$

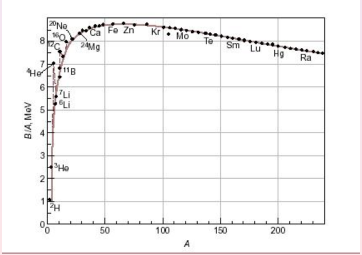
- **ALL** (gravity, strong, electroweak) interactions critical to achieve stardom
- Thermonuclear fusion halts the gravitational collapse
- Stellar evolution continues through several thermonuclear stages



Stellar Nucleosynthesis

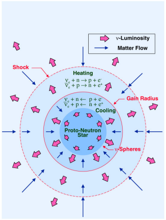
- Stars are incredibly efficient thermonuclear furnaces
  After H-burning terminates the stellar core contracts
  Gravitational energy is transformed into thermal energy
  The heavier He-ashes (with a larger Z) can now fuse
- Thermonuclear fusion continues until the formation of an Iron core
  Thermonuclear 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*

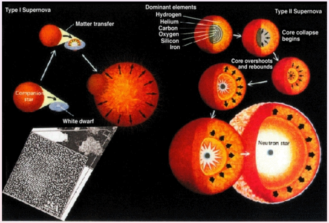




Death of a Star — Birth of a Pulsar: Core-Collapse Supernova

- 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!

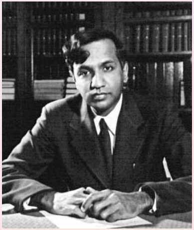
Some Historical Facts

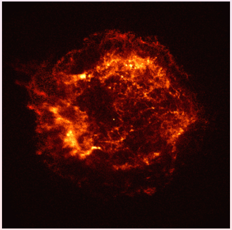
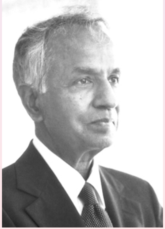
- Chandrasekhar shows that massive stars will collapse (1931)
- Chadwick discovers the neutron (1932)
  ... predicted earlier by Ettore Majorana but never published!
- Baade and Zwicky introduce the concept of neutron stars (1933)
- Oppenheimer-Volkoff compute masses of neutron stars using GR (1939)
  Predict $M_{\star} \simeq 0.7\, M_{\odot}$ 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!




S. Chandrasekhar and X-Ray Chandra

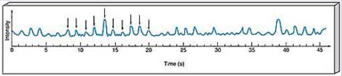
- White dwarfs resist gravitational collapse through electron degeneracy pressure rather than thermal pressure (Dirac and R.H. Fowler 1926)
- During his travel to graduate school at Cambridge under Fowler, Chandra works out the physics of the relativistic degenerate electron gas in white dwarf stars (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 ($P \sim n^{5/3} \to n^{4/3}$)
- *"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



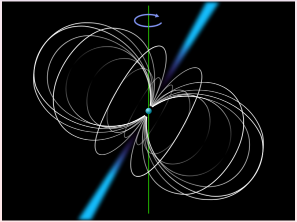
Jocelyn Bell

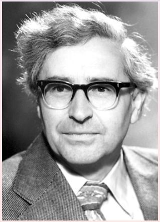
- Worked with Anthony Hewish on constructing a radio telescope to study quasars
- In 1967 as a graduate student (at the age of 24!) detected a bit of “scruff”



▸ The Sounds of Pulsars

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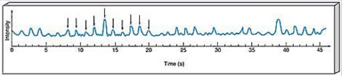

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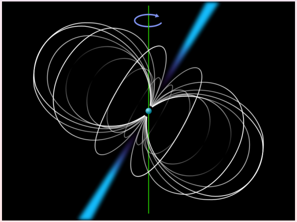
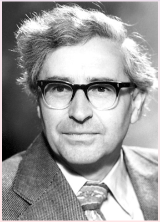


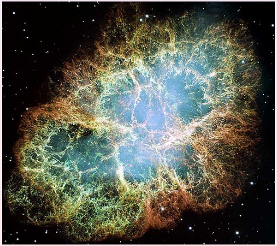


Biography of a Neutron Star: The Crab Pulsar

- 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

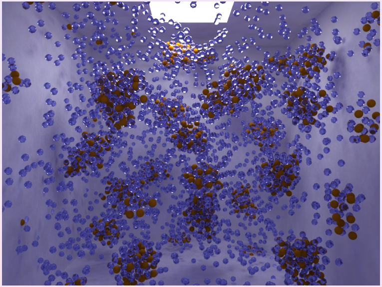
Distance: 6,500 ly
Temperature: 10^6 K
Density: 10^{14}g/cm^3
Pressure: 10^{29} atm
Magnetic Field: 10^{12} G

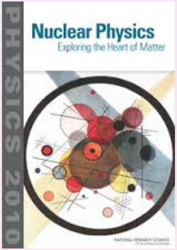


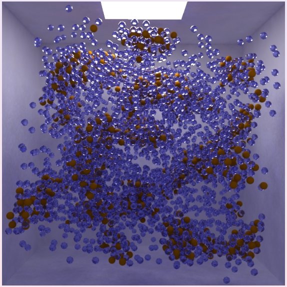
A Grand Challenge: How does subatomic matter organize itself?

"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 $T \equiv 0$
  ... cold fully catalyzed matter in thermal and chemical equilibrium
- Enforce charge neutrality *protons* $=$ *electrons* $+$ *muons*
- Enforce chemical (i.e., beta) equilibrium: $n \to p + e^- + \bar{\nu}; \quad p + e^- \to n + \nu$



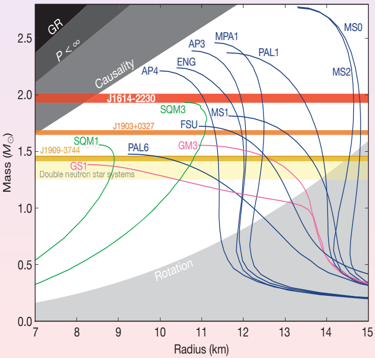




Impossible to answer such a question under normal laboratory conditions — as such a system is in general unbound!

Gravitationally Bound Neutron Stars as Physics Gold Mines

- Neutron Stars are bound by gravity NOT by the strong force
- Neutron Stars satisfy the Tolman-Oppenheimer-Volkoff equation
  GR extension of Newtonian gravity: $v_{\rm esc}/c \sim 1/2$
- Only Physics sensitive to is: **Equation of State**
- EOS must span 10-11 orders of magnitude in baryon density
- Increase from $0.7 \to 2M_\odot$ must be explained by Nuclear Physics!



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

$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

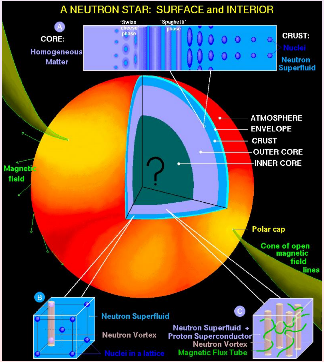
Need an EOS: $P = P(\mathcal{E})$ relation

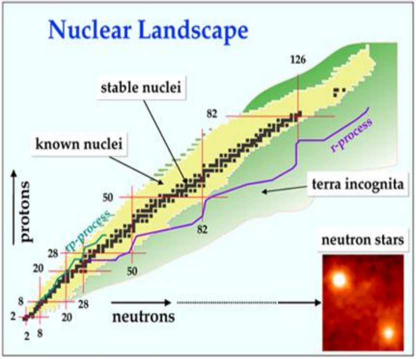
Nuclear Physics Critical

The Anatomy of a Neutron Star

FACILITY FOR RARE ISOTOPE BEAMS

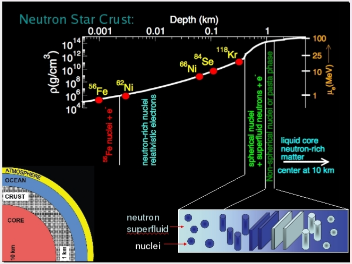
- *Atmosphere* (10 cm): Shape of Thermal Radiation ($L = 4\pi\sigma R^2 T^4$)
- *Envelope* (100 m): Huge Temperature Gradient ($10^8 K \leftrightarrow 10^6 K$)
- *Outer Crust* (400 m): Coulomb crystal of exotic neutron-rich nuclei
- *Inner Crust* (1 km): Coulomb frustrated “Nuclear Pasta”
- *Outer Core* (10 km): Neutron-rich uniform matter (n, p, e, μ)
- *Inner Core* (?): Exotic matter (Hyperons, condensates, quark matter, . . .)

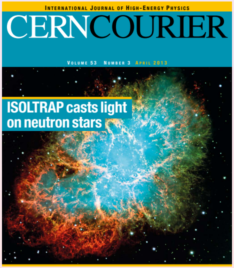




The Outer Crust: $10^{-10}\rho_0 \lesssim \rho \lesssim 10^{-3}\rho_0 \quad (\rho_0 \approx 2.4\times 10^{14}\,\mathrm{g/cm^3})$

- 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
  $E/A_{\rm tot} = M(N,Z)/A + 3/4\,Y_e^{4/3} k_{\rm Fermi} + \ldots$
- bcc Crystal of neutron-rich nuclei immersed in a uniform e^- gas
  $^{56}\mathrm{Fe},\, ^{62}\mathrm{Ni} \underset{N=50}{\Longrightarrow} {}^{86}\mathrm{Kr}, \ldots, {}^{78}\mathrm{Ni}, \ldots \underset{N=82}{\Longrightarrow} {}^{124}\mathrm{Mo}, \ldots, {}^{118}_{36}\mathrm{Kr}_{82}(?)$
- High-precision mass measurements of exotic unstable nuclei essential
  ISOLTRAP@CERN: The case of $^{82}_{30}\mathrm{Zn}_{52}$ with a 150 ns half-life!





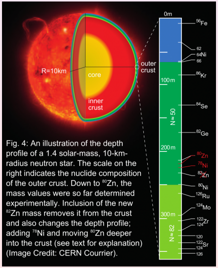
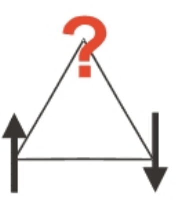


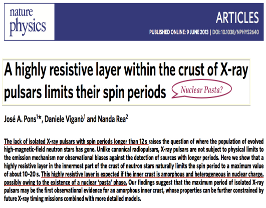
Fig. 4: An illustration of the depth profile of a 1.4 solar-mass, 10-km-radius neutron star. The scale on the right indicates the nuclide composition of the outer crust. Down to ^{80}Zn, the mass values were so far determined experimentally. Inclusion of the new ^{82}Zn mass removes it from the crust and also changes the depth profile; adding ^{78}Ni and moving ^{80}Zn deeper into the crust (see text for explanation) (Image Credit: CERN Courier).

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?





nature physics — ARTICLES

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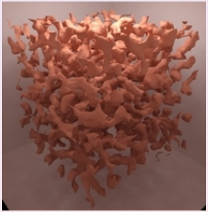
A highly resistive layer within the crust of X-ray pulsars limits their spin periods

José A. Pons[1]*, Daniele Viganò[1] and Nanda Rea[2]

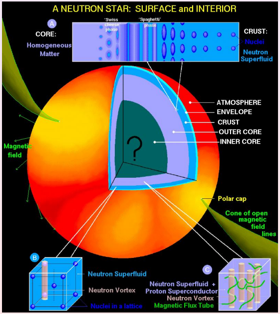
The lack of isolated X-ray pulsars with spin periods longer than 12 s raises the question of where the population of evolved high-magnetic-field neutron stars has gone. Unlike canonical radiopulsars, X-ray pulsars are not subject to physical limits to the emission mechanism nor observational biases against the detection of sources with longer periods. Here we show that a highly resistive layer in the innermost part of the crust of neutron stars naturally limits the spin period to a maximum value of about 10–20 s. This highly resistive layer is expected if the inner crust is amorphous and heterogeneous in nuclear charge, possibly owing to the existence of a nuclear 'pasta' phase. Our findings suggest that the maximum period of isolated X-ray pulsars may be the first observational evidence for an amorphous inner crust, whose properties can be further constrained by future X-ray timing missions combined with more detailed models.

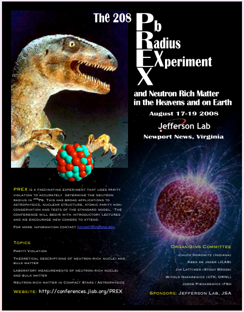


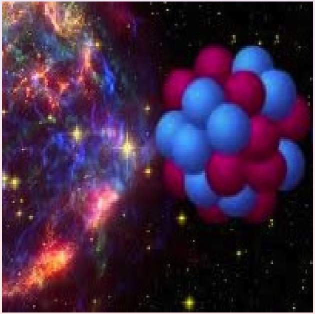
Coulomb frustration is a fundamental problem in condensed-matter physics with widespread implications in nuclear physics and astrophysics!

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!

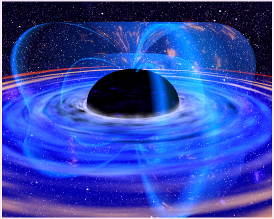


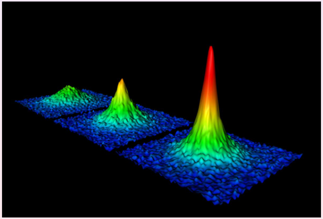


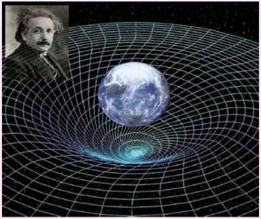


Conclusions: Neutron Stars as Physics Gold Mines

- 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: Neutrons 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 quark matter







It is all connected ...

Ten Compelling Questions

- What is the raw material for making stars and where did it come from?
  Hydrogen and Helium originated in the Big Bang
- What forces of nature contribute to energy generation in stars?
  All four: Gravitational, Electromagnetic, Strong, and Weak
- How and where did the chemical elements form? ⋆
  Thermonuclear fusion in the hot stellar interior
- How long do stars live?
  The lifetime of the star depends exclusively on its mass
- How will our Sun die?
  Our Sun will die as a white-dwarf star in about 5 billion years
- How do massive stars explode? ⋆
  Massive stars explode as spectacular Supernova
- What are the remnants of such stellar explosions?
  Black holes or neutron stars
- What prevents all stars from dying as black holes?
  A subtle quantum mechanical effect called Pauli pressure
- What is the minimum mass of a black hole? ⋆
  Approximately three times the mass of our Sun

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