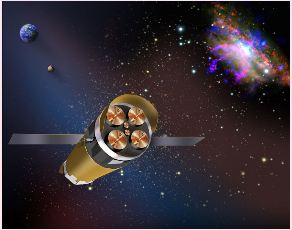
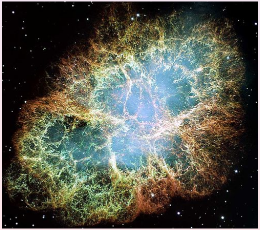
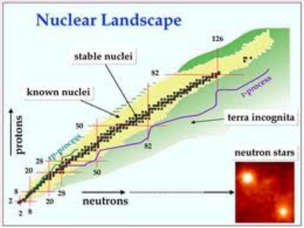
QuarkNet: A Tour to the Stars

Some Compelling Questions

- The chemical elements essential for life
  How did they form? Where did they form?
- Stars
  How are they born? How do they live? How do they die?
- The stellar graveyard
  White dwarfs, Neutron stars, Black holes

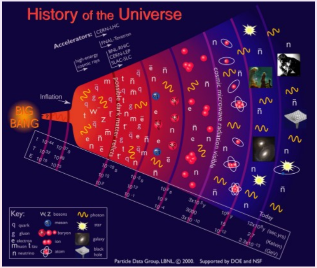


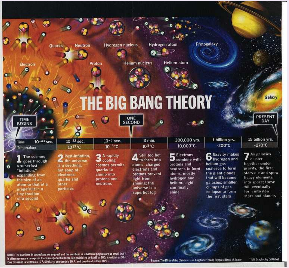




The Big Bang!

- We believe that the Universe was created about 13.7 billion years ago
- We do not understand what happened at the instant of creation!
- H, He, and traces of light elements were formed 3 minutes after creation
- Stars and galaxies form from H and He clouds after about 1 billion years

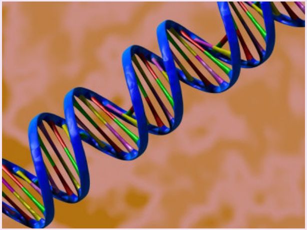


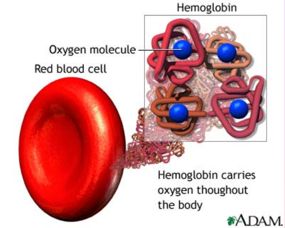


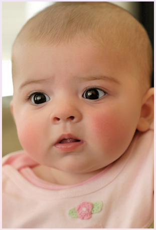
The Solar System is rich in chemical elements other than H and He; how and where did they come from?

The Human Blueprint

- Human beings are carbon-based lifeforms
- Human beings have calcium making our bones
- Human beings have iron running through our blood
- Human beings breath air which is rich in Nitrogen and Oxygen



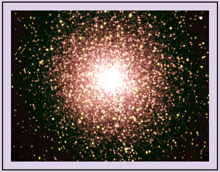




If only Hydrogen and Helium were made in the Big Bang, how and where did the rest of the chemical elements form?

A Star is Born

- A protostar achieves stardom at 10 million K
- Gravitational energy converted into thermal (kinetic) energy
- Protons overcome their Coulomb repulsion and fuse:



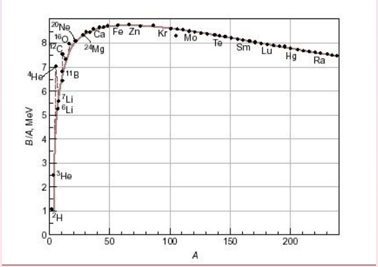
$$p + p \rightarrow d + e^{+} + \nu_e$$
$$p + d \rightarrow {}^{3}He + \gamma$$
$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$$

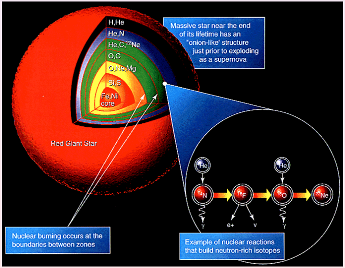
The proton-proton chain:

- **ALL** interactions in nature essential to achieve stardom
- Thermonuclear fusion halts the gravitational collapse
- Stellar evolution continues through several thermonuclear stages

Stellar Nucleosynthesis

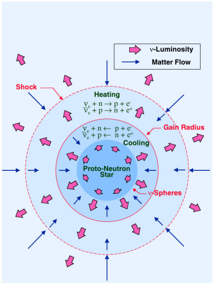
- Stars are incredibly efficient thermonuclear furnaces
  After H-burning terminates the stellar core contracts
  Gravitational energy is transformed into thermal energy
  The heavier He-ashes (with a larger *Z*) can now fuse
- Thermonuclear fusion continues until the formation of an Iron core
  Thermonuclear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





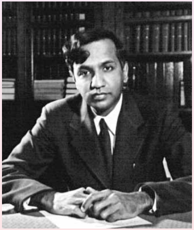
Core-Collapse Supernovae

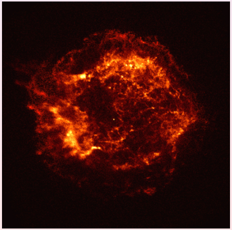
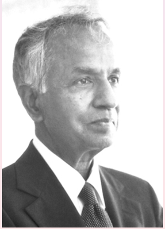
- Massive stars create all chemical elements from ^{6}Li to ^{56}Fe
- Once ^{56}Fe is produced, rapid collapse of the stellar core ensues
- As nucleons (mostly neutrons) start to touch, core overshoots and rebounds: **Supernovae Explosion**
- 99% of the gravitational energy of the collapse radiated in neutrinos
- An incredible dense object is left behind: **A neutron star or a black hole**



S. Chandrasekhar and X-Ray Chandra

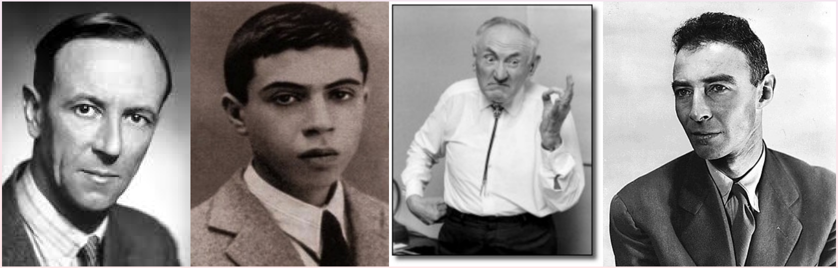
- White dwarfs resist gravitational collapse through electron degeneracy pressure rather than thermal pressure (Dirac and R.H. Fowler 1926)
- During his travel to graduate school at Cambridge under Fowler, Chandra works out the physics of the relativistic degenerate electron gas in white dwarf stars (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



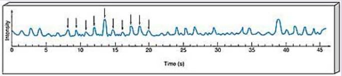
Some Historical Facts

- 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!

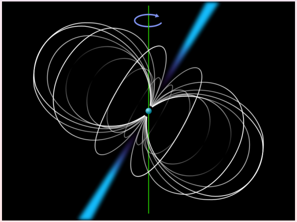


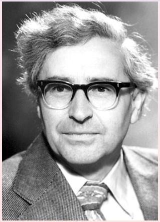
Jocelyn Bell

- 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"

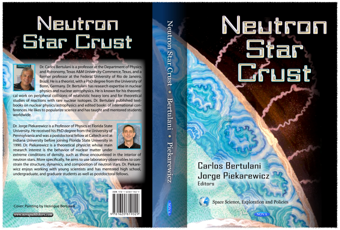


- Jocelyn Bell discovers amazing regularity in the radio signals ($P = 1.33730119\,s$)
- Speculated that the signal might be from another civilization **(LGM-1)**
- Paper announcing the first pulsar published in Nature (February 1968)
  A Hewish, S J Bell, J D H Pilkington, P F Scott, R A Collins
- Antony 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"*





Neutron Star Crust: Preface by Jocelyn Bell



Jocelyn Bell Burnell *

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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

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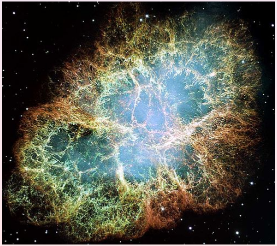
Table of Contents

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

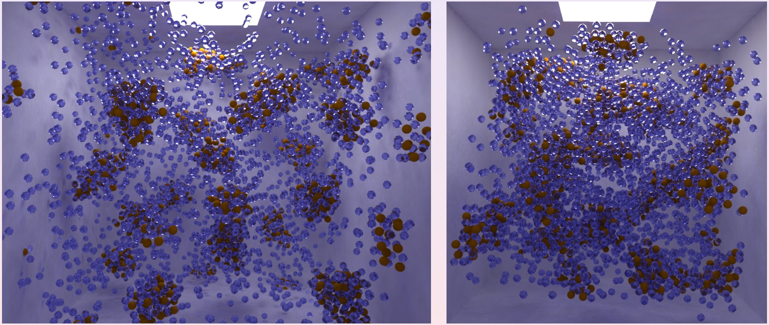
Distance: 6,500 ly
Temperature: 10^6 K
Density: 10^{14}g/cm^3
Pressure: 10^{29} atm
Magnetic Field: 10^{12} G



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 nucleons (A) and electrons (Z) in a volume V at $T \equiv 0$
- Enforce charge neutrality *protons* $=$ *electrons* $+$ *muons*
- Enforce conservation laws: Charge and Baryon number
  $n \to p + e^- + \bar{\nu}$ (beta decay) $p + e^- \to n + \nu$ (electron capture)

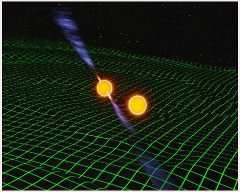
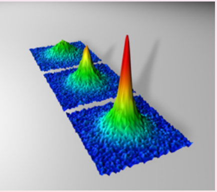
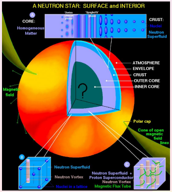


Impossible to answer such a question under normal laboratory conditions — as such a system is in general unbound!

Solution: Gravitationally Bound Neutron Stars

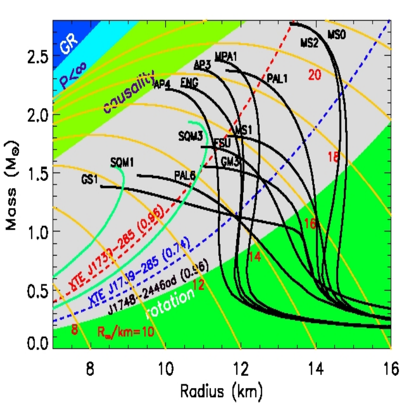
- Neutron Stars are bound by gravity NOT by the strong force
  Binding Energy/nucleon $\sim$ 100 MeV (neutron matter is unbound!)
- Gravity is the catalyst for the formation of novel states of matter
  Coulomb ("Wigner") crystal of neutron-rich nuclei
  Coulomb frustrated pasta structures
  Strange quark matter, meson condensates, color superconductors
- None of these exotic states can be produced in the laboratory!

Neutron stars are the natural meeting place of astrophysics, general relativity, atomic, nuclear, particle, and condensed-matter physics.

Neutron Stars as Nuclear Physics Gold Mines

- Neutron Stars satisfy the Tolman-Oppenheimer-Volkoff equation
  General-Relativistic extension of Newtonian gravity
  $\sqrt{R_{\rm s}/R_{\star}} = v_{\rm esc}/c \sim 1/2$
- Only Physics sensitive to is: **Equation of State**
- EOS must span 10-11 orders of magnitude in baryon density



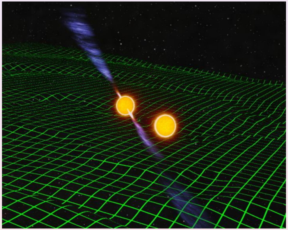
$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

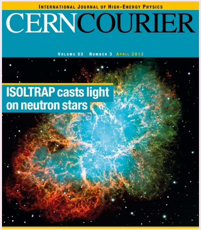
$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

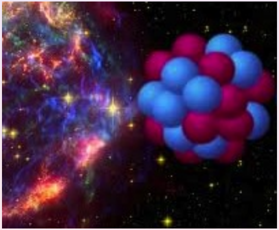
Need an $\mathcal{E}$ *vs* P relation!

Some Outstanding Questions

- How do supernovae explode?
- Where do the heavy elements form?
- What is the minimum black-hole mass?
- What is the maximum neutron-star mass?
- What is the radius of a neutron star?
- Are quarks and gluons free to roam in the neutron-star core?







Wonderful interdisciplinary field with many fundamental questions that remain to be answered