Neutron Stars and Radio Pulsars

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**How does the Sun shine?**

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- 1904, Rutherford: Radioactive decay?
- 1920, Eddington: Nuclear fusion, Einstein’s $E = mc^2$.
- 1957, Margaret Burbidge, "Synthesis of the Elements in Stars"
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Nuclear fusion: $\text{H} \rightarrow \text{He} \rightarrow$ Progressively heavier elements.

- The Iron limit: $\Delta E < 0$ for fusion to heavier elements.
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Nuclear fusion: \( H \rightarrow He \rightarrow \text{Progressively heavier elements.} \)

- The Iron limit: \( \Delta E < 0 \) for fusion to heavier elements.
- When nothing left besides Iron, gravitational collapse occurs.
The fate of a star

Gravitational collapse can be halted by:

- Electron degeneracy pressure → White Dwarfs
- Neutron degeneracy pressure → Neutron Stars
- Nothing ... → Black Holes
The fate of a star

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When the mass of a dying star $> \text{the Chandrasekhar limit}$, we get a Type II supernova explosion.

Supernova explosions in NGC3982, NGC3877.
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The supernova remnant in Cassiopeia (VLA radio image)
The fate of a star

• Baade & Zwicky (1934):
  A supernova represents “the transition of an ordinary star into a neutron star, consisting mainly of neutrons” → small radius, high density.

  ⇒ No apparent means of confirmation.

• Pacini (1967):
  Rapid rotation of NS could power a nebula such as the Crab.

• The same year, observations caught up with theory!
The discovery of radio pulsars

- Hewish et al.: interplanetary scintillation at 3.7 m.
- In 1967, Jocelyn Bell discovered radio pulses from the sky.
The discovery of radio pulsars

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Gold (1968): "A slight but steady slowing down" predicted for a rotating NS.

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[Pulsar animations and sounds.]
Basic NS Properties: M, R, T, B

- NS radius is $\approx 10 - 15$ km

(How do we know?)

A typical NS size, compared to Sydney.

Chandrasekhar Limit: NS mass is $1.4 \, M_{\odot}$.

Observed: $1.3 - 1.7 \, M_{\odot}$.

($10^{18}$ gm/cc ($10^{15}$ kg/m$^3$)).

Temperature from X-ray thermal emission spectra $10^6$ - $10^7$ Kelvin. Combined with distances: Luminosity.

NS cooling

Equation of State for condensed matter.

Magnetic field inferred from spindown: $10^8 - 10^{12}$ Gauss.

(Or up to $10^{14}$ Gauss for "magnetars".)
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The Crab Nebula

Supernova explosion witnessed in 1054 AD by Chinese astronomers; also recorded by Anasazi Indian artists.
The Crab Pulsar, B0531+21

The prototypical young pulsar – supernova remnant system.
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Pulsar B0531+21:
- Period = 33 ms (actually $0.03308471603 \pm 0.0000000011$ sec).
- Slowing down at $4.2 \times 10^{-13}$ s/s.
- Energy loss rate $\dot{E} = I\omega\dot{\omega} = 4 \times 10^{38}$ erg/sec ($4 \times 10^{31}$ Watts).

(Note: Our Sun has a total output of $\sim 3.8 \times 10^{26}$ Watts!)
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Crab Nebula:

- Radiation lifetime $\sim$ 100 years;
- Energy required $\sim 10^{38}$ erg/sec.

$\Rightarrow$ Emission powered by rotational energy loss of the pulsar.
The Crab Pulsar, B0531+21

The pulsar is visible even at optical frequencies and higher.
The Crab Nebula

Radio (VLA): wisp-like structures.
The Crab Nebula

Optical (HST): the neutron star, wisps, knots traveling at $0.5c$. 
The Crab Nebula

X-rays (Chandra): an equatorial wind and jets from the NS poles.
The Crab Nebula

Combined radio (red), optical (green) and X-ray (blue) view: A pulsar powered nebula.
• PSR B1913+16 is a binary pulsar with a neutron star companion, discovered at Arecibo (Hulse & Taylor 1974).

• Spin period = 59 ms; Orbital period = 7.75 hours.
Pulse Timing and General Relativity

- Radiates gravitational waves: Precession of Periastron.
- Agrees with GR prediction (Taylor & Weisberg 1982).

![Cumulative shift of periastron time](chart.png)

- General Relativity prediction

Year:
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000

Cumulative shift of periastron time (s):
- -30
- -25
- -20
- -15
- -10
- -5
- 0

Nobel Prize for discovery of system, 1993.

New double pulsar system J0737 3039 A and B: even better laboratory for GR tests.
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X-rays show a point source in the Cas A remnant.
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A neutron star, but ...
Very deep radio and X-ray searches reveal no pulsations!