Nature's Timepiece: The Exotic World of Pulsars

Week One: Setting the Stage

Andrew McCann
EFI & KICP @ The University of Chicago
What is a pulsar?

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- Mass $1.4 - 2 \times M_{\text{sun}}$
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- Diameter $\sim 20$ km ($D_{\text{sun}}$ is $1.4 \times 10^6$ km)
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PSR B0329+54
Period: 0.714 seconds [1.4 Hz]
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PSR B1055-52
Period: 197ms [5 Hz]
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Vela pulsar observed with the Parkes telescope in Australia

PSR B0833-45
Period: 89.3ms [11 Hz]
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PSR J0437-4715
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PSR J1811-1926 [65ms] in the nebula from SN 386
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PSR B2224+65 [0.68s] in the “Guitar” Nebula
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**Crab pulsar** [33ms] PSR B2224+65 [0.68s] in the "Guitar" Nebula

Next Week

PSR J1811-1926 [65ms] in the nebula from SN 386

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At the equator, the sun does a full rotation every 24.5 days.
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The diameter of the sun is $\sim$1.4 million km
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Take the core to be the inner 3%
(diameter of 40,000 km)
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Conservation of angular momentum:

$$L = \frac{2}{5} M R^2 \Omega$$

As the star collapses:
- $R$ of core shrinks from $2 \times 10^4$ km to 10 km
- $R^2$ shrinks from $4 \times 10^8$ km$^2$ to $1 \times 10^2$ km$^2$

$R^2$ shrinks by 6.5 orders of magnitude
$\Omega$ must increase by 6.5 orders of magnitude

Rotation of 1 per 25 days to once every 2 seconds
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- Stellar vibration/oscillation modes are too much too slow
- Pulsars are seen to slow down consistent with loss of rotational energy
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Magnetic flux is

$$M_{\text{flux}} = B \cdot A = B \cdot (4\pi R^2)$$

$B$ is the magnetic field strength and $A$ is the surface area of the star, $A = 4\pi R^2$

We saw already, as the star collapses:

$R^2$ shrinks by 6.5 orders of magnitude

To conserve $M_{\text{flux}}$, $B$ must increase by ~6.5 orders of magnitude

$B$ grows from $3\times10^5$ Gauss in the core to $1\times10^{12}$ Gauss
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- Material which falls on to a neutron star from a companion can undergo thermonuclear reaction leading to an x-ray burst
- Cyclotron resonance absorption lines in the x-ray spectra have been measured in several pulsars
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- $30$ keV indicates that the B field is $\sim10^{12}$ Gauss
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Balance centrifugal and gravitational force:

$$\Omega^2 r = \frac{GM}{r^2}$$

$$P = \frac{2\pi}{\Omega}$$

$$r = 1.5 \times 10^3 \left( \frac{M}{M_{\text{sun}}} \right)^{1/3} P^{2/3} \text{ km}$$

- $M = 1.4 \ M_{\text{sun}}$
- $P = 1.395$ milliseconds (PSR J1748-2446ad)
- [716 Hz]

$\rightarrow r = 21 \text{ km}$

- If $r > 21$ km this object would fragment and fall apart
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$\Omega^2 = \frac{GM}{r^2}$

\[ \frac{P}{2\pi} = \sqrt{\frac{GM}{r^2}} \]

\[ \frac{P^2}{4\pi^2} = \frac{GM}{r^3} \]

\[ \frac{GM}{r^3} = \frac{4\pi^2}{P^2} \]

\[ r = \sqrt[3]{\frac{GM}{\frac{4\pi^2}{P^2}}} \]

\[ r = \left( \frac{GM}{\frac{4\pi^2}{P^2}} \right)^{1/3} \]

\[ r = \left( \frac{1.4 \ M_{\text{sun}} \times 4\pi^2 \times 10^{46}}{1.395 \times 10^{-3} \text{ s}^2} \right)^{1/3} \]

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Jason Hessels
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- As photons emerge from the deep gravitational well they are red-shifted
- In a handful of cases red-shifted Iron ionization lines have been measured.
- From these one can measure the Mass to Radius ratio. Putting in Mass = 1.4 $M_{\text{sun}}$

  $\rightarrow$ Radius = 11.4 km
  $\rightarrow$ Diameter = 22.8 Km
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Discovery of the neutron in 1932 (Nobel Prize in 1935)

In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons
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Discovery of the neutron in 1932 (Nobel Prize in 1935)

Walter Baade

Fritz Zwicky

James Chadwick

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington
Fornia Institute of Technology, Pasadena

Communicated March 19, 1934

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The Discovery of Pulsars - 1967

PhD student, Jocelyn Bell, from Belfast Northern Ireland and her adviser Tony Hewish built the “4-acre” array in Cambridge (completed July 1967).

- Comprised of 2048 dipole antennas
- Bell: “By the end of my PhD I could swing a sledgehammer.”
- Transit telescope used to study scintillation of radio galaxies

In August, Bell pointed out an anomalous fluctuating source which looked like terrestrial noise.
The Discovery of Pulsars - 1967

- Signal looked like RF-noise from a car motor or an electric fence.
- Hewish dismissed it as terrestrial interference.
- Bell diligently poured over all the readings and noticed the signal appeared about the same time every night (like an astronomical signal).
First Ever Recording of Pulsar (1967)

Centre trace shows pulsed nature of emission
The Discovery of Pulsars - 1967

• Hewish (In his 1974 Nobel Prize address):

“To my astonishment the readings fell in a regular pattern, to within the observational uncertainty of 0.1s, showing that the pulsed source kept time to better than 1 part in $10^6$.”

“I could not believe that any natural source would radiate in this fashion and I immediately consulted astronomical colleagues at other observatories to inquire whether they had any equipment in operation which might possibly generate electrical interference at a sidereal time near 19h 19 m.”

“Having found no satisfactory terrestrial explanation for the pulses we now began to believe that they could only be generated by some source far beyond the solar system, and the short duration of each pulse suggested that the radiator could not be larger than a small planet. We had to face the possibility that the signals were, indeed, generated on a planet circling some distant star, and that they were artificial. I knew that timing measurements, if continued for a few weeks, would reveal any orbital motion of the source as a Doppler shift, and I felt compelled to maintain a curtain of silence until this result was known with some certainty. Without doubt, those weeks in December 1967 were the most exciting in my life.”
The Discovery of Pulsars - 1967

- They did find a Doppler shift modulation in the data – one entirely consistent with the Earth’s motion around the sun. That convinced Hewish and Bell that the signal was not made by extra terrestrials. They published their historic paper:
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**Observation of a Rapidly Pulsating Radio Source**

by

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P. F. SCOTT  
R. A. COLLINS

Mullard Radio Astronomy Observatory,  
Cavendish Laboratory,  
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

NATURE, VOL. 217, FEBRUARY 24, 1968
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NATURE, VOL. 217, FEBRUARY 24, 1968

• Shortly before they submitted their paper they discovered a second pulsar. Bell: “I switched on the high speed recorder and it came blip.... blip.... blip.... blip.... blip.... Clearly the same family, the same sort of stuff and that was great, that was really sweet. It finally scotched the little green men hypothesis cos it's highly unlikely there's two lots of little green men, opposite sides of the universe, both deciding to signal to a rather inconspicuous planet earth, at the same time, using a daft technique and a rather common place frequency. It has to be some new kind of star, not seen before, and that then cleared the way for us publishing, going public!”
The Discovery of Pulsars - 1967

- Anthony Hewish and Martin Ryle won the Nobel Prize in physics in 1975 - “for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars”.

- The exclusion of Bell from the prize has been a point of controversy.
Introduction to the series

- April 4th: Setting the Stage
- April 11th: From Death Comes New Life
- April 18th: How the Lighthouse Shines
- April 25th: Pulsars Meet Einstein
- May 2nd: Weirdos (RRATs, Giant Pulses, Magnetars and more)
- May 9th: The Gamma-ray Pulsar Revolution
- May 16th: What's Hot Right Now
- May 30th: Building a Gravitational Wave Observatory from Pulsars
- June 6th: Hunting for Gravitational Waves with LIGO