Pulsars

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17.11.2008
Outline

1. History

2. Basics
   - Neutron Stars
   - Pulsars

3. Radio Pulsars
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   - Emission Models

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The discovery of pulsars

- 1967: discovery by S. Jocelyn Bell-Burnell and Antony Hewish
- Nobel Prize for Physics in 1974 awarded to A. Hewish and M. Ryle 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”

Fig. 1: J. Bell-Burnell at IAU 2006 Assembly
Observation of a Rapidly Pulsating Radio Source

by

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In July 1967, a large radio telescope operating at a frequency of 81·5 MHz was brought into use at the Mullard Radio Astronomy Observatory. This instrument was designed to investigate the angular structure of compact radio sources by observing the scintillation caused by the irregular structure of the interplanetary medium. The initial survey includes the whole sky in the declination range $-68^\circ < \delta < 44^\circ$ and this area is scanned once a week. A large fraction of the sky is thus under regular surveillance. Soon after the instrument was brought into operation it was noticed that signals which appeared at first to be weak sporadic interference were repeatedly of three others having remarkably similar properties which suggests that this type of source may be relatively common at a low flux density. A tentative explanation of these unusual sources in terms of the stable oscillations of white dwarf or neutron stars is proposed.

Position and Flux Density

The array consists of a rectangular array containing 2,048 full-wave dipoles arranged in sixteen rows of 128 elements. Each row is 470 m long in an E.-W. direction and the N.-S. extent of the array is 45 m. Phase-scanning is employed to direct the reception pattern in declination and a time standard is used so that four different declinations
Repetition I - Properties

- formation via SNe Type II
- mass: $1.44 M_\odot < M \lesssim 3 M_\odot$
- density: $10^{14} \text{ g cm}^{-3}$
- size: 10 – 15 km
- very strong $B$-fields from $10^8$ G up to $10^{12}$ G
- conservation of angular momentum leads to fast rotation
Repetition II - Build-up

- outer crust: solid crust of heavy nuclei + relativistic degenerate electrons
- inner crust: nuclei + relativistic degenerate electrons + superfluid neutrons
- core: superfluid neutrons + a few superfluid, superconducting protons + relativistic degenerate electrons (perhaps solid core consisting of sub-nuclear particles)

Fig. 2: Neutron Star Structure
What’s it that makes a pulsar out of a NS?

Fig. 3: Lighthouse Model
The Pulsar Zoo

2 types:

- **accretion powered pulsars:**
  - energy supply via accretion
  - millisecond pulsars
  - spin behavior not always the same

- **rotation powered pulsars (radio pulsars):**
  - rotational energy is used
  - slow down
  - magnetars
Advanced Basics I

- total available energy for a rotation-powered pulsar = loss of rotational energy

\[ \dot{E} = I \omega \dot{\omega} = 4\pi^2 I (\dot{P}/P^3) \]  

(1)

with \( I \approx 10^{45} \text{ g cm}^2 \)

- dipolar magnetic fields:

\[ B = 3.2 \times 10^{19} (P \dot{P})^{0.5} \text{ G} \]  

(2)

(on the equator)
Advanced Basics II

Fig. 4: $P - \dot{P}$-diagram for non-binary pulsars with radio emission
Advanced Basics III

Although generally slowing down pulsars sometimes spin up!⇒ can be used to probe the interior of neutron stars

Fig. 5: a small glitch of the Crab pulsar
Vela Pulsar

- distance: 0.5 kpc
- $P = 0.0893 \text{s}$
- $\dot{P} = 1.25 \cdot 10^{-13}$
- $B = 3 \cdot 10^{12} \text{ G}$
- $\dot{E} = 7 \cdot 10^{36} \text{ erg s}^{-1}$
- age: 11000 yrs

$\Rightarrow$ middle-aged pulsar

Fig. 6: Vela Pulsar in X-rays (Chandra)
Crab Pulsar

- distance: 2.0 kpc
- $P = 0.0334$ s
- $\dot{P} = 4.21 \cdot 10^{-13}$
- $B = 4 \cdot 10^{12}$ G
- $\dot{E} = 4 \cdot 10^{38}$ erg s$^{-1}$
- age: 1260 yrs
  $\Rightarrow$ young pulsar

Fig. 7: Crab Pulsar in X-rays (Chandra)
Pulse Profiles

Fig. 8: pulse profiles of the Crab pulsar
⇒ no phase shift

Fig. 9: pulse profiles of the Vela pulsar
⇒ phase shift
Pulsar Spectra I

Fig. 10: spectrum of the Crab pulsar

spectrum is made up from different parts:

\[ \text{total} = \text{nebula} + \text{pulsed} (+ \text{thermal}) \]
Pulsar Spectra II

Fig. 11: spectrum of the Vela pulsar
Emission models

Requirements

• must explain phase relation
• must explain pulse profiles
• produce light at all wavelengths
• must explain polarization
• ...

⇒ several models that differ in the geometry of the emitting regions
Goldreich-Julian I

Fig. 3: Lighthouse Model
Goldreich-Julian II

Fig. 12: neutron star magnetosphere
Polar Cap Model

- explains high-energy spectrum quite well
- cannot explain double-peaked pulses

Fig. 13: emission models
Outer Gap Model

- can explain double-peaked pulses but causes problems with some other parts of the pulse profile
- some problems with very high energy radiation

Fig. 13: emission models
Two-pole caustic model

- purely geometric idea: particles radiate along the last open field lines
- fundamentally new: outward emission below the null surface \( \Rightarrow \) emission from both poles can be observed
- physical explanation by the slot gap

Fig. 13: emission models
Comparison between models and measurements

Fig. 14: predicted profiles for different models

⇒ all models have strengths and weaknesses
Pulsars with Fermi

- emitting regions will be mapped
- better spectra + shape of cutoffs
- better pulse profiles
- ...

⇒ It will be much easier to determine the correct emission model!

Fig. 15: Fermi’s first light
References I

References II

Figures
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Figure 15: http://science.nasa.gov/headlines/y2008/26augfirstlight.htm

Audio

www.vega.org.uk
Thank you for your attention!
Questions???