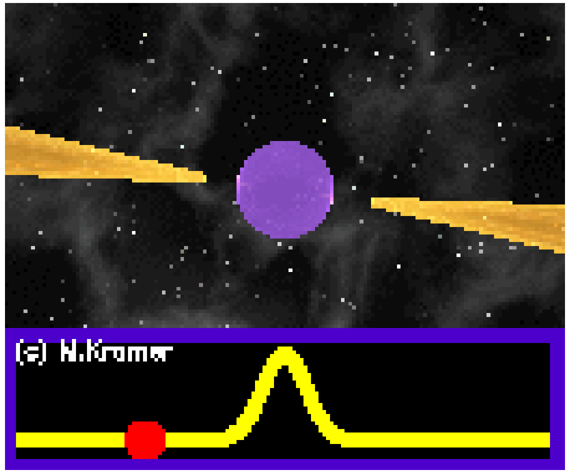
Pulsars and Supernovae II

1. DISCOVERY AND OVERVIEW

lighthouse model
interplanetary scintillation, Hewish & Bell
Nature letter
fundamental properties -- size, distance, luminosity, stability
energy supply
spin-down rates and magnetic dipole radiation
multi-wavelength observations
nomenclature

Lighthouse model

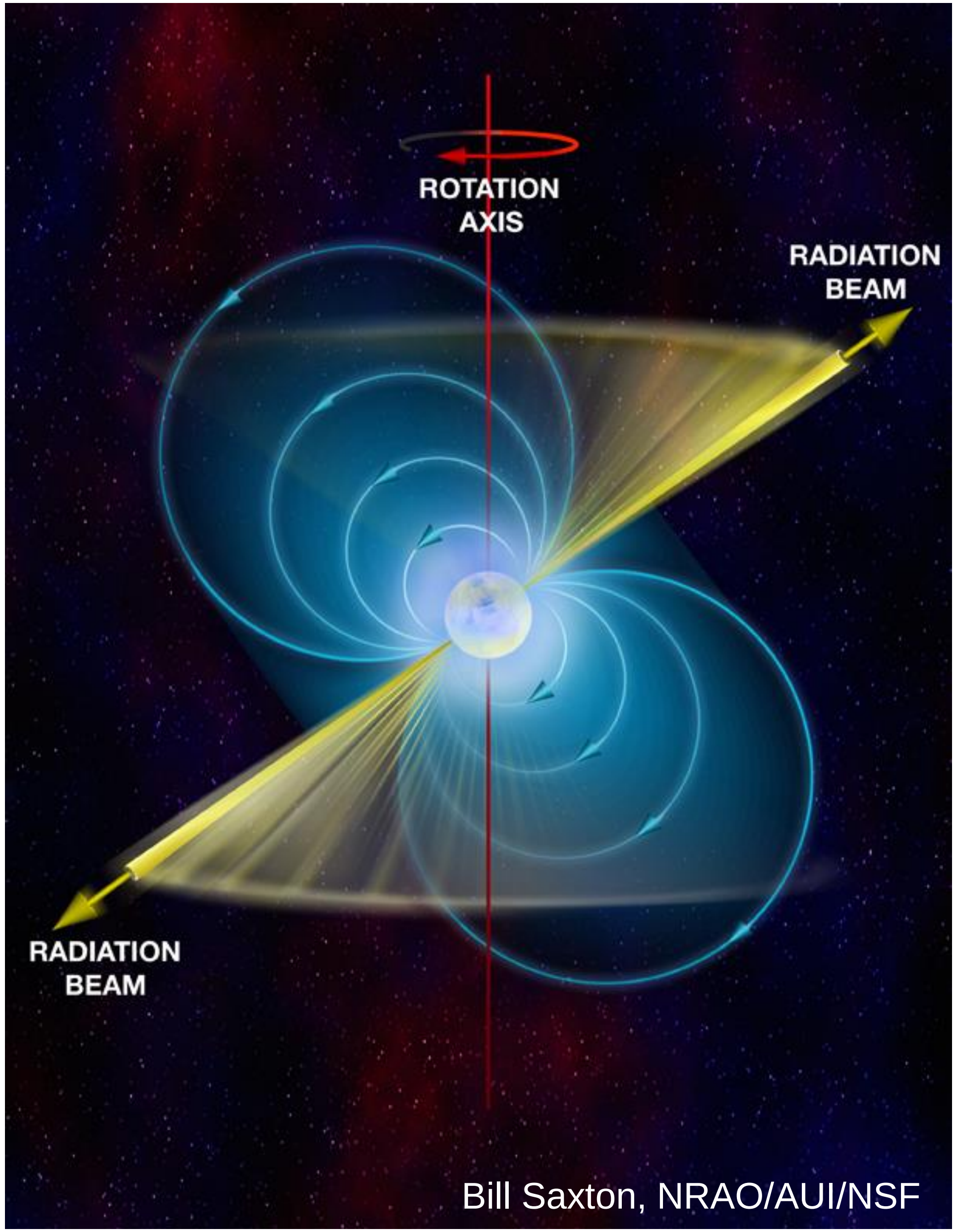
- A pulsar is a rapidly rotating neutron star with a beaming ‘hotspot’ on the surface. As the neutron star rotates the bright region may point towards us and we will see a flash, like a lighthouse:



- Radio emission is associated with a beam of radiation from the magnetic pole of the neutron star:

Lighthouse model

- An oblique rotator:



Bill Saxton, NRAO/AUI/NSF

Questions – a course outline

- Questions we will address:
  - How were pulsars discovered and what are the gross properties of radio pulsars?
  - How can pulsars be used as astrophysical tools?
  - How are the signals from pulsars distorted as they travel to Earth?
  - How do you search for and time pulsars?
  - How are pulsars distributed in the galaxy and what are the properties of the pulsar population?
  - How do pulsars radiate?
  - How were pulsars formed, and what is their internal structure?
  - Why are there binary and millisecond pulsars?
  - How do various types of pulsar fit in to the grand picture of late stellar evolution?
  - What is so special about the Crab pulsar and PSR J0737-3039?

Discovery

- Pulsar were discovered accidentally in 1967. Tony Hewish and his research student Jocelyn Bell had constructed a large radio telescope, operating at 81.5 MHz, in Cambridge to measure short timescale (~1 s) variations in the flux densities of compact extragalactic radiogalaxies and quasars.

- These fluctuations, called interplanetary scintillation (IPS), are caused by the passage of the radio waves through the turbulent solar wind and depend critically on the angular size of the source (in the same way that stars twinkle optically due to turbulent air, whereas planets do not).

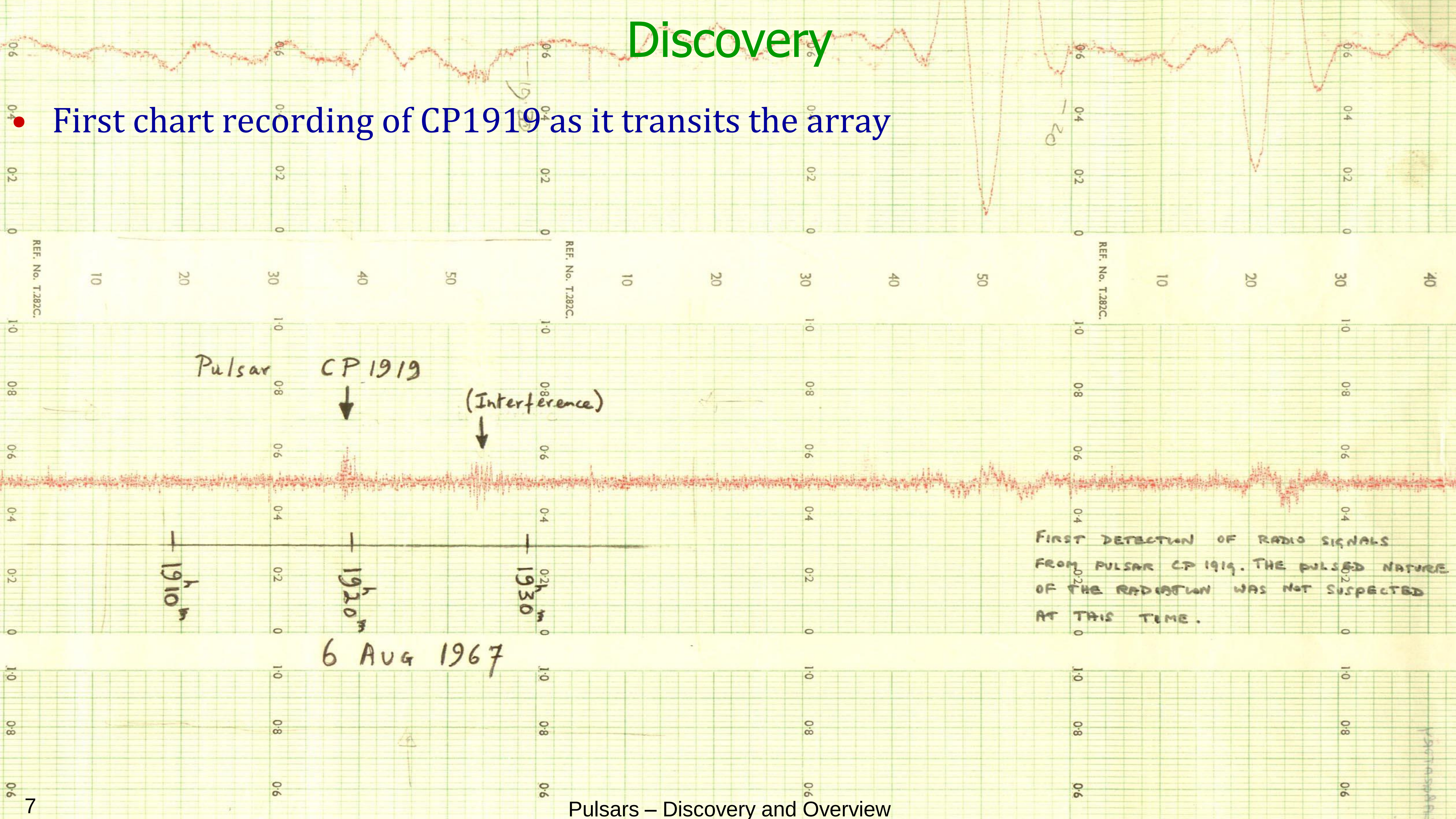
- IPS promised to give a measure of the cosmological distribution of radio galaxies and hence constrain models of galaxy formation.

- However, some of the fluctuating sources were clearly anomalous – galactic pulsars rather than scintillating galaxies!

Discovery – the 4 Acre Array

Discovery

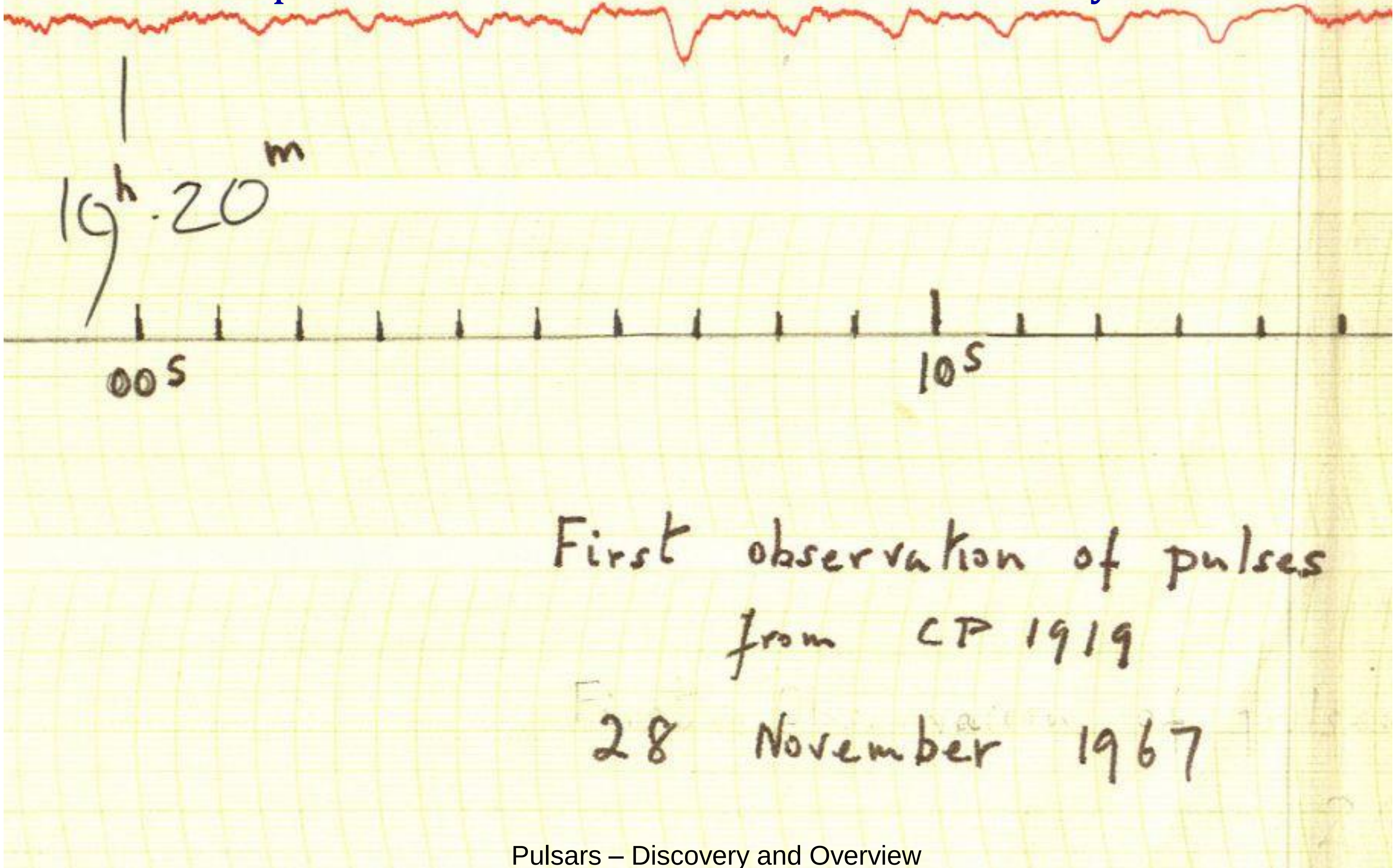
- First chart recording of CP1919 as it transits the array



FIRST DETECTION OF RADIO SIGNALS FROM PULSAR CP 1919. THE PULSED NATURE OF THE RADIATION WAS NOT SUSPECTED AT THIS TIME.

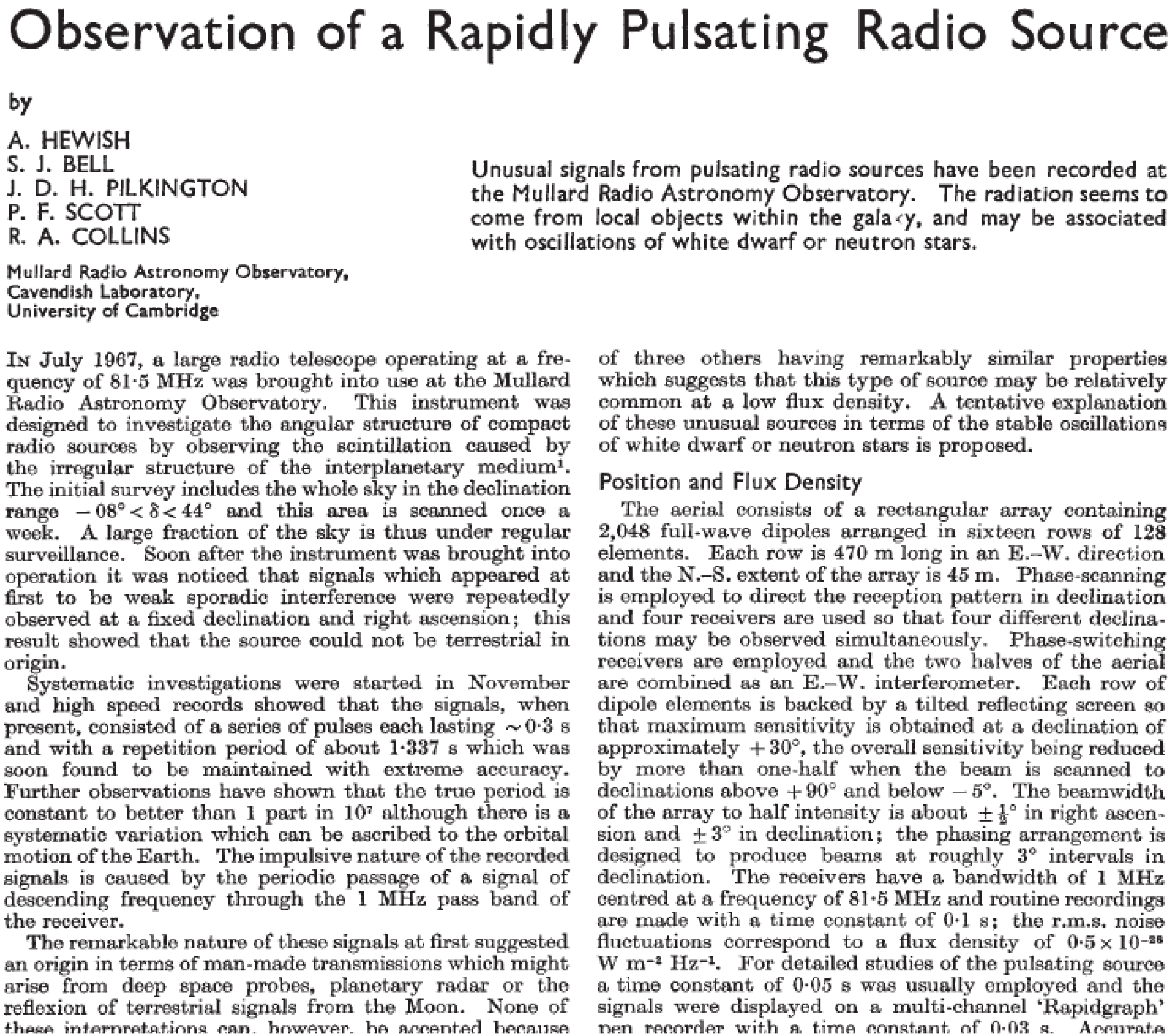
Discovery

- First observations of pulses from CP1919 as it transits the array



First observation of pulses
from CP 1919
28 November 1967

Nature letter – Feb 1968



Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
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.

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[1]. The initial survey includes the whole sky in the declination range $-08° < \delta < 44°$ 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 observed at a fixed declination and right ascension; this result showed that the source could not be terrestrial in origin.

Systematic investigations were started in November and high speed records showed that the signals, when present, consisted of a series of pulses each lasting ~0·3 s and with a repetition period of about 1·337 s which was soon found to be maintained with extreme accuracy. Further observations have shown that the true period is constant to better than 1 part in 10^7 although there is a systematic variation which can be ascribed to the orbital motion of the Earth. The impulsive nature of the recorded signals is caused by the periodic passage of a signal of descending frequency through the 1 MHz pass band of the receiver.

The remarkable nature of these signals at first suggested an origin in terms of man-made transmissions which might arise from deep space probes, planetary radar or the reflexion of terrestrial signals from the Moon. None of these interpretations can, however, be accepted because 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 aerial 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 four receivers are used so that four different declinations may be observed simultaneously. Phase-switching receivers are employed and the two halves of the aerial are combined as an E.–W. interferometer. Each row of dipole elements is backed by a tilted reflecting screen so that maximum sensitivity is obtained at a declination of approximately +30°, the overall sensitivity being reduced by more than one-half when the beam is scanned to declinations above +90° and below −5°. The beamwidth of the array to half intensity is about $\pm\frac{1}{2}°$ in right ascension and ±3° in declination; the phasing arrangement is designed to produce beams at roughly 3° intervals in declination. The receivers have a bandwidth of 1 MHz centred at a frequency of 81·5 MHz and routine recordings are made with a time constant of 0·1 s; the r.m.s. noise fluctuations correspond to a flux density of $0·5 \times 10^{-26}$ W m^{-2} Hz^{-1}. For detailed studies of the pulsating source a time constant of 0·05 s was usually employed and the signals were displayed on a multi-channel 'Rapidgraph' pen recorder with a time constant of 0·03 s. Accurate

Early deductions about pulsars (c1968)

- Pulse arrival times showed delays due to the Earth's position around the Sun, but no parallax effects. Therefore pulsars are far outside the solar system.

- Pulses appear to sweep through the radio band (-5 MHz/s for CP1919), indicating that they have been dispersed by the interstellar medium -- see later (lecture 3). The amount of dispersion indicates thay are probably local galactic objects.

- Pulses can be very bright. CP1919 showed peak flux densities of ~20 Jy.

- Pulses vary in strength – intrinsic variation or propagation effects (see later)?

Early deductions about pulsars (c1968)

- Pulsars are exceedingly regular clocks. CP1919 period was measured as 1.3372795+/- 0.000002 s, with the uncertainly due solely to the short time of observation since discovery

  (we now know period of PSR J1909-3744 to be 0.002947108021715178 s +/- 0.000000000000000002 s, a fractional accuracy better than 1 part in 10^{15}!)

- CP1919 pulses are shorter than 0.016 s, corresponding to a distance of ~5000 km at the speed of light. If the emitting region is linked causally, it must be smaller than this, so pulsars are physically small

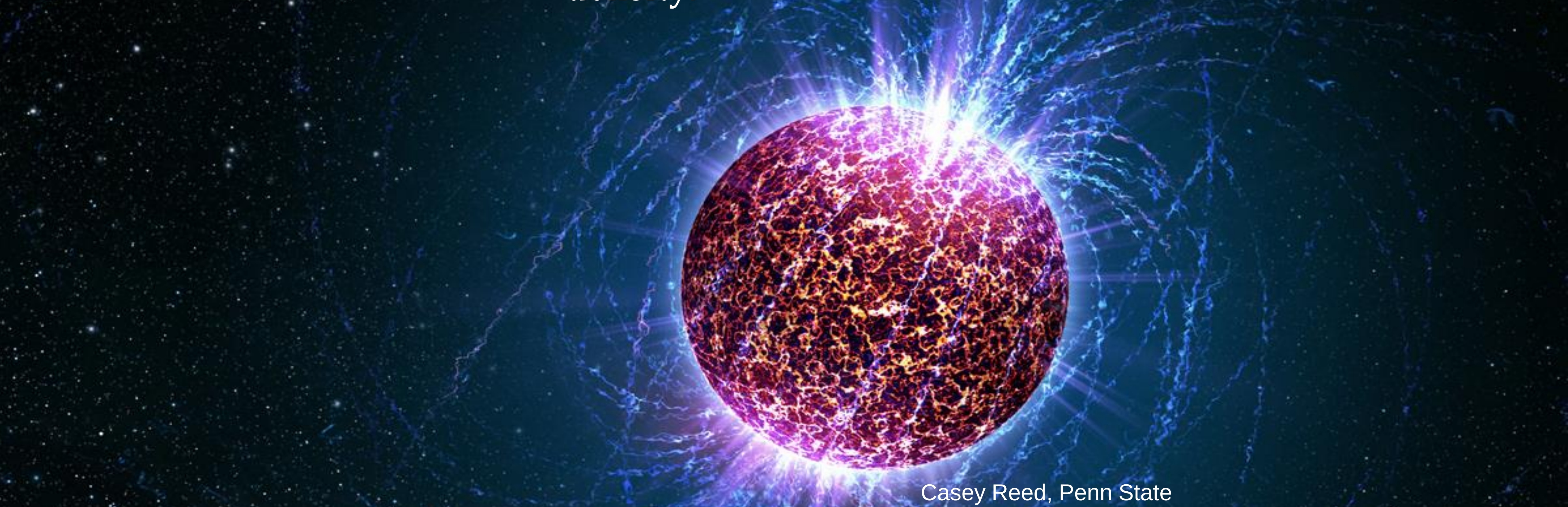
  (actually, the emitting region is now thought to be just a few tens of metres across!)

- Although early theories considered radial pulsations (cf. Cepheid variables) as the source of the signal, rather than the lighthouse effect, both imply very high densities for the object (~10^{16} kg/m^3) corresponding to a neutron star.

Neutron stars

- Baade & Zwicky, 1934:

“With all reserve we advance the view that a supernova represents the transition of an ordinary star into a new form of star, the ***neutron star***, which would be the end point of stellar evolution. Such a star may possess a very small radius and an extremely high density.”



Casey Reed, Penn State

Derived properties – brightness temperature

- Take CP1919 as the example:

Assuming a distance of 1 kpc and a size of 10 km, the solid angle is

$$\Omega_s \simeq \pi \left(\frac{5\ \mathrm{km}}{3 \times 10^{16} \mathrm{km}} \right)^2 = 8 \times 10^{-32}\ \mathrm{sr}$$

The brightness is

$$B = \frac{S}{\Omega_s} = \frac{20 \times 10^{-26}}{8 \times 10^{-32}} = 2 \times 10^{6}\ \ \mathrm{W\,m^{-2}Hz^{-1}sr^{-1}}$$

and brightness temperature is a whopping

$$T_\mathrm{b} = \frac{Bc^2}{2\nu^2 k_\mathrm{B}} = 10^{30}\ \mathrm{K}$$

- Note that the upper limit brightness temperature for incoherent electron synchrotron radiation set by inverse-Compton scattering is $\sim 10^{12}$ K. Something funny is going on…

Derived properties – density

- Size: take the fastest know pulsar, PSR J1748-2446ad in the globular cluster Terzan 5, period 0.00139595482 s (ie ~716 Hz!):

Mass M, radius R, rotation rate $\omega = \frac{2\pi}{P}$.

It will break up centrifugally if

$$\omega^2 R > \frac{GM}{R^2}$$

so for stability

$$P^2 > \frac{4\pi R^3}{3}\frac{3\pi}{GM}.$$

This constrains the mass density, ρ, to be

$$\rho > \frac{3\pi}{GP^2} = 7 \times 10^{16}\ \ \mathrm{kg\ m^{-3}}.$$

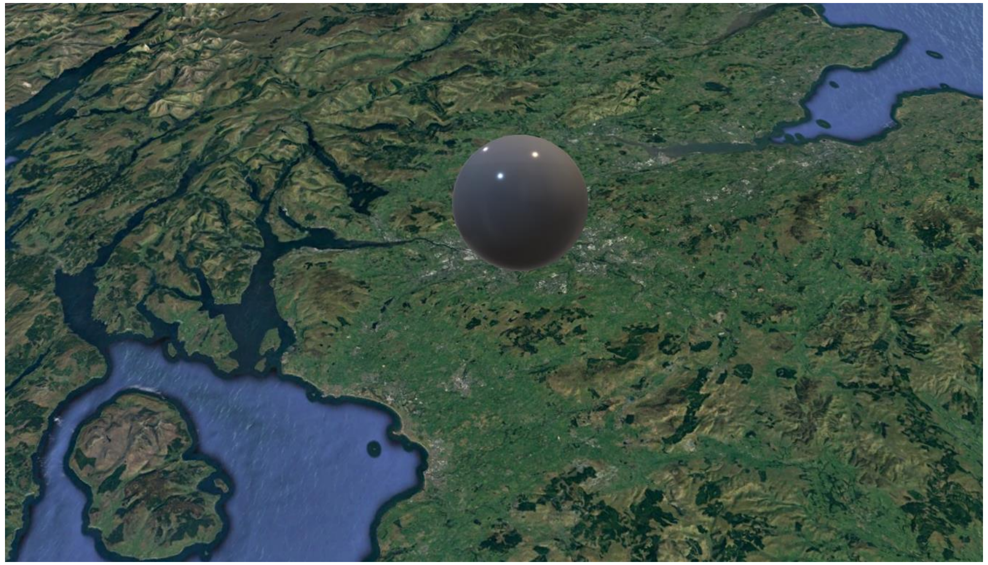
(70 kilotons per cubic millimetre)

Derived properties – size

- For a neutron star of mass $M = 1.4\ M_{\odot}$ this corresponds to a radius of

$$R < \left(\frac{3M}{4\pi\rho}\right)^{1/3} = 21\ \text{km}.$$

- So the pulse period and pulse width are both consistent with emission from or near the surface of a rapidly rotating neutron star, even for the shortest period pulsars.

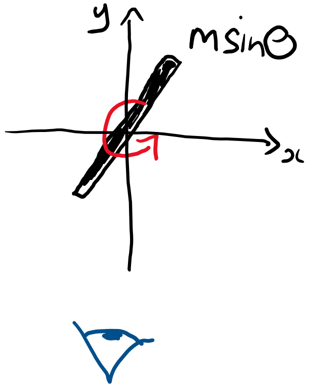


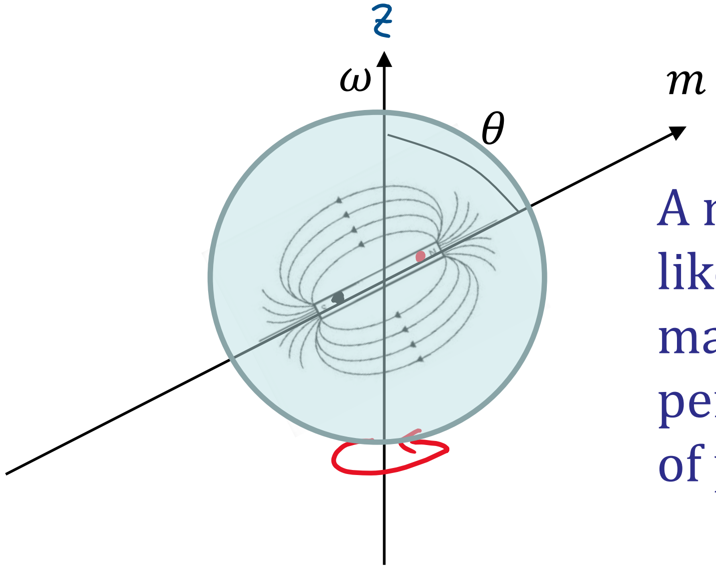
Derived properties – magnetic field

- We expect neutron stars to have strong magnetic fields – simple arguments, conserving flux during the collapse, indicate a Sun-like progenitor would result in a neutron star with $B \sim 10^8$ tesla. More sophisticated arguments boost this to 10^9 to 10^{11} T.

- We therefore have a rapidly rotating bar magnet. This will produce electromagnetic waves at the *rotation* frequency, due to magnetic dipole radiation.

From the top:





A rotating magnetic dipole m acts like two oscillating dipoles of magnitude $m\ \sin\theta$ in the plane perpendicular to ω, 90 degrees out of phase with each other.

Derived properties – dipole luminosity

- The neutron star will therefore generate very low frequency radio waves (at the rotation frequency) with luminosity

$$L = \frac{\mu_0 |\ddot{m}|^2 \sin^2\theta}{6\pi c^3}$$

$$= \frac{2\pi R^6 B_{\mathrm{p}}^2 \omega^4 \sin^2\theta}{3c^3 \mu_0}$$

This is the magnetic Lamor formula. Compare with $L = \frac{|\ddot{p}|^2}{6\pi\epsilon_0 c^3}$ for an oscillating electric dipole.

where B_{p} is the magnetic flux density at the pole of the neutron star and R is its radius. This is an important equation!

- These waves are by far the primary cause of energy loss from the rotating neutron star, but note they are NOT the radio signals we see – they are beneath the local plasma frequency and are strongly absorbed by the local interstellar medium.

Derived properties – radiation braking

- The only source of this energy is the rotational kinetic energy stored in the neutron star, moment of inertia I_{zz} :

$$E = \frac{1}{2} I_{zz} \omega^2$$

so that $L = -\dot{E} = -I_{zz}\omega\dot{\omega}$, (if I_{zz} is not changing).

- The radiation will therefore brake the pulsar, and it will spin down. If all the braking is from pure magnetic dipole radiation, then

$$I_{zz}\omega\dot{\omega} = \frac{2\pi R^6 B_{\mathrm{p}}^2 \omega^4 \sin^2\theta}{3c^3\mu_0}$$

and

$$\dot{\omega} = -\frac{2\pi R^6 B_{\mathrm{p}}^2 \sin^2\theta}{3c^3\mu_0 I_{zz}}\omega^3.$$

Derived properties – magnetic field

- Such pulsar should therefore have a “braking index” of

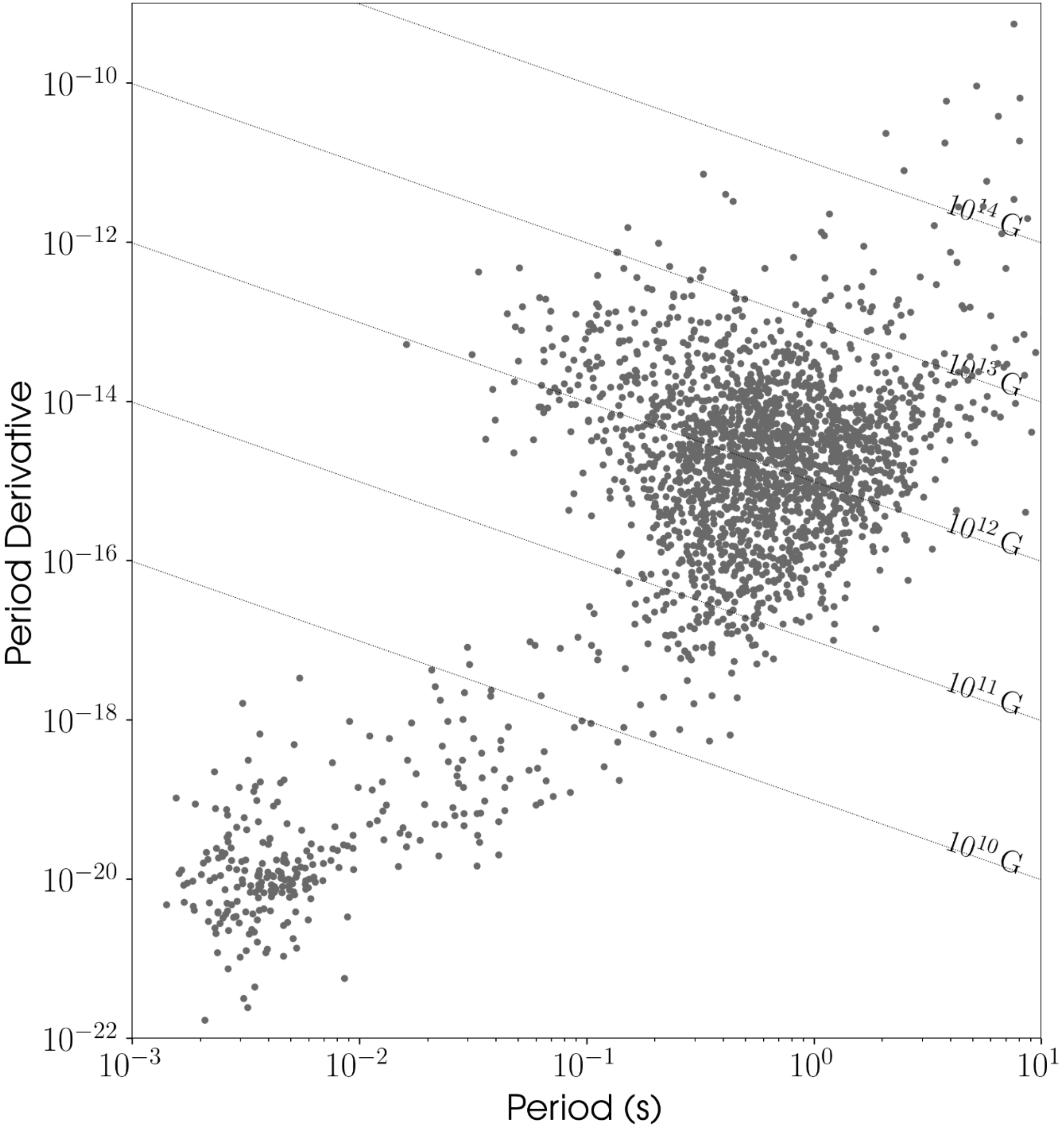
  $$n = 3, \qquad \text{where} \qquad \dot{\omega} \propto -\omega^{n}$$

  (note that n is rather hard to measure for any particular pulsar on a short timescale).

- Also if you make a reasonable guess at the moment of inertia, and radius, measurement of spin rate and spin-down give an estimate of the minimum magnetic field:

  $$B = 3.2 \times 10^{15} \left(P\dot{P}\right)^{1/2} \ \text{tesla}$$

Derived properties – magnetic field

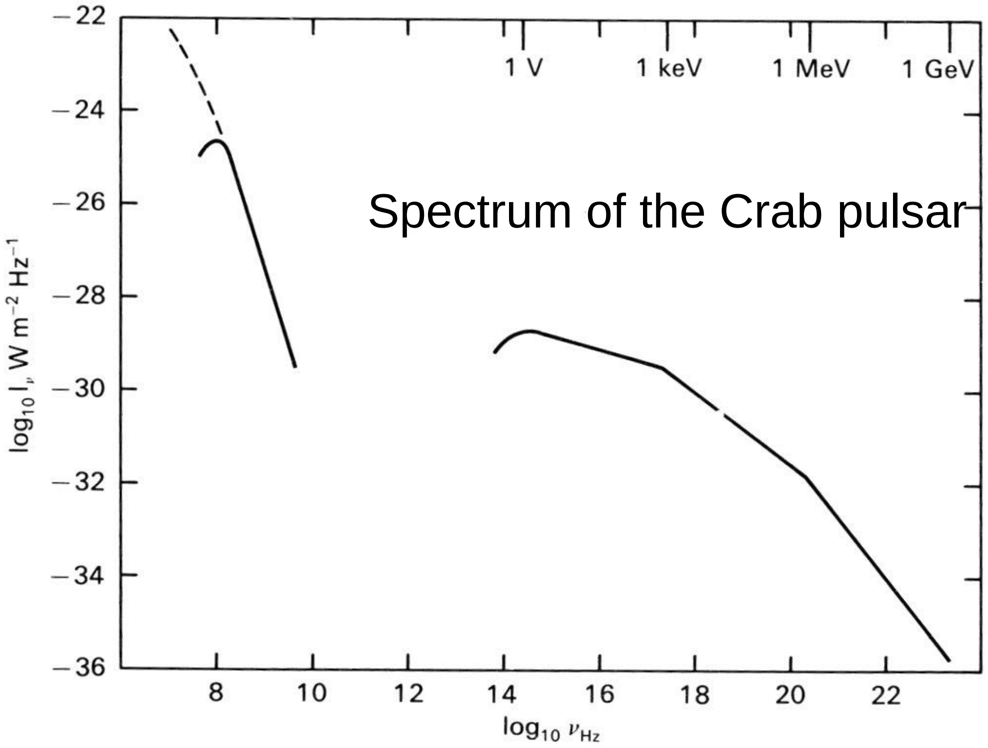


Magnetic fields can be read off a P-PDOT diagram (see later)

Note that 1 tesla = 10^4 Gauss

Pulsars at many wavelengths

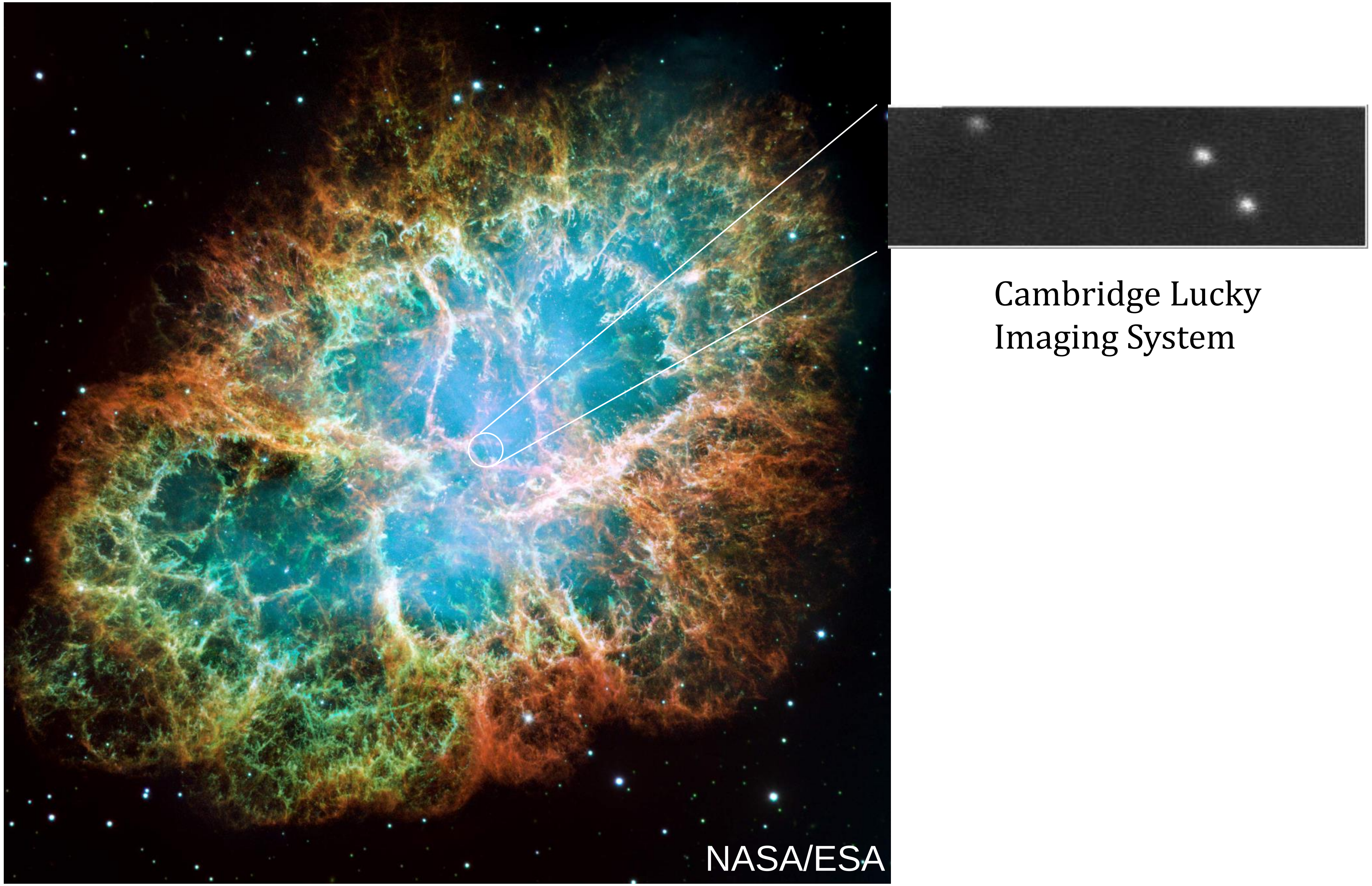
- Pulsars are seen at many wavelengths, not just radio, though the radiation mechanisms may differ.
- Radio pulsars are usually rotationally-powered, X-ray pulsars are usually accretion-powered, though some show complex emission over all wavelengths (see later!)



Spectrum of the Crab pulsar

Lyne & Graham-Smith

Crab nebula and pulsar – optical



NASA/ESA

Cambridge Lucky
Imaging System

Nomenclature

- Pulsars have always been named in terms of their position, so CP1919 was ‘Cambridge Pulsar at RA 19h 19m’, but prefixes like CP soon died out.

- Pulsars were then named in terms of their RA (hhmm) and declination (+/-dd), referred to a 1950 Besselian coordinate system, eg B1919+21. PSR is usually appended to the front, to indicate it is a pulsar: PSR B1919+21

- Precession (and redefinitions of coordinate systems) have meant that today pulsars are referred to the Julian epoch, with coordinates corrected to the year 2000, so PSR B1919+21 becomes PSR J1921+2153 (note the greater precision in dec).

- Names can therefore be confusing, with more than one name for the same object! Usually pulsars discovered before 1993 keep their ‘B’ names.