NASSP Hons programme

An Introduction to Pulsars

Marisa Geyer

Course layout

Lecture 1 *(30 Aug - 1hrs)*
Pulsar properties

Lecture 2 *(13 Sep - 30min)*
Pulsar observations and data analysis

Tutorial *(13 Sep - 30min)*
MeerKAT pulsar data

Course material

Much of what is discussed here comes from

1) NRAO 'Essential Radio Astronomy' course at:
https://science.nrao.edu/opportunities/courses/era

2) Handbook of Pulsar Astronomy by Lorimer and Kramer

3) Additional/similar material can be found on
- SARAO Web YouTube channel
- SARAO E-learning platform at
www.sarao.ac.za/e-learning-portal/

Course material

Much of what is discussed here comes from

1) NRAO 'Essential Radio Astronomy' course at:
https://science.nrao.edu/opportunities/courses/era

2) Handbook of Pulsar Astronomy by Lorimer and Kramer

3) Additional/similar material can be found on
- SARAO Web YouTube channel
- SARAO E-learning platform at
www.sarao.ac.za/e-learning-portal/

If you find typos or mistakes please get in touch!

Lecture 1 : Pulsar Properties

The topics we will cover

- The discovery of CP1919
- The minimum density spinning object
- How pulsars are born
- The interior of a neutron star
- Neutron star radius and masses
- Standard pulsar model
- NS magnetic field
- Magnetic dipole radiation
- NS Rotational energy and loss of rotational energy
- Characteristic age
- The Pulsar radio population (P-Pdot diagram)

The Discovery of CP1919

- One of the great serendipitous discoveries in astronomy
- In the 1960s Jocelyn Bell-Burnell (then a PhD student at Cambridge Uni) was helping to build a new radio telescope in Cambridge
- The real aim of the experiment was to find extra galactic compact radio sources that scintillate in the interplanetary plasma
- In 1967 she noticed some ‘scruffy’ pulses in the chart recordings.

Image credit: University of Cambridge

The Discovery of CP1919

- One of the great serendipitous discoveries in astronomy
- In the 1960s Jocelyn Bell-Burnell (then a PhD student at Cambridge Uni) was helping to build a new radio telescope in Cambridge
- The real aim of the experiment was to find extra galactic compact radio sources that scintillate in the interplanetary plasma
- In 1967 she noticed some ‘scruffy’ pulses in the chart recordings.

Image credit: University of Cambridge

The Discovery of CP1919

- The data were recorded using pen charts
- By running the chart recorder at a higher speed Jocelyn Bell-Burnell was able to separate the ‘scruff’ into distinguishable pulses
- The pulses appeared to have a period of 1.337s
- They seemed oddly ‘man made’ — but they appeared to keep sidereal time, so it could not be terrestrial
- Perhaps it was signatures from LGM: ‘little green men’

CP1919 - Could it be a spinning star?

- Pulses with period P = 1.33s
- Can this be a spinning star?
- The fastest a star can spin is set by the limit that

centrifugal acceleration (at the equator) < gravitational acceleration

$$\Omega^2 R < \frac{GM}{R^2}$$

Density of sphere — (1)

$$\rho = \frac{M}{V_{sphere}} = M\left(\frac{4}{3}\pi R^3\right)^{-1}$$

Angular velocity — (2)

$$\Omega = 2\pi/P$$

CP1919 minimum stellar density

- Pulses with period P = 1.33s
- Can this be a spinning star?
- The fastest a star can spin is set by the limit that

centrifugal acceleration (at the equator) < gravitational acceleration

$$\Omega^2 R < \frac{GM}{R^2}$$

Density of sphere — (1)

$$\rho = \frac{M}{V_{sphere}} = M\left(\frac{4}{3}\pi R^3\right)^{-1}$$

Angular velocity — (2)

$$\Omega = 2\pi/P$$

Rewriting i.t.o stellar density using (1) and (2):

$$\rho > \frac{3\pi}{P^2 G}$$

So, from only measuring the pulse period, we already have an estimate of the lower density limit density of the 'spinning object'

CP1919 minimum stellar density

- Pulses with period P = 1.33s
- The minimum density estimate of the spinning object:

$$\rho > \frac{3\pi}{P^2 G}$$

G ~ 6.67 × 10^{-11} m^3 kg^{-1} s^{-2}

$$\rho > \frac{3\pi}{(1.33s)^2\, 6.67 \times 10^{-11} \mathrm{m}^3 \mathrm{kg}^{-1} \mathrm{s}^{-2}}$$

$$\rho \gtrsim 8 \times 10^{10}\, \mathrm{kg\, m^{-3}}$$

P = 1.33 s

https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect19/lecture19.html

CP1919 minimum stellar density

- Pulses with period P = 1.33s
- The minimum density estimate of the spinning object:

$$\rho > \frac{3\pi}{P^2 G}$$

G ~ 6.67 × 10^{-11} m^3 kg^{-1} s^{-2}

$$\rho \gtrsim 8 \times 10^{10}\,\mathrm{kg\,m^{-3}}$$

P = 1.33 s

White dwarf density lies between 10^7 and 10^{11} kg m^{-3}

This means CP1919 was just within the white dwarf limit: could it be a white dwarf?

Discovery of the Crab pulsar

- Several pulsars were discovered shortly after CP1919
- Amongst them the Crab pulsar (PSR B0531+21) in 1968, associated with the Supernova remnant SN 1054
- With a spin period P = 0.033s (33ms), the Crab pulsar has a minimum density of

$$\rho > \frac{3\pi}{(0.033s)^2\, 6.67 \times 10^{-11} \mathrm{m}^3 \mathrm{kg}^{-1} \mathrm{s}^{-2}}$$

$$\rho \gtrsim 1.3 \times 10^{14}\, \mathrm{kg\, m}^{-3}$$

Too dense for a white dwarf, but …

Discovery of the Crab pulsar

- Several pulsars were discovered shortly after CP1919
- Amongst them the Crab pulsar (PSR B0531+21) in 1968, associated with the Supernova remnant SN 1054
- With a spin period P = 0.033s (33ms), the Crab pulsar has a minimum density of

$$\rho > \frac{3\pi}{(0.033s)^2\, 6.67 \times 10^{-11} \mathrm{m}^3 \mathrm{kg}^{-1} \mathrm{s}^{-2}}$$

$$\rho \gtrsim 1.3 \times 10^{14}\, \mathrm{kg\, m}^{-3}$$

Too dense for a white dwarf, but …fitted the theoretical description proposed by Baade and Zwicky 1934 of a ‘neutron star’ born through a supernova

Baade and Zwicky 1934

Baade and Zwicky published two papers in 1934 - back to back in PNAS (Proceedings of National Academy of Sciences):

“On Super-novae” and “Cosmic Rays from Super-novae”, in which they

1) compute the mass radiated away during a SNe:

“therefore it becomes evident that the phenomenon of a super-nova represents the transition of an ordinary star into a body of considerably smaller mass.”

2) and in the “additional remarks” section propose

"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”

Walter Baade

Fritz Zwicky

How Pulsars are born

Depending on a star's mass, it will end its life differently — the most massive ones (> 60 M_{sun}) will collapse to black holes,

While the intermediate ones (10 - 40 M_{sun}) will end their lives collapsing to a dense core, stopped only by neutron degeneracy pressure.

Forming dense corpses (neutron stars) with radius ~10km and masses ~1.4 M_{sun}

In the rebound shock the outer gas shells are flung out in a spectacular supernova explosion

EXTREME dead stars

- spin around their axis at up to 700 times a second
- ~10x nuclear densities
- magnetic fields > a trillion times that of Earth

How Pulsars are born

Depending on a star's mass, it will end its life differently — the most massive ones (> 60 M_{sun}) will collapse to black holes,

While the intermediate ones (10 - 40 M_{sun}) will end their lives collapsing to a dense core, stopped only by neutron degeneracy pressure.

Forming dense corpses (neutron stars) with radius ~10km and masses ~1.4 M_{sun}

In the rebound shock the outer gas shells are flung out in a spectacular supernova explosion

EXTREME dead stars

- spin around their axis at up to 700 times a second
- ~10x nuclear densities
- magnetic fields > a trillion times that of Earth

Object 4 times the height of Mt Kili, whizzing like a kitchen blender!

What's inside?

- The NS that remains is typically an order of magnitude more dense than nuclear matter. This provides a highly exotic environment beyond the scope of lab experiments on Earth.

- Various models exist for what exactly the core of the NS is made of including hyperon or boson condensates or free quarks. Many of these models are struggling to explain observations of NS > 2 M_{sun}.

- An exact model for the equation of state (EOS, that relates the density, mass and radius of neutron stars) remains an area of intensive research

What's inside?

- The NS that remains is typically an order of magnitude more dense than nuclear matter. This provides a highly exotic environment beyond the scope of lab experiments on Earth.

- Various models exist for what exactly the core of the NS is made of including hyperon or boson condensates or free quarks. Many of these models are struggling to explain observations of NS > 2 M_{sun}.

- An exact model for the equation of state (EOS, that relates the density, mass and radius of neutron stars) remains an area of intensive research

"nuclear goo" - prof Anna Watts

Limits on neutron star radius and mass

Credit: Joeri van Leeuwen

The fastest known pulsar

- The fastest known pulsar was discovered in 2004 in the globular cluster (GC) known as Terzan 5
- Q: Do you think GCs are good habitats for pulsars?
- PSRJ1748-2446ad spins at 716 Hz!
- Q: what is its minimum density? $\rho > \frac{3\pi}{P^2 G}$

Limits on neutron star radius and mass

Credit: Joeri van Leeuwen

The fastest known pulsar

- The fastest known pulsar was discovered in 2004 in the globular cluster (GC) known as Terzan 5

- Q: Do you think GCs are good habitats for pulsars?

- PSRJ1748-2446ad spins at 716 Hz!

- Q: what is its minimum density? $\rho > \frac{3\pi}{P^2 G}$

P = 1/716 s^{-1} ~ 0.0014 s

G ~ 6.67 × 10^{-11} $m^3 kg^{-1} s^{-2}$

$$\sim 7.2 \times 10^{16}\,\mathrm{kg\ m^{-3}}$$

Neutron star radius limit

Recall that the largest mass at which a white dwarf can be stable is the Chandrasekhar limit.

At this limit the star is supported by outward electron degeneracy pressure

$$M_{\mathrm{Ch}} \sim \left(\frac{\hbar c}{G}\right)^{3/2} \frac{1}{m_{\mathrm{p}}^2} \approx 1.4 M_{\odot}$$

A more massive star will collapse to a neutron star — supported through neutron degeneracy pressure

Again from the simplified definition of density:

$$\rho = \frac{M}{V_{sphere}} = M\left(\frac{4}{3}\pi R^3\right)^{-1} \rightarrow R < \left(\frac{3\,M}{4\,\pi\rho}\right)^{1/3}$$

Subrahmanyan Chandrasekhar (born 1910)

Source: Chandra X-ray Observatory

Neutron star radius limit

Recall that the largest mass at which a white dwarf can be stable is the Chandrasekhar limit.

At this limit the star is supported by outward electron degeneracy pressure

$$M_{\mathrm{Ch}} \sim \left(\frac{\hbar c}{G}\right)^{3/2} \frac{1}{m_{\mathrm{p}}^2} \approx 1.4 M_{\odot}$$

Subrahmanyan Chandrasekhar (born 1910)
Source: Chandra X-ray Observatory

A more massive star will collapse to a neutron star — supported through neutron degeneracy pressure

Again from the simplified definition of density:

Estimated mass, using White Dwarf limit

$$\rho = \frac{M}{V_{sphere}} = M\left(\frac{4}{3}\pi R^3\right)^{-1} \rightarrow R < \left(\frac{3\,M}{4\,\pi\rho}\right)^{1/3} \lesssim 20\,\mathrm{km}$$

$$\sim 7.2 \times 10^{16}\,\mathrm{kg\ m^{-3}}$$

Highest estimated density

Standard pulsar parameters are often considered to be R ~ 10km and mass ~ 1.4 Msun, though as detections of these parameters improve larger deviations are measured.

Measured masses

Credit: Venkatraman Krishnan

- The masses of pulsars in binary systems can be measured with high degree of accuracy through pulsar timing (see more in Lecture 2)
- Wide distribution of masses have been measured, and are continuously added to
- Website that keeps good track of these: https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html
- Mass measurements of heavy NS are used to constrain the EOS

Constraining the EOS

Mass measurements of these 3 pulsars have already ruled out EOS models that lie beneath these measured mass values.

Causality limit: the speed of sound in dense matter is less than the speed of light.

Figure by Norbert Wex

- The NS "equation of state" (EOS) aims to relate the density, mass and radius of neutron stars in a mathematical description
- No single conclusive EOS yet, but many models

Constraining the EOS

Animation created from figures by Norbert Wex

- The NS "equation of state" (EOS) aims to relate the density, mass and radius of neutron stars in a mathematical description
- No single conclusive EOS yet, but many models
- With each new NS mass observation one more theoretical model could potentially be ruled out, leaving only a last few standing
- This is partly why pulsar astronomers are so keen on accurate new massive NS mass measurements

Pinning down the radius - NICER
The Neutron Star Interior Composition ExploreR

Anna Watts (Nov 2023) | https://www.youtube.com/watch?v=shRtAEE47fE

Pulsars: beamed beacons of the sky

Beamed neutron stars are observed as pulsars

- dead stellar cores - but not observationally dead
- radio beams emitted from magnetic poles
- with the correct alignment, these sweep our line to produce a pulse
- Neutron stars observed in this way are called “pulsars”
- We can only see the pulsars for which the emission cuts our line of sight. This is greatly dependent on the orientation of the pulsar in the sky.
- We estimate that approximately 10% of all pulsars are beamed in Earth’s direction and therefore potentially observable to us.

by Joeri von Leeuwen

Pulsars: beamed beacons of the sky

Beamed neutron stars are observed as pulsars

- dead stellar cores - but not observationally dead
- radio beams emitted from magnetic poles
- with the correct alignment, these sweep our line to produce a pulse
- Neutron stars observed in this way are called “pulsars”
- We can only see the pulsars for which the emission cuts our line of sight. This is greatly dependent on the orientation of the pulsar in the sky.
- We estimate that approximately 10% of all pulsars are beamed in Earth’s direction and therefore potentially observable to us.

by Joeri von Leeuwen

Standard pulsar model

The misalignment between the spin axis and the magnetic axis allow us to see the pulses sweep across our line of sight (like a lighthouse).

Radio emission beamed along the open magnetic field lines, in the standard pulsar model the beam is considered to be cone-shaped.

The magnetic field lines transition from closed field lines to open field lines at the pulsar's "light cylinder radius".

The pulsar magnetosphere is associated with the closed magnetic field lines

Light cylinder radius, is the radius beyond which material in the magnetosphere would have to travel faster than the speed of light to co-rotate with the pulsar.

This standard model fits many pulsar observational properties well, but
- the details of the emission mechanism
- and the beam shape is not yet well understood for all pulsars

A counter example: PSR J0030+0451

Anna Watts | https://www.youtube.com/watch?v=shRtAEE47fE

NICER'S FIRST SURFACE MAP

NICER team J0030 papers
Data and supporting analysis (Bogdanov et al. 2019a,b, 2021);
X-PSI analysis group (Riley et al. 2019, Raaijmakers et al.19, Bilous et al. 2019);
Maryland-Illinois analysis group (Miller et al. 2019).

NICER'S FIRST SURFACE MAP

NICER team J0030 papers
Data and supporting analysis (Bogdanov et al. 2019a,b, 2021);
X-PSI analysis group (Riley et al. 2019, Raaijmakers et al.19, Bilous et al. 2019);
Maryland-Illinois analysis group (Miller et al. 2019).

NON-DIPOLAR MAGNETIC FIELD

Credit: NASA's Goddard Space Flight Center/Harding, Kalapotharakos, Wadiasingh.

Neutron star magnetic fields

NS progenitor stars (like most stars) possess dipolar magnetic fields

Let the progenitor star have a radius ~ 10^6 km. When it collapses to NS with R ~ 10 km, it means the surface is shrinking by a factor of ~ $(10^5)^2 = 10^{10}$

During the collapse the magnetic flux is conserved, and since the magnetic field scales with surface area, that means the magnetic field increases by a factor of 10^{10}!

Q: what are typical magnetic fields of massive stars?

Φ - Magnetic flux
$\vec{B}$ - Magnetic field
$\vec{A}$ - Area

Neutron star magnetic fields

NS progenitor stars (like most stars) possess dipolar magnetic fields

Let the progenitor star have a radius ~ 10^6 km. When it collapses to NS with R ~ 10 km, it means the surface is shrinking by a factor of ~ $(10^5)^2 = 10^{10}$

Φ - Magnetic flux
$\vec{B}$ - Magnetic field
$\vec{A}$ - Area

During the collapse the magnetic flux is conserved, and since the magnetic field scales with surface area, that means the magnetic field increases by a factor of 10^{10}!

Q: what are typical magnetic fields of massive stars?

The initial 100 Gauss magnetic field is scaled to become a NS field of 10^{12} G during collapse.

These strong NS magnetic fields accelerate particle cascades away from the NS surface at relativistic speeds, leading to coherent radio emission along the open magnetic field lines (the north and south pole of the pulsar)

Neutron star magnetic fields

NS progenitor stars (like most stars) possess dipolar magnetic fields

Let the progenitor star have a radius ~ 10^6 km. When it collapses to NS with R ~ 10 km, it means the surface is shrinking by a factor of ~ $(10^5)^2 = 10^{10}$

During the collapse the magnetic flux is conserved, and since the magnetic field scales with surface area, that means the magnetic field increases by a factor of 10^{10}!

Q: what are typical magnetic fields of massive stars?

The initial 100 Gauss magnetic field is scaled to become a NS field of 10^{12} G during collapse.

These strong NS magnetic fields accelerate particle cascades away from the NS surface at relativistic speeds, leading to coherent radio emission along the open magnetic field lines (the north and south pole of the pulsar)

Spinning down: magnetic dipolar radiation

- Pulsars are observed to spin down, in other words the period P is seen to slowly increase with time

$$\dot{P} = \frac{dP}{dt} > 0$$

- What causes it to slow down?

- A rotating magnetic dipole (inclined w.r.t the spin axis) emits radiation at the rotational frequency of the system.

$$P_{\rm rad} = \frac{2}{3c^3}(BR^3 \sin\alpha)^2 \left(\frac{2\pi}{P}\right)^4 \lesssim \frac{32\, B^2\, R^6\, \pi^4}{3c^3\, P^4} \qquad \text{[J/s = W]}$$

This dipole radiation extracts from the rotational energy of NS causing it to slow down.

- Q: What frequency is this magnetic dipole radiation?
- Q: For Lecture 2: does this emission propagate through the ISM?

Spinning down: magnetic dipolar radiation

- Pulsars are observed to spin down, in other words the period P is seen to slowly increase with time

$$\dot{P} = \frac{dP}{dt} > 0$$

- What causes it to slow down?

- A rotating magnetic dipole (inclined w.r.t the spin axis) emits radiation at the rotational frequency of the system.

$$P_{\rm rad} = \frac{2}{3c^3}(BR^3 \sin\alpha)^2 \left(\frac{2\pi}{P}\right)^4 \lesssim \frac{32\, B^2\, R^6\, \pi^4}{3c^3\, P^4} \qquad \text{[J/s = W]}$$

This dipole radiation extracts from the rotational energy of NS causing it to slow down.

- Q: What frequency is this magnetic dipole radiation?
- Q: For Lecture 2: does this emission propagate through the ISM?

Frequency = 1/P < 1 kHz

Spinning down: magnetic dipolar radiation

- Pulsars are observed to spin down, in other words the period P is seen to slowly increase with time

$$\dot{P} = \frac{dP}{dt} > 0$$

- What causes it to slow down?

- A rotating magnetic dipole (inclined w.r.t the spin axis) emits radiation at the rotational frequency of the system.

$$P_{\rm rad} = \frac{2}{3c^3}(BR^3 \sin\alpha)^2 \left(\frac{2\pi}{P}\right)^4 \lesssim \frac{32\, B^2\, R^6\, \pi^4}{3c^3\, P^4} \qquad \text{[J/s = W]}$$

This dipole radiation extracts from the rotational energy of NS causing it to slow down.

- Q: What frequency is this magnetic dipole radiation?
- Q: For Lecture 2: does this emission propagate through the ISM?

Frequency = 1/P < 1 kHz .. it does not propagate through the ISM.

Rotational energy

- Pulsars are observed to be spinning down with time —losing rotational energy
- We can estimate this rotational energy, and how it changes

- Rotational kinetic energy, E:

Angular velocity
$\Omega = 2\pi/P$

$$E = \frac{I\Omega^2}{2} = \frac{2\pi^2 I}{P^2}$$

Artwork by Sandbox Studio, Chicago with Corinne Mucha

Rotational energy

- Pulsars are observed to be spinning down with time —losing rotational energy
- We can estimate this rotational energy, and how it changes

- Rotational kinetic energy, E:

$$E = \frac{I\Omega^2}{2} = \frac{2\pi^2 I}{P^2}$$

Canonical moment of inertia

$$I = \frac{2\,M\,R^2}{5}$$

$$= \frac{2 \times 1.4 \times 1.98 \times 10^{30}\,\mathrm{kg} \times (10^4\mathrm{m})^2}{5}$$

$$= 1.1 \times 10^{38}\,\mathrm{kg\,m^2}$$

Rotational energy

- Pulsars are observed to be spinning down with time —losing rotational energy
- We can estimate this rotational energy, and how it changes

- Rotational kinetic energy, E:

$$E = \frac{I\Omega^2}{2} = \frac{2\pi^2 I}{P^2}$$

Moment of inertia

$$I = \frac{2MR^2}{5}$$

$$= \frac{2 \times 1.4 \times 1.98 \times 10^{30}\,\mathrm{kg} \times (10^4\mathrm{m})^2}{5}$$

$$= 1.1 \times 10^{38}\,\mathrm{kg\,m^2}$$

Pulse period (seconds)

- For a young pulsar like the Crab (in SN 1054) with P = 0.033 s, the rotational energy is:

$$E = \frac{2\pi^2 \times 1.1 \times 10^{38}\,\mathrm{kg\,m^2}}{(0.033\,\mathrm{s})^2} = 1.99 \times 10^{42}\,\mathrm{J}$$

Losing Rotational Energy

- From the observed changes in P we can estimate the loss in rotational energy.

$$\Omega = 2\pi/P$$

$$\dot{\Omega} = -\frac{2\pi\dot{P}}{P^2}$$

From: $$E = \frac{I\Omega^2}{2}$$

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = I\Omega\dot{\Omega}$$

$$\dot{E} = -\frac{4\pi^2 I\dot{P}}{P^3}$$

P Pulse period (seconds)

$\dot{P}$ Change in pulse period (seconds/seconds = unit-less)

Observables

Losing Rotational Energy

- From the observed changes in P we can estimate the loss in rotational energy.

$$\Omega = 2\pi/P$$

$$\dot{\Omega} = -\frac{2\pi\dot{P}}{P^2}$$

From: $$E = \frac{I\Omega^2}{2}$$

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = I\Omega\dot{\Omega}$$

$$\dot{E} = -\frac{4\pi^2 I\dot{P}}{P^3}$$

P Pulse period (seconds)

$\dot{P}$ Change in pulse period (seconds/seconds = unit-less)

Observables

Losing Rotational Energy: Crab pulsar

Solar Luminosity

$$L_\odot = 3.83 \times 10^{26}\, W$$

$$\dot{E}_{\rm Crab} = -\frac{4\pi^2 I\dot{P}}{P^3}$$

$$= \frac{4\,\pi^2 \times 1.1 \times 10^{38} \times 4.2 \times 10^{-13}}{(0.033)^3} W = 5 \times 10^{31} W \approx 10^5 L_\odot$$

The luminosity associated with this loss in rotational energy is comparable with the entire output of the Galaxy!

According to the standard pulsar model the bulk of this loss in rotational energy is due to the dipolar radiation we discussed.
The dipolar radiation (emitted at the spin frequency 1/P = 30Hz, or 10^7 m in wavelength) is absorbed by and heats up the surrounding Crab Nebula.

Interestingly only a small (insignificant) fraction of the loss in rotational energy is converted into radio emission.

Composite image of the Crab Nebula. Blue indicates X-rays (from Chandra), green is optical (from the HST), and red is radio (from the VLA).
Image credit: J. Hester (ASU), CXC, HST, NRAO, NSF, NASA.

Estimating Magnetic Field

- Assuming the loss rotational energy is entirely due to the magnetic field (magnetic dipole radiation), we can estimate the magnetic field of a pulsar

$$-\dot{E} = P_{\mathrm{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} \lesssim \frac{32\, B^2\, R^6\, \pi^4}{3c^3\, P^4} \quad \Rightarrow \quad B^2 \gtrsim \frac{3\, I\, c^3}{8\, \pi^2\, R^6} \times P\dot{P}$$

Q: What is the minimum magnetic field of the Crab pulsar?

Estimating Magnetic Field

- Assuming the loss rotational energy is entirely due to the magnetic field (magnetic dipole radiation), we can estimate the magnetic field of a pulsar

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} \lesssim \frac{32\, B^2\, R^6\, \pi^4}{3c^3\, P^4} \quad \Rightarrow \quad B^2 \gtrsim \frac{3\, I\, c^3}{8\, \pi^2\, R^6} \times P\dot{P}$$

Q: What is the minimum magnetic field of the Crab pulsar?

‘Characteristic Age’

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\, B^2\, R^6\, \sin^2\alpha\, \pi^4}{3c^3\, P^4}$$

‘Characteristic Age’

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{\cancel{P^3}} = \frac{32\, B^2\, R^6\, \sin^2\alpha\, \pi^4}{3c^3\, P^{\cancel{4}}}$$

First order differential Eq.

$$\boxed{\dot{P} = KP^{-1}}$$

$$K = \frac{8\, B^2 R^6 \sin^2\alpha\, \pi^2}{3Ic^3}$$

‘Characteristic Age’

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{\cancel{P^3}} = \frac{32\, B^2\, R^6\, \sin^2\alpha\, \pi^4}{3c^3\, P^4}$$

First order differential Eq.

$$\boxed{\dot{P} = KP^{-1}}$$

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\, dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau_c} dt$$

$$K = \frac{8\, B^2 R^6 \sin^2\alpha\, \pi^2}{3Ic^3}$$

Notice K is assumed constant, so that

$$\dot{P}P = K = \text{const}$$

‘Characteristic Age’

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\, B^2\, R^6\, \sin^2\alpha\, \pi^4}{3c^3\, P^4}$$

First order differential Eq.

$$\boxed{\dot{P} = KP^{-1}}$$

$$K = \frac{8\, B^2 R^6 \sin^2\alpha\, \pi^2}{3Ic^3}$$

Notice K is assumed constant, so that

$$\dot{P}P = K = \text{const}$$

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\, dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau_c} dt$$

Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

‘Characteristic Age’

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\, B^2\, R^6\, \sin^2\alpha\, \pi^4}{3c^3\, P^4}$$

First order differential Eq.

$$\boxed{\dot{P} = KP^{-1}}$$

$$K = \frac{8\, B^2 R^6 \sin^2\alpha\, \pi^2}{3Ic^3}$$

Notice K is assumed constant, so that

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\, dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau_c} dt$$

Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

Rewriting i.t.o τ_c the “characteristic age”

$$\tau_c = \frac{P}{2\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^2\right] \approx \frac{P}{2\dot{P}}$$

$$P_0 \ll P$$

Birth period P_0 much less than current P

‘Characteristic Age’

An assumption!

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\, B^2\, R^6\, \sin^2\alpha\, \pi^4}{3c^3\, P^4}$$

First order differential Eq.

$$\dot{P} = KP^{-1}$$

$$K = \frac{8\, B^2 R^6 \sin^2\alpha\, \pi^2}{3Ic^3}$$

Notice K is assumed constant, so that

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\, dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau_c} dt$$

Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

$$P_0 \ll P$$

Rewriting i.t.o τ_c the “characteristic age”

$$\tau_c = \frac{P}{2\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^2\right] \approx \frac{P}{2\dot{P}}$$

Birth period P_0 much less than current P

‘Characteristic Age’

An assumption!

$$-\dot{E} = P_{\text{rad}}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\, B^2\, R^6\, \sin^2\alpha\, \pi^4}{3c^3\, P^4}$$

First order differential Eq.

$$\dot{P} = KP^{-1}$$

$$K = \frac{8\, B^2 R^6 \sin^2\alpha\, \pi^2}{3Ic^3}$$

Notice K is assumed constant, so that

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\, dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau_c} dt$$

Test it for the Crab pulsar, where we know the correct age of the pulsar through the SN age, which was observed in the year 1054.

Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

$$P_0 \ll P$$

Rewriting i.t.o τ_c the “characteristic age”

$$\tau_c = \frac{P}{2\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^2\right] \approx \frac{P}{2\dot{P}}$$

Birth period P_0 much less than current P

‘Characteristic Age’

An assumption!

$$-\dot{E} = P_{\rm rad}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\,B^2\,R^6\,\sin^2\alpha\,\pi^4}{3c^3\,P^4}$$

First order differential Eq.

$$\dot{P} = KP^{-1}$$

$$K = \frac{8\,B^2R^6\sin^2\alpha\,\pi^2}{3Ic^3}$$

Notice K is assumed constant, so that

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\,dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau_c} dt$$

$$P_0 \ll P$$

Birth period P_0 much less than current P

Test it for the Crab pulsar, where we know the correct age of the pulsar through the SN age, which was observed in the year 1054.

Characteristic Age

$$\frac{P}{2\dot{P}} = 3.93\times10^{10}\text{s} \sim 1250\ \text{yr}$$

True Age

$$(2024 - 1054)\text{yr} = 970\text{yr}$$

Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

Rewriting i.t.o τ_c the “characteristic age”

Adding P, P-dot, magnetic field and characteristic age to one diagram!

The Radio Pulsar population

- Over 3000 pulsars discovered to date, most of which reside in the MW MeerKAT has already observed > 1500 pulsars!

Q: Do we see them outside the MW? (Answer in Lecture 2)

slow down faster

spin slower

The Radio Pulsar population

- Over 2800 pulsars discovered to date, most of which reside in the MW MeerKAT has already observed > 1500 pulsars!

‘Normal or isolated’ pulsars (P > 0.1 sec)

pulsars are born in SNR spinning fast

over the course of their lives they spin down

when the spin rate is too slow to produce radio emission, they shut off

In the computation of characteristic age we assumed the B-field stays constant, that’s why the “age arrow” is along a constant B-field, but across the characteristic age lines.

slow down faster

spin slower

The Radio Pulsar population

- Over 2800 pulsars discovered to date, most of which reside in the MW MeerKAT has already observed > 1500 pulsars!

‘Normal or isolated’ pulsars (P > 0.1 sec)

pulsars are born in SNR spinning fast

over the course of their lives they spin down

when the spin rate is too slow to produce radio emission, they shut off

In the computation of characteristic age we assumed the B-field stays constant, that’s why the “age arrow” is along a constant B-field, but across the characteristic age lines.

slow down faster

spin slower

The Radio Pulsar population

- Over 2800 pulsars discovered to date, most of which reside in the MW MeerKAT has already observed > 1500 pulsars!

'Normal or isolated' pulsars (P > 0.1 sec)

pulsars are born in SNR spinning fast

over the course of their lives they spin down

when the spin rate is too slow to produce radio emission, they shut off

In the computation of characteristic age we assumed the B-field stays constant, that's why the "age arrow" is along a constant B-field, but across the characteristic age lines.

Millisecond pulsars

Approx.10% of the pulsar population

MSPs are most often in binary systems, and have been spun up through accretion to incredible rotations of a few ms!

MSPs are used for high precision pulsar timing experiments

slow down faster

spin slower

The Radio Pulsar population

- Over 2800 pulsars discovered to date, most of which reside in the MW MeerKAT has already observed > 1500 pulsars!

'Normal or isolated' pulsars (P > 0.1 sec)

pulsars are born in SNR spinning fast

over the course of their lives they spin down

when the spin rate is too slow to produce radio emission, they shut off

In the computation of characteristic age we assumed the B-field stays constant, that's why the "age arrow" is along a constant B-field, but across the characteristic age lines.

Millisecond pulsars

Approx.10% of the pulsar population

MSPs are most often in binary systems, and have been spun up through accretion to incredible rotations of a few ms!

MSPs are used for high precision pulsar timing experiments

slow down faster

spin slower

The Evolution of Millisecond Pulsars (MSPs)

1. Binary of a massive star and a “normal” Sun-like star

2. The massive star exhausts its nuclear fuel and dies in a SN leaving a NS as its remnant.

For several 10 millions of years, that NS is likely active as a radio pulsar.

Eventually it slows down, turns off and becomes a cooling NS

3. After billions of years, the lower-mass star evolves and expands into a red giant.

The strong gravitational field rom the dense NS strips material from the red giant companion through the process of accretion. Leading to a disk of accreting material around the NS and eventually onto the NS.

This transfer of angular momentum spins up the NS, making it spin more rapidly.

4. Once accretion ends, the NS is spinning very rapidly (< P = 30ms) and is again emitting beamed radio emission as a MSP.

Because the NS has been switched on for a second time - the process is also called ‘recycling’.

Credit: B. Saxton, NRAO/AUI/NSF

Course layout

End of Lecture 1,
next up
Lecture 2: *Pulsar radio observations and data analysis*

Lecture 1 *(30 Aug - 1hrs)*
Pulsar properties

Lecture 2 *(13 Sep - 30min)*
Pulsar observations and data analysis

Tutorial *(13 Sep - 30min)*
MeerKAT pulsar data