Exploring the properties of pulsar radiation at (sub)millimeter wavelengths

Pablo Torne

p.torne@eaobservatory.org
East Asian Observatory — EAO
(Hilo, Hawaii)

torne@iram.es
Instituto de Radio Astronomía Milimétrica — IRAM
(Grenoble, France / Granada, Spain)
Contents

- Introduction to pulsars
- The radio emission mechanism problem
- Challenges to observe pulsars at short wavelengths
- Observations in the (sub)millimeter range
- Future, and how could the JCMT help
- Q&A
The Birth of Pulsars

(Very) Simplified

EVOlution of stars

Small Star → Red Giant → Planetary Nebula → White Dwarf

Large Star → Red Supergiant → Supernova → Neutron Star or Black Hole

Stellar Cloud with Protostars

Images not to scale

weebly.com
Pulsars

The Crab Nebula

Pulsars

The Crab Nebula


Credit: J. van Leeuwen

Credit: Cambridge University
A (visible) gate to the unknown

Introduction

Degenerate Stars

Sun

Earth

White Dwarf

Neutron Star

\[ M \approx 1.0 \, M_{\text{Sun}} \]
\[ R \approx 5800 \, \text{km} \]
\[ V_{\text{esc}} \approx 0.02c \]

~600x smaller ...

Not to a precise scale!

© R. Pogge

John Brady at Astronomy Central

Pablo Torne

EAO/JCMT Seminar, 26 February 2020
A (visible) gate to the unknown

Introduction

© R. Pogge

Vesc ≈ 0.7c

Vesc > c

Black Hole
M = 1.5 M_{sun}
R_S = 4.5 km
Vesc > c

Neutron Star
M=1.5 M_{sun}
R≈10 km
Vesc ≈0.7c

Manhattan
(spaceimaging.com)

© R. Pogge

M = 1.0 M_{sun}
R ≈ 5800 km
V_{esc} ≈ 0.02c
Properties of Pulsars

- Neutron stars formed in supernovae
- Mass \( \sim [1 - 2] \, M_\odot \)
- Radius \( \sim 10 \, \text{km} \)
- Rapidly rotating \( (P \sim 10 - 0.001 \, \text{seconds}) \)
- Highly magnetised \( (B_s \sim 10^8 - 10^{15} \, \text{G}) \)
- Very stable rotators \( (\Delta P \downarrow \text{down to } 10^{-20} \, \text{ss}^{-1}) \)

**Broadband emitters**

- Steep spectral sources \( (\langle \alpha \rangle = -1.8 \pm 0.2) \)
- Radio emission mechanism still unknown
  - Pulses \( T_b \sim [10^{25} - 10^{43}] \, \text{K} \) (must be coherent)

**Point-like masses with ultra-precise clocks attached**
Properties of Pulsars

- Neutron stars formed in supernovae

- Mass $\sim 1 - 2\ M_\bullet$

- Radius $\sim 10$ km

- Rapidly rotating ($P \sim 10^{-0.001}$ seconds)

- Highly magnetised ($B_s \sim 10^8 - 10^{15}$ G)

- Very stable rotators ($\Delta P$ down to $10^{-20}$ ss$^{-1}$)

- Broadband emitters

- Steep spectral sources ($\gamma > -1.8 \pm 0.2$)

- Radio emission mechanism still unknown

- Pulses $T_b \sim [10^{25} - 10^{43}]$ K (must be coherent)
The Pulsar Population

- 2700+ pulsars known

- Different ways of classifying pulsars: B-field strength, Age, Energy, Binary/Isolated, Period, Period derivative, ...

- Measurable quantities generally period (P) and its rate of change (Pdot)

- Three main subdivisions
  - Canonical / Normal
  - Millisecond
  - Magnetars
The Pulsar Population

- 2700+ pulsars known
- Different ways of classifying pulsars: B-field strength, Age, Energy, Binary/Isolated, Period, Period derivative, …
- Measurable quantities generally period (P) and its rate of change (Pdot)
- Three main subdivisions
  - Canonical / Normal
  - Millisecond
  - Magnetars
Pulsar Science

- Pulsars enable **high-precision astronomy in a wide variety of fields**, e.g.:

  - **Interstellar medium**
  - **Ultra-dense matter**
  - **Gravity tests**
  - **Binary evolution**
  - **Gravitational Waves**

**Possible experiments depends on the pulsar systems known**, e.g.:

- First binary pulsar \(\Rightarrow\) **Gravitational Waves**
- 2-\(M_\odot\) neutron star \(\Rightarrow\) Stringent constraints on EoS
- Double pulsar \(\Rightarrow\) Most stringent tests of GR
- Magnetar at Galactic Center \(\Rightarrow\) **Strong B-field around Sgr A*\)

**Discovering new pulsars expands our capabilities to do new science**
Emission Characteristics in the Radio Band

- **Brightness temperatures above thermal limit.** $T_b \sim [10^{25} - 10^{32}]$ K, up to $10^{37-41}$ K!
- Broadband emission, but with microstructure
- High degrees of linear and circular polarisation
- Spectral indices $\alpha \sim [-4, +1] \rightarrow$ Not “pure” synchrotron …
- Pulses all different, but average to a stable mean pulse
- Nulling, Mode changing

Please note:

**Non-thermal / Coherent emission**

Hankins & Eilek (2007)
Emission Characteristics in the Radio Band

- Brightness temperatures above thermal limit. $T_b \sim [10^{25} - 10^{32}] \text{ K}$, up to $10^{37-41} \text{ K}$
- Broadband emission, but with microstructure
- High degrees of linear and circular polarisation
- Spectral indices $\alpha \sim [-4, +1]$ → Not “pure” synchrotron …
- **Pulses all different, but average to a stable mean pulse**
- **Nulling**, Mode changing

---

van Leeuwen et al. (2003)
Emission Characteristics in the Radio Band

- Brightness temperatures above thermal limit. $T_b \sim [10^{25} - 10^{32}]$ K, up to $10^{37-41}$ K.
- Broadband emission, but with microstructure.
- High degrees of linear and circular polarisation.
- Spectral indices $\nu^{-4, +1}$.
- Not "pure" synchrotron.
- Pulses all different, but average to a stable mean pulse.
- Nullin, mode changing.

Jodrell Bank, University of Manchester

van Leeuwen et al. (2003)
Unknown Radio Emission Mechanism

- Still a mystery after 50 years since the discovery of pulsars
- Models must explain coherency, high degree of polarisation
- Explain very broad emission (~ 10 MHz – 300+ GHz)
- Models must work over 4 orders of magnitude of spin period, and 7 orders of magnitude in B-field

- How do we think it happens:

"Antenna mechanism"

Curvature emission by bunched particles

Lorimer & Kramer (2005)

- But there are alternative methods: relativistic plasma emission or maser mechanisms (see e.g. Melrose & Yuen 2016)
Pulsar emission models make predictions that we can try to test with observations

*Emission processes can be frequency dependent*

*Some effects may only be observable at very short wavelengths (< ~few mm)*
- Pulsar emission models make predictions that we can try to test with observations
- Emission processes can be frequency dependent

(Sub)mm- observations cover a window of pulsar emission highly unexplored, enabling certain tests of emission models not possible at other wavelengths

Poorly explored window in pulsars

Adapted from Smith (1977)
Examples

- **Coherence Breakdown**: coherent emission fails at sufficiently high frequency, incoherent emission takes over
- Features as a spectral turn-up in the spectrum
- Accompanying depolarisation?

Coherence breakdown

---

Adapted from Michel (1982)

---

Apparent turn-up in spectrum

---

Kramer et al. (1997)

---

Torne et al. (2017)

---

PSR J1745-2900
(2015 March 4-9th)

---

Torne et al. (2017)
Examples

- **Radius-To-Frequency Mapping**
  - Dependence of height-of-emission $\iff$ Observed Frequency
  - Implies narrower pulses at high frequency and depolarisation due to less ordered magnetic field

Radhakrishan and Cooke (1968)
Cordes (1978)

Decrease of polarisation

Zhao et al. (2019)

Xilouris et al. (1996)
Examples

**Radius-To-Frequency Mapping**
- Dependence of height-of-emission $\Leftrightarrow$ Observed Frequency
- Implies narrower pulses at high frequency and depolarisation due to less ordered magnetic field

Found a model that seems to work?
don’t worry …

There will *always* be a pulsar out there
that contradicts it …
The Big Puzzle: No Model Fits All

The radio emission mechanism problem
Exploring pulsar radiation at (sub)mm- wavelengths

Observations and Challenges
“Natural” Issue: Signal Weakness

- Pulsars are generally extremely faint radio sources
- Steep spectral sources → even weaker at short wavelengths

Steep spectrum on average

\[ S \propto \nu^\alpha \]

\[ \langle \alpha \rangle = -1.8 \pm 0.2 \]

Objectives at (sub)mm-\(\lambda\):

\[ \alpha > -1.2 \quad \text{(70 pulsars)} \]

\[ -0.5 < \alpha < +1.0 \quad \text{(Magnetars)} \]

Pulsars are generally weak and steep spectral sources, making their detection and study at short radio wavelengths very challenging
"Natural" Issue: Signal Weakness

Pulsars are generally extremely faint radio sources. Even weaker at short wavelengths, according to et al. (2008).

Objectives at (sub)mm:

- $\alpha > -1.2$ (70 pulsars)
- $-0.5 < \alpha < +1.0$ (Magnetars)

Steep spectrum on average $\alpha = -1.8 \pm 0.2$ on average, as reported by Maron et al. (2000).

Challenges for (sub)millimetre pulsar science.
The Importance of Magnetars

- **Magnetars** = young pulsars with very high B-fields
- Some show radio emission → **peculiar** and even less-understood **characteristics**
  - Transient nature (turn on and off)
  - Extreme variability (factors of a few in tens of minutes!)
  - Very high degree of polarisation up to very high frequencies
  - Variable pulse profiles, spectral index
- **Flat radio spectrum** → **Bright at short millimetre wavelengths!**

- Only 4 pulsars have been detected at 7 mm
- Only 4 at 3 mm (2 are magnetars)
- Only 3 at 2 mm (2 are magnetars)
- And 2 at 1 mm (both are magnetars)

Kramer et al. (1997)
Morris et al. (1997), Camilo et al. (2007), Torne et al. (2015), Liu et al. (2019)
Camilo et al. (2007), Torne et al. (2015), Torne et al. *in prep.*

Radio magnetars, due to their flat spectrum, are unique pulsars to study (sub)mm- radio emission characteristics. More telescopes with capability to detect pulsars at \( \lambda < 1.3 \) mm are of great application here! *(e.g., JCMT)*
“Technological” Issue: Lack of Sensitivity

• To be able to detect the weak pulsations at short wavelengths we need:
  - Big collecting areas
  - Large bandwidths
  - “Nice” receivers -> Low Trec, “Gaussian' noise properties -> to integrate long times
  - Good sites for low Tsky

\[
S_{\text{min}} = \beta \frac{(S/N_{\text{min}}) T_{\text{sys}}}{G \sqrt{n_p t_{\text{obs}} \Delta \nu}} \quad [\text{Jy}]
\]

Gain is difficult to change, but we can improve:
- $T_{\text{sys}}, T_{\text{obs}}$ and $\Delta \nu$
- the key to succeed if dish size ~medium-small

Good sites and state-of-the-art receivers

Big collecting areas

Large instantaneous bandwidths

Long integration times
Bolometer TES / KID Technology Promising

- TES Bolometer / Kinetic Inductance (KID) technology offering huge instantaneous bandwidths at (sub)mm-telescopes. See e.g., SCUBA2: Holland et al. (2013) + NIKA2: Adam et al. (2018) + LABOCA: Siringo et al. (2009)

![SCUBA2 @ JCMT frequency coverage](image)

SCUBA2 @ JCMT frequency coverage:

- $S_{\text{min}} = \beta \frac{(S/N_{\text{min}}) T_{\text{sys}}}{G \sqrt{n_p t_{\text{obs}} \Delta \nu}}$ [Jy]

Bolometers / KIDs up to 2-3x more sensitive than typical SiS Rx

but can they be used for detecting pulsars?

https://www.eaobservatory.org/jcmt/instrumentation/
YES! ➔ First Pulsar Detection with a KID camera

- Magnetar AXP1810–197 with NIKA2 @ IRAM 30-m, 0.6 hr observation on 23-March-2019
- OK weather (tau225~0.3)
- Proof of concept, no major issues. Worked beautifully well!

Time series with 2 mm array
(1.3 mm not shown)

Sampling time ≈ 43.7 ms

+ well-behaved noise

Individual rotations of the neutron star seen!

Pablo Torne
EAO/JCMT Seminar, 26 February 2020
Yes! → First Pulsar Detection with a KID camera

Detection with 2 mm array

Detection with 1.3 mm array

Pablo Torne

EAO/JCMT Seminar, 26 February 2020
First Exploration of Range 3.4 – 1.1 mm

- 1997: Pulsars detected for the first time at 7 mm with Effelsberg 100-m
- 1997: Morris et al., detect PSR B0355+54 at 87 GHz (λ3.44 mm) with IRAM 30-m
  - Single polarisation, 500 MHz bandwidth

**Observations at (sub)millimeter wavelengths**
First Exploration of Range 3.4 – 1.1 mm

- 2014 - 2017: Torne et al., detect B0355+54 up to 138 GHz (λ2.17 mm) with IRAM 30-m
- Highest radio frequency detection to date (for a normal pulsar)!
- BBC backend: 64 GHz bandwidth

Significant technological progress 2014 - 2019

Morris et al. (1997) First Exploration of Range 3.4 – 1.1 mm


Dr. Pablo Torne

IRAM Seminar, Grenoble (29-May-2019)
• 2007: Camilo et al.: first detections of a magnetar (AXP 1810−197) up to 144 GHz (λ 2.08 mm) with IRAM 30-m
• Confirms variability (I, α) and flat spectrum into the mm-band

First Exploration of Range 3.4 – 1.1 mm
• 2015: Torne et al. detect Galactic Center magnetar (SGR J1745–2900) up to 225 GHz (\(\lambda 1.33 \text{ mm}\))
• 2017: detections up to 291 GHz (\(\lambda 1.09 \text{ mm}\))
First Exploration of Range 3.4 – 1.1 mm

- Confirms variability ($I, \alpha$) and flat spectrum into the mm-band for a second magnetar!

Observations at (sub)millimeter wavelengths

![Graph showing averaged mean flux density vs. frequency](image1)

Torne et al. (2015)

PSR J1745-2900
(2014 July 21-24th + Aug 24th)

$<\alpha> = -0.4 \pm 0.2$

![Graph showing averaged mean flux density vs. frequency](image2)

Torne et al. (2017)

PSR J1745-2900
(2015 March 4-9th)

$<\alpha> = +0.4 \pm 0.2$
First Exploration of Range 3.4 – 1.1 mm

- Confirms variability ($I, \alpha$) and flat spectrum into the mm-band for a second magnetar!
- Evidence of high (up to 100%) linear polarisation up to 154 GHz ($\lambda$1.95 mm)

**Highest degree of linear pol. at these frequencies?**

**Total Intensity**

**Lower limit of linear polarisation**

**Flux Density (mJy)**

- 87 GHz
- 138 GHz
- 154 GHz

**Pulse Phase**

0.35 0.60 0.35 0.60 0.35 0.60

**Torne et al. (2017)**
What next?
JCMT very well suited for 0.9 — 0.4 mm window
JCMT very well suited for 0.9 — 0.4 mm window

- 15-m dish, high quality (good aperture efficiency at short wavelengths)
- Excellent site, Tsys very low and access to $\lambda < 0.8$ mm
- Large-bandwidth receivers, bolometer SCUBA2
- Atypical science case … pulsars never studied in [0.9 — 0.4] mm window
- Challenging, but worth trying!

JCMT is one of the few instruments in the world with potential for pulsar studies at (sub)mm- wavelengths
SCUBA2 Observations of a Radio Magnetar

• DDT: AXP1810−19, a recently reactivated radio magnetar with SCUBA2
• Goal: First-ever detection of pulsations from neutron stars at 0.85 and 0.45 mm → Check Coherence Breakdown!
• Requires special observing mode … tested on Friday: use of one array of SCUBA2, extract signal from Daisy pattern

Stay tuned!
Exploring the properties of pulsar radiation at (sub)millimeter wavelengths

Summary

Pulsars are fascinating objects and unique high-precision astrophysical tools.

Extensively observed in the radio band, but the emission mechanism still a mystery.

To aid in understanding the emission process: observations between millimeter and infrared.

Bolometer TES / KID promising technology for pulsar observations in those ranges.

JCMT well suited and observations of a radio pulsar with SCUBA2 planned (THANKS!)

Definitely more discoveries coming up with newer receivers and ALMA!

Thank you!