Observing pulsars with ALMA: an unprecedented opportunity to explore the millimetre wavelength regime of pulsar emission

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Advantages of mm-λ observations

Observe under-explored region of pulsar spectrum

Emission properties

Test emission models

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Xilouris et al. (1996)

Kramer et al. (1996, 1997)

Figure adapted from Michel (1982)
Advantages of mm-$\lambda$ observations II

Diminish (almost completely) the ISM effects

Scattering

$\Delta t \alpha (\nu^{-4})$

$\begin{align*}
1408 \text{ MHz} \\
610 \text{ MHz} \\
408 \text{ MHz} \\
325 \text{ MHz} \\
243 \text{ MHz}
\end{align*}$

From Lorimer & Kramer (2005)

→ Observe through dense-inhomogeneous media

Galactic Centre

ISM effects ↑↑↑

Eatough

NASA/JPL

→ Observe through dense-inhomogeneous media
Disadvantages / Challenges

Pulsars extremely faint at millimetre wavelengths

Steep spectrum

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

\[ < \alpha > = -1.8 \pm 0.2 \]

Objectives

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

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

Pulsar backends not available at millimetre observatories

- Deploy pulsar machines
- Use VLBI recorder

Löhmer et al. (2008)

Maron et al. (2000)
Need large mm-telescopes

- Frequency coverage, effective bandwidth, geographical location, altitude, …
- Need versatile, broadband backends capable of detecting pulsars
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The “pathfinder”: Pico Veleta
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- First detection of PSR at 3.44mm (87 GHz) in 1997
- A magnetar up to 144 GHz in 2007
- 2015 to 2017: PSR up to 154 GHz, Magnetar up to ~300GHz

**PSR J1745-2900**

\[ \alpha = +0.4 \pm 0.2 \]

Torne et al., in prep.

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The “pathfinder”: Pico Veleta

- First detection of PSR at 3.44mm (87 GHz) in 1997
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- Pulsars do emit within the short (<5 mm) mm-wavelength window
- Available instruments on their limit → only most luminous pulsars detectable with the 30-m
ALMA opens a new door

- Sensitivity
- Frequency coverage
- Location
- Pulsar detection capability

Credit: ESO/Y. Beletsky
The ALMA pulsar mode

Dedicated software developed as part of an NSF-funded ALMA development study “Pulsars, Magnetars, and Transients with Phased ALMA” (PI: Cordes et al.). Publicly available online at: https://github.com/xuanyuanstar/vdif2psrfits

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Phased ALMA observations on Vela

Jan. 29, 2017 ALMA (APP):

- $T_{\text{obs}} \sim 30$ min; Frequency = 86, 88, 98, 100 GHz; BW = 4x2 GHz
- Scans switching between Vela (B0833-45) ands calibrator (J0828-3731)
- Array phased in “passive” mode (no tuning of fringe solution when on source)

(Adapted from K. Liu BHC F2F slides)
Detections of the Vela pulsar

Lower side-band
87.27 GHz

Upper side-band
99.27 GHz

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Detections of the Vela pulsar

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First pulsar detection with ALMA!

High S/N detection!

(Adapted from K. Liu BHC F2F slides)
Detections of the Vela pulsar

Flipped sign in Stokes $U$, caused by 180 deg ambiguity in phase of two polarisations

(Adapted from K. Liu BHC F2F slides)
Final test: timing analysis

- Exact pulsar model from other-wavelength observations
- Timing residuals = (Time-of-arrivals @ ALMA) – (model predictions)

- Residuals as white noise: Model prediction works!
- Aligned residuals between sub-scans: No jumps introduced during source switching

(Adapted from K. Liu BHC F2F slides)
Final test: timing analysis

- Exact pulsar model from other-wavelength observations
- Timing residuals = (Time-of-arrivals @ ALMA) – (model predictions)

The mode to observe pulsars with p-ALMA works as expected!

- Residuals as white noise
- Aligned residuals between sub-scans: No jumps introduced during source switching

(Adapted from K. Liu BHC F2F slides)
Summary

- Observations at short mm-λ are challenging, but can and should be done:
  - Unique insights into pulsar radio emission properties → test models
  - Possible way to probe dense ISM and find new pulsars and magnetars
  - Potential to be a tool for precision black hole physics @ Galactic Centre
- Pico Veleta showed feasibility of short mm-λ pulsar science
- Phased ALMA:
  - The most sensitive mm- telescope, with large frequency coverage
  - Access to the southern mm- pulsar sky: ~70% of all known pulsars have dec < 0 deg
  - Demonstrated its capability to detect and study pulsars

New findings to come!
Pulsars, complementary precision tools

- Independent measurements
- EHT shadow + stars/pulsars → test near and far gravitational field

Stars

EHT shadow

Credit: MPIfR/N. Wex

Pulsars

Credit: MPIfR/R. Eatough

Credit: MPIfR/N. Wex

Short mm-λ surveys at the GC

Detectable Population
- Pico 30m ~ 5.9%
- LMT 30m ~ 6.3%
- LMT 50m ~ 9.7%
- ALMA ~ 16.6%

PSR J1745-2900 among the 2% brightest population
PSR B0355+54 among the 5% brightest population

Lower-luminosity population still undetected!
Detections of the Vela pulsar

- Lower side-band: 87.27 GHz
- Upper side-band: 99.27 GHz

No radio interference & no dispersion smearing

(Adapted from K. Liu BHC F2F slides)
Detections of the Vela pulsar

Lower side-band
87.27 GHz

Upper side-band
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Phase kept across the whole observation

(Adapted from K. Liu BHC F2F slides)