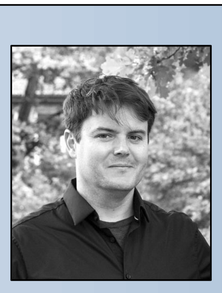
Pulsar Single-Pulse Modulation Properties from Multi-Frequency Observations



Fabian Jankowski for the SUSPECT collaboration

Paris Observatory | PSL, LPC2E, CNRS, France (fabian.jankowski@cnrs-orleans.fr, https://fabian.jankowskis.org)

Abstract. The '**S**cience **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes' (SUSPECT) project is an effort to understand the radio emission of pulsars, particularly at the single-pulse level. Our team designed and established a new pulsar observing programme at the Nançay Radio Observatory telescopes (NenuFAR, LOFAR, NRT) in France and the upgraded GMRT in India. We focus on coordinated multi-telescopes and multi-frequency single-pulse pulsar observations. Since mid-2023, we have spent, in aggregate, hundreds of telescope hours observing our first sample of 22 pulsars. Science highlights include the development of a new model for the mode switching phenomenon, its application to PSR B1822–09, and the discovery of a new bright flaring emission mode in the pulsar. The project overview paper was published in February 2025, and two Master's student projects were completed in 2023–2024. SUSPECT Paper II is close to submission.

The SUSPECT Project

- **S**cience **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT)
- New pulsar observing programme running since mid-2023, i.e. for about 2 years now
- Coordinated pulsar observations using the radio telescopes at the Nançay Radio Observatory (NenuFAR, LOFAR, NRT) and the uGMRT
- Aims
  - Understanding the wide-band single-pulse properties of radio pulsars
  - Study single-pulse properties (pulse-energy distributions, modulation)
  - Others: pulse profiles, radius-to-frequency model
- Focussed on mode switching and sub-pulse drifting
  - Master's student research projects (M2) in 2023 and 2024 supervised by FJ & Grießmeier

Fig. 1: The NenuFAR telescope (10–85 MHz) in front of the LOFAR FR606 HBA antennas (110–240 MHz) with the NRT (1.1–3.5 GHz) in the background.

Fig. 2: Some of the GMRT core antennas.

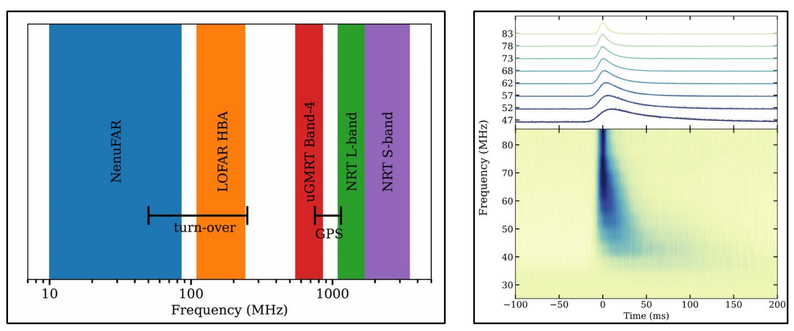


Fig. 3: Frequency coverage of our data (left). Scattering fit of PSR B2217+47's NenuFAR data with *scatfit* (FJ 2022; right).

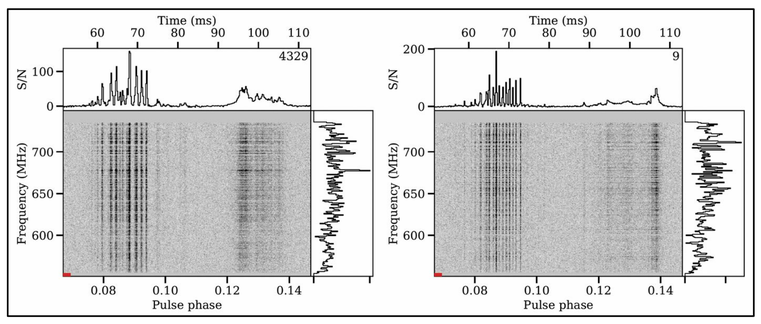


Fig. 4: Quasi-periodic shot-like micropulse emission detected in PSR B1822–09's precursor pulse component (FJ+ 2025).

Elucidating the Pulsar Radio Emission – Our Approach

- Wide-band data using several telescopes
- (Quasi)-simultaneous observations
- Two complementary approaches

1) Highest S/N single pulses, intermediate frequencies (~600 MHz), low scattering

→ probe the **intrinsic** emission GMRT & NRT

2) Long-term observing campaigns (> 5 years), low frequencies (10s – 100s MHz), timing models, rare modes, time evolution, DM & scattering

→ **intrinsic** and **extrinsic** NenuFAR & LOFAR

Project Status

- 22 pulsars observed (NenuFAR, FR606, GMRT)
- Initial data reduction completed for all
- ~12 worked on in more detail (M2 projects, paper)
- 2 Master's student projects completed

Publications

- Project overview paper published (SUSPECT Paper I; Jankowski et al. 2025)

Science Using Single-Pulse Exploration with Combined Telescopes

I. The mode switching, flaring, and single-pulse morphology of PSR B1822–09

F. Jankowski[1,*], J.-M. Grießmeier[1,2], M. Surnis[3], G. Theureau[1,2,4], and J. Pétri[5]

- SUSPECT Paper II close to submission
  - Multi-frequency pulse profiles, modulation, and pulse-energy distributions, new fitting tools
- Data for spin-off projects (Limaye+, Surnis+)

Results

- Single-pulse stacks, updated DMs, scattering parameters, pulse profiles, modulation properties, pulse energy distributions
- 3–5 radio frequency bands

Modulation Properties

- Phase-resolved modulation indices, pulse-energy distributions, flux-phase distributions
- New absolute flux density calibration and tool
- Bayesian unbinned distribution fitting using new *fitpdf* software tool

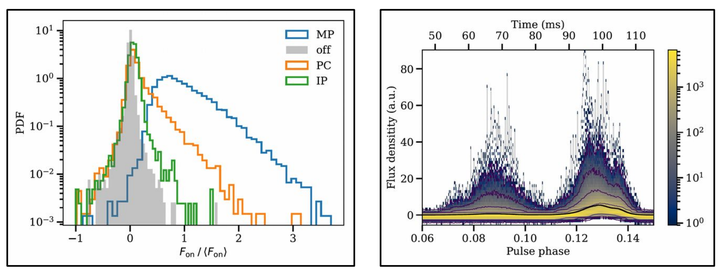


Fig. 5: Pulse-energy distributions and flux-phase distribution of PSR B1822–09 from our uGMRT data (FJ+ 2025).

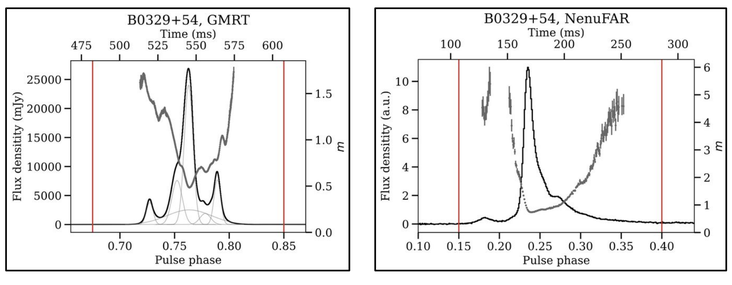


Fig. 6: Pulse profiles, phase-resolved modulation index curves, and component model for PSR B0329+54 at two frequencies.

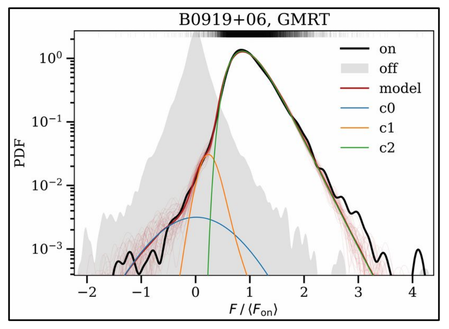


Fig. 7: PED fit of PSR B0916+06 using *fitpdf*.

- Multimodality seen
- Nulling, mode switching, ISM
- Normal, lognormal, PL distributions
- Frequency evolution

Modelling Mode Switching

- PSR B1822–09 quasi-randomly switches between several emission modes
  - Stable plasma configurations of magnetosphere
- Want to understand the physics behind it
- Can we understand and model it?
  - Yes! Hidden Markov model with AR emissions
  - Automatic mode classification
  - Mode detection and their number
  - New mode discovered!

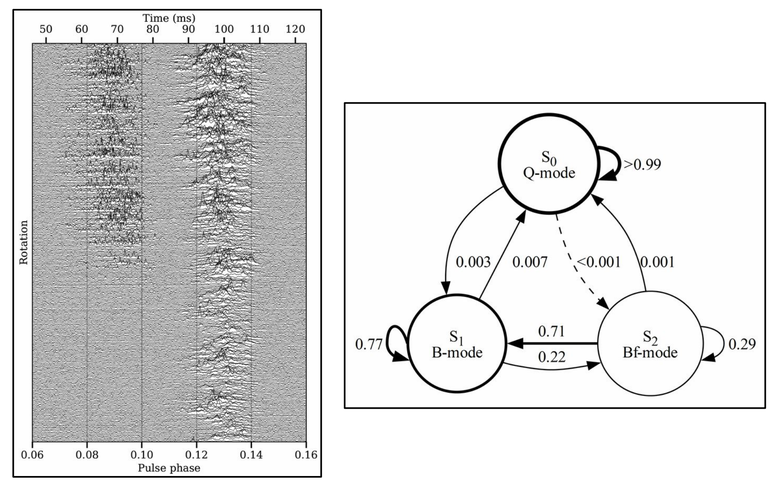


Fig. 8: Mode switching analysis of PSR B1822–09 using our uGMRT data. Joy Division plot, Markov state diagram, 3-state Markov switching model, mode-separated profiles (FJ+ 2025).

Conclusions

- The combination of high-S/N data with long-term observations is extremely powerful
- Multi-frequency data allow many interesting tests
- Coordinating several telescopes is non-trivial
- Have barely scratched the surface of what is possible with this data set. Lots of work ahead!

References

Jankowski et al. A&A **695**, A203 (2025)

Project website: https://suspectproject.com

Scatfit software, Jankowski ASCL, 2208.003 (2022)

GitHub: https://github.com/fjankowsk/scatfit