URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, 22 - 25 October, 2024

SPOTLIGHT: A Probe of the Fast Radio Transient Sky

Jayanta Roy*[1], Jayaram N. Chengalur [1], Karel Adamek[2], Kenil Ajudiya[3], Wes Armour[2], Bhavnesh Bhat[4], Siddhartha Bhattacharyya[1], Deepak Bhong[1], Jyotirmoy Das[1], Ritavash Debnath[5], Nishant P. Deo[6], Amit Deokar[7], Bidisha Dey[8], Chahat Dudeja[1], Shelton Gnanaraj[1], Gurjeet Jagwani[2], Afifa Jamal[9], Tejas Kamble[10], Santaji N. Katore[1], Sanjay Kudale[1], Ajith Kumar[1], Mekhala Muley[1], Anjan Kumar Nandi[1], Arpan Pal[1], Ujjwal Panda[1], B. S. Patil[1], Nilesh Raskar[1], Pravin A. Raybole[1], S. Harshavardhan Reddy[1], Saptarshi Sarkar[1], Raghav Wani[5], Jack White[2]

(1) NCRA-TIFR, Pune 411007, India; e-mail: jroy@ncra.tifr.res.in
(2) Oxford e-Research Centre, University of Oxford, Oxford, UK
(3) Indian Institute of Science, Bengaluru-560012, India
(4) Indian Institute of Technology Roorkee, Roorkee - 247667, India
(5) Indian Institute of Science Education and Research, Pune 411008, India
(6) Indian Institute of Science Education and Research, Kolkata 741246, India
(7) The Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India
(8) Indian Institute of Science Education and Research, Tirupati 517507, India
(9) Aligarh Muslim University, Aligarh 202001, India
(10) Indian Institute of Technology Kharagpur, 721302, India

Abstract

SPOTLIGHT is a time-domain survey instrument to perform a real-time commensal search for Fast Radio Bursts (FRBs) and Pulsars with a PetaFlop system installed at the GMRT funded under the National Supercomputing Mission (NSM). The system executes real-time HPC and AI applications to ensure simultaneous time-domain detection and arc-second imaging localisation of the detected bursts across the GMRT observing band. With an unprecedented sensitivity, SPOTLIGHT is expected to find hundreds of FRBs with possible host galaxy associations, allowing the use of the bursts as cosmological probes. The AI-assisted trigger for genuine astronomical signals enables the capturing of voltage samples spanning the burst duration to study the spectro-temporal-polarimetric properties at microsecond time resolution to probe FRB progenitor models as well as propagation imprints. With the successful execution of the SPOTLIGHT project we expect that this instrument will enable transformational, high impact science in time-domain astronomy with the GMRT over the period of its operation, along with being a trigger for cutting edge technology development.

1. Introduction

Time-domain astronomy (i.e. the study of rapidly varying sources) is a rapidly growing field of research. Here the aim is to understand the nature of celestial radio transients. Two important classes of such transient sources are pulsars and Fast Radio Bursts (FRBs). Pulsars are rapidly rotating strongly magnetised neutron stars that can be used as extremely precise celestial clocks, and allow one to probe the most extreme states of matter and gravity. Most detected pulsars are galactic objects, Whereas FRBs are extremely bright ~millisecond duration events that are detectable at cosmological distances and are the probes of highly energetic, and possibly cataclysmic events, providing a unique opportunity to study the ionised intergalactic medium (IGM).

2. The SPOTLIGHT System

The uGMRT is currently the only interferometric array capable of providing simultaneous detection and the arc-sec localisation of such fast transient sources over the full 300−1460 MHz radio spectrum. However, to enhance the discovery potential, a system like uGMRT needs to be equipped with a real-time commensal time-domain survey instrument. This is now accomplished by building a

PetaFlop computing capacity (hosting ~90 A100 GPUs installed on 60 of C-DAC's indigenously developed Rudra servers, several 10s of TB of memory and 2 PB of storage) for conducting such a real-time commensal search for FRBs and Pulsars with the GMRT, called **SPOTLIGHT** (https://spotlight.ncra.tifr.res.in/). This is funded by the National Supercomputing Mission (NSM) under MeitY and DST of Govt. of India. The system is expected to discover more than a few hundreds of FRBs with host galaxy association as well as several hundreds of pulsars over the next few years of scientific operation by piggy-backing to the ongoing observations. The system will be equipped to accept GMRT digitiser outputs at a rate of 25 GB/s using 32 of 10 GB fibre links and process them on a 24×7 basis. The correlator and beamformer will form 2000 beams covering the FWHM field-of-view using phased addition of visibilities of moderate length baselines [1, 2]. This system with ~20-times more raw compute power than the existing uGMRT backend [3] requires 80 kW of IT power and 40 kW for cooling. The PetaFlop data centre is established inside a shielded room in the GMRT providing ~100 dB isolation over the frequency range of 14 kHz to 10 GHz. This is now being integrated into the uGMRT observatory control and monitoring system to enable commensal operation [4]

The time-domain event detection system searches for millisecond bursts and periodic signals up to a dispersion measure (DM) limit of 2000 pc cm^{-3} over a frequency range of 300-1460 MHz. The multi-beam real-time search pipeline for FRBs [5] and a quasi-real-time search pipeline for pulsars [6] are being developed in collaboration with the Oxford e-Research Centre at the University of Oxford. The Deep Learning (DL) based Artificial Intelligence (AI) system optimises triggers for baseband voltage capturing to probe spectro-temporal-polarimetric properties of the bursts disentangling the intrinsic emission features from the propagation imprints. The team at NCRA is working with NVIDIA and IIT-Palakkad to jointly develop the machine learning and deep learning pipeline under the NVIDIA AI Technology Center (NVAITC) collaboration. This collaboration aims to enhance the capabilities of the SPOTLIGHT project through advanced AI technologies. Visibilities and raw data for all candidates triggered by AI classifier will be saved to disk for real-time imaging localisation [7] and quasi real time confirmation at full sensitivity and full angular resolution. The coherently dedispersed beam at the FRB discovery parameters enables spectro-temporal-polarimetric studies at high-time resolution [8]. SPOTLIGHT discoveries are expected to have a very high scientific impact since localisation is critical for using these bursts as cosmological probes [9]. Applications include measurements of the "missing baryons" in the universe, studying the magnetic field in the early universe etc. [10, 11]. A web-based real-time monitoring and discovery database is now getting developed generating prompt alerts for new and known FRB detections in SPOTLIGHT through Virtual Observatory Event (VOEvent) Service [12]. The hundreds of such localised FRBs from the SPOTLIGHT with NSM-powered GMRT will enable transformational, high-impact science in the time-domain astronomy with the GMRT.

3. Deliverables and global perspective

The emergence of modern astronomical facilities such as the uGMRT, eVLA, LOFAR, MWA, MeerKAT, ASKAP, CHIME and the construction of the international mega-science project, the Square Kilometre Array (SKA), are driving the growth and technology of next-generation radio astronomical instrumentation. GMRT is recognised as an SKA pathfinder facility and will be one of the few interferometers with this commensal transient backend. The aimed development will explore a completely new programming paradigm both in high-performance computing (HPC) and in artificial intelligence (AI) to leverage GMRT's potential in delivering cutting-edge time-domain astronomy science. This sophisticated state-of-the-art digital processing system for the GMRT will not only enable transformational science experiments but will also achieve a technological milestone in delivering a large-scale instrument for the largest interferometric array in the world.

As seen in Fig. 1, which illustrates the landscape of the transient sky populated by coherent emitters on the luminosity-pulse timescale diagram, SPOTLIGHT covers a deeper and wider parameter space compared to other large-scale surveys such as CHIME/FRB and MeerTRAP with MeerKAT. Even after significant efforts from large-scale surveys populating the transient sky on the luminosity-pulse timescale diagram (Fig. 1), there are still many gaps in the parameter space. The recent emergence of ultra-long period Galactic magnetars [14] and long-period transients [15] highlights the need to expand the parameter space of upcoming surveys while their potential as FRB progenitor models is also being examined by the community. We are currently at an important junction of placing the emerging population in the landscape of fast transients, and we aim to devise the SPOTLIGHT survey to populate the parameter space more uniformly. This will help place the GMRT and India in an excellent position to contribute both technologically and scientifically to the SKA. In summary SPOTLIGHT at the GMRT not only provides a platform for development of new transient related technologies but will also open up a new regime of parameter space and provide a rich astronomical dataset at excellent sensitivity.

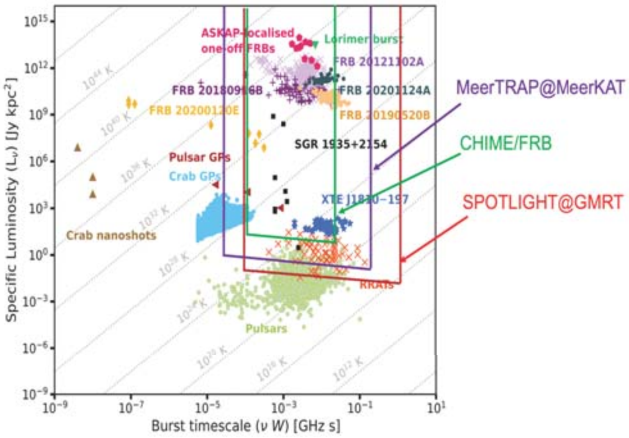

Figure 1. The luminosity as a function of burst timescale for the fast radio transient population in the coherent radio emission regime. The SPOTLIGHT survey coverage is shown along with the **CHIME/FRB** and **MeerTRAP** projects. Credit: Bailes (2022).

6. Acknowledgements

We acknowledge the funding of the data centre under NSM Phase 3. We also acknowledge support of the Department of Atomic Energy, Government of India, under project no. 12-R&D-TFR-5.02-0700 for the contributions towards the overhead cost. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research, India. The data centre was jointly built by team members from C-DAC and the GMRT backend, electrical, RFI, and mechanical teams. We thank the GMRT telescope operators for supporting the test observations during the software prototyping phase.

7. References

[1] S. H. Reddy, S. Kudale, U. Panda and the SPOTLIGHT team, “A real-time post-correlation beamformer and correlator for the SPOTLIGHT”, URSI-RCRS 2024

[2] M. Muley, S. Kudale, Nishant Pradeep Deo and the SPOTLIGHT team, “Optimal tiling of SPOTLIGHT field-of-view with multi-beam synthesis”, URSI-RCRS 2024

[3] S. H. Reddy, S. Kudale, U. Gokhakle et al., “ A Wideband Digital Back-End for the Upgraded GMRT”, vol. 06, No. 01, 2017, 1641011, https://doi.org/10.1142/S2251171716410117

[4] D. Bhong, S. Kudale, S. N. Katore and the SPOTLIGHT team, “Online control of the SPOTLIGHT and integration with the GMRT system”, URSI-RCRS 2024

[5] U. Panda, K. Ajudiya and the SPOTLIGHT team, “A multi-beam FRB detection pipeline with real-time injection for the SPOTLIGHT”, URSI-RCRS 2024

[6] J. Das, the GCGPS team and the SPOTLIGHT team, “Discoveries from GCGPS survey and its application for pulsar search with SPOTLIGHT”, URSI-RCRS 2024

[7] A. Pal, S. Kudale and the SPOTLIGHT team, “A real-time imaging localisation pipeline for the SPOTLIGHT”, URSI-RCRS 2024

[8] C. Dudeja, S. Bhattacharyya and the SPOTLIGHT team, “Spectro-Temporal-Polarimetric Study of FRBs with the SPOTLIGHT”, URSI-RCRS 2024

[9] S. Bhattacharyya, S. Sarkar and the SPOTLIGHT team, “An FRB Population Synthesis for SPOTLIGHT and Its Cosmological Inference”, URSI-RCRS 2024

[10] J.-P. Macquart, J.X. Prochaska, M. McQuinn et al., “A census of baryons in the Universe from localised fast radio bursts”, Nature, volume 581, 27 May 2020, pages 391–395
https://doi.org/10.1038/s41586-020-2300-2

[11] S. Bhandari and C. Flynn, “Probing the Universe with Fast Radio Bursts”, Universe, 7(4), 1 April 2021, 85
https://doi.org/10.3390/universe7040085

[12] S. N. Katore, S. Meshram, U. Panda and the SPOTLIGHT team, “A web-based tool for discovery database with transient alert generation of SPOTLIGHT”, URSI-RCRS 2024

[13] M. Bailes, “The discovery and scientific potential of fast radio bursts,” Science, vol. 378, no. 6620, p. eabj3043, Nov. 2022, doi: 10.1126/science.abj3043.

[14] P. Beniamini, Z. Wadiasingh, J. Hare, et al., “Evidence for an abundant old population of Galactic ultra-long period magnetars and implications for fast radio bursts”, Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 2, 20 Jan 2023, Pages 1872–1894 https://doi.org/10.1093/mnras/stad208

[15] M. Caleb, E. Lenc, D. L. Kaplan, et al., “An emission-state-switching radio transient with a 54-minute period” Nat Astron, 5 Jun 2024, https://doi.org/10.1038/s41550-024-02277-w