Review

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Fast Transients with the Square Kilometre Array and its Pathfinders: An Indian Perspective

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Abstract. In the rapidly developing field of study of the transient sky, fast radio transients are perhaps the most exciting objects of scrutiny at present. The SKA, with its wide field-of-view and significant improvement in sensitivity over existing facilities, is expected to detect a plethora of fast transients which, in addition to help resolve the mysteries surrounding their nature and origin, will also lead to other interesting applications in astrophysics. We explore some of these possibilities here, and also emphasize the current status and future plans of the Indian community working in this area, in the context of ongoing work and extension of this to the SKA.

Key words. Transient sources—radio bursts—radio telescopes: SKA—GMRT—ORT.

1. The transient sky: An introduction

Exploration of transient phenomena in the Universe is an exciting and rapidly growing area of radio astronomy. Transient radio sources are expected to be compact and are usually associated with explosive or dynamic events, and allow interesting new regimes of physics to be probed. The time scales for transient phenomena range from several months down to microseconds (or shorter). Short duration (<5 s) transients are perhaps the most exciting variety of transient events, and also the most difficult to observe and localize in the sky. The dynamic radio sky remains poorly sampled as compared to sky in X-ray and γ-ray bands. This is because currently it is difficult to obtain both high time resolution and wide fields-of-view (FoVs) simultaneously. This is where the SKA, with its wide fields-of-view and high sensitivity, is expected to open up a new parameter space in the search for radio transients.

1.1 *Fast transients: an overview*

Short time scale (<5 s) radio transients probe high brightness temperature emission, likely associated with extreme states of matter, and may throw light on physics of strong gravitational fields. They are also powerful probes of intervening media owing to dispersion, scattering and Faraday rotation. The latest class of fast radio transients are the mysterious Fast Radio Bursts (FRBs), which are characterized by their short durations ($\sim$ millisecond) and high values of the Dispersion Measure (DM, $\sim$400–1600). Although the first FRB was discovered as far back as 2007 (Lorimer *et al.* 2007), the next discoveries had to wait till 2013 (Thornton *et al.* 2013). The total number known today stands at 17, with all of them except one (Spitler *et al.* 2016), reported to have been detected only once. However, the expected rates of detectable FRBs (Champion *et al.* 2016) are quite large ($6^{+4}_{-3} \times 10^3$ sky^{-1} day^{-1}), and hence there is significant potential for enhanced detections. Most of the presently known FRBs (Petroff *et al.* 2016) have been detected with the Parkes radio telescope, one with Green Bank telescope and another with Arecibo. An exhaustive catalogue of presently known FRBs is maintained by the radio pulsar group at the Swinburne University (http://astronomy.swin.edu.au/pulsar/frbcat/).

Because of the large values of DM associated with them, FRBs are believed to be of extragalactic origin. If FRBs are indeed extragalactic, then their study will help us to understand properties of ionized Inter-Galactic Medium (IGM). None of the FRBs observed so far have not been identified with any specific host, except the recent, controversial claim of identification of the host galaxy of FRB 150418 (Keane *et al.* 2016; Williams & Berger 2016).

The understanding of the physical origin of FRBs remains as an open challenge, and there exist a number of different hypothesis including flaring stars in the Galaxy (Loeb *et al.* 2014), magnetars close to the Galactic centre (Penn & Connor 2015), collisions between neutron stars and asteroids (Geng & Huang 2015), dark matter induced collapse of neutron stars (Fuller & Ott 2015), cosmic strings (Yu *et al.* 2014; Vachaspati 2008), mergers of binary white dwarfs (Kashiyama *et al.* 2013), mergers of two neutron stars (Totani 2013), axion stars (Iwazaki 2015), collapse of supra-massive neutron stars into black holes (Falcke & Rezzolla 2014), white holes (Barrau *et al.* 2014). Recent detection of repeating bursts from one FRB (Spitler *et al.* 2016) argues against catastrophic models, at least for this event. However, the possibility of multiple types of populations of FRBs (based on their origin) can not be ruled out.

2. Fast transients with the SKA: Long-term prospects

In order to improve our understanding of the nature and origin of FRBs, and to use them as effective probes of interesting physics, it is important to increase the sample size by a significant amount. Whereas different efforts are underway with existing facilities, the SKA is expected to provide the most important boost. The higher sensitivity, coupled with the wide field-of-view, and sophisticated real-time processing techniques at high time resolutions make it very favourable for such discoveries. This increased sample, with possibilities for estimation of the spectral index, and of detection in polarized emission, alongwith rapid follow-up in other wavelengths, will be highly valuable in our aim to validate and/or rule out one or more of the competing theories for the origin of FRBs.

Moreover, the detection and localization of thousands of coherent bursts at cosmological distances (Yang & Zhang 2016) will directly locate the missing baryons in intergalactic space that constitute at least 50% of the present-day Universe's baryonic content and determine their association with galaxy and cluster halos. As cosmological rulers, these bursts measure the curvature of the Universe and can help determine the dark energy equation of state at redshifts $\geq$2.

The scattering mechanism in the IGM is still an open challenge, and the redshift distribution of a large sample of FRBs, coupled with better understanding of the spectrum and the source mechanism, will guide us to determine better the scattering model for the IGM.

The SKA can achieve all of this with a design that has a wide field-of-view, a substantial fraction of its collecting area in a compact configuration (80% within a 3 km radius), and a capacity to process high time resolution (1 ms) signals. High precision cosmology with FRBs is a very important field. SKA1 Low and SKA1 Mid will both be extremely instrumental for such studies.

3. Fast transients in the Indian context: Present scenario and future plans

There is significant interest among Indian researchers to work on fast transients, in areas of both observations and theory. Of specific interest have been studies about the potential of detecting FRBs and other transients at low radio frequencies, as well as pilot experiments for the same. Some of the recent efforts, ongoing activities and future plans are highlighted below.

Though most of the FRBs have been detected at relatively higher radio frequencies (around 1.4 GHz), there is significant interest to look at the possibilities of FRB detections at low frequencies. These cover both theoretical studies and experiments. Given a significant number of low-frequency facilities available in the country – the Gauribidanur Array, the Ooty Radio Telescope (ORT) and the Giant Metrewave Radio Telescope (GMRT) – and the potential of SKA Low in the future, these studies are very important.

Bera *et al.* (2016) have developed a general formalism for FRB detection by any radio telescope, and have shown that the detection rate of FRBs at low frequencies can be quite appreciable. In particular, they calculate the rate for the Ooty Wide Field Array, which is currently under development and will operate at a frequency of 327 MHz, to be $\sim 10^3$ events per day, for an assumed spectral index ($-\alpha$) of -1.4 (Fig. 1). This makes searching for FRBs with the SKA Low an interesting prospect. In particular, constraints on the value of the spectral index for FRBs can best be obtained by such low frequency observations.

The Indian Sky Watch Array Network (SWAN) initiative by the Raman Research Institute[1] is a proposed competitive coordinated network (40+ stations across India)

[1] http://www.rri.res.in/SWAN/SWANRRI.html

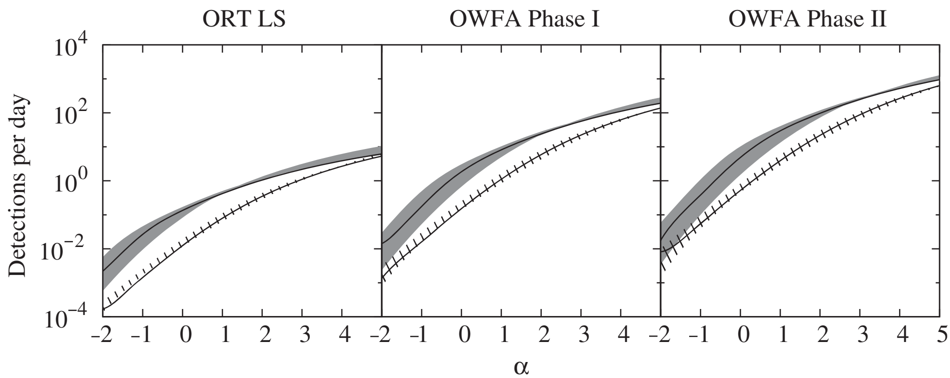

Figure 1. The number of FRBs assumed to detect by using ORT LS, OWFA Phase I and Phase II (Ali & Bharadwaj 2014) with incoherent beam formation (Bera *et al.* 2016). The energy spectrum of FRBs has been considered as $E_\nu \propto \nu^{-\alpha}$. The solid and dashed regions correspond to scattering model I (Bhat *et al.* 2004) and scattering model II (Macquart & Koay 2013) respectively. The black solid lines denote Delta function and the boundaries of the regions enclose the curves corresponding to the Schechter luminosity function with exponent in the range $-2 \leq \gamma \leq 2$.

with nominally 1000 sq. m array area at each location and operations spanning a decade in frequency: 50 to 500 MHz. The main objective is to facilitate and conduct searches and studies of fast (typically of sub-second duration) and slow transient radio radiation originating from astronomical sources. The proposed Indian-SWAN is optimized to search for a large volume of the space with required sensitivity to detect FRB signals routinely, enabling a proper, detailed study to be carried out.

Using the Arecibo radio telescope, a total of 1000 h of observations covering the entire Arecibo sky have been made using the ALFA in Meridian nodding mode, as a part of the GALFACTS continuum Full Stokes (polarization) imaging project. ALFA is a L-band, seven pixel, system with 300 MHz bandwidth. One of the data streams resulting from these observations was designed to enable search for fast transients with a special purpose pipeline, with spectral resolution of about 1 MHz, and time resolution of 1 ms (Cohen *et al.* 2016).

The Gauribidanur radio telescope has been used by Deshpande and Aswathappa, to conducted a sky survey at 35 MHz, covering the full visible sky, providing data on 3000 fields observed for 20 min each, with raw voltages recorded across a 1 MHz bandwidth. Some of these data have also been used to search for radio counterparts of the FERMI-LAT sources (Maan *et al.* 2012; Maan & Aswathappa 2014). Further, a search for fast transients has also been carried out towards several selected directions at the very low frequency of 35 MHz, using the Gauribidanur radio telescope. So far, these searches have resulted in the discovery of several energetic radio bursts from the Geminga pulsar (Maan 2015) at very low dispersion measures, and a potential detection of the radio counterpart of another gamma-ray pulsar J1732-3131 (Maan *et al.* 2012).

At the GMRT, there have been the following programs related to fast transients. Poonam Chandra and colleagues have been involved in an interesting experiment (Petroff *et al.* 2015) where they ‘shadow’ the FRB program at Parkes with lower

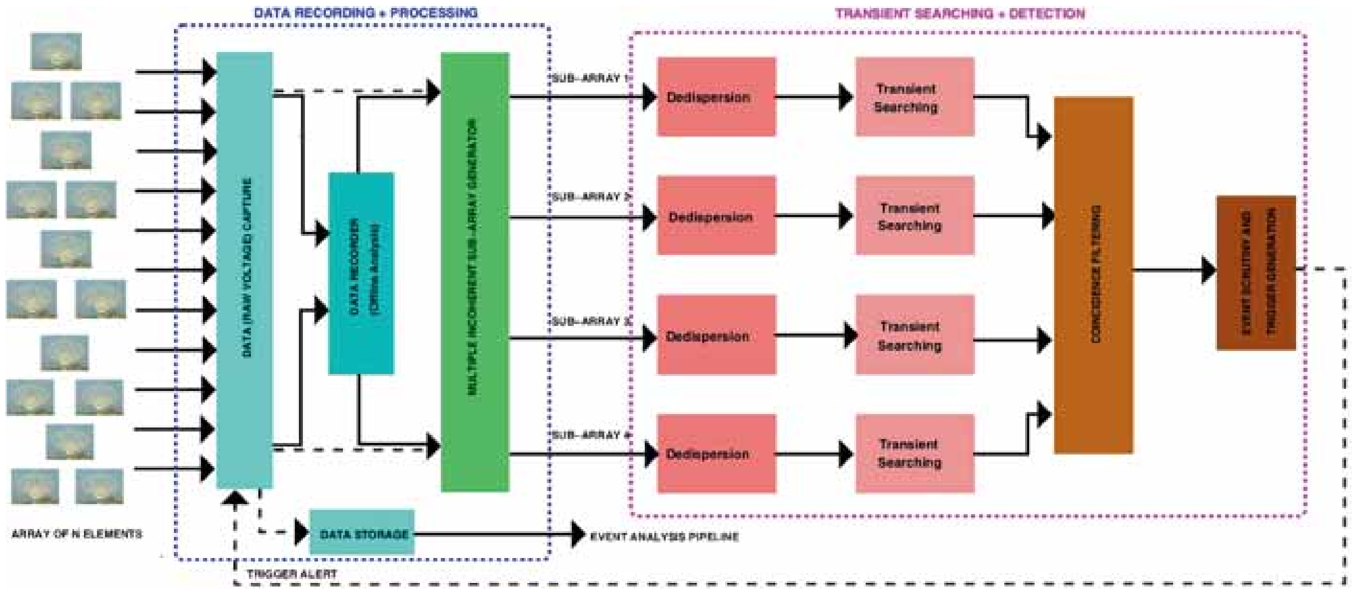

Figure 2. A diagrammatic representation of the GMRT transient detection pipeline (from Fig. 5 of Bhat *et al.* 2013). Raw voltage data from each array element are captured and made available to a processing pipeline. Multiple (incoherent) sub-array data streams are generated, and a transient search is performed on each data stream. The resulting events are assimilated through the event identification and coincidence filter algorithms to select the final candidates. For real-time implementation (dashed lines and arrows), this information is then used to generate triggers that will alert the raw data capture system to record relevant raw data segments for further detailed processing and scrutiny.

frequency observations with the GMRT, with the hope of being able to detect a FRB afterglow, following a trigger from a higher frequency detection at Parkes.

There is also an ongoing program to develop a dedicated pipeline at the GMRT, for real-time detection of fast transients. This pipeline is intended to run both as a stand-alone program as well as in piggyback mode simultaneously with other, possibly imaging, observations at the observatory. The concept for this pipeline (Fig. 2), outlined in Bhat *et al.* (2013), is particularly well-suited to multi-element telescopes like the GMRT, and will be easily extendable to the SKA mid: it splits the array into multiple sub-arrays (up to 4 or 5 is found to be optimal) and produces incoherently summed outputs for each sub-array, which are first individually searched for transient signals over a range of DMs and different pulse widths, to produce a list of possible detections for each sub-array. These are then passed through a coincidence filter, which (a) rejects false positives due to noise fluctuations in individual sub-arrays and (b) rejects a lot of the RFI that is not correlated across the different sub-arrays. The false positive rejection allows much lower than normal detection thresholds to be set, which adequately compensate the loss in sensitivity of splitting the array into multiple, incoherently summed sub-arrays.

An off-line version of this pipeline has been extensively tested on recorded data (Bhat *et al.* 2013), to verify the concepts described above. A real-time version (Ramanujam *et al.* 2015) is under final stages of testing. This pipeline runs on the 32 MHz bandwidth data produced by the existing GMRT software back-end (Roy *et al.* 2010), for which its performance has been tuned to be well within real time. The implementation utilizes the power of GPUs for accelerated computing. At present, work is on to adapt it for the full 400 MHz bandwidth data that the wide-band back-end of the upgraded GMRT (uGMRT) will deliver by the end of 2017. We will need to modify parts of the pipeline so that it continues to perform within real time for this configuration as well. The wide-band correlator will be able to produce four incoherent array beams, by dividing the 30 antennas into four different groups. The aim would be to configure this as a SKA pathfinder project on the uGMRT for fast transients.

The above initiatives, driven by the strong interest and skill sets of the Indian astronomy community in the area of fast transients, combined with an exciting set of ongoing activities and plans that would involve a much wider participation from the younger generations, provide the desired setting to build up the group's active participation in the SKA.

4. Summary

The rapidly growing field of fast transients is emerging as an overwhelmingly important area of research with the SKA. The Indian community, given its active interests in different aspects of studies of fast transients, ranging from theory and modeling to ongoing and planned experiments with various radio-astronomy facilities in the country and abroad, is well poised to make a significant impact in this exciting and relatively new branch of astronomy.

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References

Ali, S. S., Bharadwaj, S. 2014, *J. Astrophys. Astr.*, **35**, 157182.
Barrau, A., Rovelli, C., Vidotto, F. 2014, *PhRvD*, 90l7503.
Bera, A., Bhattacharyya, S., Bharadwaj, S. *et al.* 2016, *MNRAS*, **457**, 2530.
Bhat, N. D. R., Cordes, J. M., Camilo, F. *et al.* 2004, *ApJ*, **605**, 759.
Bhat, N. D. R., Chengalur, J. N., Cox, P. J. *et al.* 2013, *ApJS*, **206**, 2.
Champion, D. J., Petroff, E., Kramer, M. *et al.* 2016, *MNRAS*, **460L**, 30C.
Cohen, T., Salter, C. J., Ghosh, T. 2016, in: *the American Astronomical Society, AAS Meeting #227* (http://adsabs.harvard.edu/abs/2016AAS...22724123C).
Falcke, H., Rezzolla, L. 2014, *A&A*, **562**, 137F.
Fuller, J., Ott, C. D. 2015, *MNRAS*, **450L**, 71.
Geng, J. J., Huang, Y. F. 2015, *ApJ*, **809**, 24.
Iwazaki, A. 2015, *PhRvD*, 91b3008.
Kashiyama, K., Ioka, K., Mészáros, P. 2013, *ApJ*, **776L**, 39.
Keane, E. F., Johnston, S., Bhandari, S. *et al.* 2016, *Nature*, **530**, 453.
Loeb, A., Shvartzvald, Y., Maoz, D. 2014, *MNRAS*, **439L**, 46.
Lorimer, D. R., Bailes, M., McLaughlin, M. A. *et al.* 2007, *Science*, **318**, 777.
Maan, Y., Aswathappa, H. A., Deshpande, A. A. 2012, *MNRAS*, **425**, 2.
Maan, Y., Aswathappa, H. A. 2014, *MNRAS*, **445**, 3221.
Maan, Y. 2015, *ApJ*, **815**, 126.
Macquart, J.-P., Koay, J. Y. 2013, *ApJ*, **776**, 125.
Penn, U. L., Connor, L. 2015, *ApJ* , **807**, 179.
Petroff, E., Keane, E. F., Barr, E. D. *et al.* 2015, *MNRAS*, **451**, 3933.
Petroff, E., Barr, E. D., Jameson, A. *et al.* 2016, *PASA*, **33**, 45.
Ramanujam, N. M. *et al.* 2015, in: *the Annual Meeting of the Astronomical Society of India*.
Roy, J., Gupta, Y., Pen, U. *et al.* 2010, *ExA*, **28**, 25.
Spitler, L. G., Scholz, P., Hessels, J. W. *et al.* 2016, *Nature*, **531**, 202.
Thornton, D., Stappers, B., Bailes, M. *et al.* 2013, *Science*, **341**, 53.
Totani, T. 2013, *PASJ*, **65L**, 12.
Vachaspati, T. 2008, *PhRvL*, 101n1301.
Williams, P. K. G., Berger, E. 2016, *ApJL*, **821**, L22, arXiv:1602.08434.
Yang, Y. P., Zhang, B. 2016, *ApJ*, **830L**, 31.
Yu, Y. W., Cheng, K. S., Shiu, G., Tye, H. 2014, *JCAP*, **11**, 040.