



Explosive and Radio-Selected Transients: Transient Astronomy with Square Kilometre Array and its Precursors

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Abstract. With the high sensitivity and wide-field coverage of the Square Kilometre Array (SKA), large samples of explosive transients are expected to be discovered. Radio wavelengths, especially in commensal survey mode, are particularly well-suited for uncovering the complex transient phenomena. This is because observations at radio wavelengths may suffer less obscuration than in other bands (e.g. optical/IR or X-rays) due to dust absorption. At the same time, multiwaveband information often provides critical source classification rapidly than possible with only radio band data. Therefore, multiwaveband observational efforts with wide fields of view will be the key to progress of transients astronomy from the middle 2020s offering unprecedented deep images and high spatial and spectral resolutions. Radio observations of Gamma Ray Bursts (GRBs) with SKA will uncover not only much fainter bursts and verifying claims of sensitivity-limited population versus intrinsically dim GRBs, they will also unravel the enigmatic population of orphan afterglows. The supernova rate problem caused by dust extinction in optical bands is expected to be lifted in the SKA era. In addition, the debate of single degenerate scenario versus double degenerate scenario will be put to rest for the progenitors of thermonuclear supernovae, since highly sensitive measurements will lead to very accurate mass loss estimation in these supernovae. One also expects to detect gravitationally lensed supernovae in far away Universe in the SKA bands. Radio counterparts of the gravitational

waves are likely to become a reality once SKA comes online. In addition, SKA is likely to discover various new kinds of transients.

Key words. Radiation mechanisms: non-thermal—techniques: interferometric—gamma-ray bursts: general—supernovae: general—novae, cataclysmic variables.

1. Introduction

Square Kilometre Array (SKA) when ready will be world's largest radio telescope, to be built in Australia and South Africa. It will be built in two phases. Phase I (SKA-1) is expected to complete in 2020; Phase II (SKA-2) will be completed in 2024. Phase I will have $\sim 10\%$ of the total collecting area. SKA will have a range of detectors: from aperture arrays to dishes; and will span a frequency range from few tens of megahertz to a few gigahertz. SKA will have an unique combination of great sensitivity, wide field-of-view and unprecedented computing power. Exploration of the transient Universe is an exciting and fast-emerging area within the radio astronomy. With its wider field-of-view and higher sensitivity, the SKA holds great potential to revolutionize this relatively new and exciting field, thereby opening up incredible new science avenues in astrophysics.

1.1 Explosive transients

Transient radio sources are compact sources and are locations of explosive or dynamic events. Transient phenomenon usually represent extremes of gravitational and magnetic fields, velocity, temperature, pressure and density. In terms of duration, radio transients phenomenon can be classified into two classes, long time variability (min–days) and bursting radio sky (msec–sec; Carilli 2014). Transients in radio bands are mainly dominated by three kinds of emission mechanisms:

(1) *Incoherent synchrotron emission*: Transients with incoherent emission show relatively slow variability, and are limited by brightness temperature. These events are mainly associated with explosive events, such as Gamma Ray Bursts (GRBs), supernovae (SNe), X-Ray Binaries (XRBs), Tidal Disruption Events (TDE) etc. Incoherent transients are mostly discovered in the images of the sky.

(2) *Non-thermal coherent emission*: Transients associated with coherent emission show relatively fast variability, high brightness temperature and often show high polarization associated with them, such as fast radio bursts, pulsars, flare stars etc. The coherent emission transients are discovered in time series observations. The short-duration transients are powerful probes of intervening media owing to dispersion, scattering and Faraday rotation.

(3) *Thermal emission*: These kinds of emission are seen in slow transients like novae and symbiotic stars.

1.2 Radio selected transients

A large fraction of transients discovered in radio bands remain undetected in other bands of electromagnetic spectrum and their nature remains unclassified. Early searches for variable and transients in radio band yielded only ~ 10 variable sources

(Gregory & Taylor 1986; Langston *et al.* 1990). Due to lack of wide field monitoring of the transient sky, most of the variable radio sources were found from follow up of X-ray transients and gamma-ray bursts. However, with availability of wide field imaging techniques at low-radio frequencies and advancement in observing facilities allowed larger regions of the sky to be monitored. In the last decade, use of these techniques have resulted in several reported detections.

While at least 30 transients have been detected so far, the radio detected transients typically have no identification in other bands. This makes identifying the progenitors difficult. Out of the 30 transients detected, possible progenitor population of only about 9 have been identified by the respective authors. These include two possible cases of Radio SNe (RSNe) or orphan GRBs (Bower *et al.* 2007), one confirmed SNe, two confirmed low mass X-ray binaries, 3 probable scintillating AGNs and one possible ultra-bright RSN (Bannister *et al.* 2011). The origin of the rest of the transients are not known. Clearly, this demonstrates that for most of the transients detected first in radio band, the parent population is unknown.

1.3 Transients research in India and relevance to SKA

In India, active research is going on in transient astronomy, especially in the fields of supernovae, gamma ray bursts, pulsars and related phenomenology, novae, X-ray binaries, tidal disruption events, galactic black hole candidates and electromagnetic (EM) signatures in gravitational waves. Major observational facilities operated by National Centre for Radio Astrophysics (NCRA), Aryabhata Research Institute of Observational Sciences (ARIES), Indian Institute of Astrophysics (IIA), Inter University Centre of Astronomy and Astrophysics (IUCAA) are widely used. Researchers also avail the wealth of archival data from high energy space missions like *RXTE*, *XMM-Newton*, *Swift*, *Chandra* and *Fermi*. Groups are also working towards multimessenger astronomy mainly in the context of gravitational waves. Indian astronomers have access to several observational facilities, both presently existing and to come in the future (e.g., Pandey 2013).

The dynamic radio sky is poorly sampled as compared to sky in X-ray and γ -ray bands. To search for transient phase space, one needs the combination of sensitivity, field-of-view and time on the sky. This has been difficult to realise simultaneously, hence there have been a very few comprehensive transient surveys in radio bands. In addition, the variation in time scales (nano seconds to minutes), and complex structures in frequency-time plane makes things further difficult. The advent of the multi-beam receivers placed on the single dish telescopes, such as Parkes and Arecibo has led us to detect new phenomena such as Rotating Radio Transients (RRATs), FRBs etc. However, much larger FoV is required to discover more of such phenomena and SKA will be able to achieve the desired sensitivity with large FoV (see Table 1).

Table 1. Parameters for SKA-1 telescope.

Telescope	Fiducial freq. (GHz)	FoV (deg ²)	Resolution (arcsec)	Baseline (km)	Bandwidth (MHz)	Sensitivity ($\mu\text{Jy-h}^{-1/2}$)
SKA-1 LOW	0.11	27	11	50	250	2.1
SKA-1 MID	1.67	0.49	0.22	200	770	0.7

SKA has adopted transients as its key science goal. SKA will open up a new parameter space in the search for radio transients. Some of the basic questions to ask in the context of SKA are the following: What do we know about the radio transient sky? How can we improve searches for radio transients? What successes do we expect from SKA pathfinders? How will SKA pathfinders improve our understanding of transients?

To achieve the above goals, one needs the right combination of different technologies. Many of these technologies and ideas are being tested with the SKA pathfinders and precursors, such as Australian Square Kilometre Array Pathfinder (ASKAP), Murchison Widefield Array (MWA), LOw-Frequency ARray (LOFAR), upgraded-Giant Metrewave Radio Telescope (uGMRT) etc. The use of widely distributed many small elements for the SKA means that one needs to take advantage of the vast computing resources to be able to sample a larger fraction of the sky. Also the discovery of truly transient events relies on having excellent instantaneous sensitivity. Here it is important to note that multiwavelength observations of the sky are important for the detection and follow-up of transient sources, as they provide complementary views of the same phenomena. The SKA will be roughly contemporaneous with other International facilities like Large Synoptic Survey Telescope (LSST), Gaia, Thirty Meter Telescope (TMT) in optical/IR bands and next generation successors of *Swift*, *Chandra* and *XMM-Newton* in the gamma-ray and X-ray bands (such as *SVOM* (France-China), *SMART-X* (US) and *ATHENA* (ESA) missions).

For SKA to be an optimal telescope for transient science, the international transient Science Working Group (SWG) has recommended mainly two changes to SKA Phase 1 design:

Commensal transient searches: It is important to do near-real-time searching of all data for transient event. This will increase rate of events by at least one order of magnitude. For maximum scientific gain, the detection needs to be reported widely, globally and rapidly. There are efforts going on to implement real-time transient pipeline in uGMRT to enable commensal transient searches.

Rapid (robotic) response to triggers: One may be able to detect very early-time radio emission (coherent or very prompt synchrotron) if SKA has robotic response to external alerts, allowing very rapid follow-up of high-priority events. For example, the Arcminute Micro-kelvin Imager Large Array (AMI-LA) is the world's first robotic automated radio telescope. Its response time to *Swift* triggers are only 30 s. AMI-LA has provided the first milliJansky-level constraints on prolonged radio emission from GRBs within the first hour post-burst (Staley *et al.* 2013).

SKA is expected to increase the number of transients at least by an order of magnitude. In optical bands, LSST, which will be contemporary of SKA, anticipates finding around 1 million transients per night. However, this rate is not known at the GHz bands. But it is estimated that around 1% of the mJy sources are variable (Frail *et al.* 2012). LOFAR has recently detected a transient at 10 Jy flux density level at 60 MHz band (Stewart *et al.* 2016). The transient does not repeat and has no counterpart. The nature of this transient is enigmatic. SKA-LOW will most likely detect 100s of such transients per day in MHz band. Frail *et al.* (2012) claimed that with 10 μ Jy rms, one can expect around one transient per degree. This is achievable by SKA-1 MID.

2. Gamma ray bursts

Gamma Ray Bursts (GRBs) are non-recurring bright flashes of γ -rays lasting from seconds to minutes with an average observed rate of around one burst per day. The energy isotropically released in γ -rays ranges from $\sim 10^{48}$ to $\sim 10^{54}$ ergs. The prompt emission in majority of cases is in γ -ray bands. In a few cases, optical prompt emission is detected. The prompt emission spectrum is mostly non-thermal, though presence of thermal or quasi-thermal components are seen in a handful of bursts (see Kumar & Zhang 2014 for a review). Afterglow emission following the burst in longer wavelengths and lasting for longer time was eventually discovered leading to the confirmation that the bursts are cosmological. GRBs are one of the furthest known objects so far, the redshift distribution ranges from 0.008 to ~ 9 as of now. We currently understand them as catastrophic events generating a central engine which launches an ultra-relativistic collimated outflow.

After nearly four decades of extensive research, even though our knowledge about GRBs have definitely enhanced, the very nature of the progenitor, and the radiation physics giving rise to the observed emission in both prompt as well as afterglow phase is yet to be solved. This is mainly attributed to its nonrecurring behaviour, with the emission over only a short timescale resulting in unique and variable light curves. Some of the prominent questions that need to be answered are:

What is the nature of the content of the outflow, is it baryonic dominated or Poynting flux?
 What is radiation physics: photospheric emission or non-thermal processes such as synchrotron emission or inverse Compton?

From where exactly in the outflow does the emission occur?

What are the microphysics involved in these radiation events?

What are the dynamics of the outflow resulting in these variable light curves?

How does the transition between the prompt and afterglow phase occur and what is its nature giving rise to the X-ray flares, plateaus, steep decay in flux observed in the early X-ray afterglow?

GRBs are believed to be collimated jet emissions to reconcile with the observed energetics, however, this raises a question as to why jet breaks are not observed in all afterglow observations.

Resolving the above queries would enable us to use GRB as an effective cosmological tool to probe the early Universe. There are several theoretical models proposed for both prompt as well as afterglow emission of GRBs which are sometimes equally consistent with the data. Therefore, we are at such a juncture where it is imperative for the forthcoming observations and studies of GRBs to be able to break the current degeneracy between existing models. Afterglow emission has always been instrumental in diagnosing burst physics like the energy in the explosion, structure of jet, nature of the ambient medium and the physics of relativistic shocks. In this direction, it is evidently clear that we require a multi-wavelength observational coverage of these events extending from gamma rays to radio bands, which can prove highly constraining for existing theoretical models. This, in turn, would then become effective in developing a global model connecting prompt to afterglow emission, which can also be adequately tested. SKA, with its broad field-of-view and higher sensitivity would be able to play a key role in achieving this prospect as well as in resolving many of the above-mentioned open questions.

2.1 Long vs. short GRBs

The histogram of GRB duration reveals a bimodal distribution (Kouveliotou *et al.* 1993): the long and the short bursts. In the BATSE burst population, bursts with duration less than 2 s were classified as short and those lasting for more than 2 s were classified as long. Apart from the duration, long and short bursts also show difference in the hardness of their γ -ray spectrum (Kouveliotou *et al.* 1993). Subsequently, long GRBs at lower redshifts are found to be associated with type Ib/c broad-lined supernovae, thereby establishing their origin in the gravitational collapse of massive stars (Woosley & Bloom 2006). No short burst has so far been found associated with supernovae. Further studies have revealed that the difference lies deeper than the prompt emission, and extends to the burst environment. In accordance with the massive star hypothesis, long GRBs are predominantly found in star forming regions of late type galaxies (Fruchter *et al.* 2006) while short bursts are seen in a variety of environments (Fong *et al.* 2010). Distribution of the off-set of burst position from the photocentre of the host galaxy shows that short bursts typically are further away from the central regions of the galaxy compared to their longer cousins (Fong *et al.* 2010). These evidences support a hypothesis that long bursts are possible end stages of massive stars ($M > 15M_{\odot}$) while short bursts are associated with older stellar populations like compact objects. Currently, we believe that at least a fraction of short GRBs form due to the merger of compact object binaries (see Berger 2014 for a review). Recently, a new class of GRBs, named Ultra-Long GRBs (ULGRBs), are found to be lasting for several thousands of seconds (Levan 2015). It is speculated that ULGRBs are arising from a different class of progenitors. With the recent discovery of Gravitational Waves (GWs), a new era of Gravitational Wave Astronomy has begun which can shed more light into this model if short GRBs or their afterglows are observed in coincidence with double NS or NS-BH mergers (see section 5 of Dewdney (2015) for capabilities of SKA to carry out electromagnetic follow up of GW events).

The differences in various progenitors giving rise to different kinds of GRBs will be manifested in their environments. However, in X-ray and optical band GRBs, fireball is almost always optically thin. The early evolution of low frequency (<4 GHz) radio light curves is through the optically thick regime, the light curve peak corresponds to transition from optically thick to thin regime. Hence, radio frequencies are unique in probing the evolution of the self-absorption frequency, ν_a , which in turn can constrain the physical parameters such as density of the environments etc. Tracing the evolution of ν_a will also help in scrutinizing basic assumptions in the standard fireball model, especially of the time-invariant shock microphysics. SKA can densely sample the light curves of long as well as short GRBs at different frequencies. Thus radio emission from long versus short GRBs will reveal the difference in the environments of these two classes of GRBs.

In the *Swift* era, almost 93% of GRBs have a detected X-ray afterglow, $\sim 75\%$ have detected optical afterglows while only 31% have radio afterglows (Chandra & Frail 2012). The SKA, with its extreme sensitivity, will dramatically improve statistics of radio afterglows. Using numerical simulation of the forward shock, (Burlon *et al.* 2015) predicts around $400-500 \text{ sr}^{-1} \text{ yr}^{-1}$ radio afterglows in SKA-1 MID bands. However, Hancock *et al.* (2013) has claimed that undetected afterglows are intrinsically dim rather than sensitivity-limited.

SKA will be very crucial in lifting this degeneracy owing to its extremely high sensitivity. Burlon *et al.* (2015) have shown that the band 5 of SKA1-MID is ideally suited to observe radio afterglow during first 10 days, when the afterglow emission will be closest to the peak (Table 1).

Both long and short GRBs are collimated events with opening angles lying within few degrees. This means we can detect only those GRBs which are pointing towards us. However, in the absence of γ -ray trigger, either due to the jet pointing away from earth or due to unavailability of a dedicated triggering instrument, orphan radio afterglows can be detected by SKA owing to its high sensitivity. Burlon *et al.* (2015) predicts 300–400 orphan afterglows per all-sky per week. Orphan afterglow detection rates will help in drawing indirect limits of jet structure, as well as true rate of GRBs.

Thus SKA will trace the peak of the emission, sampling the thick-to-thin transition of the evolving spectrum, and follow-up the afterglow down to the time the ejecta slows down to non-relativistic speeds. SKA-1 MID bands 4 (4 GHz) and 5 (9.2 GHz) will be particularly suited to the detection of GRB phenomena. In fact, the SKA early science phase will roughly triple the rate of observed afterglows from GRBs pointed towards the Earth.

2.2 Unveiling the GRB reverse shock with SKA

According to the standard model, a central engine, perhaps a black-hole torus system or a millisecond magnetar, formed during the gravitational collapse of a massive star (for long GRBs) or the merger of a double compact object binary (short bursts), launches an ultra-relativistic jet. The jet energy could either be in the bulk kinetic energy of its baryonic content or in magnetic fields (Poynting flux dominated outflow). Prompt emission arises due to internal dissipation of the outflow energy. The remaining energy gets dissipated in the medium surrounding the burst ensuing longer wavelength afterglow emission. However, in majority of GRBs, the early afterglow is influenced by continuous energy supply from the central engine.

The external energy dissipation happens through a forward and reverse shock system. The forward shock runs into the ambient medium and the reverse shock runs into the ejected material. Emission from the reverse shock is seen in the early optical (Sari & Piran 1999) and radio afterglows (Laskar *et al.* 2013). Early afterglow is one of the main tools for probing the central engine. Particularly, the reverse shock emission can shed light into the magnetization of the ejecta which is an important parameter in knowing the jet launching mechanism.

There have been several observational as well as theoretical studies of radio reverse shock emission in the literature. The first detection of a radio flare, expected to be originating from the reverse shock, was for GRB990123. In recent times, deep and fast monitoring campaigns of radio reverse shock emission could be achieved using JVLA (Chandra & Frail 2012; Laskar *et al.* 2013) for a number of bursts. Reverse shock emission is brighter in higher radio frequencies where self-absorption effects are relatively lesser. Gao *et al.* (2013), Kopac *et al.* (2015) and Resmi and Zhang (2016) have done comprehensive analytical and numerical calculations of radio reverse shock emission. Figure 1 compares theoretical predictions of reverse shock emission from Resmi & Zhang (2016). The light curves are calculated by assuming a Newtonian reverse shock (thin shell regime) and ultra-relativistic forward

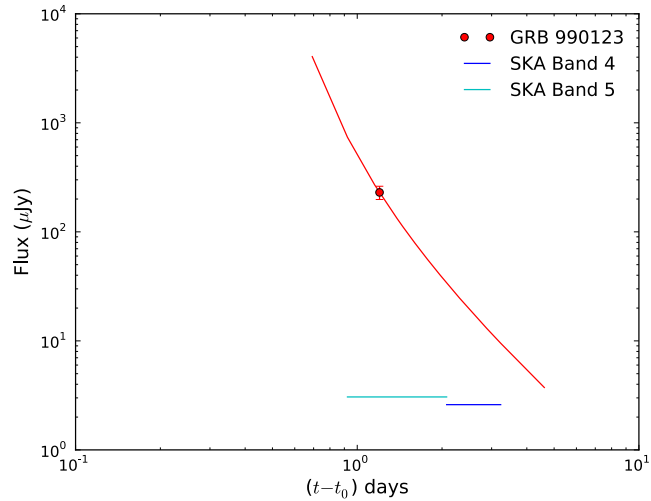


Figure 1. *Top:* Reverse and forward shock predictions in SKA-1 MID Band-4 (4 GHz) and Band-5 (9.2 GHz) for standard parameters (energy in explosion $E_{\text{iso}} = 10^{52}$ ergs; ambient medium density $n_0 = 0.1$ atom/cc; initial bulk Lorentz factor $\eta = 100$; energy content in forward and reverse shock electron populations, $\epsilon_e = 0.1$; energy content in forward shock magnetic field $\epsilon_B = 10^{-5}$). The burst is assumed to be at a redshift of 2. Reverse shock light curve strongly depends on the ratio \mathcal{R}_B of reverse to forward shock magnetic field energy density, in turn the magnetization of the ejecta. 3σ flux limits for SKA MID Band-4 and Band-5 for a 2 h on source integration are also shown for comparison. *Bottom:* Radio flare of GRB990123 in VLA 8 GHz scaled to different redshifts. 3σ limits of SKA-1 MID Band-4 and Band-5 are plotted in the relevant redshift ranges.

shock system in a constant density ambient medium. Difference in ejecta magnetization is reflected in the RS light curve peak time. Radio afterglow monitoring campaigns in higher SKA bands will definitely be useful in exploring reverse shock characteristics. In Fig. 1, we look into the detectability of GRB990123 had it been at higher redshifts. The 8 GHz peak flux and corresponding t_{obs} are scaled accordingly. Accounting for cosmological k -correction, the flux will correspond to SKA-1 MID Band-4 and Band-5 as the redshift changes. SKA-1 MID will be able to detect a bright radio flare like GRB990123 even if it happens at a redshift of ~ 10 .

2.3 Late afterglow and calorimetry with SKA

The uncertainty in jet structure in GRBs pose difficulty in constraining the energy budget of GRBs. Following the afterglow till non-relativistic transition is the key to constrain the GRB energetics independent of geometry. While X-ray and optical afterglows stay above detection limits only for weeks or months, radio afterglows of nearby bursts can be detected up to years (Frail *et al.* 2000; Resmi *et al.* 2005). A couple of very bright afterglows have been observed in time scales of several years by VLA and GMRT. GRB 030329 is the longest observed afterglow, in a campaign made possible through GMRT low-frequency capabilities even when the afterglow had gone below detection limits in higher frequencies. In Fig. 2, we plot the first two years of observations of GRB030329 radio afterglow in GMRT L band.

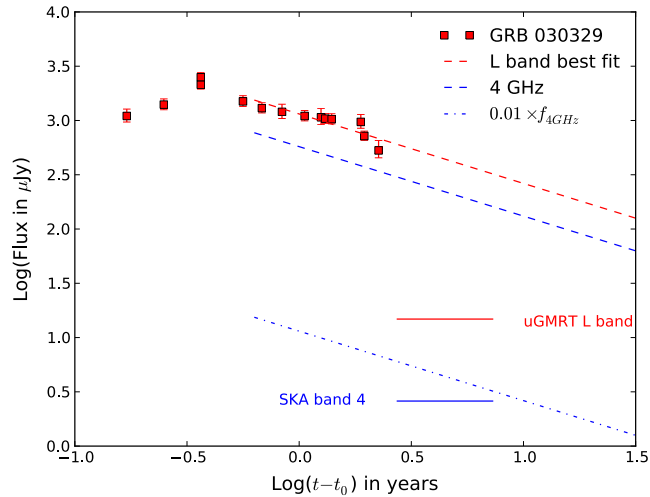


Figure 2. GMRT L-band light curve of GRB030329. Best power-law fit to late time L-band data is shown as dashed red line. A spectral factor assuming index -0.5 is used to obtain the 4 GHz extrapolation (blue dashed line). uGMRT and SKA Band-4 flux limits are for 2 h on source time. The dash-dot line correspond to a burst 100 times fainter than GRB030329 in 4GHz.

The longevity of radio afterglows also make them interesting laboratories to study the dynamics and evolution of relativistic shocks. Fireball transition into non-relativistic regime can be probed through low-frequency radio bands (Frail *et al.* 2000; van der Horst *et al.* 2008) This regime is largely unexplored due to limited number of bursts in the past that stayed above detection limit beyond sub-relativistic regime. Several numerical calculations exist for the afterglow evolution starting from the relativistic phase and ending in the deep non-relativistic phase (van Eerten & MacFadyen 2012; De Colle *et al.* 2012). SKA with its μJy level sensitivity will be able to extend the current limits of afterglow longevity. This will provide us with an unprecedented opportunity to study the deep non-relativistic regime of afterglow dynamics and thereby will be able to refine our understanding of relativistic to non-relativistic transition of the blast wave and changing shock microphysics in the GRBs. In the SKA era, these predictions can be tested against observations. Late afterglow phase where the fireball is both sub-relativistic and nearly spherical, calorimetry can be employed to obtain the burst energetics. These estimates will be free of relativistic effects and collimation corrections. Burlon *et al.* (2015) have computed the rate of detectable GRB afterglows in non-relativistic regime to be about 25% with full SKA.

2.4 Connecting prompt and afterglow physics

GRB prompt spectra, in general, look non-thermal in nature, and is generally modelled using a band function, which is a phenomenological function of two power laws smoothly joined at a peak parameterized as E_{peak} (Band *et al.* 1993). However, the study of GRB spectra using non-thermal models pointed out several spectral features as well as questions (Preece *et al.* 1998; Goldstein *et al.* 2013; Gruber *et al.*

2014; Amati *et al.* 2002; Lu *et al.* 2010; Amati *et al.* 2009) and more importantly, the origin of the observed high radiation efficiency in gamma rays (Cenko *et al.* 2010; Racusin *et al.* 2011). Pure non-thermal models faced difficulty in addressing these questions, which evoked the idea of the presence of thermal component, which is inherent in the standard fireball model, along with non-thermal component in the spectrum. Theoretical models of photospheric emission have currently become the pivot of the study of prompt emission in GRBs. The time resolved analysis of the spectrum enables us to follow the dynamic spectral evolution as well that in these outflow parameters with time, which is crucial to our understanding of how progenitor evolves within the burst (Iyyani *et al.* 2013, 2015, 2016).

BATSE was limited due to its insufficient energy window (20–2000 keV) in determining the overall shape of the GRB spectrum. The *Swift* hard X-ray detector BAT, however, is not very sensitive above about 150 keV (Meegan *et al.* 2009; Band 2006) and hence cannot measure the prompt X-ray/ gamma-ray spectrum accurately (majority of GRBs have their peak energy around 250 keV). However, this drawback was overcome by the launch of *Fermi* in 2008, providing observation over a broad energy range of nearly 7 orders of energy, 8 keV–300 GeV, made possible by two main instruments onboard: Gamma Ray Burst Monitor (GBM; Meegan *et al.* 2009) and Large Area Telescope (LAT; Atwood *et al.* 2009). Some of the key observations by *Fermi* had been: (i) the delayed onset of high energy emission for both long and short GRBs (Abdo *et al.* 2009a, b, c), (ii) longer lasting LAT emission (Ackermann *et al.* 2013), (iii) very high Lorentz factors (~ 1000) are inferred for the detection of LAT high energy photons (Abdo *et al.* 2009a), (iv) several bright bursts show a significant detection of multiple emission components such as thermal component (Guiriec *et al.* 2011; Axelsson *et al.* 2012; Burgess *et al.* 2014), power law (Abdo *et al.* 2009b) or spectral cut off at high energies (Ackermann *et al.* 2011), in addition to the traditional Band function, (iv) interestingly, the Band function is found to have a different spectral shape in these multi-component fitting (Guiriec *et al.* 2013) and (v) it was shown recently by Axelsson & Borgonovo (2015) that 78% of long GRBs and 85% of short GRBs have spectra with spectral width at full-width-half-maximum of the νF_ν peak, that is much narrower than optically thin synchrotron emission, but still broader than a blackbody.

While *Swift* and *Fermi* satellites have enriched our understanding of the GRBs by wide band spectral measurement during the prompt emission by the *Fermi* satellite and quick localization, follow up observation and the consequent redshift measurement was by the *Swift* satellite (Gehrels *et al.* 2009; Gehrels & Mészáros 2012). But currently good spectral and timing measurement from early prompt phase to late afterglow is available for a few sources and they are particularly lacking for the short GRBs. Some of the key problems that can be addressed by the observation of the radio afterglows by SKA in connection with the prompt emission would be the following:

- (i) The connection of LAT detected GRBs with delayed high energy emission with afterglow parameters and comparing the Lorentz factor estimation with both LAT detected GeV photons as well as from the afterglow physics (Kidd & Troja 2014). If the photosphere emission is detected in the prompt phase, this will also give an estimate of the dynamics of the outflow (Iyyani *et al.* 2013). This effort would enable to constrain the Lorentz factor of the outflow which is one of the key dynamic parameters directly connected to the progenitor.

- (ii) Evaluating the connection as well as comparison between non-thermal emission of both the prompt as well as afterglow emission. This would enable to constrain the microphysics of the shocks accelerating electrons to ultra-relativistic energies eventually producing the observed radiation.
- (iii) Detailed modelling of the afterglow observation of both long and short GRBs, will enhance our knowledge about the circumstellar as well as interstellar medium surrounding the progenitors. This will provide information about the host galaxy and the environment which will be crucial in assessing the various proposed progenitor models for these bursts.

SKA with its finer sensitivity would play a key role in constraining the energetics of GRBs which is crucial in estimating the radiation efficiency of the prompt emission of GRBs. This would include the crucial detection of jet breaks in radio bands as well as in constraining the dynamics of the outflow parameters. This would also strengthen our understanding of the hardness-intensity correlation (Amati *et al.* 2002) which can eventually enable us to adopt GRBs as standard candles to probe cosmology. Till date, GRB is the most distant event probed by any astronomical observatory at a photometric redshift estimate of $z = 9.4$ detected for the burst GRB 090429B (Cucchiara *et al.* 2011). In co-ordination with both space as well as ground based observatories in other wavelengths, SKA observations can be crucial in studying the timing of the onset of emission in various wavelengths which can throw light on the issue of where in the outflow does the emission occurs. There have been several detections of thermal component in early X-ray afterglow (Campana *et al.* 2006; Starling *et al.* 2012; Friis & Watson 2013). It would be interesting to find the component in longer wavelengths extending till radio bands which can then prove highly constraining in assessing its connection to the observed prompt thermal emission or whether it has a completely different origin.

The recently launched ASTROSAT satellite (Singh *et al.* 2014) carries a suite of instruments for multi-wavelength studies and the Cadmium Zinc Telluride Imager (CZTI) can act as a monitor above about 80 keV (Rao 2015; Bhalerao *et al.* 2015). CZTI, along with *Swift*, can provide prompt spectroscopy and CZTI can localize *Fermi* detected GRBs correct to a few degrees. Further, for bright GRBs it can provide time resolved polarization measurements. Hence, for a few selected bright GRBs, CZTI, in conjunction with other operational satellites, can provide wide band spectra-polarimetric information and if followed up by other ground-based observatories like SKA pathfinder uGMRT, we can have a complete observational picture of a few bright GRBs from early prompt phase to late afterglow. This will provide us with a comprehensive picture of GRBs, thus enabling a good understanding of the emission mechanisms.

3. Supernovae

Supernovae (SNe) are explosive events with two basic types: (1) thermonuclear supernovae (SNe-Ia), caused by the explosion of a massive white dwarf in a binary system. Their optical spectra are characterized by the absence of H lines and the presence of Si II absorption line; (2) Core-Collapse Supernovae (CCSNe), which mark the end of the life of massive stars. Their classification is based on the observed spectra. Presence or absence of hydrogen lines classify them as Type II and Type I.

In Type I SNe, presence or absence of silicon lines categorize them between Type Ia versus Type Ib/c. Further Type Ib and Ic are classified based on the presence and absence of helium lines, respectively. Amongst Type II SNe, the varied nature of light curves classify them into Types IIP, IIL and IIn.

The physical processes driving the radio emission, and its temporal and spectral properties, turns out to be not only a characteristic of these explosive events itself, but of the pre-explosive evolutionary history of their precursor (progenitor) as well. Typically, there is almost no thermal radio emission in these events. A common property of all supernovae which show up in the radio is the presence of some amount of circumstellar medium (CSM), either or diffuse, in the vicinity of the progenitor, and the synchrotron emission is often successfully modelled as being produced by the interaction of the explosion shock with this material. Incoherent radio emission has been detected from various types of core-collapse supernovae, which includes SNe-Ib (e.g. PS15bgt, Kamble *et al.* 2015), SNe-Ic (e.g. SN 2012ap, Chakraborti *et al.* 2015), SNe-IIn (e.g. SN 1995N, Chandra *et al.* 2009), SN 2006jd (Chandra *et al.* 2012), SN 2010jl (Chandra *et al.* 2015), and SNe-IIP (e.g. SN 2004et, Misra *et al.* 2007), 2011ja (Chakraborti *et al.* 2013), 20012aw (Yadav *et al.* 2014; Chakraborti *et al.* 2016). SKA, with an expected sensitivity ten times that of SKA-1, is expected to detect CCSNe in the local Universe by the thousands. Therefore, commensal SKA observations could easily result in an essentially complete census of all CCSNe in the local Universe, thus yielding an accurate determination of the volumetric CCSN rate. As a survey instrument, SKA will be contemporaneous with LSST and WISE, thus opening a radio vista in to the statistical properties of a dynamic Universe, while as a follow-up instrument, its high sensitivity and resolution will answer several crucial questions about the nature and origins of various SNe, both in the early and in the present Universe.

3.1 Radio view of core collapse supernovae

In supernovae, radio emission arises from shock interaction with the surrounding circumstellar medium (CSM), which provides an important probe to see their last evolution stage. Since radio-SNe can show both early and late radio emission, the most probable model would be that the emission itself comes from relativistic electrons trapped in shocked CSM (early emission) or from the reverse shock itself, as it propagates inwards into the SNe ejecta (late emission) (Chevalier 1998). Therefore, radio SNe probe the dynamics of the SN ejecta, the progenitor structure, and the CSM. Early radio emission is absorbed either by Free-Free Absorption (FFA) or Synchrotron Self-Absorption (SSA). Since SSA necessarily requires the presence of a magnetic field in the emitting region, radio spectra also provide insight into the nature of the CSM field, as well as into the generation/disruption of fields in the SNe-ejecta. In addition, signatures in the multifrequency radio light curves give concurrent information about how the shock accelerated electrons cool in the presence of a long lasting optical emission from the SN through Inverse Compton (IC) cooling or instead, whether synchrotron cooling dominates over IC cooling (Chevalier 2006). Compton cooling of electrons could keep the radio light curve relatively flat in the optically thin regime, whereas synchrotron cooling of electrons will be important if the magnetic field is efficiently built up in the explosion. Radio light curves around 100 days can indicate whether Compton cooling dominates over synchrotron cooling (Fig. 5 of Chevalier, 2006).

Radio data of a few Type IIP SNe show long periods of radio brightness (e.g. beyond 100 days as in SN 2004et, Fig. 3). Radio data on SN 2012aw shows rapid evolution of the radio spectrum between 30 to 70 days and a signature of cooling at higher frequencies (Chevalier 2006). Early observations at high frequencies are critical to the issue of IC cooling of radio emitting electrons. A fraction of Type IIP supernovae (e.g. 2011ja, Chakraborti *et al.* 2013) may happen inside circumstellar bubbles blown by hot progenitor or with complex circumstellar environments set up by variable winds.

SNe IIn are the most complex in terms of stellar evolution. They encompass objects of different stellar evolution and mass loss history. Some SNe IIn, like SN 2005gl, appear to have a Luminous Blue Variable (LBV) star as their progenitor (Gal-Yam *et al.* 2007). A special class of SNe IIn is characterized by spectral similarities to SNe Ia at peak light, but later shows SN IIn properties, e.g., SNe 2002ic and 2005gj. Some SNe IIn appear to be related to SNe Ib/c. Most recently, SN 2009ip is the unique Type IIn SN to have both a massive blue progenitor and LBV-like episodic ejections (Mauerhan *et al.* 2013; Margutti *et al.* 2013). A challenging problem in SNe IIn is that neither their evolutionary status, nor the origin of the tremendous mass loss rates of their pre-SN progenitor stars is known. The estimated mass-loss rates of SN IIn progenitors are much higher than those of usual massive stars ($10^{-4} - 10^{-1} M_{\odot} \text{ yr}^{-1}$). Thus SN IIn progenitors must have enhanced mass loss shortly before their explosions. Thus to unveil the nature of the mysterious SN IIn progenitors and mass loss related to them, we need to know the properties of the SN ejecta and dense CSM related to them.

Some SNe-Ib/Ic have been associated with long duration GRBs. However, as the cases of SN2009bb and SN 2012ap have shown, there may be a class of stellar explosions which bridge the continuum between jetted relativistic events like GRBs and the more spherically symmetric non-relativistic ‘garden variety’ supernovae, without high energy counterparts. These recently discovered radio bright hypernovae

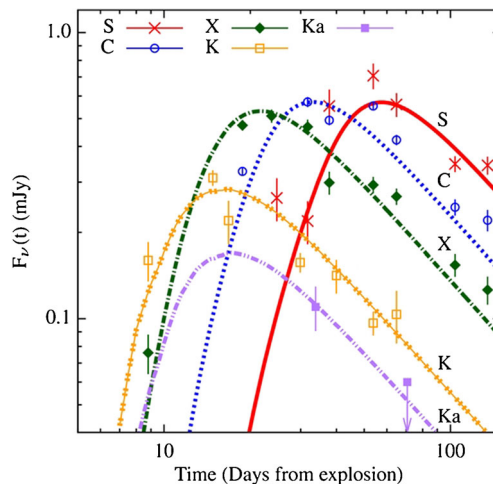


Figure 3. Radio observations of SN 2012aw. The bands are as follows: S (3.0 GHz), C (5.0 GHz), X (8.5 GHz), K (21.0 GHz) and Ka (32.0 GHz). Reproduced from Yadav *et al.* (2014).

(R-HNe) raise important questions about the nature of their central driving engines. The possibilities include: (a) relativistic jets which are formed deep inside the progenitor stars (and whose emergence is suppressed) (Margutti *et al.* 2014); (b) quasi spherical magnetized winds from fast-rotating magnetars, leading to asymmetric explosions, and (c) re-energizing of the shock, as the inner, slower moving shells successively catch up with the shocked region and refresh it (Nakauchi *et al.* 2015, and references therein). The explosion geometry is asymmetrical in the former two cases, and symmetrical in the case of the refreshed shock. Few radio hypernovae have been detected so far, and again, a radio survey like SKA would be the best option to increase the statistics for these events.

Typically, in SNe, spectral radio luminosity $L_R \simeq 10^{33}$ to 10^{38} erg s⁻¹ at 5 GHz, making them fainter by a factor of $\sim 10^4$ in the radio than in the optical. However, there is much diversity in the radio light curves, in the temporal evolution of the radio ‘spectra’, and in the onset of radio emission in different bands, as even across the same sub-class, there are both radio-bright and radio-suppressed events. The latter may partly be a selection effect, which could be resolved with the high sensitivity of the SKA, using SKA-1 MID bands.

3.2 Radio supernova searches with SKA

Radio light curves are crucial to understand the history of the progenitor star. However, currently only $\sim 10\%$ of the discovered core-collapse SNe show radio emission. Only the radio-brightest SNe are detected, and systematic searches of radio emission from core-collapse supernovae (CCSNe) are still lacking, and only targeted searches of radio emission from just some of the optically discovered CCSNe in the local Universe have been carried out. And this, in spite of optical searches missing a significant fraction of CCSNe. This is because the optically dim SNe are missing due to either being intrinsically faint or due to dust obscuration in the host galaxy. Therefore, radio supernova searches are much more promising for yielding the complete, unobscured star-formation rates in the local Universe. As an obvious consequence of the increasing sensitivity of SKA, it will be possible to study a larger number of SNe (from current 2 radio detections/yr up to 50 detections per year with SKA). We would also be able to follow-up each of them for a longer time.

The SKA-1 MID will be able to detect many such dust obscured SNe, especially for those located in the innermost regions of host galaxies. Also the detection of intrinsically dim ones will also benefit from SKA-1. The detection rate will provide unique information about the current star formation rate and the initial mass function. The commensal, wide-field, blind transient survey observations would result in an essentially complete census of all CCSNe in the local Universe, as well as an accurate determination of the true volumetric CCSN rate. SKA-1 is well suited for this. We would also be able to follow-up bright supernovae for a longer time. Commensal observations along with a weekly cadence is likely to result in the most complete sample of radio supernovae (Pérez-Torres *et al.* 2014; Wang *et al.* 2015). With an improved sensitivity level of 1 μ Jy, one can detect the brightest of radio SNe, such as the Type II_n SN 1988Z at the cosmologically interesting distance of $z = 1$.

3.3 Unveiling thermonuclear supernovae with SKA

Despite their great cosmological importance, the exact nature of progenitors of SNe-Ia remains unknown. While the canonical model is that the SNe itself is caused by thermonuclear explosion of a CO White Dwarf (WD), initiated by accretion from a secondary, the nature of the secondary itself is still debatable. In the Singly Degenerate (SD) progenitor scenario, the H- and/or He-rich secondary could be a non-degenerate star which is either MS, immediately post-MS, or even a late evolved red-giant, while in the Double Degenerate (DD) scenario, it could be another WD in close contact binary, which merges into the degenerate SNe progenitor, leading to thermonuclear runaway reaction. Despite the very large number of optical observations of bright, nearby, SNe-Ia, which track the evolution of the SNe from shock outburst to nebular stage, the exact model has not yet been confirmed. Population synthesis studies of SD and DD models (Claeys *et al.* 2014; Rutter *et al.* 2009) suggests that the DD channel is the most probable one, with multiple possible evolutionary sequences, leading to the formation of the close DD system. In any case, it is to be expected that mass loss would have occurred from the progenitor(s) prior to explosion, via stellar winds, Roche-Lobe overflow (RLOW), or in the Common Envelope (CE) phase, and a shock-CSM interaction should produce radio emission, with low frequencies (e.g. SKA bands reaching peak luminosity at a later time). This implies that the temporal, spectral and flux evolution of the radio emission would serve as a trace of the physical properties of SNe shock and CSM interaction.

To date, no SNe-Ia has been detected in the radio, though this could also be a selection effect, in that few bright SNe-Ia have been followed up in the radio band, immediately post-shock, and because a less massive and/or dense CSM would mean that the radio flux density would lie below the detection threshold of the current generation of radio telescopes. For the nearby SN-Ia SN2014J (at 3.5 Mpc), only an upper limit on flux density in the eMERLIN (37.2 and 40.8 μ Jy at 1.55 and 6.17 GHz respectively), JVLA (12.0 and 24.0 μ Jy at 5.5 and 22 GHz respectively) and eEVN (28.5 μ Jy 1.66 GHz) are known, for epochs spanning up to 35 days post explosion (Pérez-Torres *et al.* 2014) – this lack of prompt emission appears to be consistent with the DD progenitor model. Thus, for nearby Type-Ia SNe ($\simeq 2$ such events are detected each year at $V_{\text{peak}} < 13$), even a non-detection of radio emission in the SKA bands would set tight constraints on the mass loss history of the progenitor system, and hence on the theoretical model. It is also to be noted that SNe of all kinds, whose optical emission is shrouded by dust, would nevertheless be visible in the SKA bands, and therefore a survey of transient SKA sources would further constrain supernova rates as a function of various galactic properties.

In addition, supernova explosion triggers shock wave which expels and heats the surrounding CSM and ISM, and so forms supernova remnant (SNR). It is expected that more SNRs will be discovered by the SKA. This may decrease the great number discrepancies between the expected and observed. Several supernova remnants have been confirmed to accelerate protons, main component of cosmic rays, to very high energy by their shocks. The cosmic ray origin will hopefully be solved by combining the low frequency (SKA) and very high frequency (Cherenkov Telescope Array: CTA) bands' observations.

3.4 Gravitational lensing of supernovae

Time delay between multiple images of a gravitationally lensed source is a powerful diagnostic of the physics of the source and cosmology. Time delay in lensing is the only direct observable that gives the physical scale of the system. Rich galaxy clusters at intermediate redshift (~ 0.2 – 1) are powerful lenses. In the central region, multiple images are linearly magnified (according to certain characteristic way) up to a factor of 100, and so, background galaxies at redshift of the order of 1 to 3 are elongated into giant arcs of 10–30 arcseconds. (This is an important channel to possibly detect even galaxies in forming at redshifts of more than 6.) There are more than 100 highly magnified lensed galaxies recorded and the number is increasing with more and more systematic surveys.

If a supernova or GRB occurs in one such galaxy, it will appear in one of the images first, then in the other two images (or three, if magnification is sufficient for detection) at time lag of week to year scale. This was pointed out by Schneider & Wagoner (1987) and Narasimha & Chitre (1989). Position of the event and information about which image will have the event seen first can be unambiguously determined from optical observation of the system and lens model constructed from it. Multifrequency observations, specially optical and radio will be valuable in this respect.

Detecting the event in one image (even partially) allows an observer to plan and monitor the event in other images. This helps to test many aspects of the event itself with elaborate multifrequency observations. The subsequent refined models (specifically time delay measurements are important cosmological probe (specifically Hubble constant and dark energy, Dev *et al.* 2004). Metcalf & Silk (2007) pointed out that the supernova data favour dark matter made of microscopic particles (such as the lightest supersymmetric partner) over macroscopic compact objects (MCOs).

Since there are more than 100 potential targets, we expect one year of careful monitor to register one usable event. SKA-1 MID can organize such a programme and look for these events.

4. Radio selected transients

A large fraction of transients detected in radio for the first time remains undetected in other bands of electromagnetic spectrum and their nature remains unclassified. Early searches for variable and transients in radio band yielded only ~ 10 variable sources (Gregory & Taylor 1986; Langston *et al.* 1990). In the last decade, use of wide frequency imaging techniques have resulted in several reported detections. These include: (i) detection of a transient GCRT J1745–3009 with flux density ≤ 1 Jy at 325 MHz about a degree away from the galactic centre emitting coherent emission (Hyman *et al.* 2005; Roy *et al.* 2010), (ii) ten transients from multi-epoch (22 years) observations of a single field from archival VLA data at 4.8 and 8.4 GHz at \sim a few hundred μ Jy or higher level of flux density (Bower *et al.* 2007), (iii) detection of a single transient at 1.4 GHz with ~ 1 Jy flux density using Nasu observatory in Japan (Niinuma *et al.* 2007), (iv) detection of a single transient GCRT J1742–3001 at 240 MHz with flux density ~ 0.1 Jy near the galactic centre (Hyman *et al.* 2009), (v) detection of 15 transients at 843 MHz from a 22-yr survey with Molonglo observatory synthesis telescope (Bannister *et al.* 2011) at ~ 10 mJy or higher,

(vi) detection of a single transient from about 12 h of observation at 325 MHz at a few mJy level (Jaeger *et al.* 2012), (vii) detection of a single transient from 4 months of observations at 60 MHz with LOFAR at ~ 10 Jy level (Stewart *et al.* 2016).

Out of the 30 transients detected, possible progenitor population of only about 9 have been identified by the respective authors. The origin of the rest of the transients are not known. Clearly, this demonstrates that for most of the transients detected first in the radio band, the parent population is unknown. If we consider extragalactic origin for the transients of unknown origin, we note that flux densities of the detected ones except in Bower *et al.* (2007) are significantly higher than expected from orphan gamma-ray burst afterglows (mJy or lower). Given their flux densities, most of these sources could not be GRB counterparts in radio. Considering optical images of their fields and flux densities, most of these sources could not also be RSNes. Lack of optical emission in continuum images also argues against any scintillating AGN scenario. Therefore, most of the above transients do not appear to have known type of extragalactic progenitor source.

Transient emission could occur from sources within our galaxy. However, the flux densities of the sources detected in radio either lie above or near the upper limit of known stellar luminosity distribution in radio (Güdel 2002; Bower *et al.* 2007). Therefore, typical stellar radio emission cannot account for these emissions. However, coherent emission from stellar surface could occur from energetic processes (e.g., re-connection of magnetic flux tubes) like the electron cyclotron maser at the electron gyro-frequency and its harmonics, or the plasma emission at plasma frequency or its lower order harmonics. Though the bandwidth of such emission is quite small, there can be multiple spots of emission with slightly different centre frequency (Roy *et al.* 2010). These emissions could have high brightness temperature reaching $\sim 10^{16} - 10^{20}$ (Ergun *et al.* 2000; Stepanov *et al.* 2001). These types of flare emission from late type stars (e.g., M-type dwarfs) is known and detected in radio. Their flux densities recorded at cm wavelengths are typically in milliJanskys. However, at metre wavelengths or larger, some of the flares recorded are ~ 100 Jy (Abdul-Aziz *et al.* 1995). Therefore, occasional radio emission from magnetically dominated flare stars which are quite common in the solar neighbourhood could explain some of these transient emissions (Bower *et al.* 2007; Roy *et al.* 2010; Jaeger *et al.* 2012; Stewart *et al.* 2016) and could dominate the transient emissions at metre or decameter wavelengths.

Lack of identification of origin of a major fraction of radio detected transients at the present era makes it a challenging problem. SKA-1 will have a collecting area a few times larger than the GMRT, which will allow to probe for day time scale transients down to $\sim 10 \mu\text{Jy}$ within a bandwidth of a few tens of MHz at metre wavelengths. More importantly, at that wavelength range, the SKA LOW will have a large field-of-view, which will allow to observe a significant fraction of the sky at any time. Detecting long time scale weak transients will not be possible in real time. However, if near real time images of the sky are made with automated pipelines on daily basis, then a comparison of the same portion of the sky observed earlier will allow to detect these transients. This could trigger quick followup observations at other wavebands, which will help to identify their progenitors. Also, a better sensitivity would ensure detection of the brighter ones while their flux density rises/decays down. This will provide their rise/decay light curve crucial to compare with known types of transients. From the earlier detection of transients by Bower *et al.* (2007) at 5 GHz

and Bannister *et al.* (2011) at 843 MHz (assuming a steep spectral index of 0.7 for the transient flux densities, and number density of transients to fall down as a power of flux density with an index of -1.5), and a cutoff flux density of 0.1 mJy at 330 MHz (10σ) for the SKA-1, we estimate the rate of detection of long timescale transients to be $\sim 1-2$ per sq-deg per day. This detection rate is consistent with Jaeger *et al.* (2012), but almost an order of magnitude lower than what is expected from Stewart *et al.* (2016) result at 60 MHz scaled to the above flux density limit at 330 MHz. However, in the last two works, the authors discovered only one transient in each case, and only upper limit can be derived from their results.

It should be noted that the above estimation of the rate of transients assumes observations far away from the galactic plane. Results from observations near the central region of the galaxy have resulted in the detection of 4 transients with GMRT and VLA (Hyman *et al.* 2002, 2006, 2007, 2009). These observations were done over ~ 30 epochs in the last one decade and detection threshold was above a flux density limit of 0.1 Jy. This detection rate (0.005 per sq-deg per day) is an order of magnitude higher than is estimated from above. This does show a galactic contribution of transients in radio, the progenitor population of which needs to be identified. This will also help in separating the two types of transients based on their location in our galaxy or in external ones.

5. Novae outbursts

Novae form an important sub-class of transients in our galaxy as well as in other galaxies. A nova outburst is triggered by runaway thermonuclear burning on the surface of an accreting white dwarf in an interacting binary system. With outburst energy in the range of 10^{38} to 10^{43} ergs, these events are amongst the energetic explosive ones. At an estimated rate of 30 novae per year (2002), these events are fairly frequent. Although the current observed rate is much lower than the estimated, future deep surveys by facilities such as the LSST are expected to increase the number of observed events. Nova systems serve as valuable astrophysical laboratories in the studies of physics of accretion onto compact, evolved objects, and thermonuclear runaways on semi-degenerate surface which give insight into nuclear reaction networks. They also contribute to enriching the ISM with heavy isotopes of ^{13}C , ^{15}N , ^{22}Na and ^{26}Al . In addition, if the mass ejected during a nova outburst is less than that accreted since the last outburst, there is the possibility of the WD growing in mass, making at least some of these systems interesting candidates for SNe Ia progenitors. However, despite their astrophysical significance as nearby laboratories, many aspects of these relatively common stellar explosions remain poorly understood. Although much of our current understanding of these systems has come from the optical observations, multi-waveband observations have augmented and enhanced our understanding. Radio observations play a key role in addressing some of the puzzling aspects of accretion, outburst and interaction with the environment.

Radio emission from novae typically lasts longer than the optical emission, on timescales of years, rather than months. Observations at different epochs yield information on different aspects of the nova outburst. While the very early phase observations provide information regarding the distance to the nova, as the nova evolves, the observations provide clues to the mass of the ejecta. The mass of ejecta is a fundamental prediction of nova models, thereby providing a direct test of nova

theory. The primary mechanism of radio emission is thermal bremsstrahlung from the warm ejecta. In addition, in the case of novae in dense environment, the interaction of the nova ejecta with the environment gives rise to a shock, which in turn may give rise to a non-thermal, synchrotron emission component, like in the case of GK Per (Seaquist *et al.* 1989; Anupama & Kantharia 2005), RS Oph (Hjellming *et al.* 1986; Taylor *et al.* 1989; O'Brien *et al.* 2006; Kantharia *et al.* 2007; Rupen *et al.* 2008; Sokolowski *et al.* 2008; Eyres *et al.* 2009) and V745 Sco (Kantharia *et al.* 2016). The *Fermi* detection of recent novae such as V407 Cyg 2010, V959 Mon 2012, V1324 Sco 2012, V339 Del 2013 and V745 Sco has revealed that shock interaction with the dense environment can also lead to GeV gamma ray emission.

Previous radio observations of nova outbursts have illustrated unique insights into nova explosions these observations bring. Since radio emission traces the thermal free-free emission, by extension, it traces the bulk of the ejected mass. In addition, radio observations are not subject to the many complex opacity and line effects that optical observations both benefit and suffer from. Thus, in addition to being relatively easier to interpret, radio observations can also probe how the ejecta profile and dynamic mass loss evolve with time. Radio observations of novae will thus illuminate the many multi-wavelength complexities observed in novae and test models of nova explosions.

SKA and its precursors will be very well placed to study novae at various epochs of the outburst. While the thermal emission from most novae have been well observed in the higher (>1 GHz) frequencies, the sensitivities of the existing facilities are not well suited to detect thermal emission at <1 GHz. The improved sensitivity of SKA at lower frequencies will enable detection of the thermal emission at these frequencies, providing a better understanding of the evolution of the physical conditions in the nova ejecta. Also, the <1 GHz frequencies are ideal to observe the non-thermal emission from novae, especially from the recurrent nova systems (see Kantharia *et al.* 2016). A sensitivity limit of 1 mJy can detect radio emission at <1 GHz up to a distance of 10 kpc, if the non-thermal luminosity of the nova system is 10^{13} W Hz $^{-1}$ (Kantharia 2012). An important motivation for studying the non-thermal radio emission from recurrent novae is to interrogate possible evolutionary connection to the lack of detectable radio emission from Type Ia supernova systems. As has been shown by Kantharia *et al.* (2016) for the recurrent novae RS Oph and V745 Sco, changes are observed in circumstellar material with subsequent outbursts. Observations of future outbursts will establish if these changes are evolutionary, and also their impact on the evolution of the binary system itself.

6. Multi-messenger astronomy with SKA: Gravitational wave perspective

Electromagnetic counterparts of Gravitational Waves (GWs) are another important class of transients relevant to SKA science. Laser Interferometric Gravitational wave Observatory (LIGO) recently reported the first detection of a binary black hole merger (Abbott *et al.* 2016a), opening a new observational window to the Universe through GWs.

This binary black hole event (named as GW150914) was followed up electromagnetically (Abbott *et al.* 2016b) and in neutrinos (Adrián-Martínez *et al.* 2016) using various observational facilities in the world. While it has been argued that BH-BH mergers will not produce electromagnetic counterparts (Lyutikov 2016), and indeed

no electromagnetic counterparts associated with GW150914 were reported, this sets a milestone in the field of multi-messenger astronomy where a real GW signal was followed up using various electromagnetic (EM) bands. It is worth noting that the above mentioned follow ups included radio follow ups by LOFAR, MWA and ASKAP which demonstrate the capabilities of radio telescopes to carry out searches for EM counterparts of GW events. The LIGO configuration which led to the detection of GW150914 is going to evolve to much better sensitivities which will bring the detection of NS–NS and NS–BH binaries within its reach and more GW detectors are going to come online in the next few years which will considerably improve the source localization.

Phenomenon such as short GRBs and (a sub-population) FRBs have been proposed to be associated with NS–NS or NS–BH mergers. The science potential ranges from detecting radio afterglows associated with short GRBs coincident with GW observations of NS–NS or NS–BH binaries (hence directly confirming the compact binary progenitor of short GRBs), detecting orphan afterglows associated with some of the NS–NS or NS–BH mergers which might have produced a GRB which was pointed away from us and hence missing it, to somewhat speculative scenario of FRBs being detected in coincidence with GW observations (if a sub-population of the FRBs is produced due to mergers of NSs). Such joint observations can shed light on various aspects of the phenomenon including possible constraints on the models of GRB jets (Arun *et al.* 2014).

One of the interesting prospects of SKA for multi-messenger astronomy lies in the radio follow up of GW triggers using the second or third generation gravitational detectors that may be operational at the time of SKA. While it has been argued that BH–BH mergers will not produce electromagnetic counterparts (Lyutikov 2016), there are enough uncertainties in the electromagnetic science of GW waves. In addition, the network of GW detectors by the time SKA comes online, will have much higher sensitivity to detect NH–NH, NH–BH mergers, and may have the capability to localize the source to within few square degrees which makes efficient follow up of the source much simpler. The FOVs of ASKAP (30 sq degree) and SKA LOW (27 sq degree) (see Table 1 of SKA 2015) suits requirements for the EM follow up of GW triggers using a network of interferometers which will localize the sources within a few square degrees to a few tens of square degrees (see Table 3 of Fairhurst (2011) for instance), depending on the nature of the compact binary. The very fact that ASKAP took part in the radio follow up search of GW150914, shows the preparedness of SKA-like detectors to take part in such follow up efforts. The science returns from such joint radio-GW observations are enormous. It is clear that ASKAP will continue to play a crucial role in the follow up of GW triggers in the upcoming science runs of LIGO. It is interesting to note that SKA will be one of the unique instruments which by itself will be searching for gravitational waves (from supermassive BH binaries) in the pulsar timing array mode and also looking for electromagnetic counterparts to ground-based GW detector triggers. Hence multi-messenger astronomy associated with these systems is going to be very exciting.

7. Discussion and conclusions

With the high sensitivity and wide-field coverage of the SKA, very large samples of explosive transients are expected to be discovered. A major fraction of these will

be Tidal Disruption Events (TDE) followed by Type II SNe and orphan afterglows of GRBs and relativistic supernovae. Even at the ASKAP (precursor) stage, VAST-Wide surveys conducted at 1.2 GHz band for about 10,000 square degrees every fortnight will typically be expected to yield some 32 Type II SNe, 82 *Swift* 1644+57 TDE events, 8 orphan afterglows (Frail *et al.* 2012). The large number of such newly discovered sources will be a rich harvest, among which there will be quite a few that will have characteristics (such as radio brightness, counterparts at other wave bands or other physical characteristics like outflow properties) that will make it possible to follow them up intensively with high cadence. Not only will these new discoveries trace out well-populated areas of phase space of explosions (see Fig. 4), but quite likely, they will provide hitherto unknown linkages that will clarify or strengthen suspected unity among diversity (Pietka *et al.* 2015).

Radio wavelengths are particularly well suited for uncovering such phenomena in synoptic surveys, since observations at radio wavelengths may suffer less obscuration than in other bands (e.g. optical/IR or X-rays) due to dust and other absorption. At the same time a multi-waveband approach is a ‘force-multiplier’, since source identification becomes more secure and multi-waveband information often provides critical source classification rapidly than possible with only radio band data. Therefore, multi-waveband observational efforts with wide fields of view will be the key to progress of transients astronomy from middle 2020s offering unprecedented deep images and high spatial and spectral resolutions. Indian astronomers with wide-ranging

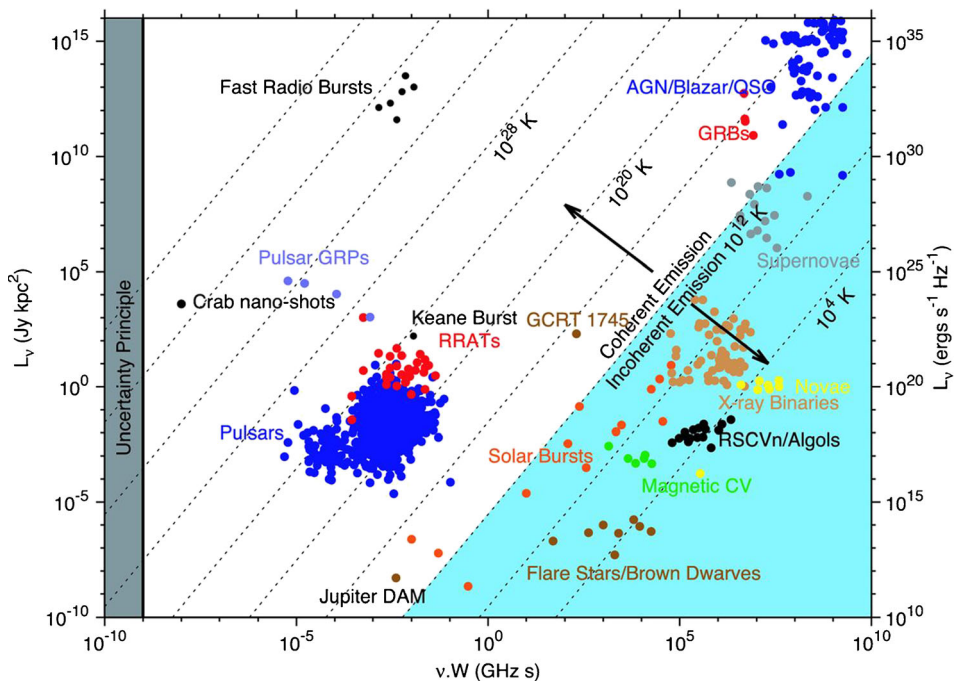


Figure 4. Parameter space for transient sources. This allows one to identify the sources of coherent radio emission (pulsars, fast radio bursts, certain emission from Jupiter and the Sun, etc.) for comparison with the more slowly varying synchrotron transients. Reproduced from Pietka *et al.* (2015).

experience of low-frequency radio astronomy in a variety of astronomical phenomena and targets would be particularly well-placed to pursue time critical transient objects with SKA and observatories at other bands.

Our strategy will also include to develop tools with machine learning capabilities to automatically and rapidly classify the transient events expected in the SKA era and follow up a few of these intensively and with multiwaveband coverage through other large facilities that India will likely have access to. These exceptional few objects have the potentials for discovery of major underlying physical processes and trends. For example, the abundance of relativistic SNe without GRB counterparts, and luminous TDE events will have implications among other things on the sources of Ultra High Energy Cosmic Rays within the Greisen–Zatsepin–Kuzmin (GZK) cutoff distance from the Earth (Chakraborti *et al.* 2011).

The SKA will be a premier instrument for transient science. This strength of the science case will continue to increase as more and more class of transients are discovered with current surveys, including uGMRT, ASKAP, MWA, etc. There is much development going on in hardware, software, simulation and data analysis techniques, all to improve the chances of detecting transients. All of the next generation telescopes have included the transient science as one of the core science goals, and this is also being reflected in developments at nearly all other wavelengths.

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