Hindawi Publishing Corporation
Advances in Astronomy
Volume 2016, Article ID 2967813, 13 pages
http://dx.doi.org/10.1155/2016/2967813

Review Article

Gamma-Ray Bursts: A Radio Perspective

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Received 13 July 2016; Revised 28 September 2016; Accepted 10 October 2016

Academic Editor: WeiKang Zheng

Gamma-ray bursts (GRBs) are extremely energetic events at cosmological distances. They provide unique laboratory to investigate fundamental physical processes under extreme conditions. Due to extreme luminosities, GRBs are detectable at very high redshifts and potential tracers of cosmic star formation rate at early epoch. While the launch of *Swift* and *Fermi* has increased our understanding of GRBs tremendously, many new questions have opened up. Radio observations of GRBs uniquely probe the energetics and environments of the explosion. However, currently only 30% of the bursts are detected in radio bands. Radio observations with upcoming sensitive telescopes will potentially increase the sample size significantly and allow one to follow the individual bursts for a much longer duration and be able to answer some of the important issues related to true calorimetry, reverse shock emission, and environments around the massive stars exploding as GRBs in the early Universe.

1. Introduction

Gamma-ray bursts (GRBs) are nonrecurring bright flashes of γ-rays lasting from seconds to minutes. As we currently understand, in the standard GRB model a compact central engine is responsible for accelerating and collimating the ultra-relativistic jet-like outflows. The isotropic energy release in prompt γ-rays ranges from $\sim 10^{48}$ to $\sim 10^{54}$ ergs; see, for example, [1]. While the prompt emission spectrum is mostly nonthermal, presence of thermal or quasithermal components has been suggested for a handful of bursts [2]. Since the initial discovery of GRBs [3] till the discovery of GRB afterglows at X-ray, optical, and radio wavelengths three decades later [4–7], the origin of GRBs remained elusive. The afterglow emission confirmed that GRBs are cosmological in origin, ruling out multiple theories proposed favouring Galactic origin of GRBs; see, for example, [8].

In the *BATSE* burst population, the durations of GRBs followed bimodal distribution, short GRBs with duration less than 2 s and long GRBs lasting for more than 2 s [9]. Long GRBs are predominantly found in star forming regions of late type galaxies [10], whereas short bursts are seen in all kinds of galaxies [11]. Based on these evidences, the current understanding is that the majority of long GRBs originate in the gravitational collapse of massive stars [12], whereas at least a fraction of short GRBs form as a result of the merger of compact object binaries (see Berger [13] for a detailed review).

GRBs are detectable at very high redshifts. The highest redshift GRB is GRB 090429B with a photometric redshift of $z = 9.4$ [14]. However, the farthest known spectroscopically confirmed GRB is GRB 090423 at a redshift of $z = 8.23$ [15], indicating star formation must be taking place at such early epoch in the Universe [16]. At the same time, some GRBs at lower redshifts have revealed association with type Ib/c broad lined supernovae, for example, GRB 980425 associated with SN 1998bw [17].

Since the launch of the *Swift* satellite in November 2004 [18], the field of GRB has undergone a major revolution. Burst Alert Telescope (BAT) [19] on-board *Swift* has been localizing ~100 GRBs per year [20]. X-ray Telescope (XRT [21]) and Ultraviolet/Optical Telescope (UVOT [22]) on-board *Swift* slew towards the BAT localized position within minutes and provide uninterrupted detailed light curve at these bands. Before the launch of the *Swift*, due to the lack of dedicated instruments at X-ray and optical bands the afterglow coverage was sparse, which is no longer the case. *Swift*-XRT has revealed that central engine is capable of injecting energy into the forward shock at late times [23–25].

GRBs are collimated events. An achromatic jet break seen in all frequencies is an undisputed signature of it. However, the jet breaks are seen only in a few *Swift* bursts, for example, GRB 090426 [26], GRB 130603B [27], and GRB 140903A [28]. Many of the bursts have not shown jet breaks. It could be because *Swift* is largely detecting fainter bursts with an average redshift of >2, much larger than the detected by previous instruments [20]. The faintness of the bursts makes it difficult to see jet breaks. Some of the GRBs have also revealed chromatic jet breaks, for example, GRB 070125 [29].

An additional issue is the narrow coverage of the *Swift*-BAT in 15–150 keV range. Due to the narrow bandpass, the uncertainties associated in energetics are much larger since one needs to extrapolate to 1–10,000 keV bandpass to estimate the $E_{\rm iso}$, which is a key parameter to evaluate the total released energy and other relations. Due to this constraint, it has been possible to catch only a fraction of traditional GRBs.

The *Swift* drawback was overcome by the launch of *Fermi* in 2008, providing observation over a broad energy range of over seven decades in energy coverage (8 keV–300 GeV). Large Area Telescope (LAT [30]) on-board *Fermi* is an imaging gamma-ray detector in 20 MeV–300 GeV range with a field of view of about 20% of the sky and Gamma-ray Burst Monitor (GBM) [31] on-board *Fermi* works in 150 keV–30 MeV and can detect GRBs across the whole of the sky. The highest energy photon detected from a GRB puts a stricter lower limit on the outflow Lorentz factor. *Fermi* has provided useful constraints on the initial Lorentz factor owing to its high energy coverage, for example, short GRB 090510 [32]. This is because to avoid pair production, the GRB jet must be moving towards the observer with ultra-relativistic speeds. Some of the key observations by *Fermi* had been (i) the delayed onset of high energy emission for both long and short GRBs [33–35], (ii) long lasting LAT emission [36], (iii) very high Lorentz factors (~1000) inferred for the detection of LAT high energy photons [33], (iv) significant detection of multiple emission components such as thermal component in several bright bursts [37–39], and (v) power-law [35] or spectral cut-off at high energies [40], in addition to the traditional band function [41].

While the GRB field has advanced a lot after nearly 5 decades of extensive research since the first discovery, there are many open questions about prompt emission, content of the outflow, afterglow emission, microphysics involved, detectability of the afterglow emission, and so forth. Resolving them would enable us to understand GRBs in more detail and also use them to probe the early Universe as they are detectable at very high redshifts. With the recent discoveries of gravitational waves (GWs) [42, 43], a new era of Gravitational Wave Astronomy has opened. GWs are ideal to probe short GRBs as they are the most likely candidates of GW sources with earth based interferometers.

In this paper, we aim to understand the GRBs with a radio perspective. Here we focus on limited problems which can be answered with more sensitive and extensive radio observations and modeling. By no means, this review is exhaustive in nature. In Section 2, we review the radio afterglow in general and out current understanding. In Section 3, we discuss some of the open issues in GRB radio afterglows. Section 4 lists the conclusion.

2. Afterglow Physics: A Radio Perspective and Some Milestones

In the standard afterglow emission model, the relativistic ejecta interacting with the circumburst medium gives rise to a forward shock moving into the ambient circumburst medium and a reverse shock going back into the ejecta. The jet interaction with the circumburst medium gives rise to mainly synchrotron emission in X-ray, optical, and radio bands. The peak of the spectrum moves from high to low observing frequencies over time due to the deceleration of the forward shock [44] (e.g., see Figure 1). Because of the relativistic nature of the ejecta, the spectral peak is typically below optical frequencies when the first observations commence, resulting in declining light curves at optical and X-ray frequencies. However, optically rising light curve has been seen in a handful of bursts after the launch of the *Swift* [45], for example, GRB 060418 [46].

The first radio afterglow was detected from GRB 970508 [7]. Since then the radio studies of GRB afterglows have increased our understanding of the afterglows significantly, for example, [47–49]. A major advantage of radio afterglow emission is that, due to slow evolution, it peaks in much later time and lasts longer, for months or even years (e.g., [50–52]). Thus unlike short-lived optical or X-ray afterglows, radio observations present the possibility of following the full evolution of the fireball emission from the very beginning till the nonrelativistic phase (see, e.g., [50–52]); also see GRB 030329 [53, 54]. Therefore, the radio regime plays an important role in understanding the full broadband spectrum. This constrains both the macrophysics of the jet, that is, the energetics and the circumburst medium density, as well as the microphysics, such as energy imparted in electrons and magnetic fields necessary for synchrotron emission [55]. Some of the phenomena routinely addressed through radio observations are interstellar scintillation, synchrotron self-absorption, forward shocks, reverse shocks, jet breaks, nonrelativistic transitions, and obscured star formation.

The inhomogeneities in the local interstellar medium manifest themselves in the form of interstellar scintillations and cause modulations in the radio flux density of a point source whose angular size is less than the characteristic angular size for scintillations [56]. GRBs are compact objects and one can see the signatures of interstellar scintillation at early time radio observations, when the angular size of the fireball is smaller than the characteristic angular scale for interstellar scintillation. This reflects influx modulations seen in the radio observations. Eventually due to relativistic expansion, the fireball size exceeds the characteristic angular scale for scintillations and the modulations quench. This can be utilised in determining the source size and the expansion speed of the blast wave [7]. In GRB 970508 and GRB 070125, the initial radio flux density fluctuations were interpreted as interstellar scintillations, which lead to an estimation of the upper limit on the fireball size [7, 29, 57]. In GRB 070125, the scintillation time scale and modulation intensity were consistent with those of diffractive scintillations, putting a tighter constraint on the fireball size [29].

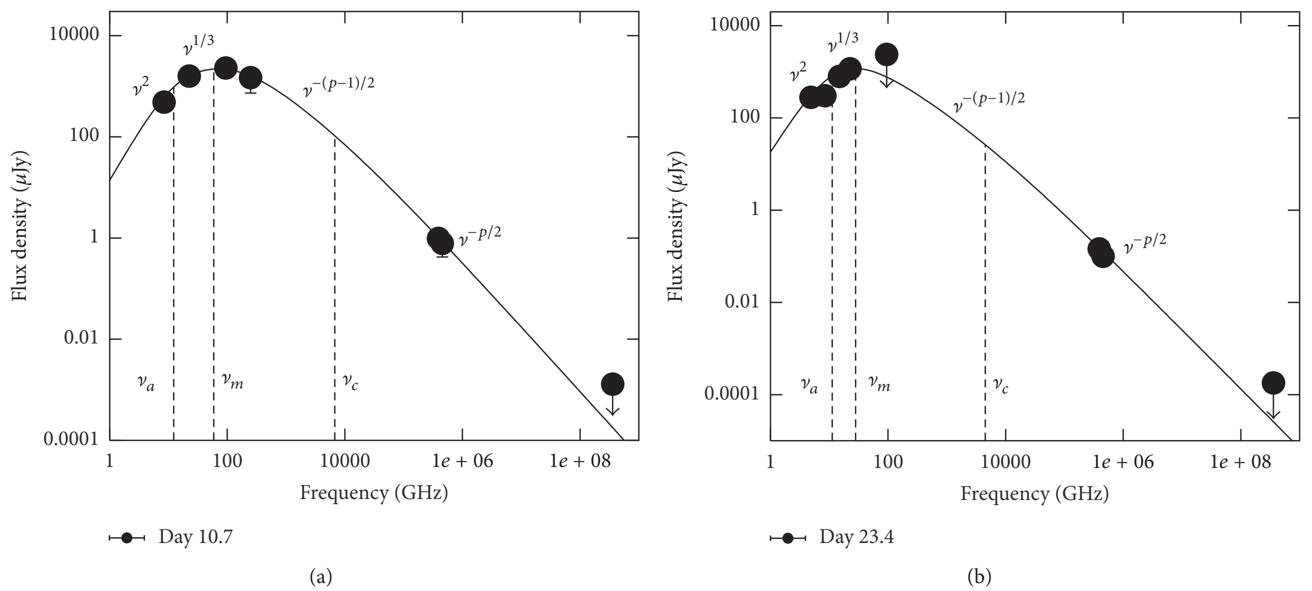


Figure 1: Multiwaveband spectra of GRB 070125 on day 10.7 and day 23.4. The spectra are in fast cooling regime. One can see that, between the spectra on day 10.7 and day 23.4, the peak has shifted to lower frequency. The figure is reproduced from Chandra et al. [29].

Very Long Baseline Interferometry (VLBI) radio observations also play a key role by providing evidence for the relativistic expansion of the jet using for bright GRBs. This provides microarcsecond resolution and directly constrains the source size and its evolution. So far this has been possible for a nearby ($z = 0.16$) GRB 030329 [58]. In this case, the source size measurements were combined with its long term light curves to better constrain the physical parameters [53, 54]. In addition, GRB 030329 also provided the first spectroscopic evidence for association of a GRB with a supernova. This confirmed massive stars origin of at least a class of GRBs.

Radio observations are routinely used in broadband modeling of afterglows and used to derive blast-wave parameters [1, 29, 59–61] (also see Figure 1). Early radio emission is synchrotron self-absorbed; radio observations uniquely constrain the density of the circumburst medium. Radio studies have also proven useful for inferring the opening angles of the GRB jets as their observational signature differs from those at higher wavelengths [50, 62–64]. Recently GRB 130427A, a nearby, high-luminosity event, was followed at all wavebands rigorously. It provided extremely good temporal (over 10 orders of magnitude) and spectral coverage (16 orders of magnitude in observing frequency [65, 66]). Radio observations started as early as 8 hours [67]. One witnessed reverse shock and its peak moving from high to low radio frequencies over time [67–70]. The burst is an ideal example to show how early to late-time radio observations can contribute significantly to our understanding of the physics of both the forward and reverse shocks.

Radio afterglows can be detected at high redshifts [16, 71] owing to the negative k-correction effect [72]. GRB 090423 at a redshift of 8.3 is the highest redshift (spectroscopically confirmed) known object in the Universe [15]. It was detected in radio bands for several tens of days [16]. The multiwaveband modeling indicated the $n\ 1\,\mathrm{cm}^{-3}$ density medium and the massive star origin of the GRB. This suggested that the star formation was taking place even at a redshift of 8.3.

The radio afterglow, due to its long-lived nature, is able to probe the time when the jet expansion has become subrelativistic and geometry has become quasispherical [50, 52, 73] and thus can constrain energetics independent of geometry. This is possible only in radio bands as it lasts for months or even years (e.g., [50–52]). GRB 970508 remained bright more than a year after the discovery, when the ejecta had reached subrelativistic speeds. This gave the most accurate estimate of the kinetic energy of the burst [50].

Reverse shock probes the ejecta and thus can potentially put constraints on the Lorentz factor and contents of the jet (e.g., [68, 69]). The shock moving into the ejecta will result in an optical flash in the first tens of seconds after the GRB under right conditions. The radio regime is also well suited to probe the reverse shock emission as well. Short-lived radio flares, most likely due to reverse shock, have also been detected from radio observations [16, 74–76] and seem more common in radio bands than in the optical bands. GRB 990123 was the first GRB in which the reverse shock was detected in optical [77] as well as in radio bands [74].

From the radio perspective, GRB 030329 holds a very important place. It was the first high-luminosity burst at low redshift with a spectroscopic confirmation of a supernova associated with it. So far this is the only GRB for which the source size has been measured with VLBI. The radio afterglow of GRB 030329 was bright and long lasting and has been detected for almost a decade at radio frequencies [52, 78]. This enabled one to perform broadband modeling in the different phases and has led to tighter constraints on the physical parameters [53, 54]. However, the absence of a counter

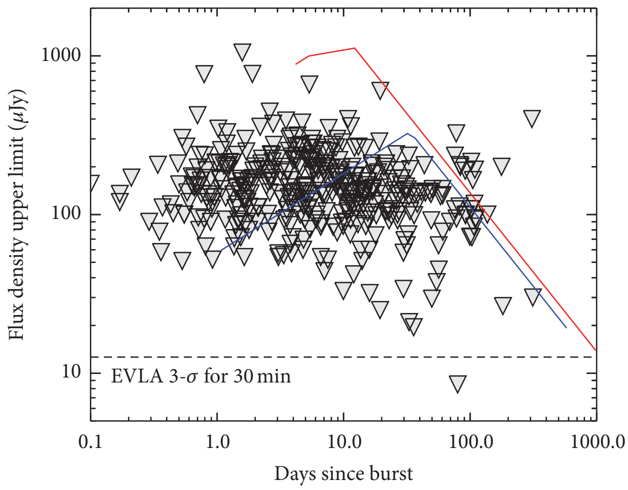


Figure 2: Plot of 3-σ upper limits at 8.5 GHz frequency band for all GRBs for which no afterglow was detected. The red line shows light curve of a rare, bright event GRB 980703 and the blue line shows the light curve of a more typical event GRB 980329. The detection fraction of radio afterglows in the first 10 days certainly appears to be mainly limited by the sensitivity. The black dashed line indicates 3-σ sensitivity of the JVLA in its full capacity for a 30-minute integration time. The figure is reproduced from [48].

jet poses serious question in our understanding of GRBs [79].

3. Open Problems in GRB Radio Afterglows

With various high sensitivity new and refurbished telescopes, for example, Atacama Large Millimetre Array (ALMA), Karl J. Jansky Very Large Array (JVLA), upgraded Giant Metrewave Radio Telescope (uGMRT), and upcoming telescopes, for example, Square Kilometre Array (SKA), the radio afterglow physics of GRBs is entering into new era, where we can begin to answer some of the open questions in the field, answers to which are long awaited. In this section, I discuss only some of those open problems in GRB science where radio measurements can play a crucial role.

This review is not expected to be exhaustive. We concentrate on only a few major issues.

3.1. Are GRBs Intrinsically Radio Weak? Since the launch of the *Swift*, the fractions of X-ray and optically detected afterglows have increased tremendously; that is, almost 93% of GRBs have a detected X-ray afterglow [80] and ~75% have detected optical afterglows [81, 82]. However, what is disconcerting is that the radio detection fraction has remained unchanged with only one-third of all GRBs being detected in radio bands [47, 48]. Chandra and Frail [48] attributed it to sensitivity limitation of the current telescopes (see Figure 2). This is because radio detected GRBs have flux densities typically ranging from a few tens of μJy to a few hundreds of μJy [48]. Even the largest radio telescopes have had the sensitivities close to a few tens of μJy, making the radio afterglow detection sensitivity limited. The newer generation radio telescopes should dramatically improve statistics of radio afterglows. For example, using numerical simulation of the forward shock, Burlon et al. [83] predict that the SKA-1 (SKA first phase) Mid band will be able to detect around 400–500 radio afterglows per $\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}$.

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) [84–86] is the largest worldwide single-dish radio telescope, being built in Guizhou province of China with an expected first light in Sep. 2016. FAST will continuously cover the radio frequencies between 70 MHz and 3 GHz. The radio afterglow of GRBs is one of the main focuses of FAST. Zhang et al. [84] have estimated the detectability with FAST of various GRBs like failed GRBs, low-luminosity GRBs, high-luminosity GRBs, and standard GRBs. They predict that FAST will be able to detect most of the GRBs other than subluminous ones up to a redshift of $z \leq 10$.

However, Hancock et al. [87] used stacking of radio visibility data of many GRBs and their analysis still resulted in nondetection. Based on this they proposed a class of GRBs which will produce intrinsically faint radio afterglow emission and have black holes as their central engine. GRBs with magnetars as central engine will produce radio bright afterglow emission. This is because the magnetar driven GRBs will have lower radiative efficiency and produce radio bright GRBs, whereas the black hole driven GRBs with their high radiative efficiency will use most of their energy budget in prompt emission and will be radio-faint. This is a very important aspect and may need to be addressed. And if true, it may reflect the nature of the central engine through radio measurements. JVLA at high radio frequencies and the uGMRT at low radio frequencies test this hypothesis. SKA will eventually be the ultimate instrument to distinguish between the sensitivity limitation and the intrinsic dimness of radio bursts [83].

3.2. Hyperenergetic GRBs. Accurate calorimetry is very important to understand the true nature of the GRBs. This includes prompt radiation energy in the form of γ-rays and kinetic energy in the form of shock powering the afterglow emission. Empirical constraints from models require that all long duration GRBs have the kinetic energies $\leq 10^{51}$ ergs. GRBs are collimated events; thus the jet opening angle is crucial to measure the true budget of the energies. While isotropic energies range of energies spread in four orders of magnitude (see Figure 3), the collimated nature of the jet makes the actual energies in much tighter range clustered around 10^{51} ergs [75, 88, 89]. However, it is becoming increasingly evident that the clustering may not be as tight as envisaged and the actual energy range may be much wider than anticipated earlier. A population of nearby GRBs have relativistic energy orders of magnitude smaller than a typical cosmological GRB; these are called subluminous GRBs, for example, GRB 980425 [25, 90]. *Fermi* has provided evidence for a class of hyperenergetic GRBs. These GRBs have total prompt and kinetic energy release, inferred via broadband modeling [61, 91], to be at least an order of magnitude above the canonical value of 10^{51} erg [1, 29, 48, 92]. The total energy budget of these hyperenergetic GRBs poses a significant challenge for some accepted progenitor models. The maximum energy release in magnetar models [93] is

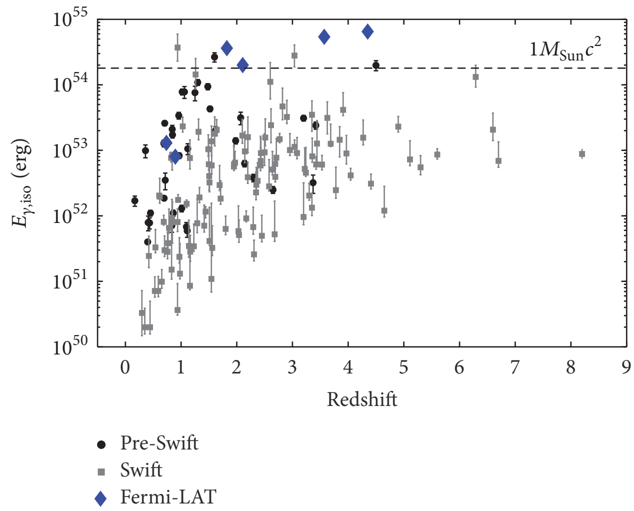


FIGURE 3: Isotropic prompt gamma-ray energy release ($E_{\gamma,\mathrm{iso}}$, in rest frame 1 keV–10 MeV bandpass) of GRBs with measured redshift. One can see a large range of $E_{\gamma,\mathrm{iso}}$. Reproduced from Cenko et al. [1].

3×10^{52} erg, set by the rotational energy of a maximally rotating stable neutron star [94, 95].

It has been very difficult to constrain the true prompt energy budget of the GRBs, mainly, for the following reasons. So far, *Swift* has been instrumental in detecting majority of the GRBs. However, peaks of the emission for various GRBs lie outside the narrow energy coverage of *Swift*-BAT (15–150 keV). In addition, extrapolation of 15–150 keV to 1–10,000 keV bandpass causes big uncertainties in the determination of prompt isotropic energies. With its huge energy coverage (8 keV–300 GeV), *Fermi* has overcome some of these limitations and provided unparalleled constraints on the spectral properties of the prompt emission. *Fermi* has been able to distinguish the true hyperenergetic bursts (such as GRB 090323, GRB 090902B, and GRB 090926A [1]; also see Figure 3). While *Swift* sample is biased towards faint bursts, *Fermi* sample is biased towards GRBs with very large isotropic energy releases (10^{54} erg), which even after collimation correction reach very high energies, for example, [1, 96], and provide some of the strongest constraints on possible progenitor models.

The uncertainty in jet structure in GRBs pose additional difficulty in constraining the energy budget of GRBs. Even after a jet break is seen, to convert it into opening angle, one needs density to convert it into the collimation angle. While some optical light curves can be used to constrain the circumburst density (e.g., Liang et al. [45]), radio SSA peak is easier to detect due to slow evolution in radio bands. With only one-third of sample being radio bright, this has been possible for only a handful of bursts. A larger radio sample at lower frequencies, at early times when synchrotron self-absorption (SSA) is still playing a major role, could be very useful. The uGMRT after upgrade will be able to probe this regime as SSA will be affecting the radio emission at longer wavelength for a longer time. However, the this works on the assumption that the entire relativistic outflow is collimated into a single uniform jet. While the proposed double-jet models for GRB 030329 [97, 98] and GRB 080319B [99] ease out the extreme efficiency requirements, it has caused additional concerns.

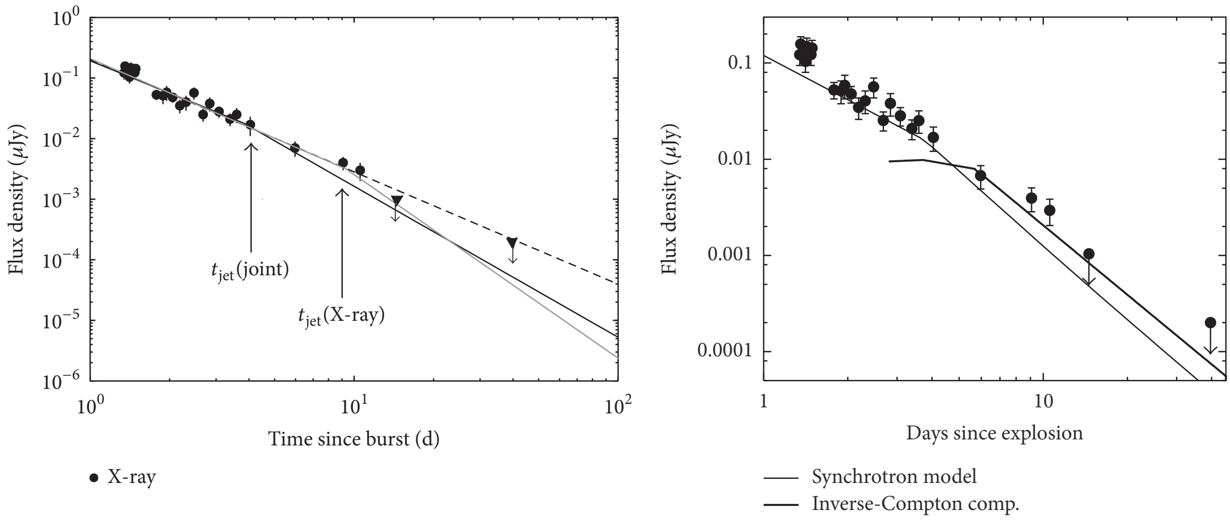
The ALMA also has an important role to play since GRB spectrum at early times peak at mm wavelengths, when it is the brightest. ALMA with its high sensitivity can detect such events at early times and give better estimation of the kinetic energy of the burst.

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 [50, 100]. The longevity of radio afterglows also makes them interesting laboratories to study the dynamics and evolution of relativistic shocks. At late stages, the fireball would have expanded sideways so much that it would essentially make transition into nonrelativistic regime and become quasispherical and independent of the jet geometry; calorimetry can be employed to obtain the burst energetics [50, 52]. These estimates will be free of relativistic effects and collimation corrections. This regime is largely unexplored due to limited number of bursts staying above detection limit beyond subrelativistic regime. Several numerical calculations exist for the afterglow evolution starting from the relativistic phase and ending in the deep nonrelativistic phase [79, 101]. 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 nonrelativistic regime of afterglow dynamics and thereby will be able to refine our understanding of relativistic to nonrelativistic transition of the blast-wave and changing shock microphysics and calorimetry in the GRBs. Burlon et al. [83] have computed that SKA1-MID will be able to observe 2% afterglows till the nonrelativistic (NR) transition but that the full SKA will routinely observe 15% of the whole GRB afterglow population at the NR transition.

3.3. Can Jet Breaks Be Chromatic?

After the launch of *Swift*, one obtained a far better sampled optical and X-ray light curves, thus expected to witness achromatic jet breaks across the electromagnetic spectrum, a robust signature associated with a collimated outflow. Several groups conducted a comprehensive analysis of a large sample of light curves of *Swift* bursts in the X-rays [102–105] and optical [106] bands. Surprisingly fewer *Swift* bursts have shown this unambiguous signature of the jet collimation. Without these collimation angles, the true energy release from *Swift* events has remained highly uncertain. A natural explanation for absence of the jet breaks can be attributed to the high sensitivity of *Swift*. Due to its high sensitivity *Swift* is preferentially selecting GRBs with smaller isotropic gamma-ray energies and larger redshifts. This dictates that typical *Swift* events will have large opening angles, thus causing jet breaks to occur at much time than those of pre-*Swift* events. Since afterglow is already weak at later times, making jet break measurements is quite difficult [103, 107].

There have been some cases where chromatic jet breaks are also seen. For example, in GRB 070125, the X-ray jet break occurred around day 10, whereas the optical jet break



(a) (b)

Figure 4: (a) X-ray light curve of GRB 070125. Best-fit single power-law models are shown with dashed lines, while the broken power-law models are shown in solid lines. The t_{jet}(joint) is the joint fit to optical and X-ray data and grey solid line t_{jet}(X-ray) is the independent fit. The independent fit shifts the jet break to ~9-10 days, which was found to be day 3 for optical bands. (b) Contribution of IC in the synchrotron model for the X-ray light curve of GRB 070125. The thin line represents the broadband model with the synchrotron component only. The thick line represents the IC light curve. One can see that IC effect can delay the jet breaks in X-ray bands [29].

occurred on day 3. Chandra et al. [29] attributed it to inverse Compton (IC) effect, which does not affect the photons at low energies but shifts the X-ray jet break at a later time (see Figure 4, [29]). As IC effects are dominant in high density medium, radio observations are an important indicator of the effectiveness of the IC effect. Chandra et al. [29] showed that, for a given density of GRB 070125, the estimated delay in X-ray jet break due to the IC effect is consistent with the observed delay. However, this area needs to be explored further for other GRBs. While high density bursts are likely to be brighter in radio bands, it may cause a burst to be a dark one in optical wavelength (Xin et al. [108] and references therein), which then make it difficult to detect the jet break simultaneously in several wavelengths. uGMRT and JVLA will be ideal instruments to probe IC effect and will potentially be able to explain the cause of chromaticity in some of the *Swift* bursts.

3.4. High-z GRBs and PoP III Stars. One of the major challenges of the observational cosmology is to understand the reionization of the Universe, when the first luminous sources were formed. So far quasar studies of the Gunn-Peterson absorption trough, the luminosity evolution of Lyman galaxies, and the polarization isotropy of the cosmic microwave background have been used as diagnostics. But they have revealed a complicated picture in which reionization took place over a range of redshifts.

The ultraviolet emission from young, massive stars (see Fan et al. [109] and references therein) appears to be the dominant source of reionization. However, none of these massive stars have been detected so far. Long GRBs, which are explosions of massive stars, are detectable out to large distances due to their extreme luminosities and thus are the potential signposts of the early massive stars. GRBs are predicted to occur at redshifts beyond those where quasars are expected; thus they could be used to study both the reionization history and the metal enrichment of the early Universe [110]. They could potentially reveal the stars that form from the first dark matter halos through the epoch of reionization [72, 111, 112]. The radio, infrared, and X-ray afterglow emission from GRBs are in principle observable out to $z = 30$ [72, 111–114]. Thus GRB afterglows make ideal sources to probe the intergalactic medium as well as the interstellar medium in their host galaxies at high z.

The fraction of detectable GRBs that lie at high redshift ($z > 6$) is, however, expected to be less than 10% [115, 116]. So far there are only 3 GRBs with confirmed measured redshifts higher than 6. These are GRB 050904 [117], GRB 080913 [118], and GRB 090423 [15]. Radio bands are ideal to probe GRB circumburst environments at high redshift because radio flux density show only a weak dependence on the redshift, due to the negative k-correction effect [72] (also see [47] and Figure 5). In k-correction effect, the afterglow flux density remains high because of the dual effects of spectral and temporal redshift, offsetting the dimming due to the increase in distance [111] (see Figure 5). GRB 050904 and GRB 090423 were detected in radio bands and radio observations of these bursts allowed us to put constraints on the density of the GRB environments at such high redshifts. While the density of GRB 090423 was $n \sim 1\,\text{cm}^{-3}$ [16] (Figure 5), the density of GRB 050904 was ~$100\,\text{cm}^{-3}$, indicating dense molecular cloud surrounding the GRB 050904 [119]. This revealed that these two high-z GRBs exploded in a very different environment.

ALMA will be a potential tool for selecting potential high-z bursts that would be suitable for intense follow-up across

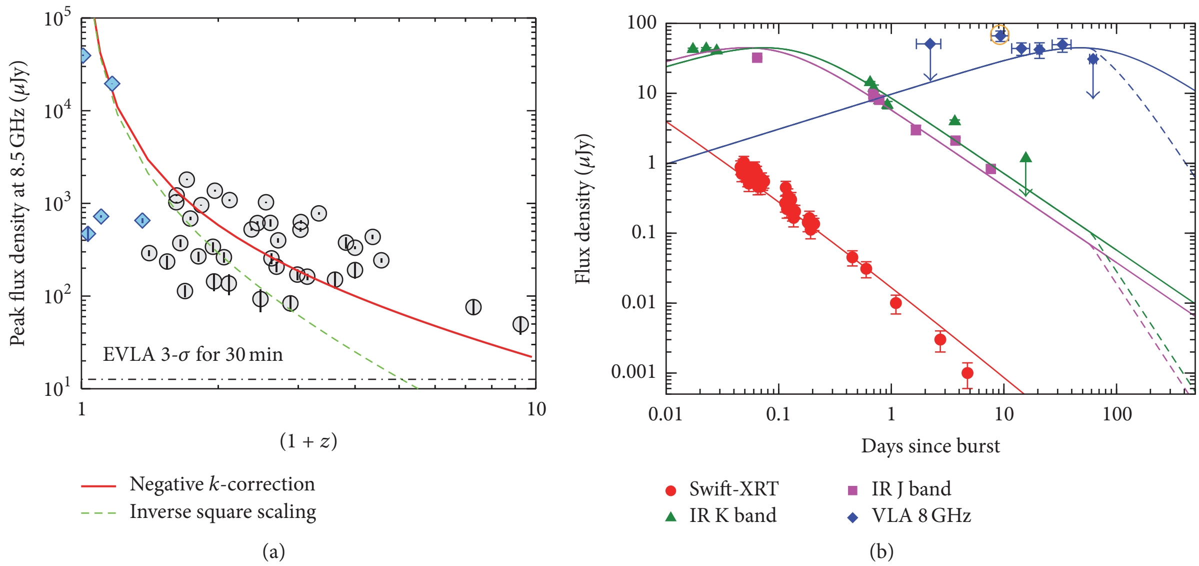


FIGURE 5: (a) The 8.5 GHz radio peak flux density versus $(1 + z)$ plot for radio afterglows with known redshifts. Blue diamonds are GRBs associated with supernovae, while the grey circles denote cosmological GRBs. The green dashed line indicates if the flux density scales as the inverse square of the luminosity distance. The red thick line is the flux density scaling in the canonical afterglow model which includes a negative k-correction effect, offsetting the diminution in distance (reproduced from [48]). (b) Multiwaveband afterglow modeling of highest redshift GRB 090423 at $z = 8.23$ (reproduced from [16]).

the electromagnetic spectrum. With an order of magnitude enhanced sensitivity the JLA will be able to study a high-z GRB for a longer timescale. For example, VLA can detect GRB 090423-like burst for almost 2 years. The uGMRT can also detect bright bursts up to a redshift of $z \sim 9$. These measurements will therefore obtain better density measurements and reveal the environments where massive stars were forming in the early Universe.

3.5. Reverse Shock. In a GRB explosion, there is a forward shock moving forward into the circumburst medium, as well as a reverse shock moving backwards into the ejecta [120]. The nearly self-similar behavior of a forward shock means that little information is preserved about the central engine properties that gave rise to the GRB. In contrast, the brightness of the short-lived reverse shock depends on the initial Lorentz factor and the magnetization of the ejecta. Thus, multifrequency observations of reverse shocks tell about the acceleration, the composition, and the strength and orientation of any magnetic fields in the relativistic outflows from GRBs [68, 69, 121–123]. In general, the reverse shock is expected to result in an optical flash in the first tens of seconds after the GRB [77], which makes it difficult to detect as robotic telescopes are required for fast triggers.

The discovery of a bright optical flash from GRB 990123 [77] leads to extensive searches for reverse shocks [124–127] in optical bands. One expected to see more evidences of reverse shocks in optical bands due to *Swift*-UVOOT; however, based on these efforts it seems that the incidence of optical reserve shocks is low. Since the peak of this emission moves to lower frequencies over time and can be probed at radio frequencies on a time scale of hours to days [74], the radio regime is well suited for studying early time reverse shock phenomena.

There have been several observational as well as theoretical studies of radio reverse shock emission in the literature after the first reverse shock detection in GRB 990123 [74]. Gao et al. [128], Kopač et al. [129], and Resmi and Zhang [130] have done comprehensive analytical and numerical calculations of radio reverse shock emissions and about their detectability. It has been shown [48, 67] that deep and fast monitoring campaigns of radio reverse shock emission could be achieved with the VLA for a number of bursts. JVLA radio frequencies are well suited as reverse shock emission is brighter in higher radio frequencies where self-absorption effects are relatively lesser. Radio afterglow monitoring campaigns in higher SKA bands (e.g., SKA1-Mid Band-4 and Band-5) will definitely be useful in exploring reverse shock characteristics [83].

Reverse shock is detectable in high redshift GRBs ($z \geq 6$) as well. Inoue et al. [131] have predicted that at mm bands the effects of time dilation almost compensate for frequency redshift, thus resulting in a near-constant observed peak frequency at a few hours after event and a flux density at this frequency that is almost independent of redshift. Thus ALMA mm band is ideal to look for reverse shock signatures at high redshifts. Burlon et al. [83] predict that SKA1-Mid will be able to detect a reverse shock from a GRB990123 like GRB at a redshift of ~10.

3.6. Connecting Prompt and Afterglow Physics. Swift is an ideal instrument for quick localization of GRBs and rapid follow-up and consequently redshift measurement [20, 132] and *Fermi* for the wideband spectral measurement during the prompt emission. However, good spectral and timing measurement covering early prompt to late afterglow phase is available for a few sources and rarely available for the short GRBs. Some of the key problems that can be addressed by the observation of the radio afterglows in connection with the prompt emission are (i) comparing the Lorentz factor estimation with both LAT detected GeV photons as well as from the reverse shock [133, 134]; (ii) comparison between nonthermal emission of both the prompt and afterglow emission, which would enable one to constrain the microphysics of the shocks accelerating electrons to ultra-relativistic energies eventually producing the observed radiation; (iii) detailed modeling of the afterglow observation of both long and short GRBs, which will enhance our knowledge about the circumburst medium surrounding the progenitors; (iv) current refurbished and upcoming radio telescopes with their finer sensitivity, which 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 strengthen the understanding of the hardness-intensity correlation [135].

The recently launched *AstroSAT* satellite [136] carries several instruments enabling multiwavelength studies. The Cadmium Zinc Telluride Imager (CZTI) on-board *AstroSAT* can provide time resolved polarization measurements for bright GRBs and can act as a monitor above 80 keV [137, 138]. So far no other instrument has such capability to detect polarization. Hence, for a few selected bright GRBs, CZTI, in conjunction with ground based observatories like uGMRT and JVLA, and other space based facilities can provide 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.

3.7. Some Other Unresolved Issues. So far I have discussed only that small fraction of on-axis GRBs, in which the jet is oriented along our line of sight. Due to large Lorentz factors, small opening angles of the collimated jets, we only detect a small fraction of GRBs [139]. Ghirlanda et al. [140] have estimated that, for every GRB detected, there must be 260 GRBs which one is not able to detect. However, their existence can be witnessed as "orphan afterglow" at late times when the GRB jet is decelerated and spread laterally to come into our line of sight. At such late times, the emission is expected to come only in radio bands. So far attempts to find such orphan radio afterglows have been unsuccessful [75, 141, 142]. Even if detected, disentangling the orphan afterglow emission from other classes will be very challenging. Soderberg et al. [141] carried out a survey towards the direction of 68 Type Ib/c supernovae looking for the orphan afterglows and put limit on GRB opening angles, $\theta_j > 0.8$ d. The detection of population of orphan afterglows with upcoming sensitive radio facilities is promising. This will give a very good handle on jet opening angles and on the total GRB rate whether beamed towards us or not.

The inspiral and merger of binary systems with black holes or neutron stars have been speculated as primary source of gravitational waves (GWs) for the ground based GW interferometers [143, 144]. The discovery of GWs from GW 150914 [42] and GW 151226 [43] with the Advanced LIGO detectors have provided the first observational evidence of the binary black hole systems inspiraling and merging. At least some of the compact binaries involving a neutron star are expected to give rise to radio afterglows of short GRBs. Electromagnetic counterparts of GW source, including emission in the radio bands, are highly awaited as they will, for the first time, confirm the hypothesis of binary merger scenario for GW waves. If localized at high energies, targeted radio observations can be carried out to study these events at late epochs.

Short GRBs arising from mergers of two neutron stars eject significant amount of mass in several components, including subrelativistic dynamical ejecta, mildly relativistic shock-breakout, and a relativistic jet [145]. Hotokezaka and Piran [145] have calculated the expected radio signals produced between the different components of the ejecta and the surrounding medium. The nature of radio emission years after GRB will provide invaluable information on the merger process [145] and the central products [146]. Fong et al. [146] have predicted that the formation of stable magnetar of energy 10^{53} erg during merger process will give rise to a radio transient a year later. They carried out search for radio emission from 9 short GRBs in rest frame times of 1–8 years and concluded that such a magnetar formation can be ruled out in at least half their sample.

In addition, radio observations can also probe the star formation and the metallicity of the GRB host galaxies when optical emissions are obscured by dust [147, 148].

4. Conclusions

In this article, I have reviewed the current status of the *Swift*/*Fermi* GRBs in context of their radio emission. With improved sensitivity of the refurbished radio telescopes, such as JVLA and uGMRT and upcoming telescopes like SKA, it will be possible to answer many open questions. The most crucial of them is the accurate calorimetry of the GRBs. Even after observing a jet break in the GRB afterglow light curves, which is an unambiguous signature of the jet collimation, one needs density estimation to convert the jet break epoch to collimation angle. The density information can be more effectively provided by the early radio measurements when the GRBs are still synchrotron self-absorbed. So far it has been possible for very limited cases because only one-third of the total GRBs have been detected in radio bands [48]. Sensitive radio measurements are needed to understand whether the low detection rate of radio afterglows is intrinsic to GRBs or the sensitivity limitations of the current telescopes are playing a major role. In the era of JVLA, uGMRT, ALMA, and upcoming SKA, this issue should be resolved. In addition, these sensitive radio telescopes will be crucial to detect radio afterglows at very high redshifts and provide unique constraints on the environments of the exploding massive stars in the early Universe. If GRBs are not intrinsically dim in radio bands and the sample is indeed sensitivity limited, then SKA is expected to detect almost 100% GRBs [83]. SKA will be able to study the individual bursts in great detail. This will also allow us to carry out various statistical analyses of the radio sample and drastically increase our overall understanding of the afterglow evolution from very early time to nonrelativistic regime. Detection of the orphan afterglow is due any time and will be novel in itself.

Competing Interests

The author declared that there are no competing interests.

Acknowledgments

The author thanks L. Resmi, Shabnam Iyyanni, A. R. Rao, Kuntal Misra, and D. Frail for many useful discussions in the past, which helped shape this article. The author acknowledges support from the Department of Science and Technology via SwarnaJayanti Fellowship Award (File no. DST/SJF/ PSA-01/2014-15). The author also acknowledges SKA Italy handbook (http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215), where many of the SKA numbers on sensitivity, GRB detection rates, and so forth are taken.

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