Radio Afterglows of Gamma-Ray Bursts: Unique Clues to the Energetics and Environments

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Abstract. Radio observations of gamma-ray burst (GRB) afterglows provide both complementary and unique diagnostics of the afterglow physics and environment of the burst. Here we concentrate on three unique aspects of GRB energetics and environments afforded by radio and submillimeter observations: the non-relativistic evolution of the fireball, the density profile of the circumburst medium, and the study of obscured star formation in GRB host galaxies.

1. Introduction

The afterglows of gamma-ray bursts (GRBs) are a broad-band phenomenon. As such, their study requires exquisite data from radio to X-rays. Still, in addition to complementary information, the radio band provides some unique diagnostics of the afterglow physics and burst environment. We illustrate this in Figure 1 which shows a heuristic radio lightcurve ranging in time from a few hours to hundreds of days after the burst. Here we concentrate on three unique aspects of radio observations: the non-relativistic expansion, the ability to probe the density and profile of the circumburst medium, and as a tracer of obscured star formation in GRB host galaxies. However, before delving into this discussion we quickly summarize the information in Figure 1 by way of introduction.

At present, even with response times to GRB alerts of minutes the radio bands provide the best way to study the synchrotron emission from the reverse shock (e.g. Soderberg & Ramirez-Ruiz 2002). Optical observations require response on the timescale of the burst duration and have been successfully made only three times (Akerlof et al. 1999; Kobayashi & Zhang 2002; Fox et al. 2002; Li et al. 2003). Only in the case of GRB 990123, the peak of the reverse shock emission was actually observed. In the radio bands on the other hand, emission from the reverse shock has been observed several times since the peak is more easily observable is \( t \sim t_{\text{dur}} \times (\nu_{\text{rad}}/\nu_{\text{opt}})^{-48/73} \sim 1 \) day (Sari & Piran 1999). In addition, the mere detection of the reverse shock in the radio on the timescale of 1 day rules out a circumburst medium with a Wind (i.e. \( \rho \propto r^{-2} \)) density profile (Berger et al. 2003a).

By the same token, the typical response time prevents optical observers from catching the peak of the synchrotron emission from the forward shock. Thus, optical observations cannot constrain the peak flux which is required for inferring the physical parameters of the burst and environment (e.g. Berger et al. 2000). The radio bands directly trace these two parameters since the peak of
the spectrum reaches the radio on the timescale of \( \sim 10 \) days. Moreover, only the radio bands trace synchrotron self-absorption, which is particularly sensitive to the density of the circumburst medium.

Perhaps the most unique aspect of the radio emission is the existence of propagation effects in the form of interstellar scintillation. A detailed discussion of scintillation is beyond the scope of this review, but it serves as a unique way to “resolve” the afterglow and infer the size of the fireball over time (e.g. Frail, Waxman & Kulkarni 2000).

Radio observations are also well-suited for inferring the opening angles of wide jets. The signature of a collimated outflow is a break in the lightcurves occurring when \( \Gamma \sim \theta_{\text{jet}}^{-1} \) (Rhoads 1997); for wide jets the break occurs at late time. Unfortunately, on such timescales the host galaxy masks the optical afterglow and the break cannot be inferred from this band. In the radio, on the other hand, the emission usually peaks on the timescale of about 10 days so wide jets are easily studied (Berger et al. 2001).

The dominance of the optical host galaxy at late time in addition to the faint X-ray afterglow indicate that only the radio bands allow us to study the long-term behavior of the afterglow. In several cases we have observed radio af-

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**Figure 1.** Heuristic lightcurve in the radio band. Timescales and scalings for the temporal evolution are indicated. The list summarizes aspects of the flux evolution which are unique to the radio bands (Lorentz factor, \( \Gamma \); source size, \( \theta \); energy, \( E \); density, \( n \); jet opening angle, \( \theta_{\text{jet}} \); density profile; magnetic field strength, \( B \); and obscured star formation rate).
The Radio Afterglows of Gamma–Ray Bursts

Teraglows over a year after the burst. One effect, which is readily detectable if the afterglow is bright enough, is the transition from relativistic to sub-relativistic expansion (Frail et al. 2000). Depending on the initial kinetic energy of the ejecta and the density of the ambient medium, this occurs on the timescale of \( \sim 100 \) days (Figure 1 and §2.).

Finally, as the radio emission fades significantly we may detect emission from the host galaxy. In all cases in which a radio host has been detected (e.g. Berger et al. 2003b) the inferred star formation rates are several hundred of \( \text{M}_\odot \text{yr}^{-1} \), indicating significant dust obscuration (§4.).

To summarize, radio observations probe the evolution of the fireball over a factor of \( \sim 10^3 \) in time. Below we focus on the information that can be gleaned from these unique observations for the study of GRB energetics and environments.

Figure 2. Radio lightcurve of GRB 980703 at 8.46 GHz. The blue line is a model fitting the first 50 days of data. Clearly an extrapolation of this model to late time (dashed blue line) does not agree with the data. This is due to a transition to sub-relativistic expansion. The red line is a model fit using the Sedov-Taylor model with a host galaxy dominating at late time. From Berger et al. in prep.
2. The Non-Relativistic Evolution: Fireball Calorimetry

Recent work has shown that the beaming-corrected $\gamma$-ray and kinetic energies of GRBs are approximately constant (Frail et al. 2001; Berger, Kulkarni & Frail. 2003). The latter, however, is inferred without knowledge of what this constant energy actually is. Instead, the kinetic energy in the afterglow phase can be inferred from broad-band observations (e.g. Panaitescu & Kumar 2002). In reality this requires exquisite data and assumptions about the hydrodynamics of the fireball which are yet to be verified.

Fortunately, radio observations at late time provide an alternative method. The principle is simple. As the fireball decelerates it eventually becomes trans- and then non-relativistic. This typically happens on the timescale of $\sim 100$ days when the peak of the synchrotron spectrum is in the radio bands. A simple signature of the transition from relativistic to sub-relativistic expansion is a flattening of the radio lightcurves compared to the jet evolution (Figure 2). Analyzing the subset of radio data following this transition in the Sedov-Taylor self-similar framework we can infer the energy, density, magnetic field strength, and size of the fireball. This method has the principle attraction that the dynamics of the spherical, non-relativistic fireball are better understood than those of relativistic expanding jets.

To date this method has been applied to two bursts, GRB 970508 (Frail et al. 2000) and GRB 980703 (Berger et al. in prep). In both cases energies of about $10^{50}$ erg have been inferred, in agreement with other methods. One possibility which is currently being investigated is whether there is evidence for evolution of the fireball parameters between the early observations and the late non-relativistic stage.

3. The Circumburst Environment: ISM vs. Wind

One of the indirect clues to the identity of GRB progenitors is the structure and density of the circumburst medium. If the progenitors are massive stars then we expect them to explode in the dense media of their birth sites. Moreover, the pre-burst stellar mass loss is expected to influence the environment, resulting (in the most simple case) in a density profile $\rho \propto r^{-2}$. On the other hand, if GRBs arise from delayed mergers of compact source binaries then the environment is expected to be the tenuous ISM of the host galaxy. This is because velocity kicks imparted to the system in the supernova explosion of the binary members will eject it away from the birth-site.

Extensive efforts have been made to infer the density and profile of the circumburst medium primarily by studying the broad-band afterglow emission (e.g. Chevalier & Li 2000). Unfortunately, these studies have been inconclusive in distinguishing between Wind and ISM density profiles due primarily to the lack of early radio and submillimeter observations, or in some cases their preclusion from the analysis.

There are two clear exceptions to this disappointing trend, which in conjunction present an interesting conundrum. In the case of GRB 011121 Price et al. (2002) inferred a Wind medium thanks to dual-band radio observations. At the same time, Bloom et al. (2002) interpreted the late-time red bump in the
Figure 3. Left: Submillimeter/radio vs. optical star formation rates for GRB host galaxies. The line designates a one-to-one correspondence between the two SFR estimates. Clearly, some hosts have a high fraction of obscured star formation. Right: $R-K$ color as a function of redshift. The ellipses are centered on the mean color and redshift for each population of galaxies and have widths of $2\sigma$. The GRB hosts are in general significantly bluer than submillimeter galaxies in the same redshift range.

optical afterglow as a supernova that exploded at the same time as the burst. These observations naturally point to a massive star as the progenitor of this burst. On the other hand, for GRB020405, Berger et al. (2003a) showed that the reverse shock emission detected at $t \sim 1$ day in the radio bands rules out a Wind medium. However, this burst also had an associated red bump indicative of a supernova (Price et al. 2003) and hence a massive stellar progenitor.

These results imply that contrary to the optimistic expectations of afterglow modelers, a Wind profile does not necessarily accompany a massive progenitor and may not be a strong clue to the nature of the progenitor. Still, the inference of Wind vs. ISM profile relies heavily on radio observations.

4. The Large-Scale Environment: Host Galaxies and Obscured Star Formation

The host galaxies of GRBs can be used as a complementary and perhaps quite promising sample for the study of cosmic star formation:

Redshifts: Thanks to the bright afterglows, the redshift of the host galaxy can be determined regardless of its brightness, via absorption spectroscopy.

Faint (Dwarf) Hosts: Some GRB host galaxies are several orders of magnitude fainter than $L_*$ and provide us with a glimpse of faint dwarfs at high redshift.

Immunity to Dust: The dust-penetrating power of GRBs results in a sample that is independent of the dust properties of the individual galaxies.

Very High Redshifts: GRBs are detectable to $z > 10$ (should they exist).

To date, GRB host galaxies have mainly been studied in the optical and NIR bands. With the exception of one source (GRB020124; Berger et al. 2002),
every GRB localized to a sub-arcsecond position has been associated with a
star-forming galaxy, with star formation rates of $\sim 1 - 10 \, M_\odot \, yr^{-1}$.

On the other hand, recent radio and submillimeter observations (Berger, Kulkarni & Frail 2001; Frail et al. 2002; Berger et al. 2003b) have revealed that
about 20% of GRB hosts are ultra-luminous with star formation rates of several
hundred of $M_\odot \, yr^{-1}$, indicating significant dust obscuration (Figure 3). While
these properties are similar to those of submillimeter-selected galaxies (Chapman
et al. 2002) the $R - K$ colors of GRB hosts are significantly bluer (Figure 3).
Exactly what this means is still not clear (one possibility is younger starbursts),
but it is evident that GRBs probe a portion of the galaxy population that is
completely missed in current submillimeter surveys.

While the present GRB sample is significantly smaller than the Lyman-
break or submillimeter samples, SWIFT should supply us with several hundred
GRB host galaxies. This sample may provide a new window to the evolution of
cosmic star formation.

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