The Unique Potential of SKA Radio Observations of Gamma-Ray Bursts.

T. J. Galama
Astronomy
Mail Stop 105-24, Robinson Lab
California Institute of Technology
Pasadena, CA 91125
U.S.A.
E-mail: tjg@astro.caltech.edu

A. G. De Bruyn
Netherlands Foundation for Research in Astronomy and Kapteyn Astronomical Institute
E-mail: ger@nfra.nl

Radio observations with the Square Kilometer Array (SKA) provide the agility, sensitivity, and spectral coverage to trace the evolution of the size, shape and spectra of gamma-ray burst (GRB) remnants from the earliest moments on. In the first hours to days after the burst a major, and unique tool, will be provided through the study of dynamically evolving radio spectra, caused by diffractive and refractive scintillation in the local ISM. Simultaneous observations from optically thin to optically thick frequencies will provide strong constraints on any model for the GRB remnant. SKA will also allow for extremely rapid (within minutes, if not seconds) follow-up observations by electronic steering of the array. SKA observations have the sensitivity to detect GRB afterglows out to redshifts of 10 or greater. They therefore allow studies of the high redshift universe, and measure the massive star formation (and massive star death rate!) history of the universe, unbiased by optical obscuration. Wide field surveys may detect thousands of GRBs within a few days of observing (depending on the amount of collimation, the width of the GRB luminosity function, the number of GRBs like GRB 980425/SN1998bw). There would be new ones, but many more would be old, fading afterglows, allowing the determination of the multivariate GRB-optical-radio luminosity function of GRBs. This should elucidate the relation of the ‘faint’ ones, like GRB 980425, to the luminous ones like GRB970508. Such surveys will also tell us whether GRB fireballs (and which ones) are collimated into jets.

1 Introduction

Gamma-ray bursts (GRBs) are the strongest phenomenon seen at γ-ray wavelengths. Since their discovery in the 1970s these events, which emit the bulk of their energy in the 0.1 – 1.0 MeV range, and whose durations span milliseconds to tens of minutes, posed one of the great unsolved problems in astrophysics. Until recently, no counterparts (quiescent as well as transient) could be found and observations did not provide a direct measurement of their distance, and thereby the true energy output was unknown by several orders of magnitude. The breakthrough came in early 1997, when the Wide Field Cameras aboard the Italian-Dutch BeppoSAX satellite allowed rapid and accurate localization of GRBs. Follow-up on these positions resulted in the discovery of X-ray [1], optical [2] and radio afterglows [3]. These observations revealed that GRBs come from ‘cosmological’ distances. GRBs are by far the most luminous photon sources in the universe, with (isotropic) peak luminosities in γ rays up to $10^{52}$ erg/s, and total energy budgets up to several $10^{53} - 10^{54}$ erg (e.g., [4]). The optical signal from GRB is regularly seen to be 10 magnitudes brighter (absolute) than the brightest supernovae, and once even 18 magnitudes brighter [5].

Here we discuss the current status of GRB afterglow observations (Sect. 2 to 6) and discuss the unique potential of SKA observations of GRBs (Sect. 7).
2 Relativistic blast-wave models

GRB afterglows are in good agreement with, so called, fireball-plus-relativistic blast-wave models (see [6] for an extensive review). The basic model is a point explosion with an energy of order $10^{52}$ ergs, which leads to a ‘fireball’, an optically thick radiation-electron-positron plasma with initial energy much larger than its rest mass that expands ultra-relativistically. The GRB may be due to a series of ‘internal shocks’ that develop in the relativistic ejecta before they collide with the ambient medium. When the fireball runs into the surrounding medium a ‘forward shock’ ploughs into the medium and heats it, and a ‘reverse shock’ does the same to the ejecta. As the forward shock is decelerated by increasing amounts of swept-up material it produces a slowly fading ‘afterglow’ of X rays, then ultraviolet, optical, infrared, millimetre, and radio radiation.

Confirmation of the relativistic blast-wave model. Radio light curves of the afterglow of GRB 970508 show variability on time scales of less than a day, but these dampen out after one month [3] (see Fig. 1). Interpreting this as the effect of source expansion on the diffractive interstellar scintillation a source size of roughly $10^{17}$ cm was derived, corresponding to a mildly relativistic expansion of the shell [3].

The first X-ray and optical (but see [7]) afterglows show power-law temporal decays, with power-law exponents in the range 1 to 2. These afterglow light curves agree well with the predictions of the relativistic blast-wave model (e.g., [8, 9, 10]).

The broad-band afterglow spectra are also power laws (in four distinct regions); together with the observed decrease of the cooling break and the peak frequency the observations conform nicely with simple relativistic blast-wave models in which the emission is synchrotron radiation by electrons accelerated in a relativistic shock [9, 10].

The brightness temperature of the GRB 990123 optical flash [3] exceeds the Compton limit of $10^{12}$ K, confirming the highly relativistic nature of the GRB source [11].

3 Progenitors and the cause of the explosion

The GRB and the afterglow are produced when relativistic ejecta are slowed down; no observable radiation emerges directly from the ‘hidden engine’ that powers the GRB. Thus, in spite of all recent discoveries the origin of GRBs remains unknown (although an important link may be provided by the possible connection of GRBs to SNe). Currently popular models for the origin of GRBs are the neutron star-neutron star and neutron star-black hole mergers, white dwarf collapse, and core collapses of very massive stars (‘failed’ supernovae or hypernovae). These models can in principle provide the required energies.

SN 1998bw/GRB 980425. Galama et al. [12] discovered a relatively rare and bright SN of type Ic within the small BeppoSAX localization of GRB 980425, and suggested that the two objects are connected. A conservative estimate of the probability of a chance coincidence of the supernova and the GRB is $9 \times 10^{-5}$ [12]. In the radio, the SN rapidly brightened and became one of the most luminous radio SNe [13]. Kulkarni et al. [13] drew attention to the fact that the radio emitting shell in SN 1998bw must be expanding at relativistic velocities, $\Gamma \gtrsim 2$; see Fig. 1. This relativistic shock could well have produced the GRB at early times. The consequence of accepting such an association is that the $\gamma$-ray peak luminosity of GRB 980425 and its total $\gamma$-ray energy budget are much smaller (a factor of $\sim 10^5$) than those of ‘normal’ GRBs. GRB 980425 is thus a member of a new class of GRBs – low luminosity GRBs related to nearby SNe (SN 1998bw is at $z = 0.0085$). Such GRBs may well be the most frequently occurring GRBs!

GRBs and SNe. But perhaps most, if not all, GRBs are associated with supernovae. There is growing evidence linking the usual GRBs – the cosmologically located GRBs – to SNe. The most direct evidence comes from the suggestion of an underlying SN in the afterglow of GRB 980326 [15]. The SN is revealed readily by its distinctive UV-poor spectrum against the
broad-band afterglow. Also for GRB 970228 there is evidence that a supernova dominated the light curves at late times \[7, 16\]. So there may not be a dichotomy between ‘normal’ and supernova GRBs, only a gradual transition. The relation between cosmologically located GRBs like GRBs (980326, 970228) and GRB 980425/SN 1998bw is as yet unclear.

**Collapsar model.** All these observational developments support the collapsar model pioneered by Woosley and collaborators (see \[17\] and refs therein) in which massive stars core collapse to form black holes. Energy is somehow extracted from the spinning black hole and the jets drill their way out and power the GRBs and their afterglows.

### 4 GRBs as potential probes of the high-redshift universe

Host galaxies have been seen in most optical afterglow images. The detection of [O II] $\lambda$ 3727 and Lyman $\alpha$ emission from some hosts indicates that these are sites of vigorous star formation. The observed connection between some GRBs and star forming regions suggests that GRBs occur at critical phases in the evolution of massive stars. If GRBs are related to the deaths of massive stars (whose total lifetime is very short), their rate is proportional to the star formation rate (SFR). In that case GRBs may very well be at very high redshifts, with $z \sim 6$ or greater, for the faintest bursts (e.g. \[18\]). GRBs may therefore become a powerful tool to probe the far reaches of the universe by guiding us to regions of very early star formation, and the (proto) galaxies and (proto) clusters of which they are part. The redshifts determined so far range between $z = 0.41$ and $z = 3.42$.

### 5 The early afterglow

The discovery of a very bright and brief optical flash coincident in time with GRB 990123 \[3\] shows that the early optical signal from GRB can be some 18 magnitudes brighter than the
brightest supernovae. The reverse shock could cause emission that peaks in the optical waveband and is observed only during or just after the GRB. GRB 990123 would then be the first burst in which all three emitting regions have been seen: internal shocks causing the GRB, the reverse shock causing the prompt optical flash, and the forward shock causing the afterglow [11, 21, 22].

6 Strongly anisotropic outflow (beaming)

An important uncertainty concerns the possible beaming of the $\gamma$-ray and afterglow emissions. This has an immediate impact on the burst energetics, and the nature and number of events needed to account for the observed burst rate [23]. If the afterglow is beamed with opening angle $\theta$, a change of the light curve slope occurs at the time when the Lorentz factor $\Gamma$ of the blast wave equals $1/\theta$. Slightly later the jet begins a lateral expansion, which causes a further steepening of the light curve. Perhaps such a transition has been observed in the optical afterglow light curve of GRB 990123 (e.g., [4]). A similar transition was better sampled in afterglow data of GRB 990510; optical observations of GRB 990510, show a clear steepening of the rate of decay of the light between $\sim 3$ hours and several days [24]. Together with radio observations [24], which reveal a similar steepening of the decline, it is found that the transition is very much frequency-independent; this virtually excludes explanations in terms of the passage of the cooling or the peak frequency, but is what is expected in case of beaming. Harrison et al. (1999) derive a jet opening angle of $\theta = 0.08$ radians, which for this burst would reduce the total energy in $\gamma$ rays to $\sim 10^{51}$ erg.

7 The unique potential of SKA observations of GRB afterglows.

- **Interstellar Scintillation.** As discussed in Sect. 4, the observations of GRB afterglows are in good agreement with the relativistic-blast wave model. However, the expansion rate and size of the blast wave have never been observed directly. Observations of the size, expansion rate and the shape of the GRB remnant would provide a stringent test of the relativistic blast wave model. The size $d$ of the GRB remnant is of the order of

$$d = \gamma ct,$$

where $\gamma$ is the Lorentz factor of the blast wave, $c$ is the speed of light and $t$ the time in the observer’s frame. Hence, after 1 week the source size is $2\gamma$ light-weeks, which, at a typical redshift of $z \sim 1$ corresponds to an angular size of $\sim 1$ microarcsecond.

Let us take GRB 970508 as an example. Radio light curves of the afterglow of this GRB show rapid variability on time scales of less than a day, but these dampen out after one month [3]. The reduced flux density modulations, interpreted as diffractive interstellar scintillation (DISS), are caused by the expansion of the source and then imply an angular diameter of at most a few $\mu$arcsec. At the redshift of GRB 970508 this corresponds to a linear diameter of roughly $10^{17}$ cm corresponding to a mildly relativistic expansion of the shell [3]. Similar estimates of the source size were derived from the observed flux density for frequencies below the self-absorption frequency [3], and from the presence of several breaks in the spectral energy distribution of GRB 970508 [10]. It is clear that with the current resolution and sensitivity of earth-bound Very Large Baseline Interferometry it is going to be impossible to ever obtain a direct measurement of the source size, except for the nearest GRBs like GRB 980425/SN 1998bw.

However, the example of GRB 970508 shows that indirect source size estimates of GRB remnants can be obtained by observations of interstellar scintillation (DISS and RISS). The current observations are still severely sensitivity limited but as we discuss below there can be fantastic progress with the sensitivity provided by SKA.
Strong scattering can be observed at frequencies below the transition frequency $\nu_0$ (typically $\nu_0 \sim 5$ GHz at high galactic latitudes \cite{26}). For $\nu > \nu_0$, the scattering is weak and the modulations scale as $(\nu/\nu_0)^{-17/12} < 1$. For $\nu < \nu_0$ we will see strong diffractive scintillation only if the size of the source, $\theta_S < \theta_D = \theta_F(\nu/\nu_0)^{6/5}$. Depending on the properties of the turbulent plasma screen we may expect to encounter such conditions in the first day(s) after the GRB event.

The other ISS parameters of interest are the decorrelation timescale $t_{\text{diff}}$ (time for significant changes in the detected flux), and the bandwidth over which the diffractive ISS is decorrelated, $\Delta \nu = \nu_0(\nu/\nu_0)^{22/5}$. These scale as: $t_{\text{diff}} \propto \nu^{1.2}$ and $\Delta \nu \propto \nu^{4.4}$. As emphasized by Goodman \cite{25} all these observables carry independent information on the properties of the ISM.

Observations of the modulation index, decorrelation time scale and decorrelation bandwidth as a function of frequency, and the determination of the transition frequency $\nu_0$ between weak and strong scattering, in early GRB afterglows, hence provide a wealth of information on the dynamically changing size and shape of the source. In principle the scintillation tool allows us to infer a crude measure of the morphology of the radio source: is it ring-like, as in spherical blast-wave models, or jet-like, in currently popular models. In the decaying, sub- or non-relativistic phase, the source may develop double structure (approaching and receding jet components) leading to distinct patterns in the dynamically changing spectra.

The scintillation method, however, will need a proper calibration before it will release its potential. This is clearly shown by the inferred sizes of two recently discovered scintillating quasars. For the radio quasar PKS 0405-385 \cite{27} an angular size of $\sim 5$ $\mu$arcsec was estimated. However, for J1819+3845, Dennett-Thorpe and de Bruyn \cite{13} estimate a size of $\sim 25$ $\mu$arcsec at 5 GHz (possibly related to relatively nearby plasma turbulence). The calibration of scintillation screen properties can be provided by the observation of angularly nearby pulsars, the perfect point sources, of which SKA could easily detect about 1 per square degree.

SKA will provide the right technical specifications for these exciting and unique observations. The proposed instantaneous bandwidth: $0.5 + f/5$ GHz and the large number of spectral channels: $10^4$, allow the recording of dynamic spectra of GRBs, as is now common for pulsars.

- **Synchrotron self absorption.** The large instantaneous bandwidth, the large number of spectral channels, and sensitivity of SKA will also allow detailed study of the transition from optically thin to optically thick frequencies and the evolution of the shape and location of this transition. Such high quality observations will provide strong constraints on models of GRB afterglows.

- **Supernova-GRBs.** As discussed in Sect. \cite{3} the most common GRBs may very well be the low luminosity GRBs like GRB 980425/SN 1998bw. The bright radio emission of such sources may easily be detected out to redshifts of $z \sim 1$, with SKA’s sensitivity. From the duration of the radio phase in SN 1998bw, its typical brightness of $\sim 10$ mJy at GHz frequencies, and some simple order-of-magnitude extrapolations to the whole sky, we derive that at any given time there will be several tens of such fading supernova-GRB radio afterglows above a flux density of $1 \mu$Jy per square degree! Most of these sources will be distant, hence small and scintillating. This is how they could be discerned. What distinguishes them from AGN, however, is that they would appear at places where previously there would have been no radio source. A survey of the sky, carried out with SKA in its first year, could provide the template, against which to pick up these new sources. (Nota bene, this is also how new radio SNe would be discovered, but they are typically orders of magnitude fainter and rarely reach the radio brightness temperatures of GRB afterglows).
• **Rapid response.** The early radio afterglow emission of GRBs is currently hard to observe: the sources are very faint at ages less than 1 day and the current response time, which is typically a few hours, is too slow. Soon, with the launch of the gamma-ray satellite HETE-II, the response time may be very much improved upon (positions will be available within tens of seconds of the event), but the sensitivity is expected to remain problematic for such early observations. SKA will provide the required sensitivity plus it will have this other unique capability: the possibility of very rapid response (we may, however, have to build a few SKA’s to cover both the northern and southern hemispheres, and provide 24h watch!). We envision that SKA may be triggered directly by future gamma-ray spacecraft, and then rapidly electronically steer to the location on the sky. Such observations may provide insight in the physics of the fireball at very early times, for example we may expect to detect emission from the reverse shock [20].

• **Wide Field Surveys.** SKA will be a unique instrument for surveying large areas of sky (as noted above in connection with the GRB 980425/SN 1988bw association). If the GRB luminosity function is bimodal (i.e. GRBs like 980425 versus the more distant GRBs like 970508) then such surveys may be dominated by supernova-GRBs. However, a substantial number of the more distant GRBs may be discovered too, depending on the amount of collimation into jets. If the GRB luminosity function is not bimodal, but very wide then we may also detect a substantial number of radio afterglows from intermediate luminosity GRBs ($E_{\gamma} \sim 10^{48-50}$ erg). Thus, thousands of GRBs and supernova-GRBs may be discovered from such surveys by their distinct observational characteristics (for example a self-absorbed synchrotron spectrum, observed ISS and the characteristic damping of ISS fluctuations with time due to expansion of the source, the fact that GRB afterglows are not expected to be recurrent, etc). An important aspect of a radio selected survey is its unbiased-to-dust nature. Afterglows may thus be discovered independent of an optical or even a GRB identification.

The statistics of radio afterglows may be compared with the numbers expected from specific spherical- or jet-fireball models. As the bulk Lorentz factor, $\Gamma$, decreases with time after the event, the observer sees more and more of the emitting surface, $\theta \sim 1/\Gamma$. It follows that if gamma ray bursts are highly collimated, many more radio transients should be observed without associated gamma rays than with them. The ratio of expected (assuming spherical symmetry) to observed number of afterglows is thus a direct measure of the amount of collimation in GRB fireballs.

The number of radio afterglows may also be compared to that of optical afterglows (subject to obscuration by dust) to reveal possibly dusty environments (expected for massive star progenitor models).

• **The high-$z$ universe and the cosmic star formation/death history.** A GRB at a redshift $z \sim 1$ may easily be a mJy bright. With SKA’s sensitivity such radio counterparts can be detected out to redshifts of 10 or greater. SKA will also be sufficiently sensitive that the radio emission of GRB hosts can be studied. Currently this is barely feasible. Such observations may provide information on the progenitors of GRBs (e.g., young or old stellar populations). Also, as discussed in Sect. 4 GRBs are expected to trace the star formation rate (SFR) in the universe. Vice versa by observing GRB hosts we will learn about the star formation (and star death!) history. Observations in the (sub-)mm band suggest that star formation at high redshift is dominated by dusty star burst galaxies [28]. Estimates of the SFR of GRB host galaxies can be accurately determined by radio observations. These observations will be insensitive to dust, a crucial fact if one wants to be complete.
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