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Radio afterglows of gamma-ray bursts

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Abstract. According to the fireball model gamma-ray burst (GRB) afterglows are the result of a shock pushed into the ambient medium by an extremely relativistic outflow from the GRB. Radio observations of GRB afterglows provide essential and unique information to constrain the physical models, by completing the coverage of the spectral energy distribution and following the behaviour until much later times than any other wavelength. Scintillation due to the local interstellar medium modulates the radio flux and permits indirect measurement of the angular size of the blastwave that is causing the afterglow.
We discuss our centimeter wavelength light curves of GRB030329, which were obtained with the Westerbork Synthesis Radio Telescope (WSRT). The optical spectra of this GRB provided conclusive evidence of the connection between GRBs and SNe. We also present our results from modeling this afterglow in the framework of the blastwave model. These radio observations provide a unique possibility to study the late stages of the blastwave evolution, examine the jet structure and circumburst medium, and determine the total burst energy.

Key words. Gamma rays: bursts – Radio continuum: general – Radiation mechanisms: non-thermal – Shock waves

1. Introduction

Gamma-ray bursts (GRBs) are the most luminous explosions currently known in the Universe. Roughly 30 years elapsed between the discovery of GRBs in gamma rays (Klebesabel et al. 1973) and of their counterparts at optical and X-ray wavelengths (Van Paradijs et al. 1997; Costa et al. 1997). These so-called afterglows were first found for GRB 970228, and a couple of months later the first radio afterglow (Frail et al. 1997) was found in the case of GRB 970508. For the latter one a redshift of 0.835 was determined (Metzger et al. 1997) which showed that GRBs originate at cosmological distances. Studying more and more GRBs over the years showed that they have an isotropic energy output of 10^{51} – 10^{54} erg (Van Paradijs et al. 2000) in gamma rays alone.

The first indications of the origin of GRBs came with the discovery of the supernova SN 1998bw coincident with the position of GRB 980425 (Galama et al. 1998). However, this was an extremely nearby GRB (redshift of 0.0085) and did not show an afterglow. Also, the associated supernova exhibited an unusual light curve at radio wavelengths (Kulkarni et al. 1998). So although there seemed to be a connection between this particular GRB and a supernova, it was not clear that this connection was generic for all GRBs.

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The fact that practically all GRB afterglows are found to be within bright star-forming regions of their host galaxies, and that late-time optical observations show flux enhancements that can be explained by the presence of a supernova (e.g. Galama et al. (2000), Zeh et al. (2004)), strengthened the GRB-supernova connection. The conclusive evidence for this connection was provided by the discovery of the supernova SN 2003dh in the optical spectrum and light curve of GRB 030329 (Hjorth et al. 2003; Stanek et al. 2003). This showed that GRBs can occur as the result of the core collapse of a rapidly rotating massive star, a so-called collapsar (Woosley 1993). This implies that GRBs are strongly connected to populations of massive stars, and they and their afterglows are useful tools for the study of the star-formation rate at high redshifts. Furthermore, understanding their progenitors tells us about star formation itself in the early stages of the Universe.

Our knowledge of the progenitors of GRBs is only valid for one class of them. The spectrum and duration of GRBs separates them into two classes, the so-called long-soft bursts and short-hard bursts (Kouveliotou et al. 1993). So far counterparts have only been detected for long duration bursts due to the limited trigger sensitivity of the past and current instrumentation in short events. One of the major breakthroughs in GRB research is expected to come from detecting the afterglows of the short bursts, which are more likely produced by merging neutron star events or by giant flares of Soft Gamma Repeaters as recently occurred in the case of SGR 1806-20 (Palmer et al. 2005).

The afterglows of long duration bursts have been studied extensively since 1997 from X-ray to radio wavelengths. The light curves at radio wavelengths are completely different compared to X-ray or optical light curves. The main advantage of radio observations is the fact that the temporal evolution of the afterglow at radio wavelengths is delayed in comparison with optical and shorter wavelengths, which gives radio observations the unique possibility to study events that otherwise would escape attention. Moreover, the radio afterglow lasts much longer than optical and X-ray afterglows which gives us the opportunity to study late-time phenomena that could not be observed otherwise.

Here we describe broadband afterglow observations and the physical parameters one can deduce from these observations in the framework of the fireball model (Cavallo & Rees (1978), Goodman (1986), Paczynski (1986)). The observations at radio wavelengths are shown to be extremely important in determining these parameters. We also show the role of radio scintillation due to the interstellar medium, which gives us extra constraints on the broadband modeling of afterglows. As an example we present the radio afterglow observations at centimeter wavelengths of GRB 030329, which were obtained with the WSRT.

2. Broadband afterglows

According to the fireball model decelerating relativistic ejecta produce the GRB and its afterglow. In this model the following stages in the evolution are distinguished (for a review see e.g. Piran (1999)):

- First a source produces a relativistic outflow. Since the opacity is very high, this inner engine is hidden and can not be observed directly. This makes it difficult to constrain GRB models and leaves only circumstantial evidence on the nature of the sources.
- The energy from the central source is transported relativistically to distances larger than 10^{16} cm where the system is optically thin. The fireball is contaminated with baryons and a conversion of radiation energy into kinetic energy takes place. If the inner engine is active for some time, shells with different Lorentz factors can be produced. Collisions between these shells, so-called internal shocks, power the GRB itself.
- After the so-called coasting phase the fireball bumps into an external medium. This can be the interstellar medium, or the dense stellar wind produced by the progenitor of

the GRB. External shocks arise due to the interaction of the relativistic matter with the surrounding matter, and cause the GRB afterglow. These shocks or blast waves are the relativistic analogues of supernova remnants. Magnetic fields cause the swept-up electrons to produce synchrotron radiation.
- When the external forward shock is formed, a reverse shock is produced moving back into the ejecta. This reverse shock can produce a bright optical flash about one minute after the burst, and a radio flare about one day after the burst. The brightness of the reverse shock emission decays very rapidly, after which the forward shock dominates.
- The relativistic outflow is not spherical but collimated. Since the shock decelerates while it is sweeping up mass, a few days after the burst the synchrotron emission angle of the electrons becomes equal to the collimation angle of the outflow, the so-called jet-break time. After this moment the collimated outflow spreads and becomes spherical after a few months after the burst. At the same time that the outflow becomes spherical, the blast wave becomes sub-relativistic and will eventually enter the Newtonian phase.

In general, GRB afterglow observations are in good agreement with the external shock scenario. Light curves at various wavelengths have been obtained for quite some bursts, and from these light curves, broadband spectra have been constructed. For the broadband spectrum synchrotron radiation is taken as the radiation mechanism. The dynamics of the relativistic shock determines the evolution of the spectrum with time. The broadband synchrotron spectrum is determined by the peak flux and three break frequencies, namely the synchrotron self-absorption frequency ν_a, the frequency ν_m that corresponds to the minimal energy in the electron energy distribution, and the cooling frequency ν_c that corresponds to electrons that cool on the dynamical timescale. The break frequencies and the peak flux can be described in terms of the energy of the blastwave E, the density of the surrounding medium n, the fractional energy densities behind the relativistic shock in electrons and in the magnetic field, ϵ_e and ϵ_B respectively, the slope p of the electron energy distribution, and the jet opening angle θ_{jet}.

From the spectra and light curves these physical parameters of the blastwave and its surroundings can be deduced. GRB 970508 was the first afterglow for which this was done (Wijers & Galama 1999), and it is still one of the best studied broadband afterglows. Observations of other afterglows have raised questions about the structure of the relativistic jet and the structure of the circumburst medium. For the structure of the jet various possibilities have been proposed, ranging from homogeneous jets to jets in which the luminosity per unit solid angle along the jet axis is larger than what is emitted off-axis. The light curves of the total flux of these different configurations are very similar to each other, but the polarization curves are very different, especially around the jet-break time (Rossi et al. 2004). However, the polarization levels are only a few percent, which makes it difficult to get polarization curves which are good enough to distinguish between the various models.

In most of the modeling efforts the structure of the medium surrounding the burst is taken to be either homogeneous or a stellar wind profile, in which the density n is proportional to r^{-2} (with r being the distance). This can be generalized by assuming that the density as a function of the distance is a power-law, i.e. $n \propto r^{-k}$, and investigate the modeling results for several values of k. Van der Horst et al. (2005) treat k as an independent parameter and find for GRB 970508 that $k \approx 0$, which means that the blast wave expands into a medium with a uniform density. For most of the afterglows the homogeneous circumburst medium gives the best fitting results. This seems to be contradicting the fact that GRBs are the result of core collapse of a rapidly rotating massive star which has lost a lot of its mass during earlier stages of its evolution via a massive stellar wind. However, the profile of the stellar wind can be modified by the interaction of this wind with the interstellar medium, and can even become homogeneous.

3. Radio afterglows

The shape of the broadband synchrotron spectrum and the way in which peak flux of the three break frequencies evolve in time, result in the fact that at optical and X-ray wavelengths the flux declines quite rapidly, especially after the jet-break time. Therefore, afterglows are at average only visible days up to several months after the burst at these wavelengths. In X-rays the afterglows are already quite faint to begin with, and in the optical in a lot of the cases they can not be distinguished from their host galaxy after some time. Because of synchrotron self-absorption at low frequencies, radio afterglows are faint at early times. However, since the peak of the spectral energy distribution moves to lower frequencies in time, the light curves at radio wavelengths increase in time, as long as both the self-absorption frequency ν_a and the frequency of the minimum electron injection energy ν_m are above the observing frequency. When both ν_a and ν_m have passed the observing frequency, a turn-over in the light curves occurs and the flux falls off steeply. In some of the radio afterglows a flattening of the light curves was observed after the phase of steep decline, e.g. in GRB 970508 and GRB 980703. The flattening corresponds to the transition to the non-relativistic phase of the blastwave. From studying the non-relativistic phase Berger et al. (2004) the blast wave energy can be inferred independent of jet collimation, since the blast wave has become spherical in this phase of its evolution. The fact that only three GRB host galaxies have been detected at radio wavelengths makes it also possible to follow-up on some radio afterglows for years after the burst.

Besides completing the spectral energy distribution and following the evolution of the blastwave into its non-relativistic phase, radio observations of GRBs are also useful in studying the reverse shock. The best example is GRB 990123 in which an optical flash was observed with a peak at approximately 1 minute after the burst (Akerlof et al. 1999), and a radio flare 1 day after the burst (Kulkarni et al. 1999). Modeling of this early emission provides the opportunity to investigate the immediate surroundings of the burst and the initial Lorentz factor of blastwave. The fact that the timescale for detecting emission from the reverse shock is so small at optical and much longer at radio wavelengths, makes radio observations on the first day after the burst important, although the emission from the forward shock is maybe not detectable at those early times.

The uniqueness of radio afterglow observations is best illustrated by the phenomenon of radio scintillation. Scintillation due to the local interstellar medium modulates the radio flux of GRB afterglows and permits indirect measurement of the angular size of the fireball. Focusing and defocusing of the wave front by large-scale inhomogeneities in the ionized interstellar medium results in refractive scintillation. This scintillation is broadband and has been seen in many sources, whereas only the most compact sources, e.g. GRB afterglows, show diffractive scintillation. Diffractive scintillation is caused by interference between rays diffracted by small-scale irregularities in the ionized interstellar medium. The resulting interference is narrow-band and highly variable. Diffractive scintillation occurs only when the source size is smaller than a characteristic size, the so-called diffractive angle. It turns out that at an average redshift of $z \sim 1$ the size of the blastwave is smaller than the diffractive angle in the first few days, but during its evolution the blastwave becomes larger than this angle. Thus, as the blastwave expands the diffractive scintillation is quenched. From studying the scintillation behaviour one can get an independent measurement of the angular size of the blastwave. Both diffractive and refractive scintillation have been observed in GRB 970508 (Frail et al. 1997), and an angular size was derived which is in accordance with the results from the broadband modeling of the afterglow.

As the afterglows are extremely weak at centimeter wavelengths, observing radio afterglows at these wavelengths requires a sensitivity that only a few radio telescopes have, i.e. the Very Large Array (VLA), the

Australia Telescope Compact Array (ATCA) and the Westerbork Synthesis Radio Telescope (WSRT). All three of the observatories are observing radio afterglows since 1997. The unique event of GRB 030329 made it also possible for other radio telescopes to do follow-up observations, which are still ongoing and will make this radio afterglow very well sampled. In the next section we present our observations obtained with the WSRT, and how these observations fit into the broadband picture.

4. GRB 030329

The closeness of the GRB 030329 (with a redshift of $z = 0.1685$ (Greiner et al. 2003)) caused a plethora of follow-up observations at all wavelengths. The afterglow was about 100 times brighter than the average afterglow, which made it possible to study its evolution for a long time and in detail. Its proximity provided an excellent opportunity to study the supernova signature in both the light curve and spectrum (Hjorth et al. (2003), Stanek et al. (2003)). Furthermore, for the first time the expansion of a GRB was directly imaged by VLBI measurements (Taylor et al. 2005).

From the early optical observations Price et al. (2003) inferred a narrow jet with a jet-break time of 0.55 days, and later time optical and radio observations (Berger et al. 2003) indicated there was a second jet component, which was wider and had a jet-break time of 9.8 days. In order to do broadband modeling of the GRB 030329 afterglow one needs to extract the contribution from the supernova associated with this GRB at optical frequencies (Hjorth et al. 2003; Stanek et al. 2003). Since the exact contribution from the supernova to the total flux in the optical is not known and because the supernova does not contribute significantly at low radio frequencies, the radio observations play a crucial role in doing proper broadband modeling and thus in determining the physical parameters very accurately.

Observations with the WSRT at centimeter wavelengths, at 1.4, 2.3 and 4.8 GHz (Fig. 1), are consistent with the scenario in which a jet with a jet-break time of 10 days is present (Van der Horst et al. 2005). These observations show an increasing flux for one month at 4.8 GHz and even for half a year at 1.4 GHz. The position of ν_a can be well determined as well as ν_m moving to longer wavelengths, eventually falling below ν_a and the observing frequency. Late time observations show an additional flux at the lowest frequencies after 50 days compared with the results obtained at higher radio frequencies, for which there are two possible explanations:

- The first explanation is a transition to non-relativistic expansion of the blastwave at $\sim$ 80 days. However, the flux at 1.4 GHz is overestimated at late times in this case. The presence of a non-relativistic transition at $\sim$ 50 days was predicted based upon X-ray data (Tiengo et al. 2004), and observed with VLA radio data (Frail et al. 2005). So there is a discrepancy between the VLA and WSRT observations in the time at which the blastwave becomes non-relativistic t_{nr}. Moreover, theoretical estimates of t_{nr}, based on determinations of the evolution of the image size (Granot et al. 2005), give a value of $\sim$ 170 days. This discrepancy could be solved by fitting the broadband afterglow light curves with the evolution of its image size.
- The second explanation for the additional flux at late times is an extra wider jet with a lower Lorentz factor. This third component, besides the two components with jet-break times of 0.55 and $\sim$ 10 days, has a jet-break time of $\sim$ 30 days. It is possible that the total jet is structured and that the Lorentz factor decreases towards the edge of the jet-cone. Alternatively, the outflow consists of a layered jet, where shocks with lower Lorentz factors follow the faster ones as they run into the circumburst medium. The WSRT observations are well fitted by this multi-component model. However, data at higher radio frequencies can not be fitted well in this model. Continuation of observations at late times at low radio frequencies of this afterglow can give us more insight in the validity of the proposed explanations.

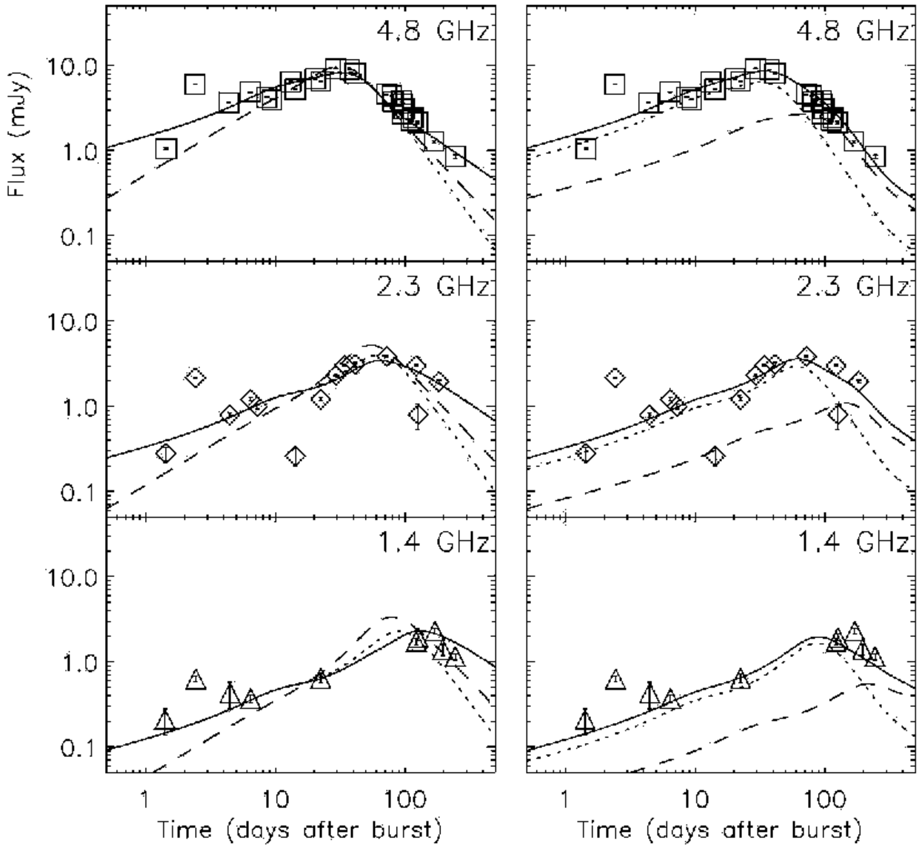

Fig. 1. The 1.4, 2.3 and 4.8 GHz WSRT light curves of the GRB030329 afterglow (Van der Horst et al. 2005). **Left:** The lines represent models with a jet-break time at 10 days. The solid line corresponds to a model in which the fireball expands into a homogeneous medium and the non-relativistic phase of the fireball evolution starts after 80 days; the dashed line corresponds to the same model but without a non-relativistic phase; the dotted line corresponds to a model with a non-relativistic phase after 80 days and expansion of the fireball into a massive stellar wind. The peak frequency falls below the self absorption frequency at 17 days. From then on, the maximum of a light curve at a given wavelength marks the passing of the self absorption frequency. **Right:** A two-component fit to the data. The first component (dotted line, with a jet break time of 10 days) is responsible for the light curves until 50 days, while the second component (dashed line, with a jet-break time of 30 days) accounts for the later peak in the light curves. The combined light curve is shown as the solid line.

5. Conclusions

Broadband observations from X-ray to radio wavelengths and broadband modeling of GRB afterglows gives us valuable information about GRBs and their surroundings. From the broadband synchrotron spectrum and its evolution physical parameters can be derived, i.e. the energy of the blastwave, the density and structure of the surrounding medium, the fractional energy densities behind the relativistic shock in electrons and in the magnetic field, the slope of the electron energy distribution, and the jet opening angle.

Radio observations are important because they complete the spectral energy distribution, especially by following the evolution of the synchrotron self-absorption frequency and the frequency that corresponds to the minimal energy in the electron energy distribution, as well as the peak flux. The radio light curves are phenomenological different from optical and X-ray light curves in the sense that the flux at radio wavelengths first increases at a timescale of weeks to months before it starts to decline. Since X-ray afterglows are very faint, and optical afterglow observations are polluted by the presence of a host galaxy or a possible supernova, radio afterglows are better in late-time follow-up of the GRB, following its evolution into the non-relativistic phase. These late-time observations can give a determination of the blast wave energy independent of the initial jet collimation.

The temporal evolution of the afterglow at radio wavelengths is delayed in comparison with optical and X-ray wavelengths, which gives radio observations the possibility to observe phenomena which would otherwise escape attention, such as the occurrence of a radio flare. This has only been observed in a few cases and is caused by the passage of a reverse shock through the shocked ejecta. Scintillation is another observational phenomenon that underlines the important role that radio observations can play in studying GRBs. From the refractive and diffractive scintillation caused by the ionized interstellar medium, an independent measurement of the source size and the expansion velocity of the blastwave can be made.

GRB 030329 provided the conclusive evidence of the connection between GRBs and supernovae. Because the afterglow was about 100 times brighter than the average afterglow, follow-up observations could be done for a long time at all wavelengths. At the lowest radio frequencies follow-up observations are still being carried out, more than two years after the burst. The WSRT and VLA late-time observations at centimeter wavelengths show the importance of doing observations with high sensitivity at these wavelengths. This shows the importance of future projects as the Low Frequency Array (LOFAR) and the Square Kilometer Array (SKA).

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