Gamma-ray burst afterglows and the nature of their host galaxies.
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Citation for published version (APA):
Vreeswijk, P. M. (2002). Gamma-ray burst afterglows and the nature of their host galaxies.
Introduction

Gamma-ray bursts are brief flashes of γ-rays, discovered by the US military Vela satellites in 1967 (Klebesadel et al. 1973). For three decades the places of origin of these explosions was unknown. In the early 1990s, the Burst And Transient Source Experiment onboard the Compton Gamma-Ray Observatory showed gamma-ray bursts to have an isotropic sky distribution (Meegan et al. 1992), and that their number versus peak flux distribution does not follow the $-3/2$ powerlaw expected for a spatially homogeneous distribution of sources (Meegan et al. 1992). These observations strongly suggest a cosmological origin. Thanks to the discovery of X-ray and optical afterglows through the accurate burst localizations of the BeppoSAX satellite, their distant extra-galactic nature was definitively established in 1997 (Van Paradijs et al. 1997; Metzger et al. 1997). Since then, observations of three dozen optical afterglows have provided more insight in the origin of these enigmatic explosions. In this introduction we discuss the history and current status of our knowledge of the physics and origin of gamma-ray burst afterglows, and the nature of their host galaxies, and provide an overview of the work presented in this thesis.

1.1 The discovery of gamma-ray bursts

Before the launch of the Vela satellites in the late 1960s, hardly anybody (but see Colgate 1968) had thought of the possible existence of gamma-ray bursts (GRBs). The report of their discovery by Klebesadel et al. (1973) caused a cascade of theories attempting to explain these elusive explosions. GRBs are short flashes of gamma rays, with a duration ranging from tens of milliseconds to tens of minutes, and an observed peak energy around 100 keV. The intrinsic rate of GRBs, with a flux limit of $\sim 0.4$ photons cm$^{-2}$ s$^{-1}$ in the 50–300 keV range, is about two per day (Paciesas et al. 1999). The various theories for their origin placed these bursts at distances ranging from the solar system to the far reaches of the universe; it was clear that a distance determination was needed in order to decide which of these theories might be correct. From the gamma-ray data alone, however, this appeared to be impossible. The gamma-ray light curves are extremely diverse, some very smooth, others with numerous spikes (see Fig. 1.1 for an
example). Observations at other wavelengths were needed to identify the sources with known objects and to determine their distance.

![Gamma-ray light curve and hardness ratio](image.png)

**Figure 1.1:** On the left: Example gamma-ray light curve, in this case of GRB 990123. On the right: Hardness ratio versus burst duration for a number of BATSE bursts. The bimodality (Kouveliotou et al. 1993) is suggestive of two classes of GRBs. Only bursts with a duration longer than roughly two seconds so far have observed afterglows.

**BATSE**

In 1991, the *Compton Gamma-Ray Observatory* (CGRO) was launched, carrying the *Burst And Transient Source Experiment* (BATSE, 25–300 keV; Fishman et al. 1985) as one of four experiments. Until its re-entry in June 2000, this gamma-ray instrument observed nearly 3000 GRBs, and determined their location on the sky with an accuracy of a couple of degrees. This sky distribution was found to be isotropic (Meegan et al. 1992), i.e. the positions of GRBs do not correlate with a source population in the Galactic disk, which in the late 1980s was the general idea, nor with nearby galaxies. This, in combination with the log N–log P (N=number, P=peak flux) distribution of bursts (which shows a systematically too low incidence of weak bursts relative to the distribution expected for a static Euclidean space), strongly suggests a cosmological distance scale. Although the Galactic halo model, which hypothesized glitches on neutron stars in a very extended spherical halo as the sources (Lamb 1995), could still survive, the most natural explanation was that GRBs occur at high redshifts (Paczynski 1995).
Two classes of bursts: long and short

BATSE data showed also that there are (at least) two distinct classes of GRBs: a class with a short duration (less than two seconds) and a hard gamma-ray “colour”, and a class of long-duration bursts with soft spectra (Kouveliotou et al. 1993). The “hardness ratio” (HR) or gamma-ray “colour” is defined as the ratio of total counts in two BATSE energy bands. For HR_{3/2} these are the 100-300 keV and 25-100 keV bands. This gamma-ray hardness is plotted versus observed burst duration for a number of BATSE bursts in Fig. 1.1. Before discussing the afterglows of GRBs, it is important to point out that all GRB afterglows observed so far at other wavelengths (X-ray, optical or radio) come from the long-duration population. This is mainly due to the fact that BeppoSAX, and other satellites such as the Rossi X-ray Timing Explorer (RXTE), have so far only triggered on long-duration bursts. The Interplanetary Network (IPN, Hurley et al. 2001) has triggered on several short-duration bursts, but the alert delay is typically a day, making it more difficult to detect the rapidly decaying afterglow. The alert delay for BeppoSAX is roughly 4-12 hours. The High Energy Transient Explorer II (HETE-II) mission (launched in October 2000) should in principle be able to localize both long and short-duration bursts accurately (error boxes ranging from arcseconds to minutes) and very rapidly (< 1 minute). So far, however, only very few bursts have been localized in this way.

1.2 GRB afterglows

1.2.1 GRBs go cosmological

It was not until the launch in 1996 of BeppoSAX with its Wide Field Cameras (WFCs, 2-20 keV; Boella et al. 1997a) that GRB afterglows were discovered. These hard X-ray cameras (with a full field of view of 40° × 40°) are capable of localizing roughly one GRB per month to an accuracy of arcminutes, which allows follow-up observations in the soft X-ray, optical/near-infrared and radio spectral ranges. The WFC localization of the GRB of February 28, 1997 (GRB970228) signified the birth of GRB optical afterglow studies: Van Paradijs et al. (1997) discovered its optical afterglow at V~21 with observations with the William Herschel Telescope (WHT) and the Isaac Newton Telescope (INT) on La Palma. At the same time, training the soft X-ray Narrow-Field Instruments (NFIs) of BeppoSAX on the position indicated by the WFCs, Costa et al. (1997) discovered the soft X-ray afterglow of this burst. The optical and soft X-ray light curves showed a steep powerlaw decay, flux \propto t^{-1.1} (e.g. Galama et al. 1997; Costa et al. 1997), fairly typical of the afterglows to follow. This immediately clarified why no optical counterparts had been seen earlier despite numerous attempts: the observations
had to be performed very quickly, within at most a few days following the burst. HST observations performed 6 months after the burst showed the optical afterglow still present at the edge of a faint nebula, presumably a galaxy (Fruchter et al. 1999b), which had already been noticed by Van Paradijs et al. (1997) from ESO's New Technology Telescope (NTT) observations.

Metzger et al. (1997) succeeded to perform spectral observations with the Keck telescope of the next GRB afterglow that was discovered: GRB 970508, and identified absorption lines that are typically seen in quasar spectra, such as of Fe and Mg, at a redshift of $z = 0.835$. Thus, the distance issue was finally settled after 30 years of GRB studies: GRBs originate at cosmological distances, making them the most powerful photon emitters in the universe.

1.2.2 The physics of the afterglow

Relativistic fireballs

The observed afterglow light curve behaviour is in good agreement with the so-called relativistic fireball model (Cavallo & Rees 1978; Goodman 1986; Paczyński & Rhoads 1993; Mészáros & Rees 1993). In this afterglow model it is assumed that the source that gives rise to the explosion is compact (radius $\leq 3000$ km), a constraint that arises from the observed millisecond variations in the gamma-ray light curves, and which implies an enormously high gamma-ray photon density. The expansion of the fireball needs to be ultra-relativistic to circumvent the large opacity to gamma-ray photon-photon interactions that would lead to the production of electron-positron pairs and a large optical depth if the expansion were non-relativistic. In the latter case a thermal spectrum would emerge, which is not observed. The inferred Lorentz factors are in the range 100–1000 (Krolik & Pier 1991; Lithwick & Sari 2001). Gamma-ray burst spectra in the gamma-ray regime in fact can be well-described by a Band function (Band et al. 1993), which is a smoothly-connected broken power law. The high Lorentz factor requires a very low baryon loading, since otherwise all the energy would be "lost" to the kinetic energy of the baryons, and no burst of radiation would be possible (Shemi & Piran 1990).

Internal and external shocks

The expanding ‘ball’ naturally forms a shell due to the relativistic motion. If the inner engine is active for some time, several shells with different Lorentz factors can be produced. It is believed that collisions between these shells, so-called internal shocks, power the gamma-ray burst itself. The shells will merge into one flow and later on sweep
up matter in the interstellar medium. When the rest-mass energy of this matter will balance the initial energy of the fireball, the flow will slow down converting its kinetic energy to radiation (the so-called external forward shock). Although it is not clear how they are formed, magnetic fields present in the flow cause the electrons that were picked up to produce synchrotron radiation. The electrons move at different speeds, or Lorentz factors. Assuming that their Lorentz factors are distributed as a power law, the resulting emitted spectrum also is a power law. As the shell slows down in the course of time (also as a power law), the typical Lorentz factor and the corresponding peak emission frequency \( \nu_m \) do the same, causing the entire spectrum to shift toward lower frequencies. Hence, when an afterglow is observed at a specific frequency, the flux will decrease as a power law in time. When the external forward shock is formed, a reverse shock is produced, moving back into the ejecta. It was predicted that such a reverse shock can produce extremely bright flashes around one minute after the burst (Mészáros & Rees 1997; Sari & Piran 1999); one such flash was indeed observed at 9th magnitude in the V band by Akerlof et al. (1999) (see § 1.6.1). The brightness of the reverse shock emission decays very rapidly, after which the forward shock emission dominates. For an extensive review on GRBs and the fireball model, see Piran (1999).

![Figure 1.2](image-url)  

**Figure 1.2:** The X-ray to radio spectrum of GRB970508 on May 21.0 UT (2.1 days after the event), which shows the agreement between the simple fireball model, and observations over a wide range in frequency. Figure after Galama et al. (1998c).
Observational constraints on fireball model parameters

In general, GRB afterglow observations are in good agreement with the external shock scenario. An excellent example is the afterglow of GRB 970508, even though the bump in the light curve at early times is not understood. Galama et al. (1998c) show that its broad-band spectrum (constructed at 11 days after the burst), covering the frequency range from X-rays to radio wavelengths, is well fit by the simple fireball model (Sari et al. 1998). Several breaks in the spectrum (shown in Fig. 1.2) are observed, and these match the expected model breaks at the synchrotron self-absorption frequency $\nu_a$, the peak frequency $\nu_m$, and the frequency that corresponds to the Lorentz factors above which the electrons cool rapidly $\nu_c$, the cooling frequency.

Wijers & Galama (1999) showed that from the location of these breaks and the peak flux, one can obtain estimates of the following internal parameters of the fireball: the blast-wave energy per unit solid angle ($\mathcal{E}$), the density of the circumburst medium ($n$), and the fractional energy density in electrons ($\epsilon_e$) and the magnetic field ($\epsilon_B$). For GRB 970508 these authors find very reasonable numbers: $\mathcal{E}=2.4\times10^{51}$ erg sr$^{-1}$, $n=0.03$ cm$^{-3}$, $\epsilon_e=0.12$ and $\epsilon_B=0.09$. To determine the break locations, the afterglow has to be well-monitored over a large range in frequency, which is far from straightforward. Chapter 3 features GRB 980703, which is an example of a fairly well-studied burst at optical, infrared and X-ray wavelengths, for which we were able to put constraints on the location of the cooling frequency, and also on the internal fireball parameters. More recently, Panaitescu & Kumar (2002), have performed broad-band modeling of a sample of 10 afterglows, where they discriminate between a homogeneous ambient density model and a stellar wind r$^{-2}$ density profile. They find that the former best fits the observations, with $n=0.1-100$ cm$^{-3}$.

1.2.3 Energetics and jets

Extreme energetics

The cosmological distance to GRBs and the observed fluences imply an enormous energy output that has to be produced by a compact object. Assuming the explosion to be isotropic, the output in gamma rays of GRB 970508 was $10^{52}$ erg. Strangely, the inferred energy output for GRBs seemed to increase with every new burst: GRB 971214 at $z=3.42$ burst out $2\times10^{53}$ erg (Kulkarni et al. 1998b) and the record holder GRB 990123 at $z=1.6$ (Kulkarni et al. 1999) an incredible $2\times10^{54}$ erg, which is equal to the energy equivalent of one solar mass ($M_\odot c^2$; see Bloom et al. 2001b, for a list of k-corrected energies). The cosmological distances had killed many models, but with this required energy release, hardly any survived. A natural way out of this problem is a jetted, or collimated outflow (Rhoads 1997), which relaxes the energy output by a factor $10^{2-3}$. 
1.2 GRB afterglows

Jetted outflow

The best evidence for such a collimated relativistic outflow is an observed break in the light curve of several GRB afterglows. When observing a jetted outflow roughly along the jet axis, the GRB will at first appear to be isotropic, due to the high Lorentz factors that cause the emission to be relativistically beamed in the forward direction, within an angle $1/\Gamma$. After about a day, this opening angle widens to typically several degrees. Then at the time when this beaming angle is becoming larger than the physical opening angle of the outflow, an observer will start to see less flux compared to the isotropic case. Such a break in the light curve has been seen in several afterglows, such as GRB 990123 (e.g. Fruchter et al. 1999c), GRB 990510 (e.g. Harrison et al. 1999) and GRB 991216 (e.g. Halpern et al. 2000). Collimation is not the only explanation for the observed breaks in the light curves. Alternative possibilities are: a sudden change in the circumburst density (Panaitescu & Kumar 2001), a fast transition from relativistic to non-relativistic bulk motion of the shock due to a dense circumburst medium (Wang et al. 2000), and a break in the powerlaw distribution of electrons in the shock (Li & Chevalier 2001), which is usually assumed to be a single powerlaw.

Jet models

Frail et al. (2001b) have combined the literature values and limits of the inferred opening angles of a sample of GRB afterglows to correct the isotropic energy releases (in $\gamma$-rays) mentioned above to a more comfortable value of about $5 \times 10^{50}$ erg (see Fig. 1.3), a conclusion that is also reached by Panaitescu & Kumar (2002). Interestingly, these authors find that the spread in the energy output distribution is significantly decreased, suggesting that there may be a standard energy reservoir for all GRBs. With the two jets illuminating only a small part of the sky, the intrinsic rate of GRBs is much higher than the observed rate. Frail et al. (2001b) estimate this beaming factor to be roughly 500, implying a 500 times higher incidence of GRBs than actually observed.

In the standard jet model used by these authors, it is assumed that the Lorentz factor $\gamma$ and energy per unit solid angle $\mathcal{E}$ are uniform across the face of the jet. An observer will then see the same burst and afterglow from everywhere within the jet cone. The observed differences between bursts are in this model due to intrinsic collimation differences from burst to burst, i.e. a burst that distributes its energy into a wider cone will appear fainter than a more collimated burst. Rossi et al. (2002) show that the observed breaks in the light curves can also be explained by adopting a model (see Wijers et al. 1997) in which $\gamma$ and $\mathcal{E}$ have a maximum value along the jet axis, and decrease as a powerlaw function away from the axis. The differences in burst fluences and jet break times are in this model explained by differences in viewing angle, and intrinsic differences between bursts need not be invoked.
Figure 1.3: The top panel shows the isotropic gamma-ray energy release of a sample of GRBs with measured jet breaks, studied by Frail et al. (2001b). These authors used the observed afterglow jet break times to infer the jet opening angles. The bottom panel shows the resulting energy outputs corrected for the beaming factor. The wide spread in isotropic energy release decreases considerably, with a median value of $E = 5 \times 10^{50}$ erg. Figure after Frail et al. (2001b).

Orphan afterglows and the Faint Sky Variability Survey

If GRBs are indeed collimated, and if at later times the optical emission is illuminating a larger part of the sky than the prompt gamma rays, one would expect to observe GRB afterglows without the prompt gamma-ray emission. These are called “orphan” afterglows. Rhoads (1997) first proposed to constrain the collimation and therefore the important quantities: burst energy output and rate, by (non-)detection of these orphans.

This is one of the prime objectives of the Faint Sky Variability Survey (FSVS): a survey in which 23 square degrees of mid-galactic latitude sky are searched for photometrically and astrometrically variable objects, down to a limiting magnitude of V~24. An overview of the FSVS is given in Chapter 8. In Chapter 9, we use the FSVS data set to search
Afterglow statistics and dark bursts

for orphan afterglows. We do not find evidence for such afterglows, and discuss the resulting constraints on the jet opening angles based on our non-detection, using the two jet models that have been briefly described here.

Polarization

An important discovery was the detection of polarization at the few percent level of a GRB afterglow (GRB 990510: Covino et al. 1999; Wijers et al. 1999), and possible polarization variability in another (GRB 990712: Rol et al. 2000). These observations suggest that, in agreement with the fireball model, synchrotron emission is the dominant emission mechanism that is producing the afterglow (as synchrotron emission in ordered magnetic fields is polarized to a typical level of 60%). If the magnetic field is highly tangled, or the field geometry is highly symmetric, one expects this net polarization to diminish. Collimation of the outflow provides a natural way to break the symmetry and leave a net polarization (Ghisellini & Lazzati 1999; Sari 1999), which is another argument in favour of jetted outflows in GRB afterglows.

1.3 Afterglow statistics and dark bursts

So far (March 2002), there have been roughly 55 localizations with a reasonably accurate error box (≤ 10 arcminutes) and within a reasonable time after the burst (about 1 day). In almost every case when (soft) X-ray observations were performed (typically 10-20 hours after the burst), an X-ray afterglow was found (around 40; see Piro 2001).

Optical and near-infrared ground-based efforts led to roughly 30 counterparts. This means that a number of optical afterglows is missed, despite intensive and early searches in some of those cases. For example at the location of GRB 970828 no optical afterglow was detected down to R=23.8, only 4 hours after the burst (Groot et al. 1998a). One explanation for this non-detection is that the region where the GRB occurred is extremely dusty, which does not affect the high-energy photons, but absorbs and scatters the optical radiation. A possible way around this, is to observe in the near-infrared passbands, that are less affected by extinction by dust, but also there strong limits have been obtained: no afterglow was detected with the NTT for GRB 001204 down to K=20, only 5 hours after the burst (Vreeswijk & Rol 2000). The nature of these dark bursts is one of the prime targets of future GRB afterglow observations. A considerable handicap for the detection of afterglows is the delay between the time of the burst and the notification of the burst sky location by the satellite teams. For BeppoSAX, the main provider of accurate localizations so far, this interval typically ranges from 4 to 12 hours. Due to the powerlaw decay, afterglows are expected to be much brighter at earlier times, and so
1 Introduction

With fast notifications from future satellite missions, the detection efficiency of optical and infrared afterglows is expected to become much higher.

At radio wavelengths roughly 20 counterparts have been discovered, a few of which have not been seen in the optical. These are good dark burst candidates. Thus also in the radio a large number of afterglows are missed, but this can be explained by the limited sensitivity in the radio as compared to at optical wavelengths.

Almost every optical/near-infrared/radio counterpart has an identified host galaxy, and for about 20 bursts the redshift has been securely determined, either from absorption lines in the afterglow spectrum or emission lines from the host galaxy. In this thesis we present three of these redshifts: for GRB990510 and GRB990712 (for both see Chapter 4), and GRB991216 (see Chapter 6). The currently highest GRB redshift is $z = 4.5$ (Andersen et al. 2000), with a median value of about $z = 1$.

1.4 The origin of GRBs: possible progenitors

Collapsars vs. binary neutron stars

The general expectation is that a system consisting of a black hole and a surrounding accretion torus or accretion disk of nuclear matter is powering the GRB (Woosley 1993; MacFadyen & Woosley 1999; Janka et al. 1999). Such a setting, just before the GRB goes off, can be reached in several ways. One way is the merging of a binary neutron star or a neutron star and a black hole (Eichler et al. 1989; Narayan et al. 1992; Ruffert & Janka 1998; Janka et al. 1999). Another popular model involves the core collapse of a rapidly rotating massive star, the ‘collapsar’ model (Woosley 1993; MacFadyen & Woosley 1999). There are several indications that the so far observed population of GRB afterglows can be best explained by the latter model.

Modeling constraints on long and short bursts

The first indication comes from the models themselves: the collapsar model naturally produces bursts that have a duration longer than a few seconds (MacFadyen & Woosley 1999), but cannot make short bursts, while the merger model can produce short bursts but has problems keeping the engine on for longer than a couple of seconds (Janka et al. 1999). In light of these two models, Fig. 1.1 is very interesting, i.e. it may well be that the short-duration population is produced by mergers, while the long bursts come from collapsars.
The discovery of SN 1998bw

In Chapter 2 we present the discovery (see Fig. 1.4) of the supernova SN 1998bw in the error box of GRB 980425 (Galama et al. 1998b). The presumed association of the GRB with a supernova (SN) of type Ic lent much support to the collapsar model (e.g. Iwamoto et al. 1998), although the hypothesis that the SN and GRB are related at first was highly debated. In the collapsar scenario, the GRB is produced in narrow cones along the rotational axis of the collapsing progenitor, accompanied by an isotropic supernova explosion. However, if the GRB and SN are indeed related, the inferred isotropic γ-ray energy release of this particular GRB, which in its gamma-ray properties is indistinguishable from the cosmological bursts, is only $10^{48}$ erg. This implies that either it belongs to an entirely different class of GRBs, or it may be that it is part of the same class, but that the γ-ray flux decreases as a function of angle from the center of the jet, as in the model of Rossi et al. (2002). In this case GRB 980425/SN 1998bw was observed at a larger angle from the jet axis compared to 'on-axis' GRBs, resulting in a much lower flux level. For a few cosmological GRBs (GRB 980326, GRB 970228 and GRB 011121) a bump in the late-time afterglow light curve has been interpreted as due to a SN 1998bw-type supernova component superposed on the gamma-ray burst afterglow light curve. This lends further support to the GRB/SN connection (Bloom et al. 1999a; Reichart 1999; Galama et al. 2000; Bloom et al. 2002).

Figure 1.4: The host galaxy of SN 1998bw before (on the right) and after (on the left) the supernova explosion. The image on the left was taken with the New Technology Telescope (NTT) at ESO, La Silla in early May 1998, and shows the new bright point source. On the right the projection of the supernova is shown with a circle in this COSMOS scan of a 1978 DSS Schmidt plate.
Location of GRB afterglows with respect to their host galaxies

For just about all GRB afterglows, a host galaxy has been detected. Fig. 7.1 shows almost all of the host galaxies that have been imaged with HST and that have an accurate position for the burst position from the early afterglow (Fruchter et al. 2002). The projected position and its error are indicated on the 2.5×2.5 arcsecond images by a circle. In nearly all cases the burst position is within the optical extent of the underlying host galaxy, which in combination with the blue colours of the galaxies, suggests that GRBs originate in regions where star formation is taking place (Bloom et al. 2001c; Fruchter et al. 2002). This is consistent with the collapsar model, in which GRBs are expected to occur in active star-forming regions. In the case of the binary neutron star merger model, however, the GRB should take place well outside its host in at least a few cases, due to the kick velocity received from the two supernovae (200–300 km s⁻¹), and the time it takes the binary to merge (10⁸ – 10⁹ years). The absence of observed afterglows well outside host galaxies suggests that the long-duration bursts originate in collapsars.

Large X-ray column densities

Another observational indication in favour of the collapsar model is the comparison made by Galama & Wijers (2001) between the host-galaxy extinction inferred from X-ray observations and the optical extinction obtained from modeling the afterglow light curves. The average X-ray extinction is very high: comparable to that of a giant molecular cloud (GMC), suggesting that GRBs occur in very dense regions. However, the optical extinction is moderate. The authors suggest that this is due to the X-ray/UV flash destroying the surroundings, which then allows the optical afterglow to be seen.

1.5 The nature of the GRB host galaxies

1.5.1 The hosts of GRB 990510 and GRB 990712

The apparent magnitudes of GRB host galaxies range from roughly V=22 to V=30 (see Fig. 7.1. They have normal luminosities (Schaefer 2000), and their V−H colour is blue compared to a HDF comparison sample (Fruchter et al. 2002).

In Chapter 4 we study two of these host galaxies in detail, at the two extremes of surface brightness: the host of GRB 990712, which is one of the nearest hosts at z = 0.43, and also bright, with V ~ 22, and that of GRB 990510 at z = 1.62, which is one of the faintest. For both we determined the redshift. Fig. 1.5 shows a Very Large Telescope
1.5 The nature of the GRB host galaxies

Figure 1.5: VLT spectrum of GRB 990712 taken 12 hours after the burst. Absorption lines of Mg I and Mg II are detected, as well as several emission lines from the underlying bright (V~22) host galaxy. Analysis of the emission line spectrum shows that the host is an actively star-forming galaxy (Vreeswijk et al. 2001b).

(VLT) spectrum of GRB 990712, taken 12 hours after the burst. Due to the comparable brightness of the OT and the bright host at this epoch, absorption features as well as emission lines are visible. From the strength of the emission lines we estimate the internal extinction, and obtain an extinction-corrected star-formation rate (SFR) from the [OII] lines of $35^{+178}_{-25} \, M_\odot \, yr^{-1}$. This shows that the host is an actively star-forming galaxy, which is what one would expect if GRBs are produced by collapsars (MacFadyen et al. 2001).

1.5.2 Are GRB hosts starburst galaxies?

It is debated whether the star formation in the early universe is produced by many faint blue star-forming galaxies (Ellis 1997), or by relatively few extreme starburst galaxies (Sanders & Mirabel 1996). If GRBs are produced by the collapse of massive stars, they are presumably originating in galaxies where the bulk of massive-star formation at high redshifts is taking place. Determination of the nature of GRB host galaxies and measurement of their star-formation rate therefore not only provides evidence in favour of or against the collapsar model, it can also provide insight in the nature and origin of star formation in the early universe.
Star-formation rates determined from radio and sub-mm observations

As we discuss in Chapter 5 and as is shown by the large uncertainty of the [OII]-determined SFR that we obtained for the host of GRB 990712, SFR estimates from optical observations may heavily underestimate the true SFR due to dust extinction (see Table 5.1). Observations in the far-infrared, sub-mm and radio continuum are much better suited for estimating the true star-formation nature of galaxies. Several GRB hosts have been observed at sub-mm and radio continuum wavelengths. For three hosts (of GRB 980703, GRB 000418 and GRB 010222), SFRs of 500–1000 M$_\odot$ yr$^{-1}$ have been claimed (Berger et al. 2001b; Frail et al. 2001a; Berger et al. 2001a), which would put them in the starburst galaxy category. Not all hosts show these huge rates though: in Chapter 5 we present Australian Telescope Compact Array (ATCA) observations of the host galaxy of GRB 990712, and obtain an upper limit of 100 M$_\odot$ yr$^{-1}$. This is the deepest radio/sub-mm limit on the SFR obtained for a GRB host galaxy to date.

Host-galaxy morphology

The morphology of galaxies can also provide clues regarding their star-formation nature. For instance, merging galaxies are excellent star-formation nurseries. The gas content of the colliding galaxies rapidly falls into the combined potential well, which sets off a burst of massive star formation. A sample of galaxies with a disturbed morphology is therefore expected to produce a higher instantaneous SFR than, for example, a sample of early-type galaxies.

In Chapter 7 we investigate the morphology of a sample of GRB host galaxies, by fitting their surface brightness profiles, and by measuring objective classification parameters, such as central concentration and asymmetry, also in order to study to what degree their morphology may be disturbed.

1.6 GRBs as potential probes of the extreme high-redshift universe

1.6.1 The 9th magnitude flash of GRB 990123 at z = 1.6

At present, the alert delay for arcminute localization of bursts by BeppoSAX (and RXTE) is typically 4–12 hours, due to the necessary ground analysis. BATSE provided positions immediately, but with error boxes of the order of degrees. Robotic telescopes such as LOTIS and ROTSE are developed to slew extremely rapidly to such a BATSE
burst, to look for a bright (V<13–15) counterpart. The afterglow of GRB 990123 was discovered at 18\textsuperscript{th} magnitude (Odewahn et al. 1999) following the arcminute position from BeppoSAX roughly 3 hours after the burst. This is on the bright side, but not uncommon for an afterglow discovery. However, the ROTSE telescope had imaged the BATSE location of this burst as early as 20 seconds after the burst. They checked the position of the afterglow, and saw an object brightening and fading in six images, peaking at an incredible V=9 (Akerlof et al. 1999). Fig. 1.6 shows the light curve of this burst (Galama et al. 1999a), including the six data points from the ROTSE telescope. The redshift was determined to be z = 1.6 (Kelson et al. 1999). This extreme optical brightness immediately shows the enormous potential of GRBs to probe the early universe. It should be realized, however, that not every GRB afterglow is this bright at early times. Upper limits from the same robotic telescopes show that GRB 990123 was fairly exceptional, possibly a one out of ten case. But with two GRBs a day on the entire sky with the current gamma-ray sensitivity, there could be a considerable number of GRBs with a 10\textsuperscript{th} magnitude flash.

![R-band light curve of GRB 990123](image)

**Figure 1.6**: R band light curve of the afterglow of GRB 990123 at z = 1.6 (Galama et al. 1999a), whose incredible 9\textsuperscript{th} magnitude optical flash was caught by the ROTSE telescope (Akerlof et al. 1999).
1.6.2 Metal absorbers

One possible use of the bright optical flashes that GRBs can produce is the study of the host-galaxy ISM and intervening absorption-line systems. The spectra of GRB 990510 that we discuss in Chapter 4 show the potential that GRBs offer to study their host galaxies, even though the galaxies themselves may be too faint to be detected. High-resolution, time-resolved spectra of bright afterglows may show evolution of the host ISM absorption features due to the burst ionizing its immediate surroundings (e.g. Perna & Loeb 1998). Detection of such a change can possibly constrain the circumburst density profile. These spectra will also offer kinematic information on sub-systems within the host (e.g. Castro et al. 2001b). We performed time-resolved spectroscopy of GRB 990510 and GRB 990712 (see Chapter 4), but the signal-to-noise and spectral resolution are too low to conclude on a possible change in the absorption-line equivalent widths.

Metal absorption-line systems are conventionally detected in QSO (quasi stellar object) lines of sight (e.g. Steidel & Sargent 1992). Against the bright background source, foreground systems give away their presence by absorbing at specific wavelengths of e.g. iron and magnesium. The systems with inferred $N_{\text{HI}}$ column densities greater than $2 \times 10^{20}$ cm$^{-2}$, so-called damped Ly$\alpha$ absorbers (DLAs), are of particular interest for studies of galaxy evolution and star formation as a function of look-back time, since they contain the bulk of the gas at high redshifts (e.g. Rao & Turnshek 2000). At some redshift this gas must have been converted into the stars that we see in present-day galaxies.

In Chapter 6 we present VLT spectroscopy of the afterglow of GRB 991216, and HST imaging of its host galaxy. We determine the probable redshift, and show that there are indications of one or two foreground absorption systems on the GRB line of sight. The spectral resolution is too low to study the metallicity of these systems, but with future rapid activation of spectrographs on 8-m class telescopes, this will become possible.

In the future, GRB afterglows are expected to complement the QSO sight lines for the study of the evolution of metal absorption-line systems. They have several advantages: 1) GRB afterglows can be brighter (e.g. GRB 990123, see Fig. 1.6). However, their brightness fades rapidly (as flux $\propto t^{-\delta}$, with $\delta$ roughly in between 1 and 2), so telescopes need to be activated quickly to profit from the extreme brightness at early times; 2) a fraction of the GRBs is expected to originate at higher redshifts than quasars (Wijers et al. 1998; Lamb & Reichart 2000; Ciardi & Loeb 2000); the current record holder is GRB 000131 at $z = 4.5$ (Andersen et al. 2000); 3) After the GRB transient has faded, the galaxies responsible for the observed absorption lines can be searched for more easily than in quasar lines of sight, where the persistent quasar emission is hampering any detection of faint intervening galaxies (Steidel et al. 1997; Turnshek et al. 2001). However, for quasars at high redshifts ($z \gtrsim 3$) the line-of-sight hydrogen column greatly reduces the quasar's intensity below Ly$\alpha$ and may allow optical observations of the...
1.7 Future GRB afterglow observations

foreground system(s). Such a detection can lead to classification of the damped Lyα system (it is presently debated whether DLA systems arise in luminous H\textsc{ii} disks, or in a mixture of galaxy types), and also allows simultaneous investigation of the gaseous and stellar components of the system. Along GRB lines of sight, after the optical afterglow has faded, its host galaxy will remain as a background source, with a magnitude ranging from 22 to fainter than 28; 4) GRB host galaxies and nearby absorption-line systems are not affected by the GRB explosion (except for the immediate circumburst environment), whereas the surroundings of quasars have been altered by their large persistent UV flux (the so-called proximity effect). Therefore, using GRB afterglows as probes of absorption systems along the line of sight may lead to an improved understanding of the conversion from gas to stars at high redshifts, and hence galaxy evolution in the early universe, and can be considered as an excellent potential use of these powerful explosions.

1.6.3 Star-formation history

If GRBs are indeed closely related to the deaths of massive stars, they could potentially be used to probe the star-formation history of the universe. As the gamma rays and X-rays are not affected by the large optical depths in regions of star formation, the view of such regions is unobscured. However, a large sample of GRB redshifts and characteristics of the host galaxies is needed before a possible relation between GRB number counts and star formation can be reached.

1.7 Future GRB afterglow observations

During the past five years the field of gamma-ray burst studies has developed extremely rapidly: their cosmological distance was established, the fireball theory was found to be in good agreement with the observations, one GRB afterglow was found to be extremely bright, and observations seem to favour the collapse of a rapidly rotating massive star as the source of long-duration GRBs. Most of these observations have been made possible by the accurate localizations by the BeppoSAX satellite, whose extremely successful mission will most likely end in 2002. HETE-II (launched in October 2000) was expected to localize (within minutes of the burst) roughly two dozen bursts a year with arcminute-sized error boxes and one dozen with an error radius of tens of arcseconds. However, until this month (March 2002), only one afterglow has been discovered based on a HETE-II localization. The Swift mission is planned for launch in the fall of 2003, and is expected to provide one 1–4 arcminute-sized error box per day (!), within seconds of the burst trigger, for at least 3 years. These rapid locations will put well-prepared ground-based telescopes in the position to attack several outstanding issues, which we discuss below.
Afterglows from short bursts

So far BeppoSAX (and RXTE) have only triggered on bursts with a duration longer than a couple of seconds; nothing is known about the afterglow behaviour of the short-duration bursts. The IPN network has triggered on short-duration events, but due to the delay time between burst and localization of typically a day, and the expected faintness of these afterglows, so far no counterparts have been detected (Hurley et al. 2002). It will be interesting to verify if these indeed are related to bursts originating from mergers of two compact stars. Such mergers may show an entirely different afterglow behaviour than the long-duration bursts. HETE-II and Swift should be capable of triggering on these short events.

The GRB/SN connection

The connection between GRBs and SNe is still debated. The way to settle this issue is to take a spectrum at the time of maximum of the supernova bump (typically 30 days after the burst) to try to identify supernova features in the spectrum. This will require an efficient spectrograph at an 8-m class telescope.

Polarization

Polarization measurements allow study of the strength and direction of the magnetic fields in the fireball. It is presently unclear how such fields are generated, and what their orientation is. For two bursts polarization has been detected with the VLT, but the few data points do not allow for strong conclusions. With HETE-II and Swift alerts it will be possible to study the evolution of the polarization in time.

High-frequency optical variability

In general the afterglow light curves follow the power laws predicted by the fireball theory. Variability is not expected and not observed. At early times, however, things might be different. The gamma-ray light curves show extremely spiky, erratic behaviour. Observing simultaneously in the gamma-ray and optical regime will help understanding the mechanism of the central engine and the causes of this variability. Also, after the gamma-ray emission has ceased, which in some cases can last for several minutes, rapid variability is expected, due to inhomogeneities in the circumburst medium. Future studies of the prompt optical afterglows and their variability may therefore provide important new information on the "engines" and the immediate circumburst medium.