What Have We Learned From GRB Afterglows?

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Abstract. The discovery by BeppoSAX and coordinated ground-based observations of persistent X-ray, visible and radio counterparts to GRB has successfully concluded a search begin in 1973, and the observed redshifted absorption lines have proved that GRB are at cosmological distances. The problem of explaining the mechanisms of GRB and their persistent counterparts remains. There are two classes of models: 1) GRB continue weakly for days at all frequencies; 2) GRB emission shifts to lower frequencies as relativistic debris sweeps up surrounding gas (in an “external shock”) and slows. 1) predicts that the visible afterglow should be accompanied by continuing gamma-ray emission, as hinted by the high energy emission of GRB940217 and the “Gang of Four” bursts of October 27–29, 1996. It also suggests that the persistent emission will fluctuate. Behavior of this sort may be found in “internal shock” models. 2) has been the subject of several theoretical studies which disagree in assumptions and details but which predict that at each frequency the flux should rise and then decline, with the maximum coming later at lower frequencies. Some of this behavior has been observed, but data from GRB970508 show that its afterglow cannot be simply extrapolated from its gamma-ray emission. It is likely that both classes of processes occur in most GRB. Comparisons between GRB show that they are not all scaled versions of the same event. These results suggest that most gamma-ray emission is the result of “internal shocks” while most afterglow is the result of “external shocks”, and hint at the presence of collimated outflows. Self-absorption in the radio spectrum of GRB970508 permitted the size of the radiating surface to be estimated, and in future GRB it may be possible to follow the expansion of the shell in detail and to construct an energy budget.

INTRODUCTION

The visible, infrared and radio afterglows of GRB970228 and GRB970508 have taught us many things. Some of them are obvious: The absorption redshift $z = 0.835$ of GRB970508 established the cosmological distance scale of GRB beyond any reasonable doubt, confirming the very strong case made on statistical grounds [1] from BATSE data. It is also evident that afterglows are very faint. This suggests that the simultaneous visible counterparts to GRB, as yet unobserved, will also be
faint, so that experiments designed to detect them will have to be very sensitive. The loss of the original HETE, carrying an insensitive ultraviolet imager, may therefore have been fortunate, for it will be replaced by HETE-2 which instead will carry a soft X-ray CCD which may yield important spectral information.

Observations of afterglows can answer a number of harder questions too:

1. What is the relative importance of internal vs. external shocks?

2. Where does a GRB end and its afterglow begin?

3. Does gamma-ray activity last as long as the afterglow, and could it be an inseparable part of the afterglow?

These questions are central to the understanding and interpretation of afterglows.

**INTERNAL VS. EXTERNAL SHOCKS**

External shocks have been widely considered for GRB since they were suggested by Rees and Mészáros [2]. They predict a hard-to-soft evolution of the spectrum. In many models the duration or elapsed time $t$ is related to a characteristic emission frequency $\nu_c$ by a power law $t \propto \nu_c^{-\alpha}$; the exponent $\alpha$ is model dependent [3–5] but is usually close to $1/2$. This is in remarkably good agreement with X-ray and soft gamma-ray observations [6] of the single-peaked GRB960720 in which $\alpha = 0.46$. However, the fact that GRB with a wide range of durations (from tenths to hundreds of seconds) have comparable $\nu_c$ argues against external shock models, which generally predict that these two quantities should vary roughly reciprocally; it is difficult for $\nu_c$ to be in the soft gamma-ray range if the duration is minutes.

There must be more to GRB than external shocks. Fenimore, *et al.* [7] and Sari and Piran [8] showed that an external shock can produce only smoothly varying time-dependent emission, not the spiky multi-peaked structure found in many (but not all) GRB. Such complex variation must reflect variation in the supply of energy; it cannot be explained solely by interaction with a heterogeneous medium, however complex. A variable outflow may radiate when different fluid elements interact with each other. This process is generally called an internal shock because it does not involve an external medium, although there need be no shock in the hydrodynamic sense of a discontinuity in pressure, density and temperature between two fluids each in thermodynamic equilibrium. Kinematic constraints require that there be inelastic interaction between streams of matter emitted with widely differing Lorentz factors in order that radiation be produced with reasonable efficiency.

Afterglows have, so far, been observed to have a smooth single-peaked time dependence in visible light (their complex time dependence at radio frequencies results from interstellar scintillation [9]), and therefore are naturally explained as a consequence of external shocks. This model predicted [3,4] both the existence of afterglows and the gradual rise to maximum which was observed in both GRB970228...
and GRB970508 [11]. However, there is no evidence that internal shocks could not produce the required time dependence, and they are therefore possible explanations for smooth single-peaked GRB and for afterglows, as well as for the multi-peaked GRB for which they are required.

Is it meaningful to distinguish an afterglow from the GRB itself? This question first arises for X-rays, whose photon energy range overlaps that traditionally assigned to GRB. It has no good answer, and should be considered a matter of nomenclature rather than of physics. Rather, we should be concerned with deciding which emission is produced by internal shocks and which by external; the taxonomist may wish to label the former the GRB and the latter the afterglow.

There are two possible limits [5]. In one all the radiation is the product of an external shock. This is excluded, at least for multi-peaked GRB. It may describe single-peaked GRB and their afterglows. External shock models successfully predicted [4] the delayed maximum of visible afterglow brightness observed in GRB970228 [10] and GRB970508 [11], and are likely to explain such afterglow emission even if they cannot explain gamma-ray emission. These models also successfully predicted [3,5] self-absorption in the radio afterglow, as was observed [12] from GRB970508.

In the other limit all the emission of a GRB is the product of internal shocks, which may continue for days [13] beyond the nominal gamma-ray duration; the afterglow is a continuation, at lower intensity, of the gamma-ray emitting phase. This has been suggested for GRB970228, where it agrees with the observed instantaneous spectrum [14], and the predicted continuing X-ray emission (beyond the decaying afterglow) has been observed from GRB970508 [15]. This hypothesis is consistent with the hours-long gamma-ray emission of GRB940217 [16], and may explain the “Gang of Four” bursts of October 27–29, 1996 [17] as a single GRB.

HOW TO INTERPRET THE DATA

Early work on GRB and their afterglows attempted to construct analytic and numerical models of the entire process. Unfortunately, several essential quantities are poorly known (and unlikely to be the same for all GRB or uniform within a single GRB), such as the distribution of energy among the electrons, ions and magnetic field, the surrounding density and magnetic field, the efficiency of radiation and the degree of collimation. As is so often the case, the real world has turned out to be more complex than theorists could imagine, and a more phenomenological approach is required.

Theories of radiation mechanisms generally predict instantaneous spectra, but observations of afterglows are rarely simultaneous across the spectrum; X-ray, visible and radio observers face different observational constraints. It is possible to fit multiparameter models [18,19] to non-simultaneous data, but the phenomenologist would like a more direct comparison of the emission in different frequency bands. For example, in each band of interest the peak spectral intensity can be measured,
or at least estimated, if measurements are obtained close to and straddling the maximum. The resulting function $F_{\text{max}}(\nu)$ is not an instantaneous spectrum, but makes it possible to compare emission mechanisms in different spectral bands.

In the case of GRB970508 $F_{\text{max}}(\nu)$ can be estimated at GHz, visible (and near-IR), hard X-ray and soft gamma-ray energies (the maximum of the soft X-ray intensity was not observed), and is shown in Figure 1. A single mechanism is unlikely to explain emission in all these bands, because $F_{\text{max}}(\nu)$ is not consistent with a single power law, as would be predicted by a single mechanism which does not have a characteristic frequency to define a spectral break. The visible data form a “hinge”; on purely phenomenological grounds it is not possible to say whether this emission is produced by the same mechanism as the GHz emission or the hard X-rays and soft gamma-rays. Neither of the limiting cases discussed in the previous section is satisfactory. A plausible hypothesis suggests that GHz and visible emission result from external shocks and hard X-rays and soft gamma-rays (the classical GRB) from internal shocks. This explains why an early model [4] underestimated the time to maximum and overestimated the brightness of the visible afterglow of GRB970508: it extrapolated from the gamma-ray emission of an assumed bright GRB, but this extrapolation was invalid (even if scaled to the lesser flux of GRB970508) because the gamma-rays were produced by a different mechanism.
It is also possible to compare [5] the properties of different GRB and their afterglows by comparing the burst-to-burst ratios of $F_{\text{max}}(\nu)$ in different spectral bands. The afterglow of GRB970508 was roughly 20 times brighter than that of GRB970228 in soft X-rays and visible light, when scaled to their soft gamma-ray brightnesses. The afterglow of GRB970508 was at least four times brighter than that of GRB970111 at 1.43 GHz, and at least 1000 times brighter than that of GRB970828 in visible light when similarly scaled (in these last two cases the ratios are lower limits because only upper limits exist to the fluxes of GRB970111 and GRB970828 in these bands). These ratios quantify the conclusion that GRB970508 had a remarkably bright afterglow, compared to the other GRB for which useful data exist, at all frequencies at which comparisons are possible.

This leads to the important (and unexpected) conclusion that afterglows are “all different”. They are not all scaled versions of the same event, and any single simple model must fail. It argues against models in which all GRB and afterglows are related by a single scaling parameter, such as the ambient density, energy or distance, or even some combination of these. A natural interpretation is that (at least in these GRB) the hard X-rays and gamma-rays are produced by internal shocks, and the lower frequency afterglow by an external shock. If so, there need be no close correlation between the brightnesses of GRB and their afterglows, partly because the mechanisms are different, but also because internal shock properties depend on the detailed temporal and spatial structure of the outflow and may well be very different in different GRB.

### A GENERIC AFTERGLOW MODEL

A generic afterglow model is based on the assumption of an external shock, which permits specific predictions to be made. The interaction between a relativistic debris shell and the surrounding medium, or among various elements of an outflowing wind, has been the subject of many papers, but the basic physics is not understood. Even the essential collisionless shock is largely a matter of speculation, although recent calculations [20] have begun to attack the problem. Still, a few features common to most afterglow models are independent of assumptions as to the mechanism of entropy production. The asymptotic ($\nu_s \ll \nu \ll \nu_c$) instantaneous spectrum [4] has the form $F_\nu \propto \nu^{1/3}$ between a self-absorption frequency $\nu_s$ and a characteristic synchrotron frequency $\nu_c$. Below $\nu_s$ the spectrum $F_\nu \propto \nu^2$, while above $\nu_c$ the flux falls off with a slope reflecting the high energy “tail” to the particle distribution function; a power law is typically observed in GRB, but its slope is unpredictable, and is observed to differ from burst to burst and with time in a given burst. The instantaneous spectra $F_\nu(t)$ are bounded from above by the function $F_{\text{max}}(\nu)$. In simple analytic models $F_{\text{max}}(\nu) \propto \nu^{-\beta}$, with the exponent $\beta$ typically [4,5] close to 0; any function of $\nu$ other than a power law would define a characteristic break frequency and require a more complex model.

As time progresses both $\nu_s$ and $\nu_c$ decrease. At a given frequency $\nu_0$ the flux $F_{\nu_0}$
FIGURE 2. Instantaneous GRB spectra for a model in which $F_{\text{max}}(\nu) \propto \nu^{-1/6}$; $t_1 < t_2 < t_3 < t_4$.

The predicted rate of the initial rise $F_\nu(t) \propto t^\delta$, where the preceding expressions for $F_{\text{max}}(\nu)$ and $t(\nu_c)$ and the instantaneous $F_\nu$ lead to

$$\delta = \frac{\beta + 1/3}{\alpha}.$$

Typically, $\delta$ is estimated to be slightly less than unity; in one model [4] $\delta = 4/5$ while in another [5] $\delta = 6/7$. Figure 2 shows the evolution of the instantaneous spectrum. $F_{\nu_0}$ rises until $t = t_3$ and then declines.

**TESTING THE GENERIC AFTERGLOW MODEL**

The predictions of the generic external shock afterglow model can be tested with data from the two observed afterglows. The predicted rise to maximum has been observed. Some data [21] suggested agreement ($\delta \approx 0.7$) with the predicted rate of rise for GRB970508, but more complete data for GRB970228 [10] and GRB970508 [11] suggest a much steeper rise, with $\delta \approx 2–3$.

These large values of $\delta$ appear to disagree with the model. Sari [22] pointed out that in the early stages of external shock models, when the relativistic debris shell has not yet been significantly slowed by the ambient medium, the luminosity
should rise $\propto t^2$ at all frequencies ($\delta = 2$), a simple consequence of the increasing ($\propto r^2$) area of the shell. If this is the explanation then the rapid rise should level out after a time

$$t \approx \left( \frac{3E}{4\pi \rho c^2} \right)^{1/3} \frac{1}{2c\gamma^{8/3}},$$

when deceleration becomes important (the earlier stages of the rising flux could be hidden under steady emission by other processes, such as internal shocks). This leads to an estimate of the ambient density $\rho$:

$$\rho \approx 10^{-33} \left( \frac{E}{10^{52} \text{erg}} \right) \left( \frac{\gamma}{10^2} \right)^8 \left( \frac{t}{10^5 \text{s}} \right)^{-3} \text{g/cm}^3.$$

If the model is correct this implies an extraordinarily low ambient density out to a radius $\sim 2c\gamma^2 t \sim 20(\gamma/10^2)^2(t/10^5 \text{s})$ pc, or a surprisingly low value of $\gamma \sim 10$. Such a low density would be remarkable, even in the intergalactic medium (although a pre-coalescence pulsar wind could create a bubble), and such a low $\gamma$ is inconsistent with gamma-gamma pair production constraints (although in a long duration internal shock model a low $\gamma$ wind could follow a brief high $\gamma$ wind which produces the gamma-ray emission).

If the afterglow is produced by internal shocks it is probably not possible to predict its time dependence. However, the instantaneous spectrum is still predictable. There is some spectral evidence that the first several hours of afterglow in GRB970228 were the product of internal shocks [14]. Internal shocks are a possible explanation of disagreements between the observed time dependence and predictions of the generic external shock model.

This early (3–8 hours after the GRB) period of roughly constant visible intensity in GRB970508 poses another problem. In either internal or external shock models, if the electron synchrotron cooling time is short compared to the duration of observation then the observed spectrum is that integrated over the electrons’ cooling history [23]: $F_\nu \propto \nu^{-1/2}$. Comparison of the visible and soft X-ray [11] fluxes during this period shows a deficiency of X-rays compared even to this spectrum, suggesting that $\nu_c$ lies within or below the X-ray band. This is consistent with emission by an internal shock with a low value of $\gamma$, as suggested by both the near constant visible intensity and the long-delayed onset of the rapid rise.

These conclusions are based on limited data from two afterglows. The outline of the external shock afterglow model is supported by the data, but the detailed interpretation, especially of the rise of the visible intensity to maximum, must await more data from more afterglows.

**THE INSTANTANEOUS SPECTRUM**

The predicted [4] instantaneous asymptotic spectrum $F_\nu \propto \nu^{1/3}$ for $\nu \ll \nu_c$ should be applicable to both internal and external shocks. It is based on several plausible
assumptions: incoherent synchrotron radiation, no cooling (radiative or adiabatic) and a phase space argument for the electron distribution function produced by a relativistic shock which heats the entire electron distribution function, rather than just a “tail” of suprathermal particles. It should apply to the synchro-Compton spectrum too, but with a different coefficient.

Like all theoretical predictions, it is only speculation until empirically tested. So far, the data are inconclusive and not completely consistent. Some X-ray and soft gamma-ray observations of GRB support the prediction [23,24], but others disagree [25,26]. The inconsistency may result from the difficulty of extracting quantitative spectral information from NaI scintillator data, which have low intrinsic spectral resolution, especially at photon energies < 100 KeV where the asymptotic spectrum is expected. This difficulty may also account for the long-standing controversy over the reality of line features in GRB radiation, and may only be resolved when data from detectors of intrinsically higher resolution become available.

Visible data [27] lead to an exponent 0.25±0.25 in the pre-maximum phase of the afterglow of GRB970508, in agreement with the predicted 1/3 (agreement is not expected at and after maximum, because then the frequency of observation exceeds $\nu_c$). Radio data [12] from the same afterglow lead to an exponent $\approx 0.2$, also in agreement with prediction. The results are encouraging, but not yet conclusive.

If a GRB were to be detected in visible light during its initial brief phase of gamma-ray emission the spectral exponent could be determined quite accurately by comparing fluxes at frequencies separated by a factor of more than $10^4$. Such simultaneous detection remains the holy grail of GRB visible counterpart research.

**SELF-ABSORPTION**

Self-absorption of GRB afterglows at GHz frequencies was predicted [3,5] and confirmed [12]. This was no great surprise; the physics is elementary, though a little different (the spectral exponent below $\nu_s$ is predicted to be 2 rather than 2.5) than in the usual case of synchrotron self-absorption by a power law distribution of electron energies. Self-absorption is important because it may lead to a measurement of the emission radius $r$ as a function of time with few uncertain assumptions. The flux for $\nu \ll \nu_s$ is

$$F_\nu = 2\pi \nu^2 m_p \zeta (1 + z) \frac{r^2}{D^2},$$

where $D$ is the distance, $z$ the cosmological redshift, $m_p$ the proton mass and $\zeta$ an equipartition factor defined as $k_B T_e / \gamma m_p c^2$; $\zeta = 1/9$ in the case of complete electron-ion-magnetic equipartition. The shock Lorentz factor (assumed $\gg 1$) drops out; this is fortunate, for it is poorly known and likely to remain so.

If $r(t)$ were inferred from measurements of the self-absorbed flux then it would be possible to reconstruct the expansion history and slowing down of the relativistic debris in an external shock model. This would permit determination of the ambient density and the efficiency of radiation as the initial kinetic energy is radiated or
shared with swept-up matter. A preliminary attempt [5] to construct such an energy budget (based on one inferred value of $r$) for the afterglow of GRB970508 led to the conclusion that the total kinetic energy after seven days was only $\sim 10^{49} n_1$ erg, where $n_1$ is the ambient particle density. This is much less than the $\sim 3 \times 10^{51}$ erg inferred from the gamma-ray radiation, assuming isotropic emission.

There are three possible implications of this result: $n_1 \gg 1 \text{ cm}^{-3}$, as might be found in a dense star-forming region; strong beaming of the gamma-rays (and therefore of the initial relativistic outflow); or a radiation efficiency $> 99\%$ in the first seven days of the event. Any or all of these are possible, and any or all would be important.

**A THEORIST’S WISH LIST**

We have compared the observed afterglows to theoretical predictions based on simple models, and have generally found qualitative agreement. In order to test the theory, particularly that of relativistic shocks, in more detail, more difficult measurements will have to be performed. Here is a list of ambitious goals a theorist might set for his observational colleagues:

1. Accurate X-ray spectroscopy at moderate resolution ($\sim 30$) to test the predicted instantaneous $F_\nu \propto \nu^{1/3}$ ($F_\nu \propto \nu^{-1/2}$ if synchrotron cooling is important). This may be performed by ZnCdTe or Ge detectors, or by X-ray CCD.

2. Simultaneous spectral measurements across several decades of frequency, with $\nu < \nu_c$ throughout (hence the intensity must not have reached its maximum anywhere in this range). This could be achieved by observation of the visible counterpart to a GRB during its strong gamma-ray activity, or by simultaneous measurements of visible and radio afterglow before the visible maximum (within the first day for GRB970228 and GRB970508).

3. Measurement of the intensity as a function of time in the self-absorbed regime of radio afterglow.

Each of these measurements is likely to be difficult. Locating and measuring a visible counterpart to a GRB within tens of seconds is much harder than doing it with several hours of imaging X-ray observations. The only afterglow observed at radio frequencies was not strong enough to be detected until long after the visible maximum, and self-absorption reduces the strength of the radio emission even more. The first goal is probably the most feasible, and would test relativistic shock theory; the last is probably the one which would lead to the greatest understanding of how GRB and their afterglows really work.
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