Shocked by GRB 970228: 
the afterglow of a cosmological fireball

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Abstract
The location accuracy of the BeppoSAX Wide Field Cameras and acute ground-based followup have led to the detection of a decaying afterglow in X rays and optical light following the classical gamma-ray burst GRB 970228. The afterglow in X rays and optical light fades as a power law at all wavelengths. This behaviour was predicted for a relativistic blast wave that radiates its energy when it decelerates by ploughing into the surrounding medium. Because the afterglow has continued with unchanged behaviour for more than a month, its total energy must be of order $10^{51}$ erg, placing it firmly at a redshift of order 1. Further tests of the model are discussed, some of which can be done with available data, and implications for future observing strategies are pointed out. We discuss how the afterglow can provide a probe for the nature of the burst sources.

Key words: gamma-rays: bursts – X-rays: transients – optical: transients – stars: neutron

1 INTRODUCTION
Gamma-ray bursts are such a mystery in large part because in the more than three decades since the first report on them (Klebesadel, Strong, & Olson 1973) they have remained invisible in any radiation other than X and γ rays. This situation ended in the early hours of February 28, when the Gamma-Ray Burst Monitor (40–1000 keV) and one Wide Field Camera (2–32 keV) on board the Italian-Dutch Satellita per Astronomia a Raggi X (BeppoSAX) triggered on a moderately bright gamma-ray burst and imaged it in X rays to give an error box only 6 arcmin across (Costa et al. 1997). It was still detected at a much fainter level by the MECS and LECS X-ray telescopes on BeppoSAX 8 hours after the burst, and again 3 days later, tightening the error box radius to under an arcmin. Optical images taken with the William Herschel and Isaac Newton Telescopes at La Palma starting only 20 hours after the burst reveal a fading source that is undoubtedly associated with GRB970228 (Van Paradijs et al. 1997), and therefore its location is now known with sub-arcsecond precision.

Initial reports of an underlying host galaxy of roughly $R = 24$ (Van Paradijs et al. 1997) appear inconsistent with later HST images that show only a very faint, if any, underlying object (Sahu et al. 1997a,b). The issue of a host and its implications for the distance scale therefore remain to be resolved, and we shall be primarily concerned here with the evolution of the gamma-ray burst itself. Because the host is so faint it is safe to assume that its contribution to all optical detections thus far is negligible.

In Section 2 we briefly review the basic properties and predictions of a blast wave. In Section 3 we discuss the light curves of GRB970228 and GRB970402 and their afterglow and show that they agree very well with the predictions of the fireball model (Rees & Mészáros 1992, Mészáros & Rees 1997a). We then briefly discuss the distance scale in relation to our results and some possible complications due to less simple blast wave models (Sect. 4). We summarise our findings and discuss some implications for observing strategies in Section 5.

2 THE SIMPLEST BLAST WAVE AND REMNANT EVOLUTION
The simplest fireball remnant model is given by the diminishing emission of a forward blast wave moving ahead of a fireball, which continues to plough into an increasing amount of external matter beyond the deceleration radius at which the bulk Lorentz factor $\Gamma$ first dropped substantially giving rise to the GRB (Rees & Mészáros ). Beyond this, the Lorentz factor decays as $\Gamma \propto r^{-3/2} \propto t^{-3/8}$, where $t$ is the observer-frame time (Mészáros & Rees 1997), and the spectrum is due to synchrotron radiation, from electrons accelerated to a power law $N(\gamma) \propto \gamma^{-p}$ above the minimum energy $\gamma_m \propto \Gamma$ imparted by the shock. The comoving intensity or
where the synchrotron break frequency \( \nu_B \propto \Gamma B \delta \gamma \), and \( \beta' = (1 - \alpha)/2 \). Observationally (Band et al. 1993), \( \alpha' = \alpha + 1 \) is around 0 (single \( B' \) synchrotron would give 1/3 but sampling a range of \( B' \) and \( \gamma_m \) can easily give a range around that), while \( \beta' = \beta + 1 \) is around 1 (ranging approximately from \(-0.5 \) to \(-0.2\)). This is the canonical GRB spectrum in \( \gamma \)-rays, the observed \( h\nu_m \) being typically in the range of 50 keV to 2 MeV.

The comoving-frame equipartition magnetic field is \( B' \propto \Gamma \sim t^{-3/8} \), so the break frequency drops in time as \( \nu_B \propto \Gamma B' \sim \Gamma t^{-3/8} \). At the same time, the comoving electron density \( \rho' \propto \Gamma \Gamma' \) and the comoving width of the emission shell \( \Delta R \sim (1/\Gamma) \sim t^{-1/8} \); the comoving intensity \( I' \propto \rho' B' \Delta R \propto \rho' B' \Delta R \propto t^{-1/8} \), so the observed flux as a function of observer time is (Mészáros & Rees 1997a) \( F_{\nu_m} \propto t^{2/3} \nu_m^{2/3} \sim \nu_m^{2/3} \). The observed break frequency \( \nu_B \) crosses the X-ray or optical band at a time \( t_{X,op} = (\nu_B/\nu_{op})^{2/3} t_\nu \), after the break frequency lies at \( \nu_B \). For \( h\nu_B \nu_{op} = 100 \text{ keV} \), \( 5 \text{ keV} \), and \( 2.3 \text{ eV} \), respectively, one has \( t_X = 7 t_\nu \) and \( t_{op} = 170 t_\nu \).

If the time-averaged flux at \( \gamma \)-rays of the GRB was \( F_{\gamma} \), then for \( t < t_{X,op} \) we have \( F_{X,op} = F_{\gamma}(\nu_{X,op}/\nu_{op})^{\alpha'} \). After \( \nu_{op} \) crosses the X-ray or the optical band, we have

\[
F_{X,op} \propto F_{\nu_m}(\nu_{op}/\nu_{op})^{\beta'} \propto \nu_{X,op}^{(3/2)/\beta'} \propto \nu_{op}^{3/\beta'} \tag{2}
\]

The expansion \( \Gamma \sim t^{-3/2} \) lasts until the remnant becomes nonrelativistic, after which the remnant enters a Sedov-Taylor phase. Here \( r \sim t^{3/2} \), \( B' \sim t^{-3/2} \gamma \sim t^{-6/5} \), \( \rho' \Delta R \sim t^{2/5} \gamma \) and \( \nu_B \sim t^{-3} \), \( F_{\nu_B} \propto t^{-3/5} \), so that the optical (and X-ray, if detectable) flux has \( \nu > \nu_B \) and goes as \( F_{op} \propto t^{(3+15\beta')/5} \sim t^{-12/5} \beta' \sim \sim 1 \). Such a break in behaviour would occur when the blast wave has swept up a rest mass energy equal to its initial energy, at time

\[
t_{av} = \left( \frac{3E}{4\pi n_m c^2} \right)^{1/3} \approx 1 \text{ yr} \left( \frac{E_{51}}{n_{-3}} \right)^{1/3} \approx 1 \text{ d} \left( \frac{E_{41}}{n_{-3}} \right)^{1/3} \tag{3}
\]

where \( E \) is the initial explosion energy and \( n \) is the density of the surrounding medium, and the two numerical expressions are scaled to typical cosmological and halo cases, respectively. Such a break has, so far, not been seen in GRB 970228. Since it has now been followed for over a month, this firmly places it well beyond the halo of our Galaxy, if the blast wave model is indeed valid.

### 3 CONFRONTATION WITH THE DATA

#### 3.1 Data on the light curve

In Table 1 are listed all the fluxes from gamma-ray to radio that have been reported since the initial trigger. All upper limits are 3\( \sigma \). Optical and near-infrared magnitudes were translated into fluxes assuming they were all calibrated on the Vega system. Of course, since many reports are preliminary, the final calibrated values may differ somewhat from the table values, but since our emphasis is on trends of the fluxes when they change by a few orders of magnitude, these corrections will not affect the results reported here. The foreground reddening at the location of the burst is \( E(B-V) = 0.14 \) (Burstein & Heiles 1982), so the magnitudes were de-reddened using \( A_B = 0.8 \), \( A_V = 0.4 \), \( A_K = 0.3 \), \( A_I = 0.2 \), \( A_{H,K} = 0.0 \).  

The X- and \( \gamma \)-ray data need a somewhat more careful treatment, since they are taken over much broader ranges of photon energy. TGRS reported clear evidence for a break in the spectrum, at \( E = 100 - 150 \text{ keV} \) if an exponential cutoff was used (Palmer et al. 1997). On the other hand, the GRBM on SAX reported significant flux above 600 keV, so the spectral change is more likely to take the form of a

<table>
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power law spectrum that changes slope at some break energy $E_b$, like the model of Band et al. (1993). The four fluxes reported for the initial strong 4-s spike (which appears contain the bulk of the burst fluence) are (in units of $10^{-6}$ erg cm$^{-2}$ s$^{-1}$, with subscripts giving the energy range in keV): $F_{40-200} = 1.7$ (Palmer et al. 1997), $F_{1.5-7.8} = 0.1$, $F_{40-600} = 4$, $F_{40-1000} = 6$ (Van Paradijs et al. 1997). Assuming a spectrum that is flat below $h\nu > E_b$ ($\alpha' = 0$) and has slope $\beta'$ above it (eq. 1), we can try to see which $(\beta', E_b)$ match the fluxes best. $E_b$ must be greater than about 40 keV and $\beta'$ in the range $-1$ to $-0.5$ to get a satisfactory fit. Since we know from the TGRS spectrum that $E_b \lesssim 150$ keV, this pins the parameters down reasonably well. To specify the X- and $\gamma$-ray fluxes, we use $E_{\text{in}} = 40$ keV and $\beta' = -0.8$. The gamma-ray flux is then given as the fitted value at 100 keV, $F_{100\text{keV}} = 4200 \mu$Jy. The OSSE upper limits were likewise translated into values at 100 keV.

The initial X-ray flux also follows from the spectral fit, and all other reported X-ray fluxes are translated into fiducial $F_{\gamma}$ values at 5 keV as well. For X rays, this is unlikely to introduce an error of more than 30%, for gamma rays it may be a bit more. Accounting for uncertainties in reddening and the preliminary calibration, most optical points should have errors under 30%. This could affect the flux offset between light curves at different bands by up to that amount, but is unlikely to affect the inferred rate of decay in any single band by much, since the reddening corrections do not affect them. Moreover, in cases where more than one measurement in the same band by the same instrument is available, which presumably suffer from calibration effects in the same manner, the decay rate from that subset is quite consistent with that of all data in that band. The flux history of GRB 970228 at various photon energies is plotted in Fig. 1.

3.2 Comparing GRB 970228 and 970402 with the blast wave model

Fig. 1 clearly confirms the prediction that the flux of GRB 970228 should decline as a power law, in bands where more than 2 measurements well separated in time are available (X-ray, $V$, $I$). Moreover, a fit with free slope to data in those bands shows that the exponent of the decay, $\delta$, is the same for all, as the model demands: $\delta = -1.2$. But then we predict the slope of the spectrum, $\beta' = 2\delta/3 = -0.8$. The spectrum in the decaying part of the light curves (i.e. above the break) also follows from the flux ratios at fixed time, i.e. from the vertical offsets between the fitted lines. This independent measurement of the spectrum gives $\beta' = -0.78$, remarkably close to the prediction.

Since after fixing the vertical level of the fit to the $V$ data all other levels are fixed in the model, we can show the predictions that follow from it for the other frequencies (Fig. 1). The agreement is quite good all the way from X rays to $K$ band. It is too early to say whether the occasional exception (e.g. the first $J$ point) constitutes interesting extra behaviour. Overall, the agreement in such detail can be regarded as a strong confirmation of the model.

It is undecided whether the initial gamma-ray burst derives from the same mechanism as the afterglow, i.e. is the initial part of the blast wave deceleration, or has a separate origin, e.g. internal shocks in the relativistic wind (Paczyński & Xu 1994, Rees & Mészáros 1992) before the deceleration by the external medium begins. There is some indication in the $\gamma$-ray light curve of GRB 970228 that speaks against the former option. The leftmost dashed curve in Fig. 1 is the prediction for the $\gamma$-ray flux assuming it originates from the blast wave itself (and can therefore be predicted from the V and X-ray light curve). It only just falls below the OSSE upper limits, and even then the break happens too early, as evidenced by the fact that the initial $\gamma$-ray flux lies above the curve. It is therefore possible that the gamma rays have a different origin. In that case, we can no longer rely on the initial $\gamma$-ray flux to set the level of emission from the blast wave before the break. This implies that the initial V magnitude of the burst could have been rather low, limited only by the first measurement ($V = 20.9$), rather than a (model dependent) value related to the initial $\gamma$-ray flux.

The sparser data on GRB 970402, which was triggered on April 2.93 UT (Feroci et al. 1997) also have some bearing on this matter. This burst lasted about 100 seconds with apparently no obviously dominating initial peak, and its peak flux was about 10 times lower than GRB 970228. It is the second GRB of which afterglow was detected, again 8 hours after the trigger, but a second attempt after 1.7 days only found an upper limit (Piro et al. 1997). Followup with 1-m telescopes at Siding Spring and SAAO (the burst is at declination $-69^\circ$) 0.7–1.9 days after trigger place upper limits of $R = 21$ on any fading counterpart (Groot et al. 1997a). From the X rays, and initial gamma rays, we once again infer that this burst has roughly the canonical spectrum of slope 0 below and slope $-1$ to $-0.8$ above the break, so we expect it to fade in time as a power law with slope $\delta = -1.5$ to $-1.2$. If we assume all emission is from the blast wave, and hence the flux at all wavelengths starts at the same value as the initial $\gamma$-ray flux, then the time at which the break lies at 5 keV follows from the X-ray detection: $t_b = 4-40$ s. The break should then arrive at $R$ after $t_R = 800-8000$ s, consistent with the $R$ limit. However, the predicted time for the gamma-ray break becomes $t_{100} = 0.5-5$ s, rather early for a burst that lasts over 100 s and is not dominated by an initial spike, as was GRB 970228. This discrepancy in the $\gamma$-ray timing, similar to the case of GRB 970228, may lend some support to the independent origin of the initial $\gamma$-ray emission.

To distinguish between these cases, measurements in the first 15 minutes in X rays or in the first few hours in optical are needed. This could be achieved with present instruments because positions with 10 arcmin accuracy become available from the Wide Field Cameras on board BeppoSAX on a 1–3 hour time scale, and a BACODINE-type alert system could spread this knowledge to observatories around the world in seconds. Also, since re-pointing the satellite is not done until after some time, the WFC data immediately following the main burst could be a sensitive diagnostic of what the initial level of the X-ray afterglow might be.

4 DISCUSSION

4.1 Galactic models

Since they have much less energy than the cosmological ones, conventional matter-dominated fireball blast waves should
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Figure 1. The light curves of GRB 970228 from γ rays to near-infrared. The lines indicate the prediction for a relativistic blast wave with $\beta' = -0.8$ and $t_V = 600\,\text{s}$.

4. Less simple fireball and remnant evolution

The decay model discussed in Sect. 2 is for the simplest external blast wave scenario, valid for a spherically expanding fireball or a flow which is uniform inside channels of smaller solid angle. Other types of emission have been also considered, e.g. from the reverse shock moving into the ejecta, or magnetic field strengths at a given time and the shorter expansion time scales at a given $\Gamma$. Thus one might expect faster turnover of both the X-ray and optical emission, due to a decrease of the optical radiation efficiency. This would be in addition to the steepening caused by moving into the Sedov-Taylor nonrelativistic phase. The late-time radio afterglow should come from a large enough region to be resolved by VLBI.

For sources within a few hundred kpc, one could expect the radio emission to turn on much sooner than in cosmological models, since it is quicker in reaching a given angular diameter, when the remnant still has sufficient internal energy to produce observable emission. Furthermore, a galactic halo neutron star would not be disrupted (since it needs to repeat many times) and thus could, in principle, produce also coherent radio emission by pulsar-type mechanisms in the magnetosphere.
from ejecta with a frozen-in magnetic field, or from internal shocks (Mészáros & Rees 1997a). These decay more rapidly than $F \propto t^{(3/2)\beta'}$ (eq. 2). However, there are additional considerations which can lead to different decay laws, including some which are slower than $t^{(3/2)\beta'}$. It is, for instance, probable that the high-$\Gamma$ fireball that gives rise to the GRB may be beamed (Mészáros & Rees 1992, 1997b), and in this case it is natural for $\Gamma$ to be a function of angle, tapering off towards the edges of the beam. In a cosmological compact binary disruption scenario, a central object (presumably a black hole) forms, which is surrounded by a temporary torus of neutron star debris. A very high bulk Lorentz factor jet emerges around the rotation axis, which would taper off into a slower wind, as it mixes with the increasingly baryon loaded wind at large angles which must result from the super-Eddington radiation from the torus. As a simple example, we can take a dependence $\Gamma \propto \theta^{-k}$ (Mészáros & Rees 1997b), where $\theta$ is the angle from the axis of rotation, outside of the main part of the jet. The deceleration of the fireball commences at a radius $r_d \propto \Gamma^{-8/3}$, which is larger for larger $\theta$. Since radiation can be seen by the observer from within a cone of angle $\sim \Gamma^{-1}$, the radiation from increasingly larger angles will be detectable by the observer, at later times which are given by the deceleration time $t_d(\theta) \propto \Gamma^{-8/3}$ for that $\Gamma \sim \theta^{-k}$. This time is of order a day for $\Gamma \sim 10$, and a month for $\Gamma \sim 3$. In the simplest case where the burst progenitor supplies equal amounts of energy into equal logarithmic intervals of $\theta$, the bolometric flux detected as a function of time will then be $F(\theta) \propto \Sigma F(\theta)/t \propto t^{-1}$. If the spectrum is again of the form $\nu \propto \nu'$, and we take the field to be a constant fraction of the equipartition value, then $\nu_m \propto \Gamma B' \gamma^2 \propto \Gamma^4 \propto t^{-3/2}$, and $F_{\nu_m} \sim L/\nu_m \propto t^{-1} t^{3/2} \propto t^{1/2}$. If the radiative efficiency does not change in time and the spectrum evolves homologically, then we have

$$ F_{\nu_m} \sim \begin{cases} F_{\nu_m} (\nu/X_{\text{op}})^{\alpha'} \propto t^{(1+3\alpha')/2} \propto t^{1/2}, & \text{for } t < t_{X,\text{op}}, \text{ if } \alpha' \sim 0 \\ F_{\nu_m} (\nu/X_{\text{op}})^{\beta'} \propto t^{(1+3\delta')/2} \propto t^{-1}, & \text{for } t > t_{X,\text{op}}, \text{ if } \beta' \sim -1 \end{cases} \quad (4) $$

If the optical radiative efficiency varies in time, the simple homologous behaviour above introduces additional changes. If we again assume that fields are a constant fraction of equipartition, then $\nu \propto \Gamma B' \gamma^2 \propto \Gamma^2 \gamma^2$, and the electrons responsible for optical radiation must satisfy $\gamma_{\text{opt}} \propto \Gamma^{-1}$, so the ratio of comoving expansion and cooling times is $t_{\text{exp}}/t_{\text{cool}} \propto \Gamma^{-2/3} \propto t^{1/3}$. Then the above time power laws remain the same as long as the optical efficiency $\xi_{\text{opt}} = \max[1, (t_{\text{exp}}/t_{\text{cool}})]$ is unity, or they could be flatter by $t^{1/3}$ if the optical efficiency was initially lower than unity and grows (e.g. the higher energy electrons emitted more efficiently at higher photon energies than at optical). There are, of course, other possibilities; for instance, if the field is frozen-in, rather than turbulent, a different $B'$ dependence needs to be used, etc. The above argument, however, indicates that there are ways in principle to explain even slower decay time scales than the simple $\propto t^{(3/2)\beta'}$, as well as faster ones. The afterglow might then probe the geometry of the emission, and for suitably oblique viewing angles one would see afterglow without a burst.

It is important to note that these are testable differ-
ences, because the dependence of the power-law slope of the temporal evolution, $\delta$, on the slope of the spectrum, $\beta'$, is not the same for eqs. 2 and 4. In the case of GRB 970228, with $\beta' = -0.8$, the predictions are $\delta = -1.2$ for the simple case and $\delta = -0.7$ from eq. 4, so the simple case is favoured for it.

5 CONCLUSION

As expected, the first detection of a gamma-ray burst in the optical has greatly furthered our understanding of these enigmatic objects. We have found that the simplest fireball model for a gamma-ray burst and its afterglow agree very well with the data obtained for GRB 970228 and GRB 970402. The longevity of the afterglow argues strongly, within the context of that model, that GRB 970228 occurred at substantial cosmological redshift. This raises the interest in unveiling the nature of the faint extended object coincident with the fading burst. Its faintness would suggest that if it is a galaxy it probably has $z > 1$, whereas the burst itself was moderately bright. For a no-evolution, standard candle cosmological burst distribution, its redshift as inferred from the peak flux in $\gamma$ rays would be smaller, perhaps $z \sim 0.3$. This would argue either for a modest width of the GRB luminosity function, or for significant evolution of their rate density. Neither is implausible, e.g. the star formation rate evolves so strongly with redshift (Lilly et al. 1996) that if the GRB rate were proportional to it (which a merging neutron star scenario would naturally demand) the GRB log $N - \log P$ distribution would seem Euclidean to $z \sim 1$.

We note that optical flashes perhaps even brighter than $V \sim 19 - 20$ from GRB at cosmological distances (Mészáros & Rees 1997a) would be of enormous importance as a tool to study absorption lines from the early intergalactic medium, features due to the ISM in the host galaxy, etc. (Miralda-Escudé, Rees & Mészáros 1997), particularly if they arise from redshifts as large as $z \sim 3 - 5$. Even at more moderate redshifts, a good spectrum obtained with a large telescope in the first day could settle distance scale definitively by showing redshifted absorption lines or even a Lyman alpha forest*; even better would be a spaced-based instrument with access to the UV part of the spectrum.

We also argue that further significant tests of afterglow models depend crucially on catching the fading counterpart within the first 0.5 to 3 hours after the trigger. This is feasible in principle with BeppoSAX since the first (10 arcmin precision) position from the WFC can be derived within the hour. The history of the first two afterglow detections show that important information comes from upper limits as well, especially at early times. So even with modest telescopes rapidly following up a GRB alert is very worth while. Since the light curve appears to evolve as a power law, one should try to integrate no longer than the time that passed since the GRB trigger in very early measurements, since the brightness of the transient may change on that time scale.

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