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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 follow-up 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 performed 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: stars: neutron – gamma-rays: bursts – gamma rays: theory – X-rays: general.

1 INTRODUCTION

Gamma-ray bursts (GRB) 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 gamma-rays. This situation ended in the early hours of 1997 February 28, when the Gamma-Ray Burst Monitor (GRBM) (40–1000 keV) and one Wide Field Camera (2–32 keV) on board the Italian–Dutch Satellite 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. 1997a). It was still detected, at a much fainter level, by the MECS and LECS X-ray telescopes on BeppoSAX eight hours after the burst, and again three days later, tightening the error box radius to under 1 arcmin. Optical images taken with the William Herschel and Isaac Newton Telescopes at La Palma, starting only 20 h after the burst, reveal a fading source that is undoubtedly associated with GRB 970228 (Van Paradijs et al. 1997), and therefore its location is now known with sub-arcsec precision.

Initial reports of an underlying host galaxy of roughly $R=24$ (Van Paradijs et al. 1997) appear inconsistent with

later *Hubble Space Telescope* images that show, if anything, only a very faint 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. We shall assume that its contribution to all optical detections thus far is not large.

In Section 2 we briefly review the basic properties and predictions of a blast wave. In Section 3 we discuss the light curves GRB 970228 and GRB 970402 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 arising from less simple blast-wave models (Section 4). We summarize 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 Γ first dropped substantially, giving rise to the GRB (Rees & Mészáros 1992; cf.

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Vietri 1997). Beyond this, the Lorentz factor decays as $\Gamma \propto r^{-3/2} \propto t^{-3/8}$, where t is the observing frame time (Mészáros & Rees 1997a), 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 energy spectrum is

$$I_\nu \propto \begin{cases} \nu^{\alpha'} & \text{for } \nu < \nu_m \\ \nu^{\beta'} & \text{for } \nu > \nu_m, \end{cases} \quad (1)$$

where the synchrotron-break frequency $\nu_m \propto \Gamma B' \gamma_m^2$ and $\beta' = (1-p)/2$. 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 γ_m can easily give a range around that), while $\beta' = \beta + 1$ is around -1 (ranging approximately from -0.5 to -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 $\nu_m \propto \Gamma B' \gamma_m^2 \propto \Gamma^4 \propto t^{-3/2}$. At the same time, since the comoving electron density $n'_e \propto \Gamma$ and the comoving width of the emission shell $\Delta R \sim r/\Gamma \sim t^{5/8}$, the comoving intensity $I'_\nu \propto n'_e B'^2 \gamma_m^2 \Delta R / (B' \gamma_m^2) \propto n'_e B' \Delta R \propto t^{-1/8}$, so the observed flux as a function of observer time is (Mészáros & Rees 1997a) $F_{\nu_m} \propto t^2 \Gamma^5 I'_\nu \propto t^0 \sim \text{constant}$. The observed break frequency ν_m crosses the X-ray or optical band at a time $t_{X,op} \sim (\nu_\gamma / \nu_{X,op})^{2/3} t_\gamma$ after the break frequency lies at γ_γ . For $h\nu_{\gamma,X,op} = 100$ keV, 5 keV and 2.3 eV, respectively, one has $t_X = 7t_\gamma$ and $t_{op} = 170t_\gamma$.

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

$$F_{X,op} \propto F_{\nu_m} (\nu_{X,op} / \nu_m)^{\beta'} \propto t^{(3/2)\beta'} \equiv t^\delta, \text{ for } t \geq t_{X,op}. \quad (2)$$

The expression $\Gamma \propto r^{-3/2} \propto t^{-3/8}$ lasts until the remnant becomes non-relativistic, after which the remnant enters a Sedov–Taylor phase. Here $r \propto t^{2/5}$, $B' \propto t^{-3/5}$, $\gamma \propto t^{-6/5}$, $n'_e \Delta R \propto t^{2/5}$ and $\nu_m \propto t^{-3}$, $F_{\nu_m} \propto t^{3/5}$, so that the optical (and X-ray, if it were detectable) flux has $\nu > \nu_m$ and goes as $F_{op} \propto t^{(3+15\beta)/5} \sim t^{-12/5}$ for $\beta' \sim -1$. 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

$$t_{nr} = \left(\frac{3E}{4\pi n m_p c^5} \right)^{1/3} \approx 1 \text{ yr} \left(\frac{E_{51}}{n_{-1}} \right)^{1/3} \approx 1 \text{ d} \left(\frac{E_{41}}{n_{-3}} \right)^{1/3}, \quad (3)$$

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 3σ . Optical and near-infrared magnitudes were

Table 1. Fluxes of GRB 970228 and its fading counterpart. Time is measured from the burst trigger (1997 February 28.124 UT).

log t (s)	F_ν (μJy)	log ν (Hz)	band	instrument	ref.
0.30	5400.	19.38	γ	SAX, TGRS	1,2
0.30	6600.	18.08	X	SAX	1,3
4.17	<0.032	19.38	γ	OSSE	4
4.46	0.15	18.08	X	SAX	5
4.57	<0.050	19.38	γ	OSSE	4
4.86	<700.	9.70	radio	Westerbork	6
4.88	16.8	14.74	V	WHT La Palma	11
4.88	17.1	14.56	I	WHT La Palma	11
5.15	<350.	9.70	radio	Westerbork	6
5.10	<0.013	19.38	γ	OSSE	4
5.36	<350.	9.70	radio	Westerbork	6
5.41	2.4	14.84	B	ARC 3.5m	7
5.49	0.0075	18.08	X	SAX	5
5.61	<1.2	14.74	V	NOT	3
5.72	<7.5	14.56	I	Palomar 1.5m	8
5.73	1.0	14.64	R	Keck II	8
5.77	<3600.	10.94	mm	BIMA	9
5.79	0.0043	18.08	X	ASCA GIS/SIS	10
5.83	<4.0	14.64	R	INT La Palma	13
5.88	<1.3	14.64	R	INT La Palma	13
5.88	<0.9	14.74	V	INT La Palma	13
5.93	0.50	14.84	B	INT La Palma	12
5.93	1.0	14.64	R	INT La Palma	12
6.01	0.0013	18.08	X	ROSAT	19
6.05	1.2	14.64	R	ESO NTT	12
6.18	6.5	14.38	J	Calar Alto 3.5m	14
6.18	<10.7	14.26	H	Calar Alto 3.5m	14
6.18	<10.7	14.13	K	Calar Alto 3.5m	14
6.35	0.29	14.74	V	HST	15
6.35	0.62	14.56	I	HST	15
6.41	1.1	14.13	K	Keck I	17
6.42	0.65	14.38	J	Keck I	17
6.50	0.44	14.64	R	Keck II	18
6.52	0.22	14.74	V	HST	16
6.52	0.43	14.56	I	HST	16

(1) Costa et al. 1997a; (2) Palmer et al. 1997; (3) van Paradijs et al. 1997; (4) Matz et al. 1997; (5) Costa et al. 1997b; (6) Galama et al. 1997; (7) Margon et al. 1997; (8) Metzger et al. 1997b; (9) Smith et al. 1997; (10) Yoshida et al. 1997; (11) Groot et al. 1997b; (12) Groot et al. 1997c; (13) Tanvir & Bloom, private communication; (14) Klose, Stecklum & Tuffs 1997; (15) Sahu et al. 1997a; (16) Sahu et al. 1997b; (17) Soifer et al. 1997; (18) Metzger et al. 1997a; (19) Frontera et al. 1997.

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 $A_B = 0.8$, $A_V = 0.4$, $A_R = 0.3$, $A_I = 0.2$, $A_{J,H,K} = 0$. 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 keV if an exponential cut-off 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 power-law spectrum that changes slope at

some break energy E_m , like the model of Band et al. (1993). The four fluxes reported for the initial strong 4-s spike (which appears to 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 $h\nu_m=E_m$ ($\alpha'=0$) and has slope β' above it (equation 1), we can try to see which (β' , E_m) match the fluxes best. E_m must be greater than about 40 keV and β' in the range -1 to -0.5 to get a satisfactory fit. Since we know from the TGRS spectrum that $E_m \lesssim 150$ keV, this pins the parameters down reasonably well. To specify the X- and gamma-ray fluxes, we use $E_m=40$ keV and $\beta'=-0.8$. The gamma-ray flux is then given as the fitted value at 100 keV, $F_{100\text{keV}}=4200$ μJy . 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_ν values at 5 keV as well. For X-rays, this is unlikely to introduce an error of more than 30 per cent; 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 per cent. 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 in which more than one measurement is available in the same band by the same instrument – these measurements 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 two 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, δ , is the same for all, as the model demands: $\delta=-1.2$. We then 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

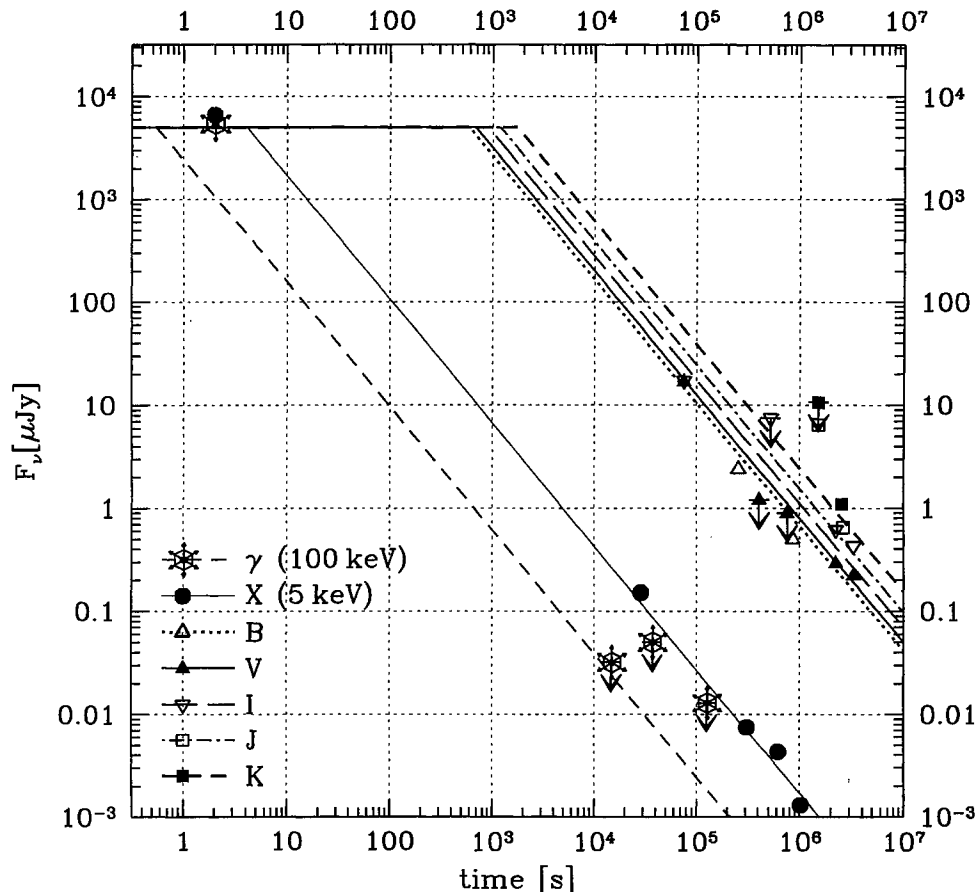


Figure 1. The light curves of GRB 970228 from gamma-rays to near-infrared. The lines indicate the prediction for a relativistic blast wave with $\beta'=-0.8$ and $t_\nu=600$ s.

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 (Paczynski & Xu 1994; Rees & Mészáros 1994) 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 left-most 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 being a (model-dependent) value related to the initial gamma-ray flux.

The sparser data on GRB 970402, which was triggered on 1997 April 2.93 UT (Ferozi et al. 1997; Heise et al. 1997) also have some bearing on this matter. This burst lasted about 100 s 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 h after the trigger, but a second attempt after 1.7 d only found an upper limit (Piro et al. 1997). Follow-up with 1-m telescopes at Siding Spring and South African Astronomical Observatory (the burst is at declination -69°) 0.7–1.9 d 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: $t_5 = 4\text{--}40$ s. The break should then arrive at R after $t_R = 800\text{--}8000$ s, consistent with the R limit. However, the predicted time for the gamma-ray break becomes $t_{100} = 0.5\text{--}5$ 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 min 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 h 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 provide 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 fade in about a day (Section 2), and thus cannot give rise to the observed long-term afterglow.

In a galactic halo model, the X-ray emission could be the result of emission from a surface initially heated to $T \gtrsim 10^7$ K, which might cool as a power law in time (regulated by some diffusion time-dependent on the depth of deposition of the energy). The optical emission is much larger than the $F_{\text{op}} \sim 10^{-4} F_X$ expected from the Rayleigh–Jeans tail of such a quasi-thermal surface emission. It is conceivable that the optical could be a separate component, perhaps associated with the reprocessing of harder radiation by circumstellar material, in which case one might expect the optical first to increase, peak, and then fade, as the irradiating ‘hard’ photons first cool to become UV and then themselves become optical, dropping off exponentially after that.

The Comptonization model for gamma-ray bursts in the Galactic halo (Liang et al. 1997a) predicted the optical brightness 20 h after the burst to be $V=25$ from the observed X-ray flux (Liang et al. 1997b), 4 mag fainter than observed. Hence it is inconsistent with the behaviour of GRB 970228. This is due mainly to the fact that the Comptonization model predicts that the spectrum below the break fades rapidly as well, in contrast with the blast-wave model.

The radiation efficiency in galactic halo blast-wave models would generally be low, 10^{-3} or less because of the smaller magnetic field strengths at a given time and the shorter expansion time-scales at a given Γ . Thus one might expect faster turn-off of both the X-ray and optical emission as a result of a decrease of the optical radiation efficiency. This would be in addition to the steepening caused by moving into the Sedov–Taylor non-relativistic phase. The late-time radio afterglow should come from a large enough region to be resolved by very long baseline interferometry.

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, also produce coherent radio emission by pulsar-type mechanisms in the magnetosphere.

4.2 Less simple fireball and remnant evolution

The decay model discussed in Section 2 is 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 also been considered, e.g. from the reverse shock moving into the ejecta, or from ejecta with a frozen-in magnetic field, or

from internal shocks (Mészáros & Rees 1997a). These decay more rapidly than $F \propto t^{(3/2)\beta'}$ (equation 2). However, there are additional considerations which can lead to different decay laws, including some that are slower than $t^{(3/2)\beta'}$. It is, for instance, probable that the high- Γ fireball that gives rise to the GRB may be beamed (Mészáros & Rees 1992, 1997b), and in this case it is natural for Γ 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 θ 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 θ . 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 the order of a day for $\Gamma \sim 10$, and a month for $\Gamma \sim 3$. In the simplest case, in which the burst progenitor supplies equal amounts of energy into equal logarithmic intervals of θ , the bolometric flux detected as a function of time will then be $F(t) \propto E(\theta)/t^{-1}$. If the spectrum is gain of the form $F_\nu \propto [\nu^{\alpha'}, \nu^{\beta'}]$ below and above a time-dependent break ν_m , 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 $F_{\nu_m} \sim L/\nu_b \propto t^{-1} t^{3/2} \propto t^{1/2}$. If the radiative efficiency does not change in time and the spectrum evolves homologously, then we have

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

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 $\nu \propto \Gamma B' \gamma^2 \Gamma^2 \gamma^2$, and the electrons responsible for optical radiation must satisfy $\gamma_{op} \propto \Gamma^{-1}$, so the ratio of comoving expansion and cooling times is $t'_{exp}/t'_{cool} \propto \Gamma^{-2/3} \propto t^{1/4}$. Then the power-law exponents of the above time dependences remain the same as long as the optical efficiency $\xi_{op} = \max[1, (t'_{exp}/t'_{cool})]$ is unity, or they could be flatter by $t^{1/4}$ if the optical efficiency were initially lower than unity and grew (e.g. if 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 an afterglow without a burst.

It is important to note that these are testable differences, because the dependence of the power-law slope of the temporal evolution, δ , on the slope of the spectrum, β' , is not the same for equations (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 equation 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 $z = 1$.

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, in preparation), 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 definitely by showing redshifted absorption lines or even a Lyman alpha forest;¹ even better would be a space-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 with the first 0.5 to 3 h 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 worthwhile. Since the light curve appears to evolve as a power law, one should

¹RAMJW thanks Richard McMahon for pointing this out.

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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