Gamma-ray bursts from stellar remnants: probing the Universe at high redshift

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ABSTRACT
A gamma-ray burst (GRB) releases an amount of energy similar to that of a supernova explosion, which combined with its rapid variability suggests an origin related to neutron stars or black holes. Since these compact stellar remnants form from the most massive stars not long after their birth, gamma-ray bursts should trace the star formation rate in the Universe; we show that the GRB flux distribution is consistent with this. Because of the strong evolution of the star formation rate with redshift, it follows that the dimmest known bursts have $z \sim 6$, much above the value usually quoted and beyond the most distant quasars. This explains the absence of bright galaxies in well-studied gamma-ray burst error boxes. The increased distances imply a peak luminosity of $8.3 \times 10^{51}$ erg s$^{-1}$ and a rate density of 0.025 per million years per galaxy. These values are 20 times higher and 150 times lower, respectively, than are implied by fits with non-evolving GRB rates. This means that GRBs are either caused by a much rarer phenomenon than mergers of binary neutron stars, or their gamma-ray emission is often invisible to us due to beaming. Precise burst locations from optical transients will discriminate between the various models for GRBs from stellar deaths, because the distance between progenitor birth place and burst varies greatly among them. The dimmest GRBs are then the most distant known objects, and may probe the Universe at an age when the first stars were forming.

Key words: gamma rays: bursts — stars: formation — binaries: close — cosmology: theory, early universe

1 INTRODUCTION
The ability of the Italian-Dutch BeppoSAX satellite (Piro et al. 1995) to accurately locate gamma-ray bursts (GRBs) with its Wide Field Cameras (Jager et al. 1995) has led to the discovery of two optical transients, associated with GRB 970228 (van Paradijs et al. 1997) and GRB 970508 (Bond 1997). The detection of redshifted absorption lines in the optical transient associated with GRB 970508 (Metzger et al. 1997) has established that it lies at cosmological distance, and here we assume they all do.

A typical dim burst (1 ph cm$^{-2}$s$^{-1}$ lasting 10 s) at $z = 1$ releases $3.5 \times 10^{49}$ erg sr$^{-1}$ in gamma rays, hence the engine behind it must provide about $4.4 \times 10^{52}$ f$_b \epsilon_{-2}$ erg. (Where needed, we assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$.) Here $f_b$ is the fraction of the sky illuminated by the gamma-ray emission, and the efficiency of conversion of the initially available energy into gamma rays is $\epsilon_{-2}$ percent. This is the natural energy scale of supernova explosions, in which of order $10^{53}$ ergs is released suddenly from the rest mass energy of a solar mass of material. The bulk is carried away in neutrinos, and about 1% becomes kinetic energy of the ejecta. The proposed GRB models related to end stages of massive stars are (i) merger of two neutron stars (Paczynski 1986; Goodman et al. 1987; Eichler et al. 1989); (ii) merger of a neutron star and a black hole (Paczynski 1991; Mochkovitch et al. 1993); (iii) ‘failed supernova’: the collapse of a massive star to a black hole surrounded by a dense torus of material that might result in a relativistic jet (Woosley 1993); (iv) a ‘hypernova’: the collapse of a rapidly rotating massive star in a binary (Paczynski 1993); (v) collapse of a Chandrasekhar-mass white dwarf (Usov 1992). Whether these are efficient enough at converting a fraction of the available energy to kinetic energy and then eventually to gamma rays (see below) is an open question, and the major unsolved issue in this class of burst models. In this paper we assume that somehow a variety of such a model manages this. The important point is that they all arise from massive stars which evolve into remnants within about 100 Myr. The binary mergers then usually take place within about 100 Myr of remnant
formation (Portegies Zwart and Spreeuw 1999), as does the white-dwarf collapse, because the favoured route has a high mass transfer rate (van den Heuvel et al. 1992). Since the expansion age of the Universe is already 1 Gyr at $z = 4.4$, it is safe to neglect the delay between (binary) stellar birth and the GRB it eventually yields in the present context. The gamma-ray burst rate therefore traces the massive star formation rate. The star formation rate as a function of redshift has recently been studied extensively, and is determined observationally with some confidence (Lilly et al. 1996; Madau et al. [1998]; Madau 1998): the luminosity density in the rest frame $U$ and $B$ band is combined with an IMF to deduce the star formation rate. The assumption of an IMF introduces an uncertainty in the deduced total star formation rate, but the basic data ($U$ and $B$ light density) are dominated by massive stars. Since GRBs come from massive stars, they may trace the UV light density in the Universe better than the total star formation rate, and our results are therefore less sensitive to the assumed IMF. A further potential source of uncertainty is dust extinction, which would cause a relative underestimate of the high-redshift star formation rate.

Recent interpretations of the afterglows (Meszéros and Rees 1978; Goodman 1986) whose energy is largely converted to a blast of gamma rays via hydrodynamic collisions within it (Paczynski and Xu 1994; Rees and Meszéros 1992) or with the ambient medium (Rees and Meszéros 1992). Since the kinetic energy comes from a fairly standardised event, it is likely that the gamma-ray luminosity distribution of bursts is not too wide, so we shall treat them as standard candles. With the fact that GRB trace star formation, this has the important testable consequence that the redshift dependence of the GRB rate has no free parameters. Only two normalisations need to be fitted, namely the local GRB rate density $\rho_0$ and the standard-candle 30–2000 keV luminosity $L_0$.

2 RESULTS

For a standard cosmology ($\Omega_0 = 1$, $\Lambda = 0$), the predicted number of standard-candle bursts in some flux range ($P_1$ to $P_2$) is

$$\Delta N(P_1 \text{ to } P_2) = 4\pi \int_{R(P_1)}^{R(P_2)} k_r \rho(z) r^2 dr,$$

where $\rho(z)$ is the observed star formation rate and $k_r$ the constant of proportionality. We follow the method of Fenimore and Bloom (1995) to account for the influence of the diversity of spectral shapes of bursts on the observed flux distribution (similar to $K$ corrections in optical photometry). The fit is done by $\chi^2$ minimisation for the same 11 flux bins of combined PVO and BATSE data used by Fenimore and Bloom (1995). The best-fit model of this type to the GRB flux distribution is shown in Fig. 1. Note that the fit was done only for $P > 1 \text{ ph cm}^{-2} \text{s}^{-1}$, for which the BATSE catalogue is 99% complete.

The fit gives $L_0 = 8.3^{+3.9}_{-2.5} \times 10^{51} \text{ erg s}^{-1}$ and $\rho(z = 0) \equiv \rho_0 = 0.14 \pm 0.02 \text{ Gpc}^{-3} \text{ yr}^{-1}$. Assuming a local galaxy number density of 0.0048 Mpc$^{-3}$ (Loveday et al. 1992) this density translates into a rate of 0.025 GEM (Galactic Events per Myr). The median redshift of bursts with $P = 1 \text{ ph cm}^{-2} \text{s}^{-1}$ is 2.6. The fit is just acceptable, with $\chi^2 = 17.3$ for 9 d.o.f. If we omit the two lowest-flux bins, in which the star formation rate is most uncertain, the fitted parameters hardly change but the fit quality improves somewhat to $\chi^2/d.o.f. = 11.7/7$. As noted earlier, inclusion of dust extinction would increase the inferred star formation rate at high redshift, which in turn would improve the fit. However, the magnitude of this correction is quite uncertain.

For comparison, we also fitted the same data with a non-evolving rate density. In that case, we recover the previously known result that $L_0 = 0.44 \times 10^{51} \text{ erg s}^{-1}$ and $\rho_0 = 3.7 \text{ GEM}$ (Fenimore and Bloom 1993). The redshift at $P = 1 \text{ ph cm}^{-2} \text{s}^{-1}$ is then 0.68, and $\chi^2/d.o.f. = 9.1/9$. This means that our assumption about the evolution of the GRB rate has quite drastic consequences: it increases the GRB luminosity by a factor 19, and the local rate is decreased by a factor 150. This large factor is a combination of the distance increase due to the larger $L_0$ and the fact that the local density in evolving models is much lower than the mean, because the star formation rate in the Universe was much higher at $z = 1$. Various indirect methods, such as time dilation (Norris et al. 1993; Fenimore and Bloom 1993) and the change of break energy with flux (Malozzi et al. 1993), have been used to statistically derive the ratio of redshifts between bright and dim bursts. The result was found to disagree with the low redshifts implied by fits to the flux distribution that assumed no evolution of the rate density (Fenimore and Bloom 1993). For our new value of $L_0$, the predicted time dilation factor is 1.9 (Fenimore and Bloom 1993), consistent with the measured value (Norris et al. 1993). Note that the slope of the cumulative flux distribution of $-1.5$ at moderate fluxes is not due to Euclidean geometry: it is a conspiracy between the curvature of space which tends to give a flatter slope and the strong evolution which gives a steeper one. Direct sup-
port of the significant redshift of bursts on the ‘Euclidean’ part of the flux distribution comes from the work of Dezalay et al. (1997a,b). From a detected hardness-intensity correlation in bright bursts seen by both ULYSSES and PHEBUS they infer $z \approx 3$ for bursts that roughly correspond to $P = 2 \text{ ph cm}^{-2} \text{s}^{-1}$ in BATSE terms. This is even slightly higher than our range of $z = 1.5 - 2.5$ at that flux level.

3 IMPLICATIONS

The twenty-fold increase in luminosity of the bursts has important implications. First, the total energy released in gamma rays in a 10-s burst goes up to $6.6 \times 10^{51} \text{ erg} \text{s}^{-1}$, requiring an initial supply of energy of $8.3 \times 10^{54} f_b/\epsilon_{-2} \text{ erg}$, which among the above mechanisms only the hypernova (Paczyński 1997) can provide if the emission is isotropic. We therefore conclude that gamma-ray beams of bursts probably illuminate no more than a few percent of the sky, hence most gamma-ray bursters escape detection in gamma rays.

Since all the models of interest entail the collapse of an already rotating system and a non-vanishing angular momentum implies cylindrical symmetry, such beaming is quite plausible in the context of these models. The higher amount of energy alleviates the baryon pollution problem: for the outflow to reach a Lorentz factor above 100, as required to produce gamma rays, it should contain at most $10^{-3} M_\odot$ of baryons, which is not easy to get; but now we can allow twenty times more.

The classical GRB rate is 1 GEM, but we now find a rate of only 0.025 GEM. Since the events could well be beamed, this does not necessarily exclude neutron star mergers as their source. The theoretical rate of NS-NS mergers is about 10 GEM (Portegies Zwart and Spreeuw 1991), implying $f_b = 0.3\%$ if all such mergers produce a GRB. (See also (Lipunov et al. 1997; Prokhorov et al. 1997), where similar conclusions are drawn using theoretical rather than observed star formation rates.) But it does mean that rarer types of event merit consideration as well. NS-BH mergers are probably about ten times rarer than NS-NS mergers, so they could be significantly beamed and still cause the observed GRB rate. The formation rate of super-soft X-ray sources is about 20 GEM (van den Heuvel et al. 1992), but since it is not known what fraction, if any, of these lead to the accretion-induced collapse of a white dwarf and a possible GRB (cf. Usoskin 1992) we cannot calculate a rate for this burst model.

The increased distance scale also removes the ‘no-host problem’ for GRBs: deep searches of GRB error boxes (Vrees et al. 1993; Fenimore et al. 1993; Schafer et al. 1997) have been used to set limits on the absolute brightness of host galaxies of 3.5 to 5.5 mag fainter than $L_\text{\star}$ (Schafer et al. 1997), suggesting that GRB do not come from galaxies. But since these estimates depend on $L_\text{\star}$ and now have to be adjusted by 3.2 mag just from the increased distance, and by another 1–2 mag depending on galaxy type, due to increased $K$ corrections (Lilly et al. 1993). This changes the limits on host galaxy luminosities to between 1.5 mag above and 1.5 mag below $L_\text{\star}$, so they are no longer inconsistent with the assumption that GRB are in normal galaxies.

Using our fit for $L_\text{\star}$ and the known gamma-ray spectra we can derive redshifts for the two GRB with detected optical afterglows. We find $z = 2$ for GRB 970228, consistent with the magnitudes of candidate hosts (Bloom et al. 1997).

But $z = 3.7$ for GRB 970508, which exceeds the maximum redshift of 2.3 allowed by the observed spectrum (Metzger et al. 1997) and shows that this burst must have been somewhat less luminous. This means that its host is 2.5 to 5 magnitudes fainter than $L_\text{\star}$ (Natarajan et al. 1997), and that the luminosity distribution of GRB must have some width. Fortunately, the shape of the GRB flux distribution is fairly insensitive to a modest broadening of the luminosity function (e.g. Ulmer, Wijers & Fenimore 1995) so this should not significantly influence our conclusions.

The best-fit redshift distribution of GRBs is shown in Fig. 3. The median redshift is similar to that of quasars; only 10% of bursts have $z < 1$, and 5% are beyond redshift 4. The dim end of the distribution is at $z = 5.3$ for the average spectrum, but goes up to $z = 6.2$ due to varying spectral shape.

Sahu et al. (1997) briefly discuss the possibility of GRBs following the star formation rate. Whilst they do not account for the variety of spectral shapes and do not perform a for-
mal fit, they conclude from visual inspection of their graphs that \( L_\gamma = 10^{52} \text{erg s}^{-1} \). They interpret this as meaning that the accepted standard luminosity fits the data. However, since they count from 100 to 500 keV instead of the range 30–2000 keV used in this and other works, their \( L_\gamma \) implies \( L_0 \approx 3 \times 10^{53} \). This is closer to our new value than to the non-evolution result, and in reasonable agreement with our \( L_0 \) given the differences between the methods.

Totani (1997) tried different power-law spectral shapes, but did not allow for variation between bursts and only considered the case of NS-NS mergers. He did study the issue of NS-NS merger times in more detail and found that the tail of late mergers can flatten the flux distribution between redshifts 0 and 1: if a substantial fraction of mergers have a long delay, then because 20 times more binaries formed at \( z = 1 \) their contribution to the present merger rate could exceed that due to current star formation. Whilst the bulk of NS-NS binaries merge within 100 Myr according to all studies, the fraction merging after more than 5 Gyr varies greatly. Tutukov & Yungelson (1994) do find a large fraction of delayed mergers, whereas in the study of Lipunov et al. (1995) it is negligible. Using this long delay, he finds a redshift of 2–2.5, for bursts with \( P = 0.4 \text{ph cm}^{-2} \text{s}^{-1} \), where we get a median of 3.8. Whether this effect is indeed important can only be decided when better estimates of the merger time distribution become available. If GRB are not due to NS-NS mergers (we present some evidence for this below) then the long delay times are not an issue in any case, of course.

4 OBSERVATIONAL TESTS

An important difference between the various compact stellar remnant models is the distance that a gamma-ray burster travels between where it was born as a massive (binary) star and where it produces the burst. A direct supernova origin (Woosley 1993) or hypernova (Paczyński 1997) would occur in short-lived objects with low space velocity, which would therefore still be in the star forming regions where they were born. In this case, an optical counterpart to a GRB should always be embedded in a galaxy or star-forming region. A NS-NS or NS-BH merger occurs in a system that has obtained a moderate to high (100–300 km s\(^{-1}\)) space velocity from the two supernova explosions that have taken place in the binary some 100 Myr before the merger. This means that such GRB should often occur up to 30 kpc away from any star forming region (corresponding to \( z = 3 \)) depending on whether the host galaxy has a deep enough potential to hold it. The optical counterpart to GRB 970228 is embedded in an extended object. That of GRB 970508 is at least 25 kpc away from any host so far detected (Natarajan et al. 1997), but the [OII] emission line seen in its spectrum (Metzger et al. 1997) suggests that it lies in a star-forming region. The recent detection of a large absorption column in the X-ray spectrum of GRB 970228 (Murakami 1997) suggests that it, too, may lie close to a star-forming region. There may thus be some tentative evidence favouring progenitors with low space velocities and very short delays between formation and burst.

Another consequence of beamed gamma-ray emission in the context of blast wave models is that the optical afterglow can come from less relativistic material which has a greater opening angle (Wijers et al. 1997, Paczyński 1997). Consequently, the population of bursters that we can see only by their optical afterglow could be many times larger than that of GRBs. A limit to this is set by high-redshift supernova searches, which have not found any GRB afterglows (Rhoads 1997). Since one of them (Pain et al. 1996) has now surveyed close to 10 square degree years, a rate of afterglows in excess of 0.3 per square degree per year is unlikely. With a GRB rate of 0.01/sq.deg./yr, this implies that \( f_{\gamma,\text{optical}}/f_{\gamma,\text{optical}} \leq 30 \). Since \( f_{\gamma,\text{optical}} \leq 0.03 \) from energy constraints, even the optical afterglows may have to be beamed.

With the evolving rate density we sample most of the star forming Universe, we predict that more sensitive instruments than BATSE would find few bursts with \( P < 0.2 \text{ph cm}^{-2} \text{s}^{-1} \), unlike in the non-evolving case (see Fig. 3). Koomers et al. (1997) recently studied untriggered bursts below the BATSE threshold and deduced that the flux distribution flattens considerably, perhaps supporting the paucity of faint bursts. At very low fluxes, there may again be increase due to the first episode of star formation in the early Universe associated with the first metal production (Miralda-Escudé and Rees 1997), or with the formation of the first stars in elliptical galaxies (Proch khov et al. 1997).

With a higher mean redshift than quasars, GRB should be lensed at least as often as quasars, of which 0.5% are multiply imaged. Therefore, the dim end of the BATSE catalogue may already contain a few examples. From the absence of lensed bursts among bright BATSE bursts Marani et al. (1997) deduce that bursts with \( P > 1 \text{ph cm}^{-2} \text{s}^{-1} \) should have \( z < 3 \); our fit is consistent with this limit.

5 CONCLUSIONS

Our results depend only on two key features of the star formation rate: rapid evolution up to \( z \approx 1 \) and a more gentle variation beyond that up to \( z \approx 2.5 \). Although little is known about the star formation rate between these redshifts, many indirect arguments suggest that the star formation rate did not evolve strongly between \( z = 1 \) and \( z = 2.5 \). Uncertainties are introduced by our lack of knowledge of the correction due to dust extinction and to a lesser extent by having to assume an IMF. However this does not change the qualitative nature of the results presented here.

Furthermore, the distance corrections due to the wide range in spectral shapes (Fenimore and Bloom 1997) that are the result of assuming that GRB are standard candles in the 30–2000 keV (rest frame) range are very important, and neglect of the spectral shape variation can lead to considerably different results. In view of this, and of the fact that we have not explored a range of parameters for the geometry of the Universe, our results obviously have a somewhat exploratory character. Other observational tests, such as the determination of redshifts from afterglow spectra and constraints from the lensing rate of GRBs, will provide additional constraints on parameters.

The logical consequence of assuming that GRB are related to remnants of the most massive stars in any of the ways hitherto proposed is that the GRB rate is proportional to the formation rate of massive stars in the Universe (with the possible exception of NS-NS mergers if those simulations which indicate significant fractions of late mergers are cor-
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We show that this assumption is consistent with the GRB flux distribution. Compared to previous, non-evolving, models of cosmological bursts we find a twenty-fold increase of the required GRB luminosity, which suggests that the gamma-ray emission is significantly beamed in order that the emitted energy can be supplied by merger/collapse models. The redshifts of GRBs are also greatly increased, and the very dimmest known ones are at $z \sim 6$, beyond the farthest known quasars. This makes them the most distant known objects, and their optical counterparts very valuable probes of the early evolution of stars and interstellar gas.

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