Gamma-ray bursts and the history of star formation

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ABSTRACT

Popular models for the origin of gamma-ray bursts (GRBs) include short-lived massive stars as the progenitors of the fireballs. Hence the redshift distribution of GRBs should track the cosmic star formation rate of massive stars accurately. A significant proportion of high-mass star formation activity appears to occur in regions that are obscured from view in the optical waveband by interstellar dust. The amount of dust-enshrouded star formation activity taking place has been estimated by observing the thermal radiation from the dust that has been heated by young stars in the far-infrared and submillimetre wavebands. Here we discuss an alternative probe – the redshift distribution of GRBs. GRBs are detectable at the highest redshifts, and because gamma rays are not absorbed by dust, the redshift distribution of GRBs should therefore be unaffected by dust extinction. At present the redshifts of GRBs can only be determined from the associated optical transient emission; however, useful information about the prevalence of dust-obscured star formation can also be obtained from the ratio of GRBs with and without an associated optical transient. Eight GRBs currently have spectroscopic redshifts. Once about a hundred redshifts are known, the population of GRBs will provide an important test of different models of the star formation history of the Universe.

Key words: dust, extinction – galaxies: evolution – galaxies: formation – cosmology: observations – gamma-rays: bursts

1 INTRODUCTION

Gamma-ray bursts (GRBs) are detectable out to the edges of the observable Universe, and so provide information about the processes occurring within their progenitors at all cosmic epochs (Piran 1999a,b). If GRBs arise either from binary mergers of massive stellar remnants (neutron stars and black holes; Paczynski 1986) or from failed supernovae collapsing to form black holes (Woosley 1993), or from the collapse of massive stellar cores (hypernovae; Paczynski 1998), then they will be associated with the formation of massive stars. See Hogg & Fruchter (1999) and Holland & Hjorth (1999) for some observational evidence that this is the case. Because high-mass stars have very short lifetimes, the rate of GRBs should trace the formation rate of massive stars in the Universe. Hence, if the distribution of the redshifts of GRBs is known, this should allow the evolution of the high-mass star-formation rate to be derived (Totani et al. 1997; Wijers et al. 1998; Hogg & Fruchter 1999; Mao & Mo 1999; Krumholz, Thorsett & Harrison 1999).

Observations of faint galaxies in the optical and near-infrared wavebands have been used to estimate the history of star formation activity (Lilly et al. 1996; Madau et al. 1996; Steidel et al. 1999); however, absorption by interstellar dust in star-forming galaxies could significantly modify the results (Blain et al. 1999a,c). It is difficult but not impossible to correct these optically derived results to take account of this effect. By making observations in the near-infrared waveband, where the optical depth of the dust is less, some progress has been made (Pettini et al. 1998; Steidel et al. 1999). However, there are considerable uncertainties in the size of the corrections that should be applied. It is now possible to detect the energy that has been absorbed and re-emitted by dust in high-redshift galaxies directly in the form of thermal far-infrared radiation, which is redshifted into the submillimetre waveband. The sensitive SCUBA camera at the James Clerk Maxwell Telescope has revealed this emission directly (Smail, Ivison & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Blain et al. 1999b, 2000; Barger, Cowie & Sanders 1999; Eales et al. 1999). It is possible to derive a history of high-mass star formation from the SCUBA observations (Blain et al. 1999a,c); at least as much energy...
is inferred to have been released from dust-enshrouded star formation activity as in the form of unobscured starlight. An independent test of the relative amount of obscured and unobscured star formation activity would be extremely valuable.

The advantage of using GRBs for this purpose is that gamma-rays are not absorbed by interstellar dust, either within the host galaxy of the GRB or in the intergalactic medium along the line of sight to the host galaxy, and so dust extinction will not modify our view of the distant Universe observed using gamma rays. However, there is a problem, as in order to determine a redshift for a GRB the spectrum of the associated burst of optical transient radiation must be detected. If the burst is heavily enshrouded in dust, then it would be difficult to detect such a transient and to obtain its spectrum.

In Section 2 we briefly review the differences between the histories of star formation derived from optical/near-infrared and far-infrared/submillimetre observations. In Section 3 we discuss and predict the associated redshift distribution of GRBs. In Section 4 we discuss the consequences for determining the history of star formation using observations of GRBs. We assume an Einstein–de Sitter world model with Hubble’s constant $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 THE HISTORY OF STAR FORMATION

In Fig. 1 we compare five currently plausible star formation histories (Blain et al. 1999a,c), two of which are based on observations made in the optical and near-infrared wavebands and three of which are based on observations in the far-infrared and submillimetre wavebands. A wide variety of observational data that has been gathered in the optical and near-infrared wavebands is also plotted. The data is described in more detail in the caption of fig. 1 of Blain et al. (1999a) and by Steidel et al. (1999).

In the first optically derived model (thin dashed line) it is assumed that no dust absorption takes place within the galaxies detected in deep optical images, and that there is no population of strongly obscured objects missing from these samples. This model closely follows the form of the history of star formation derived by Madau et al. (1996) from an analysis of the Hubble Deep Field at $z > 2$, and from observations of the Canada–France Redshift Survey fields at $z \leq 1$ by Lilly et al. (1996). In the second optically derived model (thick dashed line), dust extinction is assumed to be present. The model fits the data that has been corrected empirically to take account of the effects of dust, using radio and ISO satellite observations at $z \leq 1$ (Flores et al. 1999) and using estimates of extinction in high-redshift galaxies estimated from near-infrared spectroscopy (Pettini et al. 1998; Steidel et al. 1999).

The three different far-infrared/submillimetre models of the history of star formation fit all of the available data describing the background radiation intensity and the counts of dusty galaxies in these wavebands. The ‘Gaussian model’ (thin solid line) was derived by Blain et al. (1999c), and the ‘Modified Gaussian model’ (medium solid line) was changed slightly in order to fit the median redshift of plausible counterparts to submillimetre-detected galaxies (Smail et al. 1998) determined by Barger et al. (1999b). In the ‘Hierarchical model’ (thick solid line) the population of submillimetre-luminous galaxies is described in terms of short-lived luminous bursts induced by galaxy mergers (Blain et al. 1999a). This model provides a reasonable fit to the Barger et al. (1999b) redshift distribution if the dust temperature is assumed to be 35 K.

3 THE REDSHIFT DISTRIBUTION OF GRBS

A histogram showing the eight spectroscopic redshifts of optical transients associated with GRBs (Greiner 1999) is plotted in Fig. 2 (solid histogram; Metzger et al. 1997; Djorgovski et al. 1998a,b,c, 1999a,b; Kulkarni et al. 1998; Galama et al. 1999; Vreeswijk et al. 1999). There are indications of the redshifts for three more GRBs, which are included in the derivation of the dotted histogram shown in Fig. 2, while for about another twenty GRBs no optical transient has been detected, in some cases despite sensitive searches. These numbers were compiled on 1999 November 16.

In Fig. 2 we also present the expected redshift distributions of GRBs for each of the five star formation histories shown in Fig. 1. These redshift distributions are derived by integrating the function that describes the evolution of the global star-formation rate along a radial section of the Universe (Totani 1997; Wijers et al. 1998) and have been normalised to unity.

In this calculation we assume that a typical GRB would
be detectable at any redshift. If, in fact, there is a redshift-dependent selection function for GRBs, then the observed redshift distribution of bursts would be expected to be systematically lower as compared with the curves shown in Fig. 2. At present, there are too few redshifts with which to estimate the possible size of this effect; however, the detection of two GRBs at $z \gtrsim 3$ tends to argue against the strong anti-selection of high-redshift bursts.

4 DISCUSSION

It is clear from the histograms shown in Fig. 2 that too few redshifts are currently known to allow us to discriminate between the different models of the star formation history. Nor is the efficiency of generating GRBs from massive star formation activity known in sufficient detail to allow us to discriminate between the different models on the grounds of the absolute number of bursts observed. As an additional caveat, it seems likely that about 20 per cent of the submillimetre-selected galaxies are powered by gravitational accretion onto active galactic nuclei (AGNs; Almaini, Lawrence & Boyle 1999), and as such should not be associated with GRBs derived from exploding high-mass stars, unless a significant amount of high-mass star formation activity is taking place coevally with AGN fueling.

If much of the high-mass star formation activity in the Universe does indeed take place in dust-enshrouded galaxies, then the optical transients of GRBs that occur in these galaxies would be less likely to be detected than those in dust-free galaxies, because while the GRB gamma-ray signal can escape, the associated optical transient emission will be obscured. Therefore, the inferred GRB redshift distribution at present might in fact be biased to lower redshifts, given the large number of GRBs that do not have detected optical transient counterparts. This selection effect for the detection of optical transients will depend on the geometry and environment of the host galaxy, and so is likely to be difficult to investigate reliably until a much larger sample of high-quality follow-up observations of GRBs has been assembled.

It is interesting to note that the predicted redshift distribution of GRBs that was derived from unobscured optical observations of the star formation history, as shown by the thin dashed curve in Fig. 2, appears to provide the best agreement with the observed redshift distribution of the optical transients that has been determined so far. This suggests that there could be a common extinction bias against the detection of both dust-enshrouded star formation activity in optical galaxy surveys and of the optical transients of GRBs.

Since systematic, rapid, deep and reliable searches for optical transients began in 1998 March (Akerlof et al. 1999), nine gamma-ray bursts have been detected with optical transients, four without and a further thirteen unreported, on 1999 November 16 (Greiner 1999). If those GRBs without optical transients are in dusty regions, then this lends support to the idea that comparable amounts of high-mass star formation occurs in heavily and lightly dust-enshrouded regions. One GRB (GRB980329) has so far been detected using SCUBA at a submillimetre wavelength of 850 $\mu$m (Smith et al. 1999), although it is unclear whether there is any component of thermal dust emission involved, or if the emission is entirely attributable to synchrotron radiation from the shocked interstellar medium. See Taylor et al. (1998, 1999) for a discussion of the properties of GRBs in the radio waveband, where they are not subject to obscuration by dust.

The number of spectroscopic redshifts for the optical transients of GRBs is growing steadily, with a new determination being reported every two to three months (Greiner 1999). The number of redshifts for GRBs already exceeds the number of redshifts that have been obtained for galaxies detected in submillimetre-wave surveys that have reliable identifications. Once a sample of about 100 GRBs have redshifts then it should be possible to discriminate between the different models. As the predicted redshift distributions shown in Fig. 2 are significantly different, the GRB redshift distribution may provide a very significant constraint to the history of star formation activity at all epochs.

4.1 Dust-enshrouded infrared transients

It will be important to pay close attention to the GRBs without optical transients. If the optical and ultraviolet radiation released by the GRB is obscured by dust, then since these heated dust grains have a low heat capacity, the reprocessed thermal emission could be detected directly as a transient signal at submillimetre to near-infrared wavelengths. Intense shocking and heating of the gas in the interstellar medium of the host galaxy could also lead to detectable emission of far-infrared and submillimetre-wave fine-structure atomic line radiation, and molecular rotational line radiation (see also Perna, Raymond & Loeb 2000). Because the host galaxy of the GRB is likely to be optically thin at far-infrared and
submillimetre wavelengths, the detection of this radiation could provide a redshift for a GRB, even in the absence of an optical transient source if the opacity at optical wavelengths is very high. In the future, the large collecting area, excellent sensitivity and subarcsecond angular resolution of the Atacama Large Millimeter Array (ALMA; Wootten 2000) will make it the ideal instrument to conduct observations to search for any transient line and continuum radiation from GRBs in the submillimetre waveband. Recently, Waxman & Draine (2000) discussed the effects of a GRB on the sublimation of dust in the surrounding interstellar medium. We are currently investigating the observability of infrared transients from dust-enshrouded GRBs (Venemans & Blain, in preparation).

5 CONCLUSIONS

A large statistical sample of redshifts for gamma-ray bursts (GRBs) will allow the star formation history of the Universe to be probed in more detail than is currently possible. Once about a hundred examples are known, the fraction of dust-enshrouded star formation activity that takes place as a function of redshift can be addressed by an analysis of both the redshift distribution of the optical transients and the fraction of GRBs for which an optical transient is detected. The results will also allow the fraction of AGN in submillimetre-selected samples and the form of their evolution to be estimated in a new way. The commissioning of the ALMA interferometer array will hopefully allow the absorbed optical and ultraviolet light from dust-enshrouded GRBs to be detected in the form of a far-infrared transient signal, potentially revealing the redshift of the GRB without requiring observations in the optical waveband.

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