A new constraint for gamma-ray burst progenitor mass

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ABSTRACT

Recent comparative observations of long duration gamma-ray bursts (LGRBs) and core collapse supernovae (cc SN) host galaxies demonstrate that these two, highly energetic transient events are distributed very differently upon their hosts. LGRBs are much more concentrated on their host galaxy light than cc SN. Here we explore the suggestion that this differing distribution reflects different progenitor masses for LGRBs and cc SN. Using a simple model we show that, assuming cc SN arise from stars with main sequence masses \(> 8 \, M_\odot\), GRBs are likely to arise from stars with initial masses \(> 20 \, M_\odot\). This difference can naturally be explained by the requirement that stars which create a LGRB must also create a black hole.

Key words: gamma-rays: bursts

1 INTRODUCTION

Long duration gamma-ray bursts (GRBs) originate in hydrogen deficient core collapse supernovae (SN Ic [Woosley 1993; Hjorth et al. 2003; Stanek et al. 2003]). These supernovae differ from the bulk of the core collapse population by showing no discernible hydrogen or helium lines, and, often exhibiting very high velocities (\(\sim 30000 \, \text{km s}^{-1}\)). The most likely candidate progenitor systems are thus wolf rayet stars which have lost their hydrogen envelopes via binary interactions, stellar winds or, possibly via complete mixing on the main sequence (e.g. Izzard et al. 2004; Podsiadlowski et al. 2004a; Yoon & Langer 2005; Woosley & Heger 2006).

Absorption spectra of GRB afterglows support this picture, with some bursts exhibiting several different absorption systems with velocity shifts of several hundred km/s, possibly wolf-rayet shells from the progenitor wind (e.g. Starling et al. 2004; van Marle et al. 2005).

However, measuring the properties of the progenitor star is complex. Although in a few, nearby cases it is possible to infer the properties of the star prior to core collapse by detailed modelling of the supernova spectrum, the paucity of nearby events limits this sample. An alternative means of understanding the nature of GRB progenitors is via the study of their galactic environments. Clearly any study conducted after the event cannot contain the progenitor star itself, however the environment should be indicative of the star formation which was occurring at the time of the GRB. Recently Fruchter et al. (2006) have conducted a survey of the galactic environments of both long duration GRBs and core collapse SNe (i.e. all types of core collapse events, including SN II, Ib and Ic). These results demonstrate that GRBs are highly concentrated on their host light, significantly more so than the core collapse supernova population. Fruchter et al. (2006) further suggest that this can be explained as being due to the GRBs originating in the most massive stars, which, upon core collapse form black holes rather than neutron stars. Here we further explore this possibility and attempt to derive plausible limits on the progenitor lifetime and mass based on the observed distributions of cc SNe and GRBs upon their host light. Using a simple model, motivated by the distributions of young star clusters in a local starburst galaxy, we explore the expected distributions of stars of different masses upon their host galaxies and compare these to the observed distributions from Fruchter et al. (2006). Our results demonstrate that for plausible models more massive stars are always more concentrated on their host light than lower mass stars. Further, given that supernovae originate from stars with initial masses \(> 8 \, M_\odot\), we find that the observed distributions of GRBs on their host galaxies can naturally be explained by progenitors with initial masses in excess of 20 \(M_\odot\).

2 MODEL

2.1 A local starburst galaxy as a template

GRB host galaxies at high redshift are starburst galaxies, with high specific star formation rates (i.e. star formation
rates per unit mass - e.g. Christensen et al. 2004). A natural local analogue for such a galaxy is NGC 4038/39 – the Antennae, and here we use it as a template for constructing a simple model of a GRB host.

NGC 4038/39 have been studied in detail with the Hubble Space Telescope (HST) and the young star clusters have been identified on the basis of Hα imaging (Whitmore & Schweizer 1995; Whitmore et al. 1999). Furthermore the age of young star clusters has been determined on the basis of their multicolour properties compared to the expected synthetic colours of clusters at different ages (Fall et al. 2005). The luminosity function and surface density of clusters on NGC 4038/39 is comparable to that seen in other local star forming galaxies of varying morphology (e.g. M51 or even the LMC, Gieles et al. 2006), indicating that it is a reasonable template. Using this well defined sample of clusters it is possible to examine where they lie on their galaxy light as a function of, for example, cluster age and luminosity.

Of course NGC 4038/39 lies only ∼ 20 Mpc distant, as such the resolution of the observations are much higher than is possible for GRB host galaxies at z = 1. Thus we resampled the observations of NGC 4038/39 as they would appear at z = 1 (using a ΛCDM cosmology with $\Omega_m = 0.73, \Omega_\Lambda = 0.27, H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$). We used the u-band (F330W) WFPC2 observations of NGC 4039, which broadly corresponds to the rest-frame wavelength observed with the F606W filter (the most common filter used in Fruchter et al. 2006) at z = 1. We then use the total pixel distribution and the total cluster distribution to determine the key parameters of the model (described below). Subsequently our model galaxy was set up based on these observations so that it reasonably represents a GRB host galaxy at z = 1.

2.2 Parameters and implementation of the model

A common approach when studying the environments of astronomical objects is to determine the distance of the object in question from the centroid of its host galaxy’s light. This method however provides limited information when studying GRBs and SNe as many of their hosts are irregular galaxies with more than one bright component. Fruchter et al. (2006) therefore developed a method which is independent of galaxy morphology. In their survey the position of a GRB or a SN was determined by sorting all of the pixels of the host galaxy from faintest to brightest, and asking what fraction of the total light is contained in pixels fainter than or equal to the pixel containing the explosion.

Our aim here is to set up a simple model which can be directly compared with the observational results obtained by Fruchter et al. (2006). We therefore define the properties of our model in terms of the contents of each pixel in a galaxy consisting of 500 pixels (the mean number of pixels in the observational sample of GRB hosts). Specifically each pixel is given a number of (or no) young clusters as well as light from old clusters and low-mass field stars. The light from old clusters and low-mass stars will from here on be referred to as background light. Because of the short lifetimes of GRB and SN progenitors we take the background light to be a constant in our model. The young clusters are created according to the age and mass distributions described below.

The first two properties were taken directly from the observations of NGC 4038/39 at z ∼ 1 as described in section 2.1. The surface density of clusters expressed in terms of number of clusters per pixel is ∼ 0.15, although this is far from uniform across the galaxy. We use the observed distribution of cluster masses, which follows $dN/dM_\odot \propto M_\odot^{-1.5}$, with $M_{\odot,\text{min}} = 4 \cdot 10^4 M_{\odot}$ and $M_{\odot,\text{max}} = 10^6 M_{\odot}$, where $M_\odot$ is the cluster mass. The age distribution of clusters was taken from Fall et al. (2005) and follows $dN/d\tau \propto \tau^{-1}$, where $\tau$ is the cluster age. In order to mimic an (almost) instantaneous burst of star formation, clusters are created in the model according to this distribution over a period of 10$^7$ years.

To address the issue of the distribution of background light we investigated the light profiles of all the GRB and SN hosts in the observational sample. These are plotted in grey in Fig. 1. The light distributions for the two types of hosts are very similar although the distributions of the SN hosts fall in a somewhat narrower range than those of the GRB hosts (extreme points for the SN hosts are shown as thin black lines in the figure). This discrepancy is likely to at least in part be due to the smaller number of SN hosts present in the observational sample (the sample contains 16 SN hosts and 32 GRB hosts).

Because the total background light is larger than the total light from young clusters (a factor of 6–8 for NGC 4038/39) we can use the total light profiles of Fig. 1 to ob-
contain an expression for the distribution of background light in our model. The distribution we adopted lies roughly in the middle of the observed distributions (black dashed line in Fig. 1) and is given by $dN/dL_{\text{pix}} \propto L_{\text{pix}}^{-1.5}$ with $L_{\text{pix,max}}/L_{\text{pix.min}} = 20$, where $L_{\text{pix}}$ is the luminosity of a pixel. The solid black line shows the distribution of total light in the model after cluster light has been added as described below.

The distribution of clusters on the background light is slightly more complicated than the other items since it is hard to observationally separate the cluster light from background light in individual pixels. We do however see a clear correlation between the number of clusters and the total light for the pixels in NGC 4038/39. Since background light makes up most of the total light we conclude from this that young, massive clusters are more likely to be found in pixels with a higher amount of background light. To account for this in our model we developed a correlation method in which the probability of a given pixel containing clusters increases with the amount of background light in that pixel. Fig. 2 shows the resulting distribution of clusters on the light 14 Myr after the first clusters were created (solid line). The figure also shows the distribution of the clusters in NGC 4038/39 as it would look at $z = 1$ (dotted line). The two distributions show excellent agreement. Further the distribution of clusters, in terms of number of clusters per unit pixel luminosity, also shows excellent agreement with the observations of NGC 4038/39 as it would appear at $z = 1$. The cluster distribution of course evolves with time but it is encouraging that the model resembles NGC 4038/39 at a time when several GRBs are occurring.

In order to identify GRBs and SNe and follow the evolution of the young clusters, each cluster was populated with stars drawn from a Salpeter IMF ($dN/dM \propto M^{-2.35}$) during a period of $10^6$ years. The luminosity of a star was taken to go as $L_\star \propto M_\star^3$ (to approximate blue light) and the stellar lifetime was approximated by the main sequence lifetime according to $T_\star \propto 4 \cdot 10^6 \cdot (100/M_\star) \text{ years}$. These assumptions are somewhat simplistic but provide good agreement with results from more complete stellar evolution calculations (e.g. Pols et al. 1995; Hurley, Pols & Tout 2000) and are sufficient for our purposes here.

With this setup, the total luminosity of our galaxy right after all the clusters have been created is about $3 \cdot 10^{10} L_\odot$ and the total number of young clusters is around 70. We note that the total luminosity of our model galaxy is higher than for a typical GRB host (these are typically around $10^{10} L_\odot$), but the properties of our model scale with luminosity and our results are therefore not affected by this.

In each run of the program, roughly 500 stars which are more massive than a specified minimum progenitor mass are randomly selected, the position on the light for each selected object is calculated at the end of its lifetime, and the cumulative distribution showing the fraction of objects as a function of fraction of light is produced. Because the model galaxy evolves with time the galaxy looks somewhat different for every recorded SN or GRB, and we assume that these differences account, to first order, for the differences between the observed host galaxies.

### 3 RESULTS

Using the parameters described in the previous section we performed runs for minimum progenitor masses of 8, 20, 40, 60, and $80 \ M_\odot$. The results are shown as black lines in Fig. 3 together with the observed distributions of SNe (in red) and GRBs (in blue) from Fruchter et al. (2006).
The model distributions for all masses were KS-tested against the observed SN and GRB distributions and the resulting probabilities are shown as a function of mass in Fig. 4. While the probability of following the SN distribution decreases with increasing mass, the likelihood of following the observed GRB distribution increases rapidly from 8 to 40 $M_\odot$ and then flattens out, reaching a weak maximum around 60 $M_\odot$. The shapes of the two probability functions look the same for all realisations of the model, although the peak probabilities can change by about 0.1 between different runs. These results strongly suggest that GRB progenitors are significantly more massive than SN progenitors.

4 DISCUSSION

4.1 Robustness and limitations of the model

In this section we address the robustness of our results by considering the errors on the observed distributions as well as the uncertainties and limitations of our model.

An issue requiring discussion is how one matches our theoretical model to the observational data. Clearly the observations contain various measurement errors, whereas errors within the model are contained within the assumption which are made. The observational errors to consider are those on the photometry (i.e. the error on the value of the pixel containing the GRB or SN) and those on the astrometry (i.e. knowledge of the location of the transient on its host galaxy). The latter is normally very small (though see Fruchter et al. 2006 for a more complete discussion), while the former depends largely on the value of the pixel in question, bright pixels have markedly smaller measurement errors, while fainter pixels can change their position (as a function of host galaxy light) by up to $\sim 10\%$ based on the typical $1\sigma$ noise within a pixel. However, we expect that this effect will average out over the larger sample.

Additionally, observations at high redshift do not reveal the full optical extent of a given galaxy, since light contained within pixels of low surface brightness is not detected above the sky level. Although the majority of the light is concentrated in brighter regions the faintest pixels (typically corresponding to a few percent of the light at $z \sim 1$) are not detected. To mimic this effect we employed a surface brightness cut upon our models, removing the faintest pixels containing about 5% of the light, although we note that qualitatively our results are not strongly dependent on the effects of this cut, since the majority of the light is contained in brighter pixels.

The results from our model show that the most massive stars are significantly more concentrated on their host galaxy light than the $\sim 8M_\odot$ stars which give rise to the bulk of the cc SN. This is simply a consequence of the different lifetimes of stars of different masses; the most massive stars are found in bright, young clusters which can provide the peak of the light of a galaxy, while most of the SN occur when their clusters are fainter and therefore less likely to be in the brightest parts of a galaxy.

The exact positions on the light for GRBs/SNe with different progenitor masses of course depend on the parameters of our model. Because the model contains numerous free parameters with relatively weak constraints on their range and correlation from direct observations, we have chosen not to do detailed simulations covering all of parameter space, but simply to show that we can get good agreement with observations for a reasonable set of parameters. In order to investigate the robustness of our results we however performed several runs varying each of the key parameters listed in section 3.1 while keeping the rest of the model fixed. We found that the most important parameters are the level of background light, the distribution of clusters upon this background, and the number of young clusters.

In order to investigate the effect of varying the level of background light we performed runs with a total background ranging from 1/3 to 10 times the background of our standard model. The lower limit is set by requiring that the total cluster light never exceeds the background light in our model. We note that our analysis of the starburst galaxy NGC 4038/39 finds a background–to–cluster light ratio of around 6-8, and that therefore extremely unusual conditions would be needed to arrive at our lower limit. The upper limit corresponds to what would be expected in early type galaxies which contain relatively few supernovae and are equally not expected within our sample of GRB or SN hosts.

Decreasing the amount of background light in the model makes the contribution from cluster light more important and all progenitors therefore become more concentrated on the host light. For the lowest background the 8 $M_\odot$ progenitors fall between the observed SN and GRB distributions. Increasing the background has the opposite effect and for the highest background all the progenitors are less concentrated on the light than the observed SNe. Because the background completely dominates the total light distribution close to our upper limit, the distributions for different progenitor masses also move closer together. More massive
progenitors are however always more concentrated on the light than lower mass ones.

In this case one may wonder if it is possible for the GRB distribution to be explained by differing background to cluster light ratios in the host galaxies. However, as GRB hosts typically have a high specific star formation rates (i.e. high star formation rates per unit total luminosity) we would expect that GRB hosts would have higher cluster to background light ratios. However, we note that even in the extreme case of equal background and cluster light (which is unreasonable in essentially all galaxies) the distribution of SN progenitors remains less concentrated than is observed for GRBs.

In the runs just described we varied the amount of background light while keeping the shape of the distribution constant. As described in section 2.2 this shape was chosen as the median of the light distributions of all the hosts seen in Fig. 1. To check whether this simplification has any effect on the results we compared the result obtained when using only the median to the result obtained by averaging the results for different light distributions drawn from Fig. 1. We found that the results are indeed very similar.

As mentioned in section 2.2 the distribution of clusters in NGC 4038/39 suggests that young clusters are more likely to be found in pixels with a higher level of background light. Since it is hard to put observational constraints on this correlation for different types of galaxies we simply note that both no correlation and maximal correlation are unphysical: young clusters are always found in bright regions of galaxies and there is simply not enough space to place all of the clusters in the very brightest pixels. We therefore performed runs varying the correlation between these two extremes.

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As a side note we also point out that the correlation is degenerate with the level of background light; a similar result can be obtained using a high background together with a high correlation as with a lower background together with a low correlation.

The last parameter which was seen to significantly affect the results is the surface density of young clusters. Since the surface density of clusters on NGC 4038/39 is comparable to that seen in other local star forming galaxies (Gieles et al. 2006) we simply vary the number of clusters in the model between 1/10 and 10 times this typical value. When fewer young clusters are included the progenitors are more concentrated on the light as there are more low luminosity pixels present. Including a larger number of clusters makes the progenitors less concentrated on the light. As in the case of varying the background and correlation we however find that more massive progenitors are always more concentrated on the light than lower mass ones, and that the 8 $M_\odot$ progenitors are always well above the observed GRB distribution. Indeed, as we might expect the surface density of clusters to be higher in GRB hosts (because of their high specific star formation rates) this effect would bias the observed results in the opposite direction from that observed (i.e. it would typically make GRB progenitors seem less concentrated on their hosts).

In summary our results are robust in the following important aspects:

- For all plausible models more massive progenitors are always more concentrated on their host galaxy light than lower mass progenitors.
- We found no reasonable parameters for which a progenitor mass of 8 $M_\odot$ was close to following the observed GRB distribution, indicating that the GRB progenitors have significantly higher masses.
- In models where progenitors with a minimum mass of 8 $M_\odot$ follow the observed SN distribution, we always find that the GRB progenitors have to be more massive than 20 $M_\odot$.

Based on these results we conclude that the observed locations of SNe and GRBs on the light of their host galaxies can be explained if the GRB progenitors are significantly more massive than the SN progenitors.

Since the lifetime of a star is clearly dependent on its mass we can also place a limit on the lifetime of the stars forming the GRBs. The observed light comes from the ensemble of massive stars around the progenitor of the GRB, and it is the age of these which effectively sets the distributions seen in Figure 3. It is plausible that, as unusual stars, GRB progenitors might follow different evolutionary paths and thus have different lifetimes. For example, under the models of Yoon & Langer (2005) and Woosley & Heger (2006) rapidly rotating massive stars undergo complete mixing and have longer lifetimes than normal main sequence stars (with lower angular momentum) of the same mass. In this sense the distributions may more accurately set the age of the population rather than the mass of the progenitor. The distributions shown in Figure 3 are well reproduced by a population with $t_{SN} < 50$ Myr and $t_{GRB} < 20$ Myr. We note that these values differ from those obtained via detailed stellar evolution modelling and that most models predict shorter life times (e.g. Schaller et al. 1992). This discrepancy is due to the relatively simple treatment of the main sequence lifetimes within our code.

In deriving these results we have, of course, assumed the same basic model for GRB and SN hosts, in terms of the expected relative distribution of clusters upon them. In truth this is poorly known, although it is clear that different host galaxies differ significantly morphologically, with 50% of SN hosts being spiral, compared to only 7% of the GRB hosts in the same redshift range. Typically the star formation is likely to be more intense in the GRB host galaxies than in the SN sub-sample. So, in the language of our model the background to cluster light ratio will be lower in GRB host galaxies. This is to some extent taken into account in our model as the most massive stars end their lives while the majority of the stars in the cluster are still on the main sequence (i.e. while the cluster is at its maximum luminosity), whereas most 8$M_\odot$ stars will explode as SNe when much of the cluster light has disappeared. In practice, measuring the distribution of individual clusters on GRB and SN host galaxies will be impossible for the foreseeable future.
future, and we can not assess how well our model accounts for these plausible differences between the two types of hosts. We therefore caution against drawing strong quantitative conclusions on GRB progenitor mass from our models but note that it must *always* be significantly larger than the SN progenitor mass.

4.2 Implications of the results

A natural explanation for the preference of GRBs to occur from more massive stars is that most cc SN create neutron stars, while GRBs are likely to originate from black holes. Indeed, models imply that the dividing line between NS and black holes is that most cc SN create neutron stars. This is reasonable since SN II's dominate the types of these (e.g. SN II (H-rich) and SN Ib/c (H-poor)).

An additional constraint for GRB production comes from rotation. GRB production is thought to require the formation of a torus about the nascent black hole. These discs can only be formed in rapidly rotating stars, and therefore further limit the fraction of massive stars which can create GRBs. The majority of single stars rotate too slowly on the main sequence for torus formation, and only a small fraction are in binaries with sufficiently small separations for tidal locking to create stars with sufficient rotation for torus formation (Izzard et al. 2004; Podsiadlowski et al. 2004a; Levan, Davies & King 2006).

Finally, it should be noted that all of the SN spectroscopically associated with GRBs are of the type Ic. The lack of discernible hydrogen (or helium) lines in these spectra implies that the progenitor stars have lost their hydrogen (and helium) envelopes prior to core collapse. Therefore, even very massive stars cannot be considered candidates for GRB production if they retain significant hydrogen atmospheres.

In deriving the results above we have assumed that all stars with $M > 8 M_\odot$ create core collapse supernovae, and have not attempted to differentiate between different subtypes of these (e.g. SN II (H-rich) and SN Ib/c (H-poor)). This is reasonable since SN II's dominate the observed rate. However, there are reasons for believing that the brightness of a supernova, and therefore its detectability at high redshift, may not be independent of the progenitor mass (provided it is greater than $8 M_\odot$). For example, stars in the range 8-10 $M_\odot$ may undergo electron capture supernovae (e.g. Nomoto 1987; Podsiadlowski et al. 2004b), while stars with masses in excess of $\sim 25 M_\odot$ might create black holes either by direct collapse or fallback, but without a bright supernova (e.g. Heger et al. 2003). Both of these may create supernovae with faint optical emission, and might not be represented, even in deep optical surveys. We tested this effect by creating a model in which supernovae were drawn exclusively from the masses in the range $10 < M_{SN} < 25$. Although this slightly alters the shape of the distribution seen in Fig. 3 it still provides an excellent agreement to the supernova distribution ($P_{KS} = 0.23$, compared to $P_{KS} = 0.17$ for the $M_{SN} > 8$ distribution. )

Clearly as GRBs are rare events it is possible, or even likely, that the progenitors follow exotic pathways to their production. These pathways may plausibly involve binary interactions or even collisions (which can build up even more massive stars). As the number of interactions scales roughly as the 3/2 power of the mass of the cluster (e.g. Davies, Piotto & De Angeli 2004) more massive (and hence brighter) clusters might harbour more GRBs. We note that simply picking GRBs where the probability of a GRB occurring is proportional to the mass of the cluster does not accurately reproduce the observations. It may well be that other parameters, such as cluster core densities, are also important. However a full investigation of these is beyond the scope of this paper.

5 SUMMARY

An observational study by Fruchter et al. (2006) showed that long duration GRBs are significantly more concentrated on their host galaxy light than core collapse SNe. In this paper we have used this result in an attempt to put constraints on the mass of GRB progenitors. In order to construct a simple model of a typical GRB host we used the properties of the local starburst galaxy NGC 4038/39 as it would appear at a redshift of 1. We then specified different minimum masses of GRB/SN progenitors and studied their locations on the light of our model galaxy. We showed that the observed locations of SNe and GRBs on the light of their host galaxies can be explained if the GRB progenitors are significantly more massive than the SN progenitors. The exact value of the minimum GRB progenitor mass depends on the parameters of our model, but for a reasonable set of parameters the minimum progenitor mass was found to be significantly higher than $20M_\odot$.

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