THE RATES OF HYPERNOVAE AND GAMMA-RAY BURSTS: IMPLICATIONS FOR THEIR PROGENITORS

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ABSTRACT

A critical comparison of estimates for the rates of hypernovae (HNe) and gamma-ray bursts (GRBs) is presented. Within the substantial uncertainties, the estimates are shown to be quite comparable and give a galactic rate of $10^{-6}$ to $10^{-5}$ yr$^{-1}$ for both events. These rates are several orders of magnitude lower than the rate of core-collapse supernovae, suggesting that the evolution leading to an HN/GRB requires special circumstances, very likely due to binary interactions. Various possible binary channels are discussed, and it is shown that these are generally compatible with the inferred rates.

Subject headings: binaries: close — stars: neutron — supernovae: general — X-rays: stars

1. INTRODUCTION

While it has now been established for more than 5 years that gamma-ray bursts (GRBs) are caused by some of the most energetic explosions in the universe (van Paradijs, Kouveliotou, & Wijers 2000), no promising channel for their progenitors has been identified, a situation very much resembling that of the progenitors of Type Ia supernovae (SNe Ia) some 20 years ago. The firm and, unlike the previous case, unambiguous association of a GRB (GRB 030329) with a hypernova (HN), SN 2003dh (Hjorth et al. 2003a; Stanek et al. 2003), a highly energetic SN Ic (Mazzali et al. 2003),7 has confirmed that at least some long-duration GRBs are observationally connected with the explosion of massive stars.8

All HNe known to date belong to the class of SNe Ic, of which they form a subset. These are SNe that show neither hydrogen nor significant amounts of helium in their spectra. Their progenitors are believed to be either very massive single stars that lost their hydrogen and helium envelopes in a stellar wind or massive stars that lost their envelopes through a companion with a companion (Wheeler & Levreault 1985; Uomoto 1986; Podsiadlowski, Joss, & Hsu 1992; Nomoto et al. 1994). Two out of the three nearby GRBs known to date are associated with HNe (GRB 980425/SN 1998bw at $z = 0.008$ and GRB 030329/SN 2003dh at $z = 0.17$). The third case, GRB 031203, is heavily extinguished by dust, so a SN association cannot be firmly ruled out (Hjorth et al. 2003b).9

This interesting coincidence raises the important question of the general connection between HNe and long-duration GRBs and whether most, or perhaps even all, GRBs are associated with/cause by HNe.

This Letter addresses this question by providing a critical comparison of the rates of GRBs and HNe. As is shown in § 2, the rates of GRBs and HNe are comparable within the uncertainties and appear to be a small fraction of the global SN rate. This has important implications for the nature of their progenitors, which is discussed in detail in §§ 3 and 4.

2. THE RATES OF GRBs AND HNe

2.1. The GRB Rate

The rate of observed GRBs in a galaxy such as our own is quite well established from the BATSE monitoring as $R_{\text{GRB}} \sim 10^{-7}$ yr$^{-1}$ (e.g., Zhang & Meszáros 2004). However, since GRB fireballs are highly beamed, both geometrically and relativistically (with Lorentz factors $\Gamma \sim 100$), the true intrinsic rate must be substantially higher. It may be written as $R_{\text{GRB}} = R_{\text{GRB \, obs}} (4\pi/\Omega)$, where $\Omega$ is the solid angle within which an observer can detect the GRB. This factor depends on the jet opening angle and is typically estimated as $\sim 50–500$ (Fratil 2001; Panaitescu & Kumar 2001). The rate, however, is uncertain, as $R_{\text{GRB \, obs}}$ and $\Omega$ are estimated from two different samples, $R_{\text{GRB \, obs}}$ from the BATSE sample and $\Omega$ from the sample of GRBs with afterglow observations, and there is no robust evidence that the selection effects are the same in the two sets. In addition, the solid angle correction is based on the so-called uniform jet model, in which the opening angle is an intrinsic property of the jet. An alternative explanation of the observations calls for a structured jet, with a brighter core and dimmer wings. In this case the rate of GRBs would be smaller by a factor of 3–10 (Rossi, Lazzati, & Rees 2003). Thus the range of plausible values for the GRB rate is $10^{-6}$ to $10^{-5}$ yr$^{-1}$, of which about $2/3$ are long-duration GRBs.

2.2. The HN Rate

To date, five SNe Ic have been classified as HNe. They form quite a diverse group of objects, including the very bright and

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7 The term “hypernova” has been used for SNe with energies significantly larger (by about a factor of 10 or more) than the canonical explosion energy of 1 foe $= 10^{51}$ ergs (Nomoto et al. 2004).
8 GRBs fall into two classes: short- and long-duration bursts. Currently, very little is known about the progenitors of short bursts from an observational point of view. It is quite possible that they are caused by a completely different physical mechanism, e.g., the merger of two compact objects (van Paradijs et al. 2000). All inferences made in this Letter exclusively apply to long bursts.
9 After this work had been completed, both Bersier et al. (2004) and Tagliaferri et al. (2004) reported the possible detection (photometrically and spectroscopically, respectively) of an SN, probably similar to SN 1998bw, in the host galaxy of GRB 031203.
energetic SNe 1998bw (Iwamoto et al. 1998) and 2003dh (Mazzali et al. 2003), the moderately bright but very energetic SNe 1997ef (Mazzali et al. 2000) and 1997dq (P. A. Mazzali et al. 2004, in preparation), and the normally bright but overenergetic SN 2002ap (Mazzali et al. 2002). On the basis of spherically symmetric explosion models, their explosion energies have been estimated to range between 4 and 50 \( M_\odot \) and the progenitor masses from a lower limit of 20–25 to 40 \( M_\odot \) and above. This covers the entire mass range of single stars that are believed to become black holes (e.g., Maeder 1992; Fryer & Kalogera 2001).

Interestingly, no HN is known to have the characteristics of a SN II, although such objects might in principle occur in the lower mass range (depending somewhat on the minimum initial mass for which a single star becomes a Wolf-Rayet [W-R] star). This may provide an important clue, linking the physical cause of the HN mechanism to the process causing the loss of the hydrogen and helium envelope. In this context, we note as a caveat that the inferred initial masses of HNe are based on the final core structure expected from single-star evolution. If the pre-HN evolution was affected by binary evolution, as seems possible or even likely (see § 3), this mapping may be modified.\(^{10}\)

As the lowest initial mass that is able to produce a HN appears to be \( \sim 20 \ M_\odot \), this implies that not all SN Ic are HNe. For example, Nomoto et al. (1994) estimate that the progenitor of the normal SN Ic 1994I was 15 \( M_\odot \) (again assuming a single-star mapping of the initial to the final mass). SN Ic may come from progenitors as low in mass as \( \sim 8 \ M_\odot \) if they are in a binary (Podsiadlowski et al. 1992; Nomoto et al. 1994).

The estimated rate of all core-collapse SNe is 7 \( \times 10^{-3} \) yr\(^{-1}\) for an average galaxy and 1.2 \( \times 10^{-2} \) yr\(^{-1}\) in our Galaxy (Cappellaro et al. 1999). The latter estimate is somewhat lower than recent estimates for the Galactic pulsar birthrate of 4 \( \times 10^{-2} \) yr\(^{-1}\) based on the Parkes multibeam survey (Vranesevic et al. 2003). In contrast, the observed rate of SNe Ibc and Ic in an average galaxy in the local universe is only \( \sim 10^{-3} \) yr\(^{-1}\).

Most SNe Ibc actually appear to belong to the Ic subtype, and only a fraction of a few of \( 5\% \) of observed SN Ic are HNe. The brightness of HNe is highly diverse, ranging from normal to about 10 times normal. However, the average of the known cases is a factor of \( \sim 3\)–5 brighter than a typical SN Ic. Therefore, we expect that HNe are easier to detect and hence intrinsically less common relative to normal SNe Ic than the direct observational estimate. Being on average a factor of 4 brighter implies that in a magnitude-limited search they would be detectable in a volume larger by a factor of \( 4^{1/2} = 8 \). However, because many of the current SN searches target only selected galaxies, they are also volume limited. Thus, in a typical SN search the expected number of SNe grows more or less linearly with SN magnitude (Cappellaro et al. 1993). Reducing the observed rate by the proper factor gives us an estimate of the true HN rate of \( \sim 10^{-3} \) yr\(^{-1}\).

### 3. THE PROGENITOR CONNECTION

The estimates of the rates of GRBs and HNe in the previous section are the same to within the uncertainties (see Table 1), although the HN rate may be slightly higher. This suggests that most HNe also appear as GRBs at least from some viewing angle.

This is consistent with the fact that HNe are associated with at least two out of three nearby GRBs, one of which was typical while the other was weak. It is also consistent with the fact that only the most powerful HNe are seen in association with GRBs. Events that appear less powerful may simply be viewed off-axis, leading to an underestimation of the kinetic energy and to the nondetection of the GRB. SN 2002ap could be such a case, since there is ample evidence that the explosion was aspherical, like SN 1998bw (Mazzali et al. 2002; Maeda et al. 2003). This may also imply that the beaming correction cannot be too large.

The estimates allow for the possibility that some HNe do not produce GRBs, as in some popular models (MacFadyen & Woosley 1999) the relativistic jet may not always break through the envelope of the progenitor star. This may give rise to a “failed GRB” with an orphan afterglow, as has been suggested for SN 2002ap (Totani 2003), or to short-duration X-ray flashes (XRFs; Heise et al. 2001). Possible evidence for this comes from the reported detection of an SN-like “bump” in the light curve of an XRF (XRF 030723; Fynbo et al. 2004).

SN-like bumps have been detected in the light curves of GRB optical afterglows, but only for one such case (GRB 021211/SN 2002ap, \( z \sim 1 \)) is a spectrum available: Della Valle et al. (2003) argue that it is similar to that of the standard SN Ic 1994I. However, the extracted SN U-band light curve (other bands not being available) appears significantly brighter than the U-band light curve of SN 1994I, so an HN solution for SN 2002ap cannot be firmly ruled out. If a clear case of association of a normal SN Ic and a GRB should be revealed, we may have to lower the mass limit of stellar collapses that trigger a GRB.

These estimates are also in broad agreement with those of Berger et al. (2003) and Soderberg et al. (2004). On the basis of a comparison of the radio emission from HNe and SNe Ibc, these studies conclude that \( \lesssim 3\% \) and \( \lesssim 6\% \), respectively, of SNe Ibc can be associated with GRBs. In contrast, Lamb et al. (2004) recently argued that based on a universal jet model for XRFs and GRBs, the jet opening angle is as small as 0.5\(^{\circ}\). This would imply an XRF/GRB rate comparable to the SN Ib/c rate.

Our rate estimates suggest that GRBs and HNe constitute a small subset of core-collapse SNe (also see Paczyński 2001). Does this imply that only very massive stars become HNe/GRBs? In Table 1 we list the estimated rates for stars above various different masses, using a simple Salpeter-like mass function \( [f(M)\, dM \propto M^{-2.3} \, dM] \) and assuming for simplicity that all stars above \( 8 \ M_\odot \) produce a core-collapse SN. Clearly, even if the minimum initial mass for an HN/GRB was larger than

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\(^{10}\) For example, Brown et al. (2001) showed that if a star loses its envelope through a binary interaction soon after its main-sequence phase, its final pre-SN core structure is dramatically changed and even a 60 \( M_\odot \) star may produce a neutron star rather than a black hole (also see Podsiadlowski et al. 2004).

### Table 1: Rates in an Average Galaxy

| Objects | Rate (yr\(^{-1}\)) |
|---------|-------------------|
| Core-collapse SNe | \( 7 \times 10^{-3} \) |
| Radio pulsars (Galactic) | \( 4 \times 10^{-2} \) |
| SNe Ibc | \( 1 \times 10^{-3} \) |
| HNe | \( \sim 10^{-4} \) |
| GRBs (for different effective beaming angles \( \theta \)):
  - \( \theta = 1^{\circ} \) | \( 6 \times 10^{-4} \) |
  - \( \theta = 5^{\circ} \) | \( 3 \times 10^{-5} \) |
  - \( \theta = 15^{\circ} \) | \( 3 \times 10^{-6} \) |
| Massive stars:
  - \( >20 \ M_\odot \) | \( 2 \times 10^{-3} \) |
  - \( >40 \ M_\odot \) | \( 6 \times 10^{-4} \) |
  - \( >80 \ M_\odot \) | \( 2 \times 10^{-4} \) |
80 $M_\odot$, they would be significantly overproduced. On the other hand, the initial progenitor mass in some HNe appears to be as low as 20 $M_\odot$ (Mazzali et al. 2002; but see footnote 9).

In conclusion, it is extremely unlikely that the progenitors of HNe and GRBs are just very massive stars. Special circumstances are almost certainly needed. The most promising of these is rotation: a rapidly rotating core is the essential ingredient in the “collapsar” model for GRBs (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999). The prototype HN, SN 1998bw, shows clear evidence from the line profiles that the explosion was highly asymmetric (Maeda et al. 2002).

The role of rotation.—Massive stars are generally rapid rotators on the main sequence. However, there are many well-established mechanisms by which they can lose their angular momentum during their evolution by both hydrodynamical (e.g., winds) and magnetohydrodynamical processes (Spruit & Phinney 1998; Spruit 2002). Therefore, it is not at all clear whether the cores of massive single stars will ever be rotating rapidly at the time of explosion. In this context, rapid rotation means sufficiently rapid that the core cannot collapse directly to form a neutron star/black hole and conserve angular momentum. A simple criterion is that the specific angular momentum, $j$, near the black edge of the iron core (enclosing a mass $M_j \sim 2 M_\odot$) is larger than the value at the last stable orbit around a black hole of that mass, i.e., $j \sim 5\pi G M_c c = 2 \times 10^{16}$ ergs s $(M/2 M_\odot)$. Recent calculations taking into account magnetic torques (Heger et al. 2004) suggest that single massive stars fall short of this requirement by about 1 order of magnitude. To have a sufficiently rapidly rotating core at the time of explosion may require interactions with a binary companion that can spin up the progenitor or prevent its spin-down.

The role of binarity.—Binary interactions can spin up a star by a variety of processes. Tidal interactions can cause either component of a binary to rotate with the same frequency as the binary, spinning it up or down depending on the relative frequencies. For a star spinning synchronously with the binary orbit and filling a fraction $r$ of its Roche lobe, the ratio of its rotation frequency, $\omega$, to its (Keplerian) breakup frequency, $\omega_{\text{crit}}$, just depends on the mass ratio according to $\omega/\omega_{\text{crit}} = (1 + q)^{1/2} h(q)^{1/2} r^{-3/2}$, where $q = M_2/M_1$ is the mass ratio ($M_2$ is the Roche lobe–filling object and $M_1$ the accreting star) and $h(q)$ is the ratio of the Roche lobe radius to the orbital separation (as given by, e.g., Eggleton 1983).

If we require that in a collapsar model only the innermost core of $\sim 2 M_\odot$ can collapse directly while the rest forms a disk, we can obtain a rough estimate for the maximum orbital period where tidal spin-up can provide enough angular momentum to the core by assuming that the whole star remains in solid body rotation until the end of helium burning. At this stage the core is likely to decouple and will probably retain most of its angular momentum in the final rapid evolutionary phases. Taking the radius of the 2 $M_\odot$ core as $\sim 8 \times 10^6$ cm (typical for the core of a 30 $M_\odot$ star at the end of helium burning), one then immediately obtains a critical orbital period $P_{\text{crit}} \sim 5.6$ hr $(R/8 \times 10^6$ cm)$^2 (j/2 \times 10^{16}$ ergs s)$^{-1}$. Izzard et al. (2004), using detailed binary population calculations, concluded that there are enough binaries where tidal locking could account for the observed rates.\footnote{Note, however, that they assumed that it was sufficient to prevent the whole star (rather than just the core) from collapsing directly into a black hole, which significantly increases the critical orbital period and hence the estimated rate for this channel.}

The black hole binary Nova Sco may provide indirect ob-

4. DISCUSSION

The rates of HNe and GRBs are quite comparable, suggesting that a large fraction (most?) of HNe also produce GRBs, at least in some direction. Moreover, the rates are significantly smaller than the rates of core-collapse SNe (or even the fraction of SNe that produce black holes). Furthermore, at least at the present cosmological epoch, special circumstances are required to produce HNe/GRBs. However, numerous fundamental questions remain unanswered, and no fully self-consistent evolutionary model for the progenitors exists at this time. As long as this is the case, it is not even clear whether or not the HN and the GRB occur concurrently. Does the HN occur first and trigger the GRB through the fallback of HN ejecta, as may be required in some models (Vietri & Stella 1998; Podsiadlowski et al. 2002), or does the GRB occur and then trigger a SN-like event through the interaction of the relativistic jet with the envelope as in the collapsar model (Khokhlov et al. 1999; MacFadyen & Woosley 1999; Pruet, Woosley, & Hoffman 2003)?

Although HNe/GRBs appear to be relatively rare events at the present epoch, this need not be the case for the first generation of stars. Lower metallicity may lead to lower angular momentum loss from massive stars, and the star formation environment may be very different. It is even conceivable that at an early epoch of galaxy formation, HNe could provide the missing energy to eject half the baryons from galaxies (Silk 2003).
Finally, another important question concerns the relationship between HNe and the class of SNe Ib/c, of which they are a subgroup. Presumably, many normal SNe Ib/c are caused by the collapse of the core of a massive star that lost its H-rich envelope through binary interaction (Wheeler & Levrault 1985; Podsiadlowski et al. 1992; Nomoto et al. 1994) forming a neutron star. So perhaps one important distinction between a HN and an ordinary SN is whether a black hole or a neutron star is formed in the aftermath. However, not all black hole formation events can lead to a HN; if the minimum mass of a black hole is as low as 20–25 $M_\odot$ (Maeder 1992; Fryer & Kalogera 2001), this would overproduce HNe by a large factor (see Table 1).

A natural explanation for this dichotomy may lie in the fact that black holes can form either promptly on a dynamical timescale or on a much longer timescale by continued accretion through a disk phase or fallback. In particular, the disk accretion phase, which is the essential ingredient in collapsar models, requires a rapidly rotating core. In the case of prompt collapse, one would not necessarily expect a bright SN. This would imply the existence of a class of (very?) dim SNe Ib/c, possibly related to the dim class of SNe II (e.g., SN 1997D; Nomoto et al. 2004).

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