Binary progenitor models for long-duration gamma-ray bursts

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While it is well established that long-duration gamma-ray bursts (LGRBs) are intrinsically rare events, requiring a special evolutionary channel, the nature of the most important channels still has to be established. Here, we review some of the main binary models that have been proposed, specifically tidal spin-up models and binary mergers of various types, and then present a new model involving the recently discovered mechanism of explosive common-envelope ejection. The latter model naturally explains why LGRB-related supernovae have not observed helium and may also explain a constant-density medium around LGRBs, as has been deduced in some cases. LGRB rates as well as their metallicity dependence is also discussed for the various models.

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1. Progenitor constraints

Long-duration gamma-ray bursts (LGRBs) are some of the most energetic explosions in the Universe. Yet, the nature of their progenitors is almost completely unknown. It is clear that LGRBs are relatively rare events (see Podsiadlowski et al. (2004) and references therein). After correcting for beaming, the LGRB rate in a typical galaxy like ours is approximately $10^{-5}$ yr$^{-1}$, where the estimate has an uncertainty of about an order of magnitude. Interestingly, this rate is comparable to the hypernova rate, i.e. the rate of unusually energetic supernovae (Podsiadlowski et al. 2004). This rate implies that less than approximately 1 in 1000 core-collapse supernovae produces an LGRB and that the production of an LGRB requires some special circumstances, i.e. the progenitors cannot just be more massive single stars, but stars that are unusual in some respects, e.g. owing to a combination of low-metallicity and rapid rotation (Yoon & Langer 2005; Woosley & Heger 2006) or owing to binary evolution effects, the topic of this review.

In the presently favoured collapsar model (Woosley 1993; MacFadyen & Woosley 1999), an LGRB is triggered by the collapse of a rapidly rotating massive core. In order for the collapse to proceed via a disc phase, the specific angular momentum in the core has to be larger than a few $10^{16}$ cm$^2$ s$^{-1}$. In the
case of a single star, this requires that the star for some reason has not been spun-
down during its evolution, the normal fate for most massive star. Alternatively,
in a binary scenario it may have been spun-up by various binary processes.

One of the most puzzling constraints at the present time is that all supernovae
that have been associated with LGRBs have been Type Ic supernovae, i.e.
supernovae whose progenitors have not only lost all of their hydrogen, but also
all of their helium envelopes.

Recently, Fruchter et al. (2006) have shown that the rate of LGRBs appears to
be higher at lower metallicity, although it is not clear how strong this metallicity
bias is. Wolf & Podsiadlowski (submitted) estimated that the typical metallicity
of an LGRB host galaxy is approximately half the solar value, i.e. comparable to
the present metallicity of the Large Magellanic Cloud. At present, it is not yet
entirely clear whether this is due to an intrinsic metallicity dependence of the
LGRB rate or whether this could be caused—at least in part—by observational
selection effects.

One of the more indirect, but nevertheless potentially important constraints
on LGRB progenitors comes from the X-ray transient Nova Scorpii. This
system is one of the best-studied low-mass, black-hole binaries with an orbital
period of 2.6 d and a black hole with a mass approximately 5.4 $M_\odot$. Israelian
et al. (1999) showed that the secondary in this system has been highly enriched
with the products of explosive nucleosynthesis (e.g. Mg, Si, S, Ti) produced in
the supernova explosion that produced the black hole. Interestingly, the
chemical anomalies are best explained by an energetic supernova explosion
(hypernova; Podsiadlowski et al. 2002), implying that the formation of the
black hole in this system may have been accompanied by an LGRB. However, if
that is the case, it is puzzling why the black-hole progenitor would have been
rapidly rotating, since the primary should have been spun-down rather than
have been spun-up.

2. Tidal spin-up models

In many respects, the simplest binary process that can produce a rapidly
rotating helium star is tidal spin-up, since in a tidally locked binary a star can be
spin-up (or down) until its spin angular velocity is equal to the orbital angular
velocity (e.g. Izzard et al. 2004). Simple angular-momentum estimates, suggest
that this requires an orbital period shorter than approximately 10 h
(Podsiadlowski et al. 2004). In practice, this means that the companion is
most likely a compact object (a neutron star or a black hole). Such systems are
indeed observed; for example, the X-ray binary Cygnus X-3 contains a Wolf–
Rayet star in orbit with a neutron star or black hole (van Kerkwijk et al. 1992).
In the case of Cygnus X-3, it is not clear whether the Wolf–Rayet star will
ultimately collapse to form a black hole and produce an LGRB. Nevertheless,
similar systems that produce a black hole are likely to exist, indeed with a rate
compatible with the LGRB rate.

Detmers et al. (in preparation) have recently modelled the evolution of such
systems and, in particular, the spin-up evolution of the companion star. Indeed,
they found that tidal spin-up of the core is possible. However, they also showed
that at solar metallicity, the expected strong wind from the Wolf–Rayet star
leads to a significant widening of the binary and the ultimate spin-down of the companion. As a consequence, this channel is only likely to work at low metallicity when the wind mass-loss rate is expected to be much lower.

In cases, where the Wolf–Rayet companion filled its Roche lobe, Detmers et al. (in preparation) found that it was then likely that the Wolf–Rayet star would merge completely with the compact companion, quite similar to another LGRB model, proposed originally by Fryer & Woosley (1998).

3. Merger models

Most binary models for LGRBs proposed to date involve the merger of two stars. This is a particularly efficient way of converting orbital angular momentum into spin angular momentum. A variety of different types of binary mergers can be distinguished depending on the nature of the components and the cause of the merging.

The most widely discussed merger models consider the merging of two compact cores inside a common envelope (e.g. Fryer & Woosley 1998; Zhang & Fryer 2001; Fryer & Heger 2006; also see Joss & Becker 2003; Fryer et al. 2006), where one of the cores can already be a compact star (e.g. a neutron star or a black hole). One of the most interesting cases involves the merger of the non-degenerate cores of two massive stars. This occurs when the initial masses of the binary components are very close (typically within approx. 5–10%) and both stars already have a compact core at the time of the binary interaction, leading to a double-core common-envelope phase (as first discussed by Brown (1995); also see Dewi et al. (2006)). Statistically, it is more likely that the initially more massive star has already developed a CO core, while the less massive star has a less evolved He core. When the two cores merge, this will lead to a rapidly rotating object consisting of a CO core with a helium envelope. Since the merging process is driven by friction within the common hydrogen-rich envelope, it is not entirely clear how the merger can proceed to its conclusion and still eject the hydrogen-rich envelope completely at the same time.

This issue does not arise in the case where a Wolf–Rayet star merges with a compact companion as a result of unstable transfer: the case mentioned at the end of the previous section. In this case, the Wolf–Rayet star is expected to form a disc-like structure surrounding the compact object. It is worth noting that, if this can lead to an LGRB, the situation is somewhat different from the situation of the collapse of a rapidly rotating core (as in the original ‘collapsar’ model) since in the case of a disc-like structure it may be much easier for a relativistic jet to penetrate the surrounding envelope than in the case of a rapidly rotating core.

A similar outcome is possible when the merger is induced by a supernova kick. This can happen in close binaries consisting of two Wolf–Rayet stars, the most likely outcome of double-core evolution (Brown 1995; Dewi et al. 2006). When the more evolved star collapses to form a neutron star or black hole, this may be accompanied by a kick to the newly formed compact object which may then produce an orbit where the companion star is immediately disrupted dynamically (e.g. Brandt & Podsiadlowski 1995). The destroyed companion star will be rapidly accreted by the compact object and this may lead to an LGRB (e.g. because the neutron star collapses into a black hole). One interesting aspect of
this scenario is that there may be a significant time delay between the initial supernova, triggered by the collapse of the more massive component, and the LGRB (typically of order a few days). Our preliminary estimates of this scenario suggest that the frequency of this channel is unlikely to account for the majority of LGRBs, but could well explain a subset (perhaps as many as 10% of all LGRBs).

In all of these merger scenarios, there are a number of important, unresolved issues. Even though a merger is likely to lead to a rapidly rotating object, angular momentum losses in the post-merger phase, e.g. due to stellar winds, are likely to spin-down the merged object. Significant spin-down can be avoided either if the metallicity is low, again reducing the stellar wind mass loss, or if the merger occurs very late in the evolution of the system (i.e. as a consequence of so-called case C mass transfer after the completion of helium burning). A second important issue is that, in most of the merger scenarios, the final product still has a significant amount of helium, which at face value is inconsistent with the fact that all supernovae associated with LGRBs to date show no evidence for helium. On the other hand, if the merger leads to a disc-like structure this would make it much easier for the relativistic jet producing the LGRB to escape from its surrounding envelope.

4. Explosive common-envelope ejection

A rather different route to a LGRB was discovered by N. Ivanova (Ivanova & Podsiadlowski 2003; Podsiadlowski et al. 2006) when studying the slow merger of two massive stars after helium core burning (i.e. involving case C mass transfer). This evolution occurs when mass transfer from a red supergiant to a less massive companion is unstable. This leads to a common-envelope phase, where the secondary spirals-in inside the envelope of the original supergiant. At some stage during this spiral-in, the immersed companion itself will fill its Roche lobe and start to transfer mass to the core of the supergiant (as illustrated in figure 1).

Most importantly, the stream emanating from the secondary, which initially is mainly composed of hydrogen-rich material, can penetrate deep into the helium core of the supergiant, eroding it in the process (Ivanova & Podsiadlowski 2003).

If the initial mass ratio of the binary is relatively large, it can happen that, at some point during the merging process, the H-rich material from the secondary is mixed into the hot helium-burning shell (with a temperature of a few $10^8$ K). This leads to a nuclear runaway and the rapid expansion and ultimately the ejection of the He-rich shell and with it of the total H-rich envelope. This mechanism of ‘explosive’ merging provides a new mechanism for ejecting a common envelope. Unlike the standard case (Paczynski 1976), where the ejection energy is orbital energy, the energy source here is nuclear energy. In order to eject the envelope in a typical case, only a few percent of a solar mass of H-rich material has to be burned, less than found in the actual calculations. Explosive common-envelope ejection provides a new mechanism for CE ejection that can operate even when the orbital energy is insufficient to eject the envelope otherwise. The stream penetrates particularly deep into the core when the entropy of the secondary is low. This favours relatively low-mass companions with masses less than approximately $3 M_\odot$. This has important implications for
the origin of short-period, black-hole binaries, including the case of Nova Scorpii, as discussed elsewhere (Podsiadlowski et al. 2006).

In the context of LGRBs, one implication is that this process predicts that both the hydrogen envelope and the helium-rich layer are ejected and that the final product is a pure CO core, consistent with the constraint that all LGRB-related supernovae are of Type Ic. Furthermore, the CO core is moderately spun-up in the phase where the stream interacts with the helium core (i.e. before the explosive phase). In our calculations, the final specific angular momentum of the core is approximately $10^{16}$ cm$^2$ s$^{-1}$, consistent with the angular-momentum requirement in the collapsar model.

We can roughly estimate the occurrence rate for this channel as

$$f = \frac{10^{-2} \text{ yr}^{-1}}{\text{cc SN rate}} \times \frac{10^{-1}}{\text{black hole}} \times \frac{10^{-2}}{\text{case C}} \times \frac{10^{-1}}{\text{mass ratio}} \sim 10^{-6} \text{yr}^{-1}.$$ 

Here, the first factor gives the overall core-collapse supernova rate, while the other factors are rough estimates of what fraction of binary systems produces black holes, experiences case C mass transfer and satisfies the mass-ratio constraint for explosive CE ejection. The main uncertainty in this estimate is the range for which case C mass transfer occurs, which will also depend on the metallicity. For lower metallicity the range for case C mass transfer is significantly increased. At extremely low metallicity, where massive stars only expand to red-supergiant dimensions after helium core burning, this factor can be larger by as much as a factor of 10.

Figure 1. Schematic illustration of the process of explosive common-envelope ejection. The H-rich stream from the Roche-lobe-filling immersed companion penetrates deep into the core of the primary, mixing hydrogen into the helium-burning shell. This leads to a thermonuclear runaway ejecting the helium shell and the hydrogen-rich envelope.
Finally, we note that the explosive CE channel predicts that the CE ejection occurred late in the evolution of the primary, less than $10^4$ years before the LGRB, and that the shell from the CE ejection event should still be relatively close (within less than approx. 1 lt year). Such a shell may be important for confining the Wolf–Rayet wind in the final pre-collapse phase of the CO star, producing a constant-density wind bubble, as has been deduced for a number of LGRB events.

5. Conclusion

While at the moment it is not clear which binary channel, if any, is the most important one for producing LGRBs, there are quite a few possible channels. Most of these occur with rates that are compatible, within the uncertainties, with the observationally inferred LGRB rate. However, not all of these channels will produce LGRBs. For example, it now seems that the tidal spin-up model, which in many respects is one of the simplest channels, is unlikely to produce LGRBs at solar metallicity. In fact, most binary models favour low-metallicity progenitors just as some of the single-star models proposed. One significant difference is that in single-star models, low metallicity (less than approx. 1/5 the solar value; Yoon et al. 2006) is a necessary requirement, while in many of the binary scenarios it is not necessary but helps to increase the LGRB rate. Finally, it is not even clear that there has to be a single evolutionary channel for LGRBs since there appear to be quite a few routes, involving both single and binary stellar evolution, that can satisfy some of the main constraints of the collapsar model. If there is more than one channel or if there are different channels dominating in different environments, this could also help to explain the observed diversity of LGRB events.

References


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