

A common envelope binary star origin of long gamma-ray bursts

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ABSTRACT

The stellar origin of γ -ray bursts can be explained by the rapid release of energy in a highly collimated, extremely relativistic jet. This in turn appears to require a rapidly spinning highly magnetized stellar core that collapses into a magnetic neutron star or a black hole within a relatively massive envelope. They appear to be associated with Type Ib/c supernovae but, with a birth rate of around 10^{-6} to 10^{-5} yr⁻¹ per galaxy, they are considerably rarer than such supernovae in general. To satisfy all these requirements we hypothesize a binary star model that ends with the merging of an oxygen/neon white dwarf with the carbon/oxygen core of a naked helium star during a common envelope phase of evolution. The rapid spin and high magnetic field are natural consequences of such a merging. The evolution that leads to these progenitors is convoluted and so naturally occurs only very rarely. To test the hypothesis we evolve a population of progenitors and find that the rate is as required. At low metallicity we calculate that a similar fraction of stars evolve to this point and so would expect the γ -ray burst rate to correlate with the star formation rate in any galaxy. This too is consistent with observations. These progenitors, being of intermediate mass, differ radically from the usually postulated high-mass stars. Thus we can reconcile observations that the bursts occur close to but not within massive star associations.

Key words: binaries: close – gamma-ray burst: general – stars: neutron – white dwarfs.

1 INTRODUCTION

There is now strong evidence that the long γ -ray bursts (LGRBs) are closely associated with young star-forming regions (Woosley & Bloom 2006). Recent high spatial resolution imaging of nearby LGRBs has shown that, while they are closely associated with clusters of Wolf–Rayet stars and of O stars, they tend also to be displaced somewhat from the centres of the clusters (Hammer et al. 2006). This gives further insights into their population characteristics.

The birth rate of LGRBs is estimated to be 10^{-6} to 10^{-5} yr⁻¹ per galaxy like our own when allowance is made for the uncertainties in the beaming angle of the γ -rays. This is 1000–10 000 times lower than the birth rate of Type II supernovae (SNe) (Fryer et al. 2007). The LGRBs in which optical afterglows have been detected tend in general to be about a 100 times more luminous than Type II SNe and this has led to the suggestion that they form a new class of SNe or hypernovae (Woosley 1993; Paczyński 1998). The association with young star clusters also places them in a class distinct from Type Ia SNe which are thermonuclear explosions of

degenerate white dwarfs. At the same time, there have been unambiguous identifications of a few LGRBs with Type Ib/c SNe which are characterized by hydrogen- or hydrogen- and helium-deficient ejecta.

Type Ib/c SNe are expected at the ends of the lives of massive stars that have lost much of their mass during Wolf–Rayet evolution so the evidence suggests that the LGRBs are linked in some way to the final stages of the evolution of very massive stellar cores as they collapse to black holes or neutron stars. The total energy, of about 10^{51} erg, released is not much greater than that released in core-collapse SNe. However, it differs in that the energy is released in γ -rays in the form of collimated jets. These properties have led to the suggestion that the LGRBs form a subset of core-collapse SNe which are distinguished by the magnetic fields present in the core that collapses to a black hole or a neutron star. These fields collimate the jet. In a popular model, the γ -ray jet is believed to be launched by the magnetohydrodynamic (MHD) extraction of the spin energy of a disrupted torus or a central rapidly spinning black hole (the collapsar model; Mészáros & Rees 1997).

The Lorentz factor Γ for GRB jets is about 400 (Lithwick & Sari 2001). This is in stark contrast to the velocities of other observed astrophysical jets. For non-relativistic jets, the jet velocities are

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typically only a few times the escape speeds from the central accreting objects (Price, Pringle & King 2003). For jets from active galactic nuclei (AGNs), where the central object is a supermassive black hole, jet velocities typically have Lorentz factors in the range $3 \leq \Gamma \leq 10$ (Giovannini et al. 2001) and occasionally slightly higher, perhaps as high as $\Gamma \approx 20$ (Giroletti et al. 2004; Hough 2008). Thus it is evident that something special must be going on in the engines which produce GRBs but is not occurring in the engines which produce most other astrophysical jets. To produce an astrophysical jet it is evident that a large amount of the available accretion energy must be given to a small fraction of the material and such a process is most easily accomplished by making use of magnetic fields. From numerical and analytic models it is also evident that the production of a strong jet requires the presence of strong rotation (usually in the form of an accretion disc flow) and a strong *poloidal* magnetic field (see e.g. Tchekhovskoy, McKinney & Narayan 2008; Komissarov & Barkov 2009; Lyubarsky 2009). A more complicated field structure tends to weaken jet production (Beckwith, Hawley & Krolik 2008).

In this regard the collapsar model (e.g. MacFadyen & Woosley 1999; Woosley & Bloom 2006) which involves the collapse of a strongly magnetic rotating stellar core is the most promising. Rotation ensures that the collapse is slowed, so that for the case of collapse to a black hole maximum energy extraction is possible, and an accretion disc forms, so that the geometry is conducive to jet formation. In addition, because the accretion rate is so high (compared for example to AGN discs), being in the range of $0.1 \leq \dot{M}/M_{\odot} \text{ s}^{-1} \leq 10$ the disc is geometrically thick (thickness H is comparable to radius R) and advection dominated (Di Matteo, Perna & Narayan 2002). This means that, in contrast to AGN discs which are geometrically thin at least in their outer regions and so require field generation by local dynamo action, a poloidal magnetic field already present in the infalling material can be dragged inwards (Lubow, Papaloizou & Pringle 1994) and thus compressed and strengthened. In the centre of such a flow a compact object is likely to form either a magnetar, a highly magnetic neutron star or a black hole. Subsequent to the formation it is then possible to extract the rotational energy of such objects, for black holes through the Blandford–Znajek mechanism (e.g. Livio, Ogilvie & Pringle 1999; Komissarov & Barkov 2009, for discussion) and for neutron stars as magnetars.

Thus it is possible that a strongly magnetic rapidly spinning neutron star (the magnetar model; Usov 1992; Kluźniak & Ruderman 1998; Spruit 1999) accelerates and collimates the jets. This model requires as essential ingredients magnetic fields of about 10^{15} G and rotation periods of a few milliseconds to explain the observed release of some 10^{52} erg on the time-scales of about 10 s which are characteristic of the LGRBs. Whether such end products result from cores that collapse in the course of merging with another star (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999) or whether they are the result of peculiar stellar evolution to an anomalously rapid rotation of a progenitor star as a consequence of low metallicity (Yoon & Langer 2005; Woosley & Heger 2006) remains an open question.

The need for a binary companion, particularly to generate the rapid spin of the collapsed core immediately after formation, was pointed out by Izzard et al. (2004) but has rather been put to one side in favour of rapidly spinning low-metallicity massive single stars. However, Podsiadlowski et al. (2004), noting the link with hypernovae, reinforced the need for a binary companion. Fryer & Heger (2005) argued that the collapsar model requires two massive stars of very similar mass.

Here we propose a new binary scenario that differs radically in that the stars are of intermediate mass. As single stars these would not undergo a SN explosion at all but end their lives as carbon/oxygen (CO) or oxygen/neon (ONe) white dwarfs. It is their duplicity, so that the two cores can be merged, which allows the SN explosion to take place. This model differs from the exposed accretion induced collapse discussed by Yi & Blackman (1997) because the collapse follows the merging of two cores within a common envelope phase of evolution. This has two important consequences. First, there is mounting evidence that white dwarfs which merge during common envelope evolution develop the strongest magnetic fields found in white dwarfs (Tout et al. 2008) so that these collapsing cores are highly magnetic. Secondly, the remaining envelope, which must be hydrogen free in this case, allows for the associated Ib/c SN.

2 PROBLEMS WITH CURRENT MASSIVE STAR MODELS

One possibility, which has been aired, is that the LGRB phenomenon only occurs in the small subset of massive stars that are born rapidly rotating and hence evolve to produce rapidly rotating remnants. However, a rapidly spinning pre-collapse stellar core can also be expected to generate a strong magnetic field by a dynamo mechanism. This would brake its rotation by the transfer of angular momentum to the outer envelope that is mostly lost during the Wolf–Rayet phase prior to its collapse to a neutron star or a black hole. Thus, if strong fields are required, the end product is likely to be a slowly rotating stellar remnant, whether it be a neutron star or a black hole. There is also the question of whether fields that are strong enough to yield the very high-field (10^{15} G) neutron stars when compressed can be generated in a pre-collapse core during the evolution of a single star (Duncan & Thompson 1992).

The above conclusions are borne out by detailed stellar evolution calculations of medium and high-mass stars that lead to the formation of neutron stars and black holes. These calculations, which allow for the generation of small-scale magnetic fields by various instabilities, such as the magnetorotational (Spruit 2002), in differentially rotating radiative regions but not for dynamo generated fields in convective regions, show that angular momentum is effectively transported away from the core by magnetic stresses (Heger, Woosley & Spruit 2005). The end product is typically a slowly rotating neutron star with a birth magnetic field of 10^{12} G and spin period of 0.1 s similar to a normal pulsar.

Single stars do not generally spin fast enough, so that the postulated rapid spin is likely to have involved a binary interaction (Izzard et al. 2004). Another possibility that has been considered is that the progenitor star is both rapidly rotating and metal deficient. At low metallicity wind mass loss is suppressed and this leads to enhanced mixing so that the red giant phase is not as pronounced. Strongly magnetic and rapidly spinning end products then become a possibility (Woosley & Heger 2006). However, although observations do show that LGRBs tend to occur preferentially in low-metallicity galaxies, they do not exclusively occur in such galaxies (Sollerman et al. 2005). Indeed Savaglio (2010) finds that the GRB rate in a given galaxy simply reflects the star formation rate in that galaxy. So a more general mechanism which is not entirely dependent on metal abundance appears to be required. Moreover, there remains the problem that any single-star model is likely to overproduce LGRBs unless they can be restricted to a very small progenitor mass range.

Evidence that LGRBs tend to be displaced by 400–800 pc from star-forming regions (Hammer et al. 2006) also poses problems for single-star models. In an attempt to explain the above observations it has been proposed that an even more massive companion was able to spin up the progenitor before exploding itself and ejecting the rapidly spinning Wolf–Rayet star at high velocity from its birthplace. Even if the lone Wolf–Rayet star does not spin down because its wind is weak at its low metallicity, we might ask why exactly the first star, which would also have been spun up, would not have generated a burst itself.

Those invoking binary star models have also concentrated on massive progenitors. Fryer & Heger (2005) examine merging helium cores during a common envelope phase. These have the advantage of generating high spin rates in the collapsing cores and so are very promising. However, they require two very massive stars of similar mass and the evolution to the point of burst is very rapid. They would therefore be expected to occur close to the centroids of star-forming regions which appears to be inconsistent with observations. Alternatively Cantiello et al. (2007) invoke accretion from a more massive companion as necessary to spin up the Wolf–Rayet star while it is still on the main sequence. They argue that it does not subsequently tidally spin down as the orbit widens or as it loses mass. They further use a SN explosion and kick in the originally more massive companion to account for the apparent runaway nature of the Wolf–Rayet progenitor.

Thus it would seem that the general consensus is that the immediate progenitor of a GRB must be compact, either a neutron star or black hole, rapidly spinning, with a period of less than a few milliseconds and be associated with a very strong, 10^{15} G, magnetic field. The association with Type Ib/c SNe further requires that the progenitor be at the core of a naked helium or even more processed envelope.

3 AN INTERMEDIATE-MASS BINARY STAR SCENARIO

In order to form close binary stars with compact components it is necessary to pass through a common envelope phase of evolution (Paczynski 1976). Unstable mass transfer from a giant star that expands as it loses mass to a more compact star leads to a common giant-like envelope around two cores, the giant’s own degenerate core and the compact companion. Friction between the orbit of the cores and the envelope causes the cores to spiral together and the envelope to unbind. Tout et al. (2008) have demonstrated that the highest magnetic fields, of more than 10^9 G, are most likely generated in common envelope evolution when the two cores merge before the envelope is ejected. In the scenario which we propose here, the CO core of a naked helium giant merges with an ONe white dwarf in a final helium common envelope. The CO core acquires a very high magnetic field from the common envelope, is tidally broken up and accretes on to the ONe white dwarf carrying the magnetic field with it. On reaching the Chandrasekhar mass the ONe white dwarf undergoes accretion induced collapse to a neutron star. By conserving its magnetic flux it acquires a large-scale surface field of 10^{15} G. Both the contraction and the accretion of high angular momentum material ensure that it is rapidly spinning and the conditions are ripe to launch the relativistic jets required to drive the GRB.

However, the volume of parameter space which can give rise to this GRB progenitor is not large and this can account for the scarcity of LGRBs. A typical system that leads to such a progenitor begins life as a relatively wide binary system with a 6 and an

$8 M_{\odot}$ star, both on the main sequence, and an orbital separation of $1000 R_{\odot}$. The $8 M_{\odot}$ star evolves through hydrogen, helium and carbon core burning to a super-AGB star with an ONe core and then fills its Roche lobe for the first time. A first phase of common envelope evolution ensues and results in a mild shrinkage of the orbit and loss of the envelope to leave a massive ONe white dwarf, of about $1.4 M_{\odot}$ with the $6 M_{\odot}$ companion at $160 M_{\odot}$. Subsequently the $6 M_{\odot}$ star evolves to the early red giant branch and fills its Roche lobe. A second common envelope phase removes its hydrogen envelope to leave a $1.3 M_{\odot}$ naked helium star in a close orbit with the ONe white dwarf at $1.4 M_{\odot}$. The naked helium star develops a CO core, evolves to a giant and fills its Roche lobe for the second time. The third and final common envelope phase builds up the very strong magnetic field and causes the CO core to merge with the ONe white dwarf which collapses to a rapidly spinning neutron star and launches the relativistic jet in the process. The remainder of the CO core accretes on to the neutron star at such a high rate that carbon ignites and runaway thermonuclear reactions generate the ^{56}Ni in strong winds that can drive off any remaining helium envelope and power the Type Ib/c SN (Woosley & Bloom 2006).

The central engine of our GRB is the accretion induced collapse of a highly magnetic, rapidly spinning white dwarf and so is similar to that discussed by Yi & Blackman (1997). Fryer et al. (1999) modelled a non-magnetic collapse in two dimensions and deduced that jets would be too weak, because there would be too much material in the jet, unless highly beamed. Dessart et al. (2007) included MHDs in similar two-dimensional collapse calculations and in one model, with a large initial magnetic field, produced a jet with enough energy to power a GRB but still with too much material in the jet to be accelerated to the required velocity. This is often called the baryon loading problem. Other numerical simulations, even those that examine accretion on to black holes such as those by Porth & Fendt (2010), have similar problems. However, jet production and collimation is still far from fully understood (Lyubarsky 2010; Komissarov, Vlahakis & Königl 2010) and so we regard these models as promising rather than as creating an insurmountable problem with this scenario.

4 ESTIMATED GAMMA-RAY BURST RATES

To estimate the rate at which such systems would give rise to LGRBs we have carried out binary population synthesis with the code developed by Hurley, Tout & Pols (2002). Their standard prescription for common envelope evolution is included. Their α_{CE} parameter, the efficiency of transferring orbital energy to the envelope during common envelope evolution, is set to 1. Though this parameter is very uncertain, we do not investigate its effects in detail because the observed GRB rate is even more uncertain.

At solar metallicity, $Z = 0.02$, the range of possible initial separations that lead to the described systems is narrow. Their initial separations are mostly around $1000 \pm 25 R_{\odot}$. The precise range depends on the component masses of the system. If the system is too wide then either the third common envelope phase or the merging event is avoided. If the system is too close the ONe white dwarf accretes enough material to collapse to a neutron star before the common envelope forms. The actual distribution of initial periods of binary stars is not well known. A common practice is to assume the separation is uniform in logarithmic space (Eggleton, Fitchett & Tout 1989). With this assumption, only about 5 to 6×10^{-3} of systems have suitable initial separations. A second requirement is that one component must be massive enough to develop an ONe

core. To do so its core must ignite carbon gently before reaching the Chandrasekhar limit and become a super-asymptotic giant branch (SAGB) star. The mass boundaries for SAGB stars are not clear cut and depend on different assumptions for convective overshooting (Poelarends et al. 2008). The models used to construct the formulae used by Hurley et al. (2002) include overshooting and hence give SAGB stars from initial masses $6.4\text{--}8.1 M_{\odot}$. The fraction of SAGB stars is then around 10^{-2} for a Kroupa, Tout & Gilmore (1993) initial mass function (IMF). The secondary must then be within a suitable mass range for merging to take place. This range is less restricted than that for the separations. For most of the systems that lead to a GRB, the mass ratio q is between 0.6 and 0.85. For a flat distribution of mass ratio about 25 per cent of the binary systems fall within this range. There are also suitable systems with lower q but the range of suitable separations for these is much narrower. Our binary population synthesis shows that the fraction of binary systems with at least one component of initial mass above $0.8 M_{\odot}$ that evolve to give a GRB is of the order of 10^{-5} . Typically one such binary system is formed in our own Galaxy each year so this agrees well with the observed rarity of GRBs.

Table 1 lists the fractional rates for different metallicity populations of binary stars. As metallicity decreases our estimated rate does not vary very much. At a metallicity of $Z = 10^{-4}$ the frequency remains about the same for the same star formation rate and IMF. The suitable initial primary mass shifts to $5.1 < M_1/M_{\odot} < 6.8$ for an SAGB star in this lower metallicity environment, so the frequency of suitable initial primary mass increases even if the IMF is unchanged. However, some of the low- q systems can no longer produce GRBs because the total mass of the system when it merges is too low to trigger the accretion induced collapse. Almost all the suitable systems have q greater than 0.6. These two effects at lower metallicity balance each other out and hence the fraction of binary systems that lead to bursts remains of the order of 10^{-5} . A different q distribution which favoured the high q systems or a shift in the IMF towards intermediate-mass stars would cause the frequency of GRBs to increase at low metallicity. Otherwise, our scenario shows that the GRB rate does not have a high dependence on metallicity. This would explain the observational deduction of Savaglio (2010) that the burst rate is proportional to the star formation rate alone.

Fryer et al. (1999) raised concerns about the amount of neutron-rich ejecta from accretion induced collapse events polluting the Galaxy. Observed abundances of r -process isotopes place a rather low limit on the rate of the events they model. Dessart et al. (2007) agree and place a limiting rate of about 10^{-6} yr^{-1} on their partic-

ular highly magnetic collapses, rising to $5 \times 10^{-5} \text{ yr}^{-1}$ for their less magnetic cases. Given the uncertainties in the models this is consistent with our GRB rate. However, we note that the accretion induced collapse events considered here, because they take place within a hydrogen-free common envelope, are a rather special subset of all such events. Indeed the total rate predicted in population synthesis calculations by Hurley et al. (2002), of at least 10^{-4} yr^{-1} suggests that the amount of neutron-rich material ejected by accretion induced collapse of white dwarfs in general must be somewhat smaller than found by Fryer et al. (1999) and Dessart et al. (2007).

5 DISCUSSION

In the scenario outlined above, the properties of the stellar cores which eventually merge to give rise to a LGRB can differ from one another in a number of respects. First, the amount of helium envelope remaining at the time the cores merge can vary from several solar masses to very little. Secondly, the mass of both cores can vary as long as enough of the CO core can be accreted to drive the collapse of the ONe core. There is then a range from zero to about a solar mass of CO that can accrete on to the neutron star. Some of this can burn and be ejected in a disc wind to provide the varying quantities of ^{56}Ni seen in the associated SNe. These range from the very powerful, with as much as half a solar mass of nickel-56, to very weak, with almost no nickel-56 (Mazzali et al. 2003; Watson et al. 2007).

We can also estimate the time required for the initial binary system to evolve to the GRB. At a metallicity of $Z = 10^{-4}$, the age of a typical system is around 100–150 Myr. This gives the upper limit to the redshift of the earliest GRB of $z \approx 20$ and we should expect to see bursts back to this redshift. This is a prediction of our model.

Strongly magnetic neutron stars (magnetars) have been identified in our Galaxy as anomalous X-ray pulsars (AXPs) or soft γ -ray repeaters (SGRs; Mereghetti 2008). These are observed to have magnetic fields of $10^{14}\text{--}10^{15} \text{ G}$ and spin periods of 2–10 s. Known magnetars have ages of $10^3\text{--}10^4 \text{ yr}$ and it is unclear whether they have spun down or were born slowly rotating. With estimated birth rates of 10^{-3} yr^{-1} they are unlikely to all be related to the LGRBs. Magnetars could therefore be of two types, those that are born from single-star evolution and those that form from the merging of the cores of two stars as proposed here. As for the radio pulsars, the fields in the first group are likely to be generated by a dynamo mechanism in the stellar core that subsequently collapses to form the neutron star. Strong magnetic coupling with the stellar envelope leads to outward transport of angular momentum during stellar evolution and results in a slowly rotating neutron star following core collapse. Magnetars that are born by the merging of the cores of two stars are, on the other hand, likely to be born rapidly spinning with high fields and so give rise to LGRBs.

6 CONCLUSIONS

The γ -ray jets seen in the LGRBs have been attributed to MHD extraction of the rotational energy of a neutron star or black hole, or of a massive, about $0.1 M_{\odot}$, unstable disc that is accreted by the compact star at the time of its birth. The combination of super strong magnetic fields and millisecond spin periods that appear to be required to explain the energetics and collimation of the γ -ray jet cannot easily be produced in the stellar remnant through single-star evolution. Nor does it appear likely that single-star evolution could

Table 1. The fraction of binary systems f with at least one component of mass $0.8 M_{\odot}$ that evolve to produce a γ -ray burst for various metallicities Z . For our Galaxy, at solar metallicity this fraction is numerically equal to the rate per year.

Z	f
0.03	4.2×10^{-5}
0.02	4.2×10^{-5}
0.01	3.7×10^{-5}
0.001	1.9×10^{-5}
0.0001	2.5×10^{-5}

lead to a rapidly spinning disc around the compact star that could generate the field required to produce the MHD jet.

We have argued that the required strong fields and rapid spins may occur more naturally in binary star scenarios where merged stellar cores collapse to form neutron stars or black holes and have presented a convoluted but still simple binary star origin for GRBs in which the progenitors are intermediate-mass stars and the collapsed star is a strongly magnetic neutron star. This differs radically from previous proposals that have envisaged massive stars as the progenitors.

Our model predicts a birth rate of a few $\times 10^{-5}$ yr $^{-1}$ per galaxy at solar metallicity. The fraction of binary stars that lead to GRBs does not vary much with metallicity in our model. Thus we expect the rate of GRBs to be proportional to the star formation rate for a wide range of redshifts. We expect that the LGRBs should have characteristics of an intermediate-mass population and need only be loosely linked to young star-forming regions. Recent high-resolution imaging of nearby LGRBs appears to support this requirement. The estimated time interval between the time of formation of the component stars and the final collapse to a neutron star is about 100 Myr so that LGRBs produced by this channel should be seen up to red shifts of $z \approx 20$.

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