Gamma–ray Burst Models

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I consider various possibilities for making gamma–ray bursts, particularly from close binaries. In addition to the much–studied neutron star + neutron star and black hole + neutron star cases usually considered good candidates for short–duration bursts, there are other possibilities. In particular neutron star + massive white dwarf has several desirable features. These systems are likely to produce long–duration GRBs, in some cases definitely without an accompanying supernova, as observed recently. This class of burst would have a strong correlation with star formation, and occur close to the host galaxy. However rare members of the class need not be near star–forming regions, and could have any type of host galaxy. Thus a long–duration burst far from any star–forming region would also be a signature of this class. Estimates based on the existence of a known progenitor suggest that this type of GRB may be quite common, in agreement with the fact that the absence of a supernova can only be established in nearby bursts.

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1. Introduction

Accretion on to a black hole or neutron star is the most efficient way of extracting energy from normal matter. Since GRBs are briefly the brightest objects in the Universe, accretion on to one or other of these objects must be involved in making them. Constructing GRB models then becomes a matter of arranging that a suitable mass falls on to the accretor on the right timescale.

The total emitted energy of GRBs implies that a significant fraction of a stellar mass is involved. Since we want the burst to be sudden, we presumably have to start with some equilibrium situation involving a stellar mass, and destabilize it. Observations again tell us the infall timescale is, at least initially, extremely short. This suggests that we can pick out potential stellar reservoirs by considering their dynamical timescales.

In the collapsar picture a rapidly–rotating massive star is both accretor and reservoir. During core collapse the central regions try to form a black hole, while the rest of the core accretes on to it and makes the burst. The dynamical timescale of the core suggests that this produces a long–duration burst.

The other generic situation in which a star is disrupted on a very short timescale is in a close binary. In the rest of this paper I shall consider the various possibilities in turn.
2. Binary models for GRBs

The reasoning of the last section implies that the accretor (star 1) in any binary GRB model must be a neutron star or black hole. There are various possibilities for the reservoir or donor (star 2), which largely determine the timescale of the GRB. For simplicity I assume that the binary orbit is circular and the stars corotate with it (things are similar even if these assumptions fail). Then Roche geometry shows that mass transfer obeys the relation

\[ \frac{M_2}{M_2} = \frac{1}{D} \frac{\dot{J}}{J}. \]  

(For derivations of the relations in this Section see e.g. the review by King (1988)). Here \( J \) is the orbital angular momentum, and the main external driven of angular momentum loss \( \dot{J} < 0 \) is by gravitational radiation (see below). The quantity \( D \) is given by

\[ D = \frac{5}{6} + \frac{\zeta}{2} - \frac{M_2}{M_1}, \]

where \( \zeta \) is the mass–radius index of star 2, i.e. this behaves as \( R_2 \propto M_2^{\zeta} \) during mass transfer. If for example star 2 is a low–mass white dwarf, we have \( \zeta = -1/3 \) and the star expands as it loses mass. The importance of \( D \) is that its sign gives the sign of \( \dot{R}_L - \dot{R}_2 \), i.e. the relative motion of the Roche lobe (determined by the orbital evolution as mass is exchanged, i.e. on a dynamical timescale) and the stellar radius (determined by its response to mass loss).

Generally \( D \) is \( O(1) \). If it is positive (called stable mass transfer) we have

\[ \frac{M_2}{M_2} \sim \frac{\dot{J}}{J}, \]

i.e. mass transfer on the angular momentum loss timescale \( t_J = |J/\dot{J}| \), which for gravitational radiation is

\[ t_{GR} = \frac{5 \cdot \zeta^5}{32 G^5 M_1 M_2 (M_1 + M_2)} a^4, \]

where \( a \) is the orbital separation. Now since star 2 fills its Roche lobe its radius is comparable to the orbit, i.e. \( R_2 \sim a \text{ few} \), and so

\[ t_{GR} \sim 10^{10} \left( \frac{R_2}{R_{MS}} \right)^4 \text{ yr} \]

where the stellar radius \( R_2 \) is scaled in terms of the main–sequence value \( R_{MS} \). We immediately find that \( t_{GR} \sim \text{ few } \times 100 \text{ yr} \) for a white dwarf donor, and \( t_{GR} \sim 10^{-3} \text{ s} \) for a neutron–star donor.

Thus even stable mass transfer from a neutron–star donor produces mass flow rates of a suitable order to explain some gamma–ray bursts. The dynamical timescale (by Roche geometry very close to the orbital period \( P \)) for the donor is also milliseconds. We conclude that NS + NS and BH + NS binaries are candidates for producing short–duration GRBs.
3. Dynamical instability

However stable mass transfer from a neutron–star donor is not the only possibility for making GRBs from close binaries. In some cases instead of the stable evolution with \( D > 0 \) seen above we have \( D < 0 \). This means that the Roche lobe cuts into the star on a dynamical timescale. This is clearly an unstable feedback process, and the mass transfer rate tries to increase towards the value

\[
M_{\text{dyn}} \sim \frac{M_2}{P}.
\]  

This is evidently a promising situation for making a GRB. There are essentially three ways it can come about.

(a) Violently expanding donor

If \( \zeta < -\frac{5}{3} \), i.e. the donor expands strong on mass loss, eqn (2.2) shows we have \( D < 0 \) for any mass ratio \( M_2/M_1 \). An example where this may occur is when a neutron star is reduced by mass transfer to a mass where it wants to become a white dwarf, typically about \( 0.2M_\odot \). This effect may lead to late flares in a BH + NS binary GRB (Davies et al., 2005), which would have short duration.

(b) Very rapid mass transfer

The expression (2.2) for \( D \) assumes that tides acting within the binary feed back all the angular momentum of the transferred mass to the donor star. However it is quite likely that this assumption fails once mass transfer becomes rapid, simply because the tides cannot cope. In this situation the expression for \( D \) gets an extra term

\[
D = \frac{5}{6} + \frac{\zeta}{2} - \frac{M_2}{M_1} - \nu
\]  

(e.g. King & Kolb, 1995) with \( \nu = O(1) > 0 \). This obviously allows the possibility that \( D < 0 \). This means that even mass transfer from white dwarf donors can become unstable and produce a GRB, and the mass transfer timescale \( \sim 100 \text{ yr} \) is much shorter than the likely tidal time. Since the white dwarf has a dynamical time of \( \sim 10 \text{ s} \), this would be a long–duration GRB.

(c) Large mass ratio

For a white dwarf we have \( \zeta = -\frac{1}{3} \) so

\[
D = \frac{2}{3} - \frac{M_2}{M_1},
\]  

so mass transfer is dynamically unstable for mass ratios > \( \frac{2}{3} \). Since for a white dwarf we must have \( M_2 < 1.4M_\odot \) (the Chandrasekhar mass), \( D < 0 \) requires \( M_1 < 2.1M_\odot \), so the most likely case is with a neutron–star primary. If \( M_1 = 1.4M_\odot \), as is often found for neutron stars, instability requires \( M_2 > 0.9M_\odot \). We see that NS + massive WD is a good candidate for producing long–duration GRBs.

Before turning to these systems, two remarks are in order. First, some binaries may be unstable in more than one of the ways described above. For example NS +
NS binaries are unstable in all three ways (cf. Rosswog et al., 2003; 2004). Second, it is important to remember that dynamical instability means that the donor star is no longer a star. Intuition based on the few-body problem may be a poor guide to what happens, and a full fluid dynamical calculation is required.

4. GRBs from NS + massive WD

In the last subsection I showed that a NS+WD binary with \( M_2/M_1 > 2/3 \) is a good candidate for producing long-duration GRBs. Here I mention a few desirable properties of these systems. A full paper will be submitted for publication shortly.

First, such systems exist. The most promising object is PSR J1141–6545 (Kaspi et al., 2000) which has a 5 hr orbit and will merge in about \( 10^9 \) yr under the effect of gravitational radiation. Because the orbit is relativistic, limits on the masses are known to great precision (Bailes et al., 2003) as \( M_{\text{wd}} = 0.986 \pm 0.2 M_\odot \) and \( M_{\text{ns}} = 1.30 \pm 0.2 M_\odot \). This firmly establishes the mass ratio as \( M_{\text{wd}}/M_{\text{ns}} > 0.73 \), making dynamical instability and a GRB inevitable. There is an evolutionary scheme for them (Davies et al., 2002), which begins with two main-sequence stars very close in mass. The more massive evolves first and leaves a massive WD, transferring its envelope to the companion, which then becomes more massive than the primary was, and indeed massive enough to make a neutron star. Davies et al. (2002) show that the Milky Way birthrate is \( 5 \times 10^{-5} - 5 \times 10^{-4} \) yr\(^{-1} \), and that more than half of these systems merge within \( 10^8 \) yr. This means that they will tend to show some association with star formation, although a tail of sparser systems will not. Their space velocities are not high in general (Davies et al., 2002), so many will be found close to their hosts.

Clearly these systems would produce long-duration bursts. In at least some cases (if the WD is massive enough to have ONeMg composition) they are unlikely to produce a supernova. This may be an explanation for the recent GRB 060614, which was a long-duration burst where any supernova was at least 100 times fainter than any observed. Although as a population NS + massive WD bursts follow the star-formation history of their hosts, a long-duration burst from a galaxy devoid of recent star formation is possible. Observation of such a burst would thus be very interesting.

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