Gamma-ray burst engine activity within the quark nova scenario: prompt emission, X-ray plateau and sharp drop-off

Jan Staff,1⋆ Brian Niebergal2 and Rachid Ouyed2
1Department of Physics, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907-2036, USA
2Department of Physics and Astronomy, University of Calgary, 2500 University Drive NW, Calgary, Canada AB T2N 1N4

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ABSTRACT
Extending the three-stage model for long GRB inner engines suggested by Staff, Ouyed & Bagchi, we interpret recent Swift satellite observations of early X-ray afterglow plateaus followed by a sharp drop-off or a shallow power-law decay. The three stages involve a neutron star phase, a quark star (QS) and a black hole phase. We find that the QS stage allows for more energy to be extracted from neutron star to QS conversion as well as from ensuing accretion on to the QS. The QS accretion phase naturally extends the engine activity and can account for both the prompt emission and irregular early X-ray afterglow activity. Following the accretion phase, the QS can spin down by emission of a baryon-free outflow. The magnetar-like magnetic field strengths resulting from the NS to QS transition provide enough spin-down energy, for the correct amount of time, to account for the plateau in the X-ray afterglow. In our model, a sharp drop-off following the plateau occurs when the QS collapses to a BH during the spin-down, thus shutting off the secondary outflow. We applied our model to GRB 070110 and GRB 060607A and found that we can consistently account for the energetics and duration during the prompt and plateau phases.

Key words: stars: evolution – gamma-rays: bursts.

1 INTRODUCTION
Observations of gamma-ray bursts (GRBs) by the Swift satellite (Gehrels et al. 2004) have revealed that many GRBs show a flat segment in their early X-ray afterglow. This flat segment is often observed to start after about 10^3 s, and lasts up to 10^7 s. Following the plateau, some afterglows decay following a power law with a modest power of about −1 to −2. However, in some cases a very sharp drop-off succeeds the plateau.

In the literature, there are mainly two different explanations for the flattening that have been proposed. (i) The refreshed shocks explanation (Rees & Mészáros 1998), where slower shells ejected during the prompt engine phase catch up with the external shock and refresh it. The plateau is then followed by a shallow decay of power index −1 to −2 from the cooling of the external shock once the shells stop hitting it. (ii) Extended engine activity in the form of a secondary outflow (see e.g. Pannarale 2008). The secondary outflow explanation requires that the engine is active for longer than previously expected, and so if the engine in fact turns off at a later time it can provide an explanation for the flattening and the sharp drop-off in the observed light curve.1

In this paper, we propose an engine that can last long enough to explain the energetics and the duration of the prompt emission and the flat segment in the X-ray afterglow, in particular those light curves showing a flat segment followed by a steep decay. Refreshed shocks (Rees & Mészáros 1998) may still explain the flat segment in some afterglows, but that mechanism faces difficulties explaining afterglows with a sharp drop-off. Here, we show that flattening might also be related to an outflow from spin-down (magnetic braking) of a rapidly rotating, crustless quark star (QS) in the colour–flavour locked (CFL; Rajagopal & Wilczek 2001) phase. This outflow is ejected following a primary outflow created during accretion on to the QS (the GRB inner engine in our model). This secondary outflow leads to the observed flattening, while the sharp drop-off we argue is a consequence of the cessation of the secondary outflow from the transition of the QS to a black hole (BH).

In a previous paper (Staff, Ouyed & Bagchi 2007, hereafter SOB07), a three-stage model for long GRBs was suggested,

⋆E-mail: jstaff@purdue.edu

1 A secondary outflow might also provide an alternative explanation for flaring, as suggested in Panaitescu (2008). We will investigate flaring within our model in an upcoming paper while here we focus specifically on flattening.
involving a neutron star (NS) phase, followed by a QS phase and a plausible third stage that occurs when the QS accretes enough material to become a BH.

The advantages of our model are that, by including a QS phase, we can account for both energy and duration of the prompt emission, X-ray flaring and the flattening. We first describe this model briefly in Section 2 (see SOB07 for details). This paper focuses specifically on the sharp drop-off or shallow decay observed following flattening within the three-stage model described in SOB07. In particular we show how features inherent to the QS stage can account for the drop-off. We discuss this further in Section 3, and illustrate our model application to GRB 070110 and GRB 060607A in Section 4. Finally we summarize and conclude in Section 5.

2 THE THREE STAGES

The three stages of the GRB engine described in SOB07 are as follows.

Stage 1 is a (proto-)NS phase, the NS being born in the collapse of the iron core in an initially massive star. This NS can collapse to a QS, either by spin-down (Staff, Ouyed & Jaikumar 2006) or through accreting material, thereby increasing its central density sufficiently that it can form strange quark matter. We suggested that this stage could lead to a delay between the core collapse and the GRB. The collapse into a QS, in a quark nova (QN; Ouyed et al. 2002; Keränen, Ouyed & Jaikumar 2005), releases up to $10^{53}$ erg that might help power the explosion of the star. This can possibly explain why supernovae associated with GRBs are often very energetic (see Leahy & Ouyed 2008; Ouyed et al. 2007). If a QS is formed directly in the core collapse, stage 1 will be bypassed and the process starts from stage 2.

Stage 2 is accretion on to the QS from a hyperaccreting debris disc, formed from leftover material during the collapse of the progenitor. This launches a highly variable ultrarelativistic jet, in which internal shocks can give rise to the gamma radiation seen in a GRB (Ouyed, Rapp & Vogt 2005a). The duration of this jet must be at least as long as the observed prompt emission. It can be longer, provided that the later part of the jet does not produce significant gamma radiation. This jet will eventually interact with the surrounding medium creating an external shock that gives rise to the GRB afterglow. The afterglow light curve would follow a power law $F_t \sim t^{-1.5-2}$ (Sari, Piran & Narayan 1998). However, slower shells can catch up with the external shock at later times and refresh it. This can lead to a flat segment in the X-ray afterglow (e.g. Rees & Mészáros 1998) which is commonly seen in GRB afterglows (O’Brien et al. 2006; Liang, Zhang & Zhang 2007).

A different mechanism for explaining flattening occurs if the QS survives the accretion stage (i.e. the accretion disc cannot provide sufficient mass to drive the QS over its maximum mass limit). The subsequent magnetic spin-down of the QS can launch a pair wind that we show might explain the flat segment in our model (Section 3.2).

Stage 3, which occurs if the QS accreted sufficiently that it collapsed to a BH, is accretion on to the BH which launches another ultrarelativistic jet, as described in De Villiers, Staff & Ouyed (2005). Interaction between this jet and the QS jet or internal shocks in the BH jet itself can give rise to flaring commonly seen in the X-ray afterglow of GRBs. The BH jet has the potential to be very powerful, so if it catches up with the external shock a bump might be seen in the light curve. The relevant features and emission have been discussed in details in SOB07.

3 PROMPT EMISSION, X-RAY PLATEAU AND SHARP DROP-OFF

In our model the prompt emission is produced by internal shocks in a QS jet launched by hyperaccretion on to a QS (Ouyed et al. 2005a). In this section we will first explain that for the accreting material to be channelled to the polar cap region, this requires a very high magnetic field. If the QS survives the accretion and is rapidly rotating, this magnetic field can then spin the QS down. We will show that a similarly strong magnetic field is what is needed to get the right spin-down time to explain the observed flattening.

3.1 Prompt emission

The prompt gamma-ray emission corresponds to synchrotron emission by electrons accelerated in internal shocks in the QS jet. This jet forms an external shock upon interacting with the surrounding medium, and synchrotron emission from this external shock is responsible for the afterglow.

In order to explain the energy observed in the prompt gamma radiation, SOB07 found that the accretion rate on to the QS must be of the order of $\dot{m} \sim 10^{-3}$ to $10^{-2} \, M_\odot \, s^{-1}$. In order to create a jet, the accretion has to be channelled on to the polar cap. This can occur if the magnetic radius (the distance from the centre of the star where the ram pressure equals the magnetic pressure) is at least twice the radius of the star. The magnetic radius is given by (Ouyed et al. 2005b)

$$ R_{\text{mag}} = \left( \frac{B^2 R^6}{2 \pi \sqrt{2GM}} \right)^{2/7}, $$

where $G$ is the gravitational constant and $R_{\text{QS}}$ is the radius of the QS. With the before mentioned accretion rate, a magnetic field of the order of $B \sim 10^{14}$–$10^{15}$ G is required. It should be noted that this QS jet is much different from the typical magnetohydrodynamics (MHD) disc wind jets. A QS jet is created as the accreting material reaches the surface of the QS, and it is converted into CFL quark matter, resulting in the creation of a hot spot due to the release of excess binding energy. This region cools by emitting photons, which collide with subsequent accreting material, resulting in the ejection of material with high Lorentz factors (for details, see Ouyed et al. 2005a). For completeness, we note that the jet might not be launched immediately following the formation of the QS. For example, with such a strong magnetic field, or if it is born spinning very fast ($P < 2$ ms), the QS could be born in a propeller regime in which case we expect a delay between the formation of the QS and the launching of the jet; the QS has to spin-down for accretion to ensue.

3.2 Flattening

Panaitescu (2008) suggested that an outflow, ejected by the engine after the initial blast, can scatter the forward-shock synchrotron emission and thereby produce flux that will outshine the primary one, especially if the outflow is nearly baryon free and highly relativistic. This reflected flux can produce certain light-curve features

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2 Recent work shows that $10^{15}$ G magnetic fields can readily be obtained during QS formation due to the response of quarks to the spontaneous magnetization of the gluons (e.g. Iwazaki 2005, and references therein).

3 An alternative model for generating the radiation in a secondary, highly magnetized outflow is magnetic reconnection or dissipation processes as was proposed by Uskov (1994, for the prompt emission) and Gao & Fan (2006, for the afterglow).
such as flares, plateaus and chromatic breaks. For this to occur, the duration of this scattering outflow has to last as long as these observed features (modulo cosmological time dilation).

To account for such an outflow in our model we go back to stage 2 described in Section 2. In the event that the QS does not collapse to a BH after the accretion disc has been depleted (or may be because accretion is temporarily suppressed), spin-down of the QS due to magnetic braking (if the QS is rapidly rotating) can naturally lead to the launching of a secondary outflow in the form of a pair wind.

We next show that by using the rotational energy lost from a QS spinning down, assuming a magnetic field of $10^{15}$ G, a spin period of $\sim 2$ ms, a characteristic decay time of the order of $10^7$ s is obtained. The observed flattening in the light curves of certain GRBs can last for several times $10^7$ s and fits well with the duration from the QS spin-down.

Following the birth of a CFL QS, due to the onset of colour superconductivity the magnetic flux inside the star is forced into a vortex lattice that is aligned with the rotation axis. This subsequently forces the magnetic field outside the star to restructure itself into a dipole configuration that is aligned with the rotation axis (Ouyed et al. 2006). Such an aligned rotator will spin down by magnetospheric currents escaping through the light cylinder. Pair production from magnetic reconnection supplies these currents (Niebergal et al. 2006) with a corresponding luminosity given by (Shapiro & Teukolsky 1983)

$$L = -\dot{E}_{\text{rot}} \sim \frac{B^2 \Omega^{(6+1)} R^6}{c^3} ,$$

(2)

where $B$ is the magnetic field at the pole, $R$ is the radius of the star, $\Omega$ is the angular rotational frequency of the star, $c$ is the speed of light and $n$ is the magnetic braking index.

For an aligned rotator without field decay, the braking index is roughly $n \sim 3$; however, due to magnetic flux expulsion from a CFL QS, the magnetic field decays as prescribed by Niebergal et al. (2006). This results in an evolution of the luminosity due to spin-down, which is expressed by the relation

$$L \sim 3.75 \times 10^{48} \text{ erg s}^{-1} \left( \frac{B_0}{10^{15} \text{ G}} \right)^2 \left( \frac{2 \text{ ms}}{P_0} \right)^4 \left( 1 + \frac{t}{\tau} \right)^{-5/3} ,$$

(3)

where the characteristic spin-down time (in seconds) is

$$\tau = 3.5 \times 10^4 \left( \frac{10^{15} \text{ G}}{B_0} \right)^2 \left( \frac{P_0}{2 \text{ ms}} \right)^2 \left( \frac{M_{\text{QS}}}{1.4 \, M_\odot} \right) \left( \frac{10 \text{ km}}{R_{\text{QS}}} \right)^4 .$$

(4)

In the above equations, $M_{\text{QS}}$ is the QS mass, $P_0$ is the initial spin period, and $B_0$ is the initial magnetic field strength.

From equation (3) one can see that the luminosity, due to rotational energy extracted from spin-down of a QS, has a natural break at time $\tau$. Thus, if there was a one-to-one relationship between spin-down luminosity and observed emission, then the power-law decay of the observed light curve should change from zero to $-5/3$ after a few thousand seconds. However, the observed emission might be modified by the forward shock as discussed in Panaitescu (2008).

The energy released from the spin-down of the QS is likely to be in the form of an $e^+e^-$ wind. Bucciantini et al. (2007) performed numerical simulations where they showed that it is still possible to collimate such equatorial flows into a jet.

A relativistic outflow from the spin-down of a highly magnetized NS has been suggested before as a mechanism to produce plateaus (e.g. in Troja et al. 2007); however, they did not propose a unified model explaining both the prompt emission and the afterglow features. We have here proposed a model that can explain both the prompt GRB emission and the observed X-ray afterglow features.

3.3 Sharp versus gradual decay

Equation (3) naturally gives a break in the engine luminosity at $t = \tau$. The engine will also remain active after this break, but the engine luminosity will gradually decay (with a power law $\sim -5/3$; which is not necessarily the power-law decay in the observed emission).

If the QS collapses to a BH during spin-down, the engine will likely be shut off. A sharp drop-off will be seen as the light curve drops from the level given by the spin-down outflow to the level given by the external shock.

Although the BH is likely to be rapidly rotating, a disc is necessary in order to extract the rotational energy of a BH through the Blandford–Znajek mechanism (BZ; Blandford & Znajek 1977). Only if a disc has remained around the QS during spin-down or if it is formed after the formation of the BH can the BZ mechanism play a role. If this does not occur, the observed light curve will be generated by the external shock only after this stage. In the (in our opinion) unlikely scenario that accretion resumes following the spin-down, it can halt the pair wind and turn the QS into a BH. If a jet is launched during accretion on to the BH, then X-ray flaring might be seen during or immediately after the drop.

The high latitude/curvature effect will contribute to the light curve even after the engine has been shut off, as photons emitted from outside the cone $1/\gamma$ reaches the observer at later times. However, the spreading will be of factors of the order of 1000 for the pair wind, this spreading will be small.

4 CASE STUDY

In this section we will apply our model to two GRBs, GRB 070110 and GRB 060607A, that both show a flattening followed by a sharp drop-off. We have chosen GRB 070110 and GRB 060607A since their XRT light curves have been a challenge to ‘standard’ models. Observed properties of both GRBs are summarized in Table 1.

Based on observations of the duration of the X-ray flattening, we use equation (4) to estimate the corresponding maximum magnetic field strength. We then use equation (3) to find the spin-down luminosity. Both the magnetic field and the spin-down luminosity found this way are listed in Table 2 which is then compared to observed values (Table 1). Furthermore, now that we have an estimate for the maximum magnetic field of the QS, this gives us an estimate for the maximum accretion rate that can be channelled to the polar cap (equation 1). We assume a jet opening angle of about 10$^\circ$. The observed prompt GRB emission ($E_{\gamma, 10_{\gamma, \text{max}}}$) is then calculated by assuming that a combination of accretion efficiency and radiative efficiency leads to $\sim 1$ per cent of the total gravitational energy of the accreted material is converted to prompt radiation. As shown below, for both GRB 070110 and GRB 060607A we find that the magnetic field found based on the duration of the X-ray flattening consistently and simultaneously explains the energy of both the GRB itself and the X-ray flattening.

In our model we know the time at which the QS collapses to a BH (the time of the steep decay). The above calculations assumed that this occurred at $t_{\text{collapse}} = \tau$. However, it could also occur at $t_{\text{collapse}} < \tau$, which implies that the magnetic field is weaker than found above. Therefore, the magnetic field found above is the maximum possible magnetic field, and therefore the spin-down luminosity, accretion rate and prompt gamma-ray energy are also maximum. From our assumptions that $\sim 1$ per cent of the accreted energy is converted.

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Table 1. Observed quantities in GRB 070110 and GRB 060607A.

|                              | GRB 070110 | Reference | GRB 060607A | Reference |
|------------------------------|------------|-----------|-------------|-----------|
| Redshift (z)                 | 2.352      | 1         | 3.082       | 1         |
| $E_{X,iso}$ (erg)            | $1.85 \times 10^{52}$ | 1         | $6.16 \times 10^{52}$ | 1         |
| $T_{break}$ (engine frame)   | 6000 s     | 2         | 2750 s      | 2         |
| $L_{Obs,iso}$ (during plateau) | $10^{48}$ erg s$^{-1}$ | 3         | $6 \times 10^{48}$ erg s$^{-1}$ | 5         |
| $L_{Eng,10}$ (during plateau) | $1.5 \times 10^{48}$ erg s$^{-1}$ | 4         | $1 \times 10^{49}$ erg s$^{-1}$ | 4         |
| $T_{90}/(1 + z)$             | 25.4 s     | 2         | 24.5 s      | 2         |
| $E_{\gamma,iso}$            | $2 \times 10^{52}$ erg | 1         | $5.2 \times 10^{52}$ erg | 1         |
| $E_{\gamma,10}$             | $1.0 \times 10^{50}$ erg |           | $2.5 \times 10^{50}$ erg |           |

References: (1) Liang et al. (2007). (2) Calculated using redshift and duration from Liang et al. (2007). (3) Troja et al. (2007). (4) Observed luminosity corrected for redshift, assuming $10^\circ$ opening angle. (5) Calculated using $E_{iso,X,z}$ and $T_{break}$ from Liang et al. (2007).

Table 2. Derived quantities for GRB 070110 and GRB 060607A.

|                              | GRB 070110 | GRB 060607A |
|------------------------------|------------|-------------|
| Maximum magnetic field       | $8 \times 10^{14}$ G | $1 \times 10^{15}$ G |
| Minimum magnetic field       | $4 \times 10^{14}$ G | $7 \times 10^{14}$ G |
| $n_{acc,max}$                | $7 \times 10^{-4}$ M$_\odot$ s$^{-1}$ | $1 \times 10^{-3}$ M$_\odot$ s$^{-1}$ |
| $n_{acc,min}$                | $2 \times 10^{-4}$ M$_\odot$ s$^{-1}$ | $6 \times 10^{-4}$ M$_\odot$ s$^{-1}$ |
| Spin-down luminosity         | $2 \times 10^{48}$ erg s$^{-1}$ | $5 \times 10^{48}$ erg s$^{-1}$ |
| $E_{\gamma,10,max}$          | $3 \times 10^{50}$ erg | $6 \times 10^{50}$ erg |
| $E_{\gamma,iso,max}$         | $6 \times 10^{52}$ erg | $1 \times 10^{53}$ erg |

The maximum magnetic field is calculated using equation (4) assuming that the QS collapsed to a BH at $t = \tau$ and an initial spin period of 2 ms, whereas the minimum magnetic field is the weakest field that can channel the necessary accretion flow to the polar cap (equation 1) to explain the prompt emission. The maximum and minimum accretion rates ($n_{acc,max}$, $n_{acc,min}$) correspond to these fields, whereas the given spin-down luminosity (equation 3) and $E_{\gamma,iso,max}$ and $E_{\gamma,10,max}$ (1 per cent of accreted energy) are derived using the maximum magnetic field.

to gamma-ray photons and that the GRB jet has an opening angle of $10^\circ$, we can find the minimum accretion rate that can explain the GRB, and a corresponding minimum magnetic field that can channel this accretion to the polar cap. This we list in Table 2 as well.

4.1 GRB 060607A and 070110

The maximum QS magnetic field needed that can explain the flattening observed in GRB 070110 is $B = 8 \times 10^{14}$ G (see Table 2). The corresponding spin-down luminosity is found to be $2 \times 10^{48}$ erg s$^{-1}$. We can compare this to the observed engine luminosity assuming an opening angle of $10^\circ$ for this outflow. If we assume an efficiency of 10 per cent in converting kinetic energy to photons we see that we have an order of magnitude more energy than needed. Comparing the observed prompt gamma-ray energy to what we find from the jet launched by the QS, we again find that the jet energy is higher (by a factor of 4) than the observed gamma-ray energy. The QS magnetic field needed to explain the flattening observed in GRB 060607A is $B = 1 \times 10^{15}$ G (see Table 2). The corresponding spin-down luminosity is found to be $3.6 \times 10^{48}$ erg s$^{-1}$. Assuming 10 per cent efficiency in producing X-ray photons, we find (as for GRB 070110) that the estimated luminosity is higher than the observed. The gamma-ray energy released during the prompt phase is also higher than the observed gamma-ray energy.

The minimum magnetic field needed to explain the prompt emission in GRB 070110 is estimated to be $4 \times 10^{14}$ G (with a corresponding accretion rate of $n_{min} = 2 \times 10^{-4}$ M$_\odot$ s$^{-1}$) while for GRB 060607A it is valued at $7 \times 10^{14}$ G (with $n_{min} = 6 \times 10^{-5}$ M$_\odot$ s$^{-1}$). In both cases, we find that the minimum magnetic field is a factor of 1.5–2 smaller than the maximum magnetic field for our choice of jet opening angle. We remind the reader that the minimum and maximum magnetic fields are found independently. The minimum field is the weakest field that can channel the minimum accretion rate on to the polar cap (equation 1), whereas the maximum field is the strongest field that can give a characteristic spin-down time (equation 4) equal to or larger than the duration of the flattening.

Our results suggest that QSs associated with GRBs are born with magnetar-like fields in the range $10^{14} < B < 10^{15}$ G which is also consistent with ranges found from independent studies of magnetic field generation in quark matter (Iwazaki 2005).

The higher luminosities can be because the estimate for the magnetic field is too high, meaning that $\tau$ is larger and that the QS collapsed to a BH before $t = \tau$. A lower magnetic field implies that the accretion rate is lower. Alternatively, we may have over-estimated the efficiencies, or the opening angle of the outflow is larger.

In GRB060607A there are several X-ray flares observed until about 300 s (about 75 s when corrected for redshift). If we explain these flares by accretion on to the QS as well, that means that the accretion process lasts for at least 75 s. The derived accretion rates imply the necessity of a debris disc with a mass of the order of $\sim 10^{-1}$ M$_\odot$, which is reasonable since the QN goes off inside a collapsar, where such a large fall-back disc is in principle allowed.

5 SUMMARY AND CONCLUSION

We have presented a model to explain the flattening and occasional sharp drop-off seen in X-ray afterglows of some GRBs. Our model borrows the framework of the three-stage model presented in SOB07 which makes use of an intermediate QS stage between the NS and the BH. By appealing to a secondary outflow, from the QS spin-down due to magnetic braking, our model seems to explain the GRB itself (i.e. prompt emission), the observed flat segment (i.e. plateau) and the subsequent sharp or gradual decay following the plateau. The sharp or gradual decay depends on whether the QS collapses to a BH or not during spin-down. During spin-down, a break will be seen after a characteristic time $\tau$ given by equation (4) followed by a power law with power of $-5/3$ to $-3$ (Panaitescu 2008). A very sharp drop-off will be seen if the QS collapses to a BH during spin-down.

We would like to point out possible observational signatures of flattening caused by the secondary outflow versus the refreshed shocks case. In the latter case, both the optical and X-ray light...
curves would be produced by the external shock, so that features seen in one band (e.g. flattening or jet breaks) should be visible also in the other band. If however flattening is powered by spin-down wind, then the X-ray and optical light curves should show independent features. This might also happen in the early stages of the light curve if the external shock contributes to the light curve (Mészáros & Rees 1997). Another possible distinction resides in the fact that flattening caused by the secondary outflow can be regarded as having an 'internal' origin, where the variability in the light curve can be related to engine activity. Flattening caused by the external shock, we argue, will instead carry signatures of the surrounding environment.

We note that, if there was a way for launching ultrarelativistic jets from accretion on to NSs, then it would be tempting to not include the QS phase in our model and appeal only to NS to BH transition. However, we are not aware of any such mechanism for launching an ultrarelativistic jet from accretion on to a NS, and from an energetics perspective it seems unlikely. Hence, the additional energy available from converting hadronic to strange quark matter and during accretion on to the QS seems crucial in explaining the nature of GRBs.

In addition to an energetics point of view, the most important benefits of our GRB model involving a QS stage are as follows. (i) The QS offers an additional stage that allows for more energy to be extracted from the conversion from NS to QS as well as from accretion. Also, additional energy is released as the QS quickly evolves from a non-aligned to an aligned rotator following its birth with up to $10^{47}$ erg released in a few seconds (Ouyed et al. 2006). As such, the QS phase extends the engine activity and so can account for both the prompt emission and irregular X-ray afterglow activity. (ii) A natural amplification of the NS magnetic field to $10^{14}-10^{15}$ G during the transition to the QS (Iwazaki 2005). Such high strengths gives the correct spin-down time to for the plateau. (iii) Since QS in the CFL phase might not have a crust, the spin-down energy will most likely be extracted as an $e^+e^-$ fireball with very little baryon contamination (see discussion in Niebergal et al. 2006). Panaitescu (2008) favours a baryon free secondary outflow to explain the plateau.

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4 Panaitescu (2008) also discusses this.