Quark nova inside supernova: Application to GRBs and XROs

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Abstract

In this paper we consider a quark nova occurring inside an exploding star. The quark nova ejecta will shock when interacting with the stellar envelope. When this shock reaches the surface of the star, the energy is radiated away. We suggest that this energy may be seen in X-rays, and show here that this may explain some flares seen in the X-ray afterglow of long gamma ray bursts (GRBs). A quark nova inside an exploding star need not be followed by a GRB, or the GRB may not be beamed towards us. However, the shock break-out is likely not beamed and could be seen even in the absence of a GRB. We suggest that XRO 080109 is such an event in which a quark nova occurs inside an exploding star. No GRB is formed, but the break out of the shock leads to the XRO.

1 Introduction

Quark stars (QSs) are hypothetical objects composed of deconfined u, d, and s quarks. The strange quark matter (SQM) hypothesis states that SQM may be the absolute ground state of strong interacting matter rather than ^{56}Fe [1, 17], and therefore QSs

would be stable objects. Even before the formulation of the SQM hypothesis Itoh [3] discussed the possible existence of QSs.

QS masses and radii are likely comparable to neutron stars (NSs), but slightly smaller radius due to their higher density. A possible formation scenario for QSs is that the central density in a neutron star increases past a critical density at which quarks deconfine. This can happen either due to spin down of a rapidly rotating NS [12], or through accretion onto the NS. A QS can then be formed in a quark nova (QN) [8], during which up to 10^{53} erg can be released in an explosive event. The iron rich NS crust will likely be blown away in the explosion. For a QN to occur soon after the core collapse, either the NS magnetic field must be very high ($B \sim 10^{14} - 10^{15}$ G) and the NS rapidly rotating, or more likely through accretion. In [9] the interaction of the iron rich QN ejecta and the surrounding star was studied, and applied to long gamma ray bursts (GRBs). There it was suggested that QN ejecta leaving the star through a funnel could lead to precursor activity.

Long GRBs typically have a duration $T_{90} \sim 100$ seconds, after which the gamma radiation ends. The X-ray telescope on board Swift is sometimes able to focus onto a GRB at a timescale of around a 100 seconds. A generic X-ray light curve [19] can be constructed based on XRT observations. It shows a sharp drop in the X-ray light curve lasting for a few hundred seconds, followed by a plateau phase extending to several times 10^4 seconds, before a "normal" power law decay is seen. Overlayed on all this are one or more flares, some of which can have a fluence comparable to that of the prompt gamma emission itself yet typically they have a much lower energy. Other bursts do not show the sharp drop and plateau phase, but rather a "normal" power law from early times. There may however be flares overlayed also on this light curve.

The "normal" power law decay is what is expected from the external shock. This power should be steeper than -0.75 for pre-jet-break and steeper than -1.5 for post-jet-break light curves [6], yet not steeper than -3 [16]. Hence the external shock alone has difficulty explaining the very sharp drop, the flares, and the plateau phase, which is why other mechanisms involving the inner engine must be sought in the cases where these features are seen.

In [13] a three stage model for the inner engine of long GRBs was suggested. Stage 1 is a NS formed by the collapse of the iron core in a SN. Accretion or spin-down can make the NS explode in a QN leaving a QS behind, which leads to stage 2 that is a jet launched from hyperaccretion onto a QS giving the GRB prompt emission. When the QS has accreted sufficiently, it collapses to a black hole (BH) whereby the third stage can be reached, which is accretion onto a BH. This may launch another jet that can give rise to one big flare (or several flare in rapid succession). If accretion ends before the QS collapses to a BH, stage 3 will never be reached and instead spin down of the highly magnetized rapidly rotating QS may power a secondary outflow giving rise to a flat segment in the X-ray afterglow [14].

E_{QN}	10^{52} erg	Energy of QN going into chunks
m_{ejecta}	$10^{-5}M_{\odot}$	mass of QN ejecta going into chunks
M_{env}	$1M_{\odot}$	Mass of the stellar envelope
n_{c}	1000	number of chunks
R_{sep}	10^{10} cm	Distance at which chunks separate
T_{bb}	10 keV	The blackbody temperature
R_{env}	5×10^{11} cm	Radius of the envelope
Γ_{spread}	$0.2\Gamma_{\mathrm{avg}}$	Spread in the chunks's Lorentz factors

Table 1: The free parameters used in our model, together with their typical values and a brief explanation of their meaning.

In this paper we build on the work in [9] and explore the breakout of the shock formed when the QN ejecta interacts with the stellar envelope. We will use this to explain features seen in GRBs or XRO 080109. The expressions for describing the QN induced shock's propagation through the stellar envelope is given in section 2. In section 3 we study possible observational consequences of the QN that formed the QS leading to the GRB. Using the simple expressions presented in 2 we show that some later flares in GRBs may be formed by the ejecta launched from the QN interacting with the stellar envelope. The QN ejecta are likely ejected isotropically, so even when no GRB is seen these weaker and later flares can be seen. A QN does not have to be followed by a GRB and in section 4 we suggest that XRO 080109 was a case where a QN occurred inside a SN, but no GRB was produced. A summary of the three stage model and its features is given in section 5.

2 QN ejected chunks interacting with stellar envelope

The QN forming the QS ejects up to $0.01M_{\odot}$ from the crust of the NS. This QN ejecta breaks up into n_{c} chunks at a distance R_{sep}. The chunks are given Lorentz factors following a Normal distribution, with a standard deviation of Γ_{spread}, which is a free parameter. The average Lorentz factor is

$$\Gamma_{\mathrm{avg}} = \frac{E_{\mathrm{QN}}}{m_{\mathrm{ejecta}}c^2}, \tag{1}$$

where E_{QN} is the energy of the QN going into chunks, m_{ejecta} is the mass of the QN ejecta going into chunks, and c is the speed of light. In addition we impose a minimum Lorentz factor of 2 on the chunks. A larger Γ_{spread} results in a longer duration of the chunks interacting with the envelope. These chunks undergo a shock and is heated

up to a temperature

$$T_c = (\frac{\rho_{\text{env}}}{\rho_{\text{Fe}}})^2 \Gamma_c m_{\text{Fe}} c^2 \tag{2}$$

as they interact with the stellar envelope ($m_{\text{Fe}} c^2 = 56$ GeV), where

$$\rho_{\text{env}} = M_{\text{env}}/(4/3 \, \pi r_{\text{env}}^3) \tag{3}$$

is the density in the envelope, and $\rho_{\text{Fe}} \sim 10 \text{g/cm}^3$ is the density of iron. The shock speed is given by

$$v_{\text{shock}} = \sqrt{T_c/\mu_{\text{env}}} c, \tag{4}$$

where $\mu_{\text{env}} = 1.2$ is the mean atomic mass in the envelope and T_c is measured in GeV. Each shock has an energy

$$E_{\text{sh}} = \pi \Delta r_c^2 \sigma T_{\text{bb}}^4, \tag{5}$$

where $\sigma = 5.67 \times 10^{-5}$ is the Stefan Boltzmann constant, T_{bb} is the blackbody temperature when the shock breaks out of the star, and

$$\Delta r_c = \sqrt{\frac{4R_{\text{sep}}^2}{n_c}} \tag{6}$$

is the chunk size at birth. This energy is released instantly as the shock reaches the surface of the envelope at $t = r_{\text{env}}/v_{\text{shock}}$. Due to the different shock velocities, the shocks will break free at different times. Shocks breaking out at the same time will not necessarily be observed at the same time, since the light travel time may be different depending on where on the star the break out happened. However, the light crossing time of the star (the maximum difference in light travel time) is much smaller than the duration of the breakout of all the shocks, and so it is ignored in our calculations. We assume that all shocks have the same temperature T_{bb} when they release their energy.

The QN explosion is likely to be more or less isotropic and therefore the shocks from the chunks will be distributed isotropically at all latitudes in the star. The fraction of the released luminosity (L_{emitted}) that is observed is therefore

$$L_{\text{obs}} = \frac{L_{\text{emitted}}}{4\pi d^2}, \tag{7}$$

where d is the luminosity distance to the event. Note that the shocks are non-relativistic, so no relativistic beaming of the emitted radiation is present.

Table 1 lists the parameters in our model.

3 Application to long GRBs

In the three stage model for GRBs [13], the prompt gamma ray emission is likely to start soon after the QN. We will for now assume that the GRB jet is capable of making its way through the stellar envelope with a high Lorentz factor ($\Gamma \sim 100$). The QN ejecta is thus launched a short time before the onset of the GRB. As discussed above, the shock speed (and thus the time it takes the shock to propagate through the envelope) is proportional to ρ_{env}.

Here we consider the case of a rather thick envelope ($r > 5 \times 10^{11}$ cm). We also envision that there is a lot of structure to this envelope, so that some of the chunks can propagate unhindered through part of the envelope, and only interact with matter at higher radii. Such a scenario may be possible if there is a delay (of minutes to an hour) between the SN and the QN. For simplicity we assume that there are two envelopes surrounding the star, and the chunks can interact either with the first or the second.

3.1 GRB 070110

The X-ray afterglow light curve for this burst is quite remarkable. From about 4000 seconds to about 20000 seconds after burst trigger, the light curve looks flat. Following that, there is a very steep decay (a slope of power $\alpha > 7$)[16]. Following the flat segment and this steep decay, there are two flares overlayed on a power law decay. In [13] it was suggested that the flat segment is powered by spin down of a QS. The flat segment abruptly ends as the QS collapses to a BH, and the light curve drops sharply to the level given by the external shock. In this section we suggest that the flares seen in the light curve following the flat segment and the sharp drop is due to the QN chunks breaking out of the envelopes (see Fig. 1).

The parameters we have used to obtain this plot is: $m_{\mathrm{ejecta}} = 0.8 \times 10^{-4} M_\odot$, $E_{\mathrm{QN}} = 10^{52}$ erg, $M_{\mathrm{env}} = 0.5 M_\odot$, $r_{\mathrm{env,1}} = 9 \times 10^{11}$ cm, $r_{\mathrm{env,2}} = 11 \times 10^{11}$ cm, $R_{\mathrm{sep}} = 3 \times 10^{10}$ cm, $T_{\mathrm{bb}} = 25$ keV, $\Gamma_{\mathrm{spread}} = 0.2 \times \Gamma_{\mathrm{avg}}$. We note that the envelope is at a fairly large radius, indicating that the supernova exploded some time before (some minutes depending on the size of the exploding star and the velocity of the ejecta) the QN and the GRB occurred. The redshift for this burst is $z = 2.3$, so although the T_{bb} seems large for X-ray observations, the radiation will be redshifted from 25 keV to 7.6 keV. This is in the range of the XRT.

The total energy released as X-rays in the two flares is 7.2×10^{50} erg for the first flare and 5.9×10^{50} erg for the second flare. This is more than 10% of the total energy (10^{52} erg) released in the QN. Hence the efficiency in converting energy into X-rays must be fairly high. Because the flares are so broad due to the large envelope size the observed flux is not very high.

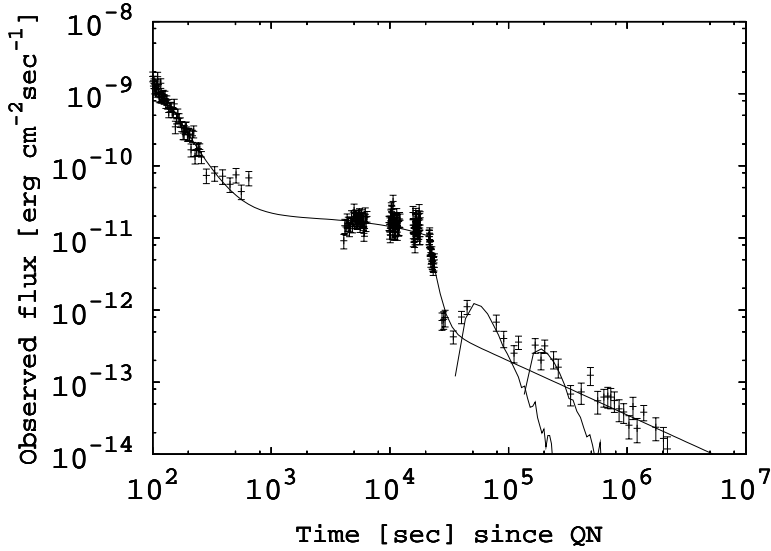We have matched three power laws, the spin down of a rapidly rotating quark

Figure 1: The XRT data points for the X-ray afterglow of GRB 070110 [2]. There are several prominent features in this afterglow: a flat plateau lasting until about 20000 seconds followed by a very sharp drop. After the sharp drop follows a decaying light curve with two flares overlayed. In addition to the data, we have plotted a power law plus the effect of a QS spinning down from 2 ms with an initial magnetic field of 5×10^{14} G [14]. At around t=20000 sec. the QS collapses to a black hole causing the abrupt drop in the light curve down to the level given by the external shock. This we indicate with a power law with power -0.75. Also shown are two flares due to the QN chunk break out from the two layers of the stellar envelope, these flares are seen at about 50000 sec. and 130000 sec. The time is the time since the QN (essentially the time since the start of the GRB), and on the vertical axis is shown the observed flux. $10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ corresponds roughly to 5×10^{46} erg/s assuming isotropic emission and a redshift z=2.35.
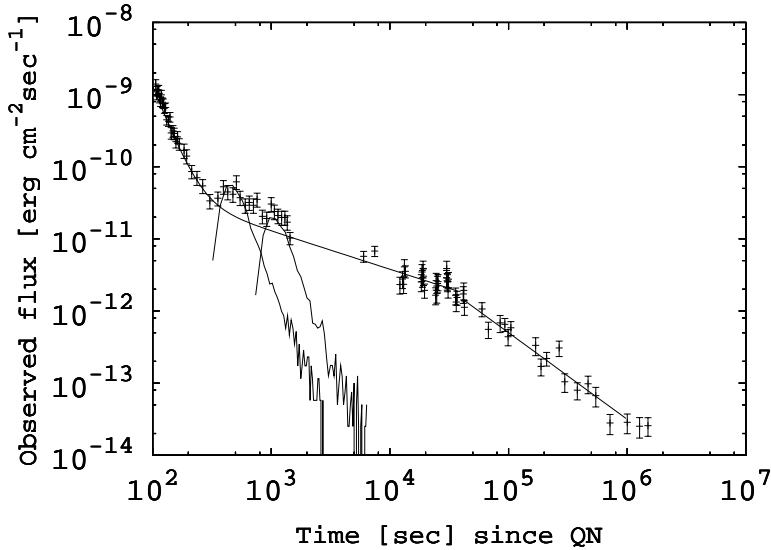
Figure 2: The XRT data points for the X-ray afterglow of GRB 081007 [2]. Two flares due to QN chunk break out is shown after 500 seconds and 1000 seconds. In addition, we plot three power laws, until 250 seconds the power is -4.1, then until 40000 seconds it is -0.53, followed by a third power law with power -1.2. The break that we found at 40000 seconds may be a jet-break [10], but the power following the break is fairly shallow indicating that this is still pre-jet break. Instead, we suggest that there is a period of refreshed shocks ending at 40000 seconds followed by the pre-jet-break decay.

star, and two flares due to QN chunk breakout to the data (see Fig. 1). First the initial decay lasting until 500 seconds with a power -2.8 which may be due to curvature effect. Following this is the spin down light curve of a rapidly rotating highly magnetized QS lasting until $t = 20000$ seconds. At t=20000 seconds the QS collapses to a BH ending the flat segment. The light curve drops abruptly (we use a power law with power -9.3) to the level given by the external shock. Following the break is another power law with power -0.75 overlayed with the two QN chunk flares seen around 10^5 seconds.

3.2 GRB 081007

GRB 081007 shows a light curve with a fairly steep decay until $t \sim 300$ seconds. After that there is a small flare around 500 seconds and another at around 1000 seconds. We assume that these flares are due to the QN chunks breaking out and plot the light curve in Fig. 2.

The parameters used to obtain this plot is: $m_{\mathrm{ejecta}} = 1 \times 10^{-4} M_\odot$, $E_{\mathrm{QN}} = 10^{52}$

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erg, $M_{\text{env}} = 5M_\odot$, $r_{\text{env,1}} = 6 \times 10^{11}$ cm, $r_{\text{env,2}} = 7.4 \times 10^{11}$ cm, $R_{\text{sep}} = 1 \times 10^{10}$ cm, $T_{\text{bb}} = 10$ keV, $\Gamma_{\text{spread}} = 0.2 \times \Gamma_{\text{avg}}$.

The redshift for this burst is $z = 0.5$, so the observed peak will be seen at 6.7 keV instead of the emitted 10 keV. This is within the XRT range.

The total energy released in X-rays in the first flare is 8.8×10^{48} erg and in the second flare it is 7.2×10^{48} erg. In this case a much lower fraction of the total QN energy (compared to GRB 070110) has been released as X-rays in these two flares. Because of the smaller envelope radius, the observed flux in these flares is higher than in the GRB 070110 case.

We have also matched three power laws to the data. The first power law has a power of -4.1 until t=250, this we suggest is the curvature emission marking the end of the QS jet. Then another with power -0.53 until $t = 40000$ at which time a break is found. This break may be a jet break [10] or the end of a flatter segment due to refreshed shocks [11]. Following the break is another power law function with power -1.2. Since the light curve following the break is fairly shallow, this may indicate that the jet break occurs later and that this break is due to the end of a period of refreshed shocks (for a discussion on the pre-jet break power see for instance [6]).

3.3 Flares in GRB afterglows

The sharp drop between 100 and 1000 seconds is often thought to be "curvature" radiation [4], that is the emission emitted outside the $1/\Gamma$ cone. This would mark the end of the jet that created the prompt emission (the QS jet in stage 2). Flares occurring before this sharp drop could therefore be due to the same mechanism as that which created the prompt emission, with the difference that the radiation is seen by XRT rather than BAT.

As mentioned in the introduction, if stage 3 is reached the BH jet may lead to one big flare. There may be a delay between the end of the QS jet and the launching of the BH jet, in which case this flare would be seen after the beginning of the sharp drop. It is also possible that there are no delay between the QS jet and the BH jet, in which case this big flare from the BH jet will occur shortly before a possible sharp drop[1].

The maximum mass that can be accreted onto the QS is assumed to be of the order $0.1M_\odot$, whereas the maximum mass that can be accreted onto the BH is all

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[1]Accretion onto a QS will only power a jet for a certain range in accretion rates ($\dot{m}$). When $\dot{m}$ is higher than what the magnetic field can channel to the polar cap then no jet is launched. This accretion rate is found by requiring that the Alfvén radius be larger than the star, $r_A = \left(\frac{B^4 r^{12}}{2GM\dot{m}^2}\right)^{1/7}$. For a star with 10^{15} G magnetic field, this critical $\dot{m}$ is about $10^{-3}M_\odot/sec$. On the contrary, $\dot{m}$ must be sufficiently high (higher than about $10^{-6}M_\odot/sec$) that it can heat the QS surface above 7.7 MeV in order for the QS to cool by photon emission (which is how the jet is launched). For accretion rates lower than this, no jet will be launched. If the accretion rate evolves over time, $\dot{m}$ may initially be in the range that can launch a jet, but later evolve out of this range.

the mass in the star that is not expelled in the explosion, probably up to $\sim 10 M_\odot$ (although we expect much smaller mass accreted to be the norm). The accretion rate is likely very high ($\dot{m} \sim 1 M_\odot/sec$), leading to a short duration. The energies involved can potentially be substantially higher than in the prompt phase.

In this paper we have suggested a third mechanism to form flares, when the QN ejecta shocks the stellar envelope and these shocks break out. The time for the occurrence of these flares depends on the thickness of the envelope, which is dependent on the initial star as well as the time delay between the core collapse and the QN. These flares can therefore occur at almost any time, both early and late. However, were they to occur before the sharp drop off following the GRB jet, they are unlikely to be seen as they would not be sufficiently bright to outshine the jet.

In bursts where the "normal" power law is seen from early times, we suggest that the external shock is sufficiently bright that it outshines possible plateau phases. Only the top of the brightest flares can be seen. For a sufficiently fast drop off of the light curve, the QN chunk break out may be observed at later times in this scenario as well.

4   Application to XRO 080109

XRO 080109 is an X-ray outburst associated with SN 2008D which is a type 1b/c SN. The XRO lasted about 500 seconds, with a peak about 65 seconds after trigger [15]. The peak X-ray luminosity is about 10^{44} erg/sec, decaying down to a few times 10^{42} erg/sec after about 700 seconds [18]. No GRB was seen in connection with this event. either means that there really was no GRB in this case, or that the GRB was beamed away from us. Radio observations and other indications [15] argues in favor of no GRB. We adopt this view here.

We propose that in XRO 080109 the iron core of the star collapsed to a (proto-) neutron star. The mechanism that explodes a supernova acted. Shortly thereafter, the compact core collapsed to a QS in a QN. A QS was therefore formed, but that does not necessarily mean that a GRB was produced. There will be no GRB (in our model) without a hyperaccretion disk forming around the QS, when no jet is formed or the jet cannot escape the stellar envelope. A hyperaccretion disk may be more likely to form in a system whose progenitor was rapidly rotating.

In Fig. 3 we show the light curve for our model XRO 080109. The parameters used to obtain this was $M_{\mathrm{envelope}} = 7 M_\odot$, $M_{\mathrm{ejecta}} = 5 \times 10^{-4} M_\odot$, $E_{\mathrm{QN}} = 10^{52}$ erg, $T_{\mathrm{bb}} = 1.7$ keV, $r_{\mathrm{envelope}} = 5 \times 10^{11}$ cm, $\Gamma_{\mathrm{spread}} = 0.45 \Gamma_{\mathrm{avg}}$. An envelope mass of $7 M_\odot$ was found in [7]. We note that $r_{\mathrm{envelope}} \sim 5 \times 10^{11}$ cm is roughly consistent with the estimate in [15] that the shock breakout occurs at $r > 7 \times 10^{11}$ cm. They speculate that this is shock breakout from a wind surrounding the exploding star. In our model, the shock breakout could be simply from the stellar envelope, provided that there was
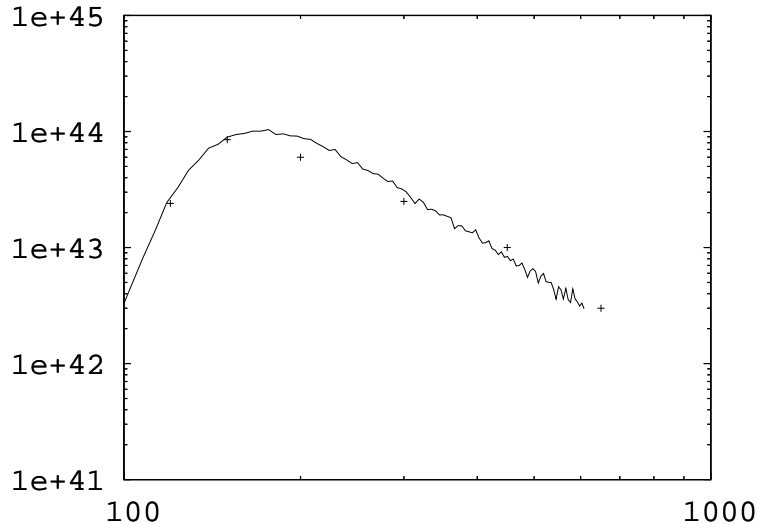
Figure 3: The model light curve for XRO 080109. The time scale on the horizontal axis is the time since the explosion.

a delay between the core collapse and the QN, during which the envelope had time to expand.

In [5] it is shown that the spectra of XRO 080109 can be fitted with two blackbody components, or one power law. The two blackbodies could be due to shock breakout of the SN shock and the QN shock. We note, however, that [5] found a photospheric radius much smaller than a solar radius, something that needs to be further explored in our model.

5 Summary

In this paper we have explored the break-out of the shock created by a QN ejecta when it interacts with the stellar envelope surrounding the QN. The QN is assumed to occur inside an exploding star. In the event of a non-uniform envelope the resulting light curve from this shock break-out can become complicated. Here we simplified the non-uniformity to assuming that there are two envelopes, one outside the other, and that a fraction of the QN ejecta interacts with the inner envelope and the rest with the outer. Based on this we find that two flares can result from the shock break-out. We suggest that these flares can explain some of the flares seen in GRB afterglows. The shock break-out is likely not beamed, whereas GRBs are. A GRB not beamed towards us will not be seen, while the QN shock break-out can still be seen. A QN can also occur inside a SN without forming a GRB at all, while the shock break out

can be seen. We suggest that this is the case in XRO 080109.

We here summarizes the three stage model, and emphasizes the new aspects proposed in this paper:

- The iron core in an initially massive, rapidly rotating star collapses, creating a (proto-)neutron star. This is the first stage in the model.

- Through spin down of the NS or accretion onto the NS (or both), the central density in the QS reaches a critical value at which a QN occurs, creating a highly magnetized QS.

- A hyperaccretion disk surrounding the QS accretes onto the QS, launching an ultrarelativistic jet in which internal shocks produces the GRB. This is the second stage in the model.

- The jet launching continues until the accretion is no longer able to heat the QS above 7.7 MeV, until accretion is no longer channeled to the polar cap (because the QS magnetic field drops or the accretion rate increases), or until the accretion halts (because there is no disk left). This leads to a sharp drop off due to curvature radiation frequently seen in the X-ray afterglow. If the external shock has already formed and is strong before the sharp drop off, the sharp drop off may not be seen.

- Flares seen before the sharp drop off may be caused by the same mechanism that created the GRB itself (internal shocks), only that the radiation is softer.

- If sufficient mass is accreted onto the QS, it will collapse to a BH and Stage 3 is reached which is continued accretion onto the BH. This can launch another jet, leading to a major X-ray flare. This flare will likely occur after the sharp drop off started, but not necessarily before it ended (it may also occur after the end of the sharp drop off).

- We assume that a maximum of $0.1 M_\odot$ can be accreted onto the polar cap. Usually accretion rates of the order $\dot{m} \gtrsim 10^{-4} M_\odot/sec$ is needed to explain the observed GRB power, indicating a total duration of the QS phase $t \lesssim 1000 sec$. However, if the accretion rate drops during stage 2, this duration may be extended.

- In the event that the QS survived the accretion stage, stage 3 will not be reached. Because of the accretion, this QS is likely rapidly rotating, and we assume it to be highly magnetized. Hence rapid spin down due to magnetic braking will occur. This can lead to an observed flat segment in the afterglow, if the spin down power outshines the external shock. The QS may reach an unstable state

during spin down, leading it to collapse to a BH. The observed light curve will then drop sharply down to the level given by the external shock.

- There may therefore be two separate outflows leading to two different light curves seen for instance as the X-ray and optical afterglow. One is created by spin down and the other by the external shock.

- In this paper we suggested that the shocks created by the chunks ejected in the QN can create observable flaring when it breaks out. In some cases this may be observed, in others it may be dwarfed by the external shock. The time at which these shocks break out depends largely on the size of the exploding star's envelope, which in turn depends on the delay between the collapse of the iron core and the QN. Here we have showed how two flares may result if the exploding star's envelope is not uniform.

- A flatter than expected light curve is also possible with the refreshed shock mechanism, in which slower part of the QS jet catches up with the external shock at later time and "refreshes" it leading to a shallower light curve. At the end of the refreshing, a break in the light curve is observed as the light curve steepens when no more material can refresh the external shock.

- A jet break can be observed in the light curve when $1/\Gamma > \theta_{\rm jet}$ (Γ being the Lorentz factor of the jet and $\theta_{\rm jet}$ being the opening angle of the jet itself) at which point the light curve steepens. Since there can be two separate outflows leading to the optical and X-ray afterglow, this may explain why the breaks (thought to be jet-breaks) are not achromatic.

- The QS jet, BH jet, and QS spin down outflow are all assumed to be beamed in two bipolar jets. The QN ejecta on the other hand is assumed to not be beamed, and it could therefore still be possible to see this even when the GRB is not beamed towards us. A QN may also occur inside an exploding star without forming a GRB (this happens if no hyperaccretion disk forms around the QS). However, the chunk break-out may still be seen. We have here suggested that XRO 080109 is such an event in which a QN occurred but no GRB was formed.

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