Testing the neutrino annihilation model for launching GRB jets

Mingbin Leng and Dimitrios Giannios

1 Department of Physics and Astronomy, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA

ABSTRACT

The mechanism behind the launching of gamma-ray-burst (GRB) jets remains debated resulting in large uncertainty over the jet composition. Both magnetohydrodynamical and neutrino annihilation models have been proposed for the energy extraction in a black hole/accretion-disc central engine. In particular, for the extreme accretion rates $\dot{M} \sim 0.1 - 1 \ M_\odot \text{s}^{-1}$ expected for bursts of duration $T \lesssim 100$ s, the disc can be an efficient neutrino emitter. Neutrino-antineutrino annihilation results in an energy deposition rate at the jet that can, in principle, account for the burst’s energetics. Recent discoveries of X-ray flares hours after the burst and of ultra-long GRBs suggest that GRB activity can last for $\sim 10^4$ s or longer. These long-lived events have fluence similar to that of classical GRBs. In view of these findings, we re-evaluate the neutrino annihilation model. We derive the maximum possible energy of a neutrino-powered jet as a function of the burst duration and show that the available energy drops fast for longer bursts. For a standard choice of the parameters, the model falls short by three to four orders of magnitude in explaining the observed energetics of events that last longer than $\sim 10^5$ s.

Key words: accretion, accretion discs — black hole physics — gamma-ray burst: general

1 INTRODUCTION

Gamma-ray bursts (GRBs) are powerful cosmic explosions of characteristic duration of seconds. Their duration distribution is bimodal. Bursts with duration $T \lesssim 1$ s ($T \gtrsim 1$ s) are referred to as short (long) GRBs (Kouveliotou et al. 1993). Long GRBs are considered to come from the collapse of the core of Wolf-Rayet stars (Woosley 1993) as demonstrated by their association with Type Ic supernovae (Galama 1998; Stanek et al. 2003). Short GRBs are probably result of merger of compact binaries (Eichler et al. 1989), though the observational evidence for the nature of the progenitor remains sparse.

Long GRBs have characteristic duration of $\sim 1 - 100$ s and isotropic equivalent, gamma-ray release of $E_{\text{iso}} \sim 10^{52} - 10^{54}$ erg (see, e.g., Bloom et al. 2003). However, recently a new population of very long GRBs has been claimed (including GRBs 101225A, 111209A, 121027A; Thöne et al. 2011; Gendre et al. 2013; Levan et al. 2014). These bursts last for $T \sim 10^4$ s and, given their luminosity of $L_{\text{iso}} \sim 10^{49} - 10^{50}$ erg s$^{-1}$, they have energy release similar to that of other powerful GRBs. Hereafter, we refer to these bursts as “ultra-long GRBs” (Gendre et al. 2013). The host galaxies of ultra-long GRBs are suggestive of massive star progenitors (Levan et al. 2014). The very long duration of these events can be accounted for by the extended size of the progenitor at core-collapse (Woosley & Heger 2012). Furthermore, GRBs exhibit powerful flares hours after the burst (Nousek et al. 2006; Zhang et al. 2006). Because of their fast rise and decay time-scales, these flares are also believed to be powered by activity of the central engine hours after the core collapse [see, however, Giannios (2006) for an alternative interpretation].

The energy source of the GRB is either the rotational energy of a strongly magnetized proto-neutron star (millisecond magnetar; Usov 1992) or the gravitational energy released during the accretion process to a newly-formed, a few solar mass black hole (Woosley 1993). Arguably, a black hole offers cleaner environment for the launch of a relativistic jet, though the protomagnetar model is viable alternative for long-duration GRB.

In the black hole scenarios, the jet may be launched by the Blandford-Znajek mechanism, provided that sufficiently strong magnetic fields thread the black hole horizon (Blandford & Znajek 1977). Such a jet is expected to be magnetically dominated. It remains to be demonstrated that the magnetic flux through the collapsing star is sufficient to power the jet (Komissarov & Barkov 2009).

An alternative to magnetically-driven jets is that of energy deposition through neutrino-antineutrino annihilation at the polar re-
The jet power also depends on the accretion rate to the black hole $M$ and its mass $M_{BH}$. Increasing $M$ the disc is denser and neutrino luminosity increases. The neutrino annihilation is a two body process and the energy deposition rate increases steeply with $M$. Also the mechanism is more effective for smaller black holes. The smaller size of the central engine results in more compact and hot discs (for fixed $M$), i.e., more effective neutrino emitters.

The calculation of the energy deposition rate due to neutrino annihilation requires a detailed model for the structure of a neutrino-cooled disc as well as general-relativistic ray tracing of the neutrino orbits (see ZB11). The jet power can be approximated by the following expression (for dimensionless black hole spin $a = 0.95$):

$$P_{\nu} \approx 1.3 \times 10^{22} \left(\frac{M_{BH}}{3 M_\odot}\right)^{-3/2} \left(\frac{P_{\nu}}{3 M_\odot}\right)^{9/4} \left(\frac{M_{\nu} \nu_{\nu}}{M_{\nu} \nu_{\nu}^{\text{max}}}ight)^{9/4} \left(\frac{M_{\nu} \nu_{\nu}^{\text{max}}}{M_{\nu} \nu_{\nu}^{\text{max}}}ight)^{9/4} \frac{M_{\nu} \nu_{\nu}^{\text{max}}}{M_{\nu} \nu_{\nu}^{\text{max}}} \text{erg s}^{-1} \text{, (1)}$$

where $M_{\nu} \nu_{\nu}^{\text{max}} = 0.021 M_{\odot} \text{s}^{-1} \left(\frac{P_{\nu}}{3 M_\odot}\right)^{3/2}$ and $M_{\nu} \nu_{\nu}^{\text{max}} = 1.8 M_{\odot} \text{s}^{-1} \left(\frac{P_{\nu}}{3 M_\odot}\right)^{3/5}$. Here $a$ stands for the standard viscosity parameter (Shakura & Sunyaev 1973). For $M < M_{\nu} \nu_{\nu}^{\text{max}}$, the efficiency drops very fast since the disc is not effectively cooling via neutrino emission and the jet power $P_{\nu}$ is less than predicted in equation. (1). Since the ‘ignition’ accretion rate $M_{\nu} \nu_{\nu}^{\text{max}}$ depends sensitively on the uncertain viscosity parameter $a$, for the purpose of this work, we use equation. (1) for any $M < M_{\nu} \nu_{\nu}^{\text{max}}$ with the understanding that we provide only an upper limit on the efficiency of the neutrino annihilation process when $M < M_{\nu} \nu_{\nu}^{\text{max}}$.

2.1 The predicted jet power

So far, we have expressed the jet power as a function of the black hole mass $M_{BH}$ and the accretion rate $M$, treating $M_{BH}$ and $M$ as independent variables. However, this is not the case in core collapse supernova where the black hole may grow substantially as a result of accretion during the GRB. On the other hand, in a compact object merger, the jet power is probably limited by the mass of the accretion disc. We discuss these two cases separately.

2.1.1 GRBs from collapsars

The typical duration of long GRBs burst of $1 \sim 100$ s is comparable to the free-fall time-scale of the progenitor Wolf-Rayet star. Since Wolf-Rayets undergo substantial mass loss during their evolution, just prior to collapse such a progenitor has a mass of $M \sim 10 \sim 15 M_\odot$ (Heger, Langer & Woosley 2000). Since at least several $M_\odot$ are ejected during the supernova explosion, the final mass of the black hole remnant is $M_f \leq 10 M_\odot$. For fast enough rotation of the progenitor, an accretion disc is expected to form around the black hole ~seconds after core collapse facilitating the jet launching. Still several seconds later the jet breaks through the collapsing star resulting in the GRB trigger. Let $M_i \geq 3 M_\odot$ be the mass of the black hole at jet breakthrough/GRB trigger (MacFadyen & Woosley 1999). For a Wolf-Rayet progenitor, the black hole undergoes modest increase in mass during the burst ($M_f \sim \text{a few } M_\odot$).

We will first estimate the jet power as a function of burst duration assuming that the mass of the black hole evolves little during the burst. As a second step, we proceed with a more general calculation that takes into account for the growth of the black hole mass.

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*Footnotes:*  
3 Hereafter, we refer to neutrinos and antineutrinos collectively as neutrinos.  
4 The approach here is to evaluate whether the maximum possible jet energy predicted by the model is adequate to explain observations.
For an average accretion rate $\dot{M}$ during a burst, the mass of the black hole evolves as $M_{\text{BH}} = M_0 + \dot{M}t$. Assuming that the accretion episode lasts time $T$ (e.g., the burst duration) during which the mass of the black hole roughly doubles ($M_f = 2M_0$), we have for the accretion rate:

$$M \sim \frac{M_f - M_i}{T} \sim \frac{M_i}{T} = 0.3 \frac{M_i}{3M_0} \left(\frac{T}{10s}\right)^{-1} \text{M}_\odot \text{s}^{-1}. \quad (2)$$

This implies for the jet power that (see equation. 1)

$$P^I_{\nu} \sim 8.5 \times 10^{50} \left(\frac{M_i}{3M_0}\right)^{3/4} \left(\frac{T}{10s}\right)^{-9/4} \text{erg s}^{-1}. \quad (3)$$

where the superscript $I$ stands for this, first, estimate of the jet power.

An alternative estimate of the jet power is to take into account the mass of the black hole that was involved as implied by the accretion rate $\dot{M} = dM/dt$. Equation. (1) can then be rewritten as

$$\frac{dM}{dt} = \left(\frac{P_{\nu}}{1.3 \times 10^{53} \text{erg s}^{-1}}\right)^{4/9} \left(\frac{M_i}{3M_0}\right)^{1/3} \text{M}_\odot \text{s}^{-1}. \quad (4)$$

Assuming that the jet power is approximately constant during the burst duration $\Delta T$ equation. (4) can be integrated analytically. Setting the integration time limits $t_1 = 0$ and $t_2 = T$ and those of the black hole mass $M_i = M_f$ and $M_0 = M_f$, and solving for the jet power as function of the initial, final mass of the black hole and the burst duration $T$ results in:

$$P^I_{\nu} = 4.3 \times 10^{51} \left(\frac{M_f}{M_i}\right)^{1/3} - 1 \left(\frac{T}{10s}\right)^{9/4} \times 10^{53} \text{erg s}^{-1}. \quad (5)$$

For a final mass of the black hole that is twice as large as the initial mass, equation. (5) gives

$$P^II_{\nu} = 4.7 \times 10^{50} \left(\frac{M_i}{3M_0}\right)^{3/4} \left(\frac{T}{10s}\right)^{-9/4} \text{erg s}^{-1}, \quad (6)$$

for $M_f/M_i = 2$. (6)

This expression is in reasonable agreement with equation. (3). The factor of $\sim 2$ difference in the predicted jet power comes for the fact that equation. (3) does not take into account the drop in the efficiency because of the increase of the mass of the black hole. In the following, unless otherwise specified, we keep expression (3) as a reference on the characteristic jet power predicted by the neutrino annihilation model.

One can exploit equation. (5) to derive a maximum possible jet power from the collapse of a massive star (not necessarily a Wolf Rayet). By allowing a fairly large mass for the final black hole of the remnant $M_f = 40M_\odot$, the jet power becomes $P^{\text{MAX}_{\nu}} = 1.4 \times 10^{52} (M_f/5M_0)^{3/4} (T/10s)^{-9/4} \text{erg s}^{-1}$ This is an order of magnitude higher than “standard” estimate in equation. (3) and may be more relevant for ultra-long GRBs. If the star is fairly extended in size and remains very massive at the moment of core collapse (e.g., as expected for blue supergiants with low mass-loss rate; Woosley & Heger 2012), it can potentially power a burst of ultra-long duration. As we discuss below, even the maximum power predicted by the model falls short by $\sim 2 \sim 3$ orders of magnitude in explaining the observed properties of ultra-long GRBs.

2.1.2 GRBs from compact object mergers

The estimate (3) for the jet power is relevant for GRBs associated with core collapse where the available matter for accretion is similar to or exceeds that of the black hole. The merger of a binary neutron star or of a black hole-neutron star system results in a black hole surrounded by a light accretion disc $M_{\text{disc}} \leq 0.1 M_\odot$ (e.g., Ruffert & Janka 1999). For the resulting accretion rate of $\dot{M} = 0.1 \left(M_{\text{disc}}/1M_\odot\right)^{1/3} \text{M}_\odot \text{s}^{-1}$, the jet power is

$$P^{\text{merge}_{\nu}} = 9.4 \times 10^{49} \left(\frac{M_{\text{BH}}}{2.5M_\odot}\right)^{3/2} \left(\frac{M_{\text{disc}}}{0.1M_\odot}\right)^{9/4} \left(\frac{T}{10s}\right)^{-9/4} \text{erg s}^{-1}. \quad (7)$$

3 COMPARISON WITH OBSERVATIONS

In Fig. 1, we schematically show the observed gamma-ray luminosity $L_{\gamma}^{\text{obs}}$ of various types of GRBs versus their observed duration $T$ (for a similar sketch see Levan et al. 2014). Long GRBs, short GRB as well as ultra-long GRBs and the X-ray flares that follow GRBs are shown. Long duration GRBs last for $T \sim 1 \sim 100$ s and have (isotropic equivalent) luminosities up to $L_{\gamma}^{\text{obs}} \sim 10^{50}$ erg s$^{-1}$ and $E_{\gamma}^{\text{iso}} \leq 10^{44}$ erg. Short GRBs typically last a fraction of a second and reach luminosity similar to that of long GRBs. Ultra-long GRBs (including GRBs 121027A, 101225A and 111209A) last for $T \sim 10^3 \sim 10^4$ s and have luminosity in the $L_{\gamma}^{\text{obs}} \sim 10^{46} \sim 10^{50}$ erg s$^{-1}$ range. X-ray flares take place $T_{\text{delay}} \sim 100 \sim 1000$ s after the GRB trigger and last for $T_f \sim 0.1T_{\text{delay}} \sim 10 \sim 100$ s (Chincarini et al. 2007). Their fluence can approach that of GRBs but it is typically $\sim 10$ times smaller: $E_{\gamma}^{\text{iso,flare}} \leq 3 \times 10^{32}$ erg (Falcone et al. 2007). The typical peak luminosity of the X-ray flares drops with time: $L_{\gamma}^{\text{flare}} \sim E_{\gamma}^{\text{iso,flare}}/T_{\text{flare}}$ (Chincarini et al. 2007).

To compare the jet power predicted by the model to the observed luminosity of GRBs, beaming and radiative efficiency corrections have to be taken into account. The relationship between the true luminosity of the burst and the observed luminosity is $L_{\gamma}^{\text{iso}} = (\Omega/4\pi) L_{\gamma}^{\text{obs}}$, where $\Omega$ is the solid angle covered by the gamma-ray emission. For jet opening angle $\theta$ and a symmetric, double jet system $\Omega \sim 2\theta^2$. Furthermore, if $\epsilon$ is the radiative efficiency of the jet, one can compare the true jet power $P_{\nu}^{\text{true}}$ to the observed (isotropic equivalent) gamma-ray luminosity

$$L_{\gamma}^{\text{obs}} = \frac{\epsilon \Omega}{4\pi} P_{\nu}. \quad (8)$$

Using equation. (3), we conclude that

$$L_{\gamma}^{\text{obs}} = 5.1 \times 10^{52} \frac{\epsilon}{0.3} \left(\frac{\theta}{0.1}\right)^{-2} \left(\frac{M_i}{3M_0}\right)^{3/4} \left(\frac{T}{10s}\right)^{-9/4} \text{erg s}^{-1}, \quad (9)$$

where we adopt $\theta = 0.1$ and $\epsilon = 0.3$ as reference values. The modelled-predicted jet luminosity is shown in Fig. 1.

For completeness we also show in Fig. 1 the observed luminosity of gamma-ray resulted from a binary merger event (see eq. 7):

$$L_{\gamma}^{\text{obs}} \approx 6 \times 10^{51} \frac{\epsilon}{0.3} \left(\frac{\theta}{0.1}\right)^{-2} \left(\frac{M_{\text{BH}}}{2.5M_\odot}\right)^{3/2} \left(\frac{M_{\text{disc}}}{0.1M_\odot}\right)^{9/4} \left(\frac{T}{10s}\right)^{-9/4} \text{erg s}^{-1}. \quad (10)$$

It is apparent that the energetics of the majority of long duration bursts and short-duration GRBs can, in principle, be accounted by the model. Some tension exists between observations and theory for short GRBs with duration $\sim 1$ s as well long GRBs of $\sim 100$ s. In the case of short-duration GRBs, these conclusions rely on the presence of a rather massive disc $M_d \sim 0.1M_\odot$ around the merger product. If the disc mass is, instead, $M_d \sim 0.01M_\odot$ (e.g., Ruffert & Janka 1999), the disc is probably too light to power short-GRBs through neutrino annihilation. The mechanism is also less effective for black hole/neutron star mergers. In that case, the final black hole has larger mass ($M_{\text{BH}} \geq 7M_\odot$).
events of duration understood in the context of the neutrino annihilation model. For challenged energetically to explain the longest events. The mechanism by a factor of as large as $10^4$ could account for the majority of the bursts with duration and black line for core collapse GRBs; see equation. (9)). While the model this model depends steeply on the accretion rate ($\dot{M}$), the jet composition is very different. Furthermore, beaming correction can be constrained by the timing of jet breaks while late time radio observations can be used to perform burst calorimetry (Frail et al. 2004).

The very long duration GRBs and X-ray flares are hard to understand in the context of the neutrino annihilation model. For events of duration $T \sim 10^4$ s, our reference estimate for the jet observed luminosity is $L_{\nu} \sim 10^{50}$ erg s$^{-1}$, i.e., short by $\sim 2$ orders of magnitude to account for X-ray flares and $\sim 3-4$ orders of magnitude for ultra-long GRBs, respectively.

4 DISCUSSION

If ultra-long bursts are conclusively shown to be of core-collapse origin, they pose a major challenge to neutrino annihilation models. In such events, the accretion rate to the black hole has to be much lower than that during regular GRBs. Since the jet efficiency in this model depends steeply on the accretion rate ($P_{\nu} \propto \dot{M}^{9/4}$), the model appears not to be energetically viable, for standard choice of the parameters. Similar problems arise when applying the model to the X-ray flares that follow a large fraction of GRBs.

One possibility is that some GRB jets are launched predominately by neutrino annihilation while others, the longer duration ones, by some other mechanism. However, there is no clear observational evidence for different mechanisms involved in different bursts. Fig. 1 indicates that the GRB variety is likely to originate from a continuum of core-collapse events powered by accretion to a few solar-mass black hole where the duration is set by the size of the progenitor. Furthermore, the observed spectral properties of GRBs and X-ray flares do not show evidence for a sharp change from one type of source to the other (as might be expected for instance because the jet composition is very different). Furthermore, relativistic jets are universally observed from a broad range of black hole accretors (e.g., blazars, microquasars) where neutrino annihilation is not of relevance. The simplest explanation is that all GRB jets are driven, predominately, by a single mechanism, unrelated to neutrino annihilation.

What if the reference values of the parameters we have adopted are not appropriate for the ultra-long GRBs? Can uncertainty in parameters have led us to underestimate the efficiency of the mechanism by a factor of as large as $10^4$? The predicted jet power depends sensitively on the black hole spin and on the available mass to be accreted. Furthermore, beaming corrections can be quite uncertain. For our reference model, we adopted a fast spinning black hole of $a = 0.95$. More extreme values of $a \sim 1$ may boost the efficiency of the mechanism by another factor of several. The mass of the collapsing stars powering the ultra-long duration GRBs may be larger leading to black holes of $\sim 50M_\odot$. This raises the energy extracted by annihilation by another factor of $\sim 10$ (see Section 2). Finally, we have normalized the jet opening angle $\theta$ to 0.1 rad, in accordance with typical expectation for GRBs. If ultra-long GRBs have an opening angle of $\theta \lesssim 0.01$ rad, in combination with the other possible boosting factors discussed above, neutrino annihilation might be able to account for observations. However, such extreme beaming appears to us as unlikely. If true, such beaming will have profound implications for the true rates for these ultra-long GRBs.

The neutrino annihilation model predicts a very specific trend among GRBs: the longer the duration, the less energetic the burst. From equation. (3), we find that the burst energy $E_{\nu} \sim P_{\nu}T \approx 7.6 \times 10^{45}(T/10^4 s)^{-1/4}$ erg. GRBs that last for $T \sim 10$, 100, 1000, $10^4$ s might have true (corrected for beaming) energy of $E \sim 4 \times 10^{52}$, $2 \times 10^{53}$, $1.3 \times 10^{53}$, $8 \times 10^{53}$ erg, respectively. One can look for such a trend in the data since it is possible to estimate the true energy of GRBs. The jet opening angle can be constrained by the timing of jet breaks while late time radio observations can be used to perform burst calorimetry (Frail et al. 2004). Even if such methods are approximate, the predicted trend of long-duration bursts being weaker than short ones is strong enough to be tested observationally.

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