Effect of magnetic field on neutrino annihilation efficiency in gamma-ray bursts

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ABSTRACT
Neutrino annihilation process on the accretion disk is one of the leading models to explain the generation of relativistic jets of gamma-ray bursts (GRBs). Under the black hole-accretion disk (BH-disk) system, the neutrino annihilation efficiency (NAE) $\eta_{\nu\bar{\nu}}$ is widely studied. The published results are mutually corroborated. However, the NAE of the neutron star-accretion disk (NS-disk) system is still uncertain due to the complicated microphysics processes and effects of strong magnetic field. In this paper, we investigate the required NAE assuming the prompt jet of GRB 070110 is driven by neutrino pair annihilation in the NS-disk system. Our calculation shows $\eta_{\nu\bar{\nu}} > 1.2 \times 10^{-3}$ under the estimated accretion rate $\dot{M} \approx 0.04 M_\odot \cdot s^{-1}$. Independent of the detailed accretion disk models, our result shows that the magnetic field may play an important role in the neutrino annihilation process on the hyper-accreting magnetized accretion disk. Compared with the theoretical value of $\eta_{\nu\bar{\nu}}$ of the non-magnetized BH-disk system, the NAE should increase significantly in the case of the NS-disk system if the GRB is powered by magnetar-disk system.

Key words: accretion, accretion disk - star: gamma-ray burst - star: magnetar

1 INTRODUCTION
Gamma-ray bursts (GRBs) are the brightest events in the universe after Big Bang. The general picture of GRBs can be divided into four stages (Kumar & Zhang 2015): 1) compact binary merging or massive star collapsing forms a compact star-accretion disk system (so-called central engine); 2) intermittent ultra-relativistic jets are emitted from the central engine; 3) energy dissipation in these relativistic jets generates gamma-ray radiation; 4) the interaction between the jets and the surrounding medium results in multi-band afterglows. The central compact star may be a black hole (BH) (e.g. Eichler et al. 1989; Narayan, Paczynski, & Piran 1992; Woosley 1993) or a neutron star (NS) (e.g. Usov 1992; Dai & Lu 1998a,b; Zhang & Mszros 2001). The neutrino annihilation process (Popham, Woosley, & Fryer 1999) and the Blandford-Znajek (BZ) process (Blandford & Znajek 1977) are the two leading models to explain the generation of relativistic jets.

As one of the leading models, the neutrino annihilation process is widely studied from theoretical side (e.g. Popham, Woosley, & Fryer 1999; Gu, Liu, & Lu 2006; Lei et al. 2009) and simulative side (e.g. Harikae, Kotake, & Takiwaki 2010; Zalamea & Beloborodov (2011); Just et al. 2016; see Liu, Gu, & Zhang 2017 for review). According to the the published results, the values of neutrino annihilation efficiency (NAE) under the BH-disk system are mutually corroborated (see section 4). However, the NAE of the neutron star-accretion disk (NS-disk) system is still uncertain due to the complicated microphysics processes and effects of strong magnetic field (Xie, Huang, & Lei 2007; Xie et al. 2009; Lei et al. 2009; Zhang & Dai 2009, 2010). And until now, no constraint on the NAE from GRB observations has been done due to the unknown launch mechanism of relativistic jets.

The premise of solving this problem is to determine the type of the central compact star. In some GRB afterglows, X-ray plateaus can be followed by a very steep decay (e.g. $t^{-8}$, so-called “internal plateau”, see Figure 1). This feature indicates that the GRB central engine remains active for some time after the prompt emission is over, and then suddenly shuts down. Therefore, the internal plateaus are difficult to be explained under the scenario of BH central engines. It is wildly believed that supra-massive strongly
2 Du et al.

magnetized NSs (also called magnetars) as the central engine of these GRBs need to be invoked (Fan & Xu 2006; Gao & Fan 2006). The spin down radiation of the supra-massive NS powers the X-ray internal plateau. The transition from the supra-massive NS to the BH through the gravitational collapse after losing rotation energy naturally accounts for the steep decay.

Usually, the magnetar model is incompatible with the BZ mechanism. Therefore, if it is true that magnetar is the central engine of a GRB, we may calculate the NAE by using the observation data of the GRB. In this paper, we find that GRB 070110 is a potential candidate which can be used to address this interesting question. In section 2, we present the properties of GRB 070110. We then calculate the NAE $\eta_{\nu,0}$ of the NS-disk system in section 3. The comparison of the NAE of the NS-disk system and the BH-disk system is shown in section 4. We interpret the result of the comparison in section 5. Finally, summary is given in section 6. Throughout this paper, a concordance cosmology with parameters $H_0 = 70\text{km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$, $\Omega_M = 0.30$ and $\Omega_{\Lambda} = 0.70$ is adopted.

2 THE PROPERTIES OF GRB 070110

Swift BAT detected GRB 070110 on 2007 January 10 (Troja et al. 2007). Its duration time $T_{90}$ (15 keV, 150 keV) is $\sim 89s$ and redshift $z$ is 2.352. The gamma-ray fluence in (15 keV, 150 keV) is $\sim 1.8 \times 10^{-6}$ erg cm$^{-2}$. Then one can obtain the observed isotropic prompt emission energy $E_{\gamma,\text{iso}} \simeq 3.1 \times 10^{52}$ erg (Du et al. 2016).

In Figure 1, it is clear that a near flat plateau is followed by a steep decay (red line). As mentioned in the introduction, this internal plateau implies that a hyper-accretion of strong magnetized NS central engine is required. Besides, in the X-ray afterglow of GRB 070110, a bump corresponding to the fall-back BH accretion after the central supra-massive NS collapsing to the BH was confirmed by Chen et al. (2017). These two reasons make us believe that the central object of GRB 070110 is a supra-massive magnetar (hereafter Mag07).

The break time $t_b(1+z)$ of the plateau is $\sim 2.0 \times 10^{4}$ s in observer frame. After considering the Galactic extinction, the fluence of X-ray plateau in 0.3 keV $- 10$ keV is $F_{x,\text{pla}} \sim 1.3 \times 10^{-11}$ erg cm$^{-2}$. So the isotropic energy of X-ray plateau in the source frame is

$$E_{\gamma,\text{iso},\text{pla}} = \frac{4\pi D_L^2}{1+z} F_{x,\text{pla}} t_b \simeq 4.3 \times 10^{51} \text{erg},$$

where $D_L$ is the the luminosity distance. Without jet break feature, the jet opening angle only can be constrained as $\theta_j > 7.4^\circ$ according to the last observed point ($t_j \sim 25$ d) in GRB 070110 X-ray afterglow (Du et al. 2016). Considering the correction of the jet opening angle, the total energy of prompt emission is

$$E_{\gamma} = E_{\gamma,\text{iso}}(1-\cos \theta_j) > 2.5 \times 10^{50} \text{erg}.$$  

1 Some authors also point out that the NS with a stiff equation of state (EoS), which has an ergosphere, can power jets via the BZ mechanism (Ruiz et al. 2012). But since the EoS may be soft (Margalit & Metzger 2017), and plasma is coupled to magnetic field in a NS, we believe that this scenario need to be further studied.

In principle, following the equations and method of Yost et al. (2003), one can obtain the total kinetic energy of GRB jets $E_{K,jet}$. However, when this method is used to fit the data, some of the parameters are degenerate, one should choose a set of seemingly reasonable parameter values by hand. Note that 0.01 $- 0.1$ is the typical value of prompt emission efficiency predicted by the matter-dominated jet (Kumar & Zhang 2015). Here, we conservatively take the prompt emission efficiency as 0.1, since the NAE is inversely proportional to the prompt emission efficiency. So the kinetic energy of the jet is

$$E_{K,jet} = E_{\gamma}/0.1 = 2.5 \times 10^{51} \text{erg},$$

and the total luminosity of the jet is

$$L_{\text{jet}} = E_{K,jet}(1+z)/T_{90} = 9.2 \times 10^{49} \text{erg} \cdot \text{s}^{-1}.$$  

Based on the above results, we then discuss how to constrain the properties of Mag07. Unlike the prompt emission, the energy injection of a magnetar is approximately isotropic. So the spin-down luminosity $L_{\text{sd}}$ can be expressed as

$$\eta_{x,\text{pla}} L_{\text{sd}} = E_{x,\text{iso,pla}}/t_b \simeq 7.2 \times 10^{37} \text{erg} \cdot \text{s}^{-1},$$

where $\eta_{x,\text{pla}}$ is the X-ray radiation efficiency of the spin-down power.

The collapse of a magnetar into a black hole should occur when a considerable amount of rotation energy is lost. So the spin-down timescale $\tau$ should be close to the break time $t_b$. We assume $\tau = t_b$, and have

$$\frac{2\pi^2 I}{P^2} = L_{\text{sd}} t_b,$$

where $I$ and $P$ are the moment of inertia and rotation period of Mag07, respectively. Theoretically, when the mass of Mag07 $M_{\text{NS}}$ equals the maximum mass $M_{\text{max}}$ that the star can support, the collapse will occur. The critical mass $M_{\text{max}}$ depends on the equation of state (EoS) and rotation period $P$ of NSs. According to the observation of binary neutron star merger GW170817/GRB 170817A, the upper limit on rest mass of NSs is constrained as $M_{\text{NS,max}} \leq 2.2 \, M_{\odot}$ (Margalit & Metzger 2017)\footnote{A stiff EoS still has the possibility of existence (Yu, Liu, & Dai 2018).}. Here, the parameters in the EoS APR4 (Read et al. 2009) that $M_{\text{NS,max}} = 2.2 \, M_{\odot}$, $I = 2.1 \times 10^{45} \, \text{g} \cdot \text{cm}^2$, and star radius $R = 11.0 \, \text{km}$ are adopted.

The spin-down luminosity of Mag07 is

$$L_{\text{sd}} = \frac{8\pi^4 B_{\text{eff}}^2 R_{\text{sd}}}{3\mu^4 P^4},$$

where $B_{\text{eff}}$ is the effective dipole magnetic field strength of Mag07, and $c$ is the speed of light.

In combination with equations (5) and (6), one has

$$P = \left( \frac{\eta_{x,\text{pla}}}{7.2 \times 10^{47} \text{erg} \cdot \text{s}^{-1} \cdot \frac{2\pi^2 I}{t_b}} \right)^{1/2}.$$  

Combining equations (5), (6), and (7) gives

$$B_{\text{eff}} = \left( \frac{\eta_{x,\text{pla}}}{7.2 \times 10^{47} \text{erg} \cdot \text{s}^{-1} \cdot \frac{3\mu^4 P^4}{2R_{\text{sd}}t_b}} \right)^{1/2}.$$  

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The dependence of period $P$ and magnetic field $B_{\text{eff}}$ on the radiation efficiency $\eta_{X,\text{pla}}$ is also shown in Figure 2. As we can see in the upper panel of Figure 2, in addition to having to be less than 1, since there is a breakup spin period 0.96 ms (dash line) for NSs (Lattimer & Prakash 2004), $\eta_{X,\text{pla}}$ has a lower limit 0.32. In the lower panel of Figure 2, corresponding to $\eta_{X,\text{pla}} \in (0.32,1)$, the range of $B_{\text{eff}}$ is $(1.1 \times 10^{15} \text{ Gs}, 1.9 \times 10^{15} \text{ Gs})$.

3 NEUTRINO ANNIHILATION EFFICIENCY

According to the observation, the mass distribution of NSs in the Milky way is usually very homogeneous in the range of $1.2 \text{ M}_\odot$ to $1.6 \text{ M}_\odot$. The average mass of these NSs is close to $1.4 \text{ M}_\odot$ (Zhang et al. 2011). So we assume the mass of the protomagnetar of GRB 070110 is $M_{\text{proto}} = 1.4 \text{ M}_\odot$. After accretion, the magnetar mass increases from $1.4 \text{ M}_\odot$ to $M_{\text{NS}} = M_{\text{NS,max}} + \Delta m$, where $\Delta m$ is the mass correction after considering the centrifugal force. The gravitational force of the extra mass should be balanced by the centrifugal force, so one has

$$\frac{G\Delta m}{R^2} = \frac{4\pi R^2}{P^2}, \quad (10)$$

where $G$ is Newtonian gravitational constant. For $P > 0.96$ ms, there is $\Delta m < 0.4 \text{ M}_\odot$. This result is also consistent with the conclusion of Breu & Rezzolla (2016) that the maximum critical mass of a uniformly rotating NS can increase at most 20 percent of the upper limit on rest mass. Accordingly, the total mass of accretion disk is $M_{\text{dis}} = M_{\text{NS}} - M_{\text{proto}} < 1.2 \text{ M}_\odot$, and the accretion rate is $\dot{M} \approx 0.04 \text{ M}_\odot \cdot \text{s}^{-1}$. The neutrino annihilation efficiency $\eta_{\nu,\varnothing}$ can be expressed as

$$\eta_{\nu,\varnothing} = \frac{L_{\nu,\varnothing} T_{\text{eff}}}{(1+z)M_{\text{dis}} c^2} \geq 1.2 \times 10^{-3}. \quad (11)$$

3 A more accurate method can be referred to Lyford, Baumgarte, & Shapiro (2003).

Figure 2. The dependence of period $P$ and magnetic field $B_{\text{eff}}$ on the radiation efficiency $\eta_{X,\text{pla}}$ (solid lines). Upper panel: There is a breakup spin period (dash line) for NSs (Lattimer & Prakash 2004) that the lower limit of the spin period is 0.96 ms. Therefore, the radiation efficiency $\eta_{X,\text{pla}}$ has a lower limit 0.32. Lower panel: Since $\eta_{X,\text{pla}}$ is in $(0.32,1)$, the range of magnetic field $B_{\text{eff}}$ is $(1.06 \times 10^{15} \text{ Gs}, 1.87 \times 10^{15} \text{ Gs})$.

4 THE COMPARISON BETWEEN THE NS-DISK SYSTEM AND THE BH-DISK SYSTEM

To see what $\eta_{\nu,\varnothing} \geq 1.2 \times 10^{-3}$ means, we compare this value to that of the BH-disk system. In order to exclude unnecessary interferences, the angular momentum, mass and accretion rate of the BH are the same as that of Mag07. Since $P > 0.96$ ms, the dimensionless spin of the BH is

$$\alpha_s \approx \frac{2\pi \dot{M}}{\gpm M_{\text{res,max}}} < 0.3. \quad (12)$$

As mentioned in the introduction, the neutrino annihilation luminosity under BH-disk system is wildly discussed. Some analytic results are shown as follows.

- By fitting the results of Popham et al. (1998), Fryer et al. (1999) obtain an approximate formula, i.e.

$$\log L_{\nu,\varnothing} (\text{erg} \cdot \text{s}^{-1}) \simeq 53.4 + 3.4 \alpha_s + 4.89 \log \dot{m} < 46.9, \quad (13)$$

where $\dot{m} = \dot{M}/(1 \text{ M}_\odot \cdot \text{s}^{-1})$ is the dimensionless accretion rate. The second line of the equation (11) uses $\alpha_s < 0.03$ and $\dot{m} = 0.04$, which is the same below.

- Similarly, by fitting results in Xue et al. (2013), there
is (Liu, Gu, & Zhang 2017)
\[
\log L_{\nu\bar{\nu}}(\text{erg} \cdot \text{s}^{-1}) \simeq 49.5 + 2.45a_\psi + 2.17\log m
\]
\[
< 46.9.
\]
\[
(14)
\]
- When the effect of BH mass into consideration, the annihilation luminosity reads as (Liu et al. 2016)
\[
\log L_{\nu\bar{\nu}}(\text{erg} \cdot \text{s}^{-1}) \simeq 52.98 + 3.88a_\psi - 1.55\log m_{\text{NS}}
\]
\[
+ 5.0\log m < 45.9.
\]
\[
(15)
\]
where \(m_{\text{NS}} = M_{\text{NS}}/M_\odot\).
- Lei et al. (2017) also develop a formula with a broad scope of application about the luminosity of neutrino annihilation, i.e.
\[
L_{\nu\bar{\nu}} = L_{\nu\bar{\nu}}^{\text{ign}} \left[ \left( \frac{m}{m_{\text{ign}}} \right)^{- \alpha_{\nu\bar{\nu}}} + \left( \frac{m}{m_{\text{ign}}} \right)^{- \beta_{\nu\bar{\nu}}} \right]^{-1}
\]
\[
\times \left[ 1 + \left( \frac{m}{m_{\text{ign}}} \right)^{\beta_{\nu\bar{\nu}} - \gamma_{\nu\bar{\nu}}} \right]^{-1},
\]
\[
(16)
\]
where
\[
L_{\nu\bar{\nu}}^{\text{ign}} = 10^{48.0+0.15a_\psi} \left( \frac{m_{\text{NS}}}{1 M_\odot} \right)^{3.3} \text{erg s}^{-1}
\]
\[
\alpha_{\nu\bar{\nu}} = 4.7, \beta_{\nu\bar{\nu}} = 2.23, \gamma_{\nu\bar{\nu}} = 0.3
\]
\[
(17)
\]
and \(m_{\text{ign}}\) and \(m_{\text{trap}}\) are the dimensionless igniting and trapping accretion rates, respectively. According to equations (16) and (17), one can obtain \(L_{\nu\bar{\nu}} < 2.0 \times 10^{47} \text{ erg s}^{-1}\) under \(a_\psi < 0.3\) and \(m < 0.04\).

All these above equations show a similar result \(L_{\nu\bar{\nu}} \sim 10^{47} \text{ erg s}^{-1}\). If one believes this value is right, then it means the NAE on the non-magnetized accretion disk around the BH is at least two orders of magnitude lower than that of the magnetar case under \(\dot{M} \simeq 0.04 M_\odot \cdot \text{s}^{-1}\).

5 THE EXPLANATION OF THE DIFFERENCE OF THE COMPARISON

It is certain that the differences between NS-disk systems and BH-disk systems lead to the different NAEs. In both systems, mass falls by the way of a neutrino dominated accretion flow (Narayan, Paczynski, & Piran 1992). The main differences should be: 1) NSs have solid surfaces, but BHs are not; 2) NSs have strong magnetic fields, while the accretion disks are magnetized, but situations under the BH-disk systems considered in section 4 are just the opposite.

For the first difference, two extra channels that annihilation of neutrinos emitted from the NS surface and annihilation between the neutrino emitted from the accretion disk and the neutrino emitted from the NS surface will make contributions to the total NAE. This enhancement depends on the accretion geometry (Zhang & Dai 2010). Considering the stability of the accretion disk, magnetic pressure should not be greater than the ram pressure of accretion flow (also can see Figure 11 of Zhang & Dai (2010)). So here, the effect of funnel accretion flow is ignored. These two extra channels may increase the NAE by one order of magnitude (Zhang & Dai 2009). The problem of excessive NAE under the NS-disk system is unsolved.

For the second difference, the energy deposition through \(\nu \rightarrow e^+e^-\) and \(\bar{\nu} \rightarrow \bar{e}^+e^-\) in the strong magnetic field will also contribute to the jet power. But, since the magnetic field of Mag07 is smaller than \(1.9 \times 10^{15} \text{ Gs} \) (see Figure 2), and the mass accretion rate is \(\dot{M} = 0.04 M_\odot \cdot \text{s}^{-1}\), this enhancement should be smaller than one order of magnitude (see Figure 7 of Zalamea & Beloborodov (2011)). In this sense, the NAE we have calculated previously should be called “equivalent neutrino annihilation efficiency”. But this effect is still not enough to improve the NAE.

It is necessary to re-examine the energy transfer in accretion process. In general, to convert gravitational potential energy into thermal energy in an accretion disk, a large viscosity coefficient is needed. This large viscosity may be induced by the magneto-rotational instability of small-scale magnetic field. However, the viscosity will lead to the decrease of the surface density of the accretion disk. That’s to say, the magneto-rotational instability will, in turn, inhibit the generation of thermal energy. Therefore, the thermal luminosity is not sensitive to the viscosity coefficient (Kato, Fukue, & Mineshige 1998). When there is a large-scale magnetic field, this situation may be relieved. According to the flux conservation, the magnetic field on the accretion disk satisfies \(B \propto r^{-1}\), where \(r\) is the radius of the disk. A large-scale magnetic field whose magnetic-pressure gradient toward the outside of the accretion disk may prevent the falling motion of matter, as well as the reduction of surface density of the disk. So, the thermalization of the accretion disk will become stronger under this situation. Lei et al. (2009) show a similar result that the strong magnetic field will increase the density of the accretion disk and thus the NAE from quantitative side.

Therefore, we get the following conclusion: the large-scale magnetic field in accretion disk can effectivly enhance the neutrino annihilation luminosity. This enhancement should be about several tens times larger than that of non-magnetized accretion disk, such that when the first two enhancements are also taken into consideration, the higher NAE is acceptable.

6 SUMMARY

The range of mass accretion rate in GRBs is believed to be \((0.01 M_\odot \cdot \text{s}^{-1}, 10 M_\odot \cdot \text{s}^{-1})\). In this paper, we only calculate the NAE under the accretion rate \(\dot{M} \simeq 0.04 M_\odot \cdot \text{s}^{-1}\) through a case study: GRB 070110. In order to get a complete \(\eta_{\nu\bar{\nu}} = \dot{m} - B_{\text{eff}}\) correlation, more samples like GRB 070110 are required. On the observation, the internal plateaus are observed both in the afterglows of short and long GRBs. It is possible to achieve the above goal in the foreseeable future. In our case, \(\eta_{\nu\bar{\nu}} > 1.2 \times 10^{-3}\) is two order of magnitude larger than that of BH central engine. The different accretion geometry between the NS-disk system and the BH-disk system is not enough to explain the higher NAE. Another effect, i.e. the large-scale magnetic field in the accretion disk will obviously improve the NAE, can supplement the deficiency of the former. We have verified previous studies through observation side.

It is worth reminding that, usually, to power a jet through the BZ mechanism, there must be a strong large-scale magnetic field in the accretion disk. Therefore, our result indicates that BZ mechanism and neutrino annihila-
Effect of magnetic field on NAE

5

tion process are both important under the hyper-accreting BH-disk system. The structure of the jet from this BH-disk system may be very different from that of the jet only launched by the BZ mechanism or only produced by the neutrino annihilation process. This structural difference may be very important for explaining some special GRBs, e.g. GRB 170817A (Abbott et al. 2017).

7 ACKNOWLEDGEMENT

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