Neutrino Annihilation Model of NDAF Explaining the Afterglow of GRB 090510

Authors: Lin Yiqing; Cheng Zaijun

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Abstract

Neutrino-dominated accretion disks around stellar-mass black holes can provide energy for gamma-ray bursts through neutrino annihilation emitted from the disk. For black hole hyperaccretion systems, accretion may cause significant evolution of black hole characteristics, which would further lead to evolution of neutrino luminosity. Considering different average accretion rates and initial black hole parameters, we analyze the time evolution of neutrino annihilation luminosity and total neutrino annihilation energy through the evolution of the accretion system. Simultaneously, we calculate the neutrino annihilation energy of the short burst GRB 090510 and compare it with theoretically predicted results, finding that the theoretically predicted neutrino annihilation energy from NDAFs is much higher than the observed value, implying that this model could potentially provide the energy required for the GRB 090510 burst.

Full Text

Preamble

The Neutrino Annihilation Model of NDAF Explaining GRB 090510

Lin Yiqing* and Cheng Zaijun
Fujian Provincial Key Laboratory of Optoelectronic Technology, Xiamen University of Technology, Xiamen, Fujian 361024, China

Abstract

A neutrino-dominated accretion disk (NDAF) surrounding a stellar-mass black hole can power gamma-ray bursts through neutrino annihilation. For black hole hyperaccretion systems, accretion can induce dramatic evolution of the black hole' s characteristics, which in turn affects the neutrino luminosity. By considering different mean accretion rates and initial black hole parameters, we analyze the evolution of the accretion system to calculate the neutrino annihilation energy for GRB 090510. Comparing with theoretical predictions, we find that the theoretical values of NDAF neutrino annihilation energy are much higher than the observed values, suggesting that this model may provide sufficient energy for the GRB 090510 explosion.

Keywords: accretion, accretion disks, black holes, gamma-ray bursts
Classification: P172.3

1. Physical Model Analysis

Gamma-ray bursts (GRBs) are high-energy phenomena where gamma-ray intensity suddenly increases from cosmic space over short timescales, typically lasting from 0.1 to 1000 seconds. Using T90 (the time over which photon counts accumulate from 5% to 95%) as the characteristic timescale, GRBs are classified into long bursts (T90 $>$ 2 s) and short bursts (T90 $<$ 2 s). These two types likely originate from different emission regions and may have fundamentally different progenitors. Long bursts are widely believed to originate from gravitational collapse of massive stars, while short bursts arise from mergers of binary neutron stars or neutron star-black hole systems. Both gravitational collapse and binary mergers can form a hyperaccretion system centered on a stellar-mass black hole with an accretion disk.

In such accretion systems, the neutrino annihilation process is generally considered to power GRBs. A neutrino-dominated accretion flow (NDAF) with extremely high accretion rates surrounding a stellar-mass black hole represents an important candidate for the central engine of GRBs. In the inner region of an NDAF, accreting material reaches extremely high densities and temperatures where protons and photons cannot escape from the disk. Instead, neutrinos carry away viscously generated heat and gravitational binding energy, and their annihilation above the disk may produce the initial fireball.

Previous work derived the maximum possible energy provided by neutrino-powered jets as a function of burst duration, demonstrating that this model can power GRBs lasting less than 100 seconds, while late X-ray flares and ultra-long GRBs are difficult to explain. However, these studies neglected central engine activity and black hole evolution, particularly the evolution of black hole spin. In NDAF models, neutrino radiation and annihilation luminosity are closely related to accretion rate, black hole mass, and black hole spin. If a stellar-mass black hole surrounded by an NDAF truly exists at the center of a GRB, then in such a black hole hyperaccretion system, accretion can cause dramatic evolution of the black hole, inevitably leading to significant changes in black hole parameters, which further affect neutrino annihilation luminosity and total neutrino energy.

We first discuss the evolution of spin under different initial parameters, confirming that black hole evolution causes substantial changes in black hole parameters. We then examine the evolution of neutrino luminosity and total neutrino energy under different parameters, analyzing how black hole parameters affect neutrino luminosity and energy. Finally, using observational data from short burst GRB 090510, we calculate the neutrino annihilation energy for this event and compare it with theoretical predictions to assess the feasibility of this mechanism for explaining the GRB 090510 explosion.

Theoretically, if a hyperaccretion system exists at the center of a GRB, the black hole' s characteristic parameters will evolve significantly over time. Ignoring the BZ mechanism and applying conservation of energy and angular momentum, we obtain the evolution equations for a Kerr black hole:

$$\frac{dM_{\rm BH}}{dt} = \dot{M} e_{\rm ms}, \quad \frac{dJ_{\rm BH}}{dt} = \dot{M} l_{\rm ms}$$

where $M_{\rm BH}$, $J_{\rm BH}$, and $\dot{M}$ are the black hole mass, angular momentum, and mean accretion rate, respectively. Below we use dimensionless parameters for calculation. The specific energy $e_{\rm ms}$ and specific angular momentum $l_{\rm ms}$ at the radius of the marginally stable orbit can be written as:

$$e_{\rm ms} = \frac{1 - 2\chi_{\rm ms}^{-1} + a\chi_{\rm ms}^{-3/2}}{\sqrt{1 - 3\chi_{\rm ms}^{-1} + 2a\chi_{\rm ms}^{-3/2}}}$$

$$l_{\rm ms} = \frac{1 - 2a\chi_{\rm ms}^{-3/2} + a^2\chi_{\rm ms}^{-2}}{\sqrt{1 - 3\chi_{\rm ms}^{-1} + 2a\chi_{\rm ms}^{-3/2}}}$$

where a is the dimensionless black hole spin and $\chi_{\rm ms} \equiv r_{\rm ms}/r_g$ is the dimensionless radius of the marginally stable orbit, with $r_g = GM_{\rm BH}/c^2$. According to these equations, we can derive the evolution of black hole spin over time:

$$\frac{da}{dt} = \frac{\dot{M}}{M_{\rm BH}} \frac{1 - 2\chi_{\rm ms}^{-1} + a\chi_{\rm ms}^{-3/2}}{1 - 3\chi_{\rm ms}^{-1} + 2a\chi_{\rm ms}^{-3/2}} \left[\frac{1 - 2a\chi_{\rm ms}^{-3/2} + a^2\chi_{\rm ms}^{-2}}{1 - 2\chi_{\rm ms}^{-1} + a\chi_{\rm ms}^{-3/2}} - 2a \right]$$

If the initial black hole mass M_i, spin a_i, and accretion rate $\dot{M}$ are given, we can obtain the black hole' s characteristic parameters at any time. The accretion rate must be related to the disk mass, which can be estimated as:

$$M_{\rm disk} = \frac{E_{\gamma,\rm iso} + E_{k,\rm iso}}{\eta c^2} \frac{\theta_j^2}{2}$$

where T_{90} and z are the burst duration and redshift, respectively. For simplicity, we use the dimensionless parameter $m_{\rm disk} \equiv M_{\rm disk}/M_\odot$.

In the NDAF model, since the neutrino annihilation luminosity $L_{\nu\bar{\nu}}$ is closely related to black hole mass $M_{\rm BH}$, spin a, and accretion rate $\dot{M}$, dramatic evolution of black hole mass and angular momentum also leads to evolution of neutrino luminosity. The theoretical expression for neutrino luminosity is:

$$L_{\nu\bar{\nu}} \approx 1.59 \times 10^{45} \left(\frac{M_{\rm BH}}{M_\odot}\right)^{-3/2} \dot{m}^{9/4} \chi_{\rm ms}^{-5} \left(\frac{a}{0.5}\right)^{-3/2} \ \mathrm{erg\ s^{-1}}$$

Integrating this expression yields the total neutrino annihilation energy:

$$E_{\nu\bar{\nu}} = \int L_{\nu\bar{\nu}} dt$$

Observationally, the fireball energy triggering GRB prompt emission and afterglow is mainly provided by neutrino-antineutrino annihilation. Therefore, the total neutrino annihilation energy equals the sum of the isotropic radiation energy $E_{\gamma,\rm iso}$ from prompt emission and the isotropic kinetic energy $E_{k,\rm iso}$ from the long-term afterglow outflow:

$$E_{\nu\bar{\nu}} \approx \frac{E_{\gamma,\rm iso} + E_{k,\rm iso}}{\eta}$$

where η is the conversion efficiency and θ_j is the jet opening angle. Selecting $\eta = 0.3$ allows calculation of the total neutrino annihilation energy from observational data.

2. Results and Analysis

Based on the above equations, we can obtain the time evolution of neutrino annihilation luminosity and total neutrino annihilation energy by appropriately specifying the black hole’ s initial mass M_i, spin a_i, and accretion rate $\dot{M}$.

The reasonableness of parameter selection is crucial, with disk mass being an important factor reflecting model validity. Short bursts originate from compact binary mergers, so the black hole mass is typically less than the total binary mass, i.e., $M_{\rm BH} < M_{\rm total}$. Simulations of double neutron star or black hole-neutron star mergers indicate disk masses of approximately $0.01 - 0.3M_\odot$. We can reasonably assume an initial black hole mass of $2.3M_\odot$ and $3M_\odot$. Using equations (1)-(5), we obtain the relationship curves for spin evolution over time, shown in [Figure 1: see original paper]. In this figure, initial spins of 0 and 0.9 are adopted, with solid and dashed lines representing initial black hole masses of $2.3M_\odot$ and $3M_\odot$, respectively. The evolution of black hole spin shows significant variation over time, which is particularly important for its effect on disk mass. The influence of initial black hole mass on spin evolution is relatively small, so we uniformly select an initial black hole mass of $2.3M_\odot$ for subsequent calculations.

Next, we calculate the evolution of neutrino annihilation luminosity using equation (7), as shown in [Figure 2: see original paper]. In this figure, solid and dashed lines correspond to an accretion rate of $0.2\dot{M}_{\odot}$ with initial spins of 0.5 and 0.9, respectively, while dash-dotted and dotted lines correspond to an accretion rate of $0.5\dot{M}_{\odot}$ with initial spins of 0.5 and 0.9, respectively. The neutrino luminosity varies significantly over time, reaching maximum values of 10^{52} erg s^{-1}.

Neutrino annihilation luminosity calculations do not directly correlate with observational data. To further test the validity of the neutrino annihilation model, we select observational data from short burst GRB 090510 to calculate the total neutrino annihilation energy $E_{\nu\bar{\nu}}$, comparing it with theoretical predictions [Figure 3: see original paper]. According to equation (6), using the T90 and redshift z of GRB 090510, when $M_{\rm disk} = 0.2M_{\odot}$, the accretion rate is 1.27. The three curves correspond to: dashed line–accretion rate 1.27, initial spin 0.9; solid line–accretion rate 1.27, initial spin 0.5; dash-dotted line–accretion rate 0.2, initial spin 0.5. The star symbol represents $E_{\nu\bar{\nu}}$ calculated from GRB 090510 observational data using equation (9). We find that the observed total neutrino annihilation energy of GRB 090510 is far below the theoretical predictions. Moreover, when initial spin or disk mass takes larger values, the accretion rate becomes larger, leading to even greater theoretical predictions for $E_{\nu\bar{\nu}}$.

Table 1 Observational data of GRB 090510

Parameter	Value
F_x (11 hours)	10^{-7} erg cm^{-2}
$E_{\gamma,\rm iso}$	10^{-14} erg cm^{-2} s^{-1}
$E_{k,\rm iso}$	10^{51} ergs
θ_j	10^{51} ergs
$E_{\nu\bar{\nu}}$	10^{48} ergs

[Figure 3: see original paper] shows the comparison between theoretical predictions and observational values of the total neutrino annihilation energy. All three curves assume an initial black hole mass of $2.3M_{\odot}$. The dash-dotted line corresponds to an accretion rate of $0.2\dot{M}_{\odot}$ and initial spin of 0.5; solid and dashed lines correspond to an accretion rate of $1.27\dot{M}_{\odot}$ with initial spins of 0.5 and 0.9, respectively. The curves terminate where the spin exceeds 0.998. The star denotes the observational result for GRB 090510.

3. Conclusions and Discussion

Short bursts most likely originate from mergers of compact binary stars, as this scenario produces relatively small accretion disks with durations comparable to the burst timescale. A neutrino-dominated accretion disk surrounding a stellar-mass black hole can power gamma-ray bursts through neutrino annihilation.

For such a black hole hyperaccretion system, disk mass is an important factor reflecting model validity. Based on short burst data and within the framework of the fireball and neutrino annihilation models, we estimate accretion disk masses using different black hole parameters. We find that short burst disk masses depend primarily on output energy, jet opening angle, and black hole parameters, with black hole spin and accretion rate being particularly important.

By selecting different initial black hole spins and mean accretion rates, we clearly observe significant spin evolution over time: accretion can induce dramatic evolution of black hole characteristics, which further leads to evolution of neutrino luminosity. We discuss the time-dependent evolution of mean neutrino annihilation luminosity and total neutrino annihilation energy under different accretion rates and initial black hole parameters. To further examine whether this model can explain prompt emission and afterglow phases, we select observational data from short burst GRB 090510 to calculate the total neutrino annihilation energy. Comparison with theoretical predictions reveals that GRB 090510' s total neutrino annihilation luminosity lies far below the theoretical curves, significantly smaller than predicted values. This suggests that the theoretical model can readily provide the energy required for the GRB 090510 explosion.

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References

1. Peng Zhaoyang, Qin Yiping. Statistical distinctions of the spectra and light curves between two classes of gamma-ray bursts[J]. *Astronomical Research & Technology—Publications of National Astronomical Observatories of China*, 2004, 1(2): 77-83.

2. Woosley S E. Gamma-ray bursts from stellar mass accretion disks around black holes[J]. *The Astrophysical Journal*, 1993, 405(1): 273-277.

3. Liu T, Hou S J, Xue L, et al. Jet luminosity of gamma-ray bursts: the Blandford-Znajek mechanism versus the neutrino annihilation process[J]. *The Astrophysical Journal Supplement Series*, 2015, 218: 12(7pp).

4. Popham R, Woosley S E, Fryer C. Hyperaccreting black holes and gamma-ray bursts[J]. *The Astrophysical Journal*, 1999, 518(1): 356-374.

5. Leng M B, Giannios D. Testing the neutrino annihilation model for launching GRB jets[J]. *Monthly Notices of the Royal Astronomical Society*, 2014, 445(1): L1-L5.

6. Song C Y, Liu T, Gu W M, et al. Evolution of stellar-mass black hole

hyperaccretion systems in the center of gamma-ray bursts[J]. *The Astrophysical Journal*, 2015, 815: 54-59.

7. Liu T, Lin Y Q, Hou S J, et al. Can black-holes neutrino-cooled disks power short gamma-ray?[J]. *The Astrophysical Journal*, 2015, 806: 58(7pp).
8. Fan Y Z, Wei D M. Short gamma-ray bursts: the mass of the accretion disk and the initial radius of the outflow[J]. *The Astrophysical Journal*, 2011, 739: 47(7pp).

Note: Figure translations are in progress. See original paper for figures.