Black Hole Hyperaccretion in Collapsars. III. GRB Timescale

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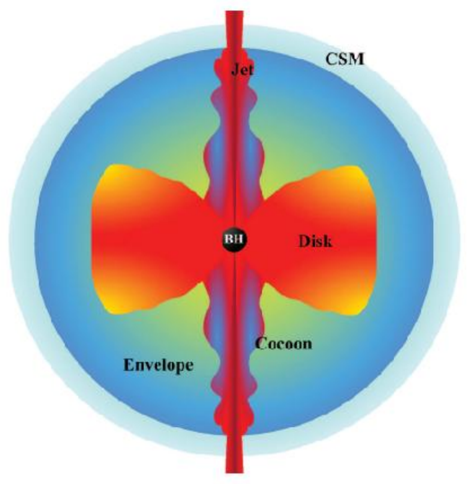
Abstract

Gamma-ray bursts (GRBs) are classified into long and short populations (i.e., LGRBs and SGRBs) based on the observed bimodal distribution of duration T_{90}. Multimessenger observations indicate that most SGRBs and LGRBs should be powered by ultrarelativistic jets launched from black hole (BH) hyperaccretion in compact-object mergers and massive collapsars, respectively. However, the duration criterion sometimes cannot correctly reflect the physical origin of a particular GRB. In the collapsar scenario, a GRB can be observed when the jet breaks out from the envelope and circumstellar medium successfully. The observed GRB duration reflects only the time the engine operates after the jet breaks out. This work studies the propagation of jets driven by the neutrino annihilation or Blandford–Znajek mechanism in massive collapsars. The signatures of the progenitors producing LGRBs, SGRBs, and failed GRBs in the collapsar scenario are exhibited. The competition between the mass supply onto the BH hyperaccretion and jet propagation into the envelope is definitely dependent on the density profiles of the collapsars. We show that duration and isotropic energy $E_{\gamma,\rm iso}$ of GRBs can help constrain the density profiles of collapsars. Finally, we propose that a collapsar-origin SGRB, GRB 200826A, might originate from a neutrino-annihilation-dominated jet launched by a ~10 $M_\odot$ collapsar whose progenitor's envelope has been stripped.

SGRB from Collapsar



Jet Propagation in collapsar

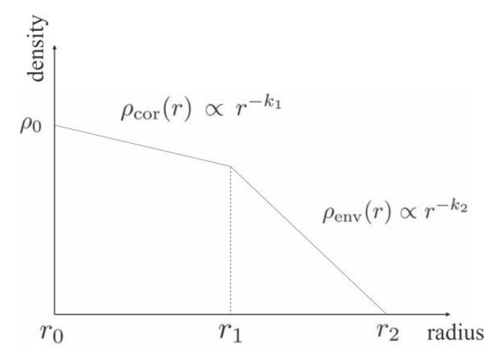
$$t_{\rm GRB} = t_{\rm eng} - t_b$$

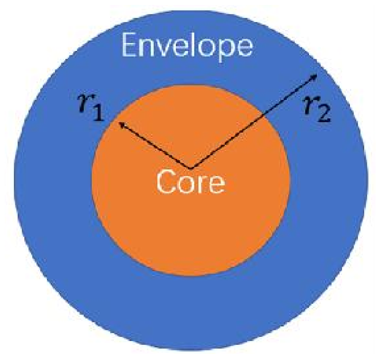
The observed GRB duration reflects only the duration of the central engine after the jet breaks out. Once the observed timescale is less than 2 s, this event is classified as an SGRB. If the jet fails to break out, then no GRB can be detected.

The purpose of this work is to systematically study the dependence of GRB durations on jet propagation in the collapsar scenario.

Method

Progenitor Model





The density profile of collapsar is divided into two parts: star core and envelope.

Jet Model

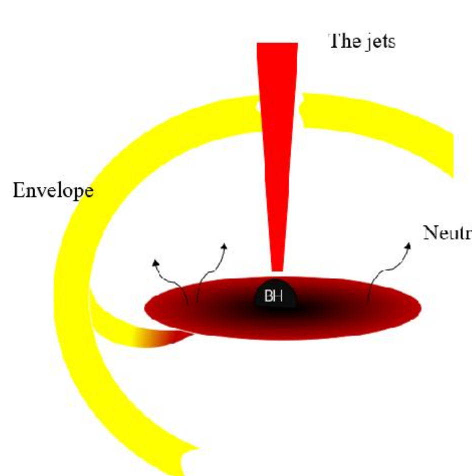
1. Neutrino annihilation

$$\log L_{\nu\bar{\nu}}({\rm erg\ s^{-1}}) \approx 49.50 + 2.45 a_* + 2.17 \log \dot{m}.$$

2. Blandford–Znajek (BZ) mechanism

$$L_j = 1.10 \times 10^{51} \dot{m} + 10^{49.50+2.45a_*+2.17\log\dot{m}}$$

Jet Propagation



$$\beta_h = \frac{1}{1+\tilde{L}^{-1/2}} \qquad r_{\rm h}(t) = \int_0^t c\beta_{\rm h}\, dt$$

$$\tilde{L} \equiv \frac{L_j(t - r_{\rm h}/c)}{\pi r_{\rm h}^2 \theta_j^2 \rho(r_{\rm h}) c^3} \qquad E_\gamma = \int_{t_{\rm b}}^{t_{\rm eng}} \zeta L_j(t)\, dt$$

Results

1. Neutrino annihilation

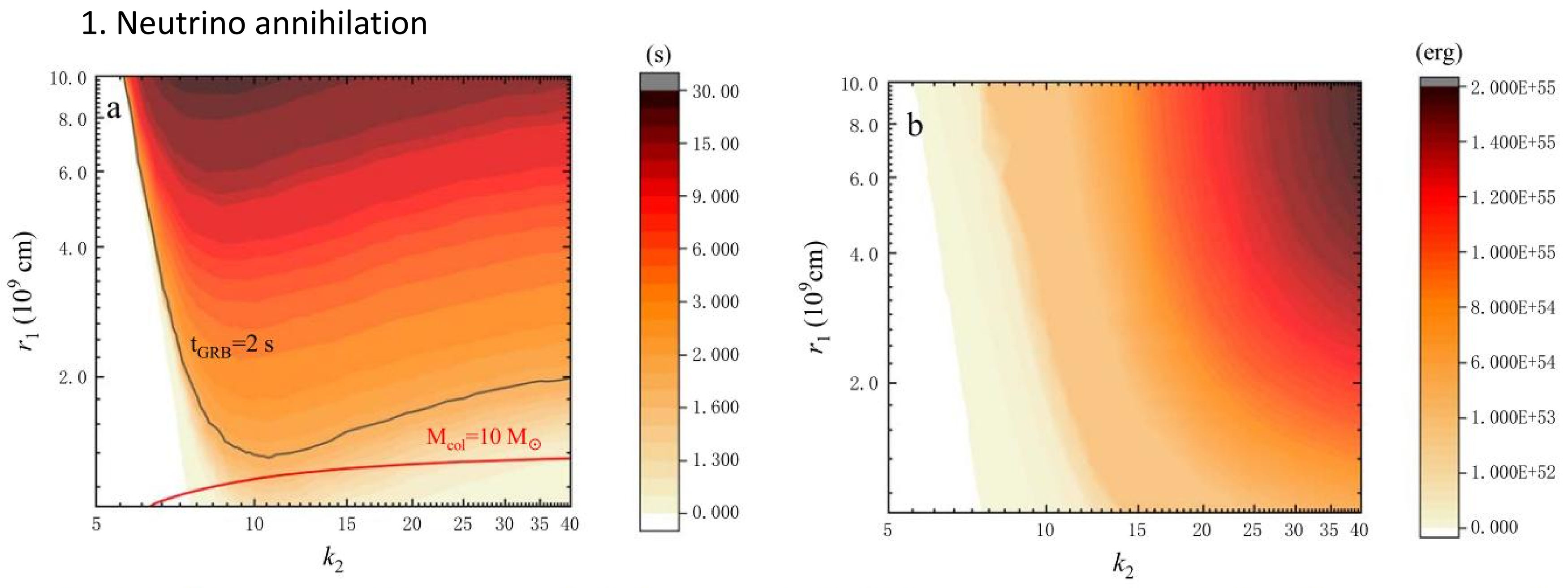
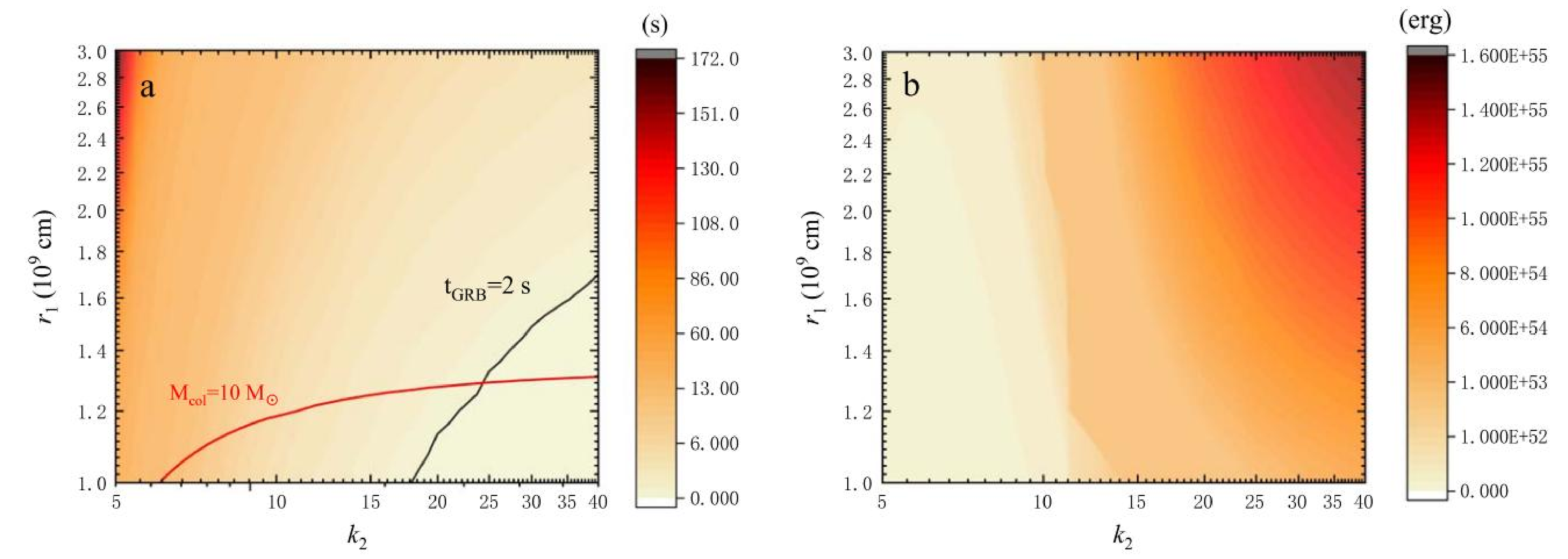


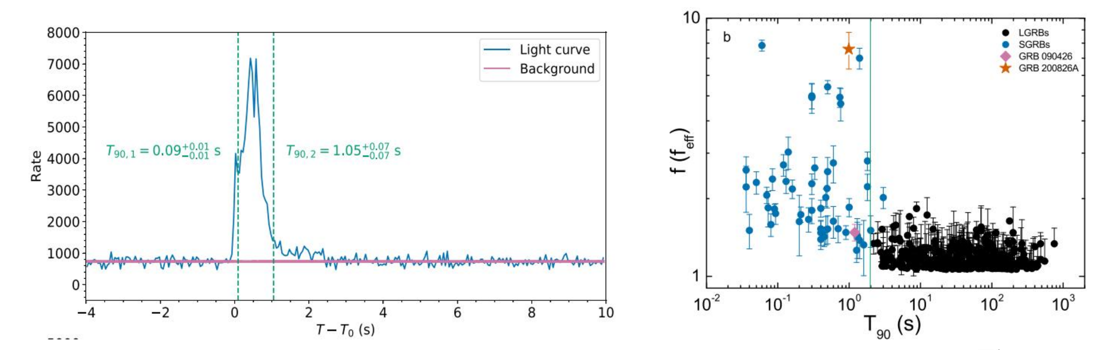
Figure 2. Panel (a): GRB duration $t_{\rm GRB}$ as function of r_1 and k_2 for the first jet model. The black line corresponds to $t_{\rm GRB} = 2$ s. The red line corresponds to collapsar mass $M_{\rm col} = 10\,M_\odot$. Panel (b): isotropic energy $E_{\gamma,\rm iso}$ as function of r_1 and k_2.

2. Blandford–Znajek (BZ) mechanism



Applications to GRB 200826A

GRB 200826A



Zhang et al. (2021)

Constrained collapsar density profiles of GRB 200826A

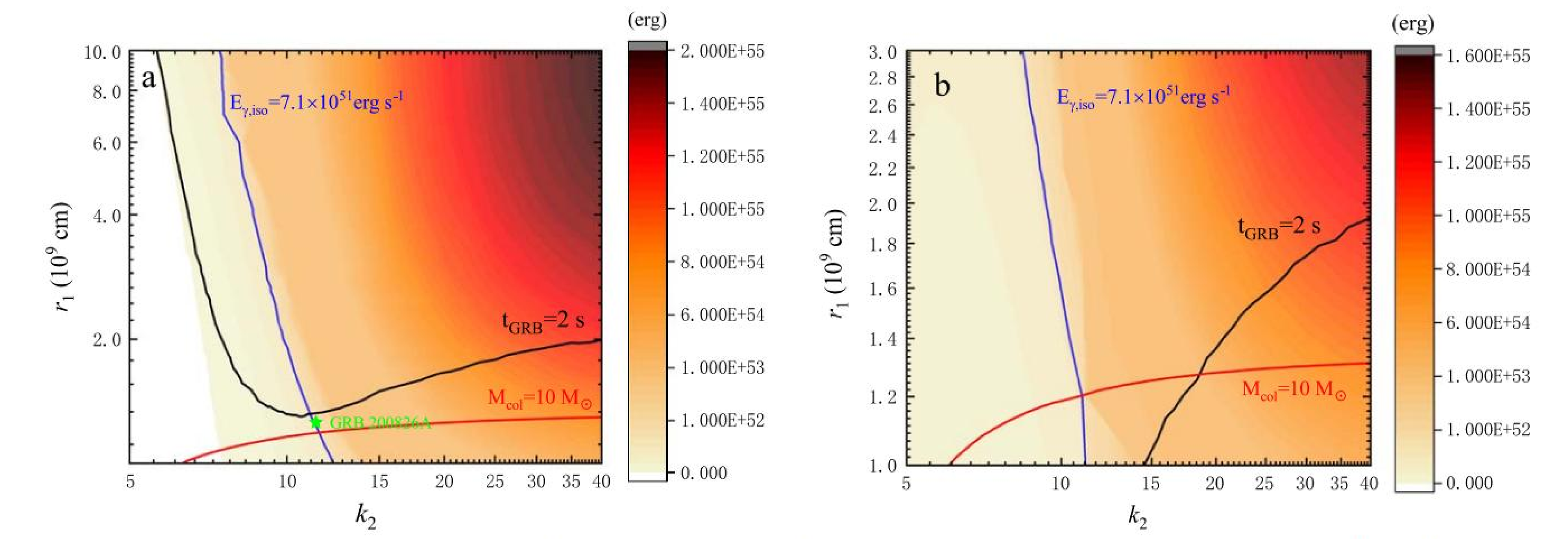


Figure 4. Constrained collapsar density profiles of GRB 200826A. The black and blue lines correspond to $t_{\rm GRB} = 2$ s and $E_{\gamma,\rm iso} = 7.1 \times 10^{51}$ erg s^{-1}, respectively. The red line corresponds to collapsar mass $M_{\rm col} = 10\,M_\odot$. Panels (a) and (b) show the results of the first and second jet models, respectively. The location of GRB 200826A is marked with green pentagram.

Summary

1. Collapsars can produce LGRBs, SGRBs, and failed GRBs in the collapsar scenario.

2. There is competition between mass supply onto the BH hyperaccretion and jet propagation into the envelope.

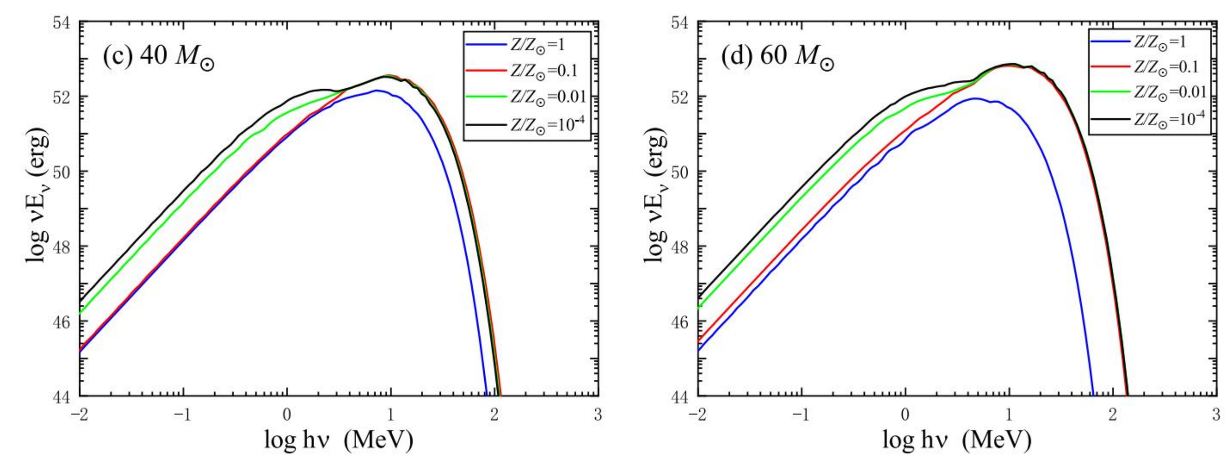
3. The duration and isotropic energy of GRBs can help constrain the density profiles of collapsars.

4. GRB 200826A might originate from a neutrino-annihilation-dominated jet launched by a ~10 $M_\odot$ collapsar whose progenitor's envelope has been stripped.

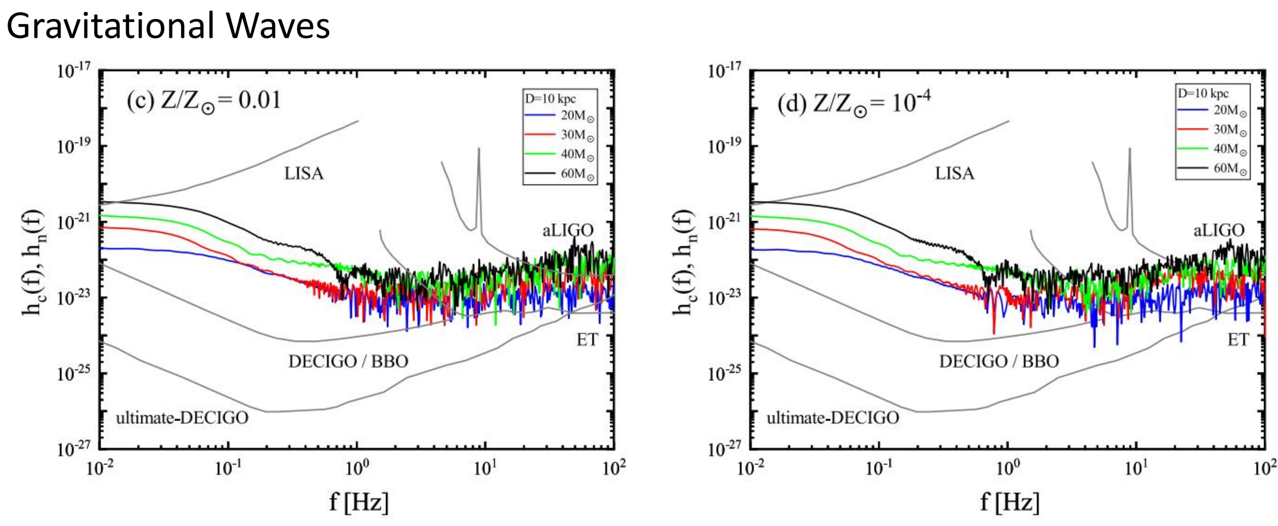
5. Combining with the electromagnetic counterparts and multimessenger astronomy, one may constrain the characteristics of collapsars and central BH accretion systems.

Multimessenger signals from NDAFs

MeV Neutrinos



Gravitational Waves



Paper 1: Black Hole Hyperaccretion in Collapsars. I. MeV Neutrinos 2019, ApJ, 878, 142
Paper 2: Black Hole Hyperaccretion in Collapsars. II. Gravitational Waves 2020, ApJ, 889, 73
Paper 3: Black Hole Hyperaccretion in Collapsars. III. GRB Timescale 2022, ApJ, 936, 182

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