GRB accretion disks and jets

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Central Engine

Mass \sim M_\odot \ (\text{energy reservoir} \sim 10^{54}\text{erg})

ms variability => size < 10^7 \text{cm} — compact object

Progenitors

binary neutron star

collapsing massive star

black hole
Accretion Disks

\[
\begin{align*}
\dot{M} [g/s] & \quad \text{neutrino-cooled} \\
10^{31} & \quad kT=1 \text{ MeV} \\
10^{18} & \quad \text{Eddington limit} \\
\end{align*}
\]

- advective (radiation-dominated)
- standard (radiatively efficient)
- advective (gas dominated)

Physical conditions in the central engine

* Black body
  \[ kT > \text{MeV} \Rightarrow e^\pm \text{population} \]

* \( \rho > 10^{10} \text{ g/cm}^3 \Rightarrow \text{electron degeneracy} \)
  \[ E_{\text{Fermi}} \sim 10 \text{ MeV} \quad \text{mild degeneracy} \]

* Neutrino cooling:
  \[ e^- + p \rightarrow n + \nu \]
  \[ e^+ + n \rightarrow p + \bar{\nu} \]
  Equilibrium n/p ratio

Complete equilibrium is achieved in the accretion disk:
thermodynamic + nuclear + \( \beta \)-equilibrium
$Y_e = \frac{\text{protons}}{\text{protons} + \text{neutrons}}$

Beloborodov (2003)

Self-consistent disk model must include feedback of low Ye (degeneracy) on the cooling rate:

\[ \dot{M} > 10^{32} \text{g/s} \]

\[ v-\text{opaque} \]

\[ v-\text{cooled} \]

Cooling $\rightarrow$ low $T \rightarrow$ degeneracy $\rightarrow$ low positron density $\rightarrow$ reduced cooling rate $\rightarrow$ higher $T$

Regulation toward mild degeneracy
Disk model
- Vertically-averaged
- Neutrino transport (escape probability)
- Full microphysics
- Advection of lepton number and heat included
- Fully relativistic (Kerr geometry)

W. Chen, A. Beloborodov

Neutron-loaded jets

1. Expansion as a single fluid. Adiabatic cooling.

2. n-p decoupling and reheating (Rossi, Beloborodov, Rees 2005)
   Multi-GeV neutrino emission (Derishev, Kocharovsky, Kocharovsky 1999; Bahcall & Meszaros 2000)

3. Neutron-fed blast wave (Beloborodov 2003)

MHD scenario (Vlahakis, Konigl, Peng 2003)
Andrei Beloborodov, Columbia (KITP Jets & Disks Conference 5-23-05) GRB Accretion Disks, Outflows, and External Blast Waves

\[ m_{\text{dec}} = \frac{M}{\Gamma} = \frac{E}{c^2 \Gamma^2} \]

GRB blast wave at the deceleration stage

\[ R_\beta \sim \tau_\beta \quad \Gamma_n c \sim 10^{16} \left( \frac{\Gamma_n}{300} \right) \text{ cm} \quad R_{\text{trail}} \sim 10 R_\beta \]
**Impact of neutrons on the afterglow light curve**

--- Fast and strongly collimated neutron component:

(Fan, Wei, Zhang 2004)

--- Slow and wide neutron component in the MHD jet model:

(Peng, Koniigl, Granot 2004)

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**Summary: GRB disks**

- Neutrino-cooled at $\dot{M} > 0.01$ Msun/s
- Neutrino-opaque at $\dot{M} > 0.1$ Msun/s
- Equilibrium $Y_e$ is achieved: $Y_e \sim 0.1$ for $\dot{M} = 0.1$ Msun/s
  $Y_e \sim 0.2$ for $\dot{M} = 1$ Msun/s
  $\Rightarrow$ neutron-rich material

- Self-consistent disk model is obtained ($Y_e +$ cooling rate + hydro)
- Inviscid mini-disks in GRBs? (size $< 30$ GM/c$^2$)

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- **Neutron-loaded jet** links accretion physics with observed explosion:
  - after initial stage of adiabatic cooling, neutrons reheat the jet
  - later survived neutrons leak out of the ejecta and change the blast wave mechanism