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A Possible Origin of Short-Term Variability in the Prompt Emission of Gamma-Ray Bursts

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Abstract. The central engine of gamma-ray bursts (GRBs) is believed to be a hot and dense disk with hyperaccretion onto a stellar mass black hole. We investigate where the magnetorotational instability (MRI) actively operates in hyperaccretion disks. The inner region of hyperaccretion disks can be neutrino opaque,and the energy- and momentum-transport by neutrinos could affect the growth of the MRI significantly. Assuming reasonable disk models and a weak magnetic field $B \ll 10^{14}$ G, it is found that the MRI is strongly suppressed by the neutrino viscosity in the inner region of hyperaccretion disks. In contrast, the MRI can drive active MHD turbulence in the outer neutrino-transparent region regardless of the field strength. This suggests that the baryonic matter is accumulated into the inner dead zone where the MRI grows inactively and the angular momentum transport is inefficient. When the dead zone gains a large amount of mass and becomes gravitationally unstable, the intense mass accretion would occur episodically through the gravitational torque. This process can be a physical origin of the short-term variability in the prompt emission of GRBs.

1. Introduction

Gamma-ray bursts (GRBs) are generally considered to be powered by the hyperaccretion onto a stellar-mass black hole ($\sim 3M_\odot$), which is formed in the context of the "collapsar" scenario or merging scenarios of compact objects (Woosley 1993; MacFadyen & Woosley 1999). The hyperaccretion rate is of the order of 0.1–1$M_\odot$ sec^{-1} and the release of the gravitational energy powers the burst. The radiative energy ejected through relativistic jets is expected to account for the observed γ-ray emission.

The key process for releasing the gravitational energy is the angular momentum transport in the disk. As in the cases of the other astrophysical disks, magnetic turbulence initiated and sustained by the magnetorotational instability (MRI) is believed to play an essential role for the angular momentum transport in hyperaccretion disks (Balbus & Hawley 1991). Detailed linear and nonlinear analyses of the MRI facilitate us to understand the role of MRI in various disk systems (Turner et al. 2002; De Villiers et al. 2003). However, the physical conditions in hyperaccretion disks are quite different from the other systems. Because the hyperaccretion disk is very dense and hot like supernova cores, it can be cooled through the neutrino radiation (Popham et al. 1999; Di Matteo et al. 2002). In addition, the energy and momentum are mainly transported by neutrinos in the neutrino-opaque region.

Masada et al. (2007; hereafter MSS07) have investigated the effects of the neutrino transport on the MRI in proto-neutron stars, and show that the heat, chemical, and viscous diffusions caused by the neutrino transport have great impacts on the MRI. The heat and chemical diffusions can reduce the effect of stratifications, and the neutrino viscosity suppresses the growth of the MRI. The hyperaccretion disk is considered to have similar properties to it. In particular, neutrinos can be trapped in the inner dense region of hyeraccretion disks and the energy and momentum are mainly transported by the neutrino. We can, thus, apply the results of MSS07 to hyperaccretion disks with little changes.

The growth time of the MRI in the absence of the viscosity is given by λ/v_A, where λ is the wavelength of a perturbation and $v_{\rm A} = B/(4\pi\rho)^{1/2}$ is the Alfvén speed. MSS07 have shown that the growth of the MRI is suppressed if the growth time is longer than the viscous damping time $\sim \lambda^2/\nu$, where ν is the kinematic viscosity. Then, a large enough viscosity can reduce the linear growth of the MRI. As the wavelength becomes longer, the larger size of the viscosity is required to suppress the MRI. Because the typical wavelength of the MRI is $\lambda \sim v_{\rm A}/\Omega$, the condition for the linear growth is given by

$$Re \equiv \frac{LU}{\nu} = \frac{v_A^2}{\nu\Omega} > 1 \ , \tag{1}$$

where Re is the Reynolds number, and Ω is the angular velocity. Here we choose $v_{\rm A}/\Omega$ as the typical length scale L and v_A as the typical velocity U. The Reynolds number is a good indicator for the fast growth of the MRI in hyperaccretion disks. In dense neutrino-opaque matters, the kinematic viscosity via the neutrino transport would be large, so that the condition (1) may not be satisfied. In this paper, we investigate where the MRI operates in hyperaccretion disks focusing on the effects of the neutrino viscosity on the growth of the MRI.

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2. The Structure of Hyperaccretion Disks

We adopt basic equations based on the Newtonian dynamics and assume a quasi-steady structure of hyperaccretion disks. Various disk models have been proposed as the central engine of GRBs (Popham et al.1999; Di Matteo et al.2002), in which the α-prescription of turbulent viscosity is addopted (Shakura & Sunyaev 1973). However, we now have an interest with the features of MRI which can initiate and sustain the turbulent viscosity. It is, thus, necessary to construct disk models independent of the α-parameter. For simplicity, we adopt power-law models for the radial distributions of all physical quantities.

The surface density $\Sigma(r)$ is one of the most important quantities in constructing the disk structure. We assume a power-law distribution with an index q,

$$\Sigma(r) = \Sigma_0 \hat{r}^{-q} \ , \tag{2}$$

where $\hat{r} = r/r_s$ is the distance from the central black hole normalized by the Schwarzschild radius. The Schwarzschild radius is given by $r_s = 2GM_{\rm BH}/c^2 = 8.9 \times 10^5 M_3$ cm, where $M_3 = M_{\rm BH}/(3M_\odot)$ is a mass of black hole normalized by 3 $M_\odot$. Here Σ_0 is a reference value of the surface density at $r = r_s$, and is choosen as $\Sigma_0 = 1.0 \times 10^{18} f_\Sigma$ g cm^{-2}, where f_Σ is an arbitrary parameter. Another key quantity is the temperature, which is assumed to retain a power-law distribution with an index p,

$$T(r) = T_0 \hat{r}^{-p} \ , \tag{3}$$

where T_0 is a reference value and is given by $T_0 = 4.3 \times 10^{11} f_T$ K. Here f_T is arbitrary parameter.

Assuming the gas pressure dominated disk, the sound speed is given by

$$c_{\rm s} = (k_{\rm B}T/m_{\rm p})^{1/2} = 6.1 \times 10^9 f_T^{1/2} \hat{r}^{-p/2} \ \ {\rm cm\ sec^{-1}} \ , \tag{4}$$

where k_B is the Boltzmann constant and m_p is the proton mass. In a gravitationally stable disk, the vertical component of the gravity in the disk is contributed by the central black hole. The hydrostatic equilibrium in the vertical direction determines the scale height of the disk,

$$H = c_{\rm s}/\Omega = 2.5 \times 10^5 f_T^{1/2} M_3 \hat{r}^{-(p-3)/2} \ \ {\rm cm} \ , \tag{5}$$

where the disk is assumed to rotate with the Keplerian angular velocity, $\Omega = \Omega_{\rm K} = 2.4 \times 10^4 M_3^{-1} \hat{r}^{-3/2}$ sec^{-1}. Then the density structure can be evaluated from the relation $\rho = \Sigma/(2H)$. Using these quantities, the radial profile of the neutrino depth is given by $\tau_{\rm tot} = 1.3 \times 10^3 f_\Sigma f_T^2 \hat{r}^{-2p-q}$. Here we assume that both absorption and scattering processes of the neutrino contribute to the neutrino depth (Burrows & Lattimer 1986). In the neutrino-opaque region, we can obtain the neutrino viscosity;

$$\nu = 8.1 \times 10^{10} f_\Sigma^{-2} f_T^3 M_3^{-1} \hat{r}^{3(1-p)+2q} \ \ {\rm cm^2\ sec^{-1}} \ . \tag{6}$$

The strength of the magnetic field is also an important quantity to investigate where the MRI operates in hyperaccretion disks. It is assumed that the pre-collapse core has a magnetic field with $B_p \approx 10^9$ G. With the conservation of the magnetic flux during the collapse, the radial structure of the magnetic field immediate after core-collapse can be estimated as

$$B_{p,{\rm disk}} \simeq 1.0 \times 10^{11} f_\Sigma^{2/3} f_T^{-1/3} f_{\rm B} M_3^{-3/2} \hat{r}^{(p-2q-3)/3} \ \ {\rm G} \ , \tag{7}$$

where $f_{\rm B}$ is the arbitrary magnetic parameter. The Alfvén speed in the disk is then given by

$$v_{\rm A} = 2.0 \times 10^4 f_\Sigma^{1/6} f_{\rm T}^{-1/12} f_{\rm B} M_3^{-1/6} \hat{r}^{(p-2q-3)/12} \ {\rm cm\ sec^{-1}} \ . \tag{8}$$

The power-law indexes of the surface density and temperature are determined by the thermal equilibrium in the disk. Considering that the advection cooling dominates the other cooling processes, the power-law indexes are given by $p = 1.0$ and $q = 0.5$ (Di Matteo et al. 2002). This corresponds to the ADAF (advection dominated accretion flow) type disk. In the following, we investigate where the MRI operates in ADAF-type hyperaccretion disks as an example.

3. Linear Growth of MRI in Hyperaccretion Disks

MSS07 derive the dispersion equation for the MRI including the effects of neutrino transport. We apply it to find out the most unstable modes of the MRI in hyperaccretion disks. The effects of the stratification due to the thermal and leptonic gradients can be ignored for this case. We focus on the linear growth rate of the axisymmetric MRI. This is because the axisymmetric mode is the fastest growing mode of the MRI, and the toroidal component of the field does not affect the linear and nonlinear growth of the MRI if the field strength is subthermal (Sano & Stone 2002).

Assuming a uniform vertical field and considering only the damping effect of the neutrino viscosity, the dispersion equation of MSS07 is then written as

$$\gamma^4 + 2\nu k^2\gamma^3 + [\nu^2 k^4 + 2(k_z v_A)^2 + \kappa^2]\gamma^2 + 2\nu k^2 (k_z v_A)^2\gamma + (k_z v_A)^2[(k_z v_A)^2 - 4\Omega^2] = 0 , \quad (9)$$

where γ is the growth rate, κ is the epicyclic frequency, ν is the neutrino viscosity, and $k = (k_r^2 + k_z^2)^{1/2}$ is the wavenumber. Radial and vertical wavenumbers are described by k_r and k_z. We solve the dispersion equation (9) numerically and show the maximum growth rate of the MRI in hyperaccretion disks.

Figure 1 shows the maximum growth rate of the MRI as a function of the radius for the cases with different magnetic parameters $f_B = 1$, 10, 10^2 and 10^3. The vertical and horizontal axes are normalized by Ω_K and r_s. The parameters f_Σ and f_T are assumed to be unity. The critical radius dividing the neutrino-opaque and neutrino-transparent region locates at $r_{crit} \sim 20 r_s$.

It is found from this figure that the maximum growth rate of the MRI in the neutrino-opaque region is much smaller than that in the neutrino-transparent region if the magnetic parameter f_B is smaller than 10^3. That is, the MRI is strongly suppressed by the neutrino viscosity when the magnetic field is weaker than the critical value, $B_{crit} \approx 10^{14}$ G. Turbulent motions at the nonlinear stage cannot be sustained when the growth rate of the MRI is much less than the angular velocity Ω (Sano et al. 2004). In contrast, MHD turbulence driven by the MRI can grow actively in the neutrino-transparent region regardless of the field strength, because the viscosity effect can beneglected there.

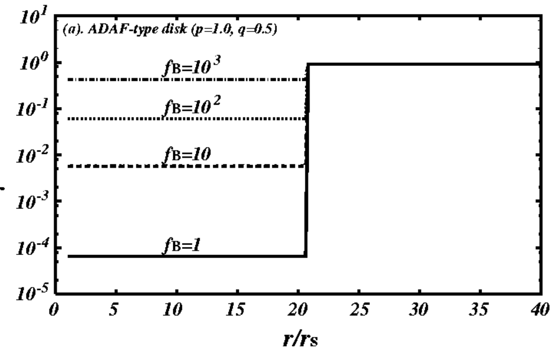

Figure 1. Maximum growth rate of the MRI as a function of the radius for the cases with different parameters $f_B = 1$, 10, 10^2, and 10^3. Other parameters are fixed to be unitiy, $f_\Sigma = f_T = 1$.

4. Episodic Accretion Model for GRBs

As is described in previous section, the MRI is suppressed by the neutrino viscosity in the neutrino-opaque region when the magnetic field is weaker than the critical value, $B_{crit} \approx 10^{14}$G. In contrast, the neutrino-transparent region is unstable for the MRI and its growth rate is of the order of the angular velocity. In what follows, we indicate that the dead zone formation could cause episodic hyperaccretion, which can be the origin of the short-term variability in the prompt emission of GRBs.

We focus on the collapsar disk of mass 1–$2M_\odot$ expected as the central engine of long GRBs and consider the relatively large dead zone ($r_{crit} \sim 20r_s$) formed in its inner part. In such the case, the angular momentum transport in the dead zone would be taken by the neutrino viscosity itself ($\alpha_\nu \sim 10^{-4}$). Thus the mass accretion rate onto the central black hole is given by $\dot{M}_{out} \simeq 10^{-4}\dot{M}_\odot$. Here $\dot{M}_\odot$ is the mass accretion rate of $1M_\odot \sec^{-1}$. On the other hand, in the outer neutrino-transparent region, the angular momentum transport is taken by the turbulent viscosity sustained by the MRI ($\alpha_t \sim 10^{-2}$). Therefore the mass inflow rate into the dead zone is given by $\dot{M}_{in} \simeq 10^{-2}\dot{M}_\odot$. Then the baryonic matter is accumulated into the dead zone as time passes. The mass accumulation rate into the dead zone $\dot{M}_{accu}$ is almost identical to the mass inflow rate ($M_{accu} \approx M_{in}$).

If the baryonic matter is accumulated continuously into the dead zone, it becomes gravitationally unstable at some evolutionary stage and the intense mass accretion of $\dot{M}_g \simeq 0.35\dot{M}_\odot$ is triggered due to the gravitational torque. The duration of the intense accretion phase should be comparable to the viscous timescale in the dead zone (Armitage et al.2001);

$$\tau_g = r^2/\nu = \simeq 0.93 \ \ f_T^{-1} M_3 (\alpha_g/0.05)(r/20r_s)^{3/2} \ \sec , \quad (10)$$

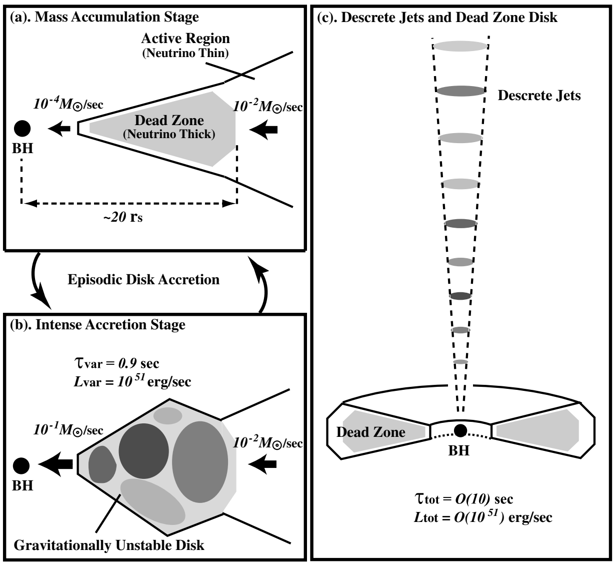

Figure 2. Schematic picture of typical three evolutionary stages of a collapsar disk with a dead zone. Fig(a) shows the mass accumulation stage. The intense accretion stage is represented in Fig(b). Stages (a) and (b) continue episodically until the baryonic matter of the outer region is depleted [Fig(c)]

where $\alpha_{\rm g}$ is the alpha-parameter in the gravitationally unstable region and is choosen as 0.05 here. In addition, the gravitational energy released in this phase is $E_{\rm g} \simeq \eta \dot{M}_{\rm g} \tau_{\rm g} c^2 \simeq 2.4 \times 10^{53} (\eta/0.42)$ erg.

After the intense mass accretion phase, the dead zone returns to a gravitationally stable state because of the decrease of the mass in the dead zone region. However, the mass accretion from the outer active region to the dead zone continues constantly. The quiescent disk progressively evolves to the intense accretion phase again. This cycle would be repeated and the explosive energy release occurs intermittently until the material in the outer active region is exhausted (Fig.2(a),(b)). Finally, the dead zone disk with a low mass accretion rate would be left after the episodic accretion stage (Fig.2(c)).

If the episodic accretion is the origin of multiple relativistic shells, the typical variable timescale $\tau_{\rm var}$ in the prompt emission of GRBs should corresponds to the duration of an intense accretion phase;

$$\tau_{\rm var} \simeq \tau_{\rm g} \simeq 0.93 \ \ {\rm sec} \ , \tag{11}$$

This could be the origin of the observable log-normal feature of the short-term variability in the prompt emission (Nakar & Piran 2002). When a few percent of the gravitational energy is converted to the radiative one, the typical peak luminosity of a variable component is evaluated as

$$L_{\rm var} \simeq f(E_{\rm g}/\tau_{\rm var}) \simeq 2.6 \times 10^{51} (f/0.01) \ \ {\rm erg \ sec^{-1}} \ , \tag{12}$$

where f is the conversion factor from the gravitational energy to the radiative one. These are almost identical to the observed timescale and peak luminosity of variable components in the prompt burst.

The episodic accretion is terminated when the material in the outer active region is exhausted. Then the total duration of the prompt burst is determined by the mass depletion time. Applying the mass inflow rate from outer active region, the total duration and luminosity of the prompt burst is evaluated,

$$\tau_{\rm tot} \simeq M_{\rm tot}/\dot{M}_{\rm in} \simeq \mathcal{O}(10) \ \ {\rm sec} \ , \qquad L_{\rm tot} \simeq f(\eta M_{\rm tot} c^2)/\tau_{\rm tot} \simeq \mathcal{O}(10^{51}) \ \ {\rm erg \ sec^{-1}} \ , \tag{13}$$

where $M_{\rm tot}$ is the total mass of the accretion disk and is assumed as 1–2$M_\odot$ here. Thus our episodic accretion model can explain many observed features of long GRBs quantitatively.

References

Armitage, P. J., Livio, M., & Pringle, J. E. 2001, MNRAS, 324, 705
Di Matteo, T., Perna, R., & Narayan, R. 2002, ApJ, 579, 706
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Masada, Y., Kawanaka, N., Sano, T., & Shibata, K. 2006, ApJ, submitted (astro-ph/0612664)
Masada, Y., Sano, T., & Shibata, K. 2007, ApJ, 655, 447
Nakar, E., & Piran, T. 2002, MNRAS, 331, 40
Sano, T., Inutsuka, S., Turner, N. J., & Stone, J. M. 2004, ApJ, 605, 321
Woosley, S. E. 1993, ApJ, 405, 273