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ON THE PROMPT SIGNALS OF GAMMA RAY BURSTS*

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Abstract

We introduce a new model of gamma ray burst (GRB) that explains its observed prompt signals, namely, its primary thermal spectrum and high energy tail. This mechanism can be applied to either assumption of GRB progenitor: coalescence of compact objects or hypernova explosion. The key ingredients of our model are: (1) The initial stage of a GRB is in the form of a relativistic quark-gluon plasma "lava"; (2) The expansion and cooling of this lava results in a QCD phase transition that induces a sudden gravitational stoppage of the condensed non-relativistic baryons and form a *hadrosphere*; (3) Acoustic shocks and Alfven waves (magnetoquakes) that erupt in episodes from the epicenter efficiently transport the thermal energy to the hadrospheric surface and induce a rapid detachment of leptons and photons from the hadrons; (4) The detached e^+e^- and γ form an opaque, relativistically hot *leptosphere*, which expands and cools to $T \sim mc^2$, or 0.5 MeV, where $e^+e^- \to 2\gamma$ and its reverse process becomes unbalanced, and the GRB photons are finally released; (5) The "mode-conversion" of Alfven waves into electromagnetic waves in the leptosphere provides a "snowplow" acceleration that gives rise to the high energy spectrum of GRB. According to this model, the observed GRB photons should have a red-shifted peak frequency at $E_p \sim \Gamma(1 + \beta/2)mc^2/(1 + z)$, where $\Gamma \sim \mathcal{O}(1)$ is the Lorentz factor of the bulk flow of the lava, which may be determined from the existing GRB data.

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1 Introduction

Gamma ray burst (GRB) events are one of the most violent releases of energy in the Universe, second perhaps only to the Big Bang itself[1]. Within a brief time of $1 - 100$ seconds an energy up to $10^{52}\Omega_\gamma/4\pi$ erg (Ω_γ is the solid angle of the GRB emission), is released as (predominantly) gamma rays in the range of hundreds of keV. Such energy is equivalent to a substantial fraction of the restmass of a typical star (for $\Omega_\gamma = 4\pi$). It is now commonly believed that such prodigious sources of energy are originated at cosmological distances[2]. This conclusion was derived from the optical observations simlutaneous to the flashs of γ-rays of the long bursts ($t_b \sim 10 - 100$ s), where the red-shifts of the optical spectra indicate that $z \sim \mathcal{O}(1)$.

The typical spectrum of a GRB consists of a relatively broad, thermal-like spectrum, with the peak energy E_p located at a few hundred keV[3], which contributes more than half of its total luminosity. In the illustrative case of GRB 990510, activities of low energy spectrum (< 62 keV) precede the main sudden onset of the high energy spectrum (> 330 keV) by a few 10s of seconds[4]. In addition to the spectrum around the peak, a substantial fraction of the total luminosity is contributed from the high energy tail, which can be characterized by a power-law with a (negative) index $\sim$ 2-2.5. In terms of the time structure, GRBs can be calssified into two tpyes: the short bursts that last for $\sim$ 1-10 sec and the long bursts that last for tens to hundreds of seconds. It is interesting to note that while the time duration and profile vary widely over several orders of magnitude, the GRB spectra described above are remarkably universal. Much attention has been devoted to analyzing GRB afterglow as a result of an expanding fireball, which leads to important correspondence between the observational data and phenomenological models[5]. However, a comprehensive understanding of the underlying mechanisms that produces such a fireball and the prompt signals are still lacking[6].

In terms of the progenitor, the current contending models for GRBs can be largely classified into two categories. One assumes the collapse of a super-massive star, or “hypernova", and the other the coalescence of compact objects such as neutron star binaries (NS-NS) or neutron star-black hole (NS-BH) binaries. We note that in both cases the release of 10^{52} ergs of energy is possible. It is likely that the GRB long bursts are generated by hypernovae, whereas the short bursts by coalescences of compact objects. Although the model that we propose in this paper is applicable to both types of progenitors, we will invoke neutron star as a reference in our discussion from time to time. A unified mechanism for the GRB, independent of long or short bursts, is desirable as both their prompt signal spectra and burst size spectra (dn/ds) are remarkably universal.

The “fireball model” of GRB proposed in 1980s[7, 8, 9], which assumes a smooth expansion of the fireball, was later regarded as having difficulty to produce the high energy tail of the spectrum[10]. This difficulty arises from the issue of “baryon loading,” where light particles (such as photons and electrons/positrons as well as neutrinos) cannot be easily detached from the opaque baryonic matter. It is generally believed that such a system would convert most of its energy into kinetic energy of the baryons rather than the luminosity. Indeed, Rees and Meszaros[10] focused on this feature as the major issue of GRB and proposed an alternative “fireball shock model.” In this model the exploding e^+e^- plasma has a bulk Lorentz factor $\Gamma \sim 10^2 - 10^3$ at a radius of $\sim 10^5$ km. While this model addresses the issue of high energy tails, with a large Lorentz factor it remains hundred keV.

We suggest that the key to the understanding of GRB lies in its prompt signals, in particular the thermal portion of the spectrum. In this article we propose a new GRB model which provides a unified picture on the early-stage evolution and thus the mechanism that produces the prompt signals of GRBs. The key ingredients of our model are:

1. In the final stage of either compact-object coalescence or hypernova explosion, large fragments of hadron matter are ejected, most likely non-isotropic. Heated by the release of a large fraction of the system’s gravitational potential energy, the hadrons are melted into quarks and gluons with temperature $\sim$ 200MeV and density $\sim 10^{38}\mathrm{cm}^{-3}$, like a molten lava. The bulk flow of such a “lava,” or *hadrosphere*, however, is only mildly relativistic.

2. The expansion and cooling of this lava results in a QCD (quantum chromodynamics) phase transition at a temperature $\sim$ 120MeV and density $\sim 2 \times 10^{37}\mathrm{cm}^{-3}$ that condensates the relativistic quarks and gluons into non-relativistic baryons. These non-relativistic baryons feel the strong gravity and stop their expansion. This results in the formation of a “hardened” hadrosphere boundary, analogous to the darkening of the lava surface.

3. Acoustic shocks and Alfven waves (magnetoquakes) that erupt in episodes from the epicenter efficiently transport the thermal energy to the hadrospheric surface and induce a rapid detachment of leptons and photons from the hadrons.

4. The detached e^+e^- and γ form an opaque, relativistically hot *leptosphere*, which expands and cools to $T \sim mc^2$, or 0.5 MeV, below which $e^+e^- \to 2\gamma$ and its reverse process become unbalanced, and the GRB thermal photons are released. The observed peak of this portion of the GRB spectrum is $E_p \sim \Gamma(1+\beta/2)mc^2/(1+z)$, where $\Gamma \sim \mathcal{O}(1)$ is the Lorentz factor for the bulk flow of the “lava,” and z is the GRB redshift factor.

5. The existence of a nonlinear e^+e^- plasma-mediated “mode-conversion” effect that converts Alfven waves into electromagnetic waves in the leptosphere. This process provides a novel “snowplow” acceleration mechanism that produces the high energy spectrum of GRB.

In the following sections we elaborate these key points of our model in more details. In Section 2 we discuss the condition for QCD phase transitions and the formation and evolution of the hadrosphere. Section 3 explains an effective mechanism for the detachment of leptons and photons from the hadrosphere. In Section 4 the mode-conversion in the leptosphere and the associated snowplow acceleration are discussed. In section 5 we present our explanation of the GRB thermal spectrum and compare it with the observed GRB data. We summarize our discussion and further prospects in Section 6.

2 Hadrosphere and QCD Phase Transition

We assume that in the final stage of either compact-object coalescence or hypernova explosion, the tremendous concentration of energy triggers the eruption of large fragments of baryon matter. The density of baryon matter under such circumstance is comparable to that of a neutron star, i.e., $\sim 10^{38}\text{cm}^{-3}$. Heated by the system's released gravitational energy, which can be as large as $\sim 0.1 - 0.3$ of the total restmass of the system, such baryon fragments can gain a thermal energy, or temperature, ~ 200MeV.

Under high temperature and density, one expects from quantum chromodynamics (QCD) that the baryon matter turns into a deconfined quark-gluon plasma[11]. A quantitative description of such QCD phase transition has been a major challenge to nuclear physicists who work lattice QCD. The standard approach is to invoke grand canonical ensemble (in which the particle number is not fixed), and therefore the relation between the temperature and the chemical potential. Nevertheless, we believe that the phase transition happens at temperature $T \geq 120$MeV for "zero" baryon and at density $\rho \geq 10^{39}\text{cm}^{-3}$ for much lower temperature[12]. Taking these conditions as our constraint and translating the chemical potential into an average particle density, we can parameterize the QCD phase boundary as

$$\left(\frac{\rho}{\rho_c}\right)^2 + \left(\frac{T}{T_c}\right)^2 = 1, \tag{1}$$

where $\rho_c \sim 10^{39}\text{cm}^{-3}$ and $T_c \sim 120$MeV. Clearly, the initial state of our system is in the quark-gluon phase.

Once quarks are deconfined at such energy-density, they are highly relativistic since their restmasses are as low as $m_u \simeq 4$ MeV and $m_d \simeq 7$ MeV for the up and down quarks, respectively. In this plasma there are about the same order of magnitude in the electron/positron (as well as neutrino) populations as well as thermal energies, since they are in (near) local thermal equilibrium with the relativistic quarks and gluons. Once this "lava" of quark-gluon plasma erupts, it adiabatically expands and cools. We call such a cluster the *hadrosphere*.

As the hadrosphere expands to the radius of ~ 50 km, the quark-gluon plasma density reduces to $\rho_{q-g} \sim 2 \times 10^{37}\text{cm}^{-3}$. From thermodynamics the temperature and density are related by

$$\rho^{1-\gamma} T = \text{const.} \tag{2}$$

For relativistic particles, $\gamma = 4/3$, and we find $T \propto \rho^{1/3}$. Since $\rho \propto 1/V \propto 1/R^3$, we have $T \propto 1/R$. Thus the temperature drops to $T \sim 120$MeV. This is the temperature for QCD phase transition when the density is much lower than the critical one: $\rho \ll \rho_c$. Once $T \simeq T_c$, the quarks and gluons condensate into hadrons. As soon as this happens, neutrons and protons so formed are nonrelativistic, which immediately feel the immense gravity and are thus gravitationally trapped. This gravitational capture of baryonic matter marks the boundary of the hadrosphere.

Note that such a quark-gluon explosion need not be spherically symmetric, and may be irregular or even in chunks. Under the extreme high densities, the hadrosphere is highly opaque and poor in convection. Thus the quark-gluon plasma near the boundary first condensate into baryons while its interior is still molten. This is analogous to the darkening of the lava surface after erupted from the volcano, where the interior of the lava is still red-hot.

3 Separation of Photons and Leptons from Hadrosphere

As mentioned in the Introduction, one seeming difficulty in the fireball model is the lack of mechanism to effciently transport the tremendous luminous energy near instantly across the baryonic matter. Given the extremely high density and therefore short mean-free-path in the fireball, the transport of energy through individual particle kinematics, i.e., thermal convection, would indeed be hard. This is the well-known problem of "baryon loading." It may be overcome, however, by the transport of energy through collective plasma excitations.

In the final stage of compact-object coalescence or the collapse of supermassive star we expect the generation of strong acoustic waves ("internal shocks") and Alfven waves (we may call this "magnetoquakes"). These waves are efficient mass and energy carriers[13] in the interior of the hadrosphere as well as the leptosphere. For example, in the NS–NS or NS–BH coalescence, the violent perturbations of the strong magnetic-field pressure of the host neutron stars ($B \sim 10^{12} - 10^{13}$G) induces the excitation of magnetoquakes. As much as $\sim \mathcal{O}(10^{52})$ erg of energy may be carried by these waves. Due to the compactness of the progenitor, the period of these magnetoquakes is about $\sim \mathcal{O}(100)\mu$sec during each episode. As these shocks approach the boundary of the hadrosphere, the tortional as well as the compressional Alfven waves in the rapidly density-graded stellar magnetosphere are expected to exhibit interesting and important properties[14]. One is precisely the possibility of transport of energies from the epicenter to the hadrosphere boundary during each episode of magnetoquake. Another is the possibility of "mode-conversion" in the leptosphere. The density of the leptospheric e^+e^- plasma decreases rapidly due to its expansion. In such an environment the torsional Alfven waves can mode-convert themselves into the usual electromagnetic waves[15].

At the surface of hadrosphere, where the non-relativistic baryons are suddenly slowed down by self-gravitation as a result of QCD phase transition, the still highly relativistic electrons and positrons, as well as photons and neutrinos, are freely radiating through the surface. Since the temperature at the surface of the hadrosphere is still much higher than that of the electron/positron restmass energy, their chemical potentials are negligible. Thus in close analogy to the standard blackbody (photon) emission process, the loss of electrons and positrons due to emission from the surface is rapidly replenished via pair production processes. From the Stefan-Boltzmann law,

$$J = \alpha T^4, \tag{3}$$

where $\alpha = 5.67\times 10^{-5}$ erg/sec/cm$^2/K^4$, the system can emit above 10^{52} ergs in 10^{-8} second with a temperature of 120 MeV and a radius of 50 km, if such an amount of energy can indeed to efficiently supplied from the heat reservoir underneath the hadrospheric surface.

4 Mode-Conversion in Leptosphere

As mentioned earlier, the emitted e^+e^- and γ are so dense that they are not freely propagating outward. With tremendous near-instant supply of electrons and positrons, the radiated e^+e^- pairs (as well as photons and neutrinos) will likely create shocks. The initial number density of leptons in the lava is as high as $\sim 10^{38}\mathrm{cm}^{-3}$, same as that of quarks and gluons (as well as photons and neutrinos) due to equipartition of relativistic particles. At a radius of 50 km, the corresponding e^+e^- density reduces to $\rho_{e^+e^-} \sim 2 \times 10^{37}\mathrm{cm}^{-3}$. So the mean-free-path is

$$l_e = \frac{1}{\rho_{e^+e^-}\sigma_{QED}} \sim 5 \times 10^{-11}\mathrm{cm}. \tag{4}$$

It is clear that under such a condition this plasma is opaque and adiabatic while expanding. On the other hand, the typical weak interaction, e.g., $e^+e^- \to \nu\bar{\nu}$, cross section is

$$\sigma_{weak} = 1.4 \times 10^{-45}\Big(\frac{4E^2}{m^2c^4} - 1\Big)\mathrm{cm}^2 \sim 10^{-42} - 10^{-45}\mathrm{cm}^2. \tag{5}$$

Thus the neutrino mean-free-path in the leptosphere is

$$l_\nu = \frac{1}{\rho_{e^+e^-}\sigma_{weak}} \sim 5 \times 10^4 - 10^7\mathrm{cm}. \tag{6}$$

This makes the neutrinos marginally opaque in the vicinity of the hadrosphere, but soon become transparent when the leptosphere expands. Therefore in our scenario the neutrinos should follow the same microscopic time structure as the prompt photon signals, but detached from the GRB slightly earlier than the photons during each episode.

As mentioned in the previous section, the internal acoustic and Alfvenic shocks can provide efficient energy transport as well as snowplow acceleration within the dense hadrosphere. In addition, the Alfven waves that continue to propagate across the leptosphere can induce a novel, linear and nonlinear phenomenon called “mode-conversion.” The density of the leptospheric e^+e^- plasma decreases rapidly due to its expansion. It has been observed in the particle-in-cell computer simulations that in such an environment the torsional Alfven waves can mode-convert themselves into ordinary electromagnetic waves[15]. Furthermore, it was observed that inside such an opaque plasma a “self-induced transparency” occurs. Namely, a large number of energetic particles are plowed and accelerated in front of the Alfven wave, which are detached from the opaque, collisional bulk plasma.

When the mode-conversion occurs in the e^+e^- plasma, the converted EM waves proceed ahead of the Alfven waves and the snowplowed particles, forming an integrated overall trinity structure. This structure is capable of converting a large fraction of the wave energy (magnetioquake energy) into kinetic energies of the accelerated particles, as well as the heating of the bulk plasma. In our scenario this mechanism provides the basis of the production of the nonthermal high energy spectrum of GRB. The mechanism of this transport is analogous to "snowplowing": particles are pushed forward in front of the shock waves. The speed of the Alfven wave scales as

$$v_{Alfven} \propto \frac{B}{\sqrt{\rho_{e^+e^-}}} \quad , \tag{7}$$

where B is the transverse magnetic field and $\rho_{e^+e^-}$ is the density of the plasma. Since the density of the leptosphere decreases as it expands, the Alfven waves may pick up non-relativistic particles such as protons in this case, and push them to near the speed of light. In the interim, as larger and larger fractions of the Alfven wave is converted to the EM wave, the acceleration is sustained by the EM wave that brings the protons (as well as electrons) to relativistic energies. More details on this aspect will be reported in a separate paper.

5 Thermal Spectrum of GRB

By the time when the leptosphere expands to a radius ~ 10,000 km and cooled to below the two-photon pair production threshold, i.e., $T \simeq mc^2 \sim 0.5$ MeV, the two-photon pair production and its reversed pair annihilation processes,

$$e^+e^- \leftrightarrow 2\gamma, \tag{8}$$

are out of balance, and the e^+e^- are largely annihilated into photons with a typical energy of $E_{p0} \sim 0.5$ MeV in the rest frame of the bulk flow. Such an annihilation would essentially erase all the positrons, and leaves behind it a residual electron (and proton) population. These electrons (and protons) are originated partially from the pre-eruption contamination by the progenitor, and partially from the surface instabilities of the hadrosphere. We assume that this ep plasma density is $\sim \mathcal{O}(0.01 - 0.1)$ of the final e^+e^- density in the leptosphere boundary, i.e., $n_{ep} \sim 10^{28-29}\mathrm{cm}^{-3}$. With a more diluted ep plasma medium, the system thus becomes relatively more transparent, very similar to the decoupling between radiation and matter, in the Big Bang Universe.

Notice that the observed typical total GRB luminosity, $\sim 10^{52}\Omega_\gamma/4\pi$ erg, when divided by the typical thermal photon energy, i.e., 0.5 Mev ($\sim 10^{-6}$) erg, gives the angular number density (number of particles per solid angle) of GRB photons,

$$N_\gamma \sim \frac{10^{52}\Omega_\gamma/4\pi}{mc^2}\mathrm{erg} \sim 10^{58}\frac{\Omega_\gamma}{4\pi}. \tag{9}$$

It is remarkable that, when normalized to the entire sphere, this number is about the same order of magnitude as the total number of baryons in the progenitor, as it should in our model. We view this as one of the strong supports of our scenario.

The observed thermal portion of the GRB spectrum from this sudden release of the thermal photons at temperature ~ 0.5 MeV at the source's rest frame is affected by three factors: the Lorentz factor of the bulk flow, Γ, of the hardosphere and the leptosphere, its beaming angle relative to our direction of observation, and the red-shift factor, $1+z$, of the event's host galaxy.

If we focus the Doppler effect associated with one particular chunk of "lava," the observed GRB frequency, ω', is related to the emitted one, ω, by

$$\omega' = \Gamma(1 + \beta \cos\theta)\omega, \tag{10}$$

where $\beta^2 = 1 - 1/\Gamma^2$ and θ is the angle between the direction of the lava bulk flow and that of our observation. In our model the individual "lava" may be ejected in different directions at random. Our observation, however, is a statistical average over the GRB hemisphere that is facing us. Such an averaging gives

$$\int_0^1 d\cos\theta(1 + \beta\cos\theta) = 1 + \frac{\beta}{2}. \tag{11}$$

The observed peak energy of the GRB thermal spectrum should thus be

$$E_p \sim \frac{\Gamma(1+\beta/2)}{1+z} E_{p0} \sim \frac{\Gamma(1+\beta/2)}{1+z} mc^2, \tag{12}$$

To further strength our theory, it would be ideal if we can derive the Lorentz factor Γ. Unfortunately we do not have a detail dynamical model for the lava eruption at this point. We do, nevertheless, have a qualitative description of it, and therefore a hueristic argument for the Lorentz factor Γ. We have assumed that the release of the system's gravitational energy can gives rise to $\sim \mathcal{O}(100)$MeV of kinetic energy per baryon. Since the lava is in quark-gluon plasma phase, its Lorentz factor should be of the order $\Gamma \sim \mathcal{O}(10)$ when they are initially ejected from the core. In the process of climbing out of the system's gravitational potential, the lava slows down to a full stop when the baryon condensate occurs near its surface. During such process, the leptons are continuously radiated from the surface of the hadrosphere. Therefore the bulk motion of the eventual "last-scattering surface" of the leptosphere, where the GRB photons are released, should be related to the time-average of the lava bulk flow, but weighed heavily on $\Gamma \sim 1$ to account for the lepton emissions after the hadrosphere stops. Thus the effective Γ should be $\mathcal{O}(1)$.

As explained before, since the detachment of leptons from the hadrosphere is induced by episodes of magnetoquakes, each of which has a period of about 100μsec due to the compactness of the progenitor, the eventual release of the prompt GRB thermal photons are also regulated by such time-modulations, resulting in fine structures in the overall GRB time structure.

The prompt burst emission of GRB was observed with at least three spacecraft: BATSE[16], BeppoSAX[17], and Ulysses[18]. For our interest we focus ourselves on the long-burst events with their red-shifts identified through the corresponding simultaneous land-based optical observations. Our samples of the GRB events are taken from

Piran, Jimenez, and Band[19], based on the data from BATSE. Unfortunately so far there are only 8 GRB events that have the spectrum peak, E_p, as well as the red-shift, z, measured. Among these the event GRB-980425 is discarded for the fact that it was very local ($z \sim 0.01 \ll 1$) and its total luminosity fell sufficiently below that of typical GRBs. Although it has never been explicitly proposed, the thermal nature of the GRB prompt burst spectrum around a few hundred keV range is suggestive from the studies by Meegan[3] and by Briggs et al.[4].

We compare these 7 events to Eq.(12) and derive the Γ factor in each case. Out of the seven, we find four events showing a threshold agreement within 20% accuracy with $\Gamma \sim 1$. Two more events are of the order $\Gamma \sim 1$ within 40% accuracy, while there is one with $\Gamma \sim 2$. The details are shown in Table 1. With the limited statistics, this agreement is encouraging. Obviously, accumulation of more observational data in the future is desired.

Burst Name	E_p^{obs}[keV]	z	$mc^2/(1+z)$	*Derived* Γ
GRB 970508	481	0.84	278	1.3 (~ 1)
GRB 970828	230	0.96	261	0.9 (~ 1)
GRB 971214	156	3.41	116	1.1 (~ 1)
GRB 980703	370	0.97	259	1.2 (~ 1)
GRB 990123	550	1.60	197	1.9 (~ 2)
GRB 990506	450	1.20	232	1.4 (~ 1)
GRB 990510	174	1.62	195	0.9 (~ 1)

6 Conclusions

We have discussed the key features of our new model for GRB. Our scenario appears to be able to provide an explicit physical framework that can explain many of the GRB thermal spectrum characteristics. These include the release of $\sim 10^{52}$ erg of energy from a compact source, the promptness of such a release, and the origin of the GRB spectral peak as well as the high energy tail. Episodes of vibrations and eruptions of acoustic shocks and magnetoquakes, which should have a period of $\sim 100\mu$sec during each burst, induce a fine structure within the overall duration of the prompt GRB signals. While our prediction suffers from the poor statistics, theoretical prediction and observational ones on the peak energy are in encouraging agreement. This comparison may shed some light on the nature of the lava flow. We look forward to further testing our model when more GRB data is becoming available.

As explained, our model can naturally accommodate the generation of a non-thermal, high energy tail in the GRB spectrum through the novel linear and nonlinear mode-conversion and snowplow acceleration mechanisms in the leptosphere. However, this issue is quite involved, and its detail discussion will be presented in a separate occasion.

We have not discussed the physics in the outer plasmosphere (which is formed beyond the boundary of the leptosphere where positrons are essentially all annihilated) in this paper since it is not so relevant to the production of the dominant GRB thermal and non-thermal spectra. The existence of the plasmosphere, however, is in our view essential to another very important astrophysical phenomenon, namely the production of ultra-high energy cosmic rays (UHECR) beyond 10^{20} eV. More details of this part of the physics, as well as the mode-conversion induced snowplow acceleration, will be reported in a separate paper soon.

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