

Very short gamma-ray bursts and primordial black hole evaporation

David B. Cline^{*}, Woopyo Hong¹

University of California at Los Angeles, Department of Physics and Astronomy, 405 Hilgard Avenue, Los Angeles, CA 90095-1547, USA

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Abstract

The search for high energy gamma-ray bursts from primordial black holes has continued for the past 20 years. No positive evidence for the existence of evaporating black holes has been reported. We discuss a very interesting group of gamma-ray bursts of very short time duration and an increasing hard spectrum from the published BATSE catalog. We point out that the trend, i.e., anti-correlation of hardness ratio versus gamma-ray burst duration, would be expected if some of the short gamma-ray bursts came from black holes evaporation. We also study the spatial distribution of these event and a possible fireball model of the PBH evaporation. Future tests for the black hole hypothesis is suggested.

1. Introduction

Ever since the theoretical discovery of the quantum-gravitational particle emissions from black holes by Hawking [1], there have been many experimental searches (see [2] for details) for high energy γ -ray radiations from primordial black holes (PBHs), which would be formed in the early universe [3,4], entering their final stages of extinction. The violent final stage evaporation or explosion is the striking result of the expectation that the PBH temperature is inversely proportional to the PBH mass, i.e., $T_{\text{PBH}} \approx 100 \text{ MeV} (10^{15} \text{ g}/m_{\text{pbh}})$, since the black hole becomes hotter as it radiates more particles and can eventually attain extremely high temperatures.

Previous theoretical efforts [5,6] have been focused on the estimation of the PBHs number density at the present universe by requiring the calculated diffuse photon spectrum from evaporated PBHs at energies around 100 MeV to be smaller than the observed diffuse extragalactic background data [7–9]. According to their estimates in the context of the standard particle physics model, the PBH explosion density of events would be allowed as high as $10 \text{ pc}^{-3} \text{ yr}^{-1}$ if holes are clustered in the galactic halo [5,6]. However, the past 20 years of direct searches for high energy radiations from the PBHs at the final stage of evaporation have lead to various upper limits on the density of events, which range from $7 \times 10^{-10} \text{ pc}^{-3} \text{ yr}^{-1}$ to $8 \times 10^5 \text{ pc}^{-3} \text{ yr}^{-1}$ (see [2] for

^{*} Corresponding author.

¹ Now at: Department of Physics, Catholic University of Taegu-Hyosung, Gyongsan, Hayang 713–702, South Korea.

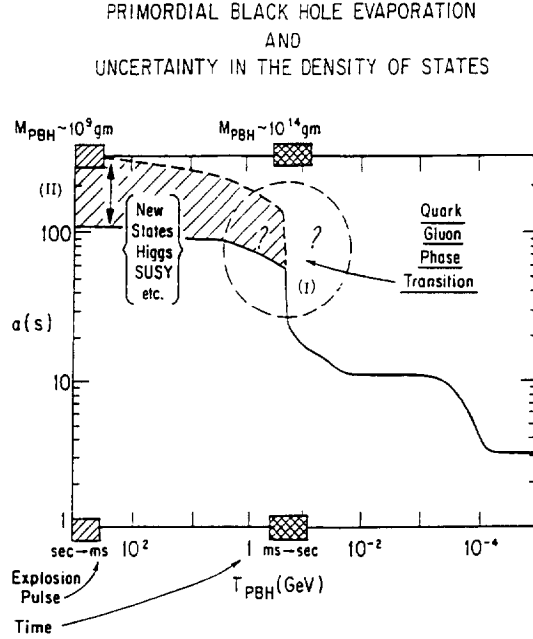


Fig. 1. The running coupling or density of states factor α showing regions of uncertainty due to the quark–gluon phase transitions (I) or the increase in the number of new elementary particles (II). It is possible that intense short γ bursts could occur at either of these temperature (the decrease of mass of the black hole is given by $dm_{\text{pbh}}/dt = -\alpha/m_{\text{pbh}}^2$). A rapid mass decrease or burst can occur when $m_{\text{pbh}} \leq 10^{10}$ g or if α changes rapidly near the quark–gluon phase transition.

a review). These final stage evaporation pictures are closely related to how the emitted particle spectrum from the PBH evaporation changes as the black hole surface temperature approaches a critical point. To be more precise, at $T_{\text{pbh}} \sim 140\text{--}160$ MeV for the Hagedorn model [10], the PBH mass would rapidly convert to hadronic matters (mostly pions) within an extremely short time and, at $T_{\text{pbh}} \sim 100\text{--}300$ MeV for the quark–gluon deconfinement phase transition, the emitted free quarks and gluons would hadronize after some distance from the PBH horizon. As a result these uncertainties in the PBH evaporation mechanism are amplified due to the present lack of understanding in the particle physics around these critical temperatures (see Fig. 1). Thus, the fact that model dependent observational upper limits from high energy γ -rays on the explosion density of events vary almost 10 orders is not too surprising.

Based on previous calculations and numerous direct observational searches for high energy radiation from an evaporating PBH, we might conclude that it is not likely to single out such a monumental event. However, we pointed out in a previous work [11] a possible connection between very short gamma-ray bursts (GRBs) observed by the BATSE team [12] and a PBH evaporation by emitting very short energy γ -rays. If we want to accept this possibility, we may have to modify a way of calculating the particle emission spectra from an evaporating PBH, in particular, at near the quark–hadron plasma (QGP) (see [13] for a review) phase transition temperature at which the T_{PBH} arrives eventually. We briefly discussed in the previous work that inclusion of the QGP effect around the evaporating PBH at the critical temperature may drastically change the resulting γ -ray spectrum. The QGP interactions around the evaporating PBH form an expanding hadronic (mostly pions) matter fireball. Shortly after the decays of pions the initial hadronic fireball converts to a fireball with mixtures of photons, leptons, and baryons. The photons could be captured inside this fireball until the photon optical depth becomes thin enough for the photons to escape as a very short γ -ray burst (an orders of milliseconds duration). As a result the average γ -ray energy emerging from such a fireball could be lower than the previous estimates [5,6]. Thus it might be more likely to be detected as very short GRBs rather than as high energy γ -ray

radiation. This scenario should be consistent with the modern pair-fireball models characteristics developed by several authors [14–19].

In this Letter, in Section 2 we suggest a qualitative model for the PBH evaporation as a fireball which is consistent with a galactic distribution. In Section 3 we present evidences for the PBH evaporation as a fireball based on the published BATSE catalog, i.e., tests for hardness ratio versus PBH burst duration and a homogeneous spatial distribution in our galaxy. Our conclusions follow in Section 4.

2. Concepts of primordial black hole fireball

While quantitative calculations should be dependent on a particle physics model, or energy injection mechanism to the fireball, we may set up general criteria for the PBH evaporation as a fireball to be seen at an order of parsecs from the earth. Since the BATSE detector's observed fluences of $\approx 10^{-7}$ ergs/cm², we require the distance to the PBH fireball (R_{pbh}) and the release of total γ -ray energy (L_{PBH}^γ) during a short period of time to be $L_{\text{PBH}}^\gamma/4\pi R_{\text{pbh}}^2 \geq 10^{-7}$ ergs/cm². In fact, the total γ -ray energy from a PBH evaporation is closely related to the PBH mass at QGP phase transition temperature (roughly $T_{\text{QGP}} \geq 160$ MeV) as $L_{\text{pbh}}^\gamma = \kappa m_{\text{pbh}}$ where κ is a QGP model dependent constant and calculable given a detailed parameter of a particle physics model. When the PBH surface temperature approaches to T_{QGP} , rapid interactions between the emitted quarks and gluons by the Hawking process at the PBH horizon ($\sim 2m_{\text{pbh}}$) may result in a local thermal equilibrium and thereafter form an expanding ultra-relativistic QGP fireball. More detailed conditions for a QGP fireball formation and its opacity at T_{QGP} are to be presented elsewhere (work in progress). Subsequently the QGP fireball converts to a dense matter fireball with the mixtures of pions, baryons, leptons, and radiation at a distance above the PBH horizon. It is expected that due to a high degree of interaction between particles in the high temperature matter fireball (mostly pions) a local thermal equilibrium is obtained at a temperature T .

The thermodynamical parameters, i.e., ρ density, P pressure, for the high temperature matter fireball evolution at an adiabatic perfect fluid limit are a function of one-parameter, i.e., the entropy density s ; $\rho \sim s^\Gamma$ where Γ is an adiabatic index. Γ is a particle model dependent constant, i.e., $\Gamma = 4/3$ (hard) for the standard model, or $\Gamma = 1$ (ultra soft) for the Hagedorn type models [10,20]. If $1 \leq \Gamma < 6/5$, the matter fireball can be treated as a perfect fluid [21]. An evolution of the high temperature matter emitted from the PBH as an adiabatic perfect fluid has been extensively discussed by Carter et al. [21]. Their analysis shows that the matter fireball, conserving the total entropy S , expands to a certain radius above the PBH event horizon

$$r_s \simeq \left[\frac{L_{\text{PBH}}}{4\pi T_{\text{PBH}}} \left(\frac{T}{s(T)} \right) \right]^{1/2}, \quad (2.1)$$

where L_{PBH} is the total energy emitted from PBH. This calculation is based on the assumption that the proper time τ taken for the matter fireball to reach the distance r_s must be longer than the characteristic interaction time τ_0 required for achieving a local thermal equilibrium:

$$\tau \sim \left[\frac{L_{\text{PBH}}}{4\pi T_{\text{PBH}}^4} \left(\frac{T^3}{s(T)} \right) \right]^{1/2} \sim \frac{1}{T_{\text{PBH}}} \left(\frac{T_{\text{PBH}}}{T} \right)^{(\alpha-3)/2} \geq \tau_0, \quad (2.2)$$

where T is determined from the equation of state by $T = d\rho/ds$ and $\alpha \equiv 1/(\Gamma - 1)$. The interaction time τ_0 is a parameter hard to calculate without a definitive particle physics model of the matter fireball. Thus, we assume that τ_0 lies between larger than the basic thermal time scale ($1/T$) and the interaction timescale in the matter fireball ($1/\Lambda_{\text{int}}$), i.e., $1/T \leq \tau_0 \leq 1/\Lambda_{\text{int}}$. Depending on the equation of state (hard or ultra soft, i.e., $3 < \alpha \leq \infty$)

and the temperature of the matter fireball, τ/τ_0 ratio shows whether a perfect fluid treatment of the matter fireball is acceptable,

$$\begin{aligned} \frac{\tau}{\tau_0} &\lesssim \left(\frac{T}{T_{\text{PBH}}} \right)^{(5-\alpha)/2} \lesssim 1 && \text{for } T \lesssim T_{\text{PBH}}; \text{ transparent} \\ \frac{\tau}{\tau_0} &\geq \left(\frac{\Lambda_{\text{int}}}{T_{\text{PBH}}} \right) \left(\frac{T_{\text{PBH}}}{T} \right)^{(\alpha-3)/2} \geq 1 && \text{for } T \geq \Lambda_{\text{int}}; \text{ opaque fluid} \\ \frac{\tau}{\tau_0} &\geq e^4 \left(\frac{T_{\text{PBH}}}{T} \right)^{(\alpha-5)/2} \geq 1 && \text{for } m_e \leq T \leq \Lambda_{\text{int}} \text{ and } T_{\text{PBH}} > T (\alpha > 5); \text{ opaque fluid,} \end{aligned} \quad (2.3)$$

where e is the electronic charge $e^2 = 1/137$. From the last condition in Eq. (2.3), we find that the matter fireball maintains its fluid validity so long as $\Gamma < 6/5$ ($\alpha > 5$) and T_{PBH} is larger than the matter fireball temperature. The question whether initial QGP interactions around PBH horizon create the matter fireball with the adiabatic index ($1 < \Gamma < 6/5$) should be investigated in great details in the future. Using the simplest picture, i.e., only π^0 s produced in the quark gluon phase transition, we can obtain the properties of the fireball. Using Eq. (2.1) and given that $L_{\text{PBH}} \sim L_{\text{QGP}} \sim 5 \times 10^{34}$ ergs and $T_{\text{PBH}} \sim T_{\text{QGP}} \geq 160$ MeV, a simple radiation dominated model would give $r_s \sim 10^9$ cm, which implies that τ is of order 100 ms. Thus, one can expect GRBs from a fireball to have both a very short rise time ($\leq 1 \mu\text{s}$ and duration of ~ 500 – 200 ms also in this model. We expect this model to be generally valid.

3. Characteristics of PBH GRBs

3.1. Hardness ratio versus burst duration

Having studied the available GRB data (see Table 1) we noticed that there is a class of very short GRBs (< 200 ms) that in many cases seem to have a fairly hard γ -ray spectrum. Fig. 2 shows the tendency for an increasing hardness ratio with the shorter GRBs burst durations. This hardness ratio is defined as the fluence (erg/cm^2) in the ~ 100 to ~ 300 keV energy range divided by the fluence in the ~ 50 to ~ 100 keV range. We can find no prediction in the literature for conventional GRB models that give this dramatic behavior. Based on this observation, we may classify some expected characteristics for γ -ray burst from the low energy spectra of the evaporating PBHs as:

Table 1
GRB events selected from the published 1B BATSE catalog [12]

Rank	Trigger #	T_{90} (ms)	Hardness ratio
1	432	34.0	7.46 ± 1.17
2	677	55.0	8.63 ± 1.11
3	289	67.0	8.22 ± 3.35
4	207	85.0	6.88 ± 1.93
5	480	128.0	4.45 ± 1.45
6	1088	128.0	7.24 ± 1.46
7	830	131.0	7.94 ± 3.22
8	1076	161.0	5.34 ± 1.71
9	1102	192.0	2.88 ± 0.72
10	1463	192.0	1.48 ± 0.25
11	1154	193	4.57 ± 1.26

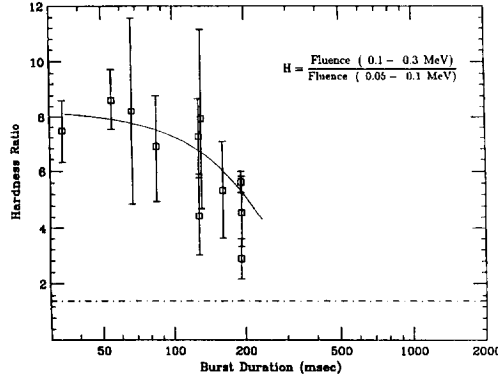


Fig. 2. Hardness ratio for some of the γ bursts reported in the literature. Note that the short time bursts have a much harder spectrum, a trend that would be expected if some of the short bursts came from PBH evaporation. A simple fitting of these data indicates an anti-correlation of hardness versus burst duration. The dash-dot curve represents the average hardness for the bursts of time duration from 1 to 2 s.

(1) There should be a short time burst of $\delta t \ll 1$ s even in the standard particle physics model [2]. In models for rapid evaporation near the critical quark–gluon phase transition temperature we may expect similar effects [11].

(2) The PBH explosion time scales as $\tau_{\text{evap}} \sim m_{\text{pbh}}^3 \sim T_{\text{pbh}}^{-3}$, thus a very short burst will produce a very high temperature, i.e. the energy spectrum average hardness should increase with short time bursts. (However detailed predictions in the 0.05–0.3 MeV range are not possible at present.)

(3) The highest energy particles should be emitted in the shortest time duration.

These characteristics are generic to PBH γ -ray bursts. In addition we might expect that very short bursts would have time frequency components indicative of the source size, i.e., $\delta t \sim l/c < 10^{-6}$ s. This could lead to a definite proof for the existence of a very compact object as the source of GRB. Conditions 1, 2, 3 can be tested with experiments on the CGRO whereas the testing of the theory that very short time structure indicates a very compact source must wait for future γ -ray telescopes in space.

As an illustration purpose, we calculate the hardness ratio based on the pure Hawking process, i.e., only the thermal emission, when the PBH evaporate very rapidly by emitting all the allowed particle states in the standard model. The life time of the PBH, τ_{evap} , over which it completely evaporates, can be approximated as [5]

$$\tau_{\text{evap}} \approx 4.89 \times 10^2 \left(\frac{m_{\text{pbh}}}{10^9 \text{ g}} \right)^3 \text{ ms.} \quad (3.1)$$

In fact there are some interesting theoretical debates at present as to whether the PBH evaporation would continue until it has completely evaporated away [22] or if the evaporation would stop when it shrinks down to an stable Planck-mass object [23], in which case it might serve as a component of the dark matter in the universe. In the following we will not consider the latter case. The total power (ergs) emitted as γ -rays from the PBH, which has mass $m_{\text{pbh}} < 10^9$ g, between $\omega_1 < \omega_\gamma < \omega_2$ and $0 < \delta t < \tau_{\text{evap}}$, is given as

$$P(\omega_1 < \omega_\gamma < \omega_2, \delta t) = \int_0^{\delta t} dt \int_{\omega_1}^{\omega_2} d\omega_\gamma \frac{\Gamma(\omega_\gamma m_{\text{pbh}}) \omega_\gamma}{\exp(8\pi\omega_\gamma m_{\text{pbh}}) - 1}. \quad (3.2)$$

The dimensionless absorption probability for the photon in the limit of low energy [24], for our case $0.05 < \omega_\gamma < 0.3$ MeV, can be given as

$$\Gamma(\omega_\gamma, m_{\text{pbh}}) \approx 4.26 \times 10^{-9} \left(\frac{m_{\text{pbh}}}{10^9 \text{ g}} \right)^4 \left(\frac{\omega_\gamma}{\text{MeV}} \right)^4. \quad (3.3)$$

Thus the hardness ratio of the PBH γ -ray burst in the limit of pure Hawking process is

$$\text{hardness}(\delta t) = \frac{P(0.1 < \omega_\gamma < 0.3 \text{ MeV}, \delta t)}{P(0.05 < \omega_\gamma < 0.1 \text{ MeV}, \delta t)} \approx 250. \quad (3.4)$$

The hardness ratio is constant for $0 < \delta t < 200$ ms since the exponential term is very small, i.e., $8\pi\omega_\gamma m_{\text{pbh}} = 9.4 \times 10^{-5} (m_{\text{pbh}}/10^9 \text{ g})(\omega_\gamma/\text{MeV})$. Of course, this is a crude approximation for the real process around the exploding PBH, which does not include any of the hadronic interactions, yet still might indicate that the final low energy γ -ray spectrum will be very hard. Thus a hard γ -ray spectrum is a natural consequence of a PBH origin! The hardness expected from a pure Hawking process is likely to greatly over estimate the actual hardness when hadrons are emitted, especially at the quark–gluon phase transition. However, we would expect this trend of increased hardness for GRBs from PGH to be an important indicator of this type of physical process. Ultimately, a particle physics model which includes the hadronic interaction for the evaporating PBH could fit the hardness ratio as a function of the burst duration, i.e.,

$$\text{hardness}(\delta t) = \exp(a_0 + a_1 \times \delta t + a_2 \times \delta t^2), \quad (3.5)$$

as indicated by the apparent increase among the observed short GRBs in Fig. 2. A general classification of GRB into two classes has been recently presented [25]. The separation between classes was taken at the two second bursts time. Thus it is not directly related to the analysis in the present paper. However we have inspected the time histories of the hard and short duration bursts and found a large number that have a very simple single spike distribution. This characteristic would also be expected for primordial black hole evaporation.

3.2. Spatial distribution

Since very short γ -rays from the PBH fireball are expected to be seen at the distance at most parsecs around the earth, we expect the short bursts selected among the BATSE data [12] to be a homogeneous and isotropic distribution of sources in a static, Euclidean space (HISE). The unusual testing for homogeneous source distribution is $V/V_{\text{max}} \equiv (C_{\text{lim}}/C_p)^{3/2}$, where C_p is the peak photon count rate and C_{lim} is the minimum detectable photon count rate just prior to the burst. The average value of the V/V_{max} from Table 1 is $\langle V/V_{\text{max}} \rangle \geq 0.24$. This number seems to deviate from the HISE, i.e., 0.5 however this test should not be taken the face value since there may be a bias due to varying thresholds for the detection of burst.

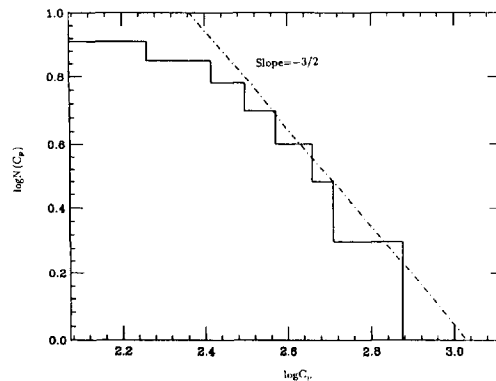


Fig. 3. Plot shows the $\log(N)$ versus $\log(C_p)$ distribution for the events in Fig. 2 with the correction suggested by Petrosian et al. [26,27] applied. Within the statistical determination the corrected distribution is consistent with a slope of $-3/2$ as expected for a Euclidean and homogeneous distribution of sources.

To make any reasonable assessment about the spatial distribution of the short GRBs, we need to study the $\log N(C_p)$ versus $\log(C_p/C_{\text{lim}})$ or $\log(C_p)$. This distribution may contain a bias due to the variable threshold, burst durations as suggested by Petrosian [26,27]. By following their suggestions, we corrected for the bias due to the variability of C_{lim} obtaining the distribution shown in Fig. 3. Within the statistical limitations the corrected distribution is consistent with a slope of $-3/2$ as expected for HISE. The other parameters of these events are also, within error, consistent with this assumption. However the low statistics and uncertainty in the correction this provides only a consistency check for the possibility that these events could be the result of the PBH GRBs.

4. Conclusion

To summarize, we have pointed out that there is a distinct class of very short time GRBs that have an increasing hardness with decreasing time duration below a few hundred milliseconds. We also pointed out that this is the generic behavior that would be expected from the evaporation of PBH in the final stages within a fireball model. The rate of short GRBs is fully consistent with current limits on the PBH density in the galaxy [2,11]. We also studied the spatial distribution of the events that is not inconsistent with a PBH origin. Finally, we described some future tests of the PBH origin of such events that would provide definite evidence for this hypothesis. The most important test would be to discover very short sub-microsecond time structure in this class of GRBs. There are no current γ -ray telescopes in space that have this ability. We can think of few observations in nature that would be as significant as the discovery of primordial black holes [1].

We want to stress that no claim is being made here that PBHs have been observed; however, we are pointing out that the characteristics of the short burst identified here could be a hint of such a phenomena that we believe deserves more attention in the future.

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