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# FURTHER EVIDENCE FOR SOME GAMMA-RAY BURSTS CONSISTENT WITH PRIMORDIAL BLACK HOLE EVAPORATION

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## ABSTRACT

Previously we identified some short burst events from the BATSE 1B catalog that were consistent with an origin of primordial black hole evaporation at the quark-gluon phase transition. We showed that these events are also consistent with arising from a homogeneous spatial distribution. Recently the PHEBUS group has also indicated that the short bursts are consistent with $V/V_{\rm max} \sim 1/2$. In this paper we describe the results of the study of the BATSE 3B catalog shape that confirm the results from BATSE 1B.

*Subject headings:* black hole physics — gamma rays: bursts

## 1. INTRODUCTION

The search for evidence for primordial black holes (PBHs) has continued since the first discussion by Hawking (1974). In fact, this was about the time that gamma-ray bursts (GRBs) were first discovered, making a natural association with PBHs (Klebesadel, Strong, & Olsen 1973). However, in the intervening years it has become clear that the time history of the typical GRB is not consistent with the expectations of PBH evaporation. We started our study with an expectation that perhaps none of the GRBs are consistent with a PBH origin and we wished to see if any GRBs had characteristics that would be consistent with PBH origins.

While the theory of the PBH evaporation has been refined, there are still no exact predictions of the GRB spectrum, time history, and so forth (Halzen et al. 1991). However, reasonable phenomenological models have been made, and the results again indicate that most GRBs could not come from PBHs (MacGibbon & Carr 1991; Cline & Hong 1992). In addition, there are new constraints on the production of PBHs in the early universe that indicate that the density of PBHs in the universe should be very small but not necessarily zero (Carr & Lidsey 1993).

After the initial discovery of gamma-ray bursts it took many years to uncover the general properties. Around 1984 several GRBs were detected, indicating that there was a class of short bursts with time duration of $\sim 100$ ms and a very short rise time (Barat et al. 1984). A separate class of GRBs was declared (Norris et al. 1984). This classification seems to have been forgotten and then rediscovered by some of us (Cline & Hong 1996). Because of the trigger conditions of BATSE and other GRB detectors, it is still unclear as to whether bias exists in the detection of short bursts or that there are even shorter bursts ($\Delta\tau \sim ms$) that have so far escaped detection (Norris et al. 1984). A few short bursts were observed by the Interplanetary Network providing a good location, but no counterparts were detected in these locations (Laros et al. 1981). The shortest published GRB prior to BATSE was 48 ms, which occurred on 1979 June 13 (with BATSE, an 8 ms burst was observed (Bhat et al. 1992). This is a prime example of a well-localized GRB, having no apparent counterpart in other parts of the electromagnetic spectrum (Barat et al. 1984). (The SIGNE detector has apparently observed shorter bursts, but no publication exists to date.)

It is still possible that there is a sizable density of PBHs in our Galaxy and that some of the GRBs could be due to PBH evaporation. Recently we showed that the BATSE 1B data (Fishman et al. 1994) have a few events that are consistent with some expectation of PBH evaporation (short bursts with time duration of less than 200 ms and that are consistent with $V/V_{\rm max} \sim 1/2$) (Cline & Hong 1996). In addition, the PHEBUS team recently reported at the ESTEC/gamma-ray burst meeting, a similar class of events observed in their experiment. These events have a short time history, which tends toward giving $V/V_{\rm max} \sim 1/2$, making them consistent with a homogeneous population of emitters (Terekhov et al. 1995). Since there is no evidence that these GRB are localized in the Galactic disk or center, it is conceivable that PBHs in the vicinity of the solar system could be the progenitors of the GRBs. We note that recently it has been proposed that there are at least two classes of GRBs (Kouveliotou et al. 1993).

In this paper we summarize our previous results (Cline & Hong 1996; Cline 1996) from BATSE 1B data (Fishman et al. 1994) and present a preliminary analysis of the BATSE 3B data (Meegan et al. 1996) from the standpoint of the original conjecture that they arise from PBHs.

## 2. PRIMORDIAL BLACK HOLE EVAPORATION

### 2.1. *The Quark Gluon Phase Transition Model*

Ever since the theoretical discovery of the quantum-gravitational particle emissions from black holes by Hawking (1974), there have been many experimental searches (see Halzen et al. 1991 for details) for high-energy $\gamma$-ray radiation from primordial black holes. They would have been formed in the early universe (Carr, Gilbert, & Lidsey 1994; Carr & Lidsey 1993) and would be now 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., $T_{\rm PBH} \approx 100$ MeV ($10^{15}$ g$/m_{\rm PBH}$), since the black hole becomes hotter as it radiates more particles and can eventually attain extremely high temperatures.

Previous theoretical efforts (MacGibbon & Carr 1991; Page & Hawking 1976) have been focused on the estimation of the number density in the present universe of PBHs 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 (Trombka et al. 1977; Fichtel, Simpson, & Thompson 1978; Gibbs 1988). According to their estimates, in the context of the standard model of particle physics, the PBH explosion density of events could be as high as 10 $\mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$ if holes are clustered in the Galactic halo (MacGibbon & Carr 1991; Page & Hawking 1976). However, the past 20 years of direct searches for high-energy radiation from the PBHs at the final stage of evaporation have led to various upper limits on the density of events, ranging from $7 \times 10^{-10}\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$ to $8 \times 10^{5}\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$ (see Halzen et al. 1991 for 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 $T_{\mathrm{PBH}} \sim$ 140–160 MeV for the Hagedorn model (Hagedorn 1965), the PBH mass would rapidly convert to hadronic matter (mostly pions) within an extremely short time and, at $T_{\mathrm{PBH}} \sim$ 100–300 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 because of the present lack of understanding in particle physics around these critical temperatures. Thus, the fact that model-dependent upper limits on the explosion density of events, observed as high-energy $\gamma$-rays, vary almost 10 orders of magnitude.

Hawking (1974) showed in a seminal paper that an uncharged, nonrotating black hole emits particles with energy between $E$ and $E + dE$ at a rate per spin of helicity state of

$$\frac{d^2N}{dtdE} = \frac{\Gamma_s}{2\pi\hbar}\left[\exp\left(\frac{8\pi GME}{\hbar c^3}\right) - (-1)^{2s}\right]^{-1} . \tag{1}$$

Here $M$ is the PBH mass, $s$ is the particle spin, and $\Gamma_s$ is the absorption probability. One can consider this particle emission as coming from the spontaneous creation of particle-antiparticle pairs near the black hole's event horizon. One particle of the particle-antiparticle pair escapes to infinity while the other returns to the black hole. Thus, the PBH emits massless particles, photons, and light neutrinos, as if it were a hot blackbody radiator with temperature $T \cong (10^{16}\ \mathrm{g}/M)$ MeV, where $M$ is the black hole mass. A black hole with one solar mass, $M_1 \cong 2 \times 10^{33}$ g, has an approximate temperature of $10^{-3}$ K, while a black hole with mass of $6 \times 10^{14}$ g has a temperature of $\sim$20 MeV. The temperature of a black hole increases as it loses mass during its lifetime. The loss of mass from a black hole occurs at a rate, in the context of the standard model of particle physics, of

$$\frac{dM}{dt} = -\frac{\alpha(M)}{M^2} , \tag{2}$$

where $\alpha(M)$, the *running constant*, counts the particle degree of freedom in the PBH evaporation. The value of $\alpha(M)$ is model dependent. In the standard model, with a family of three quarks and three leptons, it is given (Cline & Hong 1992; Hawking 1974, 1975) as $\alpha(M) = (0.045\ S_{j=+1/2} + 0.162\ S_{j=1}) \times 10^{-4}$, where $S_{j=+1/2}$ and $S_{j=1}$ are the spin and color degrees of freedom for the fermions and gauge particles, respectively. For the standard model one obtains $\alpha(M) = 4.1 \times 10^{-3}$. In the Hagedorn-type picture, a model different from the standard model, the number of emitting particle states grows exponentially with mass (Huang & Weinberg 1970) $\rho(m) \sim m^{-\beta}\exp(m/\Lambda)$, where $5/2 \leq \beta \leq 7/2$ and 140 MeV $\leq T \leq$ 160 MeV. These models were motivated by the apparent exponential increase in the hadronic resonance seen by accelerator experiments. While lattice calculations give no evidence for the Hagedorn-type models, such models are not yet excluded.

A reasonable model of the running coupling constant is illustrated in Figure 1, where the regions of uncertainty are indicated. These are the regions where there could be a rapid increase in the effective number of degrees of freedom due to the quark-gluon phase transition. The phase transition would lead to a rapid burst in the PBH evaporation or, at high energy, there could be many new particle types that would also lead to an increase in the rate of evaporation. Also shown in Figure 1 are the regions in PBH temperature where short duration $\gamma$-ray bursts may occur when the PBH mass is either $10^{14}$ or $10^{9}$ g.

Black holes at the evaporation stage at the present epoch can be calculated as having $M_* \cong [3\alpha(M_*)\tau_{\mathrm{evap}}]^{1/3} \cong 7.0 \times 10^{14}$ g for $\alpha(M_*) \cong 1.4 \times 10^{-3}$. The bound on the number of black holes at their critical mass, constrained by the observed diffuse gamma-ray background, has been put in the 10–100 MeV energy region (Halzen et al. 1991):

$$N = \left.\frac{\mathrm{dn}}{d(\ln M)}\right|_{M=M_*} \leq 10^5\ \mathrm{pc}^{-3} . \tag{3}$$

Thus, the number of black holes with critical mass $M_*$ in their final state of evaporation is

$$\frac{dn}{dt} = \frac{3\alpha(M_*)}{M_*^3} N = 2.2 \times 10^{-10}\ N\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1} . \tag{4}$$

### 2.2. *Concept of a Primordial Black Hole Fireball*

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 (Cline & Hong 1992) a possible connection between very short gamma-ray bursts (GRBs) observed by the BATSE team (Fishman et al. 1994) and PBH evaporation emitting very short energetic $\gamma$-rays. If we want to accept this possibility, we may have to modify the method of calculating the particle emission spectra from an evaporating PBH, in particular, at or near the quark-gluon plasma (QGP) (see Rafelsky & Muller 1982 for a review; Cline 1996) phase transition temperature at which the $T_{\mathrm{PBH}}$ 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 $\gamma$-ray spectrum. The QGP interactions around the evaporating PBH form an expanding hadronic (mostly pions) matter fireball. Shortly after the decay 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

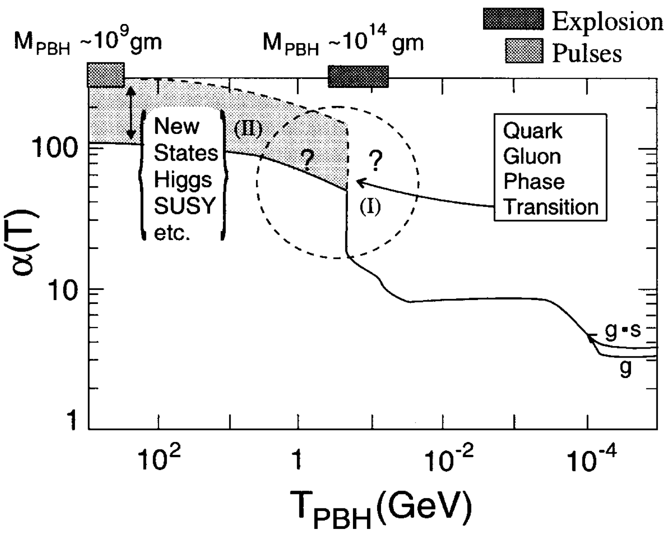


FIG. 1.—Running coupling or density of states factor $\alpha$, showing regions of uncertainty due to the quark-gluon phase transitions (I) or the increase in the number of new elementary particles (II). It is possible that intense short $\gamma$-ray bursts could occur at either of these temperatures (the decrease of mass of the black hole is given by $d\,m_{\rm PBH}/dt = -\alpha/m_{\rm PBH}^2$). A rapid mass decrease or burst can occur when $m_{\rm PBH} \le 10^{10}$ g or if $\alpha$ changes rapidly near the quark-gluon phase transition.

to escape as a very short $\gamma$-ray burst (duration on the order of milliseconds). As a result, the average $\gamma$-ray energy emerging from such a fireball could be lower than the previous estimates (MacGibbon & Carr 1991; Page & Hawking 1976). Thus it might be more likely to be detected as very short GRBs rather than as high-energy $\gamma$-ray radiation. This scenario should be consistent with the modern pair-fireball model's characteristics developed by several authors (Goodman 1986; Paczyński 1986; Shemi & Piran 1991; Mészáros, Laguna, & Rees & 1993; Narayan, Paczyński, & Piran 1992; Piran & Shemi 1993; Piran, Shemi, & Narayan 1993).

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 Earth. Since the BATSE detector's observed fluences of $\approx 10^{-7}$ ergs cm$^{-2}$, we require the distance to the PBH fireball ($R_{\rm PBH}$) and the release of total $\gamma$-ray energy ($L_{\rm PBH}^{\gamma}$) during a short period of time to be $L_{\rm PBH}^{\gamma}/4\pi R_{\rm PBH}^2 \ge 10^{-7}$ ergs cm$^{-2}$. In fact, the total $\gamma$-ray energy from a PBH evaporation is closely related to the PBH mass at a QGP phase transition temperature (roughly $T_{\rm QGP} \ge 160$ MeV) as $L_{\rm PBH}^{\gamma} = \kappa m_{\rm PBH}$, where $\kappa$ is a QGP model-dependent constant and calculable, given a detailed parameter of a particle physics model. When the PBH surface temperature approaches $T_{\rm QGP}$, rapid interactions between the emitted quarks and gluons by the Hawking process at the PBH horizon ($\sim 2\,m_{\rm PBH}$) may result in a local thermal equilibrium and thereafter form an expanding ultrarelativistic QGP fireball. 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, because of 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 thermodynamics parameters, i.e., the density $\rho$ and the pressure $P$, for the high-temperature matter fireball evolution at an adiabatic perfect fluid limit are a function of one parameter, i.e., the entropy density $s$, with $\rho \sim s^{\Gamma}$, where $\Gamma$ is an adiabatic index. $\Gamma$ 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 (Hagedorn 1965; Frautschi 1971). If $1 \le \Gamma < 6/5$, the matter fireball can be treated as a perfect fluid (Carter et al. 1976). An evolution of the high-temperature matter emitted from the PBH as an adiabatic perfect fluid has been extensively discussed by Carter et al. (1976). Their analysis shows that the matter fireball, conserving the total entropy $S$, expands to a certain radius above the PBH event horizon:

$$r_s \cong \left[\frac{L_{\rm PBH}}{4\pi T_{\rm PBH}^4}\frac{T^3}{s(T)}\right]^{1/2}, \tag{5}$$

where $L_{\rm PBH}$ is the total energy emitted from PBH. This calculation is based on the assumption that the proper time $\tau$ taken for the matter fireball to reach the distance $r_s$ must be longer than the characteristic interaction time $\tau_0$ required for achieving a local thermal equilibrium:

$$\tau \sim \left[\frac{L_{\rm PBH}}{4\pi T_{\rm PBH}^4}\frac{T^3}{s(T)}\right]^{1/2} \sim \frac{1}{T_{\rm PBH}}\left(\frac{T_{\rm PBH}}{T}\right)^{(\alpha-3)/2} \ge \tau_0\,, \tag{6}$$

where $T$ is determined from the equation of state by $T = d\rho/ds$ and $\alpha \equiv 1/(\Gamma - 1)$. We have made the approximation that the fireball can be parameterized by a temperature. In general, these processes will have a strong nonthermal property. The interaction time $\tau_0$ is a parameter hard to calculate without a definitive particle physics model of the matter fireball. Thus, we assume that $\tau_0$ lies between the basic thermal time scale ($1/T$) and the interaction time scale in the matter fireball ($1/\Lambda_{\rm int}$), i.e., $1/T \le \tau_0 \le 1/\Lambda_{\rm int}$. Depending on the equation of state (hard or ultrasoft, i.e., $3 < \alpha \le \infty$) and the temperature of the matter fireball, the ratio $\tau/\tau_0$ indicates whether a perfect fluid treatment of the matter fireball is acceptable:

$$\begin{cases} \dfrac{\tau}{\tau_0} \le \left(\dfrac{T}{T_{\rm PBH}}\right)^{(5-\alpha)/2} \le 1\,, & \text{for } T \le T_{\rm PBH}, \\ & \quad \text{transparent}\ ; \\ \dfrac{\tau}{\tau_0} \ge \left(\dfrac{\Lambda_{\rm int}}{T_{\rm PBH}}\right)\left(\dfrac{T_{\rm PBH}}{T}\right)^{(\alpha-3)/2} \ge 1\,, & \text{for } T \ge \Lambda_{\rm int}, \\ & \quad \text{opaque fluid}\ ; \\ & \text{for } m_e \le T \le \Lambda_{\rm int} \text{ and} \\ \dfrac{\tau}{\tau_0} \ge e^4\left(\dfrac{T_{\rm PBH}}{T}\right)^{(\alpha-5)/2} \ge 1\,, & \quad T_{\rm PBH} > T(\alpha > 5)\,, \\ & \quad \text{opaque fluid}\,, \end{cases} \tag{7}$$

where $e$ is the electronic charge, $e^2 \propto 1/137$. From the last condition in equation (7), we find that the matter fireball maintains its fluid validity so long as $\Gamma < 6/5$ ($\alpha > 5$) and $T_{\rm PBH}$ is greater than the matter fireball temperature. This question, whether initial QGP interactions around PBH horizon create the matter fireball with the adiabatic index ($1 \le \Gamma < 6/5$), should be investigated in greater detail in the future.

Using the simplest picture, i.e., only $\pi^0$s produced in the quark-gluon phase transition, we can obtain the properties of the fireball. Using equation (5) and given that $L_{\rm PBH} \sim L_{\rm QGP} \sim 5 \times 10^{34}$ ergs and $T_{\rm PBH} \sim T_{\rm QGP} \ge 160$ MeV, a simple radiation-dominated model would give $r_s \sim 10^9$ cm, which implies that $\tau$ is of order 100 ms. Thus, one can expect GRBs from a fireball to have both a very short rise time ($\leq 1$ $\mu$s) and duration $\sim 50$–200 ms also in this model. This spread in times is due to the uncertainty in the model.

The PBH evaporation proceeds through a relatively low-energy hadronic fireball (compared to halo or cosmological GRB models, which require fireballs with 9–17 orders of magnitude more energy), while one expects relatively simple time structure pulses from the small spatial structure. While the evaporation energy for each PBH will be the same, there will likely be some differences in the GRB pulses. Even in the simple fireball model we have employed, there will be likely fluctuations in the number of different kinds of hadrons from the stochastic processes, which are observed in all such hadronic phenomena (e.g., in $e^+e^-$ collisions all at the same energy). Furthermore, the hadronization of the quarks will also be somewhat stochastic. The production of baryons (i.e., protons, neutrons, etc.) will load the fireball differently than, for example, pions because of the large mass difference. Thus, while one would expect similar GRBs, and very likely simple single short time pulses, it is not likely that they will be identical because of the aforementioned effects. However, because of the very small emission region of the PBH evaporation, one would expect much more similar structures than for the other sources of GRBs, in our opinion. Further details of the structure would require an extremely detailed computer simulation beyond the scope of this work. The same is true for all current models of GRB sources.

### 2.3. *Possible Hardness of the Gamma-Ray Spectrum*

We can now give a general prescription for the properties of the gamma-ray burst from PBH evaporation:

1. There should be a short time burst of $\delta t \ll 1$ s even in the standard particle physics model (Halzen et al. 1991). In models for rapid evaporation near the critical quark-gluon phase transition temperature we may expect similar effects (Cline & Hong 1992; Cline 1996).
2. The PBH explosion timescales are $\tau_{\rm evap} \sim m_{\rm PBH}^3 \sim T_{\rm PBH}^{-3}$, and 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 at the final collapse ($M_{\rm PBH} \sim 10^9$ g). However, the average energy of the $\gamma$-rays from quark-gluon transition will likely be in the megavolt range.

These characteristics are generic to PBH $\gamma$-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 *Compton Gamma Ray Observatory*, whereas the testing of the theory that very short time structure indicates a very compact source must wait for future $\gamma$-ray telescopes in space.

As an illustration, 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 particles states in the standard model. The lifetime of the PBH, $\tau_{\rm evap}$, over which it completely evaporates, can be approximated as (MacGibbon & Carr 1991)

$$\tau_{\rm evap} \cong 4.89 \times 10^2 \left(\frac{m_{\rm PBH}}{10^9\ {\rm g}}\right)^3 {\rm ms}\ . \tag{8}$$

In fact, there are some interesting theoretical debates at present as to whether the PBH evaporation would continue until it has completely evaporated away (Hawking 1992) or if the evaporation would stop when it shrinks down to a stable Plank-mass object (Barrow, Copeland, & Liddle 1991), 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 $\gamma$-rays from the PBH, which has mass $m_{\rm PBH} < 10^9$ g, between $\omega_1 < \omega_\gamma < \omega_2$ and $0 < \delta t < \tau_{\rm evap}$, is given as

$$P(\omega_1 < \omega_\gamma < \omega_2, \delta t) = \int_0^{\delta t} dt \int_{\omega_1}^{\omega_2} d\omega_\gamma \frac{\Gamma(\omega_\gamma, m_{\rm PBH})\omega_\gamma}{\exp(8\pi\omega_\gamma m_{\rm PBH}) - 1}\ . \tag{9}$$

The dimensionless absorption probability for the photon in the limit of low energy (Page 1976), for our case $0.05 < \omega_\gamma < 0.3$ MeV, can be given as

$$\Gamma(\omega_\gamma, m_{\rm PBH}) \cong 4.26 \times 10^{-9} \left(\frac{m_{\rm PBH}}{10^9\ {\rm g}}\right)^4 \left(\frac{\omega_\gamma}{\rm MeV}\right)^4 . \tag{10}$$

Thus the hardness ratio of the PBH $\gamma$-ray burst in the limit of pure Hawking process is

$$H(\delta t) = \frac{P(0.1 < \omega_\gamma < 0.3\ {\rm MeV}, \delta t)}{P(0.05 < \omega_\gamma < 0.1\ {\rm MeV}, \delta t)} \cong 250\ . \tag{11}$$

The hardness ratio ($H$) is constant for $0 < \delta t < 200$ ms since the exponential term is very small, i.e., $8\pi\omega_\gamma m_{\rm PBH} = 9.4 \times 10^{-5} (m_{\rm PBH}/10^9\ {\rm g})(\omega_\gamma\ {\rm MeV}^{-1})$. 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 $\gamma$-ray spectrum will be very hard. Thus a hard $\gamma$-ray spectrum is a natural consequence of a PBH origin! 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.,

$$H(\delta t) = \exp(a_0 + a_1 \delta t + a_2 \delta t^2)\ . \tag{12}$$

## 3. ANALYSIS OF BATSE DATA

We noticed, after having studied the available GRB data, that there is a class of very short GRBs ($<200$ ms) that in many cases seem to have a fairly hard $\gamma$-ray spectrum. For these events, an examination of the time distribution of the hardness ratio has been made. Most of these events have a simple "single spike" time history, which is a quality required for an event with a PBH origin. This hardness ratio, as defined in equation (11), is the fluence (ergs cm$^{-2}$) in the $\sim 115$ to $\sim 320$ keV energy range divided by the fluence in the $\sim 55$ to $\sim 115$ keV range. The data are taken from the BATSE catalogs (Fishman et al. 1994; Meegan et al. 1996). The preliminary duration of the bursts is taken to be the value of $T_{90}$. The interval $T_{90}$ is defined as the time between the point when 5% of the total counts have been detected and the point when 95% of the total counts have been detected. While $T_{90}$ is generally a good for an approximation of the duration, for short duration bursts a more detailed study of the fine time structure and thus the burst duration is needed.

Since very short $\gamma$-rays from the PBH fireball are expected to be seen at the distance at most parsecs around Earth, we expect the short bursts selected among the BATSE data (Fishman et al. 1994; Meegan et al. 1996), to be a homogeneous and isotropic distribution of sources in a static, Euclidean space (HISE). The usual testing for homogeneous source distribution is $V/V_{\max} \equiv (C_{\lim}/C_p)^{3/2}$, where $C_p$ is the peak photon count rate and $C_{\lim}$ is the minimum detectable photon count rate just prior to the burst. Since any of the three different timescales can generate the trigger for the event, the maximum value of $C_p/C_{\lim}$ from the BATSE catalog is used to determine $V/V_{\max}$.

### 3.1. *Study of* BATSE 1B *Data*

We have previously presented analysis of data from the BATSE 1B Catalog (Fishman et al. 1994; Cline & Hong 1996). A slight tendency for an increasing hardness ratio with the shorter GRBs burst duration was observed. We can find no prediction in the literature for conventional GRB models that give this dramatic behavior.

To make any reasonable assessment about the spatial distribution of the short GRBs, we need to study the $\log[N(C_p)]$ versus $\log(C_p/C_{\lim})$ or $\log(C_p)$. This distribution may contain a bias which is due to the variable threshold burst duration as suggested by Petrosian (1993) and Petrosian et al. (1994). By following their suggestions, we corrected for the bias due to the variability of $C_{\lim}$. 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, because of 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 $\gamma$-ray bursts.

### 3.2. *Study of* BATSE 3B *Data*

The BATSE catalogs are cumulative; therefore, the 3B Catalog also includes the data from the 1B Catalog. For this reason the analysis of the data in the 3B Catalog (Meegan et al. 1996) proceeded in a similar manner to that described in § 3. However, the duration of each burst was determined by fitting the high time resolution data, the Time Tagged Event (TTE) data. The fit was made to a combination of a Gaussian and a fourth-order polynomial. The Gaussian fit the peak and the polynomial fit the background events. The duration was calculated as equal to 3 times the full width (3 $\sigma$) for the Gaussian fit. The cuts on the data were based on the burst duration, the completeness of the data, and the quality of the data. These cuts were:

1. Short duration bursts where $T_{90} < 250$ ms.
2. Insisting that complete sets of data were available for both the hardness ratio and spatial distribution analysis. This includes the TTE data for the duration calculation, the fluence data for the hardness ratio, and the counts in the peak $C_p/C_{\lim}$ for the $V/V_{\max}$ tests.
3. A cut on the quality of the data was made, requiring single spike data and a peak count rate at least twice the background level. This removed weak bursts and bursts with multiple peaks.
4. A cut was made on data with a duration less than 100 ms.

TABLE 1

HARDNESS RATIO VERSUS DURATION (BATSE 3B)

| Trigger Number | Duration (s) | $T_{90}$ (s) | Hardness Ratio |
|---|---|---|---|
| 01453 ........... | $0.006 \pm 0.0002$ | 0.192 | $6.68 \pm 0.33$ |
| 00512 ........... | $0.014 \pm 0.0006$ | 0.183 | $6.07 \pm 1.34$ |
| 00207 ........... | $0.030 \pm 0.0019$ | 0.085 | $6.88 \pm 1.93$ |
| 02615 ........... | $0.034 \pm 0.0032$ | 0.028 | $5.43 \pm 1.16$ |
| 03173 ........... | $0.041 \pm 0.0020$ | 0.208 | $5.35 \pm 0.27$ |
| 02463 ........... | $0.049 \pm 0.0045$ | 0.064 | $1.60 \pm 1.55$ |
| 00432 ........... | $0.050 \pm 0.0018$ | 0.034 | $7.46 \pm 1.17$ |
| 00480 ........... | $0.062 \pm 0.0020$ | 0.128 | $7.14 \pm 0.96$ |
| 03037 ........... | $0.066 \pm 0.0072$ | 0.048 | $4.81 \pm 0.98$ |
| 02132 ........... | $0.090 \pm 0.0081$ | 0.090 | $3.64 \pm 0.66$ |
| 00799 ........... | $0.097 \pm 0.0101$ | 0.173 | $2.47 \pm 0.39$ |

The hardness ratio of the bursts selected, after making the listed cuts, from the BATSE 3B data (Meegan et al. 1996) is shown in Table 1. Table 1 also lists the calculated duration and the $T_{90}$ duration. Figure 2 shows a tendency for an increasing hardness ratio with the shorter GRBs burst duration.

We corrected for the variability of $C_{\lim}$, by following the method suggested by Petrosian (1993) and Petrosian et al. (1994), and obtained the distribution shown in Figure 3. Within the statistical limitations, the corrected distribution is consistent with a slope of $-3/2$, as expected for HISE. (It is difficult to estimate the uncertainties for these short

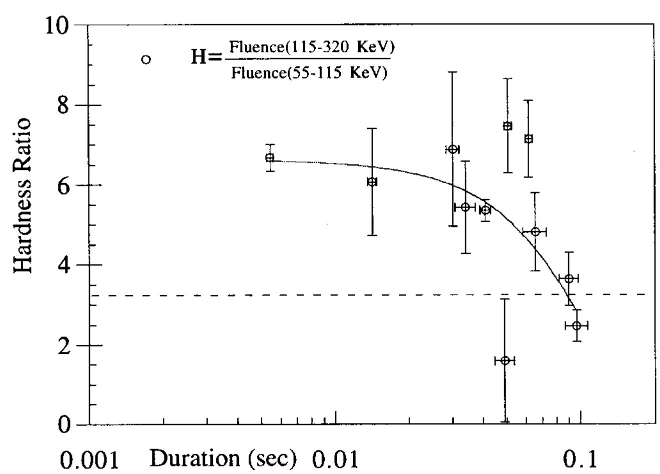


FIG. 2.—Hardness ratio for some of the $\gamma$-ray bursts reported in the BATSE 3B Catalog. A simple fitting to eq. (12) of these data indicates an anticorrelation of hardness vs. burst duration. The dashed line represents the average hardness for the bursts of time duration greater than 2. Note that these short time bursts have a much harder spectrum, a trend that would be expected if some of the short bursts came from PBH evaporation. Events have been selected with a single spike time history as would be expected for PBH evaporation.

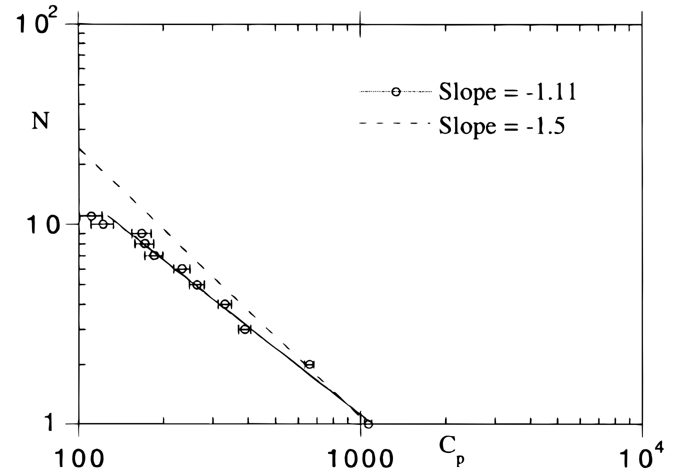


FIG. 3.—Plot shows the log $N$ vs. log $C_p$ distribution for the events in Fig. 2 with the correction suggested by Petrosian (1993) and Petrosian et al. 1994) applied. Within the statistical determination the corrected distribution is consistent with a slope of $-3/2$ as expected for a Euclidean and homogeneous distribution of sources.

bursts due to the threshold effects, and we believe the observed distributions in Fig. 3 are consistant with the HISE predictions.) We note that these results are consistent with the recent PHEBUS results (Terekhov et al. 1995) presented in Table 2.

Figure 4 shows the spatial distribution of the selected events presented in Table 1. The selected events are reasonably isotropic, with no clustering in either the Galactic center or in the Galactic plane as would be expected if they were from neutron stars. The full BATSE results (Meegan et al. 1996) are very isotropic, while the results shown in Figure 4 are only reasonably isotropic due to low statistics. The cut made on weak bursts removes possible faint, and hence distant, bursts. For this reason, and perhaps due to low statistics, our results are not very homogeneous even though they are reasonably isotropic.

## 4. GAMMA-RAY BURST RESULTS

### 4.1. *Overview of Results Presented Here*

Lacking a full description of the manner in which PBHs "explode," we must resort to phenomenolgy. We believe it is unlikely that the standard QCD framework can be used for PBHs with the temperature of about 100–200 MeV (Cline & Hong 1992). This is precisely the region where there does not seem to be an adequate description available (Halzen et al. 1991). However, the simple Hagedorn model is also likely excluded. We have studied a mixed model and used this to help get some insight into the general properties of the final stages of PBH evaporation. In addition, we believe it is essential to study unusual cosmic events, such as GRBs, to possibly identify unusual behavior that could be characteristic of PBH evaporation. We have described a class of GRBs that are intriguing from this standpoint, as seen in Table 1. In Figure 5 we show some examples of the GRBs from the BATSE data. These are remarkably simple single bursts as would be expected from a simple event like a PBH evaporation, within the limitations of the model presented here. (Please see the comment at the end of § 2.2.) We have not studied the GRBs with burst duration greater than 200 ms; however, we know that bursts with a 1–2 s duration are "soft" in comparison.

In Table 2 we present the various tests that might be made for a PBH origin to GRBs. So far there seems to be reasonable agreement between this hypothesis and the available data. We find it significant that both our analysis of the BATSE data reported here, and the analysis of PHEBUS short burst data (Terekhov et al. 1995) are consistent with $V/V_{\max} \sim 1/2$.

### 4.2. *Limits on PBH Density in the Galaxy*

In order to determine the likely density of PBHs in the vicinity of Earth, a model of the $\gamma$-ray emission as well as the detector response is needed. In Table 3 we provide a rough

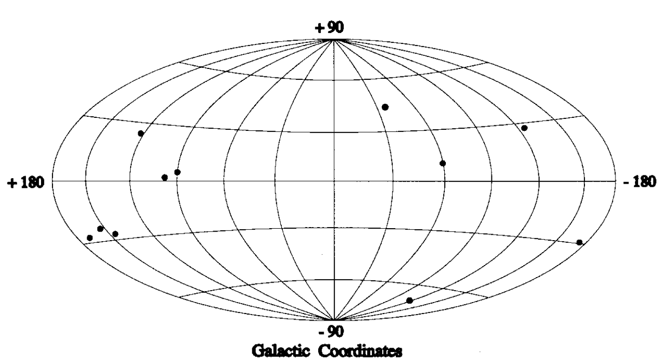


FIG. 4.—Plot shows the angular distribution, in Galactic coordinates, of the BATSE GRB events from the 3B Catalog presented in Table 1.

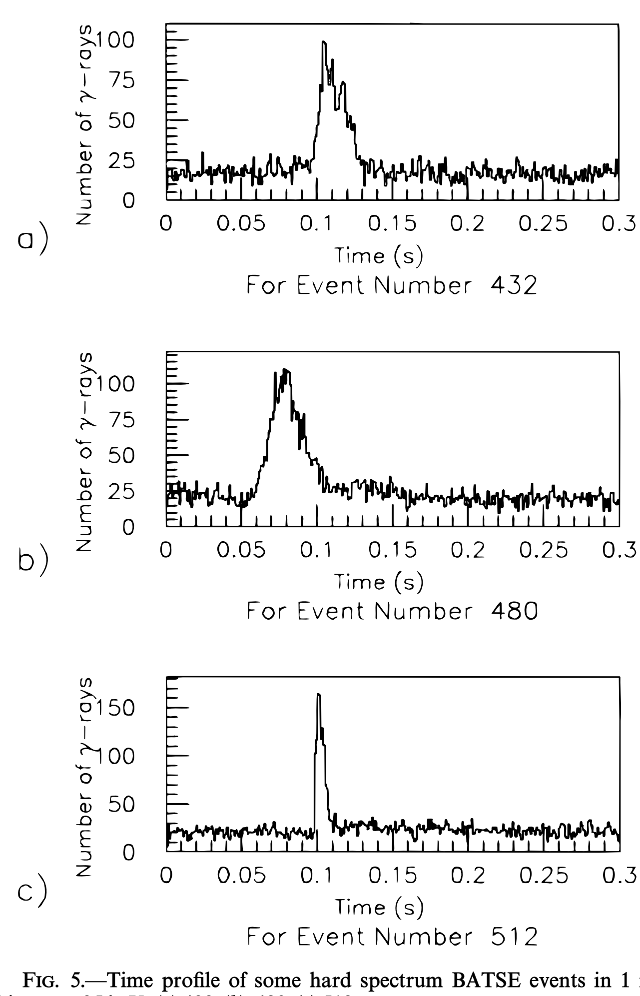


FIG. 5.—Time profile of some hard spectrum BATSE events in 1 ms bins at $>25$ keV: (*a*) 432, (*b*), 480, (*c*) 512.

TABLE 2

CHARACTERISTICS OF SELECTED GRBs CONSISTENT WITH THE PBH EVAPORATION HYPOTHESIS

| Event Characteristics | GRB Events (Selected) | Expectation for PBH Evaporation |
|---|---|---|
| Time duration ........................................ | Time duration $\sim 100$ ms | In Fireball picture $\Delta\tau \approx 200$ ms. |
| Event hardiness in $\gamma$ spectrum $H = \frac{F(115\text{–}320\ \mathrm{KeV})}{F(55-115\ \mathrm{KeV})}$ .............................. | PHEBUS short burst data[a] have hard spectrum. Hardest $\gamma$ spectrum of any GRB $\langle H \rangle \cong 6$ for BATSE (1B–3B) data | Expect hard $\gamma$ spectrum, but exact value not calculable. However, in pure Hawking Process $\langle H \rangle \sim 250$. |
| Time history of event ................................ | Most events have simple time history: one peak | Simple time history: one peak only in event. |
| $\ln N$–$\ln S$ test for population spatial structure...... | BATSE 3B: corrected $\ln N$–$\ln S$ with slope $\sim -3/2$ PHEBUS short events:[b] $V/V_{\max} = 0.48 \pm 0.05$ | Expected $\frac{V}{V_{\max}} = \frac{1}{2}$ or $\ln N - \ln S$ with a slope $= -3/2$. |
| Fine structure in events .............................. | In one BATSE event time structure of $\sim 100\ \mu$s observed[c] | Fine time structure could reveal size of source. |
| Limit rate of GRB from PBH expected............ | $\sim 11/614$ GRB $\sim 2\%$ (1B–3B) data; Low rate | Expect low rate and $\Omega_{\mathrm{PBH}} \sim 10^{-7}$; perhaps 10 yr. |

[a] Terekhov et al. 1995.
[b] Data presented at the ESLAB-ESA conference 1995 April by J. P. Dezalay from Terekhov et al. 1995.
[c] Bhat et al. 1992.

TABLE 3

ESTIMATED DETECTION EFFICIENCIES FOR GRBs FROM A PBH

| $N_{\mathrm{PBH}}$ | Model of PBH Distribution | $N$(no detection assumed) | $N$(detection limit) |
|---|---|---|---|
| $\sim 10^4$–$10^5$ pc$^{-3}$...... | Universe $\gamma$ background ($\Omega_{\mathrm{PBH}} \sim 10^{-8}$) | $\sim 10^{-5}$–$10^{-4}$ pc$^{-3}$ yr$^{-1}$ | Diffuse $\lambda$ spectrum (input) |
| $\sim 10^{10}$ pc$^{-3}$.......... | "Mild" Galactic concentration | $\sim 2$ pc$^{-3}$ yr$^{-1}$ | Could only be detected if Hagedorn model correct (EGRET) |
| $\sim 10^{12}$ pc$^{-3}$.......... | "Reasonable" Galactic concentration | $\sim 10^2$ pc$^{-3}$ yr$^{-1}$ | Can be detected in the mixed model (BATSE) |
| $\sim 10^{15}$ pc$^{-3}$.......... | "Extreme" Galactic concentration | $\sim 10^5$ pc$^{-3}$ yr$^{-1}$ | Most likely can only be consistent if hard QCD model (possible detection with air shower detector $E_\gamma \gg$ TeV) |

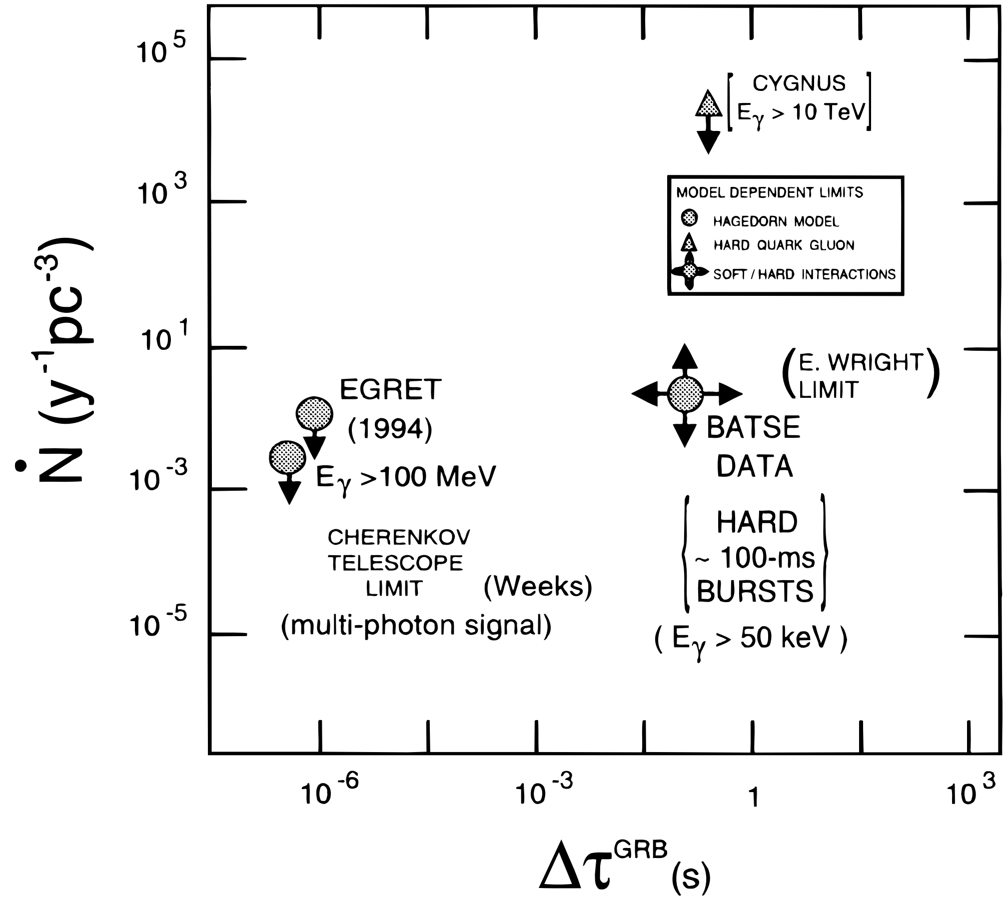


FIG. 6.—Limits for some of the PBH-GRB bursts reported in the literature (Cline 1996; Wright 1996). $\dot{N}$ refers to the limit on the number of evaporating PBHs (yr$^{-1}$ pc$^{-3}$). The limits are determined by the detectors used to observe the GRB. The $\Delta\tau$ of the GRB and the model used to calculate the GRB luminosity.

estimate of the detection efficiency in this search. Figure 6 is then constructed from the limits on GRBs from PBHs claimed in several searches and the detector efficiencies given in Table 3 (Cline 1996).

### 4.3. *Further Tests of the PBH Origin*

One way to demonstrate that a GRB event was coming from an exotic source like a PBH would be to have observed even a shorter time structure. For example, if nanosecond structures were observed, this would presumably limit the size of the progenitor to $\leq c \times (n \text{ s}) \leq 30$ cm. In this case there would be no known astrophysical object, i.e., neutron star, black hole of several solar masses, etc., that could be the origin of the burst. Thus, a study of the fine structure of the short duration GRBs could yield further evidence concerning this hypothesis. Another important test is $V/V_{\max} \sim 1/2$ combined with a galactic coordinate plot of the events that is isotropic. This would presumably help to rule out neutron stars as the origin of short bursts. We note that one observed short GRB has fine structure of $\sim 100\ \mu$ (Bhat et al. 1992).

## 5. 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 a 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 (Halzen et al. 1991; Cline & Hong 1992; Cline 1996). We also studied the spatial distribution of the events and find that it is not inconsistent with a PBH origin. We are not making a strong claim that these events are definitely due to PBHs; only that this is an interesting possibility that should be seriously considered. 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 submicrosecond time structure in this class of GRBs. There are no current $\gamma$-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 (Hawking 1974).

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