13

FERMILAB

UCLA-APH-0075-4-95

Fermilab Library
0 1160 0049381 1

THE SEARCH FOR GRB FROM PRIMORDIAL BLACK HOLE EVAPORATION

DAVID B. CLINE
University of California Los Angeles, Physics Department 405 Hilgard Ave., Los Angeles, CA 90095-1547

UCLA-APH0075-4/95

Abstract. The search for high energy γ bursts from primordial black holes (PBH) has continued for the past 20 years. We summarize the current searches for PBH-GRB events. We discuss a very interesting group of γ 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 vs. γ burst duration, would be expected if some of the short γ bursts came from black holes evaporation. We discuss the possibility that the onset of the quark-gluon plasma can give rise to such GRB from PBH evaporation.
Key words: PBH - GBH

1. Introduction

Ever since the invention of "Primordial Black Holes" there have been suggestions for the experimental detection of such objects[1]. However, the real time detection depends on the final state evolution of the PBH; as the PBH's temperature is rising as it sheds mass, into the region of hadronic interactions and hadronic final states[1]. The most extreme model used to simulate this final state was the Hagedorn model that predicted an explosion lasting $\sim 10^{-7}$ sec (and very heavy particle luminosity), whereas other QCD inspired calculation suggested a final state collapse time of the order of seconds[4]. We questioned the validity of the QCD inspired calculations pointing out that final state interactions and non perturbation effects could increase the low energy particle luminosity and even the collapse time, both of which must make detection easier[2,3,4].

There are three recent developments:

1. New search for GRB from PBH by the EGRET and CYGNUS detectors (recent preprints from these groups C. Fichtel, et al., and D. Coyne, et al.)
2. New estimates of the amount of PBH that may occur from the early universe by B. Carr, et al. (FNAL preprint 94/109, 1994).
3. A suggestion by W. Hong and the author that some of the BATSE GRB events could have the characteristics expected from PBH evaporation within a specific model of the hadronic interaction (UCLA preprint).

Hawking showed in a seminal paper that an uncharged, non-rotating black hole emits particles with energy between E and $E + dE$ at a rate per

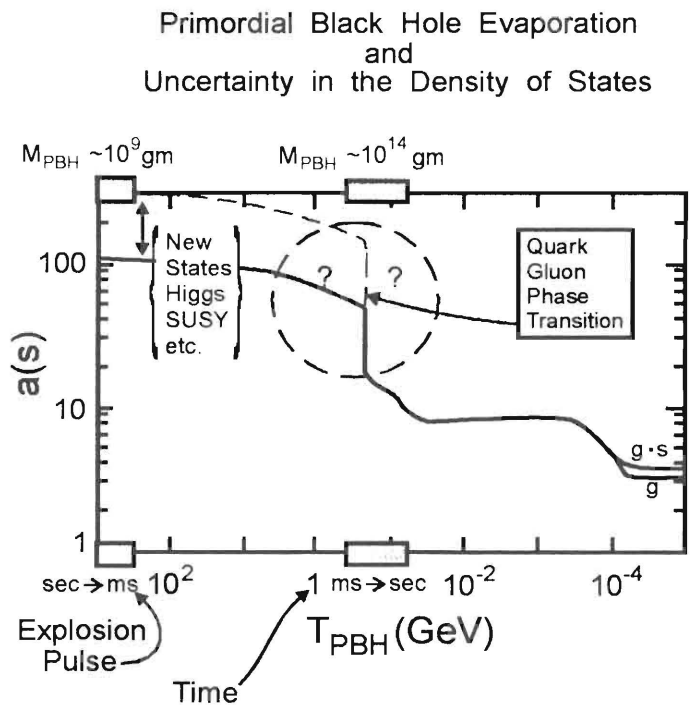

Fig. 1. The running coupling or density of states factor α showing regions of uncertainty due to the quark-gluon phase transitions (I) or the increase in the number of new elementary particles (II). It is possible that intense short γ bursts could occur at either of these temperatures.

spin or helicity state as

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

Here M is the mass of the PBH, s is the particle spin and Γ_s is the absorption probability[4]. Heuristically, one can think that this particle emission comes from the spontaneous creation of paris of particles near the event horizon of the black hole. One particle, with a positive energy, escapes to infinity and the other particle has negative energy which tunnels through the horizon into the black hole where there are particle states with negative energy with respect to infinity. The PBH thus emits massless particles (photons, light neutrinos) as if it were a hot black body with temperature

$$T \simeq 10^{16}\left[\frac{1g}{M}\right]\text{ MeV}$$

where M is the mass of the black hole. A solar mass hole of $M_s \simeq 2 \times 10^{33}$g has a temperature of about 10^{-3}K while a hole of mass 6×10^{14}g has a temperature of 20MeV. The temperature increases as it loses mass during its' lifetime. The black hole loses mass at a rate in the context of the standard model of particle physics:

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

where $\alpha\ (M)$, the *running constant*, counts the particle degree of freedom in the PBH evaporation. The value of the $\alpha\ (M)$ is model dependent. In the standard model family of three leptons and three quarks, it is given as[6,7]

$$\alpha(M) = \left[0.045\, S_{j=1/2} + 0.162\, S_{j=1}\right] \times 10^{-4}$$

where $S_{j=1/2}$ and $S_{j=1}$ are the degrees of freedom (spin and color) for the fermions and gauge particles respectively. For the standard model $S_{j=1/2} = 90$ and $S_j = 1 = 30$ at $T \sim 100$GeV, and we obtain $\alpha(M) = 4.1 \times 10^{-3}$. In non-standard models, for example in the Hagedorn-type picture, the number of emitting particle states grows exponentially with mass[8]

$$\rho(m) \sim m^{-\beta}\ exp\left[\frac{m}{\Lambda}\right]$$

where $5/2 \leq \beta < 7/2$ and $140\,\mathrm{MeV} \leq 160\,\mathrm{MeV}$. These models were motivated by the apparent exponential increase in the hadronic resonance seen at accelerators. While there is no evidence for the Hagedorn type models in the lattice calculations, such a model is not yet ruled out.

A reasonable model of the running coupling is shown in Figure 1, where we indicate the regions of uncertainty where there could be a rapid increase in the effective degrees of freedom due to the quark-gluon phase transition, leading to a rapid burst in the PBH evaporation or at very high energy, where there could be many new particle types that would also increase the rate of evaporation. We also show, in Figure 1, the regions in PBH temperature where short γ bursts may occur when the PBH mass is 10^{14} or 10^9 grams!

Unfortunately, Experimental Physicists or Astrophysicists don't have the time or patience (or perhaps ability) to understand in detail quantum gravity and also build detectors. However, we take these suggestions as indicating there is a possibility that PBH have a violent ending that might be experimentally detectable[6].

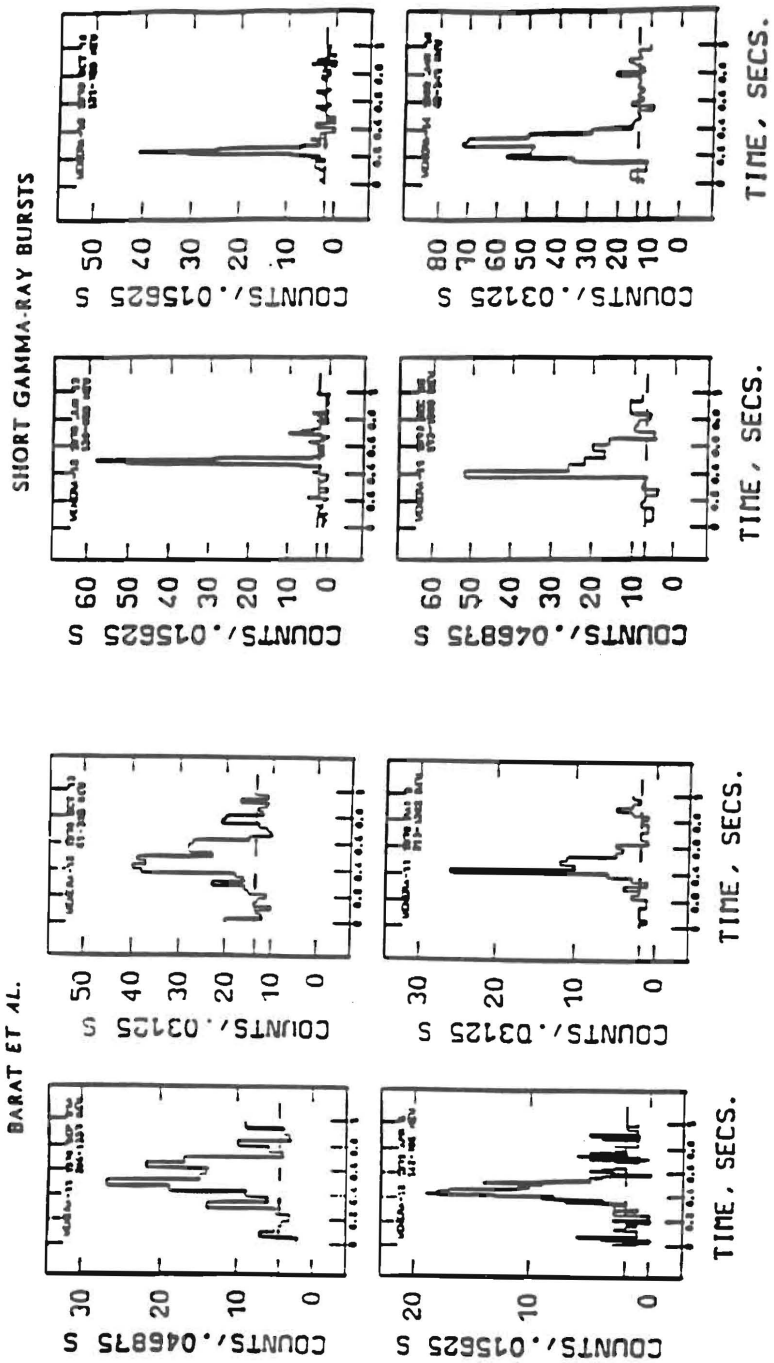

Fig. 2. Eight short GRB from past observations.

N^{PBH}	*Model of PBH Distribution*	$\dot{N}$ (*no detection assumed*)	$\dot{N}$ (*detection limit*) [*depends on hadronic theory*]
$\sim 10^4 - 10^5$ $(pc)^{-3}$	*Universe* γ *background* $(\Omega^{PBH} \sim 10^{-8})$	$10^{-5} - 10^{-4}$ $(pc)^{-3} yr^{-1}$	{*diffuse* γ *spectrum (input)*}
$\sim 10^{10}$ $(pc)^{-3}$	*mild galactic concentration*	$2(pc)^{-3} yr^{-1}$	*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 3TeV detector*

2. The Concept of a PBH & Formation in the Early Universe

Black holes at the evaporation stage at the present epoch can be calculated as

$$M_* \simeq [3\alpha\,(M_*)\,\tau_{\rm evap}]^{1/3} \simeq 7.0 \times 10^{14}{\rm g} \tag{3}$$

for $\alpha\,(M_*) \simeq 1.4 \times 10^{-3}$ [8]. The bound on the number of black holes at their critical mass has been put by the constraint of the observed diffuse gamma-ray background in the 10 – 100 MeV energy region[7] (see Table 1).

$$N = \frac{dn}{d\,(\ln M)}\,|_{M=M_*} \leq 10^5\,{\rm pc}^{-3} \tag{4}$$

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

$$\frac{dn}{dt} = \frac{3\alpha\,(M_*)}{M_*^3}\,N = 2.2 \times 10^{-10}\,{\rm N\,pc}^{-3}\,{\rm year}^{-1} \tag{5}$$

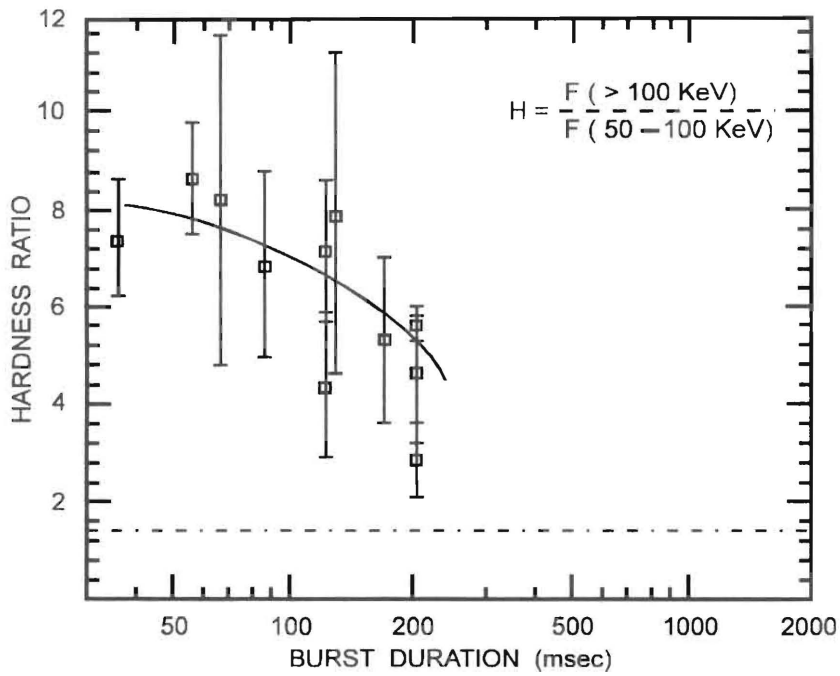

Fig. 3. Anti-correlation of hardness and GRB time.

This rate is directly proportional to the particle emission degree of freedom and is therefore highly model dependent. If they are clustered in the galaxy, the exploding PBH density is estimated as ~ 20 per year pc^3 [9].

PBH would be formed in the Early Universe from density fluctuations. So far, no one has ruled out the possibility that such objects could also be formed at various phase transitions in the Early Universe.

The ultimate stage of the PBH explosion is extremely model dependent. In the standard model of elementary particle physics, one expects to observe emission products in the form of gamma-rays, electrons, positrons, neutrinos, protons and anti-protons. These emission products have energies right up to the Planck mass, i.e., $\sim 10^{19}$ GeV, with some uncertainties. The PBH final stage emission mechanism in the high energy limit in the Hagedorn type models and the Standard Model can be summarized as follows[6,11]: (see Figure 1)

> At $\tau_{tot} \sim 1$, the fireball becomes transparent and the photons escape in one crossing time. To see millisecond duration bursts the fireball should expand to a macroscopic scale, i.e. $R_0 \geq 10^8 \sim 10^9$ cm since the

duration of burst to an observer is approximately given as

$$10 \leq \delta t_{\text{burst}} \simeq \frac{2R_o}{c} \leq 50\,\text{msec}$$

where the size of the emission radius, R_0, depends on the detail parameters of the fireball, i.e. the total energy of the fireball and photon interactions with leptons and hadrons, etc. We also expect that, by the time the fireball has expanded to macroscopic radii, due to the constant Lorentz factor of the expanding fireball, ($\gamma_f = 2 \times 10^{16}\,\text{g}/\text{M}_{\text{PBH}} \sim 300$)[2], some proportions of γ energy released from the fireball will be in the range of (0.1 to ~ 100) GeV.

While a detailed model of low energy hadronic interactions does not exist, we note that heavy ion collisions may provide some important insight. At present, these data are described by a limiting hadronic temperature model similar to the Hagedorn type model[12].

3. Survey of GRBs & Unusual Events that Might Signal PBH Evaporation

We have studied many of the experimental papers and noticed that there is a class of fairly short GRB (< 1 sec) that in many cases seem to have a fairly hard γ spectrum[13]. Figure 2 shows the profile of some of these events. Recently, the BATSE group has recorded a very interesting short (ms) GRB that also has a hard spectrum (Figure 3)[14]. However, we must be careful that the harder spectrum is not somehow involved in the detection process for these very short GRB. The BATSE event also has a very hard spectrum as do other short bursts time structure (Figure 4)[14,15]. It occurs to be that one way to demonstrate that a GRB event was coming from an exotic source like a GRB, would be to have observed even a shorter final structure. For example, if nanosecond structure were observed this would presumably limit the size of the progenitor to

$$\begin{bmatrix}\text{Size of}\\ \text{Object}\end{bmatrix} \lesssim [\text{nanosecond}] \times [\text{c}] \leq 30\,\text{cm}$$

In this case there would be no known astrophysical object, i.e. neutron star, several solar mass black hole, etc., that could be the origin of the burst. Figure 5 show some of the hard BATSE events in Figure 3. It is remarkable that these events appear to be nearly identical as would be expected if they come from PBH evaporation.

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 amoung the BATSE data (Fishman, et al., 1994) to be

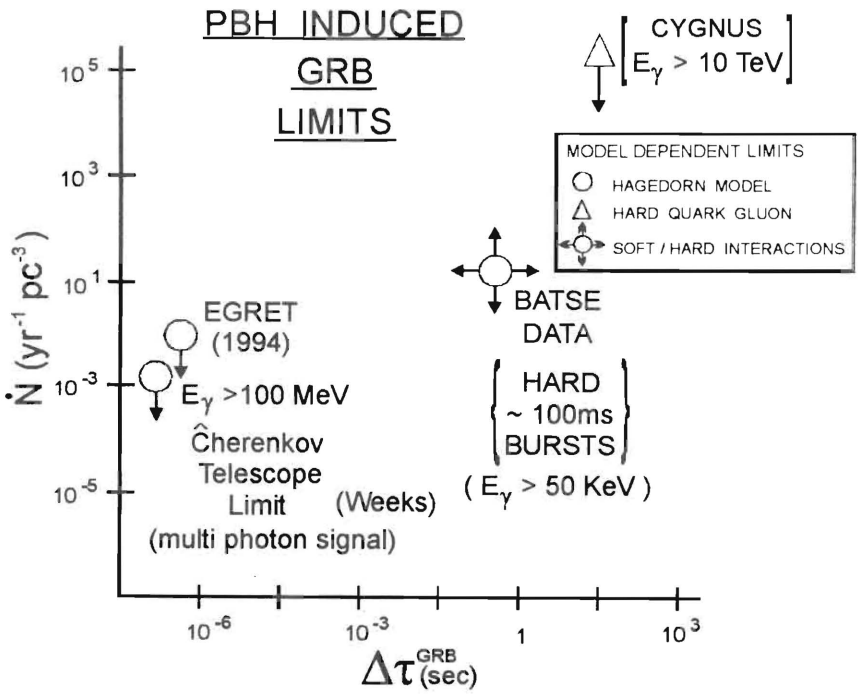

Fig. 4. Limits for some of the PBH-GRB bursts reported in the literature. Note that the short time bursts from BATSE have a much harder spectrum, a trend that would be expected if some of the short bursts came from PBH evaporation.

homogeneous and isotropic distribution of sources in a static, Euclidean space (HISE). The usual testing for homogeneous source distribution in $V/V_{\rm Max} \equiv (C_{\rm limit}/C_{\rm p})^{3/2}$, where $C_{\rm p}$ is the peak photon count rate and $C_{\rm limit}$ is the minimum detectable photon count rate just prior to the burst. The average value of the $V/V_{\rm Max}$ from Table 1 is $< V/V_{Max} \geq 0.24$. This number seems to deviate from the HISE, i.e., 0.5. However this test should not be taken at face value since there may be a bias due to varying thresholds for the detection of burst.

To make any reasonable assessment about the spatial distribution of the short GRB's we need to study the $\log N\,(C_{\rm p})$ vs. $\log\,(C_{\rm p}/C_{\rm limit})$ or $\log\,(C_{\rm p})$. This distribution may contain a bias due to the variable threshold, burst durations as suggested by Petrosian (Petrosian 1994; Petrosian, et al., 1992). By following their suggestions we corrected for the bias due to the variability of $C_{\rm limit}$, obtaining 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. The other parameters of these events are also,

TABLE II

Fireball from the quark-gluon phase transition.

$$L_{QGP} \sim 5 \times 10^{34}\,\text{Ergs} \qquad T_{QGP} \leq 160\text{MeV}$$
$$\sim L_{PBH} \qquad \sim T - PBH$$
$$r_s \sim \left[\frac{L_{PBH}}{4\pi T_{PBH}} \left(\frac{T}{S(T)}\right)\right]^{1/2} \left(\substack{\text{Carter, et al.} \\ 1976}\right)$$

Where S is the total entropy

A simple **radiation dominated** model would give

$$r_s \sim 10^9\text{cm}$$

$$\Rightarrow \quad \tau \sim \mathcal{O}\ (100\text{ms})$$

Thus expect GRB from Fireball to have

i) Very fast rise time ($\leq \mu$sec)

ii) Durations $\sim$ 100ms or 50 for an order of magnitude

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 GRB's.

4. Future Search for PBH – Bursts

Lacking a full description of the manner in which PBH "explode", we must resort to a phenomenology. We believe it is unlikely that the standard QCD frame work can be used for PBH with the temperature of $\sim$(100 – 200) MeV. This is precisely the region where there does not seem to be an adequate description available. However, the simple Hagedorn model is likely ruled out as well. We have studied a mixed model and used this to help get some insight into the general properties of PBH evaporation in the final stages. In addition, we believe it is essential to study unusual cosmic events, such as GRB, to possibly identify unusual behavior that could be characteristic of PBH explosions. We have described a class of GRB that are intriguing from this stand point!

There have been recent searches for very high energy γ bursts. These, and the limits on the density of PBH in the local vicinity from the analysis presented here are summarized in Table 2.

In Table 3 we list some possibilities for the unique detection of PBH evaporation. Obviously, it will require new instruments and much larger data

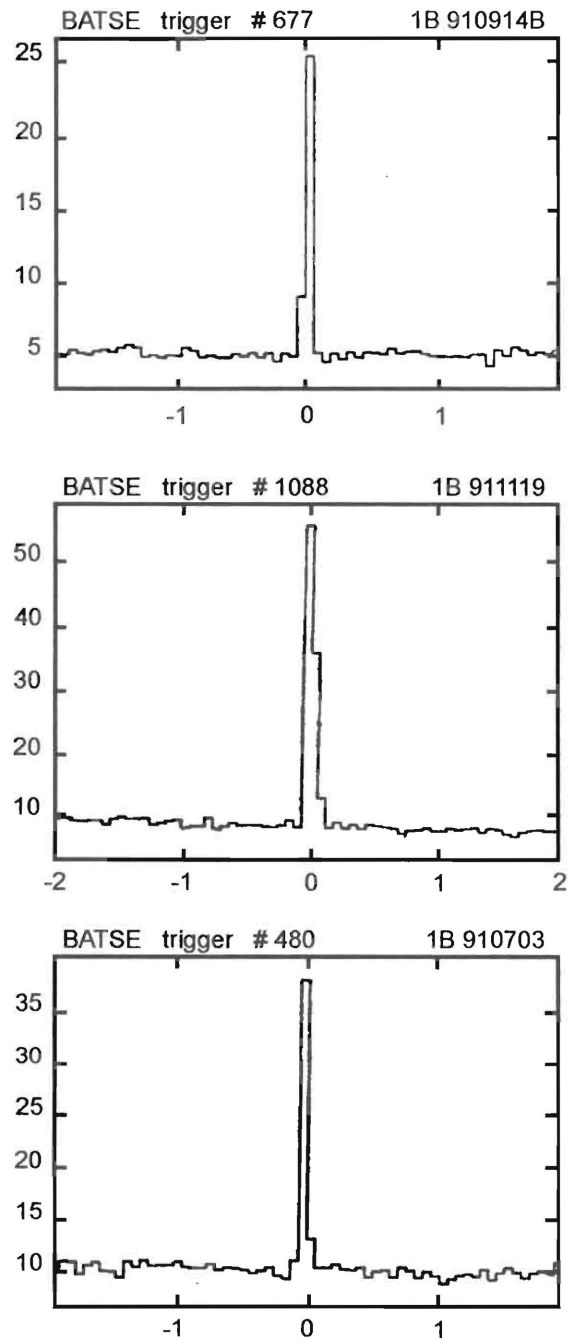

Fig. 5. Time profile of some of the hard spectrum BATSE events.

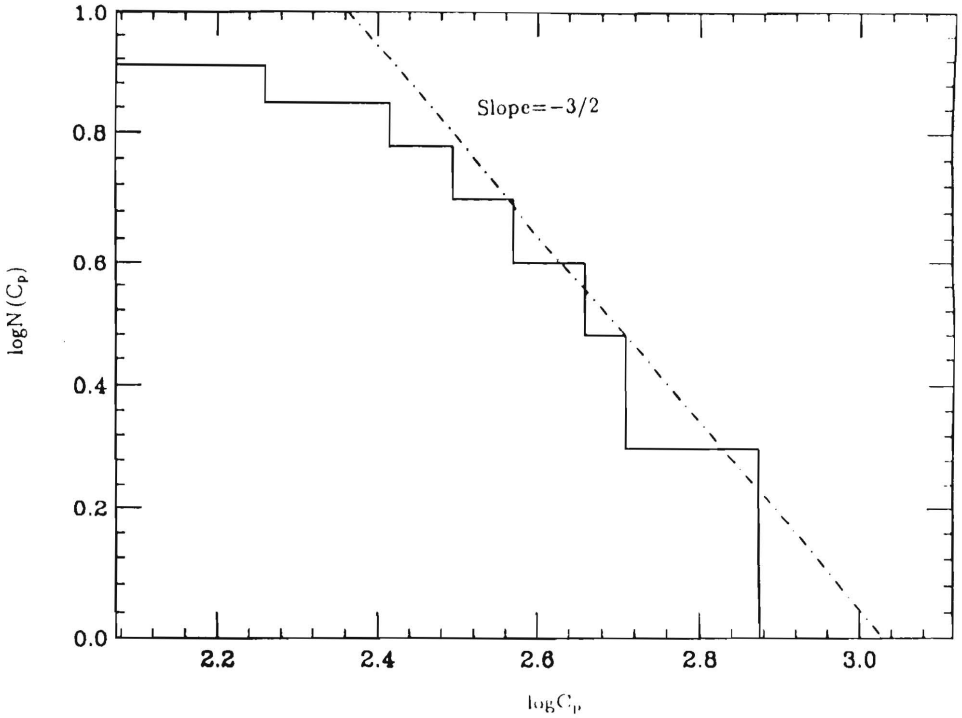

Fig. 6.

samples from experiments like Batse! Recently, two papers have appeared claiming that there may be several classes of γ burst events[16,17]. It is also conceivable that there are further subclasses of events, some arising from PBH evaporation.

5. Conclusions

The search for signals for primordial black holes has been going on since 1975. The traditional very short GRB ($\Delta\tau \sim 10^{-7}$sec) signature is likely incorrect in current physics theory. However, short GRB's **can occur** from PBH under the following conditions

i) $M_{PBH} \sim 10^9$grams, QCD Burst

ii) $M_{PBH} \sim 5 \times 10^{14}$grams, Quark-Gluon phase transition.

TABLE III
Possible discrimination between PBH and other sources of GRB's

		PBH	**n or n×n stars**
1.)	Source Size and GRB Rise Time	μs $\leq$	$\geq$ msec
2.)	Fine Structure	μs $\leq$	$\geq \Delta\tau > \frac{\ell_{\rm Fireball}}{c}$ $\gtrsim \frac{10^7}{3\times10^{10}}$ $\sim \frac{1}{3} \times 10^{-3}$sec
3.)	$V/V_{\rm Max}$ Test	$\sim \frac{1}{2}$	$\frac{1}{2} <$ if cosmological
4.)	Lines due to Magnetic Fields	not expected	expected for neutron stars – not for n × n collisions
5.)	Powerful Neutrino Source	yes	unlikely
6.)	Constraints from diffuse γ spectrum	OK – perhaps explain "10MeV" Bump as well	

While no candidates for (i) exist, there are several BATSE events that could be due to (ii). If these events are due to PBH, the density in the galaxy could be $\lesssim 10^{10}$pc^{-3}.

References

Page D.N., and Hawking S.W., 1976, Astr.J. **206**, 1.
Rees M.J., 1977, Nature **266**, 333-334.
McGibbon J.H. and Weber B.R., 1990, Phys. Rev **D41**, 3052-3079.
Carter B., Gibbons G.W., Lin D.N.C., and Perry M.J., 1976, Astro. Astrophys. **52**, 427-438.
Hawking S.W., 1992, Phys. Rev. Lett. **69** 406 (1992).
Cline D.B. and Hong W., 1992, APJ Letts. **401**, L57.
Hawking S.W., 1974, Nature (London) **30**, 248; Hawking, S.W., 1975, Commun. Math. Phys. **43**, 199.
Huang K. and Weinberg S., 1970, Phys. Rev. Letts. **25** 895.
Halzen F. and Zas E., 1989, MAD/PH/528.
Carr B.J., 1976, Astro. J **206**, 8.

This has been carried out with Mr. W. Hong of UCLA. See Ref. 6.
Stocker H., et al., Nucl. Phys. **A400** 63 (1983).
Barat C., et al., Astro. J **285**, 781 (84).
Bhat P.N., et al., Nature, **V359** 217 (1992).
Dezalay J., et al., Proc. of Huntsville Gamma Ray Burst Meeting, published by AIP **265** 304 (1992).
C. Kouvelioton, et al., Ap J. 413 L101 (1993).
D. Q. Lamb, et al. Ap. J. 413 L11 (1993).