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POSSIBLE EVIDENCE FOR PRIMORDIAL BLACK HOLES[a]

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We present evidence here from the study of a distinct sub class of very short, very hard gamma-ray bursts (GRBs) that $m \sim 10^{14}$ gm primordial black holes (PBHs) may exist in the local Galaxy environment. Some possible "smoking gun" observations that could prove this conjecture are listed here. The discovery of PBHs, while providing a new window on the early Universe, would also be of enormous importance in general.

1 Concept of the Search

We list the main ingredients to the method of the search here, which serves as a brief summary of this paper:

1. Primordial black holes with $m \sim 10^{14}$ gm can be produced in the early Universe; while $\Omega_{PBH} < 10^{-8}$, there can still be many in the vicinity of the Solar System.
2. A burst of photons could be produced as $T_{PBH} \sim T_{QGP}$ (QGP, quark–gluon phase), from the Hawking radiation.
3. We questioned: Are there any GRB events that could come from PBH evaporation?
4. Do these events have the characteristics expected from a homogeneous isotropic local source?
5. Are there other features of the events that are similar or that suggest a unique GRB population?
6. Is there a plausible mechanism that could produce these PBHs in the early Universe?

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2 Evaporation of PBHs at $T = T_{QG}$

Ever since the theoretical discovery of the quantum-gravitational particle emissions from black holes by Hawking,[1] there have been many experimental searches for high-energy γ-ray radiation from PBHs (which would be formed in the early Universe) 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.*, $T = T_{PBH} \approx 100$ MeV (10^{15} g/m_{PBH}), since the black hole becomes hotter as it radiates more particles and eventually can attain extremely high temperatures.

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 that we can single out such a monumental event. However in a previous work,[2] we pointed out a possible connection between very short GRBs observed by the BATSE team and a PBH evaporation caused by the emission of very low-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–gluon plasma (QGP) phase transition temperature at which the T_{PBH} arrives eventually. We assume that a first-order phase transition occurs at the QGP temperature (Fig. 1A). Tables 1 and 2 give more information about this model.

In the previous work, we briefly discussed that including the QGP effect around the evaporating PBH at the critical temperature might 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 (orders of milliseconds duration) GRB.

Lacking a full description of the manner in which PBHs "explode," we must resort to phenomenology. We believe it is unlikely that the standard QCD framework can be used for PBHs with a temperature of about 100–200 MeV.[2] This is precisely the region where there does not seem to be an adequate description available.[4] However, the simple Hagedorn model is also likely excluded. We have studied a mixed model and used it to help get some insight into the general properties of the final stages of PBH

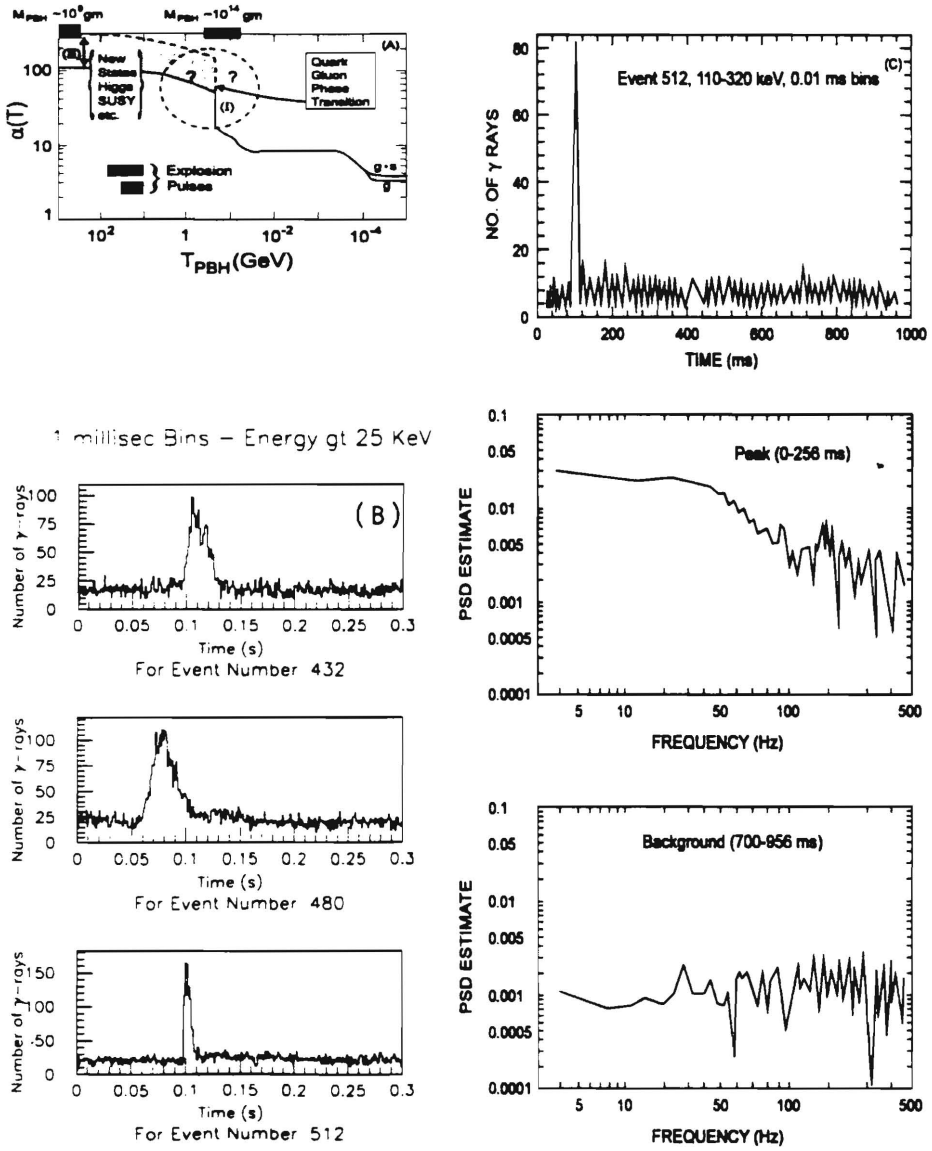

Figure 1: (A) The running coupling constant showing a possible first-order phase transition of the QGP temperature. (B) Time profile refit of the BATSE 3B events using the TTE data. (C) Fast Fourier analysis of one of the events analyzed here, showing the PSDs.

Table 1: Mass loss near the QGP transition temperature., T_{QGP}

Mass Loss Rate:

$$\frac{dm}{dt} = -\frac{\alpha(m)}{m^2} = \dot{m}$$

near $T = T_{QGP}$. $\left[\text{NOTE: } \tau_0 = \frac{m_0^{-3}}{\alpha(m_0)}\right]$

$$\frac{d}{dt}[\dot{m}] = \frac{d}{dT}\left(-\frac{\alpha}{m^2}\right)$$

$$\frac{d\dot{m}}{dT} = \left(\frac{m_0}{\tau_0}\right)\left[+\frac{1}{m}\left(\frac{dM}{\alpha T}\right) - \frac{1}{\alpha}\left(\frac{d\alpha}{dT}\right)\right]_{T=T_{QGP}}$$

$$d\left(\dot{m}\right) = -\left(\frac{m_0}{\tau_0}\right)\left[-\frac{1}{\alpha}\left(\frac{d\alpha}{dT}\right)\right]_{T=T_{QGP}} dT$$ - "explosion" for $\frac{1}{\alpha}\frac{d\alpha}{dT} \rightarrow \alpha$ at QGPT

assume first-order transition.

Table 2: Fireball from the QGP transition (simple model).

$L_{QGP} \sim 5 \times 10^{34}$ ergs/s $T_{QGP} \geq 160$ MeV
$\sim L_{PBH}$ $\sim T_{PBH}$

$$r_S \sim \left\{\frac{L_{PBH}}{4\pi\, T_{PBH}}\left[\frac{T}{S(T)}\right]\right\}^{1/2}$$ (from Ref. 3)

where S is the total entropy.

A simple radiation-dominated model (*i.e.*, $\pi^o \rightarrow \gamma\gamma$) would give
$r_s \sim 10^9$ cm $\rightarrow \tau \sim \theta$ (100 ms) , rise time << 100 ms.

Thus, expect GRB from fireball to have

- Very fast rise time ($\leq$ ms) and to be model-dependent (a guess),
- Durations of ~ 100 ms for an order of magnitude,
- Low energy photons (~ 1 - 10 MeV),
- Hard spectrum.

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 of short durations, which could yield further evidence concerning this hypothesis. Another important test is $V/V_{max} \sim ½$ combined with a Galactic Coordinate plot of the events, which is isotropic. We note that one observed short GRB has a fine time structure of ~100 μs.[5]

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 pc from the earth. Since the BATSE detector's observed fluences of ≈ 10^{-7} ergs/cm^2, we require the distance to the PBH fireball (R_{PBH}) and the release of total γ-ray energy (L^{γ}_{PBH}) during a short period of time to be $L^{\gamma}_{PBH}/4\pi R^2_{PBH} \geq 10^{-7}$ ergs/cm^2. In fact, the total γ-ray energy from a PBH evaporation is closely related to the PBH mass at QGP transition temperature (roughly $T_{QGP} \geq 160$ MeV) as $L^{\gamma}_{PBH} = \kappa m_{PBH}$, 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 (~ 2 m_{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, 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.

3 The Evidence from the GRB Events

We present in Fig. 1B, the time profile of three of the BATSE 3B events analyzed here (Table 3); note the similarity of these events. We have also carried out a fast Fourier transform of 7 of the 11 events presented in Table 3 (with an analysis of one of the events shown in Fig. 1C). The remarkable similarity of these events suggests a common origin. Figure 2A–C provides information on the spatial and hardness distribution of the events. Note the very short time structures of these events in Table 3. Table 4 lists the various tests for the PBH hypothesis that we have made and the consistency. For additional information, see Ref. 6.

While there could be other origins for these events other than PBH evaporation, we believe that this analysis suggests that the theoretical study of the evaporation at the QGP transition could be useful. We also note that this transition is assumed to occur

Table 3: Hardness ratio versus duration (BATSE 3B)

Trigger No.	Duration (s)	T_{90} (s)	Hardness Ratio
1453	0.006 ± 0.0002	0.192	6.68 ± 0.33
512	0.014 ± 0.0006	0.183	6.07 ± 1.34
207	0.030 ± 0.0019	0.085	6.88 ± 1.93
2615	0.034 ± 0.0032	0.028	5.43 ± 1.16
3173	0.041 ± 0.0020	0.208	5.35 ± 0.27
2463	0.049 ± 0.0045	0.064	1.60 ± 1.55
432	0.050 ± 0.0018	0.034	7.46 ± 1.17
480	0.062 ± 0.0020	0.128	7.14 ± 0.96
3037	0.066 ± 0.0072	0.048	4.81 ± 0.98
2132	0.090 ± 0.0081	0.090	3.64 ± 0.66
799	0.097 ± 0.0101	0.173	2.47 ± 0.39

at $t_{universe} \sim 10^{-6}$ s, which is a very short time in the early Universe, and this is similar to what we assume here.

3 Possible Smoking Gun for PBH Observation

In Table 4, we summarize the basic evidence for PBHs. In this work, all tests are positive so far. We list the possible concentrations of PBHs in this Galaxy, based on different assumptions concerning the clustering, in Table 5. Figure 4(D) gives some limits on other searches for PBH evaporation, as well as the results presented here.

While we have presented circumstantial evidence for PHGs, this can hardly be considered a proof for the observation of such a fundamental class of objects in Nature. So what would constitute a smoking gun proof? The following are some ideas:

1. If V/V_{max} could be measured reliably for the GRB with $\Delta\tau < 100$ ms and were exactly 1/2, this would prove that the GRB population has no edge - or is homogeneous. By elimination, all other explanations of these events, except a local powerful GRB site (*i.e.*, PBH), would be eliminated, provided no clustering in the Galactic Plane was observed.

2. Unique single-event tests could also prove that the parent of the GRB must be nearby. For example, suppose a GRB is shown to be at the same exact angular location of a nearby quiet star. Thus, it must have originated in front of the star,

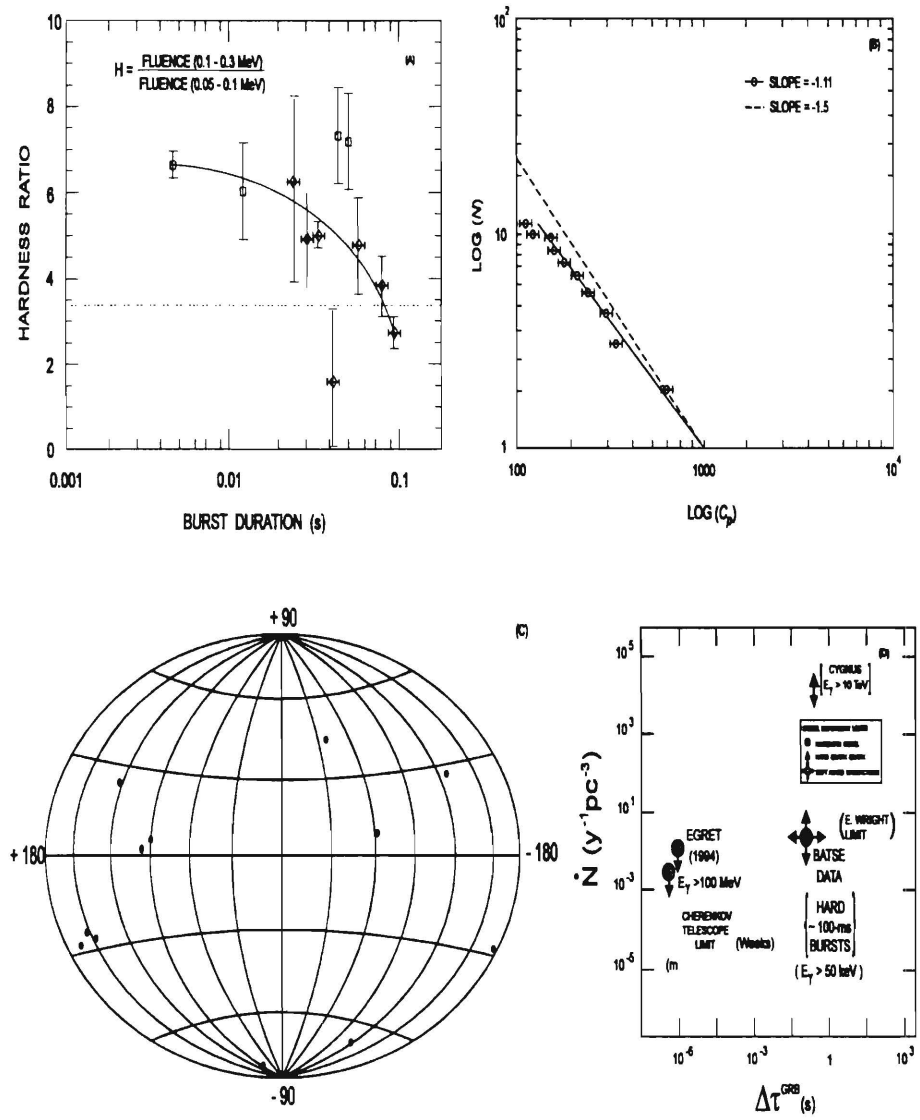

Figure 2: (A) Hardness vs duration for the 11 events presented here; note the correlation. (B) The $\ln(N)$ vs $\ln(C_p)$ plot for the 11 events. They are fully consistent with the expectation of an Euclidian space density, as would be expected for a local source. (C) Galactic coordinate of the events. Note that there is no concentration in the Galactic Dish or center. (D) Various limits on PBH density as described in Ref. 6.

Table 4: Characteristics of selected GRBs consistent with the PBH evaporation hypothesis.

Event Characteristics	GRB Events (Selected)	Expectation for PBH Evaporation
Time duration	~100 ms	In fireball model, $\Delta\tau \approx 200$ ms
Hardness in γ spectrum	PHEBUS short-burst data[b] have hard spectrum	Expect hard γ spectrum, but exact value not calculable. However, in pure Hawking Process, $\langle H \rangle \sim 250$
$H = F\,\frac{(0.1-0.3)}{(0.05-0.1)}$ MeV	Hardest γ spectrum of any GRB $\langle H \rangle \approx 6$ for BATSE (1B-3B) data	
Time history	Simple for most events - 1 peak	Simple - 1 peak
$\ell n(N) - \ell n(C_p)$ test for population spatial structure	BATSE 3B: corrected $\ell n(N) - \ell n(C_p)$ with slope $= -3/2$ PHEBUS short events:[c] $V/V_{max} = 0.48 \pm 0.05$	Expected: $V/V_{max} =$ ½ or $\ell n(N) - \ell n(C_p)$ with a slope $= -3/2$
Fine time structure	In one BATSE event, time structure of ~ 100 μs observed[d]	Could reveal size of source
Limit rate of GRB from PBH expected	~ 11/614 GRB is ~2% (1B-3B) data; Low rate	Low rate and $\Omega_{PBH} \sim 10^{-7}$ - perhaps 10/y

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

Table 5: Estimated detection efficiencies for GRBs from a PBH.

N_{PBH} (pc^3)	Model of PBH Distribution	N (No Detection Assumed) ($pc^3 \cdot y$)	N (Detection Limit)
$\sim 10^4 - 10^5$	γ background of the Universe ($\Omega_{PBH} \sim 10^{-8}$)	$\sim 10^5 - 10^4$	Diffuse γ spectrum (input)
$\sim 10^{10}$	"Mild" galactic concentration	~ 2	Could only be detected if Hagedorn model is correct (EGRET)
$\sim 10^{12}$	"Reasonable" galactic concentration	$\sim 10^{10}$	Can be detected in the mixed model (BATSE)
$\sim 10^{15}$	"Extreme" galactic concentration	$\sim 10^5$	Most likely can be consistent if hard QCD model (possible detection with Air Shower detector, $E_\gamma \gg$ TeV)

otherwise the photons would have been absorbed. If the star were known to be at a distance of a few parsec (or if a neutron star were in between, which is very unlikely), this could prove the conjecture!

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