Short γ-Ray Bursts and Primordial Black-Hole (PBH) Evaporation*

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We provide a brief review of the phenomenology of PBH evaporation and of the early study of short gamma-ray bursts (GRBs). Models of PBH evaporation lead to the expectation of short GRBs from PBHs. We then discuss a class of short GRBs in the BATSE 2B data and show that they are broadly consistent with a PBH origin. Finally, we describe the initial study of the power spectrum density from three short GRBs using BATSE TTE data. The PSDs could provide some insight into the mechanism of short GRB formation in the future.

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EXPECTATIONS OF PBH EVAPORATION FROM CURRENT MODELS

Ever since the invention of "primordial black holes" (PBHs), there have been suggestions for the experimental detection of such objects [1,2]. However, the real-time detection depends on the final state evolution of the PBH; as it sheds mass, the temperature of the PBH rises into the region of hadronic interactions and hadronic final states. The most extreme model used to simulate this final state was the Hagedorn model, which predicted an explosion lasting $\sim 10^{-7}$ s, whereas other QCD-inspired calculations suggested a final state collapse time of the order of seconds [3]. 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 would make detection easier [4]. We note that there are already indications of two classes of GRBs [5]. The point here is to see if there are GRBs that could be consistent with PBH evaporation, not to attempt to prove the existence of PBHs at this stage. There are two recent developments:

1. New estimates of the amount of PBHs that may occur from the Early Universe [6];

2. A suggestion [7] that some of the BATSE GRB events could have the characteristics expected from PBH evaporation within a specific model of the hadronic interactions.

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Hawking [2] showed that 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:

$$\frac{dM}{dt} = -\frac{\alpha(M)}{M^2} \quad , \tag{1}$$

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.

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, because of the quark–gluon phase transition, leading to a rapid burst in the PBH evaporation. At very high energy, where there could be many new particle types, the rate of evaporation would also increase. Also shown in the figure are the regions in PBH temperature where short GRBs may occur when the PBH mass is 10^{14} or 10^9 g.

Black holes at the evaporation state in the present epoch can be calculated as

$$M_* \simeq [3\alpha(M_*)\tau_{\rm evap}]^{1/3} \simeq 7.0 \times 10^{14}\ {\rm g} \quad , \tag{2}$$

for $\alpha(M_*) \simeq 1.4 \times 10^{-3}$. Thus, the number of black holes with critical mass M_* in their final state of evaporation is

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

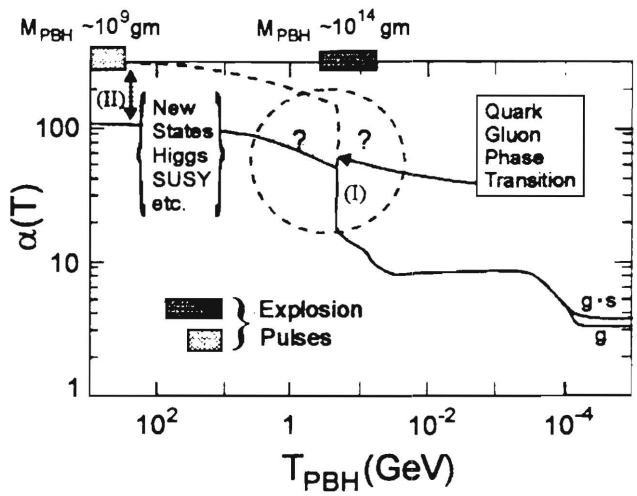

FIG. 1. The running coupling constant or density-of-states factor, α, showing regions of uncertainty due to the quark–gluon phase transitions (I) or the increase in the number of new elementary particles (II). Also shown is the location (at the top of the mass of the black hole) where short GRBs could occur.

This rate is directly proportional to the particle emission degrees of freedom and, therefore, is highly model dependent. If PBHs are clustered in the galaxy, the exploding PBH density is estimated at $\sim 10/\mathrm{y\ pc}^3$ [4]. PBHs would be formed in the Early Universe from density fluctuations [6].

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 [8]. In the fireball model, we would expect the PBH evaporation to give GRBs of time duration of a few hundred ms or less [7].

In Table 1, we list the general properties of the GRB from PBHs from the considerations above. In Figure 2, we provide a more detailed flow diagram of the various constraints (see Table 1) that lead to the expected detection rate.

The concept of a PBH with $\sim 10^{14}$ g and $\Omega_{\mathrm{PBH}} \sim 10^{-8}$ is not contradicted by any known cosmological or other constraint. Therefore, the GRB data should be studied to see if a constraint exists (no events) or if candidates for such events exist with properties:

- $\Delta\tau \leq 200$ ms; hard γ spectrum (fireball model),
- Isotropic–homogeneous distribution ($V/V_{\mathrm{max}} \sim 1/2$),
- No visible counterpart,
- $d \sim$ (1–10) pc,
- $10 \leq$ detected/y!,
- Source size $\ll$ neutron star.

Table 1. Properties of GRBs from PBHs Used in this Analysis.

II. EARLY STUDY OF SHORT BURSTS

A large body of work exists from the 1980s on the short GRBs [7]. We have studied many of the experimental papers on GRBs and noticed that there are short GRBs (few 100 ms) that, in many cases, seem to have a hard γ spectrum [7]. Recently, the BATSE group has recorded a very interesting short (ms) GRB that also has a hard spectrum [9]. It also has characteristics that are consistent with a PBH origin in our model.

Since very short γ-rays from the PBH fireball are expected to be seen at a distance of, at most, parsecs around the earth, we expect the short bursts selected among the BATSE data [10] to be homogeneous and have an isotropic distribution of sources in a static, Euclidean space (HISE).

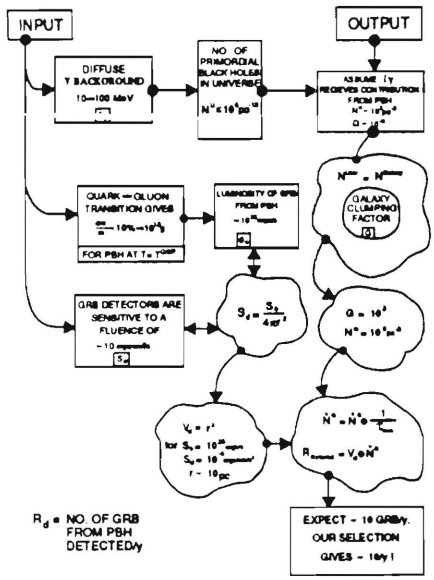

FIG. 2. Constraints and estimate of the number of GRBs from PBHs at the quark–gluon phase transition, indicating that ≤ 10 events/y would be detected by BATSE.

To make any reasonable assessment about the spatial distribution of the short GRBs, we need to study the log $N(C_p)$ vs $\log(C_p/C_{\rm lim})$ or log (C_p). This distribution may contain a bias due to the variable threshold, burst durations as suggested by Petrosian [13]. By following their suggestions, we corrected for the bias due to the variability of $C_{\rm lim}$. (The Petrosian analysis is justified, because of the expected loss of short weak bursts.) The corrected distribution is consistent with a slope of $-3/2$, as expected for HISE (of course, the statistical limitation is evident). We note as well that the short bursts observed by PHEBUS [12] also give $V/V_{\rm max} \sim 1/2$.

III. PROPERTIES OF THE BATSE 2B SHORT BURSTS

We apply the following cuts to the 2B data:

1. Short duration bursts where $T_{90} < 200$ ms.
2. Insisting on data availability for both the hardness ratio and spatial distribution analysis. This includes T_{90} and the fluence data for the hardness ratio and the counts in the peak $C_p/C_{\rm lim}$ for the $V/V_{\rm max}$ tests. A cut was made requiring single-spike data with a reasonable fluence in the $E > 20$-keV energy range. The cut was that the fluence in channel 4 ($E > 300$ keV) is $> 10^{-7}$ ergs/cm^2.

The BATSE 2B data are consistant with the observations we made concerning the 1B data except that the hardness spectrum does not show a clear falloff [14]. Our analysis of the short bursts confirms that they are consistent with a PBH origin [7,14].

IV. PRELIMINARY STUDY OF TTE DATA AND SIZE OF SOURCE

It is not clear at present how one will finally decode the relevant information from GRBs to determine key issues (*e.g.*, the distance scale or energy production method). We believe the fine time structure of the short bursts could give some information about the source size through relations such as

$$[\text{Source Size}] \leq \frac{c}{f} \quad , \tag{4}$$

where f is the highest frequency component in the time structure of the burst, and c the speed of light. To this end, we have started to carry out a Fourier analysis of the BATSE TTE data for short bursts [13]. A preliminary result of the analysis of three events is given here. Figure 3 shows the PSDs for three BATSE triggers, showing that high-frequency components are needed [13]. We will analyze more events in this way to see if a pattern emerges to provide a unified explanation for these events.

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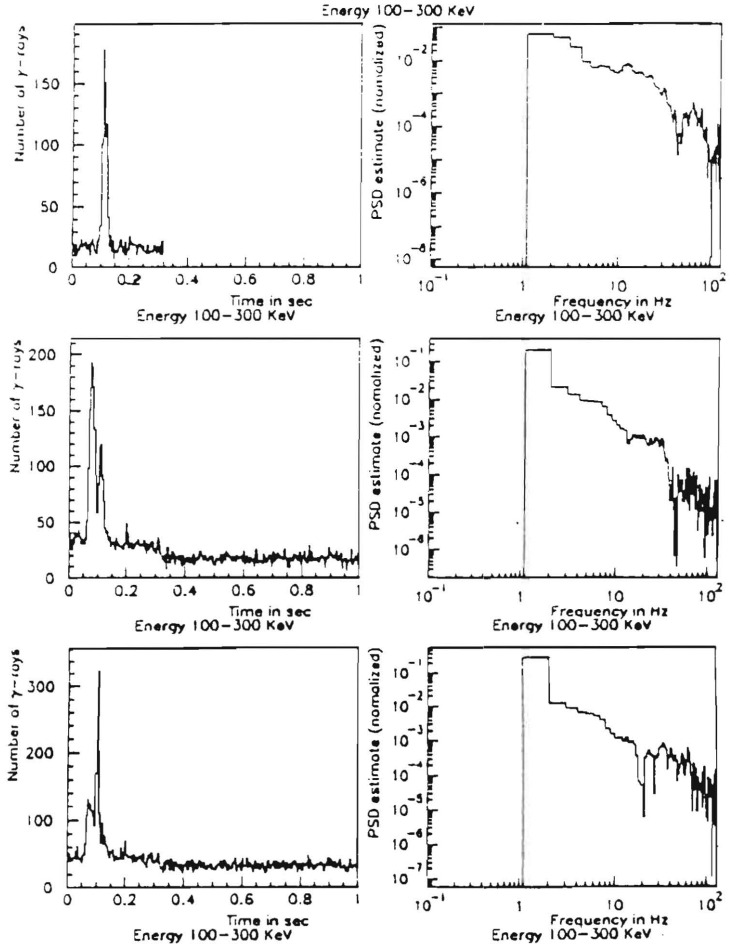

FIG. 3. Event time shapes and PSDs for three very short BATSE events.