May 5, 1993

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SIGNALS FOR PRIMORDIAL BLACK HOLES†

DAVID B. CLINE

Departments of Physics & Astronomy, University of California Los Angeles
405 Hilgard Avenue, Los Angeles, California 90024

ABSTRACT

One of the most intriguing concepts in modern astrophysics is that of an unstable Primordial Black Hole, largely invented by Steven Hawking. Contrary to common perception, the existence and abundance of such objects in the Galaxy is poorly constrained. We discuss some possible methods to improve current limits or perhaps discover such objects, provided the final state of the PBH is a rapid explosion process near the quark-gluon phase transition conditions. We also comment on some unusual Gamma Ray burst events in this connection.

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]. (At this meeting some people even questioned whether this collapse time was too short.) 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].

The situation is made somewhat more confusing by two recent developments

(1) Recent suggestions that PBH "decay" into more stable objects with mass $\gtrsim M_{\text{Planck}}$

(2) a recent paper by S. Hawking in which he states that a rapid explosion might be expected and we quote directly from this paper[5]:

† Invited Talk and prepared for the Proceedings of the Neutrino meeting held in Venice, Italy, March 2-4, 1993.

"What seems to be happening is that the semiclassical approximation is breaking down in the strong-coupling regime. In conventional general relativity, this breakdown occurs only when the black hole gets down to the Planck mass. But in the two- and four-dimensional dilatonic theories, it can occur for macroscopic black holes when the dilation field on the horizon approaches the critical value. When the coupling becomes strong, the semiclassical approximation will break down. Quantum fluctuations of the metric and the dilaton could no longer be neglected. One could imagine that this might lead to a tremendous explosion in which the remaining mass energy of the black hole was released. Such explosions might be detected as gamma-ray bursts."

Hawking showed in a seminal paper that an uncharged, non-rotating black hole emits particles with energy

$$(E,\ E + dE)$$

at a rate per spin or helicity state

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

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

$$T \simeq 10^{16}\left[\frac{1g}{M}\right]\ \text{MeV} \tag{2}$$

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:

$$\frac{dM}{dt} = -\frac{\alpha(M)}{M^2} \tag{3}$$

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]

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

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 $T \sim 100\text{GeV}$, 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]

$$\rho(m) \sim m^{-\beta} \, exp\left[\frac{m}{\Lambda}\right] \tag{5}$$

where $5/2 \leq \beta < 7/2$ and $140\,\text{MeV} \leq 160\,\text{MeV}$. 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.

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].

THE CONCEPT OF A PBH & FORMATION IN THE EARLY UNIVERSE

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

$$M_* \simeq [3\alpha\,(M_*)\,\tau_{\text{evap}}]^{1/3} \simeq 7.0 \times 10^{14}\text{g} \tag{6}$$

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 $10-100\,\text{MeV}$ energy region[7] (see Table 1).

$$N = \frac{dn}{d\,(\ln M)}\,|_{M=M_*} \leq 10^5\,\text{pc}^{-3} \tag{7}$$

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

$$\frac{dn}{dt} = \frac{3\alpha\,(M_*)}{M_*^3}\,N = 2.2 \times 10^{-10}\,\text{N}\,\text{pc}^{-3}\,\text{year}^{-1} \tag{8}$$

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]:

At $\tau_{\rm tot} \sim 1$, 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

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

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, ($\gamma_f = 2 \times 10^{16}\,{\rm g/M_{PBH}} \sim 300)^2$, 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].

SURVEY OF GRBs & SEARCH FOR UNUSUAL EVENTS

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 1 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 (Fig. 2)[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 (Fig. 3)[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. Unfortunately, there are no

detectors in space now, or being planned, that would have nanosecond time resolution and sufficient area to collect adequate statistics to observe such structure.

SUMMARY

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!

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TABLE 1

Primordial Black Hole Phenomenology

1) Formed IN EARLY UNIVERSE – Zel'dovich Spectrum

2) Follow Beckenstein's and Hawking's 1st law of BH Thermodynamics

3) $T = 10^{16}/M(\text{grams})\,\text{MeV}$

4) All PBH with $M < 5 \times 10^{14}$ GRAMS HAVE DECAYED

$$\dot{M} = -\alpha \left[\frac{M}{M^2}\right] \quad \sim (20/\text{year}\,??)$$

5) We STUDY DECAY of

$$M_{PBH} = 5 \times 10^{14}\,\text{g}$$

$$T = 20\,\text{MeV}$$

FINAL EXPLOSION PICTURE

- QCD-Like – Hard Spectrum
- Hagedorn-like $\sim$ Soft Spectrum (∞ # grams)
- Hybrid – Mixture of Hard and Soft
- In this model we get energy release of $\sim 10^{33}$ergs in $\sim \mathcal{O}(\text{ms})$

6) COMPARE WITH γ BURSTERS

A small fraction are compatible with this picture

7) What are CONSEQUENCES OF ASSUMING A FEW % ARE PBH

i) They are local [r < few parsecs]

ii) Neutrino Burst – SNBO

iii) Perhaps a small flux of higher energy γ's

- that can be detected in future γ telescopes
- $\sim (1 - 10)\,\text{m}^2$

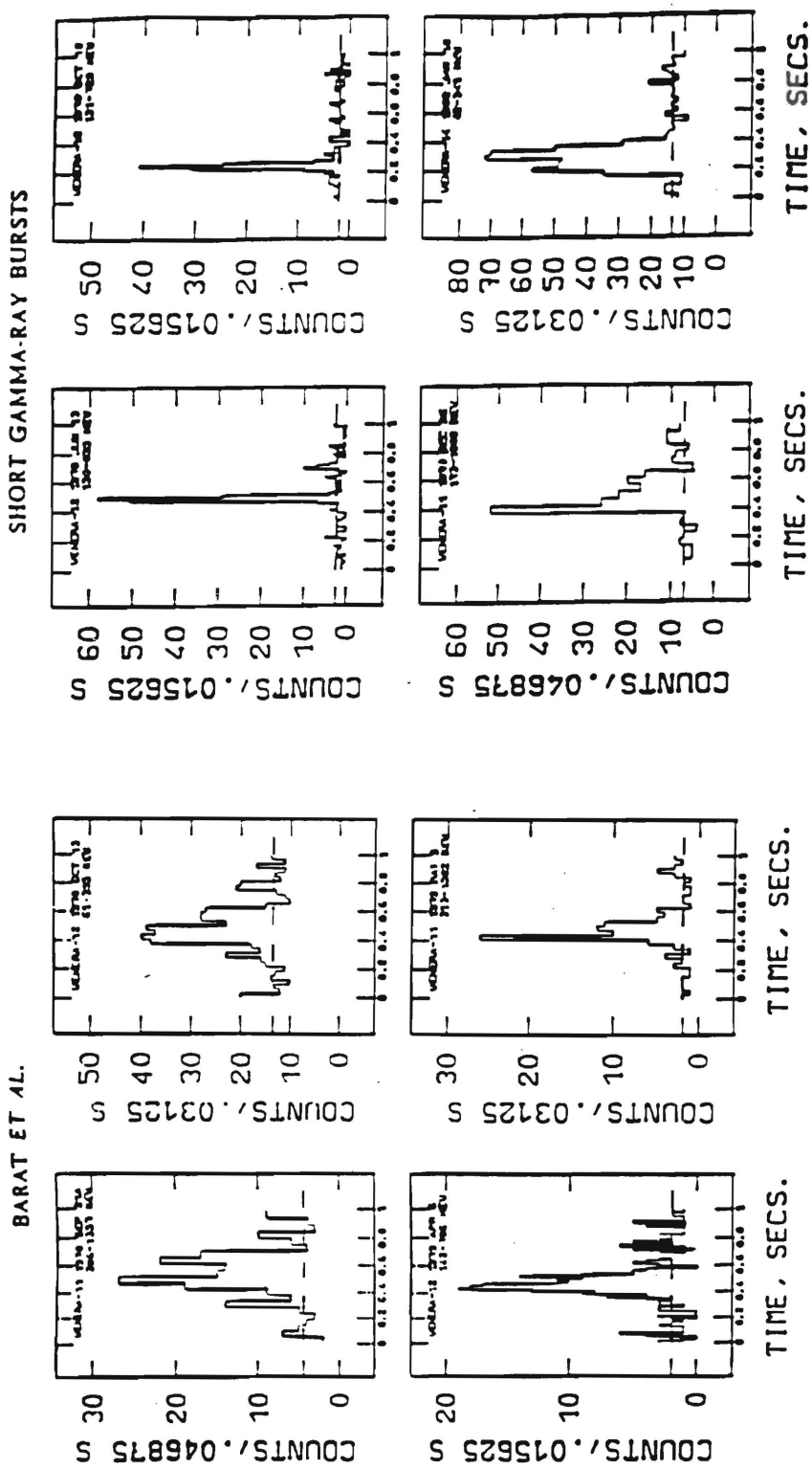

Fig. 1: Eight short GRB from past observations.

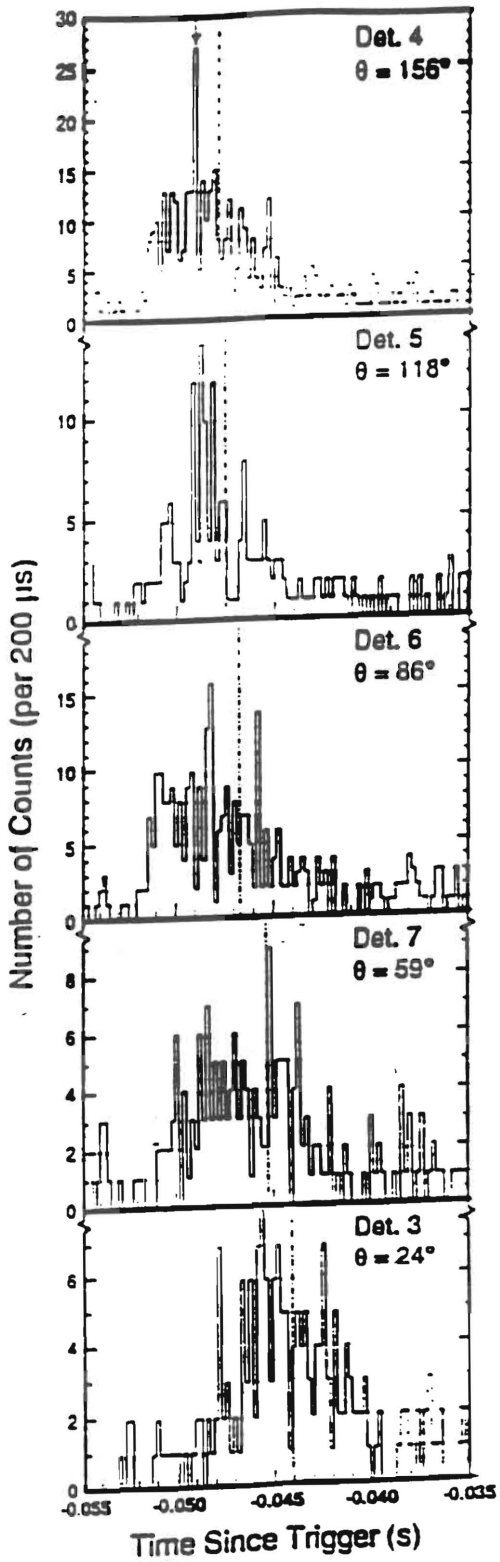

Fig. 2: Observation of a very short time GRB by BATSE.

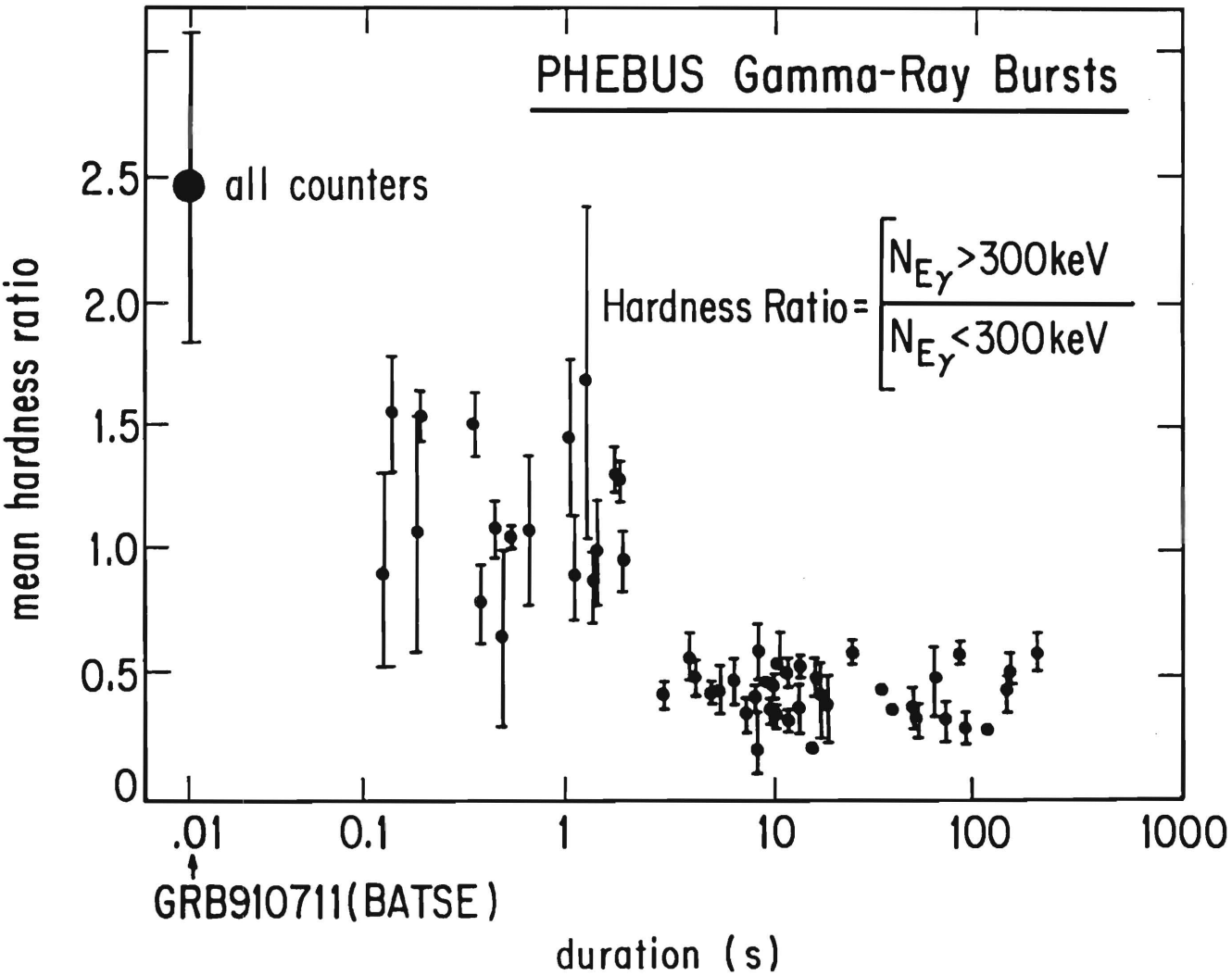

Fig. 3: Hardness spectrum of some short GRB events.