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Possible Evidence for Gamma Ray Bursts from Primordial Black Holes.

David B. Cline and David Sanders

University of California, Los Angeles, Department of Physics and Astronomy, 405 Hilgard Ave., Los Angeles, CA 90095 USA

UCLA-APH-0078-9/95

We discuss a very interesting group of GRBs 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. GRB duration, would be expected if some of the short GRBs came from the evaporation of black holes. We show other aspects the event consistent with this hypothesis and suggest further tests of the concept.

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1 Introduction

The possible existence of Primordial Black Holes[1] (PBHs), with the mass the same as a small mountain (10^{14} g), having a Schwarzschild radius smaller than that of an electron, is so interesting that it should be proven or dismissed in some way. (We recall that even in the 1960's the hypothetical W particles which were also considered very implausible to "really" exist and at that time the mass was guessed to be only 2 GeV.) Primordial Black Holes may have been produced in the Big Bang and are evaporating through exotic particle physics processes such as the quark-gluon phase transition, and emission of possible Higgs and SUSY particles all the way to the GUT and Planck energies.

As was initially discussed by Page and Hawking[2], the only likely way to detect the PBH is through a Burst of Photons (a Gamma Ray Burst). However, using the preferred model of hadrons at the time (the Hagedorn model), they expected Bursts of $\sim 10^{-7}$ sec duration. Today, few would expect this model to describe the hadron final state, but we use QCD models with the expected quark-gluon phase transition. In this report we discuss the study of existing Gamma Ray Burst data to see if events with the expected morphology to fit PBH evaporation are excluded in the data set. In order to carry out the search, we have developed a simple model of the rough properties of such Gamma Ray Bursts (GRBs).

2 Primordial Black Hole Evaporation at the Quark Gluon Phase Transition.

The present abundance of PBHs in the universe is strongly constrained by the diffuse γ radiation in the 100 MeV region. This constraint translates into a limiting density in the universe of $10^5 - 10^6$ PBHs/pc^3, which would give a tiny fraction of $\Omega_{PBH} \lesssim 10^{-7}$ (see [3,4]). However, if PBHs exist at the limiting level, we would expect a large enhancement in the galactic density to perhaps $\lesssim 10^{10}$ PBHs/pc^3.

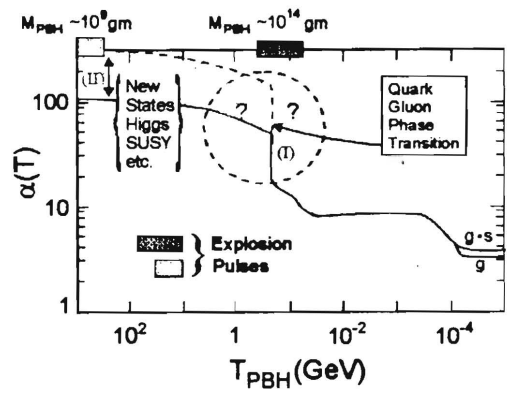

Figure 1: The running coupling constant or density of states factor, α, showing regions of uncertainty due to the quark-gluon phase transitions (I) or the increase in the number of new elementary particles (II). We also show on the same graph at the top of the mass of the black hole where short GRBs could occur.

Hawking[1] 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:

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

where $\alpha(M)$, the *running constant*, counts the particle degrees of freedom in PBH evaporation. The value of the $\alpha(M)$ is model-dependent.

A reasonable model of the running coupling constant 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 GRBs may occur when the PBH mass is 10^{14} or 10^9 grams.

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

$$M_* \simeq [3\alpha(M_*)\tau_{\rm evap}]^{1/3} \simeq 7 \times 10^{14}{\rm g} \qquad (2)$$

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

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

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 $\sim$ 20 per year[5]. PBHs would be formed in the Early Universe from density fluctuations[4].

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[6]. In the fireball model we would expect the PBH evaporation to give GRBs of time duration of a few hundred milliseconds or less[5,7].

3 Study of GRB Data

In the early 1980's it was noticed that a small fraction of the GRBs were short with very symmetrical bursts[8]. The rate in the small detectors of the day was about 2/year. We have carefully studied the BATSE data and find the rate of such events is about 8/year. The difference is likely due to detecting weaker bursts.

We have studied the BATSE data and find the following:

i) The short bursts show increasing hardness. When we select events with the cut $\Delta\tau \leq 200$ ms and require a single spike in each event, this yields 17 events. We also can use the variability parameter invented by Lamb[9] and defined as $V = C_{64}/C_{1024}$. If we select $V \geq 0.7$ events we find the hardness distribution shown in Fig. 2.

   Although this reduces the sample to 6 events, it clearly shows that the events have enhanced hardness at small $\Delta\tau$.

ii) We have studied the ln(N)-ln(S) distribution using the data correction method discussed by Petrosian[10]. The resulting distribution is shown in Fig. 3 and is consistent with the sources coming from a Homogeneous Isotopic Euclidean space.

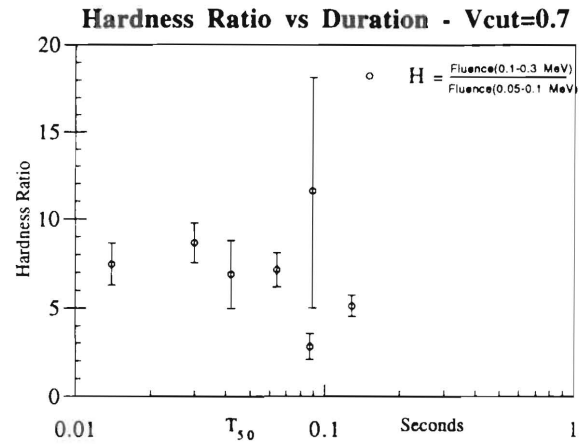

Figure 2: The hardness vs. T_{50} for BATSE - 2B data when the cut V> 0.7 is applied.

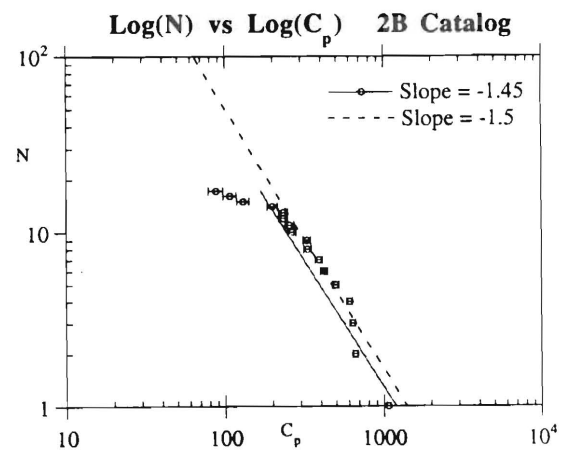

Figure 3: The ln(N)-ln(S) plot for 17 BATSE - 2B events with the correction of Petrosian applied.

   There is no evidence for a boundary. The positions of the sources in Galactic coordinates are shown in Fig. 4. There is no evidence for a galactic center or plane concentration.

iii) Shot Noise Distribution

   The short time structure of one short burst has been analyzed by the BATSE team[11] and has important fine structure on the 10-100μsec scale, suggesting a compact source as the origin. This is consistent with the expectation of a PBH origin of these events.

4 Future Tests of the PBH Hypothesis

Table 1 lists the expected characteristics of the GRB from PBHs at the quark-gluon phase transition and a comparison with existing GRB data. Remarkably, so far there is a consistency of explanation for the PBH hypothesis.

Table 1: Characteristics of Selected GRBs Consistent with the PBH Evaporation Hypothesis

Event Characteristics	GRB Events (Selected)	Expectation for PBH Evaporation
Time duration	Time duration $\sim$ 200 msec	In Fireball picture $\Delta\tau \simeq$ 100 msec
Event hardiness in γ spectrum $H \equiv \frac{F(0.1-0.3\text{MeV})}{F(0.05-0.1\text{MeV})}$	PHEBUS short burst data have hard spectrum[12] Hardest γ spectrum of any GRB $\langle H \rangle \cong 6$ for BATSE data	Expect hard γ 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
V/V_{max} test for population spatial structure	BATSE 2B - corrected $\ln(N) - \ln(S)$ distribution consistent with slope $\sim -3/2$ PHEBUS short events $V/V_{\text{max}} = 0.46 \pm 0.14$	Expected V/V_{max}=1/2 or $\ln(N) - \ln(S)$ slope =-3/2
Fine time structure in events	In one BATSE event time structure of $\sim 100\mu$sec observed[11]	Fine time structure could reveal size of source
Limit rate of GRBs from PBH expected	$\sim$ 17 in 366 GRBs $\sim$ 5 % (1B-2B) data - Low rate	Expect low rate and $\Omega_{PBH} \sim 10^{-7}$ - perhaps 10/year

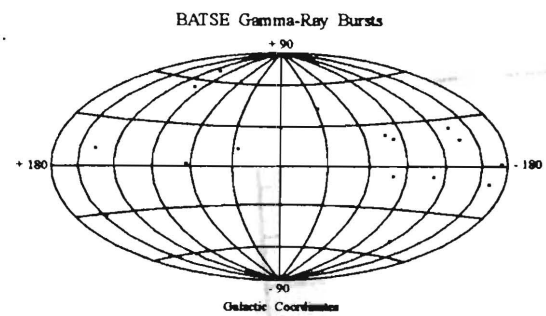

Figure 4: The galactic coordinators position for the 17 BATSE 2B events.

We believe the study of the shot noise in the BATSE TTE data could further help us determine the size of the compact source driving the GRBs. If one can demonstrate that there are fluctuation at the level of 3μsec this would limit the size to 9 km which would be less than that expected for a neutron star, again producing some evidence for a more compact source. (A PBHs with a size of 10^{-13} cm would be a clear candidate.) There are other possible tests if the PBH abundance in the galaxy is $\sim 10^{10}/\text{pc}^3$; there will be high energy gamma rays bursts (the $m \sim 10^9$ g region of Fig. 1). These might be detected by a very large area, high-energy array of telescopes (much larger than any in construction or existence today). We note that Kouveliotou[13] has shown that the GRBs have at least 2 classes of events.

We thank G. Fishman, Jay Norris and J. Bonnell for discussion and help with the BATSE data story.

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