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Further Evidence for Gamma Ray Bursts Consistent with Primordial Black Hole Evaporation*

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Abstract

Previously, we identified some short burst events from the BATSE 1B catalogue that were consistent with an origin of primordial black hole evaporation at the quark-gluon phase transition. We showed that these events are also consistent with arising from a homogeneous spatial distribution. Recently, the PHEBUS group has also indicated that the short bursts are consistent with $V/V_{\max} \sim 1/2$. In this note we describe the results of the study of the BATSE 2B catalogue shape which confirm the results from BATSE 1B.

Subject headings: black hole physics- cosmology- gamma rays: short bursts

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1 Introduction

The search for evidence for primordial black holes (PBHs) has continued since the first discussion by Hawking (1974). In fact, this was about the time that gamma ray bursts (GRBs) were first discovered, making a natural association with PBHs (Klebesadel *et al.* 1973). However, in the intervening years it has become clear that the time history of the typical GRB is not consistent with the expectations of PBH evaporation. We started our study with an expectation that perhaps none of the GRBs are consistent with a PBH origin or to see if any GRBs had characteristics that would be consistent with PBH origins.

While the theory of the PBH evaporation has been refined, there are still no exact predictions of the GRB spectrum, time history, and so forth (Halzen *et al.* 1991). However, reasonable phenomenological models have been made and the results again indicate that most GRBs could not come from PBHs (MacGibbon & Carr 1991; Cline & Hong 1992). In addition, there are new constraints on the production of PBHs in the early universe that indicate that the density of PBHs in the universe should be very small, but not necessarily zero (Carr & Lidsey 1993).

After the initial discovery of Gamma Ray Bursts it took many years to uncover the general properties. Around 1984 several detections indicated that there was a class of short bursts with time duration of ~ 100 msec and a very short rise time (Barat *et al.* 1984). A separate class of GRBs was declared (Norris 1984). This classification seems to have been forgotten and then rediscovered by some of us (Cline & Hong 1994). Due to the trigger conditions of BATSE and other GRB detectors, it is still unclear as to whether bias exists in the detection of short bursts or that there are even shorter bursts ($\Delta\tau$ ~ msec) that have so far escaped detection (Norris 1984). A few short bursts were observed by the Interplanetary Network providing a good location, but no counterparts were detected in these locations (Laros *et al.* 1981). The shortest published GRB to date (48 msec) - June 13, 1979 - is a prime example of a well localized GRB with no apparent counterpart in other parts of the electromagnetic spectrum (Barat *et al.* 1984). (The SIGNE detector has apparently observed shorter bursts but no publication exists to date.)

It is still possible that there is a sizable density of PBHs in our galaxy and that some of the GRBs could be due to PBH evaporation. Recently, we showed that the BATSE 1B data (Fishman *et al.* 1994) have a few events that are consistent with some expectation of PBH evaporation (short burst with time duration of less than 200 msec and that are consistent with $V/V_{\max} \sim 1/2$) (Cline & Hong 1994). In addition, the PHEBUS team recently reported at the ESTEC/Gamma Ray Burst meeting, a similar class of events observed in their experiment. These events have a short time history which tend towards giving $V/V_{\max} \sim 1/2$, making them consistent with a homogeneous population of emitters (Dezalay 1995). Since there is no evidence that these GRB are localized in the galactic disk or center, it is conceivable that PBHs in the vicinity of the solar system could be the progenitors of the GRBs. We note that recently it has been proposed that there are at least two classes of GRBs (Kouveliotou *et al.* 1993)

In this report we summarize our previous results (Cline & Hong 1994) from BATSE 1B data (Fishman *et al.* 1994) and present a preliminary analysis of the BATSE 2B data (Meegan *et al.* 1994) from the standpoint of the original conjecture that they arise from PBHs.

2 Primordial Black Hole Evaporation

2.1 The Quark Gluon Phase Transition Model

Ever since the theoretical discovery of the quantum-gravitational particle emissions from black holes by Hawking (1974), there have been many experimental searches (see Halzen *et al.* 1991 for details) for high energy γ-ray radiation from primordial black holes formed in the early universe (Carr, Gilbert, & Lidsey 1994; Carr & Lidsey 1993), now 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., $T_{\rm PBH} \approx 100$ MeV $(10^{15}\,{\rm g}/m_{\rm PBH})$, since the black hole becomes hotter as it radiates more particles and can eventually attain extremely high temperatures.

Previous theoretical efforts (MacGibbon & Carr 1991; Page & Hawking 1976) have been focused on the estimation of the PBHs' number density in the present universe by requiring the calculated diffuse photon spectrum from evaporated PBHs at energies around 100 MeV to be smaller than the observed diffuse extragalactic background data (Trombka *et al.* 1977; Fichtel, Simpson, & Thompson 1978; Gibbs 1988). According to their estimates in the context of the Standard Model of particle physics, the PBH explosion density of events could be as high as 10 $\rm pc^{-3}yr^{-1}$ if holes are clustered in the galactic halo (MacGibbon & Carr 1991; Page & Hawking 1976). However, the past 20 years of direct searches for high-energy radiation from the PBHs at the final stage of evaporation, have led to various upper limits on the density of events, ranging from 7×10^{-10} $\rm pc^{-3}yr^{-1}$ to 8×10^{5} $\rm pc^{-3}yr^{-1}$ (see Halzen *et al.* 1991 for a review). These final stage evaporation pictures are closely related to how the emitted particle spectrum from the PBH evaporation changes as the black hole surface temperature approaches a critical point. To be more precise, at $T_{\rm PBH} \sim 140-160$ MeV for the Hagedorn model (Hagedorn 1965), the PBH mass would rapidly convert to hadronic matters (mostly pions) within an extremely short time and, at $T_{\rm PBH} \sim 100-300$ MeV for the quark-gluon de-confinement phase transition, the emitted free quarks and gluons would hadronize after some distance from the PBH horizon. As a result, these uncertainties in the PBH evaporation mechanism are amplified due to the present lack of understanding in the particle physics around these critical temperatures. Thus, the fact that model-dependent upper limits on the explosion density of events, observed as high energy γ-rays, vary almost 10 orders of magnitude.

Hawking (1974) 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 spin of helicity state of:

$$\frac{d^2N}{dtdE} = \frac{\Gamma_s}{2\pi\hbar}\left[\exp\left(\frac{8\pi GME}{\hbar c^3}\right) - (-1)^{2s}\right]^{-1}. \tag{2.1}$$

Here M is the PBH mass, s is the particle spin and Γ_s is the absorption probability. One can think that this particle emission comes from the spontaneous creation of particle-antiparticle pairs near the black hole's event horizon. One particle of the particle-antiparticle pair escapes to infinity while the other returns to the black hole. Thus, the PBH emits massless particles, photons and light neutrinos, as if it were a hot black-body radiator with temperature $T \cong (10^{16}\,\mathrm{g}/M)$ MeV, where M is the black hole mass. A black hole with one solar mass, $M_1 \cong 2\times10^{33}$ g, has an approximate temperature of 10^{-3}K, while a black hole with mass of 6×10^{14} g has a temperature of ~20 MeV. As a black hole loses mass during its lifetime, its temperature increases. The loss of mass from a black hole occurs at a rate, in the context of the Standard Model of particle physics, of:

$$\frac{dM}{dt} = -\frac{\alpha(M)}{M^2}, \tag{2.2}$$

where $\alpha(M)$, the *running constant*, counts the particle degree of freedom in the PBH evaporation. The value of $\alpha(M)$ is model-dependent. In the Standard Model, with a family of 3 quarks and 3 leptons, it is given (Cline & Hong 1992; Hawking 1974, 1975) as $\alpha(M) = [0.045\,S_{j=+1/2} + 0.162\,S_{j=1}]\times10^{-4}$, where $S_{j=+1/2}$ and $S_{j=1}$ are the spin and color degrees of freedom for the fermions and gauge particles respectively. For the Standard Model one obtains $\alpha(M) = 4.1\times10^{-3}$. In the Hagedorn-type picture, a model different from the Standard Model, the number of emitting particle states grows exponentially with mass (Huang & Weinberg 1970) $\rho(m) \sim m^{-\beta}\exp(m/\Lambda)$, where $5/2 \le \beta \le 7/2$ and $140\ \mathrm{MeV} \le T \le 160\ \mathrm{MeV}$. These models were motivated by the apparent exponential increase in the hadronic resonance seen by accelerator experiments. While lattice calculations give no evidence for the Hagedorn-type models, such models are not yet excluded.

A reasonable model of the running coupling constant is illustrated in Figure 1, where the regions of uncertainty are indicated. These are the regions where there could be a rapid increase in the effective number of degrees of freedom due to the quark-gluon phase transition. The phase transition would lead to a rapid burst in the PBH evaporation or, at high energy, there could be many new particle types that would also lead to an increase in the rate of evaporation. Also shown in Figure 1 are the regions in PBH temperature where short duration γ-ray bursts may occur when the PBH mass is either 10^{14} or 10^9 grams.

Black holes at the evaporation stage at the present epoch can be calculated as having $M_* \cong \left[3\alpha(M_*)\,\tau_{\mathrm{evap}}\right]^{1/3} \cong 7.0\times10^{14}\,\mathrm{g}$ for $\alpha(M_*) \cong 1.4\times10^{-3}$. The bound

on the number of black holes at their critical mass, constrained by the observed diffuse gamma-ray background, has been put in the 10-100 MeV energy region (Halzen *et al.* 1991).

$$N = \frac{dn}{d(\ln M)}|_{M=M_*} \leq 10^5 \mathrm{pc}^{-3} \tag{2.3}$$

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

$$\frac{dn}{dt} = \frac{3\alpha(M_*)}{M_*^3} N = 2.2 \times 10^{-10} N \mathrm{pc}^{-3} \mathrm{yr}^{-1}. \tag{2.4}$$

2.2 Concept of a Primordial Black Hole Fireball

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 to single out such a monumental event. However, we pointed out in a previous work (Cline & Hong 1992), a possible connection between very short gamma-ray bursts (GRBs) observed by the BATSE team (Fishman *et al.* 1994) and PBH evaporation emitting very short energetic γ-rays. If we want to accept this possibility, we may have to modify the method of calculating the particle emission spectra from an evaporating PBH, in particular, at or near the quark-hadron plasma (QGP) (see Rafelski 1982 for a review) phase transition temperature at which the T_{PBH} arrives eventually. We briefly discussed in the previous work that inclusion of the QGP effect around the evaporating PBH at the critical temperature may 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 γ-ray burst (on the order of milliseconds duration). As a result, the average γ-ray energy emerging from such a fireball could be lower than the previous estimates (MacGibbon & Carr 1991; Page & Hawking 1976). Thus it might be more likely to be detected as very short GRBs rather than as high energy γ-ray radiation. This scenario should be consistent with the modern pair-fireball models characteristics developed by several authors (Goodman 1986; Paczynski 1986; Shemi & Piran 1991; Mészáros, Laguna, & Rees & 1993; Narayan, Paczynski, & Piran 1992; Piran & Shemi 1993; Piran, Shemi, & Narayan 1993).

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 parsecs from the earth. Since the BATSE detector's observed fluences of $\approx 10^{-7}\mathrm{ergs/cm}^2$, we require the distance to the PBH fireball (R_{PBH}) and the release of total γ-ray

energy ($L^{\gamma}_{\rho\mathrm{BH}}$) during a short period of time to be $L^{\gamma}_{\rho\mathrm{BH}}/4\pi R^2_{\mathrm{PBH}} \geq 10^{-7}\,\mathrm{ergs/cm^2}$. In fact, the total γ-ray energy from a PBH evaporation is closely related to the PBH mass at a QGP phase transition temperature (roughly $T_{\mathrm{QGP}} \geq 160$ MeV) as $L^{\gamma}_{\rho\mathrm{BH}} = \kappa m_{\mathrm{PBH}}$, 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 T_{QGP}, rapid interactions between the emitted quarks and gluons by the Hawking process at the PBH horizon ($\sim 2m_{\mathrm{PBH}}$) may result in a local thermal equilibrium and thereafter form an expanding ultra-relativistic QGP fireball. 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 due to 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.

The thermodynamics parameters, i.e., ρ density, P pressure, for the high temperature matter fireball evolution at an adiabatic perfect fluid limit are a function of one parameter, i.e., the entropy density s; $\rho \sim s^{\Gamma}$ where Γ is an adiabatic index. Γ is a particle model-dependent constant, i.e., $\Gamma = 4/3$ (hard) for the standard model, or $\Gamma = 1$ (ultra soft) for the Hagedorn type models (Hagedorn 1965; Frautschi 1971). If $1 \leq \Gamma < 6/5$, the matter fireball can be treated as a perfect fluid (Carter *et al.* 1976). An evolution of the high temperature matter emitted from the PBH as an adiabatic perfect fluid has been extensively discussed by Carter *et al.* (1976). Their analysis shows that the matter fireball, conserving the total entropy S, expands to a certain radius above the PBH event horizon:

$$r_s \cong \left[\frac{L_{\mathrm{PBH}}}{4\pi T^4_{\mathrm{PBH}}} \frac{T^3}{s(T)} \right]^{1/2}, \tag{2.5}$$

where L_{PBH} is the total energy emitted from PBH. This calculation is based on the assumption that the proper time τ taken for the matter fireball to reach the distance r_s must be longer than the characteristic interaction time τ_0 required for achieving a local thermal equilibrium:

$$\tau \sim \left[\frac{L_{\mathrm{PBH}}}{4\pi T^4_{\mathrm{PBH}}} \frac{T^3}{s(T)} \right]^{1/2} \sim \frac{1}{T_{\mathrm{PBH}}} \left(\frac{T_{\mathrm{PBH}}}{T} \right)^{\frac{\alpha-3}{2}} \geq \tau_0, \tag{2.6}$$

where T is determined from the equation of state by $T = d\rho/ds$ and $\alpha \equiv 1/(\Gamma - 1)$. The interaction time τ_0 is a parameter hard to calculate without a definitive particle physics model of the matter fireball. Thus, we assume that τ_0 lies between the larger than the basic thermal time scale ($1/T$) and the interaction time scale in the matter fireball ($1/\Lambda_{\mathrm{int}}$), i.e., $1/T \leq \tau_0 \leq 1/\Lambda_{\mathrm{int}}$. Depending on the

equation of state (hard or ultra soft, i.e., $3 < \alpha \leq \infty$) and the temperature of the matter fireball, the ratio τ/τ_0 indicates whether a perfect fluid treatment of the matter fireball is acceptable:

$$\begin{cases} \dfrac{\tau}{\tau_0} \leq \left(\dfrac{T}{T_{\mathrm{PBH}}}\right)^{\frac{5-\alpha}{2}} \leq 1 & \text{for } T \leq T_{\mathrm{PBH}}\text{; tranparent} \\ \dfrac{\tau}{\tau_0} \geq \left(\dfrac{\Lambda_{\mathrm{int}}}{T_{\mathrm{PBH}}}\right)\left(\dfrac{T_{\mathrm{PBH}}}{T}\right)^{\frac{\alpha-3}{2}} \geq 1 & \text{for } T \geq \Lambda_{\mathrm{int}}\text{; opaque fluid} \\ \dfrac{\tau}{\tau_0} \geq e^4\left(\dfrac{T_{\mathrm{PBH}}}{T}\right)^{\frac{\alpha-5}{2}} \geq 1 & \text{for } m_e \leq T \leq \Lambda_{\mathrm{int}} \text{ and } T_{\mathrm{PBH}} > T(\alpha > 5); \\ & \text{opaque fluid} \end{cases} \quad , (2.7)$$

where e is the electronic charge $e^2 = 1/137$. From the last condition in equation (2.7), we find that the matter fireball maintains its fluid validity so long as $\Gamma < 6/5$ ($\alpha > 5$) and T_{PBH} is larger than the matter fireball temperature. This question, whether initial QGP interactions around PBH horizon create the matter fireball with the adiabatic index ($1 \leq \Gamma < 6/5$), should be investigated in greater detail in the future.

Using the simplest picture, i.e., only π^0s produced in the Quark Gluon Phase transition, we can obtain the properties of the fireball. Using equation (2.5) and given that $L_{\mathrm{PBH}} \sim L_{\mathrm{QGP}} \sim 5 \times 10^{34}$ ergs and $T_{\mathrm{PBH}} \sim T_{\mathrm{QGP}} \geq 160$ MeV, a simple radiation dominated model would give $r_s \sim 10^9$ cm, which implies that τ is of order 100 msec. Thus, one can expect GRBs from a fireball to have both a very short rise time ($\leq 1\mu$ sec) and duration ~50-200 msec also in this model.

2.3 Possible Hardness of the Gamma Ray Spectrum

We can now give a general prescription for the properties of the Gamma Ray Burst from PBH evaporation:

1. There should be a short time burst of $\delta t \ll 1$ sec even in the standard particle physics model (Halzen *et al.* 1991). In models for rapid evaporation near the critical quark-gluon phase transition temperature we may expect similar effects (Cline & Hong 1992).
2. The PBH explosion time scales are $\tau_{\mathrm{evap}} \sim m_{\mathrm{PBH}}^3 \sim T_{\mathrm{PBH}}^{-3}$, and thus, a very short burst will produce a very high temperature, i.e., the energy spectrum average hardness should increase with short time bursts. (However detailed predictions in the 0.05 - 0.3 MeV range are not possible at present).
3. The highest energy particles should be emitted in the shortest time duration at the final collapse ($M_{\mathrm{PBH}} \sim 10^9$ grams). However, the average energy of the γ-rays from Quark-Gluon Transition will likely be in the MeV range.

These characteristics are generic to PBH γ-ray bursts. In addition, we might expect that very short bursts would have time frequency components indicative of the source size, i.e., $\delta t \sim l/c < 10^{-6}$ sec. This could lead to a definite proof for the existence of a very compact object as the source of GRB. Conditions 1,2,3 can be tested with experiments on the *Compton* Gamma Ray Observatory, whereas the testing of the theory that very short time structure indicates a very compact source must wait for future γ-ray telescopes in space.

As an illustration purpose, we calculate the hardness ratio based on the pure Hawking process, i.e., only the thermal emission, when the PBH evaporate very rapidly by emitting all the allowed particle states in the standard model. The life time of the PBH, $\tau_{\rm evap}$, over which it completely evaporates, can be approximated as (MacGibbon & Carr 1991)

$$\tau_{\rm evap} \cong 4.89 \times 10^2 \left(\frac{m_{\rm PBH}}{10^9 \, {\rm g}} \right)^3 \text{ msec.} \tag{2.8}$$

In fact there are some interesting theoretical debates at present as to whether the PBH evaporation would continue until it has completely evaporated away (Hawking 1992) or if the evaporation would stop when it shrinks down to an stable Plank-mass object (Barrow, Copeland & Liddle 1991), in which case it might serve as a component of the dark matter in the universe. In the following we will not consider the latter case. The total power (ergs) emitted as γ-rays from the PBH, which has mass $m_{\rm PBH} < 10^9$g, between $\omega_1 < \omega_\gamma < \omega_2$ and $0 < \delta t < \tau_{\rm evap}$, is given as

$$P(\omega_1 < \omega_\gamma < \omega_2, \delta t) = \int_0^{\delta t} dt \int_{\omega_1}^{\omega_2} d\omega_\gamma \frac{\Gamma(\omega_\gamma, m_{\rm PBH}) \omega_\gamma}{\exp(8\pi \omega_\gamma m_{\rm PBH}) - 1}. \tag{2.9}$$

The dimensionless absorption probability for the photon in the limit of low energy (Page 1976), for our case $0.05 < \omega_\gamma < 0.3$ MeV, can be given as

$$\Gamma(\omega_\gamma, m_{\rm PBH}) \cong 4.26 \times 10^{-9} \left(\frac{m_{\rm PBH}}{10^9 \, {\rm g}} \right)^4 \left(\frac{\omega_\gamma}{\rm MeV} \right)^4. \tag{2.10}$$

Thus the hardness ratio of the PBH γ-ray burst in the limit of pure Hawking process is

$$Hardness(\delta t) = \frac{P(0.1 < \omega_\gamma < 0.3 \text{ MeV}, \delta t)}{P(0.05 < \omega_\gamma < 0.1 \text{ MeV}, \delta t)} \cong 250. \tag{2.11}$$

The hardness ratio is constant for $0 < \delta t < 200$ msec since the exponential term is very small, i.e., $8\pi\omega_\gamma m_{\rm PBH} = 9.4 \times 10^{-5} (m_{\rm PBH}/10^9 g)(\omega_\gamma/{\rm MeV})$. Of course, this is a crude approximation for the real process around the exploding PBH, which does not include any of the hadronic interactions, yet still might indicate that the final

low energy γ-ray spectrum will be very hard. Thus a hard γ-ray spectrum is a natural consequence of a PBH origin! Ultimately, a particle physics model which includes the hadronic interaction for the evaporating PBH could fit the hardness ratio as a function of the burst duration, i.e.,

$$Hardness(\delta t) = \exp(a_0 + a_1 \times \delta t + a_2 \times \delta t^2). \tag{2.12}$$

3 Analysis of BATSE Data

Having studied the available GRB data, we noticed that there is a class of very short GRBs (< 200 msec) that in many cases seem to have a fairly hard γ-ray spectrum. For these events, an examination of the time distribution of the hardness ratio has been made. Most of these events have a simple "Single Spike" time history, a quality required for an event with a PBH origin. This hardness ratio, as defined in equation 2.11, is the fluence (ergs/cm^2) in the ~100 to ~300 keV energy range divided by the fluence in the ~0.05 to ~0.1 MeV range. The data is taken from the BATSE Catalogs (Fishman *et al.* 1994; Meegan *et al.* 1994). The duration of the bursts is taken to be the value of T_{90} . The interval T_{90} is defined as the time between the point when 5% of the total counts have been detected and the point when 95% of the total counts have been detected. While T_{90} is good for an approximation of the duration, a more detailed study of the fine time structure and thus the burst duration is needed in the future.

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 among the BATSE data (Fishman *et al.* 1994; Meegan *et al.* 1994) to be a homogeneous and isotropic distribution of sources in a static, Euclidean space (HISE). The usual testing for homogeneous source distribution is $V/V_{\max} \equiv (C_{\text{lim}}/C_{\text{p}})^{3/2}$, where C_{p} is the peak photon count rate and C_{lim} is the minimum detectable photon count rate just prior to the burst. Since any of the three different time-scales can generate the trigger for the event, the maximum value of C_p/C_{lim} from the BATSE Catalog is used to determine $V/V_{\max}$.

3.1 Study of BATSE 1B Data

We have previously presented analysis of data from the BATSE 1B Catalog (Fishman *et al.* 1994). Here we are presenting corrections to errors made in those presentations. Table 1 lists the duration and the hardness ratio of the bursts selected from the BATSE 1B data (Fishman *et al.* 1994; Cline & Hong 1994). Figure 2 shows a tendency for an increasing hardness ratio with the shorter GRBs burst duration. We can find no prediction in the literature for conventional GRB models that give this dramatic behavior.

To make any reasonable assessment about the spatial distribution of the short GRBs, we need to study the $\log(N(C_{\text{p}}))$ vs. $\log(C_{\text{p}}/C_{\text{lim}})$ or $\log(C_{\text{p}})$. This distribution may contain a bias due to the variable threshold, burst duration as

suggested by Petrosian *et al.* (1993, 1994). By following their suggestions, we corrected for the bias due to the variability of $C_{\rm lim}$, 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, within error, consistent with this assumption. However due to 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 GRBs.

3.2 Study of BATSE 2B Data

The BATSE catalogs are cumulative; therefore, the 2B Catalog also includes the data from the 1B Catalog. For this reason the analysis of the data in the 2B Catalog (Meegan *et al.* 1994) proceeded in a similar manner to that described in section 3.1. The cuts on the data were based on the burst duration, the completeness of the data, and the quality of the data. These cuts were:

1. Short duration bursts where T_{90}<200 msec.
2. Insisting that data was available 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.
3. 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 greater than 10^{-7}ergs/cm^2.

Table 2 lists the duration and the hardness ratio of the bursts selected, after making the listed cuts, from the BATSE 2B data (Meegan *et al.* 1994). Figure 4 shows a slight tendency for an increasing hardness ratio with the shorter GRBs burst duration.

In order to study the hardness the variability parameter V is used. The variability parameter V as defined by Lamb, Graziani, & Smith (1993) is $V \equiv C_{64}/C_{1024}$, where C_{64} is the peak photon count rate on the 64 ms time scale and C_{1024} is the peak photon count rate on the 1024 ms time scale. Table 3 lists the duration and the hardness ratio of the bursts selected from Table 2, after making a cut on the variable V of $V_{\rm cut} = 0.7$. Figure 5 shows a plot of the results of this cut. Figures 4 and 5 are consistent with an enhanced hardness at short burst duration. This is consistent with the assumptions made in equation 2.11.

We corrected for the bias due to the variability of $C_{\rm lim}$, by following the method suggested by Petrosian *et al.* (1993, 1994), and obtained the distribution shown in Figure 6. Within the statistical limitations, the corrected distribution is consistent with a slope of -3/2, as expected for HISE. Figure 7 shows the spatial distribution of the selected events presented in Table 2. The selected events are reasonably isotropic, if not very homogeneous, due perhaps to low statistics.

4 Gamma Ray Burst Results

4.1 Overview of Results Presented Here

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 the temperature of about 100-200 MeV (Cline & Hong 1992). This is precisely the region where there does not seem to be an adequate description available (Halzen *et al.* 1991). However, the simple Hagedorn model is also likely excluded. We have studied a mixed model and used this to help get some insight into the general properties of the final stages of PBH 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 intriguing from this standpoint, as seen in Tables 1 and 2. In Figure 8 we show some examples of the GRBs from the BATSE data. These are remarkably simple single bursts as would be expected from a simple event like a PBH evaporation. Within the limitations of the model presented here, we have not studied GRBs with burst duration greater than 200 msec. However, we know that bursts with a 1-2 second duration are "soft" in comparison.

In Table 4 we present the various tests that might be made for a PBH origin to GRBs. So far there seems to be reasonable agreement between this hypothesis and the available data. We find it significant that both, our analysis of the BATSE data reported here and the PHEBUS short burst data, are consistent with $V/V_{\max} \sim 1/2$.

4.2 Limits on PBH Density in the Galaxy

In order to determine the likely density of PBHs in the vicinity of the earth, a model of the γ-ray emission as well as the detector response is needed. In Table 5 we provide a rough estimate of the detection efficiency in this search. Figure 9 is then constructed from the limits on GRBs from PBHs claimed in several searches and the detector efficiencies given in Table 5 (Cline 1994).

4.3 Further Tests of the PBH Origin

One way to demonstrate that a GRB event was coming from an exotic source like a PBH, would be to have observed even a shorter time structure. For example, if nanosecond structure were observed this would presumably limit the size of the progenitor to $\leq c \times (\text{n sec}) \leq$ 30 cm. In this case there would be no known astrophysical object, i.e., neutron star, black hole of several solar masses, etc., that could be the origin of the burst. Thus a study of the fine structure of the short duration GRBs could yield further evidence concerning this hypothesis. Another important test is $V/V_{\max} \sim 1/2$ combined with a Galactic Coordinate plot of the events that is isotropic. This would presumably help to rule out Neutron Stars as the origin of short bursts. We note that one observed short GRB has fine time structure of ~100 μsec (Bhat et al. 1992).

5 Conclusion

To summarize, we have pointed out that there is a distinct class of very short-time GRBs that have an increasing hardness with decreasing time duration below a few hundred milliseconds. We also pointed out that this is the generic behavior that would be expected from the evaporation of a PBH in the final stages within a fireball model. The rate of short GRBs is fully consistent with current limits on the PBH density in the galaxy (Halzen *et al.* 1991; Cline & Hong 1992; Cline 1994). We also studied the spatial distribution of the events and find that it is not inconsistent with a PBH origin. Finally, we described some future tests of the PBH origin of such events that would provide definite evidence for this hypothesis. The most important test would be to discover very short sub-microsecond time structure in this class of GRBs. There are no current γ-ray telescopes in space that have this ability. We can think of few observations in nature that would be as significant as the discovery of primordial black holes (Hawking 1974).

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Tables

Table 1: Hardness vs. Duration (BATSE 1B)

Trigger Number	T_{90} (sec)	Hardness Ratio
432	0.034	7.46±1.17
677	0.055	8.63±1.11
289	0.067	8.22±3.35
207	0.085	6.88±1.93
480	0.128	7.14±0.96
1088	0.128	9.30±0.73
830	0.131	7.53±0.89
1076	0.161	7.65±0.83
512	0.183	6.07±1.34
1102	0.192	3.52±0.42
1463	0.192	1.30±0.14
1154	0.193	8.04±1.29

Table 2: Hardness Ratio versus Duration (BATSE 2B)

Trigger Number	T_{90} (sec)	Hardness Ratio
432	0.034	7.46±1.17
677	0.055	8.63±1.11
207	0.085	6.88±1.93
491	0.100	8.11±4.33
480	0.128	7.14±0.96
568	0.128	11.04±2.82
1088	0.128	9.30±0.73
2049	0.128	5.51±0.95
2167	0.128	5.10±0.59
830	0.131	7.53±0.89
474	0.152	11.73±1.14
1076	0.161	7.65±0.83
512	0.183	6.07±1.34
729	0.183	11.81±7.02
1453	0.192	6.68±0.33
1665	0.192	7.51±1.01
1154	0.193	8.04±1.29

Table 3: Hardness Ratio versus Duration (BATSE 2B)

$V_{cut} = 0.7$

Trigger Number	T_{90} (sec)	Hardness Ratio
432	0.034	7.46±1.17
677	0.055	8.63±1.11
207	0.085	6.88±1.93
480	0.128	7.14±0.96
2167	0.128	5.10±0.59

Table 4:
Characteristics of Selected GRBs Consistent with the PBH Evaporation Hypothesis

Event Characteristics	GRB Events (Selected)	Expectation for PBH Evaporation
Time duration	Time duration ~200 msec	In Fireball picture $\Delta\tau \approx 200\,\text{msec}$
Event hardiness in γ spectrum $H = \frac{F(0.1-0.3\ \text{MeV})}{F(0.05-0.1\ \text{MeV})}$	PHEBUS short burst data[1] have hard spectrum Hardest γ spectrum of any GRB $\langle H \rangle \cong 8$ for BATSE (1B-2B) data	Expect hard γ spectrum - but exact value not calculable However, in pure Hawking Process $\cdot \langle H \rangle \sim 250$
Time history of event	Most events have simple time history - one peak	Simple time history - one peak only in event
$\ln(N) - \ln(S)$ test for population spatial structure	BATSE 2B - corrected $\ln(N) - \ln(S)$ with slope ~ -3/2 PHEBUS short events $V/V_{\max} = 0.46 \pm 0.14$	Expected $\frac{V}{V_{\max}} = \frac{1}{2}$ or $\ln(N) - \ln(S)$ with a slope =-3/2
Fine time structure in events	In one BATSE event time structure of ~ 100 μs observed[2]	Fine time structure could reveal size of source
Limit rate of GRB from PBH expected	~ 17 /366 GRB ~5% (1B - 2B) data - Low rate	Expect low rate and $\Omega_{PBH} \sim 10^{-7}$ - perhaps 10/year

1. Data presented at the ESLAB-ESA Conference, April 1995 (Dezalay 1995)
2. (Bhat et al. 1992)

Table 5: Estimated Detection Efficiencies for GRBs from a PBH

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

Figure Captions

Figure 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 temperature (the decrease of mass of the black hole is given by $d\,m_{\rm PBH}/dt = -\alpha/m_{\rm PBH}^2$). A rapid mass decrease or burst can occur when $m_{\rm PBH} \leq 10^{10}$ grams or if α changes rapidly near the quark-gluon phase transition.

Figure 2. Hardness ratio for some of the γ bursts reported in the BATSE 1B Catalog. Note that the short time bursts have a much harder spectrum, a trend that would be expected if some of the short bursts came from PBH evaporation. A simple fitting of these data indicates an anti-correlation of hardness vs. burst duration. The dashed line represents the average hardness for the bursts of time duration from 1 second to 2 seconds.

Figure 3. Plot shows the $\log(N)$ vs. $\log(C_{\rm p})$ distribution for the events in Fig. 2 with the correction suggested by Petrosian *et al.* (1993,1994) applied. Within the statistical determination the corrected distribution is consistent with a slope of -3/2 as expected for a Euclidean and homogeneous distribution of sources.

Figure 4. Hardness ratio for some of the γ bursts reported in the BATSE 2B Catalog. A simple fitting of these data indicates an anti-correlation of hardness vs. burst duration. The dashed line represents the average hardness for the bursts of time duration from 1 second to 2 seconds. Note that these short time bursts have a much harder spectrum, a trend that would be expected if some of the short bursts came from PBH evaporation. Events have been selected with a single spike time history as would be expected for PBH evaporation.

Figure 5. Plot shows the Hardness ratio of the events in Fig. 4 with $V_{\rm cut} = 0.7$.

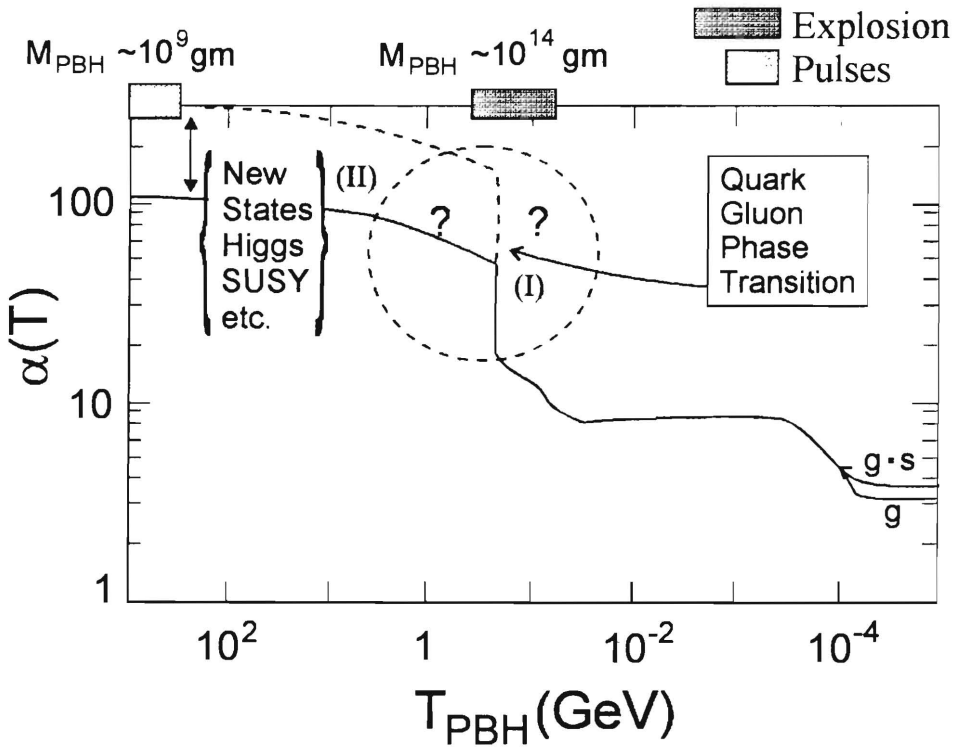
Figure 6. Plot shows the $\log(N)$ vs. $\log(C_{\rm p})$ distribution for the events in Fig. 4 with the correction suggested by Petrosian *et al.* (1993,1994) applied. Within the statistical determination the corrected distribution is consistent with a slope of -3/2 as expected for a Euclidean and homogeneous distribution of sources.

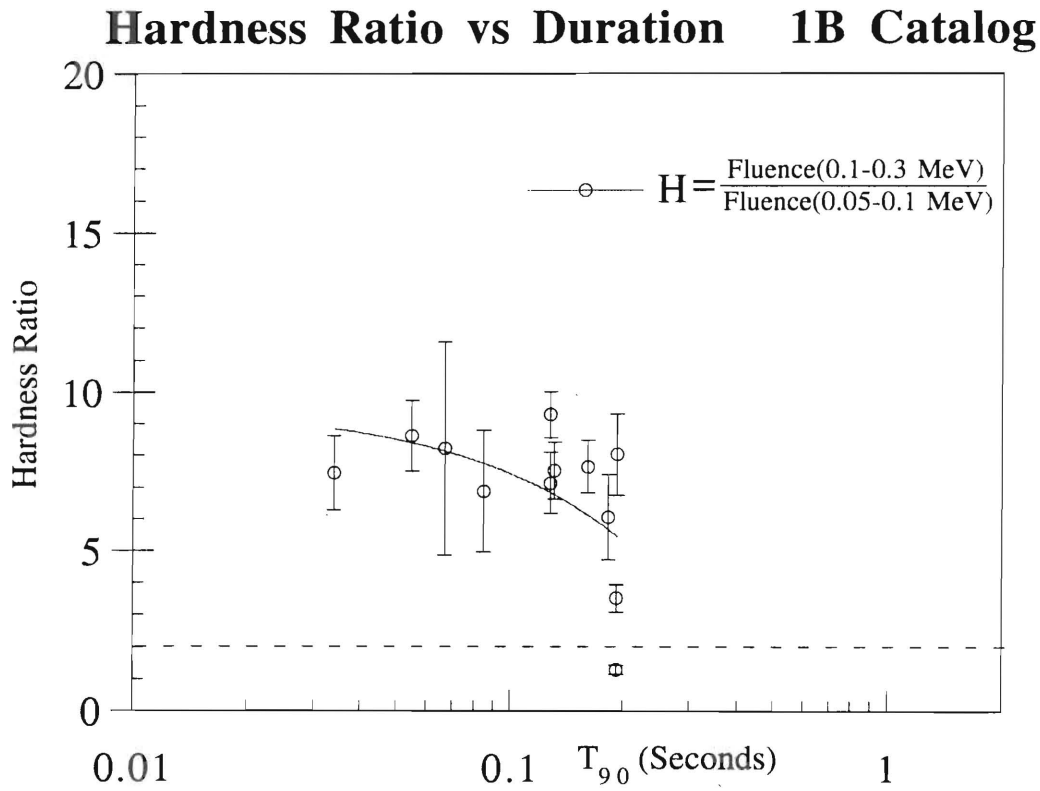
Figure 7. Plot shows the angular distribution, in Galactic coordinates, of the events in from the 2B Catalog presented in Table 2.

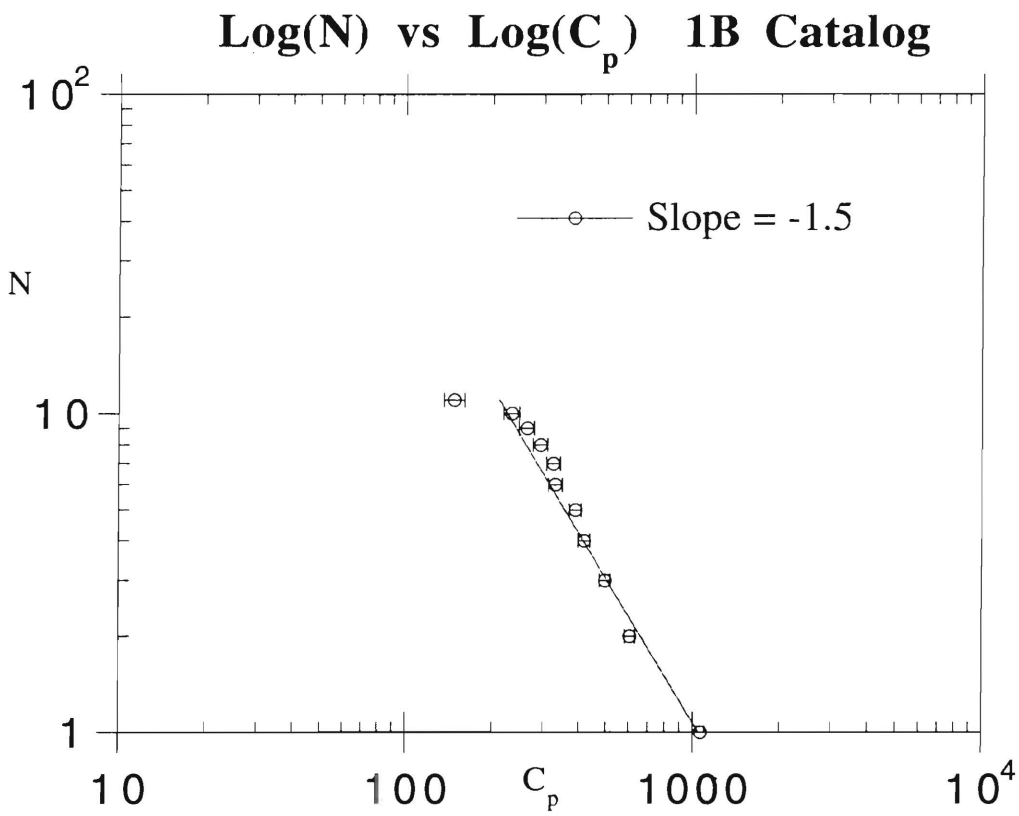
Figure 8. Time profile of some hard spectrum BATSE events.

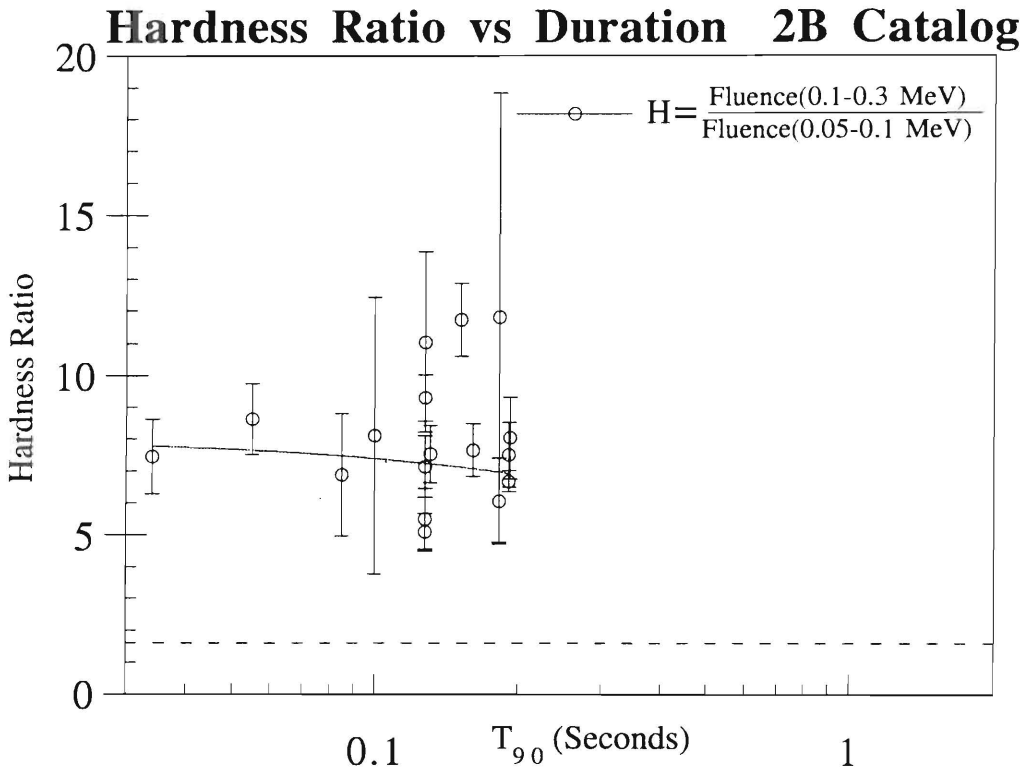
Figure 9. Limits for some of the PBH-GRB bursts reported in the literature (Cline 1994; Wright 1995). $\dot{N}$ refers to the limit on the number of PBH evaporations ($\rm yr^{-1}\,pc^{-3}$). The limits are determined by the detectors used to observe the GRB, the $\Delta\tau$ of the GRB and the model used to calculate the GRB luminosity.

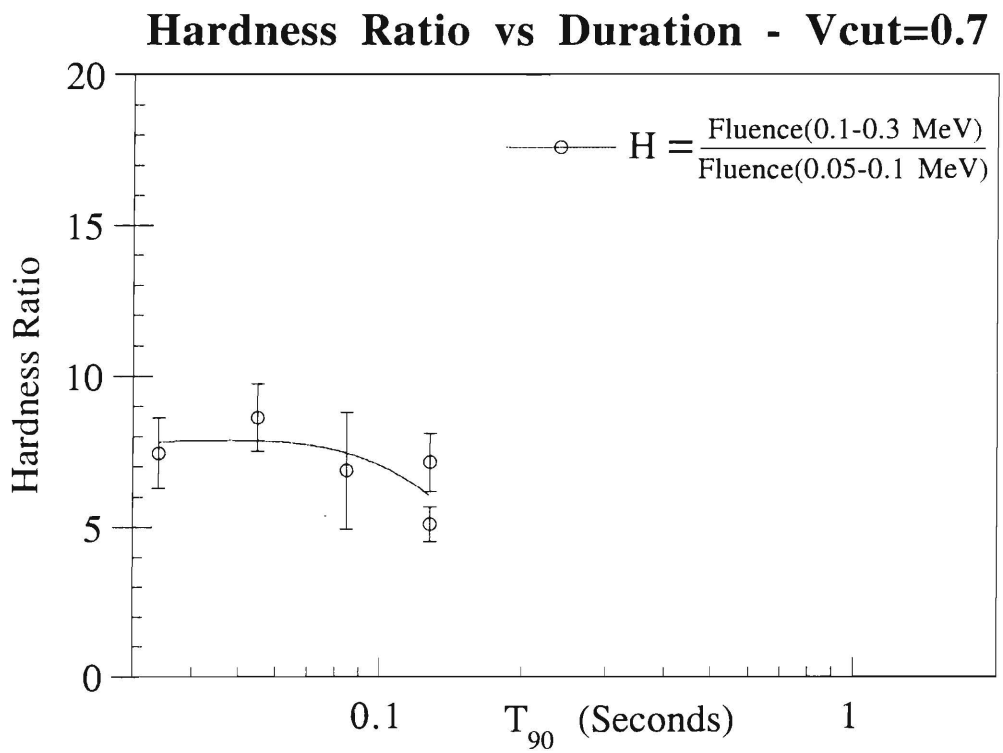
Primordial Black Hole Evaporation
and
Uncertainty in the Density of States

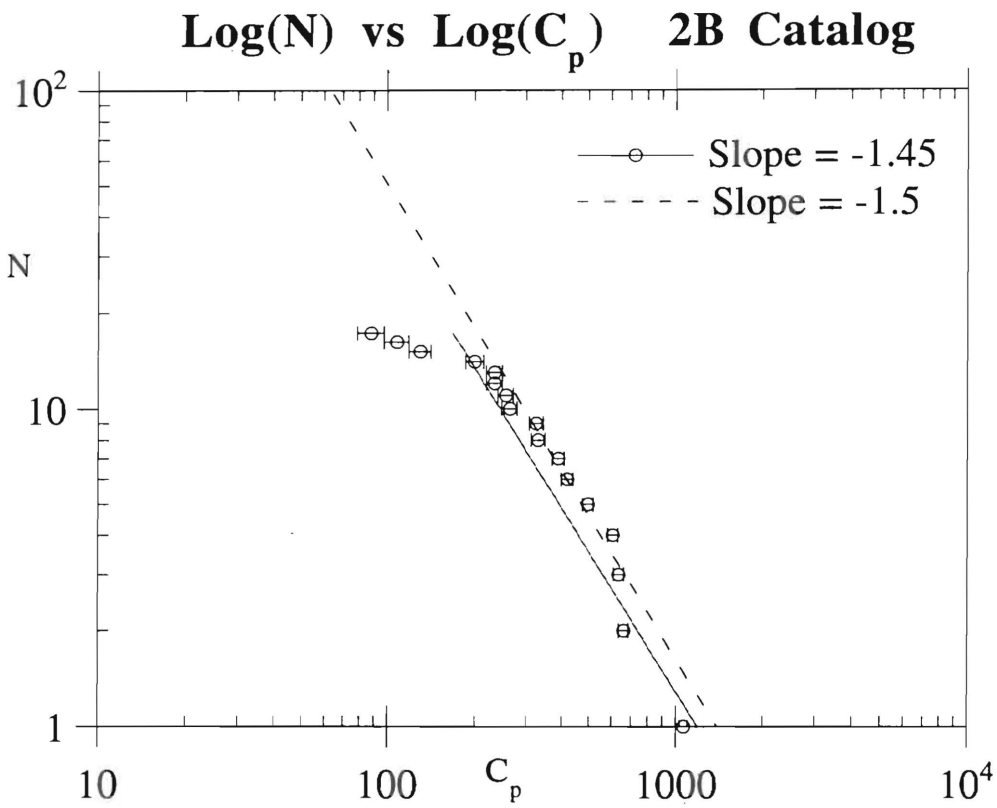



Hardness Ratio vs Duration 1B Catalog
H = Fluence(0.1-0.3 MeV) / Fluence(0.05-0.1 MeV)
Hardness Ratio
20
15
10
5
0
0.01
0.1
1
T90 (Seconds)

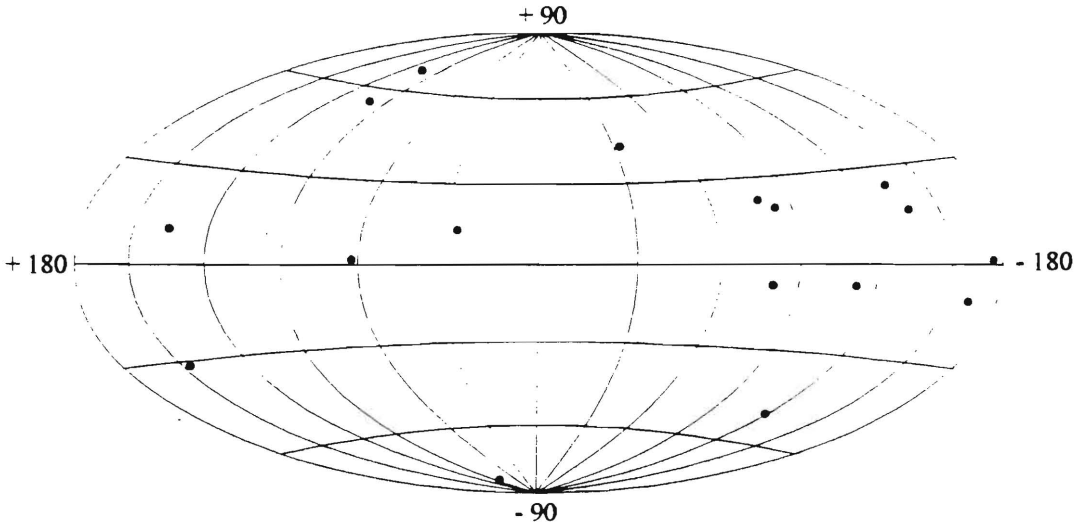

Log(N) vs Log(C_p) 1B Catalog
Slope = -1.5
N
10^2
10
1
10
100
C_p
1000
10^4


Hardness Ratio vs Duration 2B Catalog
H= Fluence(0.1-0.3 MeV) / Fluence(0.05-0.1 MeV)
Hardness Ratio
20
15
10
5
0
0.1
T90 (Seconds)
1

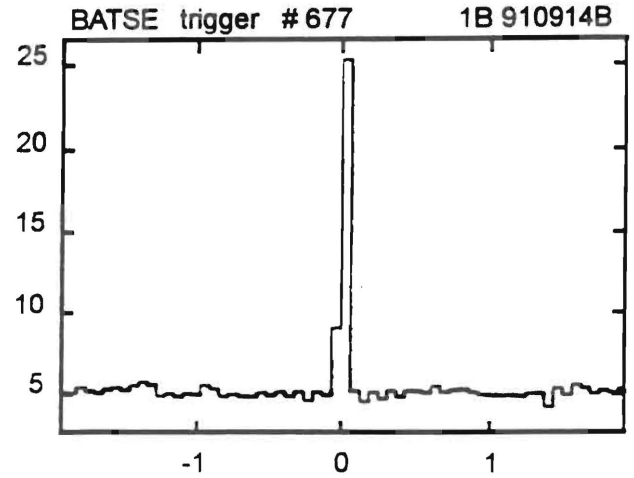

Hardness Ratio vs Duration - Vcut=0.7
H = Fluence(0.1-0.3 MeV) / Fluence(0.05-0.1 MeV)
Hardness Ratio
20
15
10
5
0
0.1
1
T90 (Seconds)

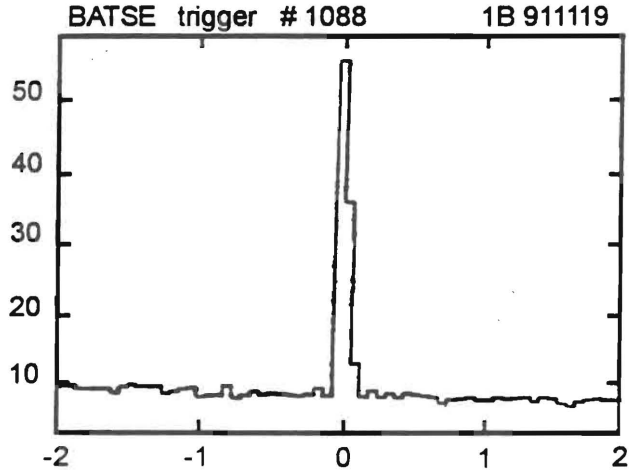

Log(N) vs Log(C_p) 2B Catalog
Slope = -1.45
Slope = -1.5
N
10^2
10
1
10
100
C_p
1000
10^4

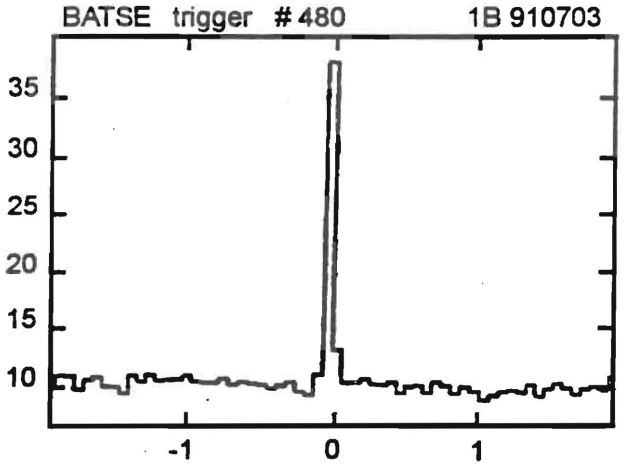
BATSE Gamma-Ray Bursts

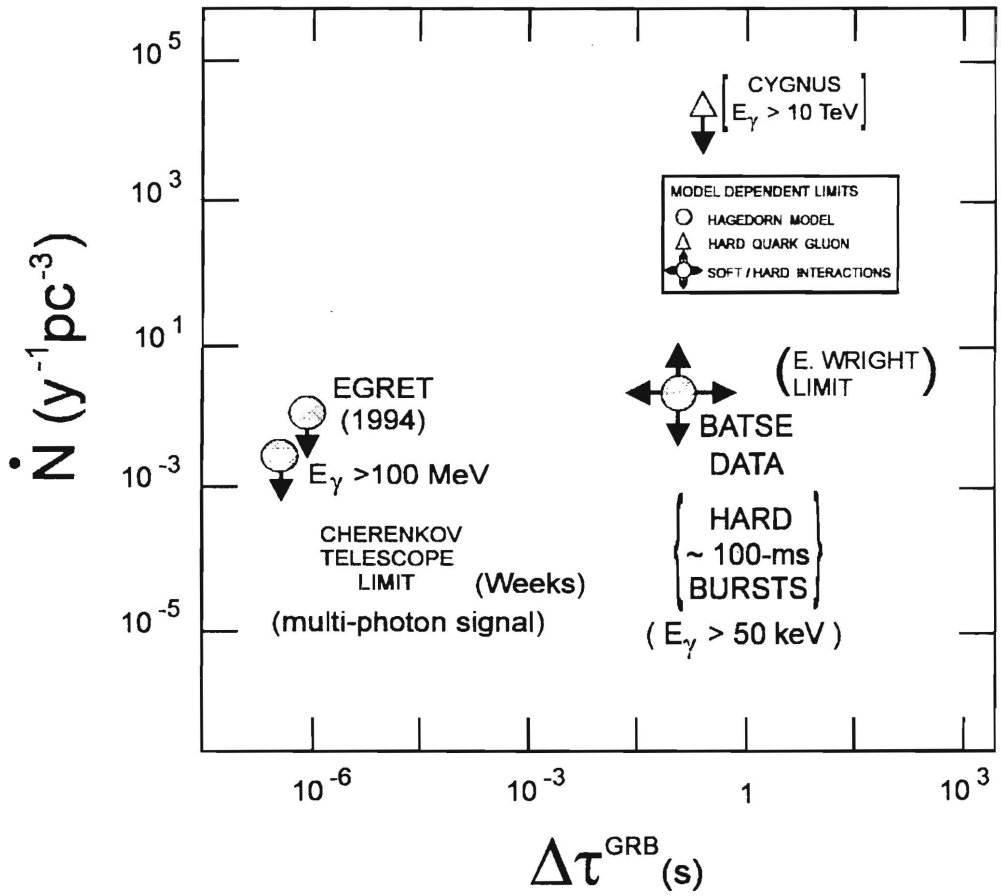


Galactic Coordinates


BATSE trigger # 677
1B 910914B
25
20
15
10
5
-1
0
1


BATSE trigger # 1088
1B 911119
50
40
30
20
10
-2
-1
0
1
2


BATSE trigger # 480
1B 910703
35
30
25
20
15
10
-1
0
1


CYGNUS
E_γ > 10 TeV
MODEL DEPENDENT LIMITS
HAGEDORN MODEL
HARD QUARK GLUON
SOFT / HARD INTERACTIONS
(E. WRIGHT LIMIT)
EGRET
(1994)
E_γ >100 MeV
BATSE
DATA
CHERENKOV
TELESCOPE
LIMIT
(Weeks)
(multi-photon signal)
HARD
~ 100-ms
BURSTS
(E_γ > 50 keV)
10^5
10^3
10^1
10^{-3}
10^{-5}
$\dot{N}$ ($y^{-1}pc^{-3}$)
10^{-6}
10^{-3}
1
10^3
$\Delta\tau^{GRB}$ (s)