PRINT-94-0050 (UCLA)

Fermilab Library
0 1260 0034931 0

Very Short Gamma-Ray Bursts and Primordial Black Hole Evaporation

David B. Cline and Woo-pyo Hong*
Department of Physics and Astronomy
University of California, Los Angeles
405 Hilgard Ave, Los Angeles, Ca 90024

FERMILAB
MAR 14 1994
LIBRARY

December, 1993

The search for gamma-ray bursts from primordial black holes has continued for the past 20 years. We discuss a very interesting group of gamma-ray bursts of very short time duration and an increasing hard spectrum from the BATSE catalog and other observations. These events could be due to primordial black hole evaporation. We also indicate how a unique observation might be carried out in future.

Ever since the theoretical discovery of the quantum-gravitational particle emissions from black holes by Hawking [1], there have been many experimental searches [2] for high energy γ-ray radiations from primordial black holes (PBHs) 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, since the black hole

*hong@uclahep.bitnet, 41988::hong

NAME | LOAN | M.S.
RETURN TO FERMILAB LIBRARY

becomes hotter as it radiates more particles and can eventually attain extremely high temperatures. PBHs would be formed in the early universe with arbitrarily small masses and number density, depending on the possible formation mechanisms [4]. A positive or even a negative result for the existence of PBH evaporation would be very crucial for testing many fundamental assumptions in the early universe, for example, the nature of inflation [4]. Previous efforts [3, 5] have been focused on the calculations of the PBHs number density bounds at the present epoch under the cosmological constraints such as the diffuse mega-electronvolt extragalactic γ-ray background data [6], the standard nucleosynthesis, the microwave background, and the galaxy formation conditions (see for a review ref. [3]). In particular, the PBH explosion density of events would be allowed as high as 10 $pc^{-3}yr^{-1}$ if holes are clustered in the galactic halo [3, 5, 8] , under the assumption that the diffuse photon spectrum from evaporated PBHs at energies around 100 MeV is smaller than the observed background data [6]. On the other hand, the past 20 years of direct searches for high energy radiations from the PBHs at the final stage of evaporation have lead to upper limits in the literature on the density of events, which range from 7×10^{-10} $pc^{-3}yr^{-1}$ to 8×10^{5} $pc^{-3}yr^{-1}$ [2].

In fact, these observational upper limits depend very strongly on the particle physics models for the PBH final stage evaporation. According to the standard model of three quarks-leptons families the PBH evaporates its mass ($\sim 10^9 g$) in an explosion by converting to very high energy quarks and leptons (average energy $\sim$ 5 TeV) and luminosity of $\sim 10^{30}$ erg, lasting 0.1 sec. The quark-gluon fragmentation then yield a very intense bursts of low energy particles [2]. On the other hand, one extreme particle model invoked by Hagedorn [7] would predict an outburst of relatively lower particle energy (average energy $\sim$ 0.25 GeV) and higher luminosity ($\sim 10^{34}$ erg from $\sim 10^{14} g$ PBH), lasting about 0.1 microsecond [5]. 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, the PBH mass will 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 deconfinement phase transition [8], the emitted free quarks and gluons will 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 (see Fig. 1). Thus, the fact that model dependent observational upper limits from high energy γ-ray on the explosion density of events vary almost 10 orders is not too surprising. We pointed out in a previous work [8] that there is a lack of consideration of the quark-gluon plasma effect around the critical temperature and there could be particle interactions around the evaporating PBH that form an expanding fireball. 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 (an order of milliseconds duration). As a result the average photon energy emerging from such a fireball could be much lower than the previous estimates [2, 8]. It is quite intriguing that in this context some of the short γ-ray bursts observed by the BATSE detector on the Compton Gamma Ray Observatory (CGRO) [9] could originate from exploding PBHs. Having studied the available GRB data we noticed that there is a class of very short GRBs (< 200 mse) that in many cases seem to have a fairly hard γ-ray spectrum. Fig. 2 shows the profile of some of these events and the tendency for an increasing hardness ratio with the shorter GRBs burst durations. This hardness ratio is defined as the fluence (ergcm^{-2}) in the ~ 100 to ~ 300 KeV energy range divided by the fluence in the ~ 50 to ~ 100 KeV range. We can find no prediction in the literature for conventional GRB models that give this dramatic behavior. Based on this observation, we may classify some

expected characteristics for γ-ray burst from the low energy spectra of the evaporating PBHs as:

1. There should be a short time burst of $\delta t \ll 1$ sec even in the standard particle physics model [2]. In models for rapid evaporation near the critical quark-gluon phase transition temperature we may expect similar effects [8]

2. The PBH explosion time scales as $\tau_{\mathbf{evap}} \sim m^3_{\mathbf{pbh}} \sim T^{-3}_{\mathbf{pbh}}$, 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.

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 CGRO 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.

Unfortunately, the exact hardness spectrum of the GRB from a PBH is impossible to calculate in any existing model due to uncertainties of the hadronic interaction. As an approximation, we have calculated 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, $\tau_{\mathbf{evap}}$, over which it

completely evaporates, can be approximated as [3]

$$\tau_{\rm evap} \simeq 4.89 \times 10^2 \left(\frac{m_{\rm pbh}}{10^9 g}\right)^3 \quad \text{msec} \tag{1}$$

In fact there are some interesting theoretical debates at present as to whether the PBH evaporation would continue until it has completely evaporated away [10] or if the evaporation would stop when it shrinks down to an stable Planck-mass object [11], 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

$$P\left(\omega_1 < \omega_\gamma < \omega_2, \delta t\right) = \int_0^{\delta t} dt \int_{\omega_1}^{\omega_2} d\omega_\gamma \frac{\Gamma(\omega_\gamma m_{\rm pbh})\omega_\gamma}{\exp(8\pi\omega_\gamma m_{\rm pbh}) - 1} \tag{2}$$

The dimensionless absorption probability for the photon in the limit of low energy [12], for our case $0.05 < \omega_\gamma < 0.3$ MeV, can be given as

$$\Gamma(\omega_\gamma, m_{\rm pbh}) \simeq 4.26 \times 10^{-9} (\frac{m_{\rm pbh}}{10^9 g})^4 (\frac{\omega_\gamma}{\rm MeV})^4 \tag{3}$$

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

$$\text{Hardness} \quad (\delta t) = \frac{P(0.1 < \omega_\gamma < 0.3 \quad \text{MeV}, \delta t)}{P(0.05 < \omega_\gamma < 0.1 \quad \text{MeV}, \delta t)} \simeq 250 \tag{4}$$

The hardness ratio is constant for $0 < \delta t < 200$ msec since the exponential term is very small, i.e., $8\pi\omega_\gamma m_{\rm pbh} = 9.4 \times 10^{-5}(m_{\rm pbh}/10^9 g)(\omega_\gamma/MeV)$. 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.,

$$\text{Hardness} \quad (\delta t) = \exp(a_0 + a_1 \times \delta t + a_2 \times \delta t^2) \tag{5}$$

as indicated by the apparent increase among the observed short GRBs in Fig. 2. A general classification of GRB into two classes has been recently presented [13]. The separation between classes was taken at the two second bursts time and is not directly related to the analysis in the present paper.

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 PBH in the final stages. The rate of short GRBs is fully consistent with current limits on the PBH density in the galaxy [2, 8]. 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 submicrosecond 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 [1].

Acknowledgement: We wish to thank members of the BATSE team for sending us recent information on the short GRB events and in particular to G. Fishman for helpful discussion.

References

[1] Hawking, S.W., Nature **248**, 30 (1974); Commun. Math. Phys. **43**, 199 (1974).

[2] See Halzen, F. *et al.*, Nature **353**, 807 (1991) and references therein.

[3] See for example: MacGibbon, J.H. & Carr, B.J., Astrophys, **J 371**, 447 (1991).

[4] Carr, B.J. and Lidsey, J.E., Phys. Rev. D**41**, 543 (1993); Dolgov, A. & Silk, J., Phys. Rev. D**47**, 4244 (1993).

[5] Page, D.N. & Hawking, S.W., Astrophy. J.**206**, 1 (1976).

[6] Trombka, T.I. *et al.*, Astrophys. J.**212**, 925 (1977); Fichtel, C.E., Simpson, G.A. & Thompson, D.J., Astrophys. J.**222**, 833 (1978); Gibbs, K.J. Nucl. Instr. Meth. A**264**, 67 (1988).

[7] Hagedorn, R., Nuovo. Cimento, **64A**, 811 (1965).

[8] Cline, D.B. & Hong, W.P., Astrophys. **J.401**, L57 (1992).

[9] Fishman, G.J., *et al.*, Astrophys. J. Suppl. (1993).

[10] Hawking, S.W., Phys. Rev. Lett., **69** 406 (1993).

[11] Barrow, J.D., Copeland, E.J. & Liddle, A.R., Phys. Rev, **D43**, 1106 (1991).

[12] Page, D.N., Phys. Rev. **D13**, 198 (1976).

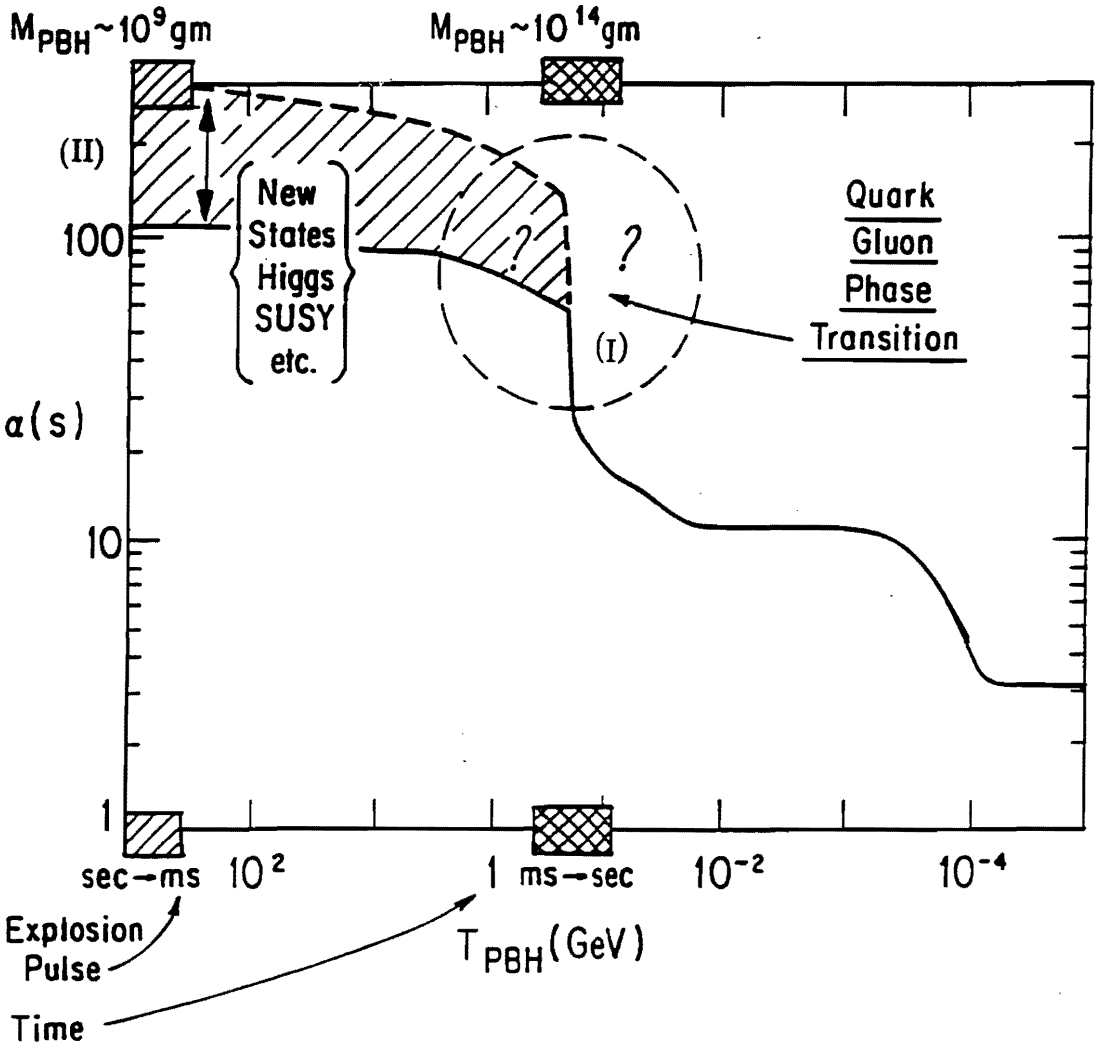
[13] Kouveliotou, C., *et al.*, Astrophys. J. **413**, L101 (1993).

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 $dm_{\rm pbh}/dt = -\alpha/m_{\rm pbh}^2$). 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 literature. 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 dash-dot curve represents the average hardness for the bursts of time duration from 1 second to 2 seconds.

PRIMORDIAL BLACK HOLE EVAPORATION
AND
UNCERTAINTY IN THE DENSITY OF STATES



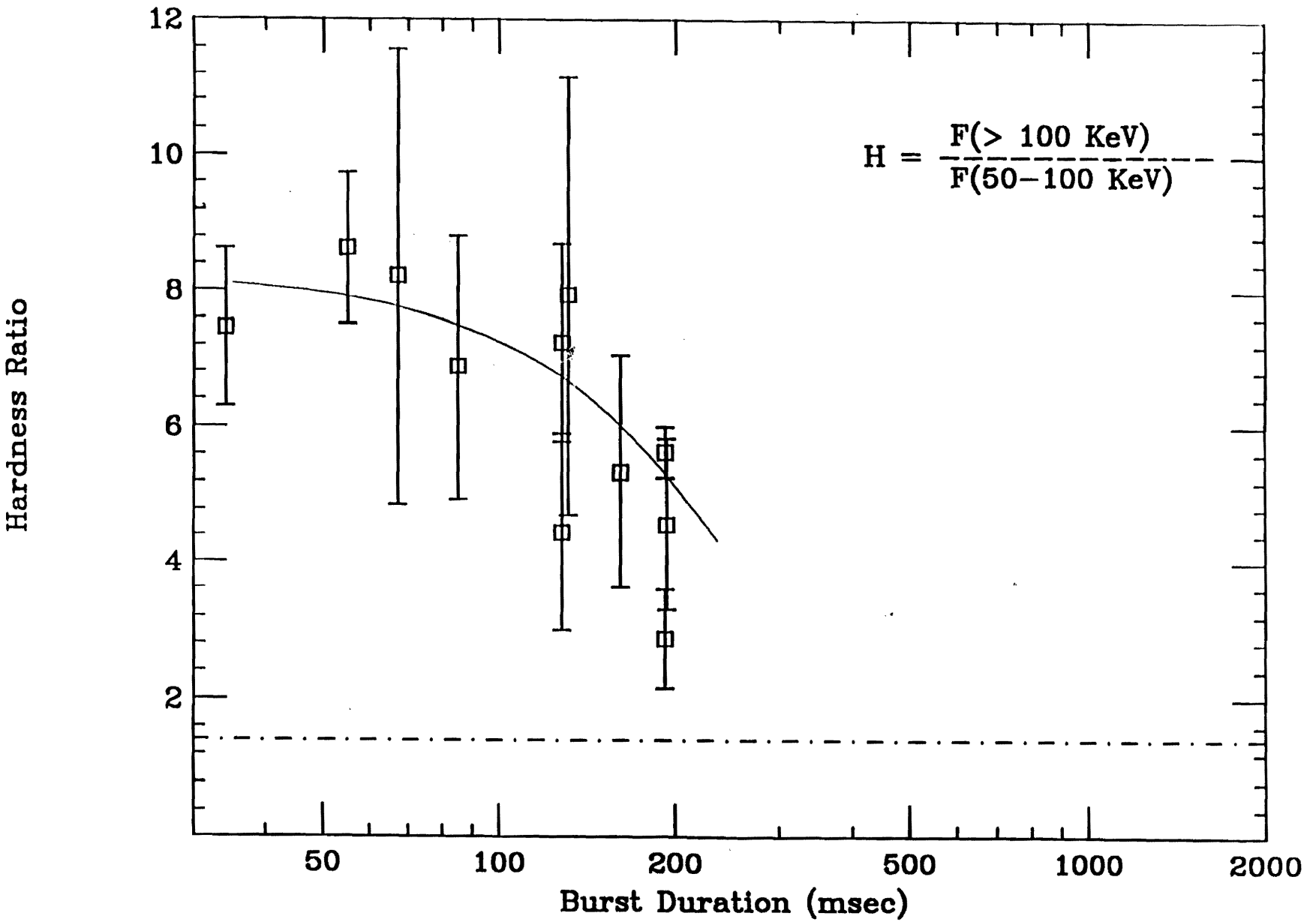

12
10
8
6
4
2
Hardness Ratio
50
100
200
500
1000
2000
Burst Duration (msec)
H = F(> 100 KeV) / F(50–100 KeV)

Fig. 3