GAMMA RAY BURSTS AND PARTICLE PHYSICS

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We provide a brief review of the current situation concerning Gamma Ray Bursts. With emphasis on the role that particle physics may play in the interesting phenomena. The current understanding of GRB origins allows for a large range of physical processes from primordial black hole evaporation to neutron star and black hole collisions. There does not seem to be a simple standard luminosity function and the burst times range from MS to 1000's of seconds 5 orders of magnitude. It is likely that some type of fireball model is needed to explain the GRBs. No counterparts of GRB have been detected. We indicate some ways in which progress can be made in either the study of the fine time structure ($\sim \mu s$) or the detection of very high energy photons ($> 100 GeV$) to $> 100 TeV$). We also indicate how a small but unique class of the GRB could come from Primordial Black Hole evaporation.

1. General Properties of Gamma Ray Bursts

In 1973 a satellite was deployed to monitor the possibility of above ground nuclear explosions. It ended up giving the first evidence for cosmic bursts of gamma rays now called Classical Gamma Ray Bursts (CGRB). The discovery is credited to Klebesadel, Strong and Olson in 1973.¹ These events consisted of bursts of photons in the energy range of 50 KeV to 10 GeV (the largest energy detected so far) with a time duration from $\sim 35ms$ to over 1000 seconds and with an observed fluence (the energy-flux of photons) of $\sim 10^{-7} ergs/cm^2/sec$ to $\sim 10^{-5} ergs/cm^2/sec$. In the late 70's and 80's, many GRB were detected by a large array of detectors on satellites². Most of these detectors were small and only observed the largest fluence events. From these studies it was already clear that there were no obvious sources (i.e. Galactic Center, LMC etc.) as there are for quiescent Gamma Ray 's. The source locations plotted on the Galactic coordinates was isotropic. The major limitation of these studies was the inability to observe low fluence GRBs even so the experimenters had already suggested that the spatial distributions of GRB was not consistent with being homogeneous.³ With the launch of the Compton Observatory and the BATSE (Burst and Transient Source Experiment) a new era began.⁴ This

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detector had enough photon detection area to increase dramatically the number of GRBs observed per year and to study the distribution of the faint bursts.⁵ In a beautiful experimental study the properties of the GRB were further evaluated.⁴ By now there are more than 1500 GRBs detected since the original observations, yet as we shall see the mystery of the source of the events is even deeper!⁶ In spite of all the work we still do not know for certain if the sources are Cosmological, Galactic or a mixture of the two.

In this brief review we will provide an update summary of the known properties of GRB and the search for Counterpart locations for the event. We will also briefly review various models proposed to explain the bulk of the data. Of course since the distance scale (Galactic Halo ~ 200 kpc or cosmological $\sim$ GPC) is not yet known, the input model is also poorly defined. We will discuss a situation where particle physics may be important either from exotic GRB sources like Primordial Black Holes⁷ or in the processes that generate the high energy radiation such as fireballs formed from neutron star collisions through the intense emission of neutrinos and anti neutrinos.⁸

1.1. *Spatial properties of the GRB.*

There are two quantities that can be measured relatively well in the current Gamma Ray Telescopes on Satellite.

- 1) The approximate location in galactic coordinates of the GRB source. (In general to ~ 5 degrees accuracy).⁴
- 2) The peak of the photon counting rate ($C_{\max}$ and the level of noise or minimal signal that could be detected of $C_{\min}$).⁴

These two types of measurement provide nearly all of the current spatial information about GRBs shows a plot of 657 BATSE events indicating a large degree of isotropy.⁹ (see Fig. 1a). For example the current value of dipole momenta is consistent with zero. The current value of the dipole moment of the distribution is $0.031 \pm .021$ for 520 bursts.⁹ From the early study of Radio Galaxies a technique was developed to measure the spatial distribution of the sources where the volume that was sampled for an observed volume V and the potential volume that could have been sampled (before the signal became less than the noise or $C_{\min}(V_{\max})$. The ratio of $\langle V/V_{\max} \rangle$ for a large sample of GRB should be $1/2$ if the distribution is homogeneous. Any deviation from $1/2$ indicates a non-homogeneous population but does not really allows to determine the origin of the non-homogeneous distributions (i.e. due to evolution in a cosmological population or an edge for say an extended halo distributions).

The current value of $\langle V/V_{\max} \rangle$ for 657 events of the BATSE data is 0.33 ± 0.007 and clearly deviates from $1/2$.⁹ Fig. 1b shows the distribution of $\ell n N - \ell \left(\frac{C_{\max}}{C_{\min}} \right)$ which would have a slope of $-3/2$ that would correspond to $V/V_{\max} = 1/2$. It is

BATSE GRB OBSERVATIONS

Fig. 1b. $V/V_{\max}$ distributions for the events in Fig. 1a.

clear that the source of the deviation are the faint or low fluency bursts that are less populous than would be expected for the homogenous population.

These are the two keys spatial features of the total sample of GRB to date. There is an ongoing debate about various sub-samples of the data as to whether there is evidence for galactic structure or repeating sources and so forth. However, there is little doubt about the properties of the full sample of GRB.

1.2. *Temporal properties of the GRB.*

As mentioned in the introduction the light curve (or burst time profile) of the GRB covers a very large dynamic range. The mean time duration of the burst varies from $\lesssim$ ms to 1000 sec or so, more than five orders of magnitude. The majority of the bursts have a very complex time profile with much variation and shapes. Fig. 2a-d shows 4 different shapes of GRB that illustrate this behavior.⁴

1.3. *Spectral Behavior*

By now there are enough measurement of the photons in different energy ranges from values detectors to provide a general picture of the classical GRB spectrum.¹⁰ Very roughly if we plot νF_γ where ν is the photon frequency and F_γ the flux the product is almost constant from 0.1 - 100 MeV at least. The measurements beyond 100 MeV are not good enough to tell if the trend continuous. Actually the generic spectra does have a break in the vicinity of 500 KeV in as illustrated in Fig. 3, although there are clearly events that do not show this simple behavior.

One important point about the spectrum. If there is a universal GRB spectrum, the effects of red shift for cosmological sources should be readily apparent. This effect may have been seen in the data. However, critics of these ideas claim this could be an intrinsic property of the GRB or more importantly they point out that burst are not static. The spectrum shape changes during the period of the burst and this makes it difficult to conclude these Lorentz effects, have been observed.¹¹

Several GRBs observed with various telescopes (EGRET, PHEBUS,) have been found to have the energy spectrum continue well above 100 MeV and in some few cases even above a few GeV.¹² Because of the spectral drop off the spectrum with energy (most likely as E_γ^{-2}) and the small detector area of those telescopes with a deep enough detector to contain a GeV electro magnetic shower in (i.e. BATSE is not sensitive above $\sim 1 - 2$ MeV!) one expects such observations only in the brightest GRBs. The existence of such events is consistent with with all GRB having such higher energy photons. As we shall see later, the existence of such medium energy photons most likely restricts the theoretical models to a small class of "fireball" models with rapidly expanding energy fronts. The observation of such higher energy γ 's in the TeV to PeV range would also provide evidence about the minimal distance to the GRB site due to the absorption of such high energy photons on the IR or microwave background.

Fig. 2.a-d. Time distribution for some GRB from the 80's (a,c) and BATSE data (b,d) showing the large dynamic range of the time distribution.⁴

Fig. 3. Example of a spectrum of GRB multiplied by E^2 , showing an approximate constant spectrum at relatively higher energy.

Thus the γ energy spectrum from the GRB is of crucial importance for the eventual understanding of the source of these events.

1.4. Variability of the GRB Time History.

Nearly every GRB has a very different time structure as well as the overall time duration varying over more than 4 orders of magnitude. As we shall see later the time variability could eventually give information on the source size and even the mechanism. Furthermore, it is now known that the energy spectrum also varies over the period of the burst usually going from hard to soft. The time history variability will be perhaps the most difficult aspect of the GRB to explain in the long run. In Fig. 2a-d we show some typical GRB time histories. There have been numerous attempts to:

1. Find some sort of periodic behavior.
2. Find a "shot" noise signal in the data that deviates from the simplest expectation.¹³
3. Search for evidence of micro burst structure where a very large number of low energy photons could presumably pile up to imitate the GRB structure observed. One sees these types of variability in many astrophysical observations but there is no evidence for any of these effects in the GRBs.¹⁴

1.5. *Classes of GRBs.*

In 1984 the available data on GRBs suggested at least three possible classes of corresponding to the event duration of ~ 100 ms, 1 sec and much longer burst.¹⁵ It must be recalled that all the burst detectors until BATSE only observed strong GRB (i.e. Fluence $> 10^{-6} \text{ erg/cm}^2$). After the data from BATSE was studied it appears that they are only two clearly dependent classes $\sim 1 \text{ sec}$ and (10 - 100) sec.¹⁶ However, there are still arguments that there is a separate class of ~ 100 ms bursts.⁷ The major distinction between the classes seems to be the hardness of the events with the shorter burst being harder. There are also arguments that the short bursts may have a different value of V/V_{max} than the long bursts.¹⁷

Since the origin of GRB is not known, and there is as yet no model that is accepted for the origin of these events, it is necessary to turn to morphology or phenomenology to attempt to find classes of events or evidence of repeating the sources or even possibly evidence for gravitational leasing (several identical events separated in time). There have been claims for all of the above in the literature.

In the early to mid 1980's there was a school of thinking that there were three classes of GRB classified by the time duration of the GRB.¹⁵

- a) $\Delta\tau \sim 100$ ms.
- b) $\Delta\tau \sim 1$ sec.
- c) $\Delta\tau \sim 10 - 100$ sec.

More recently the BATSE team and others have identified at least two classes $\Delta\tau \lesssim 1$ sec and $\Delta\tau > 10 - 100$ sec.¹⁶ This separation of GRB into two groups has gained widespread acceptance largely because the event distribution seems to have two peaks as shown in Fig. 4. We shall say more about this later when we discuss models of GRB and then the search for GRB from Primordial Black Holes.

The issue of repeaters (either spatially or temporal) has caused great controversy which is not yet fully decided. However, it is far to say that the evidence for repeating is considered by most marginal.¹⁸

1.6. *Evidence for Red Shift*

If the GRB originate at cosmological distance we would expect to see some "red shift" effects (dependent on Z). This could take two forms:

- 1) Weaker bursts would come from larger distance and the Red Shift would give a longest time pulse.
- 2) Stronger bursts near by should have a harder spectrum than joint forces.^{19,20}

There is evidence for and against both of these effects in the literature. The major problem is that GRB are not static events: for example a burst may change from bright to faint during the bursts duration and the hardness can also change in

Fig. 4. Histogram of time distribution for 433 BATSE events showing the clear two population spectrum.

time. The other problem is that the intrinsic luminosity of the GRB is not likely to be a standard candle. Thus any variation observed may be due to the source luminosity rather than the effect of a red shift. At present there is no compelling evidence that GRB are cosmological.

If GRB all had the same time profile and the same source of luminosity function, it would be trivial to search the data for effects of red shift (as was just observed by Hubble since galaxies do behave in a rather similar manner). Unfortunately the converse is true due to the great variability in the time structure and it is extremely difficult to even define a "Standard Gamma Ray Burst" from which to search for evidence of Lorentz variation of the variables due to the large distance scale and expansion of the universe. Again this is a controversial issue with strong proponents (opponents) on both sides.

2. Attempts to Find Counterparts of GRB Sources.

To start with, we point out that no counterpart of a GRB has been uniquely identified to date. This includes searches in the 1980's when many bright GRBs were very well located by an Interplanetary network. However, the search goes on. In order to search for counterparts three types of events are studied:

- (i) Search for a counterpart at the same time the GRB occurs (Flaring Source).
- (ii) Search for a counterpart after the GRB for several hours to several days

2. Find a "shot" noise signal in the data that deviates from the simplest expectation.¹³

3. Search for evidence of micro burst structure where a very large number of low energy photons could presumably pile up to imitate the GRB structure

(Fading Source).

- (iii) Search for a static source at the location of the GRB (either before or after the GRB).

In the past 20 years many searches for all of the types of events have been made with no success. Ref. 21 provides a clear recent summary. Without the identification of a counterpart for which distance scale can be determined progress in unique determination of the origin of GRBs is likely to be very slow.

3. Models of GRBs.

There are various types of constraints that can be placed on the sources of GRB.

3.1. Distance Scale and Luminosity.

From the observed fluence and to obtain an isotropic distribution, we can see that for near by source $d \sim 10pc$ of $\mathcal{L} \sim 10^{34}$ ergs/sec to a disk source at $d \sim Kpc$ $\mathcal{L} \sim 10^{38}$ ergs/sec and for an extended halo ($d \sim 300Kpc$) $\mathcal{L} \sim 10^{44}$ ergs/sec on to cosmological sources ($d \sim GPC$) where $\gtrsim 10^{51}$ ergs/sec is required: thus the uncertainty in $\mathcal{L}$ as 16 orders of magnitude. However, for all the distance scales it is difficult to invent photon sources with these luminosities especially since some of the bursts have very long time duration and enormous energies.

3.2. Temporal.

Very approximately we would expect the "size" of the source (ℓ) to be related to the most rapid time variation on the GRB ($\Delta\tau$) as (we take this as the laboratory frame). $\ell \sim C\Delta\tau$ for a GRB $\Delta\tau \sim sec$, $\ell \gtrsim 10^{10}$ cm. However, some events have recorded time variation of ms to $100\mu s$ giving $\ell \sim 10^6$ cm to 10^7 cm. There are of course very crude arguments but they indicate that the source of most GRB is probably compact.

There is a simple problem associated with a model of a static source of radius R that releases energies such as 10^{51} ergs and where there are photons with observed energies about the threshold for $\gamma + \gamma \rightarrow e^+ + e^-$ with $R \sim 10^{10}$ cm per compact source.²² The optical depth of the source is limited by this pair production and we would expect the resulting spectrum to be a thermal spectrum with is not observed. This is the reason there is so much activity on fireball modes (to be discussed in more detail later). In these models the emitting photosphere with a Lorentz factor $\gamma \gg 1$. Then in the center of mass of the $\gamma\gamma$ collision the energy can be kept below e^+e^- threshold. In this case one has an expanding then source and there is no requirement of thermodynamics. As we shall see however the fireball properties are changed if there are baryons in the system which greatly reduces the emission. At

present the data from all existing experiments do not favor any of these models!

3.3. Photon-Photon and e^+e^- Plasma Interaction Effects.

Producing photons above 1 MeV in the presence of e^+e^- pairs or other photons is difficult since there is a strong process due to e^+e^- pair production. And since photons of 10 GeV have been observed from GRB, this problem is even more constraining.²²

3.4. Particle Physics Input.

The intrinsic luminosity of GRB sources can vary from 10^{34} ergs/sec to 10^{51} ergs/sec depending on the distance to the GRB from earth. These are impressive energy release even in the small values. What Astrophysics processes can give such enormous release. Here is a possible list of candidates:

$\mathcal{L} \sim 10^{34}$ erg/sec	Primordial Black Hole Evaporation
	Neutron Star Quarks
	Super String Effects
$\mathcal{L} \sim 10^{40}$ erg/sec	Accretation onto a Neutron Star
$\mathcal{L} \sim 10^{50}$ erg/sec	Neutron $\times$ Neutron Star collision energy transferred by
	$\nu_x + \bar{\nu}_x \rightarrow e^+ + e^-$

Some or perhaps all of these effects are related to elementary particle interaction. The sources in the 10^{34} erg/sec luminosity range are either exotic particle physics processes like Primordial Black Hole Evaporation²³, “Neutrino Balls” superstring or exotic processes inside of Neutron stars. In the case of neutron stars the effects are likely related to the large magnetic fields and could also possibly generate radio wave signals counterparts. These sources would be at distances of parsecs.

In the 10^{40} erg/sec the sources would likely be in the extended galactic halo ($d \geq 100kpc$). In this case the energy source would likely be some sort of accumulation disk near a neutron star or Black Hole. Reaching 10^{50} erg/sec luminosity is not trivial: various ideas have been put forward such as colliding neutron stars or BH.⁸ We know that binary systems slowly spin down due to gravity waves and other effects. Thus NS-NS, NS-BH, BH-BH systems would be expected to eventually collide releasing energy similar to a supernova explosion (10^{53} ergs).⁸ However, there must be some mechanism to take the energy well outside of the system. The most likely process would likely be through the escape of energetic ν and $\bar{\nu}$ and subsequent conversion of energy into the electromagnetic system such as

$$\begin{aligned}\nu_x + \bar{\nu}_x &\rightarrow e^+ + e^- \\ \nu_x + e &\rightarrow \nu_x + e\end{aligned}$$

Getting the neutrinos out assumes there are no mechanisms for converting the neutrino into another neutrino. For example neutrino oscillation could give

$$\nu_x \rightarrow \nu_e \text{ with } \nu_e + e \rightarrow \nu_e + e \text{ depleting the energy.}$$

Thus this mechanism has to be carefully studied from the stand point of neutrino interactions and oscillations. In addition, converting the energy to high energy photons is not without problems such as the optical depth due to absorption by the e^+e^- plasma. Fireball formation can help this process to work. Nevertheless the NS-NS collision remains the favored explanation for those that believe the GRB come from cosmological distances.¹⁹

3.5. Fireball Formation.

Since the early days of particle physics, the concept of relativity fireball particle emission (was involved). (It could go back to the 1930's with the Heisenberg model air showers). After the days of bootstrap models and the Hagedorn model the fire ball model was used to explain high energy particle hadronic interaction. Even today there are models of heavy ion collision that are essentially a fireball model.²⁴ We briefly describe some of the concepts of the fireball model here.

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.²⁵, 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.²⁶ An evolution of the high temperature matter emitted from the GRB source as an adiabatic perfect fluid has been extensively discussed by Carter *et al.* (1976).²⁶ Their analysis shows that the matter fireball, conserving the total entropy S expands to a certain radius above the event horizon:

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

where L_{PBH} is the total energy emitted from GRB source. The 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_o required for achieving a local thermal equilibrium:

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

where T is determined from the equation of state by $T = dp/ds$ and $\alpha \equiv 1/\Gamma - 1$. The interaction time τ_o is a parameter hard to calculate without a definitive particle physics model of the matter fireball. Thus, we assume that τ_o lies between the

larger than the basic thermal time scale ($1/T$) and the interaction time scale in the matter fireball $1/\Lambda_{\text{int}}$. 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_o indicates whether a perfect fluid treatment of the matter fireball is acceptable:

$$\begin{cases} \frac{\tau}{\tau_o} \leq \left(\frac{T}{T_{PBH}} \right)^{\frac{3-\alpha}{2}} \leq 1 & \text{for } T \leq T_{PBH}; \text{ transparent} \\ \frac{\tau}{\tau_o} \geq \left(\frac{\Lambda_{\text{int}}}{T_{PBH}} \right) \left(\frac{T_{PBH}}{T} \right)^{\frac{\alpha-3}{2}} \geq 1 & \text{for } T \geq \Lambda_{\text{int}}; \text{ opaque fluid} \end{cases}$$

where e is the electronic charge $3^2 = 1/137$. From the last condition in the above equation, 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.

3.6. Neutrino Oscillation Constraints.

One of the central problem of the $10^{50} - 10^{51}$ erg/sec source is the transfer of energy from the initiating source ($Ns \times Ns$, $Ns \times BH$, $BH \times BH$ collision) into the plasma region where the GRB photon originate.⁸ The most widely discussed mechanism for this energy transfer is through the neutrinos in

$$\nu_x + \bar{\nu}_x \rightarrow e^+ + e^-$$

A similar process occurs in Supernova II explosions. In addition to predicting the flux and energy spectrum of the neutrinos, it is necessary for any model to consider possible effects of neutrino oscillations on the neutrino transmission through the medium. We would expect some constraints on neutrino oscillations similar to those derived by Fuller and co-workers for supernova R processes!²⁷

Another type of constraint will involve the mixture of low mass particles (photon pions) etc. and high mass (baryons) in the process. In fireball models the presence of large amount of baryons "loads" the expanding front and reduces the energy of the radiation.

Another particle physics input has to do with the quark gluon phase transition and its effect on the entropy of the system. Finally, the acceleration of particles to high energy (10 GeV detected so far and possibly even higher energy requires a knowledge of the acceleration mechanism and the particle spectrum (charged particles, photons, neutrinos) or more exotic particles).

Thus the ultimate understanding of many properties of the GRB source will undoubtedly require important elementary particle physics input. We will give some specific examples in the following part of the report.

4. Primordial Black Hole Evaporation and Very Short GRB.

There could be exotic sources that contribute to the GRB population. Even since the invention of "Primordial Black Holes" there have been suggestions for the ex-

perimental detection of such objects.²³ 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. The most extreme model used to simulate this final state was the Hagedorn model that predicted an explosion lasting $\sim 10^{-7}$ sec, whereas other QCD inspired calculation suggested a final state collapse time of the order of seconds.^{26,9,28} We note that there are already indications of two classes of GRBs. The viewpoint taken here is to see if there are GBR's that could be consistent with PBH evaporations, not to attempt to prove the existence of PBHs at this stage!²⁵ There are two recent developments:

- (i) New estimates of the amount of PBH that may occur from the early universe by B. Carr, et al. (Physics. Rev. D50, 4853, 94).
- (ii) A suggestion by W. Hong and the author that some of the BATSE GRB events could have the characteristics expected from PBH evaporation within a specific model of the hadronic interaction.

Hawking showed the temperature increases as it loses mass during its' lifetime.²³ The black hole loses mass at a rate in the context of the standard model of particle physics:

$$\frac{dm}{dt} = -\frac{\alpha(M)}{M^2}$$

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

A reasonable model of the running coupling is shown in Fig. 5, 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 Fig. 5, the regions in PBH temperature where short γ burst may occur when the PBH mass is 10^{14} or 10^9 grams!

4.1. The concept of a PBH & Formation in the Early Universe.

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

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

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 as

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

Fig. 5. 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). We also show on the same graph at the top of the mass of the black hole and at the bottom the regions in temperature where short GRBs could occur.⁷

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 ~ 10 per year pc^3 . PHB would be formed in the Early Universe from density fluctuations.²⁹

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. In the fireball model we would expect the PBHs of time duration of a few hundred milliseconds or less²⁵.

4.2. Survey of GRBs & Unusual Events that Might Signal PHB Evaporation.

We have studied many of the experimental papers on GRBs and noticed that there are a short GRBs (few 100ms) that in many cases seem to have a hard γ spectrum (Fig. 6). Recently, the BATSE group has recorded a very interesting short (ms) GRB that also has a hard spectrum.¹³ Which also has the characteristics consistent with a PBH origin in our model.

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 to short bursts selected among the BATSE data⁴ to be homogeneous and isotropic distribution of sources in a static, Euclidean space (HISE).

To make any reasonable assessment about the spatial distribution of the short GRBs we need to study the $\log N(C_p)$ vs. $\log (C_p/C_{\text{limit}})$ or $\log (C_p)$. This distribu-

Fig. 6. Anti-correlation of hardness and GRB time (using T90 BATSE data).

tion may contain a bias due to the variable threshold, burst durations as suggested by Petrosian.³⁰ By following their suggestions we corrected for the bias due to the variability of C_{limit} , obtaining the distribution shown in Fig. 7. [The Petrosian analysis is justified due to 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 also give $V/V_{\text{max}} \sim 1/2$. In Fig. 8 we show some of the hard-short time GRBs.¹³ They have a remarkable similarity as would be expected for a simple source such as a Primordial Black Hole.

The search for signals for primordial black holes has been going on since 1975. The traditional very short GRB ($\Delta\tau \sim 10^{-7}$ sec) signature is likely incorrect in current physics theory. However, short GRBs can occur from PBH under the following conditions:

- (i) $M_{\text{PBH}} \sim 10^9$ grams, QCD Burst.
- (ii) $M_{\text{PBH}} \sim 10^{14}$ grams, Quark-Gluon phase transition.

While no candidates for (i) exist, there are several BATSE events that could be due to (ii).⁷ If these events are due to PHB, the density in the galaxy could be $< 10^{10} \text{ pc}^{-3}$.

5. Search for High Energy Gamma Radiation From GRB sites.

One important key to both the physical mechanism and distance to GRB sites would be the detection of high energy photons ($> 100\text{GeV}$) to ultra high energy photons ($> 100\text{TeV}$). To date this search is null and is reaching the level of background in both energy ranges.³² We quote from two recent researches (which provide references to previous searchers).

Fig. 7. Plot shows $\log(N)$ vs. $\log(C_p)$ distribution for events in Fig. 6 with the correction of Petrosian (1993) applied. (BATSE B1 Data)¹³

- 1) In the 100 GeV to TeV range the recent search by the Wipple Observatory Team is negative.³¹
- 2) In the > 50 TeV range the recent search by the CYGNUS group is negative.³³

This and other searches are close to the limit of νF_γ from the low energy data. If this trend continues it could be either due to a high energy cutoff in the source spectrum or due to the description of the γ 's by the IR background (or both). In the latter case this would imply a cosmological distance. A recent review by Hurley

et al. provides some interesting speculation on the extrapolation of GRB energy spectrum into the very high energy domain.¹²

Summary

In this brief report on the properties of GRB and the possible particle physics connection we have surveyed the data and some of the large number of theories concerning this very interesting phenomenon. While the origin of GRB still is a mystery, it seems plausible that this violent energy source should have particle physics implications. During the next few years it may be possible to answer the following questions:

- (i) Are any of the GRBs strongly suggestive of the PBH origin?
- (ii) Does neutrino-antineutrino pair production and annihilation play any role in the electromagnetic energy emission?
- (iii) Are there ultra high energy photons associated with the GRBs?

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Fig. 8. Time profile of some of the hard spectrum BATSE events.

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