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POSSIBILITY OF UNIQUE DETECTION OF PRIMORDIAL BLACK HOLE GAMMA-RAY BURSTS

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ABSTRACT

We describe the properties of primordial black hole (PBH) burst emission, pointing out the aspects that are model-dependent and estimate the upper limit of the PBH density in the universe and in the Galaxy. We then suggest methods to detect the γ, ν bursts from PBHs. Finally, we compare with the current data on γ-ray bursts (GRBs) and point out that some of the events may have the expected characteristics for PBH bursts within the distance of a few parsecs. Specific tests of this assumption are proposed which may be carried out in the next few years.

Subject headings: black hole physics — cosmology: theory — gamma rays: bursts

1. INTRODUCTION

The concept of primordial black holes (PBHs) that "explode" at the end of their life goes back to the early work of S. Hawking and others (Page & Hawking 1976; Carr 1976). There are several recent calculations along these lines (MacGibbon & Weber 1990; MacGibbon & Carr 1991). A major difficulty in the experimental detection of PBHs is to achieve a current understanding of the hadronic and leptonic spectrum of particles produced in the process. While several approaches have been taken to this problem, we question here whether present calculations are adequate to correctly estimate the hadronic and photonic spectrum. We identify the reason for this viewpoint below. Also, the possibility of a PBH magnetic field or of hadronic or γ-γ interaction in the vicinity of the exploding PBH has not been, to our knowledge, taken into account. Instead, we take the approach that certain "invariant" properties of the PBH evaporation process can be used as a signature and investigate the current constraints on PBH density as well as techniques to uniquely detect PBHs in future.

There are three unique features of a PBH "explosion" in decreasing order of uniqueness: (1) the neutrino burst; (2) the short time duration of the burst; and (3) the hardness of the photon spectrum. In addition, due to the luminosity limitation, γ-ray bursts from PBH must occur relatively close to Earth ($\lesssim 10$ pc). We will show later how this leads to another signature for PBHs. We consider feature (1) to be the unique signature, and we return to it later. Features (2) and (3) are the key to present estimates of the frequency of PBH bursts in our Galaxy: they are not entirely independent.

Model-dependent calculations of the spectra of a $\sim 7 \times 10^{13}$ g PBH burst suggests that for a very soft hadronic spectrum (Hagedorn 1965, 1970) the time duration is of the order of 10^{-7} s, and for a hard (QCD-like) spectrum, the time duration for the burst of $\sim 10^{10}$ g PBH is much longer, ~ 1 s (Page & Hawking 1976). We consider these two calculations to be the extremes of the possibilities and note that an important region of the explosion kinematics falls into the region on *non-perturbative QCD effects which are presently impossible to calculate from first principles.* As an example, we cite the low-energy particle spectrum observed at current $\bar{p}p$ collisions or heavy ion collisions which are not directly calculable by QCD techniques or the Hagedorn-type model. Generally, from such data one would conclude that the low-energy particle spectrum is softer than a QCD approach but not as soft as the Hagedorn approach would suggest. We note the hadron spectrum increases exponentially in contrast to QCD calculation.

Lacking a better model, we assume the real spectrum is a mixture of a Hagedorn and QCD-like spectrum. We also note the Veneziano model, in which hadrons are made of strings of three quarks or strings of quark-antiquark pairs and each string degree of freedom corresponds to a particle state of definite mass and spin (Veneziano 1974), may provide such an intermediate-type model. A similar model could provide an adequate fit to the $\bar{p}p$ collision and ion collision data. In this model typical bursts from a $\sim 10^{14}$g PBH could have luminosity between 10^{33} and 10^{34} ergs and time duration would be in the range of tens of milliseconds. We take as an upper limit burst time of $\mathcal{O}(50)$ ms.

We can inquire how many of the GRBs observed through the years have a time interval of a few ms or less. We can also calculate the expected explosion rate of PBHs using an estimate for the density of PBHs in the Galaxy not in conflict with any known observation and obtain ~ 20 explosions per year within a parsec. We note this is of the same order as some of the γ bursters that have been observed over past decades (see, for example, Higdon & Lingenfelter 1990). Consequently this value is of order or less than 50 bursts per year (recent unpublished results from the BATSE suggest a similar number). We thus assume some of the short time γ bursters are due to PBH explosion and follow the consequences in this *Letter*. No burst has yet been observed with less than 5 ms time duration. In model-dependent calculations of the spectra, this would imply the mixed-type picture is more correct, assuming some of the GRB actually arise from PBHs. We note the pure Hagedorn model is not suggested by the observed short time γ burst data. Thus we feel that the concept of a mixed spectrum is more likely realistic for the exploding PBH.

The second possibility of detecting PBH is to observe the high-energy gamma spectrum component in coincidence with the low-energy component. Models of γ burst photon spectra (i.e., from neutron stars) do not predict high-energy photons (i.e., above 100 GeV, for example). Unfortunately, the predicted flux for very high energy (i.e. $\gtrsim 100$ TeV) is unreliable and unlikely to be detected by air shower arrays on Earth. Consider the 1978 March 25 event (Hueter & Gruber 1982) that was energetic and a short burst. Crudely extrapolating the observed spectrum by an E^{-2} law, the expected photon flux would not be detectable by an air shower array on Earth. Thus an intermediate-size γ-ray detector is needed to detect ~ 100 GeV photons in coincidence with $\sim$MeV photons being detected by current satellite detectors. Such a detector, an area of at least (10–100) m^2, could be mounted in the space station, for example.

We now turn to another method to identify potential PBH events. Current data from γ burst detectors provide a strong indication that events are isotropic but not homogeneous in space (Fishman et al. 1991). Models of cosmological source to Galactic and halo component models are currently being invoked to explain these data. We assume the bulk of γ bursters will show this behavior. The PBH events, however, must occur near Earth and will thus appear to be nonisotropic in Galactic coordinates (since the solar system is displayed by ~ 8 kpc from the Galactic center). Events with a short time burst will appear to have a dipole and quadrupole moment inconsistent from the expectation of isotropy.

2. A BRIEF REVIEW ON PBH EVAPORATION

Hawking showed that an uncharged, nonrotating black hole emits particles with energy $(E, E + dE)$ at a rate per spin or helicity state

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

where M is the mass of the PBH, s is the particle spin, and Γ_s is the absorption probability (Hawking 1974, 1975). Heuristically, one can think that this particle emission comes from the spontaneous creation of particle pairs near the event horizon of the black hole. One particle, with positive energy, escapes to infinity, and the other particle has negative energy which tunnels through the horizon into the black hole where there are negative energy particle states with respect to infinity. The PBH thus emits massless particles (photons, light neutrinos) like a hot blackbody with temperature

$$T \simeq 10^{16}\left(\frac{1g}{M}\right) \text{MeV}, \quad (2)$$

where M is the mass of the black hole. 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:

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

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 of three leptons and quarks family, it is given as

$$\alpha(M) = (0.045S_{j=1/2} + 0.162S_{j=1}) \times 10^{-4}, \quad (4)$$

where $S_{j=1/2}$ and $S_{j=1}$ are the degrees of freedom (spin and color) for the fermions and gauge particles respectively. For the standard model, $S_{j=1/2} = 90$ and $S_{j=1} = 30$ at $T \sim 100$ GeV, we obtain $\alpha(M) = 4.1 \times 10^{-3}$ (Halzen & Zas 1989).

In nonstandard models, for example, in the Hagedorn-type pictures, the numbers of emitting particle states grows exponentially with mass (Hagedorn 1970; Veneziano 1974; Huang & Weinberg 1970)

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

where $5/2 \le \beta < 7/2$ and 140 MeV $\le \Lambda \le$ 160 MeV. These models were motivated by the apparent exponential increase in hadronic resonance seen at accelerators. Thus the final explosion of PBH in this picture will be much more violent.

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

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

for $\alpha(M_*) \simeq 1.4 \times 10^{-3}$. Page & Hawking (1976) have put the bound on the number of black holes at their critical mass by the constraint of observed diffuse gamma-ray background in the 10–100 MeV energy region (Trombka et al. 1977; Fitchel, Simpson, & Thompson 1978)

$$N = \left.\frac{dn}{d(\ln M)}\right|_{M=M_*} \le 10^5 \text{ pc}^{-3}. \quad (7)$$

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

$$\frac{dn}{dt} = \frac{3\alpha(M_*)}{M_*^3} N = 2.2 \times 10^{-10} N \text{ yr}^{-1} \quad (8)$$

This rate is directly proportional to the particle emission degree of freedom and is highly model dependent.

3. A FIREBALL ANALYSIS FOR AN EXPLODING PBH

Next, the possibilities of producing ms GRBs from an energetic fireball (γ, relativistic e^+e^- pairs, nonrelativistic p and $\bar{p}$) of the exploding PBH in the context of the mixed model is discussed. The ultimate stage of PBH explosion is extremely model dependent. In the standard model of elementary particle physics, one expects to observe emission products (in the form of gamma rays, electrons, positrons, neutrinos, protons, and antiprotons) with energies right up to the Planck mass, i.e., $\sim 10^{19}$ GeV, with some uncertainties (Carr 1976). But Carter et al. (see Carter et al. 1976) showed that, if the Hagedorn-type models are correct, the final output will be in the form of medium-energy γ-rays in the range between ~ 0.5 and ~ 140 MeV in an explosive burst lasting $\delta t_{\text{pbh}} \sim 10^{-8}$ s soon after the PBH enters the hadronic temperature range. We point out here that Carter et al. did not properly consider the opacity due to photons, relativistic e^+e^- pairs, nonrelativistic p and $\bar{p}$. We show that the fireball is optically thick enough so that the fireball should expand far greater distances than the estimated photosphere radius, $R_p \sim 10^2$ cm (where photons can emerge), in the paper of Carter et al. The PBH final stage emission mechanism in the high-energy limit in the Hagedorn-type models and the standard model can be summarized as follows:

1. Depending on the equation of state with an adiabatic index Γ of the high-temperature matter, the particle opacity of an exploding PBH can be either very high or completely transparent: for the Hagedorn-type soft equation of the state ($1 < \Gamma < 6/5$), the fireball is extremely opaque, and for the "standard" model ($\Gamma > 6/5$), the Hawking spectrum for particles emission is acceptable.

2. As soon as PBH temperature reaches the hadronic regime ($140 \lesssim T_{\text{PBH}} \lesssim 160$ MeV), the PBH emission become highly

explosive in the Hagedorn-type models and the mass of PBH ($6.3 \times 10^{13} \leq M_{\rm PBH} \leq 7 \times 10^{13}$ g) which corresponds to a total energy of ($10^{33} \lesssim L_{\rm PBH} \lesssim 10^{34}$ ergs) will be converted into the form of a "homogeneous pressureless" expanding fireball of very heavy hadrons.

3. The initial fireball of hadrons will continue to expand as a pressureless cloud until a decompression wave moving inward sets up due to the density changes of the expanding fireball. There will be a critical radius ($R_c \sim 10^{-2}$ cm and corresponding time $\delta t_c \sim 10^{-6}$ s) after which the fireball proceeds at speeds comparable with that of light to reach the electron pair threshold density.

4. Finally the fireball reaches the photosphere radius ($R_{\rm pho} \sim 10^2$ cm) and photons can escape from the surface within the time scale of $\delta t \sim 10^{-8}$ s, corresponding to the duration of the final explosive burst as seen by a distant observer, would be the order of the time required for light to cross the photosphere radius. The total energy released is the same as the initial energy ($10^{33} \lesssim L_{\rm PBH} \lesssim 10^{34}$ ergs) since the total entropy of the fireball is conserved until the matter ceases to be opaque.

An exact spectrum calculation of particles coming from the photosphere will be extremely difficult. We expect the fireball to radiate electrons, positrons, muons, photons, protons, antiprotons, and neutrinos with some proportions of the PBH's original mass (see Page & Hawking 1976) since all hadrons in the opaque fireball annihilate each other and decay very quickly into stable particles within the time scale of $\sim 10^{-10}$ s. As noticed in the explosion procedures (*c*) and (*d*) of Carter et al.'s argument, the obvious opacity due to photons, leptons, and nonrelativistic hadrons is ignored. Also when $\beta \rightarrow 7/2$ (for the mixed model case) the energy released would be much slower than $5/2 \leq \beta \leq 3$ (for the Hagedorn-type models). Detailed calculations will be required to obtain the parameters of the fireball (work in progress). The results will depend on the exact spectrum of the particles in the mixed model. However, we expect these effects to further soften the hadronic particle spectrum and lengthen the time of the burst. In general we can calculate the total optical depth, from center to edge of the sphere of the fireball, in terms of the total density of particles ($n_{e^+} + n_{e^-} + n_\gamma + n_p + n_{\bar{p}}$) and corresponding cross sections:

$$\tau_{\rm tot} = (n_{e\pm}\sigma_{\gamma e\pm} + n_\gamma \sigma_{\gamma\gamma} + n_p \sigma_{\gamma p} + n_{\bar{p}} \sigma_{\gamma\bar{p}})R_0 \; . \qquad (9)$$

At $\tau_{\rm tot} \simeq 1$ the fireball becomes transparent and the photons escape in one crossing time. To see a ms duration burst, the fireball should expand to a macroscopic scale, i.e., $R_0 \geq 10^8$–10^9 cm since the duration of burst to an observer is approximately given as

$$10 \lesssim \delta t_{\rm burst} \simeq \frac{2R_0}{c} \lesssim 50 \text{ ms} ,$$

where the emission radius R_0 depends on detail parameters of the fireball, i.e., the total energy of the fireball and photon interactions with leptons and hadrons, etc. We also expect that, by the time the fireball has expanded to macroscopic radii, due to the constant Lorentz factor of the expanding fireball ($\gamma_f = 2 \times 10^{16}\, g/M_{\rm PBH} \sim 300$) (see Rees 1977), some proportions of γ energy released from the fireball will be in the range of 0.1 to ~ 100 GeV.

4. DETECTION OF NEUTRINO SIGNALS FROM PBHS

At the final stage, PBH evaporation in the mixed model, we expect that the neutrino flux intensity is a few orders higher than photon flux. Not understanding the neutrino burst mechanism of the fireball in detail, we assume that the MacGibbon & Weber's numerical simulation for black hole temperatures ($T_{\rm PBH} = 0.1$ GeV) is a close approximation for the mixed model (around $140 \lesssim \Lambda \lesssim 160$ MeV). The ratio of neutrino flux to photon flux for our calculation is adopted from their simulation result (see MacGibbon & Weber 1990) for the electron antineutrino energy ranges (1–10 MeV). Mutliplying this ratio to the observed gamma-ray burst (see Hurley 1989), we obtain an instantaneous neutrino flux from such a burst (Fig. 1). In the search for electron antineutrino bursts from PBHs in the energy range $1 \leq E_{\bar{\nu}_e} \leq 10$ MeV, the dominant neutrino interaction is $\bar{\nu}_e + p_{\rm free} \rightarrow e^+ + n$. The SNBO (Super Nova Burst Observatory) detector (Cline et al. 1990) is a neutron-counting detector to measure supernovae ν_μ and ν_τ neutrinos. In the deep underground site with an extremely low neutron background, such as the WIPP site in New Mexico, there is about 10% of water in the detector medium, i.e., in NaCl. Free protons in the water will be absorption sources for electron antineutrinos. Thus the expected total event rate for $\bar{\nu}_e + p \rightarrow e^+ + n$ is

$$T = \int_{1.3}^{E_{\bar{\nu},e}} F(E_{\bar{\nu}_e})\epsilon N_p \sigma(E_{\bar{\nu}_e}) dE_{\bar{\nu}_e} \; , \qquad (10)$$

where N_p is the numbers of free protons, $\epsilon \simeq 1$ is neutron detection efficiency, $\sigma(E_{\bar{\nu}_e}) = 9.77 \times 10^{-44}(E_{\bar{\nu}_e} - 1.3)(E^2_{\bar{\nu}_e} - 0.51^2)^{1/2}$ cm^2 (total absorption cross section) and $F(E_{\bar{\nu}_e})$ is instantaneous flux from a burst in a kiloparsec (see Fig. 1). We plot total event rates for different PBH temperatures of $\Lambda_{\rm PBH}$. From Figure 2 we conclude that a large SNBO detector will be adequate to search for a neutrino burst from gamma-ray bursters if they originate from a PBH explosion.

5. CONSTRAINT ON NUMBER DENSITY OF EXPLODING PBHS FROM BATSE DATA AND COMMENTS ON SPATIAL DISTRIBUTION

On the basis of the above fireball model argument in the mixed model, we may expect to see more explosions than the Page & Hawking bound suggests (~ 20 yr^{-1} pc^{-3}). The general form of the calculated diffuse spectrum (MacGibbon & Carr 1991) is an E^{-1} slope below 100–300 MeV, correspond-

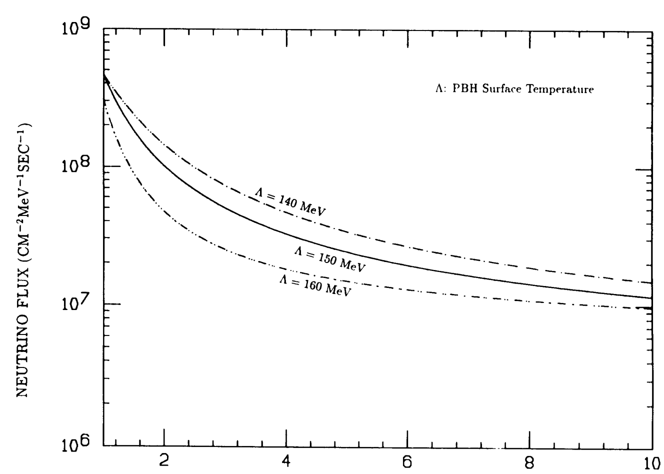

FIG. 1.—Expected instantaneous electron antineutrino fluxes from PBH explosion in a parsec for different PBH surface temperatures. Ratio of electron antineutrino flux to photon flux from the final stages of PBH evaporation is taken from numerical calculations of MacGibbon & Weber (1990).

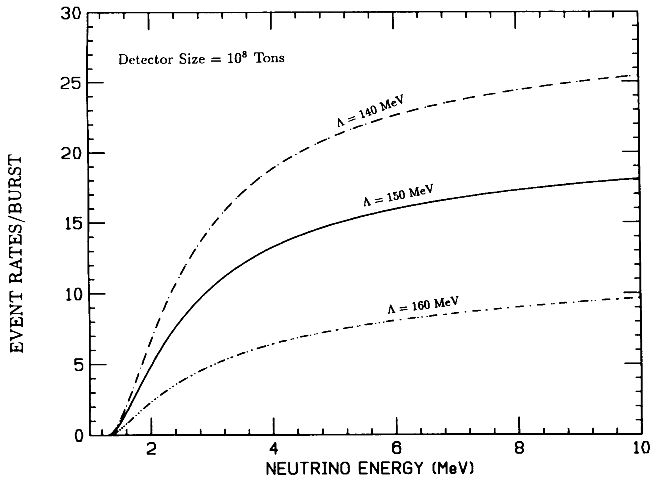

FIG. 2.—Expected total events rate for SNBO detector per PBH burst in a parsec for an idealistic neutron detector with a large detector volume 10^8 tons of NaCl.

ing to direct photon emission, turning over into an E^{-3} slope above 300 MeV. The Page & Hawking bound is obtained by matching to the observed diffuse gamma-ray spectrum at 100 MeV (Trombka et al. 1977; Fitchel et al. 1978). We point out that the observed diffuse spectrum has a powerlaw of $E^{-2.5}$ which is not consistent with the calculated power law spectrum, i.e., E^{-3}, of Page & Hawking nor with the modified spectrum of MacGibbon & Carr (QCD spectrum included). Further, the E^{-1} slope is sensitive to the redshift when photons are emitted (in QCD calculations, the slope is determined by jet fragmentation; see MacGibbon & Carr 1991) and an initial PBH mass spectrum in the early universe. Thus direct matching to the observed diffuse gamma-ray spectrum at 100 MeV may not give a direct constraint on the exploding PBHs number density in the mixed model since the PBH explosion in the mixed model at each stage of the universe may generate different diffuse gamma-ray spectrum than the standard model. Therefore we note that the mixed model considered here will provide a weaker constraint on the PBH density in comparison with the diffuse gamma-ray spectrum. The more reliable PBH explosion number density bound, if the fireball assumption is correct, should be constrained from BATSE data

$$\left.\frac{dn}{dt}\right|_{\rm BATSE} = \frac{\alpha(M_*)}{M_*^3} N_{\rm BATSE} \lesssim 50 \text{ pc}^{-3} \text{ yr}^{-1} \qquad (11)$$

and $N_{\rm BATSE} \sim 10^{11}$ pc^{-3} for a PBH fireball luminosity of $\sim 10^{34}$ ergs s^{-1} and $N_{\rm BATSE} \sim 10^{12}$ pc^{-3} for $\sim 10^{33}$ ergs s^{-1} since the recent BATSE data (Fishman et al. 1991) indicates more weaker bursts.

Several specific searches have been made for PBH–γ bursts in the past using either (1) very high gamma-rays ($E_\gamma >$ TeV) or (2) multiple photon coincidence (Halzen et al. 1990). The mixed model of PBH explosion assumed here would fail to provide a signal for these searches. We do not believe a sensitive Earth-based search for PBH explosion has been carried out, in particular for GeV γ energy ranges. Dedicated high-resolution γ-ray detectors for $1 \le E_\gamma \le 100$ GeV, mounted in a balloon or a space station with an area of (10–100) m^2 (see Cline et al. 1988 for a review), will be required to detect GeV γ-rays in coincidence with $\sim$MeV bursts.

As the BATSE detector accumulates more ms events in the future, we expect to see a homogeneous spatial distribution of PBH explosions, i.e., $\langle V/V_{\rm max}\rangle_{\rm PBH} = 0.5$. If a few percent of the total bursts show nonisotropic distributions in the Galactic coordinates, then we may easily identify such bursts as ms bursts due to the PBH explosions.

6. CONCLUSIONS

We have reviewed the current search for evidence for PBH through the detection of the PBH explosion products. We expressed doubt about the ability from first principles to calculate adequately this spectrum based on the inability of calculating nonperturbative QCD effects. Searching for another way to identify PBH explosions, we proposed that short time (ms) γ bursters could be examples of PBH decays, based on this assumption. We identified future tests of the concept that more than $\sim$20 yr^{-1} pc^{-3} are due to PBH explosion. Finding no direct experimental contradiction to this possibility, we believe it deserves a careful study in future.

After completing this *Letter*, we were informed that the BATSE group saw a 6 ms gamma-ray burst event on 1991 July 11 (private communication). The event is a strong candidate for a gamma-ray burster from a primordial black hole explosion.

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