Milagro Limits on the Rate-Density of Primordial Black Holes

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Primordial Black Holes (PBHs) created early in the universe are dark matter candidates. One method of detecting these PBHs is through their Hawking radiation. PBHs created with an initial mass of $5.0 \times 10^{14}$ g should be evaporating today with bursts of high-energy particles, including gamma radiation in the GeV - TeV energy range. The Milagro high energy observatory, which operated from 2000 to 2008, is sensitive to the high end of the PBH evaporation gamma ray spectrum. Due to its large field-of-view, more than 90% duty cycle and sensitivity up to 100 TeV gamma rays, the Milagro observatory is ideally suited for the direct search of PBH bursts. Based on a search in Milagro data, we report PBH upper limits according to the standard model.

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1 Introduction

In the present universe, stellar processes can create black holes (BHs) with masses greater about $3M_\odot$. Processes in the Early Universe, however, may have created BHs with sub-stellar masses. Density fluctuations in the early universe could have created BHs with arbitrarily small masses down to the Planck scale [1]. These BHs are referred to as Primordial Black Holes (PBHs).

In a ground-breaking theoretical study, Hawking showed that due to quantum-gravitational effects, BHs possess a temperature [2]. In addition, he showed that the BH temperature is inversely proportional to its mass [2]. The immediate implication of this finding is the realization that a BH with a temperature higher than its surrounding environment will evaporate. Stellar mass BHs have temperatures much lower than that of the present Cosmic Microwave Background radiation and they will not lose mass through evaporation. On the other hand, PBHs with initial masses smaller than $\sim 5.0 \times 10^{14}$ g have already evaporated and may contribute to the extragalactic background radiation. PBHs with an initial mass somewhat greater than $\sim 5.0 \times 10^{14}$ g should be evaporating now [3] with bursts of high-energy particles, including gamma radiation in the MeV – TeV energy range, making them candidate gamma ray burst (GRB) progenitors.

The properties of the final PBH burst depend on the physics governing the production and decay of high-energy particles. As the BH evaporates and loses mass over its lifetime, its temperature and the number of distinct particle species emitted increase. The higher the number of fundamental particle degrees of freedom, the faster and more powerful will be the final burst from the PBH, with the spectral details differing according to the particle physics model. Hence, the nature of the final burst will also provide information on the correct model of high-energy particle physics [1].

Various detectors have searched for PBHs events using direct and indirect methods. These methods probe the PBH distribution on various distance scales. One can probe the PBH rate density at the cosmological scale using the 100 MeV extragalactic gamma ray background, which results in a limit of $< 10^{-6}$ pc$^{-3}$yr$^{-1}$ [1] assuming no PBH clustering. On the galactic scale, if PBH are clustered in the Galaxy, we would expect to see anisotropy in the 100 MeV gamma ray measurements. Indeed such an anisotropy has been detected which results in a PBH limit of $< 0.42$ pc$^{-3}$yr$^{-1}$ [4]. On the kiloparsec scale the best limit comes from the antiproton flux studies which is $< 0.0012$ pc$^{-3}$yr$^{-1}$ [5]. It is important to note that however, the antiproton background limit depends on the distribution of PBHs within the Galaxy and the propagation of antiprotons through the Galaxy, as well as the production and the propagation of the secondary antiproton component which is produced by interactions of cosmic-ray nuclei with the interstellar gas. On the parsec scale, the limits are set by searches for the direct detection of individual bursting PBHs and are independent of the assumptions of PBH clustering. The best limits come from the Very High Energy (VHE) searches.
done by the Imaging Air Cherenkov Telescopes (IACTs) and Extensive Air Shower arrays (EAS). For the parsec scale, the current best limit is $< 4.6 \times 10^5 \text{pc}^{-3}\text{yr}^{-1}$.

In this paper, we present new PBH limits based on a search done using the data from the Milagro observatory. These limits are obtained assuming standard model of Hawking radiation and particle physics.

2 Milagro Observatory

Milagro is a water Cherenkov gamma ray observatory (EAS type) sensitive to the gamma rays in the energy range $\sim 100$ GeV to 100 TeV. This observatory is located near Los Alamos, New Mexico, USA at latitude 35.9° north, longitude 106.7° west and altitude of 2630 m, and was operational from 2000 to 2008. The Milagro detector had two components: a central rectangular 60 m $\times$ 80 m $\times$ 7 m reservoir filled with purified water and an array of 175 smaller outrigger (OR) tanks surrounding the reservoir. These OR tanks were distributed over an area of 200 m $\times$ 200 m. The reservoir was light-tight and instrumented with two layers of 8″ photomultiplier tubes (PMTs). The top layer consisted of 450 PMTs (air-shower or AS layer) 1.5 m under water and the bottom layer had 273 PMTs (muon or MU layer) 6 m under the water surface. Each outrigger tank contained one PMT. The observatory detected VHE gamma rays by detecting the Cherenkov light produced by the secondary particles from the gamma ray air shower as they pass through the water. Various components of the detector were used to measure the direction of the gamma ray photon and to reduce the background due to hadron-induced showers. The Milagro detector did not have good energy resolution and the median energy of the gamma rays detected from a Crab-like source was $\sim 3$ TeV. However, because of its large field-of-view of $\sim 2$ sr and a high-duty cycle which was over 90%, the Milagro observatory is an ideal instrument to search for emission from PBH candidates.

3 Methodology

3.1 PBH Spectrum

The temperature ($T$) of a black hole depends on the remaining lifetime ($\tau$) of the black hole (the time left until the total evaporation is completed) as follows:

$$T = \left[ 4.7 \times 10^{11} \left( \frac{1 \text{sec}}{\tau} \right) \right]^{1/3} \text{GeV}. \quad (1)$$
For BHs with temperatures greater than several GeVs at the start of the observation, the time–integrated photon flux can be parameterized (for \( E > \sim 10 \text{ GeV} \)) as \[ dN \over dE \approx 9 \times 10^{35} \begin{cases} \left( \frac{1 \text{ GeV}}{T} \right)^{3/2} \left( \frac{1 \text{ GeV}}{E} \right)^{3/2}, & E < T \\ \left( \frac{1 \text{ GeV}}{E} \right)^3, & E \geq T \end{cases} \]

where \( E \), the gamma ray photon energy, is measured in GeV.

### 3.2 Detectable Volume Estimation

The expected number of photons detectable by an observatory on the ground from a PBH burst of duration \( \tau \) seconds at a distance \( r \) and zenith angle \( \theta \) is

\[
\mu(r, \theta, \tau) = \frac{(1 - f)}{4 \pi r^2} \int_{E_1}^{E_2} \frac{dN(\tau)}{dE} A(E, \theta) dE.
\]

where \( f \) is the dead time of the detector and \( dN(\tau)/dE \) is the gamma ray emission spectrum integrated over remaining time from \( \tau \) to 0. The values \( E_1 \) and \( E_2 \) correspond to the lower and upper bounds of the energy range searched and \( A(E, \theta) \) is the effective area of the detector as a function of photon energy and zenith angle. Typically the function \( A(E, \theta) \) is obtained from a simulation of the detector. For Milagro, we have parameterized the effective area for three zenith angle bands as

\[
A(E, \theta) = 10^{a \log E^2 + b \log E + c} \text{ m}^2
\]

and parametrization parameters are given in Table 1.

| Zenith Angle Range (\( \theta \)) | a    | b    | c    |
|----------------------------------|------|------|------|
| 0° - 15° (\( \theta_1 \))       | -0.4933 | 4.7736 | -2.4272 |
| 15° - 30° (\( \theta_2 \))      | -0.5037 | 5.0102 | -3.4015 |
| 30° - 45° (\( \theta_3 \))      | -0.4273 | 4.7931 | -4.3030 |

Table 1: Effective area parametrization parameters for various zenith angle bands.

The minimum number of counts needed for a detection, \( \mu_\sigma(\tau) \), for different burst durations are estimated by finding the number of counts required over the background for a 5\( \sigma \) detection with 99% probability after trials correction. This has been done using a Monte Carlo simulation in the ref [11] and we have used those numbers in our calculation (see Table 2).

By substituting \( \mu_\sigma \) values corresponding to various burst durations into Equation 3 and solving for \( r \), we calculate the maximum distance from which a PBH burst could be detected by the Milagro observatory for the three zenith bands and for various
| Burst Duration (s) | \( \mu_\circ \) | \( UL_{99} \) (pc\(^{-3}\)yr\(^{-1}\)) |
|------------------|--------|-----------------|
| 0.001            | 11     | 2.8 \times 10^5 |
| 0.01             | 16     | 1.1 \times 10^6 |
| 0.1              | 22     | 4.8 \times 10^4 |
| 1.0              | 35     | 3.3 \times 10^4 |
| 10.0             | 65     | 3.4 \times 10^4 |
| 100.0            | 150    | 6.2 \times 10^4 |

Table 2: Counts needed over the background, \( \mu_\circ(\tau) \), for a 5\( \sigma \) detection with 99% probability and calculated 99% confidence upper limits for various burst durations (\( \tau \)).

burst durations,

\[
r_{\text{max}}(\theta_i, \tau) = \sqrt{\frac{(1 - f)}{4 \pi \mu_\circ(\tau)}} \int_{E_1}^{E_2} \frac{dN}{dE} A(E, \theta_i) \, dE. \tag{4}
\]

Denoting the field-of-view of the detector by \( \text{FOV}(\theta_i) = 2\pi(1 - \cos \theta_{\text{max}}) \) sr, the detectable volume is then

\[
V(\tau) = \sum_i V(\theta_i, \tau) = \frac{4}{3} \pi \sum_i r_{\text{max}}^3(\theta_i, \tau) \times \frac{\text{effFOV}(\theta_i)}{4\pi} \tag{5}
\]

where \( \theta_i \) refers to zenith angle band and \( \theta_{\text{max}} \) corresponds to the maximum zenith angle in band \( i \). The effFOV is the effective field-of-view for the given zenith angle band. We calculate this by subtracting the FOV of the smaller band from the larger band as shown below:

\[
V(\tau) = \frac{1}{3} \left[ r_{\text{max}}^3(\theta_1, \tau) \cdot \text{FOV}(\theta_1) + r_{\text{max}}^3(\theta_2, \tau) \left[ \text{FOV}(\theta_2) - \text{FOV}(\theta_1) \right] + r_{\text{max}}^3(\theta_3, \tau) \left[ \text{FOV}(\theta_3) - \text{FOV}(\theta_2) \right] \right] \tag{6}
\]

### 3.3 Upper Limit Estimation

If PBHs are uniformly distributed in the solar neighborhood, the X% confidence level upper limit (\( UL_X \)) to the rate density of evaporating PBHs can be estimated as

\[
UL_X = \frac{n}{V \times P}, \tag{7}
\]

if, at the X% confidence level, zero bursts are observed over the search duration \( P \). Here \( V \) is the effective detectable volume and \( n \) is the expected upper limit on
the number of PBH evaporations given that zero bursts are observed. Note that
\[ P_{\text{Poisson}}(0|n) = 1 - X \Rightarrow n^0 e^{-n}/0! = 1 - X \Rightarrow n = -\ln(1 - X) \Rightarrow n = \ln(1/(1 - X)). \]
Thus for \( X = 99\% \) we have \( n = \ln 100 \approx 4.6 \) and the upper limit on the evaporating PBH rate density will be

\[ UL_{99} = \frac{4.6}{V \times P}. \quad (8) \]

4 Results and Discussion

Even though Milagro had been operating since 2000, for this search only the last five
years of Milagro data have been used: specifically from 03/01/2003 to 03/01/2008.
(Due to various detector-related issues some of the data taken during this period also
was not used). The final analysis utilized 1673 days (4.58 years) worth of good data.
This corresponds to \( \sim 93\% \) of the total Milagro data collected during the five year
period.

Searches were performed for durations ranging from 250 \( \mu s \) to 6 minutes. No
external triggers were used. The entire reconstructed data set was systematically
searched in time, space and burst duration. No statistically significant event was
observed over the 4.58 years of data. Based on this null detection, we have calculated
upper limits for the PBH rate density using the methodology outlined in section for various burst durations (with $E_1=50$ GeV, $E_2=100$ TeV and negligible deadtime). Our results are shown in Table and in Figure 1.0.

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