Milagro Limits and HAWC Sensitivity for the Rate-Density of Evaporating Primordial Black Holes

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Abstract

Primordial Black Holes (PBHs) are gravitationally collapsed objects that may have been created by density fluctuations in the early universe and could have arbitrarily small masses down to the Planck scale. Hawking showed that due to quantum effects, a black hole has a temperature inversely proportional to its mass and will emit all species of fundamental particles thermally. PBHs with initial masses of $\sim 5.0 \times 10^{14}$ g should be expiring in the present epoch 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 well suited to perform a search for PBH bursts. Based on a search on the Milagro data, we report new PBH burst rate density upper limits over a range of PBH observation times. In addition, we report the sensitivity of the Milagro successor, the High Altitude Water Cherenkov (HAWC) observatory, to PBH evaporation events.

Keywords: Primordial Black Holes

1. Introduction

Primordial Black Holes (PBHs) are created from density inhomogeneities in many scenarios of the early universe [1]. The initial mass of a PBH is expected to be roughly equal to or smaller than the horizon or Hubble mass at formation, giving possible PBH masses ranging from that of supermassive black holes down to the Planck mass. PBH production can thus have observable consequences today spanning from the largest scales, for example influencing the development of large-scale structure in the Universe, to the smallest scales, for example enhancing local dark matter clustering. Additionally, PBHs in certain mass ranges may constitute a fraction of the dark matter in the universe [1]. For particle physics, the greatest interest is in the radiation directly emitted by a black hole. By evolving an ingoing solution past a gravitationally collapsing object, Hawking showed that a black hole will thermally emit (‘evaporate’) all available species of fundamental particles [2] with a temperature inversely proportional to the black hole mass.

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16 PBHs with an initial mass of $\sim 5.0 \times 10^{14}$ g should be expiring now with
17 bursts of high-energy particles, including gamma radiation in the GeV –
18 TeV energy range [3].

19 Detection of radiation from a PBH burst would provide valuable in-
20 sights into the early universe and many areas of physics, as well as confirm
21 the amalgamation of classical thermodynamics with general relativity. Ob-
22 served PBH radiation will give access to particle physics at energies higher
23 than those which will likely ever be achievable in terrestrial accelerators.
24 Non-detection of PBHs in dedicated searches also gives important informa-
25 tion. One of the most important cosmological motivations for PBH searches
26 is to place limits on the initial density fluctuation spectrum of the early
27 universe. In particular, PBHs can form from the quantum fluctuations asso-
28 ciated with many types of inflationary scenarios [4]. Other PBH formation
29 mechanisms include those associated with cosmological phase transitions,
30 topological defects or an epoch of low pressure (soft equation of state) in
31 the early universe (for a review see [1]).

32 Evaporating PBHs are candidate sources for gamma-ray telescopes, as
33 they produce short bursts of gamma rays. While most gamma-ray bursts
34 (GRBs) are generally thought to be produced by the collapse of massive
35 stars (long duration GRBs) or the merger of compact objects (short dura-
36 tion GRBs) at cosmological distances [5], some short duration GRBs show
37 behavior, such as large offsets from the host galaxy or anisotropic sky distri-
38 bution, that may indicate a more local origin. Models of PBH evaporation
39 based on Standard Model physics predict a unique TeV gamma-ray spec-
40 trum [6].

41 Various detectors have searched for PBH events using direct and in-
42 direct methods. These methods probe the PBH distribution on various
43 distance scales. One can probe the PBH density on the cosmological scale
44 using the 100 MeV extragalactic gamma-ray background, which produces
45 a limit on the corresponding cosmological average PBH burst rate density
46 of $< 10^{-6} \text{ pc}^{-3}\text{yr}^{-1}$ [1; 7]. On the galactic scale, if PBHs are clustered
47 in the Galaxy, we would expect to see an enhancement in the local PBH
48 density and anisotropy in the 100 MeV gamma-ray measurements. Indeed,
49 such an anisotropy has been detected and results in a corresponding Galac-
50 tic PBH burst limit of $< 0.42 \text{ pc}^{-3}\text{yr}^{-1}$ [8]. On the kiloparsec scale, the
51 Galactic antiproton background can be used to give a PBH burst limit of $<$
52 $0.0012 \text{ pc}^{-3}\text{yr}^{-1}$ [9]. However, the antiproton-derived limit depends on the
53 assumed PBH distribution within the Galaxy and the propagation of an-
54 tiprotons through the Galaxy, as well as the production and propagation of
55 the secondary antiproton component produced by interactions of cosmic-ray

nuclei with the interstellar gas. On the parsec scale, the PBH burst limits are directly set by searches for the detection of individual bursting PBHs and are independent of assumptions of PBH clustering. The best direct search limits come from the Very High Energy (VHE) searches conducted with Imaging Air Cherenkov Telescopes (IACTs) and Extensive Air Shower (EAS) arrays. On the parsec scale, the current best PBH limit from direct searches is $< 1.4 \times 10^4 \text{ pc}^{-3}\text{yr}^{-1}$ [10].

2. Milagro and HAWC Observatories

In this paper, we present new PBH burst limits based on the direct search method using the data from the Milagro observatory. These limits are obtained assuming the standard model of Hawking radiation and particle physics [11; 6]. Milagro was a water Cherenkov gamma-ray observatory (EAS type) sensitive to gamma rays in the energy range $\sim 50 \text{ GeV}$ to 100 TeV . The observatory was located near Los Alamos, New Mexico, USA at latitude 35.9° north, longitude 106.7° west and an altitude of 2630 m , and was operational from 2000 to 2008 [12]. The Milagro detector had two components: a central rectangular $60 \text{ m} \times 80 \text{ m} \times 7 \text{ m}$ reservoir filled with purified water and an array of 175 smaller outrigger (OR) tanks distributed over an area of $200 \text{ m} \times 200 \text{ m}$ surrounding the reservoir. The reservoir was light-tight and instrumented with two layers of 8-inch photomultiplier tubes (PMTs). The top layer consisted of 450 PMTs (the ‘air-shower’ layer) 1.5 m below the water surface and the bottom layer had 273 PMTs (the ‘muon’ layer) 6 m below the surface. Each outrigger tank contained one PMT. The observatory detected VHE gamma rays by detecting the Cherenkov light generated by the secondary particles from the gamma-ray-induced air shower as the secondary particles passed through the water. Various components of the detector were used to measure the direction of the gamma ray and to reduce the background due to hadron-induced showers. Because of its large field-of-view, $\sim 2 \text{ sr}$, and high duty cycle, over 90%, Milagro was well suited to search for burst emission from PBHs.

In this paper we also present the sensitivity of the High Altitude Water Cherenkov (HAWC) observatory to PBH bursts. HAWC, the successor to Milagro, is the next generation VHE observatory presently under construction at Sierra Negra, Mexico at an altitude of 4100 m . HAWC will consist of 300 water tanks, each 7.3 m in diameter and 4.5 m deep. Each tank will house three 8-inch PMTs (reused from Milagro) and one 10-inch PMT [13]. The PMTs will detect Cherenkov light from secondary particles created in extensive air showers induced by VHE gamma rays of energy in the range

94 ~ 50 GeV to 100 TeV. HAWC has two data acquisition (DAQ) systems: the
 95 main DAQ and the scaler DAQ. The main DAQ system measures the arrival
 96 direction and energy of the high-energy gamma-rays by timing the arrival
 97 of particles on the ground. The direction of the original primary particle
 98 may be resolvable with an error of between 0.1 and 2.0 degrees depending
 99 on its energy and location in the sky. The scaler DAQ system counts the
 100 number of hits in each PMT, allowing a search for excesses over background
 101 noise. The scaler DAQ system is more sensitive to lower energy air showers
 102 than the main DAQ system. HAWC has a large field-of-view (1.8 sr corre-
 103 sponding to 1/7 th of the sky) and will have a high duty cycle of greater
 104 than 90%. Thus, HAWC will be able to observe high-energy emission from
 105 gamma-ray transients [14].

106 3. Methodology

107 3.1. Primordial Black Hole Burst Spectrum

108 The properties of the final burst of radiation from a PBH depend on
 109 the physics governing the production and decay of high-energy particles.
 110 As the black hole evaporates, it loses mass and hence its temperature and
 111 the number of particle species that it emits increase until the end of its
 112 evaporation lifetime. In the Standard Evaporation Model (SEM) [11; 15],
 113 a PBH should directly radiate those fundamental particles whose Compton
 114 wavelengths are on the order of the size of the black hole. When the black
 115 hole temperature exceeds the Quantum Chromodynamics (QCD) confine-
 116 ment scale (250–300 MeV), quarks and gluons should be directly emitted
 117 by the black hole [7; 11]. The quarks and gluons will then fragment and
 118 hadronize as they stream away from the black hole, analogous to the jets
 119 seen in terrestrial accelerators [11; 3]. On astrophysical timescales, the jet
 120 products will decay into photons, neutrinos, electrons, positrons, protons
 121 and anti-protons.

122 Detailed studies using the SEM to simulate the particle spectra from
 123 black holes with temperatures of 1 – 100 GeV have shown that the gamma-
 124 ray spectrum is dominated by the photons produced by neutral pion decay
 125 in the Hawking-radiated QCD jets and is broadly peaked at photon energies
 126 of ~ 100 MeV. The photons which are directly radiated (not the result of
 127 decay of other primary particles) are visible as a much smaller peak at a
 128 much higher photon energy proportional to the black hole temperature [11].
 129 As the evaporation proceeds to higher temperatures, the greater will be
 130 the number of emitted fundamental particle degrees of freedom. As new
 131 particle degrees of freedom become available, the luminosity of the burst

will increase. The energy spectrum is determined by the correct high energy particle physics model. In this work, we will assume the SEM as our emission and particle physics model.

For temperatures well below the Planck temperature, the temperature (T) of a black hole can be expressed in terms of the remaining evaporation lifetime (τ) of the black hole (that is, the time left until the black hole stops evaporating) as follows [15; 16]:

$$T \simeq \left[4.8 \times 10^{11} \left(\frac{1\text{sec}}{\tau} \right) \right]^{1/3} \text{ GeV}. \quad (1)$$

The emission rate increases as the black hole shrinks and therefore the remaining evaporation lifetime decreases as T increases. For black holes with temperatures greater than several GeV at the start of the observation, the time integrated photon flux can be parameterized as [16]

$$\frac{dN}{dE} \approx 9 \times 10^{35} \text{ particles m}^{-2}\text{GeV}^{-1} \begin{cases} \left(\frac{1\text{GeV}}{T} \right)^{3/2} \left(\frac{1\text{GeV}}{E} \right)^{3/2}, & E < T \\ \left(\frac{1\text{GeV}}{E} \right)^3, & E \geq T \end{cases} \quad (2)$$

for gamma ray energies $E \gtrsim 10$ GeV. The E^{-3} fall off at $E \geq T$ comes from the $\tau \propto T^{-3}$ dependence in Equation 1, which is less steep than the high energy exponential tail in the instantaneous Hawking spectrum at each T [16]. Figure 1 shows the resulting gamma-ray spectrum for various PBH remaining lifetimes ranging from 0.001 s to 100 s.

3.2. Detectable Volume Estimation

In order to calculate the upper limits on the PBH burst rate density, it is necessary to calculate the PBH detectable volume for a given detector. In general, the expected number of photons detectable by an observatory on the Earth's surface from a PBH burst of duration τ at a non-cosmological distance r and zenith angle θ is

$$\mu(r, \theta, \tau) = \frac{(1-f)}{4\pi r^2} \int_{E_1}^{E_2} \frac{dN(\tau)}{dE} A(E, \theta) dE \quad (3)$$

where f is the dead time fraction of the detector and dN/dE is the black hole gamma ray spectrum integrated from remaining time τ to 0. The values E_1 and E_2 correspond to the lower and upper bounds respectively 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 and HAWC,

Figure 1: Time-integrated gamma-ray spectrum over various PBH remaining lifetimes using the parametrization of Equation 2. The black hole temperature at the start of observation is shown in parentheses.

the dependence of $A(E, \theta)$ on the zenith angle is usually given in discrete bands (represented by θ_i). We will define these bands specifically for a given observatory in Section 4.

The background cosmic-ray flux at the Earth's surface is much higher than the background gamma-ray flux. Most events detected by EAS arrays such as Milagro or HAWC are air showers induced by cosmic rays. To search for the emission from a PBH burst one needs to look for an excess that cannot be explained by statistical fluctuations of the background.

In this paper, we estimate $\mu_o(\theta_i, \tau)$, the minimum number of counts needed for a detection for different burst durations τ , by finding the number of counts required over the background for a 5σ significance (after correcting for multiple trials). First, we calculate the background rates ($R(\theta_i)$) utilizing a Monte Carlo simulation (for HAWC) or actual data (for Milagro). The background rate depends on the spatial bin-size, burst duration and background rejection parameters, as well as the zenith angle band θ_i . In section 4, we optimize these parameters to minimize the background rates and maximize the sensitivity. Using the background rates, we then find the $\mu_o(\theta_i, \tau)$ values required for a 50% probability of detecting a 5σ excess after a given number of trials, based on the Poisson fluctuations of the signal

179 around $\mu_o(\theta_i, \tau)$.

180 We define a 5σ detection after correction for N_t trials to be the number
181 of counts n which would have a Poisson probability P corresponding to a
182 Bonferroni corrected p-value p_c given by

$$p_c = p_o/N_t = P(\geq n|n_{\text{bk}}). \quad (4)$$

183 Here, $p_0 = 2.3 \times 10^{-7}$ is the p-value corresponding to 5σ , $n_{\text{bk}} = \tau R(\theta_i)$ is
184 the number of background counts expected over the burst duration τ , and
185 $P(\geq n|n_{\text{bk}})$ denotes the Poisson probability of getting n or more counts when
186 the Poisson mean is n_{bk} . We take the value of $\mu_o(\theta_i, \tau)$ to be the amount
187 of expected signal which would satisfy this criterion 50% of the time. We
188 find $\mu_o(\theta_i, \tau)$ by estimating the Poisson probability P of finding at least n
189 counts to be 50% according to the relation

$$P(\geq n|(n_{\text{bk}} + \mu_o(\theta_i, \tau))) = 0.5. \quad (5)$$

190 By equating the values of $\mu_o(\theta_i, \tau)$ found from Equation 5 to $\mu(r, \theta_i, \tau)$
191 in Equation 3 and solving for r , we calculate the maximum distance from
192 which a PBH burst could be detected by the high-energy observatory,

$$r_{\text{max}}(\theta_i, \tau) = \sqrt{\frac{(1-f)}{4\pi\mu_o(\theta_i, \tau)} \int_{E_1}^{E_2} \frac{dN(\tau)}{dE} A(E, \theta_i) dE} \quad (6)$$

193 for various zenith angle bands θ_i and burst durations τ . Denoting the effec-
194 tive field-of-view of the detector for a given zenith band by

$$\text{FOV}_{\text{eff}}(\theta_i) = 2\pi(\cos \theta_{i, \text{min}} - \cos \theta_{i, \text{max}}) \text{ sr} \quad (7)$$

195 where $\theta_{i, \text{min}}$ and $\theta_{i, \text{max}}$ are the minimum and maximum zenith angles in
196 band i , the detectable volume is then

$$V(\tau) = \sum_i V(\theta_i, \tau) = \frac{4}{3}\pi \sum_i r_{\text{max}}^3(\theta_i, \tau) \frac{\text{FOV}_{\text{eff}}(\theta_i)}{4\pi}. \quad (8)$$

197 3.3. Upper Limit Estimation

198 If the PBHs are uniformly distributed in the solar neighborhood, the X%
199 confidence level upper limit (UL_X) on the rate density of PBHs bursts (that
200 is, the number of bursts occurring locally per unit volume per unit time)
201 can be estimated as

$$UL_X = \frac{m}{VS} \quad (9)$$

if at the $X\%$ confidence level the detector observes zero bursts. Here V is the effective detectable volume from which a PBH can be detected, S is the total search duration and m is the upper limit on the expected number of PBH bursts given that at the $X\%$ confidence level zero bursts are observed at Earth. Note that for Poisson fluctuations $P(0|m) = 1 - X$ and so $m = \ln(1/(1 - X))$. If $X = 99\%$ and $m = \ln 100 \approx 4.6$, the upper limit on the PBH burst rate density will be

$$UL_{99} = \frac{4.6}{VS}. \quad (10)$$

4. Results

4.1. Milagro Limits on the Rate-Density of PBH Bursts

During the early days of its operation, Milagro had lower angular resolution prior to the addition of the outrigger array and used a triggering system that did not accept many of the low energy events. Thus, for this search we used the last five years of Milagro data: specifically from 03/01/2003 to 03/01/2008. (Due to various detector-related issues, 7% of the data taken during this period was also not used.) Selection cuts were made to increase the quality of the data searched. Reconstructed events which have a predicted angular reconstruction error greater than 2° were rejected. (This corresponds to $n_{fit} > 20$ where n_{fit} is the number of PMTs participating in the reconstruction of the shower.) The maximum zenith angle used was 45° and the best limits were obtained with no gamma-hadron separation cut applied, because such a cut also strongly lowered the Milagro photon effective area at energies below 1 TeV. Overall, our analysis utilized 1673 days (4.58 years) worth of good data, amounting to $\sim 93\%$ of the total Milagro data collected during the five year period (neglecting the dead time). The Milagro search and its optimization presented here are described in further detail in [17].

We performed a blind search (that is, a search utilizing no external triggers) for burst durations ranging from $250 \mu s$ to 6 minutes. First we created skymaps for overlapping time intervals, each offset by 10% of the pre-set burst duration. We then spatially binned the skymap and searched for locations with significant excess over background in the Milagro data. The optimum bin-size was determined using a Monte-Carlo simulation and varied with the pre-set burst duration. For short durations the optimum bin size was of order $\sim 1.8^\circ$ and for long durations it was $\sim 0.8^\circ$: for short durations, Milagro was signal-limited requiring a larger bin-size to accumulate more

237 signal; for long durations, Milagro became background-dominated, requiring
 238 a more restricted bin-size to reduce background contamination.

239 No statistically significant (5σ) event was observed over the 4.58 years
 240 of data. Proceeding on the basis of null detection, we calculated the upper
 241 limits on the PBH burst rate density following the methodology described
 242 in Section 3. For Milagro, we parameterized the effective area as $A(E, \theta_i) =$
 243 $10^{a_i(\log E)^2 + b_i \log E + c_i} \text{ m}^2$ with the parameters a_i , b_i and c_i given in Table 1
 244 for three zenith angle bands. Figure 2 shows the Milagro effective area
 curves for the selected three zenith angle bands.

Zenith Angle Band θ_i	a_i	b_i	c_i
$0^\circ - 15^\circ (\theta_1)$	-0.4933	4.7736	-2.4272
$15^\circ - 30^\circ (\theta_2)$	-0.5037	5.0102	-3.4015
$30^\circ - 45^\circ (\theta_3)$	-0.4273	4.7931	-4.3030

Table 1: Milagro effective area parametrization for various zenith angle bands.

245 We utilized a Monte Carlo simulation to calculate the $\mu_o(\theta_i, \tau)$ values for
 246 various burst durations. Because the trials in our search were not independent,
 247 we took N_t in Equation 4 to be the effective number of independent
 248 trials calculated using the method described in [17]. The effective number
 249 of independent trials ranged from $\sim 0.1\%$ to $\sim 40\%$ of the total number of
 250 trials depending on the search duration, with the shorter search durations
 251 having the lower fraction of effective trials. The dependence of the limit
 252 on the estimated number of independent trials is quite mild ($\sim N_t^{0.018}$) so
 253 that varying the estimated trials by 3 orders of magnitude produces less
 254 than 15% change in the limit. The resulting $\mu_o(\theta_i, \tau)$ values are listed in
 255 Table 2. These $\mu_o(\theta_i, \tau)$ values and the Milagro effective area parameteriza-
 256 tions were then used to derive the maximum detectable distance of a PBH
 257 burst, $r_{\max}(\theta_i, \tau)$, using Equation 6 assuming an energy range of $E_1=50$
 258 GeV and $E_2=100$ TeV and a deadtime of 7%. The derived $r_{\max}(\theta_i, \tau)$ val-
 259 ues were then used to calculate the effective volume that was probed by the
 260 Milagro observatory. Using Equation 10, we calculated 99% upper limits
 261 for various PBH remaining lifetimes and the effective total search period of
 262 4.58 years. Our results are shown in Table 2 and in Figure 3. According to
 263 our results, Milagro is most sensitive to burst durations of about 1 s. For
 264 shorter durations, the Milagro data is starved for signal photons; for longer
 265 durations, the background tends to dominate the signal. We note that Mi-
 266 lagro has a systematic flux uncertainty of $\sim 30\%$ [18] which translates into
 267 an $\sim 50\%$ uncertainty in our calculated limit (shown as a pink shaded band
 268

in Figure 3).

Burst Duration τ (s)	$\mu_{o,\tau}$	UL_{99} ($\text{pc}^{-3}\text{yr}^{-1}$)
0.001	11	3.1×10^5
0.01	16	1.2×10^5
0.1	22	5.4×10^4
1.0	35	3.6×10^4
10.0	65	3.8×10^4
100.0	150	6.9×10^4

Table 2: Counts ($\mu_o(\tau)$) needed over the background for a 5σ detection with 99% probability and calculated 99% confidence upper limits (UL_{99}) for various burst durations (τ) for Milagro.

4.2. Improved HAWC Sensitivity to the Rate Density of PBH Bursts

Milagro’s successor HAWC is located at a higher altitude and features a better detector design, allowing for superior sensitivity to PBH bursts. In this section, we apply our methodology to estimate the HAWC sensitivity to PBH bursts. In our calculations, all relevant characteristics of the HAWC detector are encoded in the effective area. We calculate the effective area using a Monte Carlo simulation which models the interaction of photons and cosmic rays in the atmosphere and the response of the detector to the extensive air showers generated by these particles. The effective area is then defined as the ratio of the number of events that satisfies a given set of cuts to the total number of events multiplied by the total throw area of the Monte Carlo simulation. In our case the Monte Carlo throw area is a circle of 1000m radius. The cuts are comprised of a trigger cut, an angle cut and a gamma-hadron separation cut. For the trigger, HAWC will use events with $nHit$, the number of PMTs hit by the air shower, greater than a certain value. The angle cut is employed to specify the direction of the photons and is a measure of HAWC’s angular resolution. In the simulated events we use an angular parameter $DelAngle$ which is the difference between the true location of the particle in the sky and the reconstructed sky location of the particle. This is a proxy for the angular search bin-size. Because the background is predominantly protons, the angle cut was not used to calculate the HAWC effective area for protons and the gamma-hadron separation cut was used to reduce background events. The standard gamma-hadron separation parameter for HAWC is called compactness and is defined as $nHit/CxPE40$ where $CxPE40$ is the number of photoelectrons recorded in

Figure 2: Effective Area for photon detection for HAWC and Milagro as a function of energy. The Milagro effective area curves use $nHit > 50$, $DelAngle < 1.5$ deg and no gamma-hadron separation cuts. The HAWC effective area curves use $nHit > 100$, $DelAngle < 0.8$ deg and $nHit/CxPE40 > 7$. The HAWC cuts are optimized for the PBH spectrum and utilize an $nHit$ cut that is well above the intrinsic threshold. This and the fact that Milagro used no gamma-hadron cut result in an effective area for Milagro which is larger than for HAWC at low energies. However, HAWC has superior sensitivity in the PBH search.

the strongest hit PMT outside a 40m radius from the reconstructed shower core. The shower core represents the location on the ground where the original particle would have hit had it not interacted with the atmosphere. Figure 2 shows the HAWC effective area $A(E, \theta_i)$ for photons as a function of photon energy and zenith angle band using the optimum cuts for a 10 s burst search ($nHit > 100$, $DelAngle < 0.8$ deg, and with $nHit/CxPE40 > 7$).

In order to estimate the background rate $R_b(\theta, \xi)$ where ξ is a measure of the spatial resolution of HAWC, we used the ATIC cosmic ray spectrum given in Reference [19]

$$\frac{dN_p}{dE} = 7900 \times \left(\frac{E}{1\text{GeV}} \right)^{-2.65} \text{ particles m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1} \quad (11)$$

and convolved it with the HAWC proton effective area for a given zenith

306 angle band,

$$R_b(\theta_i, \xi) = \int_{E_1}^{E_2} \frac{dN_p}{dE} A_p(E, \theta_i) dE \times 2\pi(1.0 - \cos(\xi)) \times 1.2 \quad (12)$$

307 In Equation 12, the $2\pi(1.0 - \cos(\xi))$ term represents the patch in the sky
 308 that corresponds to the spatial resolution of HAWC in steradians. In our
 309 case $\xi = DelAngle$. The factor 1.2 is a correction factor incorporating the
 310 other particle species in the cosmic ray background.

Parameter	Values
$nHit \geq$	30, 70, 100, 150, 200, 250
$DelAngle \leq$	$0.1^\circ, 0.3^\circ, 0.8^\circ, 1.0^\circ, 3.0^\circ, 8.0^\circ$
Compactness $\geq$	1, 2, 3, 4, 5, 6, 7, 8, 9, 10

Table 3: Various parameter cuts used for the simple parameter search.

311 Because we seek the sensitivity in the case where there is no prior knowl-
 312 edge of the burst location, we need to take into account the number of trials
 313 performed for the search. For example, if the HAWC field-of-view (1.8 sr)
 314 is divided into spatial bins of radius 0.7° , then there will be approximately
 315 10^4 spatial bins (trials) per time bin searched. The optimum spatial bin-
 316 size depends on the search duration, the trigger criteria, and the value of the
 317 gamma-hadron separation parameter. The number of time bins is estimated
 318 by dividing the total search period (estimated as 5 years for HAWC) by the
 319 burst duration τ . Thus the total number of trials depends on the burst du-
 320 ration τ , the optimal spatial bin-size $DelAngle$, the trigger criterion $nHit$
 321 and the value of the compactness parameter. In order to find the optimum
 322 set of cuts, we performed a simple parameter search and identified the set
 323 of values which give the best PBH limit according to the method described
 324 in Section 3.

325 For burst durations ranging from 0.001 s to 100 s, we performed cuts
 326 on all parameter combinations given in Table 3 on the Monte Carlo output
 327 and calculated corresponding effective areas for photons and protons. Us-
 328 ing Equations 11 and 12, we then calculated the background rate and the
 329 background number density $n_{bk}(\theta_i, \xi) = \tau R_b(\theta_i, \xi)$ (see Equation 4) which
 330 depends on the zenith angle band and the spatial resolution. As remarked
 331 earlier, the effective number of independent trials differs for each parame-
 332 ter combination. Taking this into account, we have calculated the $\mu_o(\theta_i, \tau)$
 333 values corresponding to burst durations ranging from 0.001 s to 100 s for

Duration τ (s)	nHit	DelAngle (deg)	Compactness
0.001	30	3.0	3
0.01	30	3.0	3
0.1	70	1.0	4
1.0	70	1.0	5
10.0	100	0.8	7
100.0	100	0.8	7

Table 4: Optimized cuts for various burst durations.

334 various zenith angle bands. These $\mu_o(\theta_i, \tau)$ values and the effective area for
 335 photons are then inserted into Equation 6 (with $E_1=50$ GeV and $E_2=100$
 336 TeV) and the maximum distances $r_{\max}(\theta_i, \tau)$ at which a PBH burst can be
 337 detected by the HAWC observatory is calculated for various burst durations
 338 τ assuming negligible dead time. Using these $r_{\max}(\theta_i, \tau)$ values and Equa-
 339 tion 8, we have determined the effective detectable volume $V(\tau)$ for each
 340 burst duration. The PBH limit for each parameter combination was calcu-
 341 lated using Equation 10 and the set of cuts that gives the best limit for a
 342 given burst duration was selected. The resulting optimized parameter cut
 343 values are given in Table 4. The corresponding values of $\mu_o(\theta_i, \tau)$ for a 5σ
 344 detection are given in Table 5 with the associated background counts and
 345 number of trials factor.

346 The final 99% confidence level upper limits on the PBH burst rate den-
 347 sity are given in Table 6, assuming zero PBH bursts are observed over the
 348 5 year HAWC search period. For each burst duration, the maximum de-
 349 tectable distance for zenith angle band θ_1 and the corresponding effective
 350 detectable volume are also shown in Table 6. We note that HAWC sys-
 351 tematic uncertainties have not been included in this study. In Figure 3,
 352 the blue, green, and red thin dashed curves denote the PBH rate density
 353 upper limits that HAWC will set if zero PBH bursts are detected over a
 354 one, two and five year search period respectively. Upper limits based on
 355 earlier null detections from various other observatories are also shown in
 356 Figure 3 [20; 21; 22; 23; 10]. All limits shown in Figure 3 were obtained
 357 based on the PBH Standard Emission Model [11; 6].

Figure 3: PBH Burst Rate Density Upper Limits from Milagro and projected for HAWC, compared with limits from previous direct search experiments [20; 21; 22; 23; 10]. The pink band represents the 50% systematic uncertainty of the Milagro limit. All limits are at the 99% Confidence Level (we have rescaled the reported 95% CL HESS limit to 99% CL) and were obtained based on the PBH Standard Emission Model.

Duration τ (s)	Zenith Angle Band θ_i	Number of Trials	Bgnd. Counts n_{bk}	$\mu_o(\theta_i, \tau)$
0.001	$0^\circ - 26^\circ$ (θ_1)	3.3×10^{13}	0.0637	10.6
0.001	$26^\circ - 37^\circ$ (θ_2)	3.3×10^{13}	0.0240	8.6
0.001	$37^\circ - 46^\circ$ (θ_3)	3.3×10^{13}	0.0083	7.7
0.001	$46^\circ - 53^\circ$ (θ_4)	3.3×10^{13}	0.0026	6.7
0.01	$0^\circ - 26^\circ$ (θ_1)	3.3×10^{12}	0.6372	17.0
0.01	$26^\circ - 37^\circ$ (θ_2)	3.3×10^{12}	0.2397	13.4
0.01	$37^\circ - 46^\circ$ (θ_3)	3.3×10^{12}	0.0832	10.6
0.01	$46^\circ - 53^\circ$ (θ_4)	3.3×10^{12}	0.0256	8.6
0.1	$0^\circ - 26^\circ$ (θ_1)	3.0×10^{12}	0.1355	11.5
0.1	$26^\circ - 37^\circ$ (θ_2)	3.0×10^{12}	0.0456	9.6
0.1	$37^\circ - 46^\circ$ (θ_3)	3.0×10^{12}	0.0144	7.7
0.1	$46^\circ - 53^\circ$ (θ_4)	3.0×10^{12}	0.0036	6.7
1.0	$0^\circ - 26^\circ$ (θ_1)	3.0×10^{11}	1.0481	18.6
1.0	$26^\circ - 37^\circ$ (θ_2)	3.0×10^{11}	0.3422	14.3
1.0	$37^\circ - 46^\circ$ (θ_3)	3.0×10^{11}	0.1055	10.6
1.0	$46^\circ - 53^\circ$ (θ_4)	3.0×10^{11}	0.0251	8.6
10.0	$0^\circ - 26^\circ$ (θ_1)	4.6×10^{10}	2.4405	23.2
10.0	$26^\circ - 37^\circ$ (θ_2)	4.6×10^{10}	0.7039	16.0
10.0	$37^\circ - 46^\circ$ (θ_3)	4.6×10^{10}	0.1912	11.5
10.0	$46^\circ - 53^\circ$ (θ_4)	4.6×10^{10}	0.0451	8.6
100.0	$0^\circ - 26^\circ$ (θ_1)	4.6×10^9	24.4049	51.3
100.0	$26^\circ - 37^\circ$ (θ_2)	4.6×10^9	7.0394	31.6
100.0	$37^\circ - 46^\circ$ (θ_3)	4.6×10^9	1.9118	20.8
100.0	$46^\circ - 53^\circ$ (θ_4)	4.6×10^9	0.4513	14.2

Table 5: Counts $\mu_o(\theta_i, \tau)$ needed over the background for a 5σ detection with 50% probability for various burst durations and zenith angle bands for HAWC.

Burst Duration τ (s)	r_{max} (pc)	Effective Volume $V(\tau)$ (pc^3)	PBH Upper Limit ($\text{pc}^{-3} \text{ yr}^{-1}$)
0.001	0.033	0.000016	56861
0.01	0.044	0.000042	21976
0.1	0.062	0.000092	10038
1.0	0.078	0.000172	5354
10.0	0.089	0.000227	4059
100.0	0.085	0.000191	4822

Table 6: The maximum detectable distance (for zenith band θ_1), the detectable effective volume and HAWC PBH limit in the event of null detection in 5 years for various remaining PBH lifetimes.

5. Discussion

In this work, we report new PBH burst rate density upper limits on parsec scales based on a direct search performed with Milagro data. These new Milagro limits probe various burst timescales previously not investigated. For 1 s bursts, which were probed by numerous earlier experiments, the Milagro limit is now the most constraining. Only the HESS limit at 30 s is more constraining than the Milagro limits. Milagro's successor, the HAWC observatory, will be even more sensitive to PBH bursts. As seen in Figure 3, a null detection from a 5 year search with the HAWC Observatory will set PBH upper limits which are significantly better than the upper limits set by any previous PBH burst search including Milagro. Also note that HAWC will surpass the current HESS best limit for a 30 s burst in one year. According to our study, if a PBH explodes within 0.074 parsec (15,000 AU) of Earth and within 26 degrees of zenith, HAWC will have a 95% probability of detecting it at 5σ (as optimized in a 10 s search after trials corrections). HAWC would see with 95% probability a PBH burst within 37 degrees of zenith if it happens within 0.058 parsec (12,000 AU) of Earth.

Direct search limits are limits on the local distribution of very low mass black holes, regardless of their initial mass or their formation era and mechanism. A 10^9 g black hole has a remaining evaporation lifetime of 1 s and a 7×10^{11} g black hole has a remaining evaporation lifetime of 5 years. It can be shown that the evaporation rate [15] of an individual black hole whose remaining lifetime is much less than the age of the universe implies that the number density function of any population of BHs with present masses $\sim M \ll 5 \times 10^{14}$ g has the form $dn/dM \propto M^2$ around M [24]. From Figure 3, a null detection from a 5 year HAWC search would correspond to an upper limit on the number of local bursts of less than 2.0×10^4 pc $^{-3}$ over 5 years and hence to an upper limit on the local density in 7×10^{11} g or lighter black holes of $\rho(\leq M) \lesssim 5 \times 10^{-18} M_\odot$ pc $^{-3}$. This applies to very small black holes produced in the present universe as well as primordial black holes. This limit is well below the total (visible and dark matter) local dynamical mass density in the solar neighborhood (the Oort limit) determined from Hipparcos satellite measurements, $\rho_{\odot, Oort} = 0.102(\pm 0.010) M_\odot$ pc $^{-3}$ [25], and the local dark matter density in the solar neighborhood, $\rho_{\odot, DM} = 0.008(\pm 0.003) M_\odot$ pc $^{-3}$ [26]. If the present number density function for such small black holes, $dn/dM \propto M^2$, can be extrapolated to black holes of present mass 5×10^{14} g, a null detection from a 5 year HAWC search would correspond to an upper limit on the local density in 5×10^{14} g black holes of $\rho(\leq M) \lesssim 10^{-6} M_\odot$ pc $^{-3}$, five orders of magnitude less than $\rho_{\odot, Oort}$.

397 Direct search limits on the local rate density of PBH bursts are higher
 398 than the average cosmological PBH burst rate density limit implied by the
 399 100 MeV extragalactic gamma-ray background constraint on the emission
 400 of 5×10^{14} g black holes [7; 27]¹. However, PBHs have the gravitational
 401 properties of cold dark matter and so should be clustered in our Galaxy,
 402 enhancing the local PBH burst rate density by many orders of magnitude
 403 over the average cosmological rate [28]. Thus a substantial number of PBHs
 404 that evaporate producing gamma ray bursts may exist in our Galaxy. PBHs
 405 clustered in our Galactic halo should also contribute an anisotropic Galactic
 406 gamma-ray background, separable from the extragalactic gamma-ray back-
 407 ground. Wright claims that such a halo background has been detected [8].
 408 The direct search limits are also weaker than the average Galactic PBH
 409 burst rate density limit on kiloparsec scales implied by the Galactic antipro-
 410 ton background [9] but the antiproton-derived limit depends on the assumed
 411 PBH distribution, the propagation of antiprotons within the Galaxy, and the
 412 secondary antiproton component. Direct search limits are independent of
 413 assumptions concerning the PBH spatial distribution.

414 In deriving the new limits, we have assumed the Standard Evapora-
 415 tion Model in which the Hawking-radiated particles leave the vicinity of the
 416 black hole without substantially interacting with other Hawking-radiated
 417 particles. As shown in detail in [3], the energy of the Hawking-radiated par-
 418 ticles and the time interval between subsequent emissions are such that self-
 419 interactions between the Hawking-radiated particles or their decay products
 420 should not form a QED or QCD photosphere around the evaporating black
 421 hole nor modify the predicted PBH gamma ray burst spectra. However,
 422 if the PBH is embedded in an ambient high density plasma or strong mag-
 423 netic field, interactions may arise with the net effect that the predicted PBH
 424 burst gamma ray spectrum may be enhanced at low energies and decreased
 425 at high energies. Because of the remaining BH lifetime's $\tau \propto T^{-3}$ depen-
 426 dence (see Equation 1), as-yet unknown particle modes manifesting at high
 427 temperatures are unlikely to substantially modify the predicted spectra by
 428 more than a factor of 2. An exception would be the low temperature Hage-
 429 dorn Model in which all of the final burst emission is produced at a black
 430 hole temperature close to the QCD confinement scale, $\Lambda_{QCD} \simeq 250 - 300$
 431 MeV [7]. The low temperature Hagedorn Model would generate a stronger

¹We note that all limits on the expected burst rate derived from the extragalactic or
 galactic gamma ray or antiproton backgrounds have assumed an extrapolation of the form
 $dn/dM \propto M^2$ from masses of 5×10^{14} g down to the very small masses of presently
 bursting PBHs.

burst in gamma rays detectable at lower energies but is not consistent with the QCD behaviour observed in terrestrial accelerators [3].

In conclusion, the HAWC observatory has the ability to directly detect emission from nearby PBH bursts. This capability is scientifically very important, given the large number of early universe theories that predict PBH formation and the uncertainty in the degree to which PBHs may cluster locally. A confirmed direct detection of an evaporating PBH would also provide unparalleled insight into general relativity and high energy particle physics.

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