Searching for primordial black holes with the VERITAS gamma-ray experiment

G Tešić, for the VERITAS Collaboration
1 Department of Physics, McGill University, Montreal, QC, H3A 2T8, Canada
E-mail: gordana.tesic@mcgill.ca

Abstract. Primordial black holes (PBHs) could have been formed in the early Universe from gravitational collapse of matter-energy density fluctuations, collapsing cosmic strings or phase transitions. Setting a limit on the number density of PBHs is important for cosmology, particle physics and quantum gravity. According to some theoretical models, PBHs evaporate and could produce bursts of very-high-energy (VHE; \( E > 100 \text{ GeV} \)) gamma rays which could be seen by detectors on Earth. We present the results from a search in 700 hours of VERITAS data for evidence of gamma-ray bursts due to evaporating PBHs. A new constraint on the number density of PBHs is derived by comparing the VERITAS data with a model prediction.

1. Introduction

Primordial black holes (PBHs) may have been formed in the early history of our Universe from the gravitational collapse of overdense matter-energy regions. Depending on the time of their creation, PBHs can have a wide range of masses, because their initial masses are of the order of the particle horizon mass \( M_h = c^3 t / G \) [1, 2]. It was hypothesized by Hawking [3] in 1974 that black holes with mass \( M \) can radiate elementary particles with a blackbody spectrum of temperature \( T_{\text{BH}} = 1 / (8\pi GM) \) (where \( c = h = k = 1 \)), due to the quantum-gravitational effects occurring in close proximity to the black-hole horizon. The black hole loses its mass due to Hawking radiation as \( \frac{dM}{dt} = -\alpha(M)/G^2 M^2 \) [4], where the number of available degrees of freedom (\( \text{dof} \)) is included in the factor \( \alpha(M) \). As the black hole evaporates, its temperature increases, thus more particle \( \text{dof} \) are available to be radiated. When \( T_{\text{BH}} \) reaches the quantum-chromodynamics energy scale of \( \Lambda_{\text{QCD}} \approx 200 - 300 \text{ MeV} \), free quarks and gluons are emitted, fragmenting further into hadrons, photons and leptons, leading to a non-thermal spectrum for an evaporating PBH. Since there are more \( \text{dof} \) for quark and gluons (72) than for leptons and photons (26), the final spectrum of both leptons and photons originates mostly from the decaying hadrons [5]. The lifetime \( \tau \) of the PBH can be expressed as a function of its initial mass as \( \tau = G^2 M^3 / 3\alpha(M) \), so if PBHs were formed with initial mass of \( \sim 5 \cdot 10^{11} \text{ kg} \), they would be in the final stage of their evaporation at the present epoch.

PBHs are important for probing many current theories, including cosmological models of phase transitions, primordial inhomogeneities and inflationary scenarios, high-energy physics at the highest energy scales, and quantum gravity, as well as the models of gravitational collapse. Our search with the Very Energetic Radiation Imaging Telescope Array System (VERITAS) for evidence of very-high-energy (VHE; \( E > 100 \text{ GeV} \)) gamma-ray bursts from evaporation of PBHs is presented in this contribution.
2. VERITAS experiment

VERITAS is a major ground-based gamma-ray observatory [6] situated at the basecamp of the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona, USA (1.3 km above sea level; 31.68 N, 110.95 W). It is an array of four 12m-diameter imaging atmospheric Cherenkov telescopes (IACTs), capable of detecting VHE gamma rays with energies between 100 GeV and 30 TeV originating from non-thermal processes in various astrophysical environments. The detection method of IACTs is based on recording the Cherenkov light images of electromagnetic cascades that are initiated by gamma rays impacting the upper atmosphere. A detailed description of this technique can be found elsewhere [9].

Each reflector in the array consists of 345 individual hexagonal mirror facets in a Davies-Cotton layout [7], to give a total mirror area of 113 m². In the focal plane of each telescope there is a pixellated camera composed of 499 photomultiplier tubes (PMTs), with a total field of view (FoV) of ~3.5°. The total collection area of the array is approximately 10^5 m². The energy threshold of the experiment of \(E > 100\) GeV is set by the effective area, which falls off rapidly below this energy (see Figure 1). At energies ~1 TeV the energy resolution of the detector is 15% and its angular resolution for a single event (68% containment radius) is 0.1°.

![Figure 1. Effective area plotted versus gamma-ray energy for three different zenith angles: 0° (red), 20° (blue) and 40° (black).](image)

3. Data analysis

3.1. Observational sample and quality data selection

The data used in this study were taken between January 2008 and December 2009 on moonless nights with extremely stable atmospheric conditions (sky temperature in the FoV stable to within 0.15K during each 20-minute observing run). The average dead time was about 10%, leading to a total live time of 700 hours. Due to the dependence of the effective area on the zenith angle of observations, as shown in Figure 1, this data set was subdivided into three different zenith-angle bins, which are listed together with the corresponding live times in Table 1. The main source of background for gamma rays originates from air showers induced by cosmic rays. In order to separate these cosmic-ray events from gamma-ray events, the standard calibration and analysis methods used by VERITAS were applied [10, 11, 12].

3.2. Burst search

A burst is defined as two or more events arriving from the same direction within a short time period \(\Delta t\). The arrival direction is defined by a space window equal to the angular resolution of the array (0.1°). The size of the time window defining a burst depends on the properties of the detector, such as the energy range, background rate and dead time, as well as on models predicting the number of expected bursts. Based on these criteria, a time window of \(\Delta t = 1\) s was chosen for our analysis.

Bursts in the data can also originate from random coincidences. In order to estimate the expected background rate due to such coincidences, the method used in Reference [15] is applied.
Table 1. Zenith-angle bins with corresponding live times for the partial VERITAS data sample used in this work.

| Zenith angle $z$ (°) | Live time (h) |
|----------------------|--------------|
| $z \leq 20$          | 235.02       |
| $20 < z \leq 40$     | 421.89       |
| $z > 40$             | 43.20        |

This method consists of scrambling the arrival times of all events, while keeping their arrival direction unchanged. Bursts found in the scrambled data sample are counted as background. The scrambling procedure is repeated ten times, and the average number of false bursts found is taken as an estimate of the background.

### 3.3. Model predictions

Based on the energy threshold of VERITAS and the energy spectra predicted by various models (e.g. [5, 13, 14]), the model of a non-rotating, uncharged black hole without a chromosphere by MacGibbon and Webber [5] was chosen for estimation of the expected signal at the detector.

The number of predicted gamma-ray events, $N_{\text{th}}$, which can be detected at an angular distance $\theta$ from the centre of FoV during a time period $\Delta t$, from a given PBH at a distance $r$ from the detector, is calculated by convolving the detector response function $A(E, \theta)$ with the model spectrum:

$$
N_{\text{th}} = \frac{1}{4\pi r^2} \int_0^{\Delta t} \int_0^\infty \frac{d^2 N(E, t)}{dEdt} A(E, \theta)dtdE,
$$

(1)

The size of a burst is defined as the number of events belonging to that burst. The total number of bursts of size $s$ that is expected to be observed over a time period $\tau$ is given by:

$$
n_{\text{th}}^{(s)}(\Delta t) = \rho_{\text{pbh}} \tau \int_{\Delta \Omega} \int_0^\infty r^2 P(s, N_{\text{th}})d\Omega dr,
$$

(2)

where $\rho_{\text{pbh}}$ is the number of PBHs evaporation per unit time and unit volume, $\Delta \Omega$ is the solid angle covered by our observations, and $P(s, N_{\text{th}})$ is the probability of detecting a burst of a given size $s$, assuming a model-predicted number of gamma rays $N_{\text{th}}$. This probability is given by a Poisson distribution $P(s, N_{\text{th}}) = e^{-N_{\text{th}}} N_{\text{th}}^s / s!$.

By comparing the predicted number of bursts with the observations, a limit on the number of expected bursts is inferred. That limit is then translated into the limit on the black-hole evaporation rate $\rho_{\text{pbh}}$ by using Equation 2.

### 4. Results

In 700 hours of live time, about ten thousand two-fold and several hundred three-fold coincidence events were found. These numbers are consistent with the expectations from random background. The number of counted bursts was compared to the model prediction over the parameter space $\rho_{\text{pbh}} = [10^3, 10^7]$ pc$^{-3}$yr$^{-1}$ by using an extended maximum-likelihood technique. At each parameter point, the difference $\Delta(-2\ln L) = 2\ln L_{\text{max}} - 2\ln L$ was computed, where $L_{\text{max}}$ is the value of the maximum-likelihood function. The $\Delta(-2\ln L)$ function is shown in Figure 2. From the $\Delta(-2\ln L)$ function, the 99% confidence-level upper limit on the PBH evaporation rate is $\rho_{\text{pbh}} < 1.29 \cdot 10^5$ pc$^{-3}$yr$^{-1}$. This limit is about thirteen times more constraining than the previous VHE limit set using the Whipple 10-m telescope [15] with the same time window of $\Delta t = 1$ s. When analysis of our complete data sample (~ 2200 h) is completed, we can expect
Figure 2. $\Delta(-2\ln L)$ functions plotted versus PBH evaporation rate: all zenith angle bins combined (solid red curve), $z > 40^\circ$ only (dashed black curve), $20^\circ < z \leq 40^\circ$ only (dashed green curve) and $z < 20^\circ$ (dashed blue curve). View this figure in colour.

an upper limit perhaps as low as $\rho_{\text{pbh}} \sim 6 \cdot 10^4 \text{ pc}^{-3}\text{yr}^{-1}$. If steeper PBH spectra were used, our limits would be less constraining (e.g., by almost two and four orders of magnitude, for models [13] and [14], respectively). Recent searches for PBHs have been reported by other VHE experiments, such as H.E.S.S. [16] and Milagro [17], but without the upper limits published.

5. Discussion and Conclusion
We performed a search for gamma-ray bursts due to evaporating PBHs using the VERITAS detector. The measured signal is consistent with background expectations, leading to an upper limit on the PBH evaporation rate of $\rho_{\text{pbh}} < 1.29 \cdot 10^5 \text{ pc}^{-3}\text{yr}^{-1}$. This limit is an order of magnitude lower than the previous VHE limit set using the Whipple 10-m telescope [15]. Tighter constraints are expected from analysis of the full data sample from our experiment. This analysis is in progress.

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