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# Search for primordial black holes with SGARFACE

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ABSTRACT

The short gamma-ray front air-cherenkov experiment (SGARFACE) uses the Whipple 10 m telescope to search for bursts of $\gamma$-rays. SGARFACE is sensitive to bursts with duration from a few ns to $\sim$20 μs and with $\gamma$-ray energy above 100 MeV. SGARFACE began operating in March 2003 and has collected 2.2 million events during an exposure time of 2267 h. A search for bursts of $\gamma$-rays from explosions of primordial black holes (PBH) was carried out. A Hagedorn-type PBH explosion is predicted to be visible within 60 pc of Earth. Background events were caused by cosmic rays and by atmospheric phenomena and their rejection was accomplished to a large extent using the time-resolved images. No unambiguous detection of bursts of $\gamma$-rays could be made as the remaining background events mimic the expected shape and time-development of bursts. Upper limits on the PBH explosion rate were derived from the SGARFACE data and are compared to previous and future experiments. We note that a future array of large wide-field air-Cherenkov telescopes equipped with a SGARFACE-like trigger would be able to operate background-free with a 20–30 times higher sensitivity for PBH explosions.



## 1. Introduction

SGARFACE is designed to detect short bursts of $\gamma$-rays with energies above 100 MeV using the air-Cherenkov technique [1]. The design allows detection of bursts lasting up to $\sim$20 μs and has a directional accuracy of up to a few arc-minutes [2]. Bursts of this type could be produced by the evaporation of primordial black holes (PBH), from emission associated with giant radio pulses from pulsars [3], or by a high-energy component accompanying very short gamma-ray bursts.

Primordial black holes would have been the first objects formed by the gravitational collapse of inhomogeneities in the early universe [4–6]. Inhomogeneities may have resulted from density fluctuations [7] present after inflation [8], the presence of cosmic strings [9,10], collapse of domain walls [11], or from bubble collisions during a phase transition [12]. Consequently, even without a detection, limits on the PBH density provide important insight into many aspects of the physics of the early universe [13], including: cosmological phase transitions [14] and references therein, structure formation [15,16], mass clustering [17], and magnetic monopoles [18].

Three effects have been used to search for PBHs:

(1) *Gravitational effects:* Black holes of mass $\gtrsim 10^{-8}\,M_\odot$ ($2 \times 10^{25}$ g) may be detectable by their gravitational effects in microlensing observations [19,20] or from mass clustering measured with the Ly$\alpha$ forest [15]. A significant number of heavier PBHs may have formed binary systems [21] and may be detected from the gravitational radiation emitted during coalescence. An upper limit on the BH density in the mass range from 0.2 to 1.0 $M_\odot$ has been reported by the LIGO collaboration [22].
(2) *Hawking radiation:* Black holes of mass less than $10^{14}$ g may be detected by their emitted Hawking radiation [23]. Black holes of mass, $M$, emit real particles with a black-body energy spectrum at temperature $T = 1.06(10^{13}\,\mathrm{g}/M)$ GeV [24]. As mass accretion by PBHs is thought to be negligible [25], PBHs will evaporate completely in $10^{64}(M/M_\odot)^3$ years, where $M_\odot \approx 2 \times 10^{33}$ g is the Solar mass. At the present time, black holes with an initial mass of $4.5 \times 10^{14}$ g [26] would be reaching the final phase of their evaporation which might be

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explosive. PBHs that have already evaporated, would have left an imprint on the cosmic particle backgrounds and set stringent limits on the PBH density; a discussion is given in Section 1.1. Lastly, PBHs may also be detectable as transient gamma-ray sources in the solar system [27,28].

(3) *Accretion effects:* The accretion onto light black holes may produce distinct observable radiation in the relatively dense environments of interstellar space, in binary systems, or near planets [29].

The types of particles emitted by Hawking radiation and their energy spectra are well understood below the QCD confinement temperature of $T_c \approx 175^{+5}_{-18}$ MeV [30]. Above this temperature, it is unknown whether individual elementary particles will be emitted in the strong gravitational field, or if a phase transition of the surrounding vacuum occurs and a thermodynamic model of the emission is valid. If the standard particle physics model (SM) is valid at all temperatures, the emission spectra can be determined from the quark-gluon jet-fragmentation functions convolved with the Hawking emission function [24,26]. This would result in a slow evaporation at high temperatures: the final explosion would last about 1 s with $\gamma$-rays of energies above 400 GeV being emitted [31,32]. Twenty-two percent of the total energy would be emitted in $\gamma$-rays with a flux spectrum peaking at ~100 MeV and falling off as $E^{-3}$ at higher energies [26].

On the other hand, in thermodynamic models of the QCD phase transition point, the large number of hadronic resonances implies a large phase space and therefore the final evaporation becomes extremely rapid, resulting in an explosion. The most extreme thermodynamic model is that of [33,34], referred to as the Hagedorn model (HM), where the density of states, $\rho_s$, increases exponentially with mass: $\rho_s \propto m^{-5/2} e^{m/T_c}$. In this picture, the ground state of the vacuum contains elementary and composite particles, which are evaporated by the gravitational field of the PBH. During the final explosion, 10–30% of the mass at $T_c$ is converted into gamma-rays between 100 MeV and 1 GeV; the explosion lasts ~100 ns [27].

Instead of completely evaporating, PBHs may leave behind Planck mass relics, see [13] and references therein. Because of their small mass, Planck relics do not affect $\gamma$-ray emission, but may possibly contribute to dark matter [35,36]. If extra dimensions exist below the currently measured scale of gravity, ~10 μm [37], black hole evaporation would release less detectable energy [38,39].

For SGARFACE, we consider the detection of PBHs via their final-stage $\gamma$-ray radiation in the Hagedorn model. The nominal burst is assumed to come from a black hole of mass $6.5 \times 10^{13}$ g, corresponding to $T = 160$ MeV. It is assumed that 20% of the mass-energy, or $7.5 \times 10^{45}$ eV, is emitted in the form of 1 GeV $\gamma$ rays. Realistically, the $\gamma$-ray spectrum would not be a $\delta$-function, but a product of the direct $\gamma$ emission with the decays from hadrons. It is straightforward to scale the upper limits on the PBH explosion rate presented in Section 3 with the total burst energy and the average energy of $\gamma$-rays, see Section 2.6.

### 1.1. Summary of PBH searches

Limits on the PBH explosion rate have been placed by direct searches for the final-stage emission and require a particular particle physics model. Limits on the PBH density that have been derived from cosmic particle background spectra require an assumed initial PBH mass spectrum. To compare the results, assumptions need to be made on PBH clustering in the galactic halo [31,40,17] and, in the case of charged particle backgrounds, the enhancement due to confinement by the Galactic magnetic field [28].

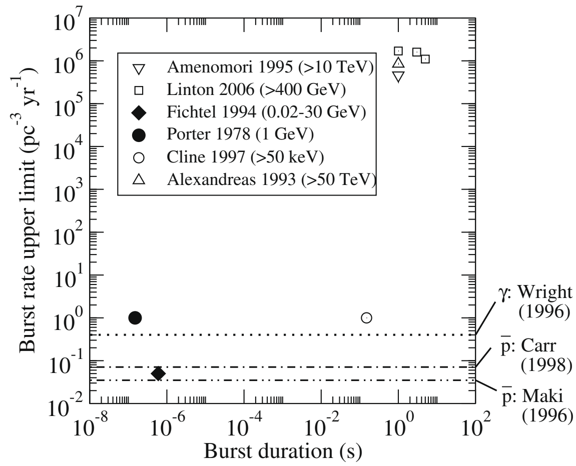


**Fig. 1.** Limits on the density of PBH explosions. Direct-detection limits are at 99% CL, except for [51], and use $\Omega_m = 0.06$. The limits from particle background measurements have possibly large systematic uncertainties associated with them.

Air-Cherenkov telescopes (ACT), due to their large collection area, but small field of view of ~4°, are well suited to search for individual explosions. The sensitivity to detect standard model PBH explosions is limited to distances of 0.4 pc [32], and to about 200 pc for the HM bursts. Upper limits on the explosion rate are shown in Fig. 1, where Hagedorn burst models have been assumed at time scales shorter than 1 μs and SM bursts at longer time scales. The first search for HM bursts was carried out by [41–43], who arrived at an upper limit for bursts of 150 ns duration. The results of their two experiments were carefully reanalyzed using air-shower simulations to characterize the trigger threshold across the field of view. The revised value of their more sensitive, short-baseline, experiment is shown in Fig. 1.

The first search for SM bursts of duration between 0.01 s and 1 s and energy above 7 TeV was carried out by [44] with a pair of scintillation particle detectors separated by 250 km. Several groups, using single or closely spaced detectors, have set limits at other energies and duration [32,45–49]. Some of the limits shown in Fig. 1 were standardized to the same SM burst by [31]. Satellites, though they have a small collection area, are useful in searching for PBH explosions because they are essentially background-free and have a large field of view. EGRET data was searched for multiple $\gamma$-ray tracks within its trigger window of 600 ± 100 ns [50]. Using BATSE data, a possible association of PBH explosions was made with some short (6–200 ms) X-ray bursts on the basis of the spectral evolution and spatial isotropy [51].

The evaporation of PBHs over the lifetime of the universe would have left an imprint on the observed cosmic particle spectra: $\gamma$, $e^{\pm}$, $p$, $\bar{p}$, and $\nu$.[1] The underlying assumption in placing limits on the PBH density using particle backgrounds is that the initial PBH mass distribution arose from scale-invariant density fluctuations [27]. Using the measured anisotropy in the EGRET $\gamma$-ray background above 100 MeV, [40] determined the rate of PBH explosions to be less than 0.07–0.42 pc$^{-3}$ yr$^{-1}$, the confidence level of this upper limit is not given. Of the charged particles, $\bar{p}$ are the most effective in setting limits on the PBH density [28,52], however additional uncertainties on the leakage time out of the Galaxy are introduced. The limit on the PBH explosion rate from the $\bar{p}$ data is (0.011–0.067) pc$^{-3}$ yr$^{-1}$, where $\bar{p}$ are produced by jet-fragmentation. Here, the systematic error due to uncertainties in the halo enhancement may be as large as a factor of two [52]. The most recent and stringent upper limit comes from

[1] We use the following constants: $H_0 = 71$ km/s/kpc, $13.6 \times 10^9$ yr as the age of the universe, and a critical density of $1 \times 10^{-29}$ g/cm$^3$.