New Limit on the Rate-Density of Evaporating Black Holes

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Data taken with the CYGNUS detector between 1989 September and 1993 January have been used to search for 1 s bursts of ultrahigh-energy gamma rays from point sources at arbitrary locations in the northern sky. We find no evidence for such bursts. We set a theory-dependent upper limit on the rate-density of evaporating black holes of 8.5×10^5 pc^{-3}yr^{-1} at the 99% C.L. When the same emission spectrum is used to recalculate previous upper limits based on direct searches, this limit is the most restrictive by nearly 2 orders of magnitude.

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Density fluctuations in the early Universe could have led to the formation of black holes [1]. The black hole mass spectrum and number density are sensitive to the equation of state of the early Universe and the form of the initial density fluctuations [2]. These primordial black holes (PBHs) should be detectable through the Hawking radiation that they emit [3]. The spectrum of Hawking radiation is thermal, with a temperature determined by the surface gravity at the event horizon [$T=(10^{13}/M)$ GeV, where M is the mass of the black hole in grams].

Evaporation of a black hole occurs because all fundamental particles with a rest mass smaller than about 5 times the surface temperature of the hole are emitted as Hawking radiation. The evaporation results in reduced mass, higher temperature, and a luminosity increasing as $1/M^2$. This runaway process is further enhanced by the availability of new emission modes (fundamental particles) as the temperature increases. These processes lead to a lifetime of order $10^{10}(M/10^{15})^3$ yr for PBH masses between 10^{12} and 10^{14} g, assuming only the known particle states [4]. The actual lifetime and particle flux depend on the true number of fundamental particles at energy scales above 100 GeV. Therefore the evaporation of a PBH is sensitive to physics at energy scales that have not been attained in Earth-based accelerators. The observed spectrum is determined by convoluting the fundamental emission spectrum with the quark fragmentation functions [4]. The resulting spectrum is roughly a power law at energies above a few TeV in the last seconds before the explosion. While the absolute number of photons emitted is rather sensitive to the choice of fragmentation model, the shape of the spectrum is not [5].

An upper limit on the original number density of PBHs per logarithmic mass interval (10^4 pc^{-3}) has been set by assuming that the diffuse flux of 100 MeV gamma rays is due to past gamma ray emission by PBHs [6]. While this limit is very restrictive, it cannot be used to set a direct limit on the number of PBHs evaporating at the present time in the solar neighborhood. One needs to make assumptions about the clustering of PBHs that may have occurred on galactic (and possibly more local) scales. If PBHs have clustered like visible matter in the galaxy, the local density could be 10^6–10^7 times higher [4,6]. Then the indirect upper limit on the rate-density of evaporating black holes would be between 1 and 10 PBH evaporations per cubic parsec per year in our galactic neighborhood [6].

A direct search for the final explosive phase of the evaporation can determine the density of primordial black holes in the local solar neighborhood (a few parsecs from the sun). Most previous direct searches for PBHs have been carried out using atmospheric Čerenkov telescopes. While the lower energy threshold of these detectors enables them to probe greater distances, the larger aperture and operating time of an extensive air-shower array allow a larger volume of space to be examined.

We have developed a technique to search for short bursts of ultrahigh-energy (UHE) gamma radiation from an arbitrary direction. We have used this technique to search 3.3 yr of data taken with the CYGNUS air-shower array for 1 s bursts of gamma radiation. The fact that no strong 1 s burst is observed sets an upper limit to the rate-density of evaporating primordial black holes that is 2 orders of magnitude smaller than that of any previous direct search.

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The CYGNUS air-shower array, located in Los Alamos, New Mexico, has been described elsewhere [7]. This paper describes the analysis of $\sim 284\times 10^6$ air showers taken with the CYGNUS-I array between 1989 September and 1993 January. The array consists of 108 scintillation counters (each 1 m^2) deployed over 22000 m^2. For a source at zenith the median primary energy for gamma-ray-initiated events is ~50 TeV, assuming that cosmic gamma rays and protons have similar energy spectra.

A straightforward search strategy employs the binning of the sky spatially, according to the angular resolution of the array, and temporally, according to the expected duration of the burst. In order to obtain good sensitivity to a burst from an arbitrary direction and starting at an arbitrary time, one needs overlapping bins, both in space and in time. Given the angular resolution of the CYGNUS array and the amount of time the array has been operating, there are roughly 10^{12} bins to be examined. Nearly all of these bins are empty.

A more efficient search method allows the events in the data set to determine the bin locations. In this approach, each event defines the center of an angular bin and the beginning of a temporal bin. This binning is as sensitive as the straightforward binned analysis.

The duration of the search window that maximizes the sensitivity to evaporating black holes depends on the energy threshold of the detector and the observed background rate. The optimal search-window duration is determined by maximizing the ratio of the number of source photons emitted above the energy threshold of the detector to the number of events in the window necessary to yield a significant signal. For the CYGNUS array, with a background rate of $\sim 0.02\ \mathrm{s}^{-1}$ in a circular bin of radius 2.1°, the optimal search window is 1 s.

It has been shown [8] that for a small number of expected events in the source bin, N_{exp}, the angular radius of the bin that maximizes the significance of a signal is

$$r_{\mathrm{opt}} = (1.58 + 0.7 e^{-0.88 N_{\mathrm{exp}}^{0.36}})\sigma , \qquad (1)$$

where σ is the angular resolution of the detector. For the case with no *a priori* source location (using the events in the data set to determine the center of each bin), the optimal bin radius is $\sqrt{2}$ times larger. From an analysis of the shadows of the sun and moon we have determined the angular resolution of the array to be 0.7°. A circular bin with radius 2.1° is used for the burst search.

For each interval the expected number of background events is given by

$$N_{\mathrm{exp}} = \int\int\int \epsilon \mathcal{E}(ha,\delta) \mathcal{R}(t) d(\cos\delta) d(ha) dt , \qquad (2)$$

where $\mathcal{E}(ha,\delta)$ is the relative efficiency of the array as a function of the local coordinates, ha (hour angle), and δ (declination) and $\mathcal{R}(t)$ is the event rate during the interval. The parameter $\epsilon = 1$ if ha, δ, and t fall within the source bin and equals 0 otherwise.

The function $\mathcal{E}(ha,\delta)$ is determined for each run, typically 4 h long, from a two-dimensional histogram of the events in the run in the local coordinate system (1° × 1° bins in hour angle and declination). The event rate, $\mathcal{R}(t)$, is determined by counting the total number of detected events within 10 s of the event that determines the beginning of the search window.

For each event in the data set the number of additional events, N_{obs}, arriving within 1 s and within 2.1° of that event is found. This number is compared with the expected number, N_{exp}, and the probability of observing N_{obs} or more events is calculated. The distribution of the probabilities is shown in Fig. 1. The probability distribution expected from random fluctuations of the cosmic-ray background was found by associating the observed event times with the directions of other events [8] and performing the same analysis. This distribution is not shown in the figure because it is indistinguishable from the observed distribution.

Since the typical number of background events is small (~0.01), the discrete nature of the Poisson probabilities is evident. The peaks in the probability distribution correspond to 0, 1, 2, and 3 additional events observed. There were no 1 s intervals with more than 4 events from the same direction in the sky. The pretrial probability of the most significant 1 s interval is 3.2×10^{-8}. After accounting for the $\sim 284\times 10^6$ trials this is not significant. We conclude that there is no evidence in the data set for bursts of 1 s duration from any point in the northern sky.

The expected number of gamma rays detectable by the CYGNUS array from an evaporating black hole at a distance r and zenith angle θ is

$$\mu(r,\theta) = \frac{1-f}{4\pi r^2} \int \frac{dN}{dE} A(E,\theta) dE , \qquad (3)$$

where f is the dead time of the detector (0.09 for the

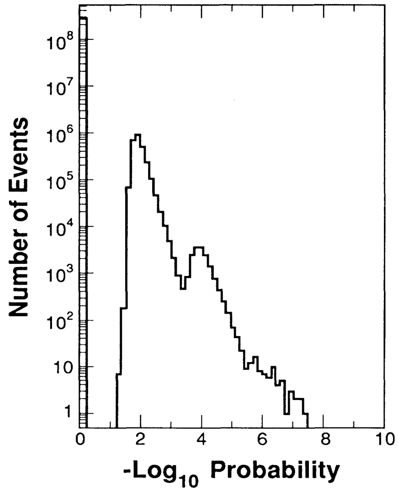

FIG. 1. The probability distribution of all 1 s bursts.

CYGNUS array), dN/dE is the differential source spectrum [4], and $A(E,\theta)$ is the effective area of the array as a function of gamma-ray energy and zenith angle. The function $A(E,\theta)$ is obtained from a simulation of the detector.

An estimate of the volume of space probed by the detector may be obtained by setting μ equal to 1 plus the maximum number of events observed in any of the bins and solving for r as a function of zenith angle θ. This function, $R_{\max}(\theta)$, is shown in Fig. 2. The approximate volume probed is given by integrating $(2\pi/3)R^3_{\max}(\theta)$ over all zenith angles.

To find the actual volume of space probed by a detector one must allow for the Poisson fluctuations about the mean number of detectable gamma rays. These fluctuations enable one to detect the evaporation of PBHs beyond $R_{\max}$. The actual volume probed by the detector is

$$V=2\pi\int_0^\infty r^2\mathcal{P}(r,\theta)dr\,d(\cos\theta)\,, \qquad (4)$$

where $\mathcal{P}(r,\theta)$ is the Poisson probability of observing more than N' events given an expectation of $\mu(r,\theta)$ [as given by Eq. (3)]. N' is the maximum number of events observed $(=4)$ in any of the bins. As the Poisson fluctuations in the signal become small,

$$V\rightarrow 2\pi/3\int R^3_{\max}(\theta)d(\cos\theta)\,.$$

The volume examined by this experiment is 1.64×10^{-6} pc^3. If PBHs are uniformly distributed in the solar neighborhood, the 99% C.L. upper limit to the rate-density of evaporating black holes is $4.6/V/T=8.5\times10^5$ pc^{3}yr^{-1}, where T is the duration of the data set used in this analysis (3.3 yr).

A comparison of this result and previous upper limits is given in Table I. The published upper limits were obtained using various assumptions about the emission spectra. To make a comparison between the previous results and this one, the previous upper limits need to be recalculated using the more modern emission spectrum given by Eq. (16) of Ref. [4]. Without detailed knowledge of each experiment Eqs. (3) and (4) cannot be evaluated. We have estimated the effect of the new emission spectrum on the old results in the following manner. The published results were converted to 99% C.L. upper limits and then multiplied by $(N^a_\gamma/N^b_\gamma)^{-3/2}$. N^a_γ is the number of gamma rays emitted above the energy threshold of the detector in the duration of the search window according to Ref. [4] and N^b_γ is the number assumed in the original publication. The $\frac{3}{2}$ power arises because the distance probed is proportional to the square root of the number of photons emitted, and the volume probed is proportional to the cube of the radius. The present result is nearly 100 times more sensitive than any previous result. While future calculations of the spectrum of gamma radiation may change, the relative experimental sensitivities depend primarily on the shape of the emission spectrum.

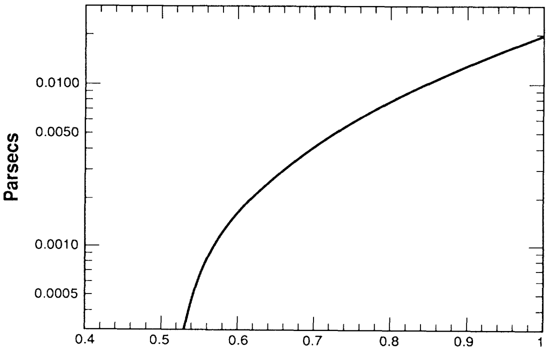

FIG. 2. The maximum distance to an evaporating black hole that is detectable by the CYGNUS array as a function of the cosine of the zenith angle.

TABLE I. Comparison of upper limits on the rate-density of evaporating primordial black holes. The updated upper limits have been calculated with the emission spectrum given in Ref. [4].

Reference	Published Upper limit (pc^{-3}yr^{-1})	Updated upper limits 99% C.L. (pc^{-3}yr^{-1})
[9]	7×10^5	5.4×10^8
[10]	6×10^3	4×10^9
[11]	8.7×10^5	2.3×10^9
[11]	3.0×10^4	8.0×10^7
[12]	2.7×10^3	7.2×10^8
[13]	2.3×10^4	2.1×10^8
[14]	1.0×10^4	1.7×10^8
This result	⋯	8.5×10^5

We have developed a technique to search for short bursts of UHE radiation from an arbitrary direction in the overhead sky. This technique has been applied to a search for 1 s bursts of UHE gamma radiation. We find no evidence for any such burst in 3.3 yr of data. The absence of a significant burst of 1 s duration allows us to set an upper limit to the rate-density of evaporating black holes of 8.5×10^5 pc^{-3}yr^{-1}. While this limit is ~5 orders of magnitude larger than the indirect limit obtained from the diffuse 100 MeV gamma-ray flux, no assumptions on the clustering of PBHs are made. Our upper limit is 2 orders of magnitude smaller than that obtained with the best previous direct search. An extensive air-shower array with an energy threshold of ~500 GeV, such as the proposed MILAGRO detector, could improve upon this upper limit by roughly 3 orders of magnitude.

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