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A New Limit on the Rate–Density of Evaporating Black Holes

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Abstract

Data taken with the CYGNUS detector between 1989 and 1993 have been used to search for 1 second bursts of ultra-high energy (UHE) gamma rays from any point in the northern sky. There is no evidence for such bursts. Therefore the theory-dependent upper limit on the rate-density of evaporating black holes is $6.1 \times 10^5 pc^{-3} yr^{-1}$ at the 99% C.L.. After renormalising previous direct searches to the same theory, this limit is the most restrictive by more than 2 orders of magnitude.

1. INTRODUCTION The evaporation of black holes, first predicted by Hawking, arises from the application of quantum field theory in the curved space-time near a black hole [1, 2, 3]. The evaporation takes the form of particle emission near the event horison with a consequent decrease in the mass of the black hole. Elementary particles with a mass ~less than the surface temperature of the black hole are emitted. Particle fragmentation and decay processes (in addition to the direct emission of photons) lead to the emission of high energy (100 GeV - 100 TeV) gamma radiation.

We have searched for 1 second bursts of UHE gamma radiation from any point in the overhead sky. The burst duration was chosen to maximise the sensitivity to the evaporation of primordial black holes.

2. THE CYGNUS EXPERIMENT The CYGNUS air shower array, located in Los Alamos, NM, has been described elsewhere [4, 5]. This paper describes the analysis of ~280 million events taken with the CYGNUS-I array since 1989 September. The median primary energy for gamma-ray-initiated events is 50 TeV at the zenith.

3. SEARCH TECHNIQUES AND RESULTS 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 resolution of the CYGNUS array and the length of time the array has been operating, roughly 1 trillion bins need to be examined. Nearly all of these 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 optimal in the sense that it is as sensitive as a straightforward binned analysis would be with an infinite number of overlapping bins.

It has been shown [6] 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

$$r_{opt} = (1.58 + 0.7e^{-0.88 N_{exp}^{0.16}}) \times \sigma, \tag{1}$$

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. The angular resolution of the detector is 0.7° and $N_{exp} \sim 0.02$ therefore a circular bin with radius 2.1° is used for this search.

The search window that maximizes the sensitivity to evaporating black holes depends on the energy threshold of the detector and the observed cosmic-ray 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, the optimal search window for directions near the zenith is 1 second.

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

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

where $E(ha, \delta)$ 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 ϵ is 1 if ha, δ, and t are such that they fall within the source bin and 0 otherwise.

The function $E(ha, \delta)$ is determined for each run, typically 4 hours long, from a 2-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 events that occurred within 10 seconds of the burst. While integration over longer time periods yields a smaller statistical uncertainty in the determination of $\mathcal{R}(t)$, systematic effects become dominant.

For each event in the data set the number of events, N_{obs}, arriving within 1 second and within 2.1° of the event is found. This number is compared with the expected number, N_{exp}, and the Poisson probability of observing N_{obs} or more events is calculated. The distribution of the probabilities is shown in Figure 1. Since the typical number of expected events is small (~ 0.02) the quantisation of the Poisson probabilities is evident. The most significant excess observed has a post-trials probability of 17%. We conclude that there is no evidence in the data set for strong bursts of 1 second duration from any point in the northern sky.

4. UPPER LIMIT TO THE RATE-DENSITY OF EVAPORATING BLACK HOLES

The maximum distance to an evaporating black hole that is detectable, as a function of zenith angle, θ, is given by

$$R_{max}(\theta) = \left[\frac{1}{4\pi n_{det}(\theta)} \int \frac{dN}{dE} A(E, \theta) dE \right]^{\frac{1}{2}}, \tag{3}$$

where $n_{det}(\theta)$ is the minimum number of detected air showers necessary to establish a signal, $\frac{dN}{dE}$ is the differential source spectrum [7], and $A(E, \theta)$ is the effective area of the array as a function of gamma ray energy and zenith angle. We determine n_{det} by requiring a signal with a chance probability smaller than 10^{-1} after accounting for the roughly 280 million trials (events) involved in the search. At zenith, $n_{det} = 5$ and at a zenith angle of 45°, $n_{det} = 3$. The effective area of the array $A(E, \theta)$ is found from simulation. The function $R_{max}(\theta)$ is shown in Figure 2.

Integration of $R_{max}(\theta)$ over all zenith angles yields a volume of 2.3×10 [illegible] pc^{3} over which the array is sensitive to the evaporation of primordial black holes. The data set spans 3.3 years. Since we observed no candidate sources, the 99% C.L. upper limit to the rate-density of evaporating black holes is $6.1 \times 10^5 pc^{-3} yr^{-1}$.

Table 1 gives this result and previous results. The previous upper limits were obtained using various assumptions about the emission spectra. To make a direct comparison of the previous results and this one, we have also recomputed the previous upper limits using the more modern emission spectrum given in equation 16 of reference [7]. This was done by converting the published results to 99% C.L. upper limits and then multiplying them by $(N_\gamma^{frag}/N_\gamma^{pub})^{-3/2}$. N_γ^{frag} is the number of gamma rays emitted above the energy threshold of the detector in the duration of the search window according to reference [7] and N_γ^{pub} is the number assumed in the original publication. The 3/2 power arises because the radius 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 probed. As can be seen from the table, the present result is 130 times more sensitive than any previous result. While future calculations of the spectrum of gamma radiation may change, the relative sensitivities of the of the experimental results given in Table 1 depend only on the spectral index of the emission.

Reference	Published Upper Limit ($pc^{-3}yr^{-1}$)	Updated Upper Limit 99% C.L. ($pc^{-3}yr^{-1}$)
[8]	7×10^7	5.4×10^8
[9]	6×10^4	4×10^9
[10]	8.7×10^5	2.3×10^9
[10]	$3. \times 10^4$	$8. \times 10^7$
[11]	2.7×10^4	7.2×10^8
[12]	2.3×10^4	2.1×10^8
[13]	$1. \times 10^4$	1.7×10^8
This Result		6.1×10^5

5. CONCLUSIONS

We have developed a new technique for searching for short bursts of UHE radiation from any point in the overhead sky. This technique has been applied to a search for 1 second bursts of UHE gamma radiation. We find no evidence for any such burst in 3.3 years of data. The absence of a significant burst of 1 second duration allows us to set an upper limit on the rate-density of evaporating black holes of $6.1 \times 10^5 pc^{-3} yr^{-1}$. This is a factor of 130 smaller than the previous best upper limit.

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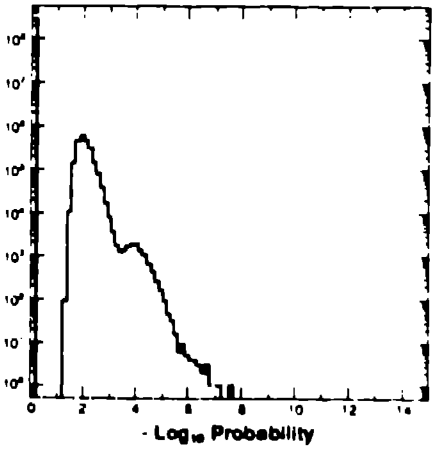

Figure 1. The differential probability distribution of all 1 second intervals

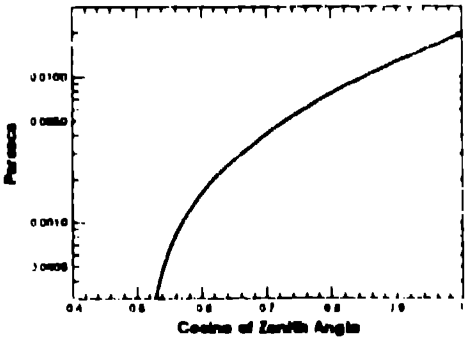

Figure 2: Maximum distance to an evaporating primordial black hole that is detectable as a function of cosine of the zenith angle.

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