CASA-MIA: A "Precision" EAS Detector

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ABSTRACT

The CASA-MIA detector was constructed to search for sources of UHE neutral radiation. As such it has established limits well below those of previously reported observations and of most contemporaneous detectors. In addition to its primary mission, however, CASA-MIA measures the lateral distribution of both electrons and muons in EAS throughout a range of energies and with a degree of sampling not previously available.

INTRODUCTION

Located on the U.S. Army's Dugway Proving Ground (40.2° N, 112.8° W, 870 g-cm^{-2}) CASA-MIA is composed of two separate but closely coupled detectors, the Chicago Air Shower Array (CASA)[1] and the Michigan Muon Array (MIA)[2]. CASA consists of 1089 scintillation detectors distributed uniformly on a 15 m grid. Encompassing nearly 0.25 km^2 CASA samples showers from well below 100 TeV to nearly 10^{17} eV. MIA is comprised of 1024 scintillation counters divided into 16 widely separated "patches". This earth shielded array, totalling more than 2500 m^2 active area, measures the penetrating component of EAS.

The 1089 stations of CASA operate in a highly autonomous fashion; each contains four separate scintillation counters and the electronics necessary to measure the arrival time of the shower front and its density. Two or more counters within a station must fire in coincidence before the station participates in an event. A participating station exchanges fast-timing signals with its four nearest neighbors; the relative time of arrival of the shower front between adjacent stations is measured in this manner. Lead placed atop each station is used to convert gamma rays within the shower to $e^{\pm}$ pairs.

MIA is a somewhat more conventional detector in that signals from each of the counters are brought to a common central location. The time at which each muon counter fires is measured relative to a stop provided by the surface array. The arrival time of the shower front is reconstructed at each counter to to $\pm$ 60 ns. The estimated threshold for MIA's counters is $\sim$ 750 MeV. No pulse-height information is provided by the muon array.

The CASA-MIA detector is complemented by a four element steerable Cerenkov telescope and by the University of Utah's HiRes EeV atmospheric fluorescence detector. These instruments provide a measure of both the Cerenkov component and the longitudinal development of a portion of the events observed by CASA-MIA.

ANALYSIS PROCEDURES

Analysis begins with determination of the shower core location and arrival direction (Figure 1 indicates the density and timing distribution for an atypical event). The core location is calculated using one of several methods depending upon the number of stations participating in the event and whether or not the core fell within the array. (The efficacy of these methods have been verified by artificially imposing an array boundary on otherwise contained showers, an approach which is greatly simplified by CASA's large size and absolute uniformity.) Typical errors for cores falling within the array range from ± 2.2 m for small showers down to ± 0.5 m for the largest observed showers. The arrival direction is determined by fitting a cone of fixed slope (0.075 ns-m^{-1}) to the shower front. The angular resolution, expressed as the half angle of a cone containing 63% of the showers incident from a point source (σ_{63}), has been estimated by (among other methods) an analysis of the shadowing of the isotropic flux of cosmic rays by the Sun and Moon. The result indicates that CASA's angular resolution is typically 1.2° improving to 0.5° with increasing shower size.

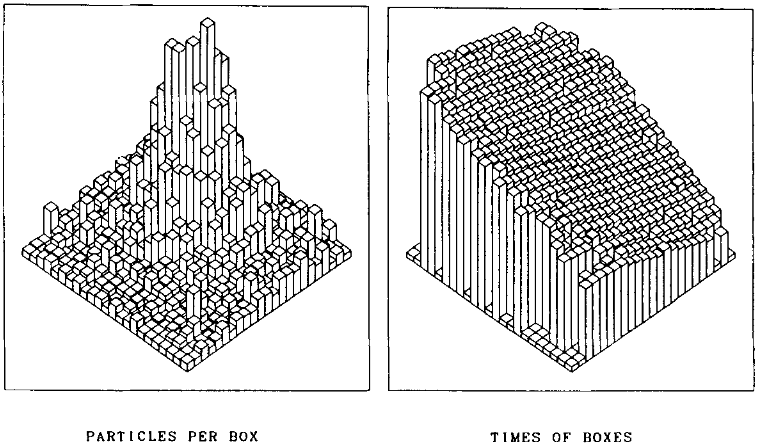

Figure 1: The particle density and time-of-arrival distribution for a large shower. The estimated primary energy is $\sim 2 \times 10^{16}$ eV.

An estimate of the shower size is made by performing a maximum likelihood fit to the Nishimura-Kamata-Greisen function (Figure 2). The effects of triggering, of saturation, and of accidentals to the observed densities are all incorporated into the fit. Similarly, the shower's muon content is determined by a fit to the Greisen distribution. Here also the effects of saturation and of accidentals are taken into account. For the data discussed herein (obtained during the construction phase when the arrays were approximately one-half their present size) the mean reconstructed shower size is ~ 38500 electrons. The muon size is ~ 3150 in a typical shower.

Determination of the primary's energy is based on a parameterization of the reconstructed size versus overburden (i.e. zenith angle and pressure). This parameterization was derived by means of the "constant intensity technique" wherein the measured integral flux above a particular size is equated to previously measured values of the all particle cosmic ray flux (Figure 3). Corrections are incorporated for the mixed primary composition. CASA detects 75% of the vertical proton showers incident above 69 TeV. For sources which culminate overhead the median energy of detected gamma rays (assuming a spectrum similar to that of the background) is 137 TeV. The detection efficiency for gamma rays from such a source is $\sim$ 75% above 65 TeV.

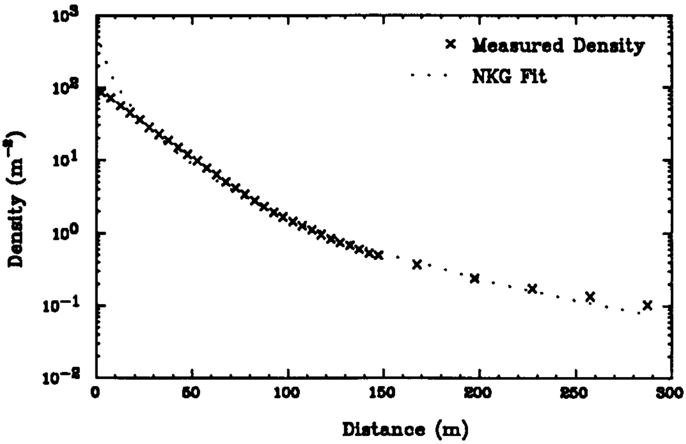

Figure 2: A fit of the NKG distribution to the observed particle density (note saturation near the core). The estimated shower size is $\sim 4.2 \times 10^5$.

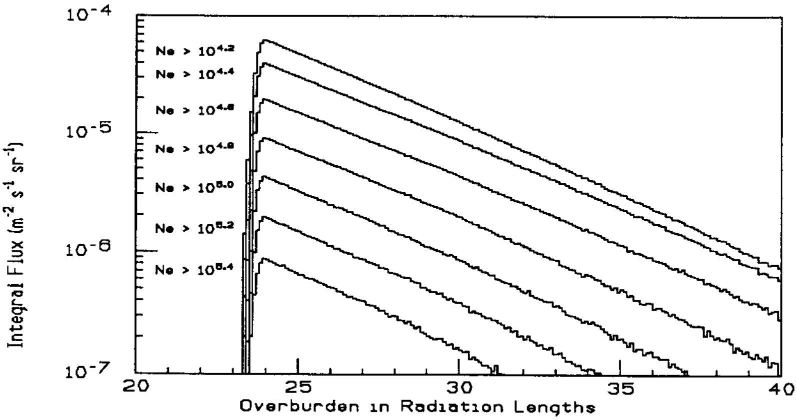

Figure 3: The measured absolute flux for showers of various sizes as a function of overburden (zenith angle).

The expected number of muons ($N_{\mu exp}$) for showers of a particular size and zenith angle are determined from a large number of background events with observed muon number (N_μ). R_μ, the ratio of the log of $N_\mu/N_{\mu exp}$ is indicated in Figure 4. Showers with R_μ less than zero are in a relative sense muon poor. The precise value of R_μ at which to place a cut depends on the expected response of the detector to gamma ray initiated showers and hence on Monte Carlo simulations. For these analysis showers with one-quarter the expect number of muons were identified as muon poor gamma ray candiates; more than 90% of the background is eliminated while retaining approximately 70% of gamma ray initiated showers.

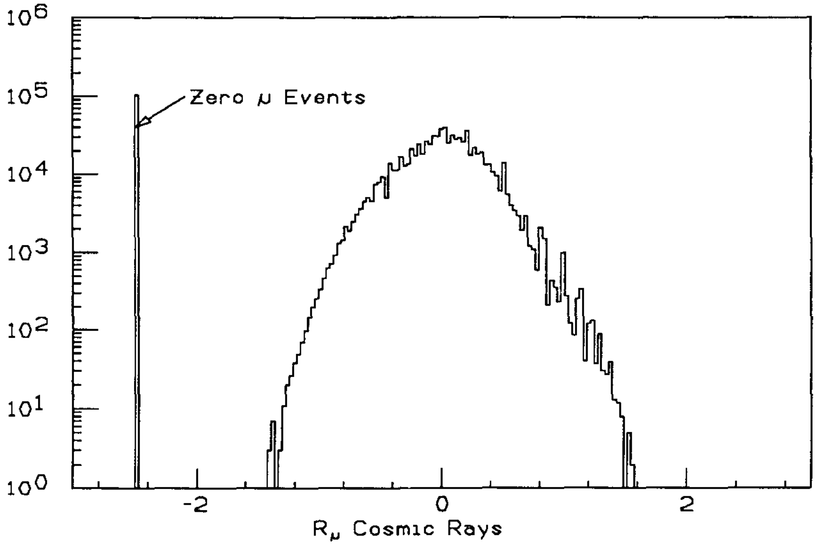

Figure 4: The distribution of Log(Observed muon size/Expected muon size); events having zero detected muons are as indicated.

Both the detector acceptance and an estimate of the background are obtained daily from the data itself, thus automatically incorporating the effect of varying observing conditions (e.g. pressure).

THE SEARCH FOR UHE NEUTRAL RADIATION

Data obtained from January 31, 1990 through January 30, 1991 have been searched for evidence of neutral UHE emission from three point sources: Cygnus X-3, Hercules X-1, and the Crab nebula/pulsar[3,4,5]. During this period both CASA and MIA were under construction and operating at approximately one-half their present size. Nonetheless, more than 280 million events were obtained. These data were subjected to minimal integrity cuts (e.g. valid UTC recorded, arrival direction and shower size successfully reconstructed) after which 240 million events remained. A muon poor sub-set of the data was defined as those events containing less than $\sim$ 23% of the expected number of muons. Results of this analysis are indicated in Table 1; no evidence exists for a significant excess in either the all (uncut) data set or the muon poor sub-set.

	E_{median} (TeV)	All Data	Muon Poor
Cygnus X-3	190	1.9×10^{-13}	7.9×10^{-14}
Hercules X-1	190	6.6×10^{-14}	3.4×10^{-14}
Crab Nebula	240	7.4×10^{-14}	2.2×10^{-14}

Table 1: Upper limits for continuous emission for both the all data set and the muon poor sub-set (cm^{-2}-s^{-1}).

These results for Cygnus X-3 are presented in Figure 5 in the context of previous observations and upper limits.

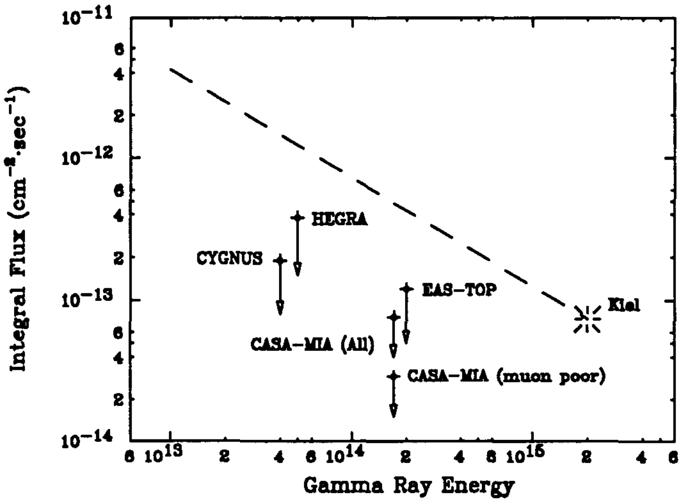

Figure 5: Reported observations and upper limits for the flux of neutral radiation from Cygnus X-3. An E^{-1} integral spectrum is indicated.

CONCLUSION

Based on one year of data CASA-MIA has established upper limits from a number of astrophysical objects well below those previously possible. An additional 700 million events have been obtained to date and are presently undergoing analysis. CASA-MIA is now logging events at a rate of over 20 Hz; more than 740 million additional events each year.

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