

# RECENT RESULTS FROM THE CASA-MIA EXPERIMENT

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## ABSTRACT

Results from the CASA-MIA cosmic ray experiment are presented. I discuss the apparatus and its performance, including new results on the identification of the shadows of the sun and moon used to determine the angular resolution. Limits on the emission of 100 TeV  $\gamma$ -rays from the Crab Nebula are well below extrapolations from TeV observations. A search for diffuse  $\gamma$ -rays from the Galactic plane give limits approaching some recent predictions.

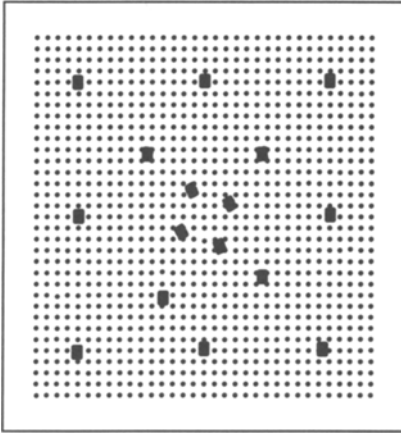
## INTRODUCTION

The Chicago Air Shower Array (CASA) and Michigan Muon Array (MIA) comprise a large cosmic ray air shower detector which was built primarily to search for astrophysical  $\gamma$ -rays with energies exceeding about 100 TeV. It is located at Dugway, Utah, at the site of the Fly's Eye installation (40.2°N, 112.8°W, mean atmospheric depth 870 g/cm<sup>2</sup>). CASA measures the size and direction of air showers while MIA samples the muons. Air showers initiated by  $\gamma$ -rays are expected to have far fewer muons than showers from ordinary (hadronic) cosmic rays of similar energy. We greatly reduce the cosmic ray background when searching for  $\gamma$ -rays by selecting showers with unusually low muon content.

The apparatus is shown in Figure 1 and fully described elsewhere<sup>1</sup>; we give a brief summary here. CASA has 1089 stations uniformly arranged on a square grid with 15 m spacing, enclosing  $2.3 \times 10^5$  m<sup>2</sup>. Each station has four plastic scintillators totaling 1.44 m<sup>2</sup> and is covered by one radiation length of lead. Fast timing information is exchanged between neighboring stations. Data are transmitted to a central computer via an ethernet network where triggers are formed.

MIA is composed of 1024 counters arranged in 16 groups or "patches" of 64 counters each. It is the largest muon detection array ever employed in an air shower experiment. Each counter is a 0.64 cm thick plastic scintillator with an area of 2.5 m<sup>2</sup>. The counters are buried under 3m of earth in order to select muons. Punch-through of air shower electrons is negligible. MIA does not participate in the formation of event triggers for  $\gamma$ -ray astronomy.

The energy threshold  $E_0$  is defined here as the  $\gamma$ -ray energy at which the array trigger is 75% efficient. For vertical  $\gamma$ -rays we estimate  $E_0 \approx 65$ TeV. The observed cosmic ray trigger rate is about 24 Hz. CASA-MIA has recorded nearly  $2 \times 10^9$  events since beginning operation in 1990.



**Figure 1** Arrangement of the CASA-MIA array. The grid points show the locations of the 1089 CASA surface stations. The grid spacing is 15m. The darkened rectangles indicate the sixteen patches of MIA buried muon counters. Each muon patch has 64 separate counters. Several facilities at the site are not shown, including four tracking Cerenkov telescopes, a pair of imaging Cerenkov telescopes, and the Fly's Eye II installation at the center of the array. The HiRes Fly's Eye prototype is 3.3 km to the southwest of the center.

## ANALYSIS AND RESOLUTION

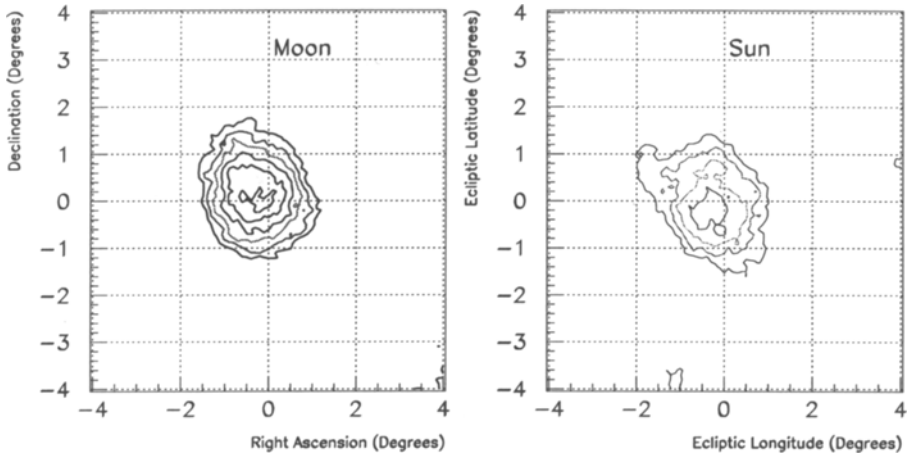
Triggered events are reconstructed in order to determine the size and direction of the shower<sup>1,5</sup>. The lateral distributions of surface particles, mostly electrons and photons, are fit to a standard NKG form which gives an estimate of the total size (related to the primary energy). The muon densities are separately fit to a Greisen function. The shower direction is reconstructed by determining the shower front geometry using the surface array timing information.

For purposes of UHE  $\gamma$ -ray astronomy, we evaluate the muon size of showers by comparing to the average muon size of showers of similar total size and direction. Specifically, we construct the quantity  $R_\mu = \log N_\mu - \langle \log N_\mu \rangle$  where  $N_\mu$  is the reconstructed total muon size. An equivalent quantity,  $r_\mu$ , is computed the same way using the observed number of muon counter hits. A cut for  $\gamma$ -rays accepts "muon poor" events with  $R_\mu$  or  $r_\mu < -1.0$  (i.e., showers with less than about a tenth of the average number of muons). This cut retains most  $\gamma$ -rays while rejecting the vast majority hadronic events.

One of several means of estimating the directional resolution of our analysis is to make use of an interesting effect first proposed by Clark<sup>2</sup>. The sun and moon will block the passage of UHE cosmic rays and so cast a type of "shadow" on earth. We have observed deficits in the intensity of events from the directions of both the sun and the moon. Using a larger data set than recently published<sup>3</sup>, the shadows are shown in Figure 2.

The statistical significance if the lunar deficit is about  $7\sigma$  and that of the sun about  $5\sigma$  with respect to the expected intensity. The sun's deficit is slightly less than that of the moon and is somewhat less circular. This is qualitatively expected because of the effects of the solar magnetic field.

The sun's shadow also appears slightly offset from the true position. While not statistically significant, we note that the offset is in the same direction



**Figure 2** Deficits in the number of events collected from the direction of the moon and the sun. Contours express the statistical significance of the deficit, in units of Gaussian  $\sigma$ , with respect to the expected cosmic ray intensity. Contours begin at  $2\sigma$  significance and increment in  $1\sigma$  steps.

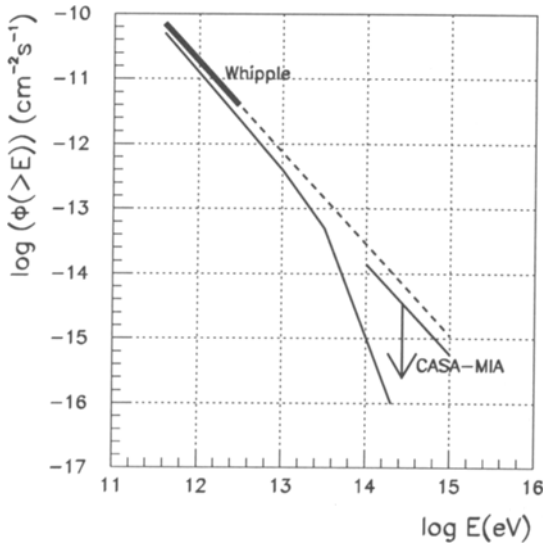
as that recently reported by the Tibet group<sup>4</sup> (in pre-1992 data). However, great care must be exercised when comparing results from different experiments. Solar magnetic effects are very complex. The structure of the solar field is both geometrically intricate and variable in time. Comparison of our results to that of the Tibet group must await more concurrent data.

Examination of the deficits confirms our estimates of the pointing accuracy of our reconstruction techniques. Angular resolution is defined here as  $\sigma_{63}$ , the angle within which 63% of the events from a point source will reconstruct. We find  $\sigma_{63} \approx 1.0^\circ$  for showers of median size, improving to  $0.5^\circ$  for larger events.

### POINT SOURCE SEARCHES

Observations of ultra-high energy (UHE)  $\gamma$ -rays from objects such as x-ray binaries have been interpreted in the past as signatures of the location of cosmic ray accelerators. CASA-MIA has not observed any emission from previously reported objects<sup>5</sup>. Upper limits on the intensity of emission are well below previous reports. There have been no conflicting observations by other experiments during the era of CASA-MIA operation. It is possible that sources of UHE  $\gamma$ -rays have time-varying intensity and may not be visible at this time.

The Crab Nebula is the only confirmed Galactic source of  $\gamma$ -rays above 1 TeV<sup>6</sup>. CASA-MIA has not seen UHE  $\gamma$ -rays from this object and our limits are below a simple power law extrapolation of the lower energy results (Figure 3). Thus it appears that the  $\gamma$ -ray spectrum is becoming steeper at higher energies. Such behavior is in qualitative accord with some recent models<sup>7</sup> of inverse-Compton acceleration processes in the Nebula. Note that these models



**Figure 3** Upper limits on  $\gamma$ -ray emission (90% CL) from the Crab Nebula, based on analysis of muon-poor events. The heavy solid line is the measurement at TeV energies by the Whipple group<sup>6</sup>. The dashed line is a power law extrapolation from the Whipple result. The solid line approximately represents a recent model of deJager and Harding<sup>7</sup>.

do not involve an underlying hadronic accelerator, i.e. a source of cosmic rays.

### DIFFUSE GAMMA RAYS

Regardless of whether there are point sources of UHE  $\gamma$ -rays, there will be a flux of photons which arise as secondary products of the interaction of ordinary cosmic rays on interstellar gas and dust. This so-called diffuse flux should appear over broad sky regions with intensity that varies with density of material along the line of sight. Diffuse  $\gamma$ -rays with energies beyond about 10 GeV have not yet been observed.

If diffuse UHE  $\gamma$ -rays can be found, it would be the first observation to explore the distribution of UHE cosmic rays throughout the Galactic volume. It would also provide the first verification that UHE  $\gamma$ -rays do indeed yield muon-poor air showers.

Discrimination of  $\gamma$ -ray showers from the hadronic background using muons is a particularly powerful tool in this search. The method has been described elsewhere<sup>8</sup>. We compare the distribution of relative muon size for events which originate from the galactic plane to those which come from other parts of the sky. As shown in Figure 4, there is no discernable excess of muon-poor showers from the galactic plane.

The data used here have more than  $10^9$  events. To reduce the effects of uncertainty in the absolute intensity of cosmic rays, we express the result in terms of the ratio of fluxes  $J_\gamma/J_{CR}$ . Our results imply that  $J_\gamma/J_{CR}$  is well below  $10^{-4}$ ; Figure 4 shows upper limits (90% CL) on this quantity as a function of  $\gamma$ -ray energy. Also shown is a recent theoretical prediction<sup>9</sup>. We anticipate that

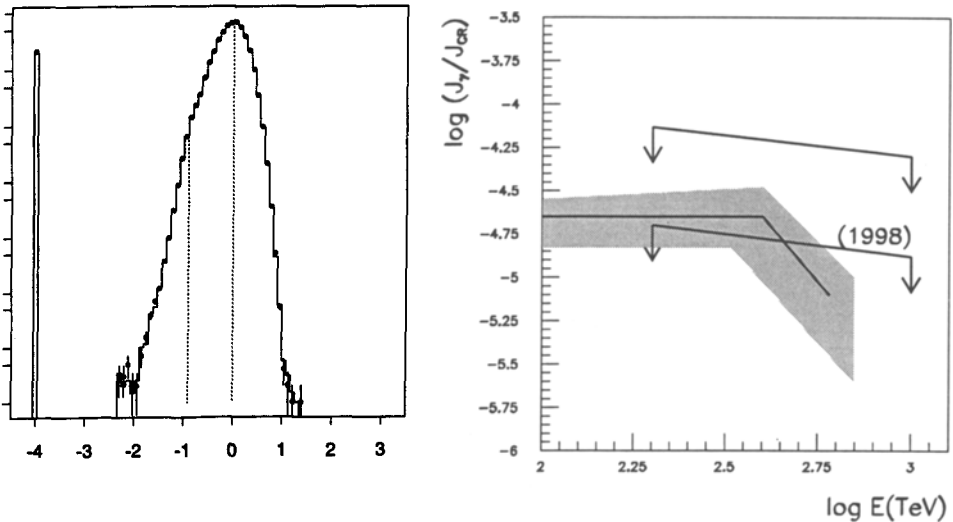


Figure 4 Left, the distribution of relative muon size  $\tau_\mu$  for events within  $5^\circ$  of the plane of the Galaxy (points) and the expected background derived from the data (histogram). Right, upper limits (90% CL) on Galactic diffuse gamma ray emission, expressed as the logarithm of the fraction of  $\gamma$ -rays relative to the cosmic ray flux. The “1998” curve shows the anticipated improvement with 4 more years of data, assuming continuous operation of the array. The shaded region indicates a recent prediction<sup>9</sup> (with uncertainties) for the Galactic diffuse gamma ray flux.

we will be able to identify diffuse Galactic  $\gamma$ -rays within a few more years of operation.

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