A SEARCH FOR DIFFUSE GAMMA RAYS WITH ENERGIES ABOVE 10^{14} eV FROM MOLECULAR CLOUDS IN THE GALAXY

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ABSTRACT

Diffuse gamma-rays from molecular clouds are excellent tracers of cosmic rays in the galaxy over a wide range of energies. For example, diffuse emission detected by EGRET already places significant constraints on the spectrum and origin of galactic cosmic rays at GeV energies. Likewise, by measuring diffuse gamma rays with ground-based air shower experiments, we can probe the galactic distribution of cosmic rays in the energy regime above 100 TeV.

The Chicago Air Shower Array (CASA) which operates in coincidence with the Michigan muon array (MIA) is the world's most sensitive experiment to gamma-rays with energies $\gtrsim$ 100 TeV, and is well-suited for studies of diffuse sources based upon the muon content of air showers. We describe a search for diffuse gamma-ray emission from molecular cloud regions observed by CASA-MIA. If we assume that the flux of cosmic rays is uniform in the galaxy, then we predict that diffuse emission will probably be detectable by CASA-MIA within the lifetime of the experiment. Furthermore, if there are sources of cosmic rays in close proximity to certain molecular clouds, then the spectrum of gamma-rays from these clouds will be stronger and harder. By searching for such enhancements in the diffuse emission, and by correlating the CASA-MIA results with emission detected at lower energies by EGRET, we may identify or constrain the nature of cosmic rays sources in both energy regimes.

INTRODUCTION

The primary scientific aim of the CASA-MIA experiment has been to investigate the long standing puzzle of the origin of cosmic rays with energies above 10^{14} eV. While there exist plausible models for generating the cosmic rays with energies below 100 TeV, the origin of ultrahigh energy (UHE) cosmic rays above 100 TeV remains unknown. Large ground-based air shower experiments, such as CASA-MIA, can be used as telescopes to search for UHE gamma-rays from potential sources of cosmic rays. Gamma-ray emission should accompany the acceleration of cosmic rays. And while charged cosmic ray nuclei will be deflected by the irregular magnetic fields of the galaxy, gamma-rays will propagate in a straight line directly from the source. Research in this field has thus far primarily been directed towards searches for continuous, periodic, and episodic gamma ray emission from point sources such as Cygnus X-3 and Hercules X-1. During the early 80's there were several reports by previous smaller experiments that these compact objects might be significant sources of gamma rays at 10^{15} eV. Unfortunately, no such point sources have been detected by CASA-MIA (in data collected from mid-1989 through April 1991), nor by other large area arrays (such as CYGNUS) operating since the mid-80's. Based upon the CASA-MIA data gathered thus far, we can already conclude that the bulk of the UHE cosmic rays do not originate from a small number of bright galactic point source accelerators (see McKay, *et al.*, 1993). Therefore, we are now pursuing other approaches to study the origin of UHE cosmic rays, including searches for extragalactic sources and a search for galactic diffuse sources.

Gamma ray emission from diffuse gas clouds is an important tracer of cosmic rays in the galaxy, and can be used to probe the origins of cosmic rays of energies ranging from 100 MeV to 500 TeV or more (*e.g.*, Hunter and Kanbach, 1991). We expect a diffuse flux of gamma rays from regions of concentrated hydrogen gas density, such as the galactic plane and giant molecular clouds. In these regions, the permeating flux of high energy cosmic rays will interact with the gas to produce new hadronic particles, including neutral pions, which subsequently decay into gamma rays.

THE CASA-MIA DETECTOR

When ultrahigh energy (UHE) cosmic rays and gamma-rays strike the upper atmosphere of the earth, they produce large cascades of electromagnetic and hadronic particles. At ground level, the showers consist largely of electrons, photons, and muons. A sparse array of detectors sampling even a fraction of the shower particles can determine the total number of particles in the shower and the arrival direction of the primary particle with reasonable precision. The combination of the Chicago Air Shower Array (CASA) and the Michigan Muon Array (MIA) comprise the largest and most sensitive such array built to date.

The CASA experiment consists of 1089 scintillation detectors laid out on a square grid of 15m spacing (**Figure 1**). The experiment is located at Dugway, Utah (40.2°N, 112.8°W). The total collection area of the experiment is roughly 230,000 m^2.

At the Dugway site, beneath CASA, we have constructed a very large array of buried muon counters – the Michigan Muon Array (MIA). This array consists of 1024 scintillation counters buried 3 meters below ground level. The counters are grouped into sixteen "patches" and have a total scintillator area of 2500 m^2.

In showers initiated by cosmic ray nuclei, muons are produced from charged pion and kaon decay in the central hadronic core. Showers initiated by gamma-rays do not produce muons in significant quantities because the cross section for γ-air hadroproduction is much smaller than the cross section for electron-positron pair production (γ-air $\rightarrow e^+e^-$). Extensive simulations predict that the number of muons in 100 TeV gamma-ray showers is twenty to fifty times less than the number in cosmic ray showers of the same energy.

EXPERIMENTAL TECHNIQUE

To search for diffuse concentrations of cosmic gamma rays, we employ the technique developed by Matthews *et al.*, (1991). We search for gamma ray emission by looking for a localized excess of cosmic rays which are muon-poor with respect to the number of muons expected from hadron-initiated showers.

Detected muons are fit to a Greisen lateral distribution to determine the total number of muons (muon size) for each shower. We parameterize the muon content by the quantity:

$$R_\mu \equiv \log_{10} \frac{(N_{\mu\_obs})}{(N_{\mu\_exp})}, \qquad (1)$$

where N_{μ_obs} and N_{μ_exp} represent the muon size actually observed and the muon size *expected* for hadronic showers. Since most gamma-ray induced showers will have significantly fewer muons, we expect that the R_μ distribution for gamma rays will be shifted relative to hadron showers.

To determine if there is evidence for gamma ray emission from a localized candidate source region of the sky, we examine the distribution of R_μ for showers within some "on-source" region, and we search for an excess of muon-poor events. The excess is determined relative to some comparison "off-source" region which presumably contains a background of uniformly hadronic showers. To compare the R_μ distributions from source and background regions, we normalize so as to match the total number of events with $R_\mu > 0.0$, assuming that all such events are purely hadronic.

Figure 2 demonstrates the application of this technique to real data for a preliminary analysis presented in Borione *et al.*, 1993. The R_μ distribution for candidate diffuse source events within the galactic plane ($b_{II} = \pm 5°, 50° < \ell_{II} < 200°$) is plotted against the R_μ for the off-source background region. Analysis of residuals, (χ^2_ν =1.07, ν = 64 d.o.f., see **Figure 3**) shows no significant difference between the source and background distributions, and gives us confidence that the systematics have largely been removed. Remaining systematic fluctuations are likely due to binning effects which we expect to scale with the statistical errors.

CASA-MIA SENSITIVITY TO DIFFUSE EMISSION

Figure 4 shows the current and projected CASA-MIA sensitivities to diffuse flux from molecular clouds in the plane of the galaxy. Results through 1991 (163 million events) were already reported by Covault *et al.*, 1991. Flux sensitivities for 1993 are based on an analysis of over 700 million events, as reported in Borione *et al.*, 1993. **Table 1** shows the current flux limits obtained for several candidate regions. These flux limits represent the most sensitive search for UHE diffuse emission that has been achieved thus far.

The predicted flux limit for 1998 is a conservative extrapolation of the sensitivity achievable over the lifetime of the CASA-MIA experiment, assuming that there are no changes or improvements to the muon rejection system and that there are no unanticipated sources of systematic error. We note that because the muon rejection efficiency increases with energy, the sensitivity of CASA-MIA to diffuse emission is relatively flat in the region from 200 to 500 TeV.

We predict that during the 5 to 10 year lifetime of the experiment, CASA-MIA is likely to detect the combined diffuse flux from the plane of the galaxy. If there are indeed regions of enhanced diffuse flux, then CASA-MIA may detect this emission in the near future. In fact, CASA-MIA can already rule out a naive extrapolation of the diffuse spectra seen in the COS-B satellite data by Bloemen (1991) and will place strong constraints on any spectral hardening coming from the outer part of the galaxy during the lifetime of the CASA-MIA experiment.

Searches for diffuse emission at 100 TeV are also likely to be improved and complemented by observations of diffuse emission at 1 GeV by the EGRET experiment aboard the Compton GRO spacecraft. In particular, if there are regions of stronger-than-expected diffuse emission at 1 GeV, then these regions may be in proximity to sources of cosmic rays at these energies. If future measurements indicate that enhancements of diffuse emission detected at GeV energies are spatially correlated with enhanced emission at ultrahigh energies then this would be evidence that the sources of cosmic rays within both energy regimes are associated.

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Candidate source region	Galactic coordinates l^{II}	b^{II}	Area (deg²)	Median energy (TeV)	Significance (σ)	I_γ/I_{CR} 90% CL (10^{-4})
Galactic plane		±1°	–	190	-0.2	2.4
				260	-0.5	2.2
				350	+0.8	2.0
Galactic plane		±5°	–	190	+0.9	1.11
				260	-0.1	1.00
				350	+0.2	0.93
Galactic plane		±10°		190	+0.8	0.79
				260	+0.6	0.71
				350	+0.3	0.66
CAS OB6	135°	2°	25	220	-0.3	9.4
				320	-0.7	8.4
				420	+1.4	7.9
PER OB2	157°	-21°	25	150	+1.7	8.9
				220	-0.7	8.0
				290	+0.1	7.5
Cygnus region	80°	3°	25	150	+0.0	8.0
				220	+0.2	7.2
				290	+1.2	6.8
Taurus region	172°	-15°	100	180	-1.8	4.7
				240	-1.6	4.2
				350	-2.8	3.9
SNR G78.2+2.1	78°	2°	4	150	+2.3	23
				220	+1.4	21
				290	+0.3	20

Table 1: Current results from CASA-MIA on the search for diffuse emission from several candidate regions. No significant excesses have been detected from any candidate source region. Results for the galactic plane are the most sensitive limits obtained thus far. G78.2+2.1 is a supernova remnant in the vicinity of a molecular cloud (See Drury *et al.*, 1993).

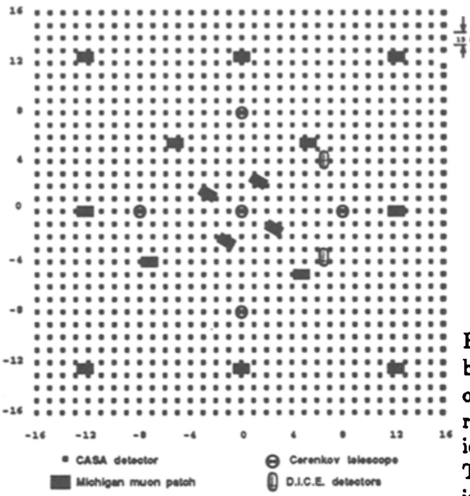

Figure 1: The UMC (Utah-Michigan-Chicago) air shower detector facility at Dugway, Utah. Each small point on the regular grid represents one of 1089 surface stations (CASA). Also shown are the underground muon counters (MIA) arranged in 16 patches.

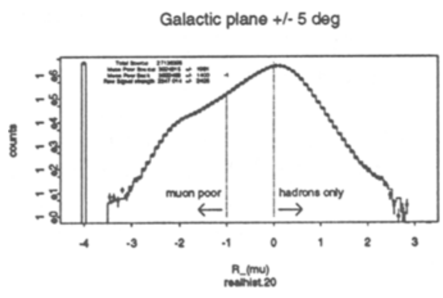

Figure 2: $R\mu \equiv \log(N_\mu(\text{observed})/N_\mu(\text{expected}))$ distribution for CASA-MIA (UMC) events within 5 degrees of the galactic plane (points with errors) compared against the background distribution (solid line histogram). To reduce systematics, the background was sampled only from off-plane events with the same distribution of local sky coordinates (Az-El) as the source events.

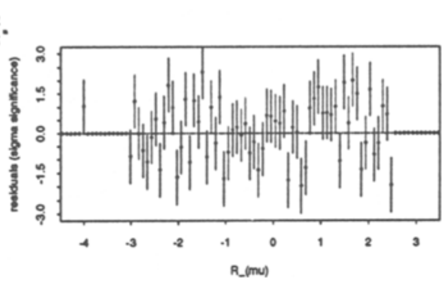

Figure 3: Residual differences between source and background distributions events within 5 degrees of the galactic plane. Residuals are shown as a ratio of events (top) and in terms of sigma significance differences (bottom) on a bin-by-bin basis. The reduced Chi-squared (χ^2_ν), is ~ 1.07, indicating that the systematics of the background are not large compared to the fluctuations expected from background statistics alone. There is no evidence of excess muon poor events above a fraction of 10^{-4}.

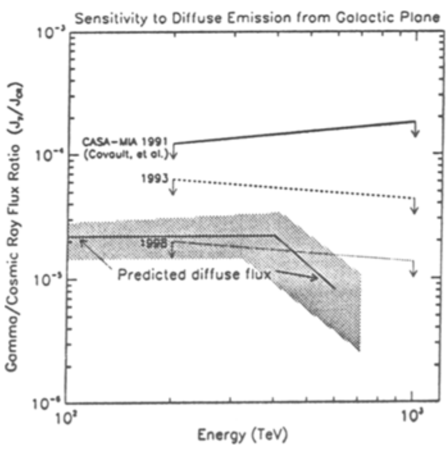

Figure 4: Projected CASA-MIA sensitivity to diffuse gamma ray emission from the central plane of the galaxy ($b_{II} = \pm 5°, 50° < \ell_{II} < 200°$). Sensitivities are given in terms of the fraction of gamma rays relative to the detected all-particle flux of cosmic rays at the earth. The prediction for the gamma ray flux is derived by Aharonian (1991). The CASA-MIA flux limits (90% confidence) are indicated assuming continuous operation of the array.