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100 TeV Observations of the Cygnus Region by CASA-MIA

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Abstract: The Cygnus arm of the galaxy contains a large number of energetic astrophysical sources, including numerous supernova remnants, pulsar wind nebulae, and X-ray binary systems. Indeed, in terms of potential galactic sources needed to explain the origin of the high energy cosmic rays, Cygnus is the most promising region accessible to northern hemisphere observatories using the air shower or atmospheric Cherenkov techniques. This paper reports results from observations of the Cygnus region by the CASA-MIA detector, operating from 1990 to 1997. Consisting of a large air shower array of 1089 detectors covering an area of $0.23\,\mathrm{km}^2$, CASA-MIA was the largest and most sensitive experiment built to study sources of 100 TeV radiation. Results are presented based on an extended survey of Cygnus, covering the important regions of interest to very high energy astronomy.

Introduction

Cosmic ray particles span a remarkable range of energies, from the MeV scale to more than 10^{20} eV. At energies above 1 TeV, we know that cosmic rays do not originate from local sources in or nearby our Solar System. Therefore, these high-energy particles must come from acceleration sites in the Galaxy at large or from outside the Galaxy. Remarkably, after many years of research, the exact sites of high-energy cosmic ray acceleration remain mysterious.

Efforts to pinpoint the origins of these particles are hampered by the fact that they are largely electrically charged and are thus deflected in the inhomogeneous magnetic field of the Galaxy, reaching Earth with a very isotropic arrival distribution. It is natural to search for neutral radiation (e.g. gamma rays or neutrinos) from point sources which would signal possible acceleration sites.

Supernova remnants (SNRs) in our Galaxy are generally regarded as the most likely source of high-energy cosmic rays. The putative production mechanism involves the acceleration of particles in the shock fronts formed as the remnant propagates outward, sweeping up material from the interstellar medium. SNRs are attractive candidate sources because they appear to have the power budget necessary to produce and replenish the cosmic rays and because shock acceleration can naturally produce the power-law distribution of particle energies that is observed. Indeed, recent detection of TeV gamma rays from a number of supernova remnants have strengthened their case as very high energy (VHE) particle accelerators, but we are not yet fully certain which particles are the dominant species being accelerated (i.e. electrons, protons, or nuclei).

Other possible galactic sources of high-energy particles include pulsars and pulsar wind nebulae (PWN), compact binary systems (microquasars), OB associations, Wolf-Rayet stars, etc. The survey by the HESS atmospheric Cherenkov telescope array of the central region of the Galactic plane has been very successful and has discovered more than two dozen galactic sources of TeV gamma-radiation [2]. Many of these sources can be plausibly associated with SNRs and PWN, but there are also many unidentified objects.

In the northern hemisphere, a survey by the HEGRA Cherenkov telescope revealed an unidentified VHE gamma-ray source, TeV J2032+4130, in the Cygnus region of the Galactic plane [3]. Quite recently, the Milagro water Cherenkov detector reported evidence for the emission of gamma rays at a median energy of 20 TeV from several regions of the Galactic plan [4,5]. Three of these potential sources, MGRO J2019+37, MGRO J2031+41, and MGRO J1908+06, have a statistical significance greater than $4.5\,\sigma$ after accounting for the trials involved in the search. The first two sources are located in the Cygnus region. For the brightest source, MGRO J2019+37, the non-detection of TeV gamma-ray emission at $<$ 10% Crab level by HEGRA could well imply a relatively hard source spectrum (dN/dE $\sim$ E^{-2}) in order to explain the Milagro result [6].

The various results discussed above strongly motivate continued, and expanded, exploration of the Galactic plane at energies from 100 GeV to 100 TeV. In particular, the Cygnus region of the Galaxy is a very attractive target for northern hemisphere telescopes. At the lower energies, the new atmospheric Cherenkov telescopes VERITAS and MAGIC should carry out the most sensitive observations of this region during the next few years. At higher energies, results have come from the Tibet AS-γ Observatory, the Cygnus air shower array, and the CASA-MIA experiment [7]. The published CASA-MIA results are based on only the first $\sim$ 20% of the data collected by the experiment. Also, analysis was based on a general all-sky survey technique and was not designed to specifically focus on the Galactic plane. Here we present preliminary results from a re-analysis of the full CASA-MIA data set that concentrates on the Cygnus region of the Galactic plane.

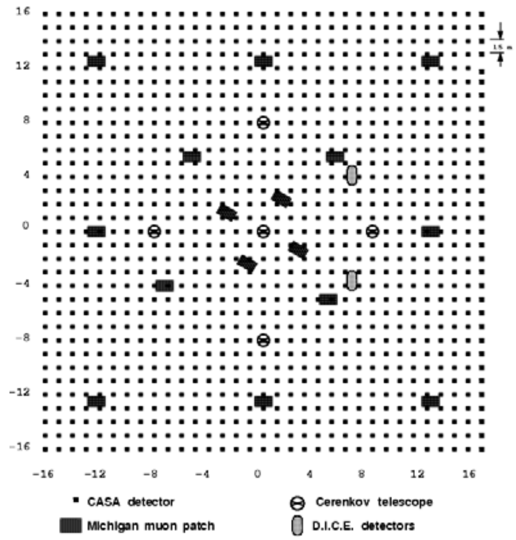

Figure 1: Plan view of CASA-MIA cosmic ray experiment. The CASA and Michigan muon detectors are discussed in the text. The Cherenkov telescopes and DICE detectors were not used in this analysis.

The CASA-MIA Experiment

The CASA-MIA experiment was located at Dugway, Utah, USA (40.2°N, 112.8°W, 1450m a.s.l.); it consisted of two major components: the Chicago Air Shower Array (CASA), a large surface array of scintillation detectors, and the Michigan Array (MIA), a buried array of scintillation counters sensitive to the muonic component of air showers.

CASA comprised 1089 detectors placed on a 15 m square grid and covering an area of 0.23 km^2. MIA consisted of 1024 counters located beneath CASA in 16 patches. The total active area of MIA was 2400 m^2 and the counters were buried at a depth of $\sim$ 3.5 m yielding a muon energy threshold of approximately 0.8 GeV. Figure 1 shows a plan view of the CASA-MIA experiment as completed.

A complete description of CASA-MIA and its performance characteristics can be found elsewhere [8]. Briefly, the shower size is estimated from the number of surface detectors struck, the shower core from the location of the maximum particle density, and the shower direction from the surface detector timing information. The mean number of struck CASA stations is 19 and the mean shower size is approximately 25,000 equivalent minimum ionizing particles. Shower cores are determined with a statistical accuracy of better than 8 m. The shower direction is measured with a single event angular resolution that varies with shower size. The angular resolution is $\sim 1.5^\circ$ for small showers and it improves to $< 0.4^\circ$ for large showers.

The number of detected muons is determined from those muon counters hit within a narrow time window (width $\sim$100 ns) around the expected arrival time. The average number of real muons recorded is 8.5 per event and the average number of accidental muons is 0.63 per event.

Air showers created by gamma-ray primaries are expected to contain far fewer muons than showers initiated by cosmic rays. We therefore use the detected muon content of the shower to reject a substantial portion of the cosmic-ray background. We define the relative muon content, of a specific shower, r_μ, by the logarithm of the ratio of the observed muon number to the expected number of muons for showers having similar zenith angles, core positions and number of CASA stations hit. The cut on r_μ to select gamma-ray showers, and also the quality factor associated with the cut, depends on the number of CASA stations hit. For the overall data set, the sensitivity of CASA-MIA improves by a quality factor of 2.9 from cutting on the shower muon content.

The energy response of the experiment is determined by the constant intensity method, which is described in more detail in [9]. The median energy of the detected showers depends on the declination of the source region. Sources in the Cygnus region transit nearly overhead and have median gamma-ray energies in the 115-120 TeV range.

Summary of Observations

The data used for this analysis were taken between March 4, 1990 and August 10, 1995, with a gap of 255 days in 1991. The experiment had usable data on 1627 days and an instrumental deadtime of approximately 5.4%. Calibration runs taken at the start of data runs, losses due to tape backup failures, and downtime for array maintenance leads to the reduction in the livetime to 1378 days ($\sim$ 85% of the total).

To ensure data integrity, we impose a comprehensive set of data quality cuts on a run-by-run basis and on an event-by-event basis. For data in which we only use information from the surface array (*all data*), the final sample consists of 1.93×10^9 reconstructed events. For data in which we use information from both the surface and muon arrays (*muon data*), the final sample consists of 1.60×10^9 reconstructed events. By comparison, the data sample used in [7] consisted of 3.5×10^8 reconstructed events.

Results

The analysis of the CASA-MIA data for the Cygnus region of the Galactic plane is ongoing. The results will be presented at ICRC 2007.

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