Ultra High Energy Cosmic Ray Research with CASA-MIA

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Abstract

Ultra high energy (UHE) cosmic rays are particles reaching Earth that have energies greater than 10^{14} eV [1]. These particles are produced in astrophysical sources that are sites of extreme particle acceleration but because they are largely charged, they bend in the magnetic field of the Galaxy and their directional information is scrambled by the time they reach Earth. Thus, even after many years of research, the origin of these particles remains a profound mystery.

Starting in 1985, Jim Cronin developed the idea for a large air shower array to search for and detect point sources of gamma rays at these energies. The idea was to build a powerful enough detector to definitively establish the existence of gamma-ray point sources and to hence determine the origin of the ultra high energy cosmic rays. This idea became the Chicago Air Shower Array – MIchigan muon Array (CASA-MIA). During the decade between 1987 and 1997, CASA-MIA was constructed and was successfully operated. It remains the most sensitive cosmic-ray observatory ever built at these energies. This talk describes the CASA-MIA experiment: its scientific motivation, its development, construction and operation, and its scientific results and legacy.

1 Scientific Motivation for CASA-MIA

Cosmic rays were discovered in 1912 by Victor Hess during balloon experiments carried out in Austria. Hess flew in an open-air balloon to altitudes of 5 km and discovered an increasing ionization of the air with increasing altitude rather than a decreasing one [2]. This result argued for a penetrating radiation entering the Earth's atmosphere from above. Many years of research followed the initial discovery of cosmic rays, with much of it connected to the Enrico Fermi Institute and the University of Chicago. We now know that cosmic ray particles are mostly charged nuclei that arrive isotropically at Earth. As shown in Figure 1, the particles span a remarkable range of energies, from the MeV scale to more than 10^{20} eV. At the higher energies above 10^{12} eV ($= 1$ TeV), we know that they do not originate from sources in or nearby our Solar System, but instead must come from acceleration sites in the Galaxy at large or from outside the Galaxy. Remarkably, after almost a century of research, the exact sites of high-energy cosmic ray acceleration remain unknown.

Several difficulties hamper efforts to pinpoint the origins of h igh-energy cosmic rays. First, since most cosmic rays are electrically charged, any information contained in the directions of the particles arriving at Earth is lost due to deflection in the Galactic magnetic field (see Figure 1). A second difficulty relates to the energetics of the mechanisms for their

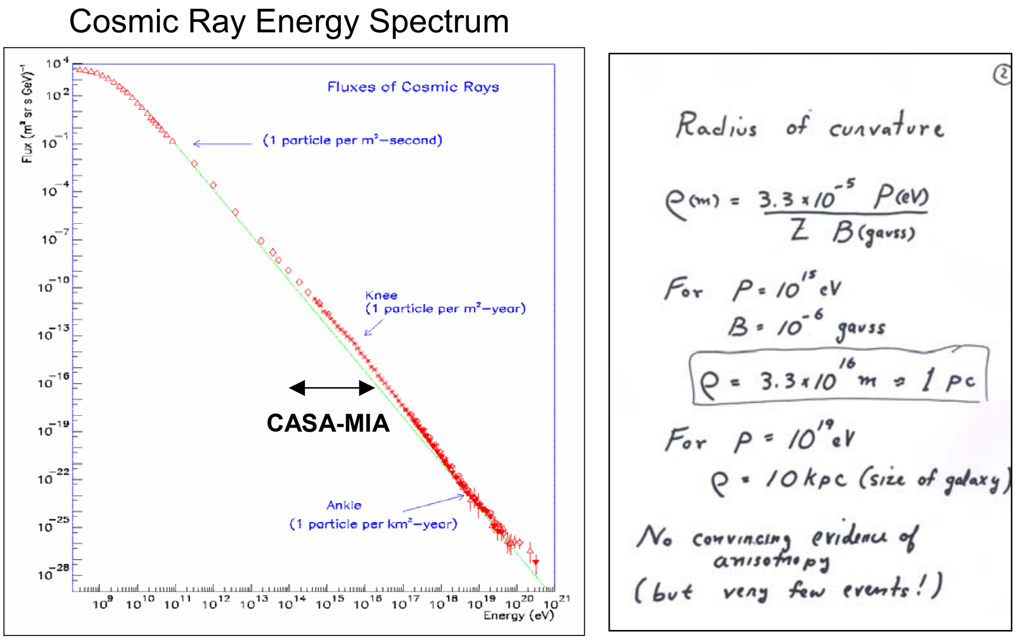

Figure 1: *Left: The cosmic ray energy spectrum. The flux of cosmic rays is shown as a function of energy from* 10^8 *eV to* 10^{21} *eV. The sensitive range of the CASA-MIA experiment is shown by the arrow; figure was originated by S. Swordy. Right: Calculation by Jim Cronin on the radius of curvature for a* $10^{15}\ eV$ *proton, demonstrating the need for a neutral particle to do astronomy at these energies.*

acceleration. The standard picture for producing high-energy cosmic rays involves shock acceleration in supernova remnants (SNRs). This picture has gained acceptance largely because it is energetically plausible. SNR acceleration models offer a reasonable explanation for the cosmic-ray origin up to $\sim 10^{14}$ eV, but the models become less realistic (and many questions remain) at energies above this point. Thus, it is natural to search for neutral radiation from point sources which could directly point back to the acceleration sites, an idea initially suggested by Cocconi in 1960 [3].

In the early 1980's, several experiments reported intriguing results that seemed to shed light on the origin of cosmic rays. These experiments detected an excess of air shower events coming from the direction of X-ray binary sources, such as Cygnus X-3 and Hercules X-1. X-ray binaries are systems in which an ordinary star orbits a compact object (neutron star or black hole) and they typically have large and variable X-ray emission. In the case of Cygnus X-3, the Kiel and Haverah Park experiments detected an apparent signal of 10^{15} eV particles that was modulated at the 4.8 hr orbital periodicity of the source [4]. Although the statistical significance of each detection was low (less than five standard deviations above background), the results were exciting because, if true, they implied that Cygnus X-3 channeled a substantial fraction of its luminosity into ultra high energy particles. In fact, it was pointed out that if Cygnus X-3 consisted of a 10^{17} eV accelerator with a luminosity of $\sim 10^{39}$ ergs/s, only a few such objects would be required to explain the origin of the high-energy cosmic rays [5].

Another wrinkle in the story came from the details of the experimental data itself. In studying apparent signals from Cygnus X-3 and Hercules X-1, several experiments reported air shower data that could not easily be explained by assuming a gamma-ray primary particle (see summary in [6]). For example, in the showers arriving from Hercules X-1, more muons were detected than expected from gamma-ray primaries. Again, the statistical significance of this effect was weak, but the results stimulated the community to question whether gamma rays behaved differently at ultra high energies than expected, or indeed whether the primary particles were in fact gamma rays.

2 The Vision for CASA-MIA

Gamma-ray sources typically have power-law energy spectra, where the photon flux falls rapidly with increasing energy. Astronomy at energies above 1 TeV therefore requires very large collection areas only available to ground-based instruments. High-energy particles (cosmic rays and photons) interact in the Earth's atmosphere to produce extensive air showers. These showers can be detected either by air shower arrays – arrays of counters sensitive to the charged particles and energetic photons that penetrate to ground level or by atmospheric Cherenkov telescopes – optical telescopes sensitive to the Cherenkov radiation in the shower. A key aspect of these two types of telescopes is that they are sampling devices with an effective collection area that is much larger than the physical size of the detectors.

In the mid 1980's, several groups began to develop new and more capable experiments designed to study sources of UHE cosmic rays and gamma rays. A key effort was initiated by groups from the University of Utah and the University of Michigan at a site on Dugway Proving Grounds in western Utah. These groups developed the Utah-Michigan Experiment, consisting of a surface array and a large buried muon array. The purpose of the muon array was to determine the muon content of each shower in order to discriminate between cosmic-ray and gamma-ray initiated showers. Air showers initiated by gamma rays are expected to have far fewer muons (by a factor of approximately ten) than showers initiated by cosmic-ray nuclei.

Jim Cronin became intrigued by the exciting, but puzzling, results coming from air shower detectors [7], and he quickly immersed himself in the methodology and techniques of UHE cosmic ray physics. He developed a vision for a new detector that would:

1. be a *definitive* experiment with the goal of quickly verifying the anomalous point sources and measuring their properties in detail, without regard to their periodic or transient nature,

2. consist of a much larger and much more sensitive surface array using a state-of-the-art design, and

3. employ a large muon array to reject hadronic cosmic rays.

Jim Cronin's vision developed into a proposal for the Chicago Air Shower Array (CASA) that was submitted to the National Science Foundation (NSF) in 1987. The proposal requested funding (approximately $3M) to build a surface array of 1064 detectors covering an

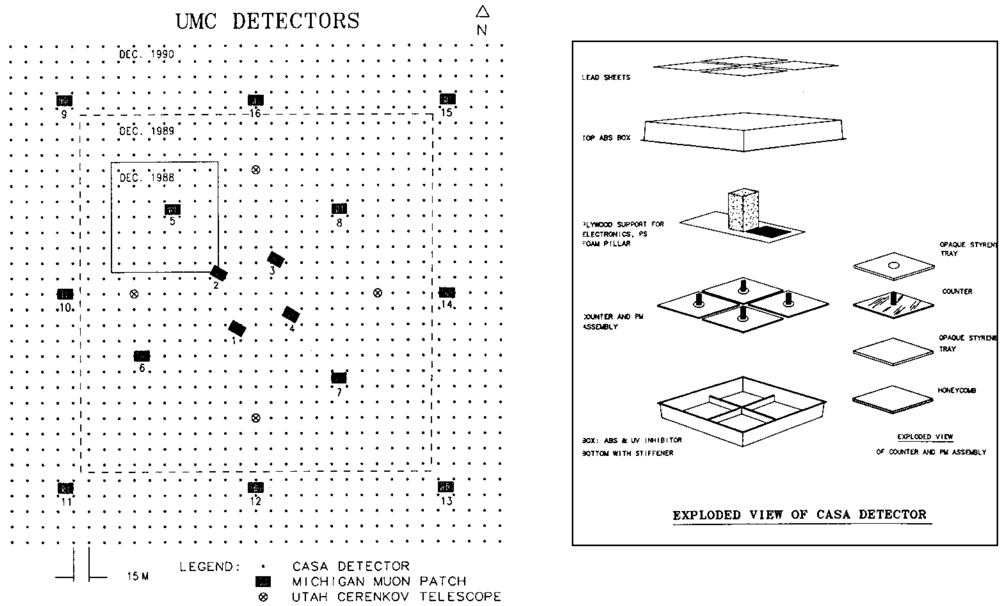

Figure 2: *Left: plan view of the CASA-MIA experiment at Dugway UT, USA, consisting of 1089 surface detectors (CASA), 1024 buried muon counters distributed into 16 patches (MIA), and four small Cherenkov telescopes. Right: exploded view a CASA station, consisting of four scintillation counters enclosed in a water-tight box and covered by four sheets of lead.*

area of 480 m x 480 m. Each detector (or *station*) would consist of four scintillation counters and complete local electronics, encompassing analog, digital, high-voltage, calibration, and Ethernet communication circuitry. CASA would operate in conjunction with a large muon array (MIA), consisting of 512 buried muon counters to be built and installed by the group from the University of Michigan. The NSF proposal was funded and CASA-MIA was constructed as proposed, except that the final CASA was somewhat larger (comprising 1089 detectors) and the final MIA was twice as large (comprising 1024 scintillation counters) as originally proposed.

Full details of the CASA-MIA experiment can be found in a detailed instrument paper written by Jim Cronin [8]. As shown in Figure 2, the 1089 CASA detectors were distributed on a regular grid with a 15 m spacing. The area enclosed by CASA was 0.23 km^2. MIA consisted of 1024 scintillation counters (total scintillator area of 2400 m^2) distributed in 16 patches of 64 counters each. The MIA counters were buried beneath approximately 3 m of earth and had a typical muon energy threshold of ~ 1 GeV.

An exploded view of a single CASA station is shown in Figure 2. The four scintillation counters in each station allowed for local alert (2 out of 4 counters) and trigger (3 out of 4 counters) conditions. Each counter consisted of a square sheet of acrylic scintillator read out by a single photomultiplier tube (PMT) glued to the center of the sheet. The counters were placed in an ABS plastic box, sealed to keep out water and covered by four sheets of lead (1/4" thick), designed to convert the low-energy gamma rays in the shower.

The heart of the CASA experiment was the electronics board mounted on a plywood

 

Figure 3: *Left: Members of the CASA-MIA experiment at the 22nd Int. Cosmic Ray Conference (Dublin, 1991). Front row (left to right): Brian Fick, Kevin Green, Timothy McKay, Rene Ong, Alexander Borione. Back row (left to right): David Nitz, John van der Velde, James Matthews, James Cronin, Hans Krimm, Corbin Covault. Right: Brian Newport (left) and Timothy McKay carrying a CASA detector ("Chaucer") into the field for installation.*

sheet in each detector. This board had analog electronics to measure the time of arrival and the particle density of the shower at the station. The differences in arrival times between adjacent stations, measured with an accuracy of ~ 1 ns, were used to determine the shower direction. The particle density information was used to determine the shower core and shower size (estimated total number of charged particles in the shower) and ultimately the energy of the primary particle. The electronics board contained digital electronics (CPU, co-Processor, memory, etc.) to read out the PMT timing and pulse-height information, to control an onboard high-voltage supply that powered the PMTs, and to transmit the recorded information from each detector to the central site over an Ethernet link.

3 The Construction of CASA-MIA

CASA-MIA was constructed and installed by a group of hard-working and very dedicated scientists at the Universities of Chicago, Michigan, and Utah. At Chicago, the initial group consisted of Jim Cronin, postdoctoral fellows Kenneth Gibbs, Brian Newport, Rene Ong, and Leslie Rosenberg, (the so-called "Gang of Four") and graduate students Nicholas Mascarenhas, Hans Krimm, and Timothy McKay. This group was augmented/replaced over time by postdocs Mark Chantell, Corbin Covault, Brian Fick and Lucy Fortson and by graduate students Alexander Borione, Joseph Fowler, and Scott Oser. Considerable help at Chicago came from staff members Marty Dippel, Harold Sanders, Marypat Sharer and Aspasia Sotir-Plusis. The University of Michigan group was led by Daniel Sinclair and John van der Velde, along with scientists Kevin Green, James Matthews, and David Nitz, and graduate students Michael Catanese and Ande Glasmacher. David Kieda collaborated from the University of Utah. Figure 3 shows a number of the members of CASA-MIA.

Figure 4: *Aerial view of CASA-MIA showing the 1089 CASA detectors, surrounding the Flye's Eye II apparatus and two house trailers used for the CASA living quarters and laboratory (photo by Kenneth Gibbs).*

The construction and deployment of CASA-MIA was a large undertaking that took place over several years between 1988 and 1991. All the raw materials for the surface array were delivered to Chicago where the individual detectors were constructed and assembled in the hi-bay area of the Accelerator Building of the Enrico Fermi Institute. Scintillation counters were assembled, wrapped and installed into the detector plastic boxes. Jim Cronin played a major role in the construction effort by gluing most of the PMTs to the scintillator sheets. The electronics boards were commercially fabricated and then debugged at Chicago. The completed CASA detectors, along with electronics and cabling, were shipped to Utah in large semi-trailers. The counters for the buried muon array were partially assembled in Michigan and then shipped to Utah for installation.

Considerable physical labor was required to install the CASA-MIA detectors and to bring them up to operational status. Most of this labor came from CASA-MIA physicists, along with teams of undergraduate students from the Universities of Chicago and Michigan. Figure 3 shows a CASA station being carried into the field. An engineering array of 49 CASA stations was completed in early 1989; the first scientific results from CASA came from this small array. By early 1990, 529 CASA stations were operational and the full CASA-MIA experiment (1089 CASA stations and 1024 muon counters) was commissioned in early 1991.

On April 22, 1991, the experiment suffered a setback when lightning struck the surface array. A major repair effort was mounted that lasted approximately seven months. In the process, every CASA electronics board was serviced. In addition, a large protection grid of wires was installed to prevent any further lightning damage. CASA-MIA started full operations for science in December 2001. An aerial view of the completed experiment is shown in Figure 4.

4 The Operations and Performance of CASA-MIA

CASA-MIA operated very successfully and largely without interruption for the five year period from 1992 to 1997. A very large data sample was collected during this time, consisting of approximately 3×10^9 air shower events, stored on more than 2,000 8 mm data tapes. The trigger rate varied with atmospheric pressure but was typically ~ 20 Hz. The median number of CASA stations per event was 19 and the median number of detected muons per event was 8.

The running and maintenance of CASA-MIA was carried out completely by the scientists working on the experiment, along with Michael Cassidy who served as a resident technician. The work involved long, single-person shifts, characterized by physical labor, standard routines, and solitude. The beautiful scenery made up for the fact that no running water existed at the site! J. Robert Oppenheimer could well have been describing the CASA-MIA experience when he wrote to a friend: "My two greatest loves are physics and desert country ... " [9].

The performance characteristics of CASA-MIA are well documented in other papers [6,8]. The median gamma-ray energy for a source passing near zenith was 115 TeV. The gamma-ray angular resolution varied with the detected shower size and was $\sim 0.7^\circ$ for showers with the median number of CASA stations. A critical feature of CASA-MIA was its ability to reject background cosmic rays using the measured muon content of the shower. For each shower, a relative muon content was determined from the ratio of the number of observed muons to the number of detected muons. Requiring this ratio to be small eliminated most cosmic-ray showers, while keeping a high percentage of the gamma-ray events. For showers at the median energy of 115 TeV, the efficiency for a cosmic-ray shower to pass the low-muon criterion was $\sim 6 \times 10^{-2}$; i.e. approximately 17 cosmic-ray events were rejected for each one accepted. At higher energies, the rejection power increased dramatically; for example, at a median energy of 5,000 TeV, the cosmic-ray efficiency was reduced to $\sim 1 \times 10^{-4}$.

5 Scientific Results

The results from CASA-MIA were written up in a series of eleven scientific publications [6,8,10-18]. The results can be categorized into three major areas:

- **Point Sources:** The primary scientific goal of CASA-MIA was to detect point sources of ultra high energy gamma rays. In this regard, nature was not kind and no clear detections were made by CASA-MIA. However, strong limits were set on the emission from the most interesting sources, such as X-ray binaries (Cygnus X-3 and Hercules X-1) [6], the Crab Nebula [14], and active galactic nuclei [13]. Searches for transient and periodic emission from a number of sources were also carried out, along with a general survey of the overhead sky [12].

  Figure 5 shows some of the CASA-MIA results on Cygnus X-3. The CASA-MIA flux limits are two orders of magnitude lower then the earlier reported fluxes [4], essentially ruling out this object as a significant source of ultra high energy photons during this

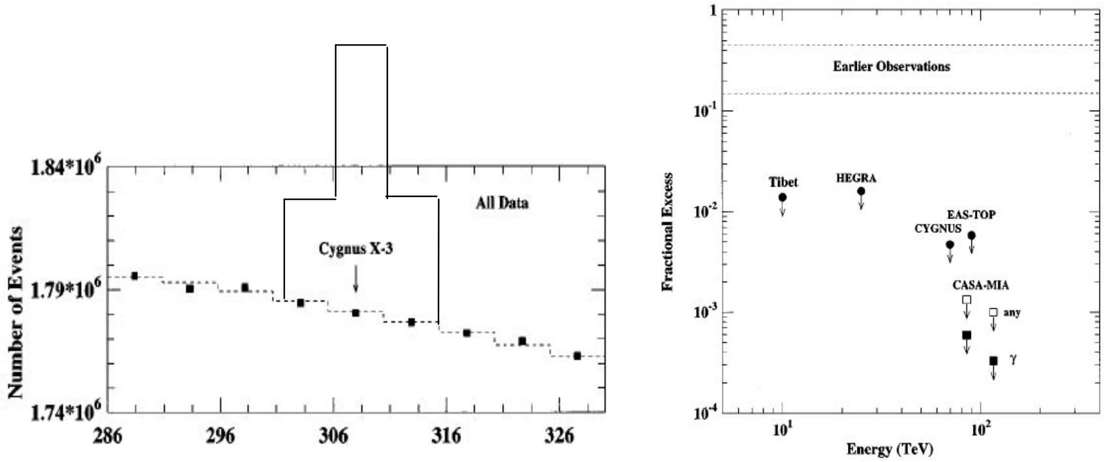

Figure 5: *Results from CASA-MIA on steady emission from the X-ray binary system Cygnus X-3. Left: scan in right ascension across a strip in declination that contains Cygnus X-3. The points correspond to the detected numbers of CASA-MIA events, the dotted curve corresponds to the background estimation, and the solid histogram corresponds to the expected numbers of events assuming the flux measured by the Kiel experiment [4]. Right: limits from several experiments on the flux of ultra high energy gamma rays from Cygnus X-3 as a function of energy. For the CASA-MIA results, the open squares indicate the limits for any neutral particle and the solid squares indicate the limits for gamma rays.*

epoch. Very recently, the HESS atmospheric Cherenkov telescope array has detected TeV gamma rays from the X-ray binary system LS 5039 and has observed a modulation of the gamma-ray signal at the same period as the orbital period of the system [19]. Evidently X-ray binary systems do produce high-energy gamma rays, but the HESS telescope operates with excellent sensitivity at a much lower energy than CASA-MIA and the extrapolated flux at 100 TeV energies would be quite low. A similar situation exists with the Crab Nebula. The Crab is a recognized standard candle at TeV energies and gamma-ray emission has been detected from it up to 50 TeV by atmospheric Cherenkov telescopes. However, the energy spectrum of the Crab appears to roll over and drop strongly at energies above 20 TeV, as indicated earlier by the CASA-MIA data [14].

- **Diffuse Sources:** By using the large muon detector to provide separation between gamma-ray and cosmic-ray primaries, CASA-MIA studied sources of diffuse gamma-radiation with great sensitivity. One significant result was a study of possible diffuse emission from the region of the Galactic plane, tracing the interactions of high-energy cosmic rays with molecular clouds in the plane [15]. This study produced the best constraint on this type of emission at these energies. A second analysis searched for bursts from arbitrary directions in the sky to constrain cosmic explosions that occur on short time scales, such as those expected in the evaporation of primordial black

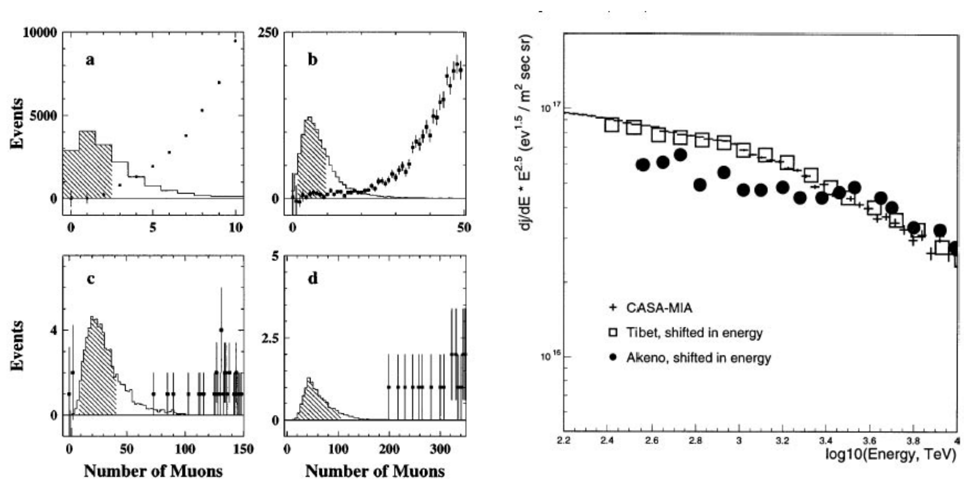

Figure 6: *Left: Results from the CASA-MIA analysis of diffuse isotropic gamma-ray emission [16]. A histogram of the number of detected muons is shown for four different samples selected by shower size (number of alerted CASA stations, N): a) $N > 100$, b) $N > 250$, c) $N > 500$, and d) $N > 700$. The points are the CASA-MIA data, the solid histograms are the expected numbers of events assuming a isotropic gamma-ray/cosmic ray ratio of 10^{-3}, and the shaded regions correspond to the range over which the isotropic limits are calculated. Right: Energy spectrum of cosmic rays as measured by CASA-MIA [17] and the Akeno and Tibet experiments (slightly shifted in energy). The differential flux of cosmic rays multiplied by $E^{2.5}$ is shown as a function of $log_{10}(E)$.*

holes. A third result, perhaps the most significant and long-lasting one to emerge from CASA-MIA, came from a search for diffuse isotropic emission. Such emission could come from many astrophysical sources in our present universe or from the decay of some cosmological particle produced in the early universe [16]. This work provides a basic limit on the electromagnetic fraction of the cosmic rays at a level less than 2×10^{-5} at the highest energies accessible to CASA-MIA. Figure 6 shows some of the data and a summary of the results from the diffuse isotropic analysis.

- **Cosmic-Ray Studies:** Combining a very large and uniform surface array with a large muon detector, CASA-MIA had excellent capability for measurements of the properties of the ultra high energy cosmic rays (i.e. the particles that served as the background to gamma-ray sources). The energy spectrum of the cosmic rays was determined from a study of the distribution of the electron and muon shower sizes [17]. As shown in Figure 6, the spectrum measured by CASA-MIA shows a relatively smooth steepening in the energy range above 10^{15} eV, in contrast with some results from other, earlier experiments that indicated a sharp feature, or ”knee”, in the energy spectrum. The cosmic-ray composition was determined from the CASA-MIA data using a multi-parameter statistical fit to the surface and muon detector data [18]. In this study, the composition was seen to change gradually from a mixed composition at lower energies below 10^{15} eV to a heavier composition (i.e. increasing fraction of iron) at higher energies approaching 10^{16} eV.

Improved measurements of the properties of the cosmic rays were carried out by several instruments developed to work in conjunction with CASA-MIA. The Dual Imaging Cherenkov Experiment (DICE), consisting of two telescopes designed to image the Cherenkov light in air showers, was developed and operated by a Chicago-Utah group led by Simon Swordy and David Kieda. The Broad LAteral Non-imaging Cherenkov Array (BLANCA) consisted of 144 vertically-oriented Cherenkov detectors that measured the lateral distribution of the Cherenkov light. BLANCA was a substantial experiment made possible, in part, by the very hard work of Lucy Fortson, Joseph Fowler, and Clem Pryke and by the general-purpose design of the CASA electronics. DICE and BLANCA made independent measurements of the composition of cosmic rays in the energy range between 10^{14} and 10^{16} eV. A prototype version of the Fly's Eye HiResolution detector was developed by the University of Utah group and was situated to measure the longitudinal profile of air showers that also triggered MIA. In this way, spectral and composition measurements were extended to energies above 10^{17} eV.

6 Conclusions: The Legacy of CASA-MIA

CASA-MIA and the ancillary experiments at the same site ceased operations in 1999. Many of the CASA scintillation counters were re-used for other purposes, such as the Cosmic Ray Observatory Project (CROP) in Nebraska.

CASA-MIA placed the strongest constraints on both point and diffuse-source emission of gamma rays at ultra high energies. The general notion of a few bright sources producing the bulk of the high-energy cosmic rays has been largely ruled out. The origin of these particles is still an important and active area of research. Recent observations by atmospheric Cherenkov telescopes operating near 1 TeV have shown that there are a wide variety of very high-energy galactic sources, including pulsar wind nebulae, supernova remnants, microquasars, binary pulsars, and so forth. Thus, the general picture of cosmic acceleration in our Galaxy is slowly coming into focus.

Perhaps as important as its scientific legacy, the CASA-MIA experiment that was inspired and realized by Jim Cronin demonstrated the power of detectors with excellent instrumentation and sensitivity. This brought attention and funding to very high-energy astrophysics, as well as new people interested in this field of research. New experiments exploring other avenues of particle astrophysics have emerged after CASA-MIA, including solar heliostat Cherenkov telescopes, such as CELESTE and STACEE, TeV Cherenkov telescope arrays such as CANGAROO, HESS, MAGIC, and VERITAS, neutrino telescopes such as IceCube, ANTARES, and ANITA, and experiments exploring the highest energy cosmic rays, such as the Pierre Auger Observatory and the Telescope Array.

7 Acknowledgments

I would like to thank James Pilcher and Angela Olinto for the opportunity to speak at this wonderful symposium honoring the work of Jim Cronin. It was truly an honor and privilege to do so. The talk would not have been possible without help from many CASA-MIA collaborators, most especially Corbin Covault, Lucy Fortson, Brian Fick, Kenneth Gibbs, Kevin Green, Hans Krimm, James Matthews, Timothy McKay, David Nitz, and Aspasia Sotir-Plusis. The most important and heartfelt thanks go to Jim Cronin himself who has had such an important influence on the careers of many young scientists over the years.

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