Search For Cosmic Ray Proton Anisotropy with the Fermi Gamma Ray Space Telescope Large Area Telescope

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Preliminary report on the investigation of Cosmic Ray Proton (CRP) anisotropy using data received during the first three years of the Fermi Gamma Ray Space Telescope (FGST) mission. Cosmic Ray Anisotropy has been found using several experiments utilizing cosmic ray muon detection techniques including IceCube [1] and the Super-Kamiokande-I Detector [9]. The energy range of these muon detections spans from 10 TeV through 400 TeV. The FGST has already observed anisotropy in Cosmic-Ray electron detection at energies greater than 60 GeV on the level of $10^{-4}$ to $10^{-3}$ [2].

I. INTRODUCTION

Cosmic Ray astronomy was pioneered by Bruno Rossi in the 1930s and has relied on ground-based detection of cosmic ray muons. These muons are produced due to a series of successive interactions between particles of Earth’s atmosphere and incoming Primary Cosmic Rays. These interactions create both electromagnetic and hadronic showers of particles including muons. These muons have been detected at enormous energies corresponding to Cosmic Ray energies on the order of 10$^{16}$ electron volts. Until recently these muons have been the only outlet for particle physicists to observe such extraordinarily energetic collisions.

Despite the high energy of these interactions, there are many issues surrounding ground based detection specifically the turbulence and veritable unpredictability of half of the interacting medium, namely Earth’s atmosphere. There are also copious amounts of background events caused by secondary physical processes which has required many experiments to construct shields that restrict the particle energies reaching the detector surfaces. The Fermi Gamma Ray Space Telescope (FGST) however provides scientists with an alternative to the often noisy and difficult ground based measurements by avoiding Earth’s atmosphere entirely. The FGST was primarily designed as a gamma-ray detector but has proved its utility in the field of direct Cosmic Ray detection.

The field of Cosmic Ray astronomy is currently focused on determining the origins of Cosmic Ray emissions which remains a mystery to astrophysicists since Rossi’s first detections [10]. There are multiple competing theories as to the cosmic processes that could cause such rapid acceleration of observed cosmic ray particles. The central purpose of this paper will be to observe anisotropy, directional dependence, of Cosmic Ray protons (CRPs). This effect has already been observed in ground based muon detections [1, 9] as well as by the FGST in relatively low-energy (GeV) Cosmic Ray electrons and positrons (CRE) detection [3]. By detecting this anisotropy at lower energy ranges, $\sim$1 TeV in CRPs and comparing to these previous detections, a great deal may be learned about the source of Cosmic Rays.

II. THEORY

II.1. Cosmic Rays and Ground Based Detection

Interstellar space is composed of neutral and ionized gas, dust, photons, neutrinos and high-energy charged particles. These high-energy particles exist typically in the form of Cosmic Rays. These extremely energetic and highly relativistic conglomerates of charged particles are composed of roughly 90% protons and 10% helium nuclei with smaller contributions from nuclei of heavy elements. The source of these streams of high energy particles has yet to be identified but many astrophysicists believe that production may be tied to supernova remnants (SNRs) [11]. Blandford suggests that expanding shock waves from these massive stellar explosions accelerate Cosmic Ray particles through the diffusive shock acceleration process [5]. Fermi described this acceleration as the result of charged particles colliding against irregularities of magnetic fields as well as against the highly heterogeneous interstellar medium [7]. Other sources have been theorized including pulsar wind nebulae such as the Crab Nebula, high-mass binary sources such as Cygnus X-3 [11], and blazar active galactic nuclei jets (AGNs) [3].

Ground based detection of Cosmic Rays focuses on the detection of tertiary decay products of interactions between primary Cosmic Rays, typically at energies of $\sim$10$^{16}$ eV, and particles in the Earth’s atmosphere. Working most nearly as a cosmically driven particle collider, massive air showers of particles form in the upper atmosphere that include pions. Adam C. Powell in 1947 observed that pions typically decay into a single muon and neutrino, $\pi^+ \rightarrow \mu^+ + \nu_\mu$. This decay results in the production of muons which can be observed using ground based detectors. These Cosmic Ray muons are weakly interacting due to there high mass, $\sim$ 10 m_e, and...
resulting high momentum, requiring the development of rather innovative detection methods.

Two collaborations utilize large subterranean facilities in order to restrict the high amount of background events associated with the detection of muons and even more weakly interacting neutrinos. The IceCube neutrino detector, which is located at the geographic South Pole, uses the Cherenkov Radiation produced by charged secondary particles moving faster than light can travel through the ice. These charged particles are caused produced due to ionization and stochastic interactions as muons propagate through the ice [1]. The second large ground based detector, the Super-Kamiokande, also utilizes this form of detection and incorporates a large “overburden” atop the detector to restrict the energies of detectable particles to the range of cosmic ray muons and neutrinos [9].

The Fermi Gamma-Ray Space Telescope provides a much cleaner method of detection that actually helps create and accommodate the massive air showers created in Earth’s atmosphere within its 1.8m $\times$ 1.8m $\times$ 0.72m Large Area Telescope [4]. This detection method results in a lower background event count rate and a greater angular view of the night sky. The Fermi collaboration has already used the detector to detect and study Cosmic Ray electrons and positrons (CREs) which exist at 100GeV and are most likely from relatively nearby locations less than $\sim$1.6 kpc [3]. These CREs however would most likely not produce the muons observed in the ground based detectors. These muons are instead produced by hadronic Cosmic Rays which suggests a stream composed of predominately protons.

While the LAT has been designed and proven to be an excellent gamma ray and electron positron detector but it is not a strong proton detector. This is due to the length of hadronic showers caused by the protons compared to the electromagnetic showers caused by interacting gamma rays. The proton shower takes too long to develop within the LAT making the determination of the proton energy very difficult. However, despite the design of the LAT as a gamma ray detector, most of the triggered events are in fact protons [2]. Therefore the LAT does have the capability of directly detecting CRPs as well as the ability to track their incident direction.

II.2. Cosmic Ray Anisotropy

The last few decades have seen the detection of measurable, energy dependent sidereal anisotropy in Cosmic Ray arrival direction [1]. This anisotropy comes from many different sources including the Compton and Getting effect, Solar and diurnal effects, and even seasonal changes in atmospheric temperature. The Compton and Getting effect states that the motion of the solar system relative to the rest frame of the Cosmic Ray plasma should cause an energy independent anisotropy with a maximum in the direction of motion. The diurnal and Solar effects act similarly but describe the motion of Earth about its axis and its motion around the Sun respectively. These three effects can and have been well modeled and subtracting them should leave purely effects of galactic origin particularly those from nearby SNRs [9]. If there is an anisotropy that favors the direction of the galactic center, these observations may also be used as yet another secondhand observation of dark matter [11].

This lack of directional symmetry has been observed at IceCube and Super-K at similar amplitudes on the order of $10^{-4} - 10^{-3}$ [1, 9]. The SNR theory however has been challenged by Butt who states that the observed anisotropy is of too low an intensity for galactic sources, such as SNRs, to be a viable option. Instead galactic sources should accelerate cosmic rays to high enough energies that the particles would escape the galaxy relatively quickly leading to observations of much higher anisotropy than has been detected using ground based detectors [7]. By understanding the source of this anisotropy in the same way as the solar and diurnal contributions, the direction and corresponding location of Cosmic Ray sources may be better understood.

III. EXPERIMENTAL METHOD

III.1. Fermi Large Area Telescope

The data set that is used during this research comes from the FGST’s Large Area Telescope (LAT) seen in Figure (1). The Fermi Gamma Ray telescope promises to be a very capable CRP detector due to its ability to detect particles of wide a energy range $\sim$30 MeV - 300 GeV, and its position in low Earth orbit. The LAT has a field of view of roughly 20% of the sky. Starting in August 2008, the telescope entered a survey mode which saw the LAT observing the entire sky every two Earth orbits. This corresponds to a new picture of the gamma-ray sky every 3 hours. This is certainly a huge step forward in gamma-ray astronomy but is also very promising for the study of cosmic rays and the determination of their origins [4].

The LAT detects these high-energy particles by incorporating a somewhat typical particle detector setup including a tracker fabricated of silicon and high-Z material layers and an electromagnetic calorimeter. The tracker is formed using 16 separate modules with 16 layers of tungsten paired with silicon detectors positioned immediately below each layer. The telescope takes advantage of the fact that high-energy gamma rays cannot be reflected or refracted and instead interact with the tungsten layers to form an $e^- e^+$ pair, causing an electromagnetic particle shower. In this way the tracker allows a precise determination of the direction of approach of incident particles as well as catalyzes their shower formation so that it may be contained within the 0.72m depth of the telescope [4].

After passing through the tracker, the resulting $e^- e^+$ pair may be read by an electromagnetic calorimeter to de-
termine the energy of the incident particle. The calorimeter also provides an important characterization for reconstructing the electromagnetic particle shower resulting from incident gamma rays. Surrounding the LAT tracker and calorimeter layers is a segmented anticoincidence detector (ACD) used to provide initial charged-particle background rejection. The ACD was designed to provide a minimum of 0.9997 efficiency [4]. Despite its original purpose as a gamma ray telescope, the physicists have realized the potential for using the LAT to detect Cosmic Ray matter including CREs [3] and potentially protons.

There is difficulty in detecting protons simply because of the high energeticcs of CRPs relative to CREs and the limited depth of the LAT itself discussed in Section II.1. However, the LAT is regularly triggered by CRPs and the tracker is absolutely capable of determining their trajectory prior to interaction with the electromagnetic calorimeter. The Tungsten layers within the tracker induce hardronic showers at high rates, allowing the silicon layers to readily detect the resulting particles. These events are usually filtered out by lower level computer techniques for the sake of clearer gamma ray analysis. Therefore information about the energy of the incident CRPs is difficult to gather but any anisotropy should be detectable by the LAT’s tracker [3]. Also, by restricting the energies of detected events to $\geq$ TeV, the dramatic bending of CRP paths caused by the Earth’s magnetic field can avoided allowing for more accurate determinations of the CRP’s incident trajectory.

### III.2. Analysis Techniques

The first steps of analysis include first setting the range of detected particle energies, event energies, that are of interest to the analysis, and using the selected data points to observe a well known feature of the sky. The IceCube and Super-K experiments used observations of the moon to establish the validity of their data sets [1, 9]. For this analysis an observation of the Moon will allow both a determination of the angular resolution of the LAT at the selected energy range, by comparing observed distances with accepted measures, but also demonstrate that the events detected by the LAT are indeed cosmic of origin and unique from the typical Solar and Terrestrial background events.

This analysis will involve first ascribing both temporal and spatial, right ascension and declination, coordinates to each detected event. Then using a database which calculates the spatial coordinates of the Moon in the sky, the Moon’s position will be determined for the detection time of each event. Following the assignment of coordinates, a histogram of events against angular separation will be made and a dip in the plot will provide evidence of lunar detection.

After this initial step, a Monte Carlo simulated data set corresponding to an isotropic directional dependence will be created using identical cuts on energy and other variables used to create the files of actual data. While experiments like IceCube required sweeps in right ascension at constant declination, the LAT is able to measure the anisotropy in 2D. Therefore by scanning over events in both right ascension and declination and comparing the simulated data to detected events, the extent of the anisotropy may be shown. This analysis will be made more substantive through the use of corrections for the effective area and exposure of the detector at specific equatorial coordinates by comparing the rates of exposure to the rates of event detection for each of the 16 segments.

In order to provide a more rigorous analysis, sweeps in right ascension along constant lines of declination, and vice versa, will be made and the intensities fit to a harmonic function used in both the IceCube and Super-K analyses for seemingly empirical purposes. This equation is written as follows in Equation 1

$$F(x) = A_1 \cdot \left[ \frac{x - \phi_1}{180} \right] + A_2 \cdot \left[ \frac{2 \pi}{180} \cdot (x - \phi_2) \right]$$

By doing rather simple chi-squared and other statistical analysis between the isotropic data and the new resulting fit function, the observation of anisotropy should become more quantitative. A more complicated analysis could include setting confidence limits for anisotropies of various strengths and direction corresponding to theoretical predictions of source position, composition and production mechanism using the simulated data set to ensure the significance of observed deviations. Through these steps the precise direction and nature of a Cosmic Ray source may be identified and better understood.

The error analysis on these intensity data points will most likely be composed of Poisson, $\sqrt{n}$, statistics and systematic errors corresponding to ranging anisotropies due to diurnal and Solar considerations as described in Section II.2.
[10] Rossi, B. 1948, Rev. Mod. Phys. 20 3