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Search for EeV Protons of Galactic Origin

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Cosmic rays in the energy range 1 - 3 EeV are thought to have a light, probably protonic, composition. To study their origin one can search for anisotropy in their arrival directions: extragalactic cosmic rays should be isotropic, but galactic cosmic rays of this type should be seen mostly along the galactic plane, and there should be a shortage of events coming from directions near the galactic anticenter. Guided by models of the galactic magnetic field that indicate that the enhancement along the galactic plane should have a standard deviation of 20° - 35° in galactic latitude, and the deficit in the galactic anticenter direction should have a standard deviation of about 50°, we use the data of the Telescope Array experiment to search for these effects. Neither an enhancement along the galactic plane nor a deficit in the galactic anticenter direction is found. Using these data we place an upper limit on the fraction of EeV cosmic rays of galactic origin at 0.9% at 90% confidence level.

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1. Introduction

In studying ultrahigh energy cosmic rays, a fluorescence detector can observe the development profile of extensive air showers initiated by primary cosmic rays. A detector with pixel size of 1^o, can measure the depth of shower maximum, Xmax, to an accuracy of 20 g/cm^2 [1]. This is sufficient to determine, on a statistical basis, the composition of primary cosmic rays. Although there is disagreement among experiments in some energy ranges [1], [2], [3] from about 1 to 3EeV all fluorescence measurements indicate that the composition is light, and probably protonic. If this is the case, an interesting question is, are the sources of these cosmic ray protons galactic or extragalactic. One way to answer this question is to look for anisotropy in their arrival directions. While extragalactic protons should be isotropic, one would expect that EeV protons of galactic origin should be concentrated near the galactic plane. The reason is that the critical energy (E_C) of the galactic magnetic field - the energy where the Larmor radius equals the coherence length of the irregular component - is thought to be 0.3 EeV, so protons of 1 - 3 EeV should spiral around the regular component of the field and their directions should not be randomized by the irregular component. Of course at energies below E_C the regular component tends to keep cosmic rays inside the galaxy, while the irregular component randomizes their directions. If galactic cosmic ray sources have a distribution similar to that of pulsars, there should be many more sources within the solar circle in the Galaxy than outside of the circle. This would produce a second anisotropy signal, a relative shortage of events in the direction of the galactic anticenter [4]. To search for these anisotropy signals it would be useful to be able to estimate the geometrical size of the effects: how wide should the enhancement along the galactic plane be, and how wide should the shortage of events be when looking along the galactic plane in the direction of the galactic anticenter. To perform these estimates we have constructed a model of the galactic magnetic field, and traced protons of 0.3, 1.0, and 3.0 EeV through the field to the vicinity of the earth. The result [4] is that the angular scale of the enhancement in galactic latitude b should be on the order of 20^o - 35^o, and the angular scale of the deficit centered at galactic longitude l=180^o is about 50^o.

2. Telescope Array Surface Detector Data

To perform the search we used the data of the surface detector of the Telescope Array (TA) experiment. TA is the largest experiment studying ultrahigh energy cosmic rays in the northern hemisphere. The TA experiment consists of a surface detector (SD) [5] covering 700 km^2, and 48 fluorescence telescopes [7],[6], located at three sites, which overlook the SD. The data described here were collected over 6 years, from 11 May, 2008 to 11 May, 2014. The TA SD consists of 507 scintillation counters each 3m^2 area, deployed in a grid of 1.2km spacing in the desert of Millard County, Utah, USA. There are 2 layers of plastic scintillator in each counter. The counters are solar-powered, read out by a radio system, and calibrated using single muons every 10 minutes, to determine the pulse heights of a minimum ionizing particle (MIP) and a vertical equivalent muon (VEM). The SD trigger is satisfied when within an 8 μs window 3 adjacent counters have energy deposits equivalent to 3 MIPs or more. Every second the counters are queried as to the times of 3 MIP hits, and when the trigger conditions are satisfied, all counters are instructed to report the FADC wave forms of hits above 0.3 MIP energy deposit. TA SD analysis consists of two steps: the first is a fit to the time that counters are struck, to determine the direction of the air shower, and the second is a fit to the distribution of counter pulse heights as a function of distance perpendicular to the path of the air shower. The VEM/m^2 signal at a distance of 800m from the shower core, called S800, is determined and the cosmic ray energy is found from a look-up table with inputs S800 and sec(θ), where θ is the zenith angle of the shower. The energies come from a Monte Carlo simulation of the SD using CORSIKA [8] and the hadronic generator QGSJet II-3 [9]. Although the approximation technique called thinning [10] is used in our Monte Carlo simulation, we carry out a process called dethinning [11] to restore lost shower information. Upon comparing the energies of cosmic rays found in this way, and those found for the same events using the data of our fluorescence detectors, we see a difference of a constant fraction of 1.27 [12], independent of energy. Because the fluorescence detector energy measurement is more accurate since it is a calorimetric determination, we correct the SD energy (downward) by this factor. Choosing events of energies between 1 and 3 EeV, we show in Figure 1 histograms of the galactic latitude, b, and longitude, l. The data is shown as black points with error bars, and the red histogram is the prediction of our Monte Carlo simulation for an isotropic distribution. No excess at low galactic latitudes is evident, nor does a deficit of events show up at l = 180^o, the direction away from the galactic center.

3. Results

To search for evidence for galactic origin of cosmic rays in our data we compare the galactic latitude data shown in Figure 1 (left) to the Monte Carlo distribution for isotropic events. We calculate the fractional difference $F = (N_{\mathrm{Data}} - N_{\mathrm{MC}})/N_{\mathrm{TOTAL}}$ between the data and Monte Carlo for 2 cuts on galactic latitude b: $|b| < 20^o$ and $|b| < 35^o$. Here N_{Data} and N_{MC} are the numbers of data and isotropic Monte-Carlo events that pass the cut on $|b|$ and N_{TOTAL} is the total number of events in our data between 1 and 3 EeV, which is 10554 for the 6 years of TA SD data. No significant enhancement was found. For the two cuts on b, the 90% confidence level upper limits on F were 1.6%, and 1.9%, respectively.

We searched for a deficit of events in the direction of the galactic anticenter, by comparing the galactic longitude l data shown in Figure 1 (right) to the Monte Carlo simulation for isotropic events for $130^o < l < 230^o$ and evaluating the fractional difference between the data and Monte Carlo. Again, no significant deficit was found. The 90% confidence upper limit was 0.9%.

4. Summary

We have searched for evidence that cosmic rays in the 1 - 3 EeV energy range, thought to be largely protons, are of galactic origin. Models of the galactic magnetic field predict that if this were true, anisotropy should be present in cosmic rays' arrival directions. No anisotropy is seen, and upper limits on the fraction of cosmic ray protons of galactic origin are placed at 0.9% at 90% confidence level.

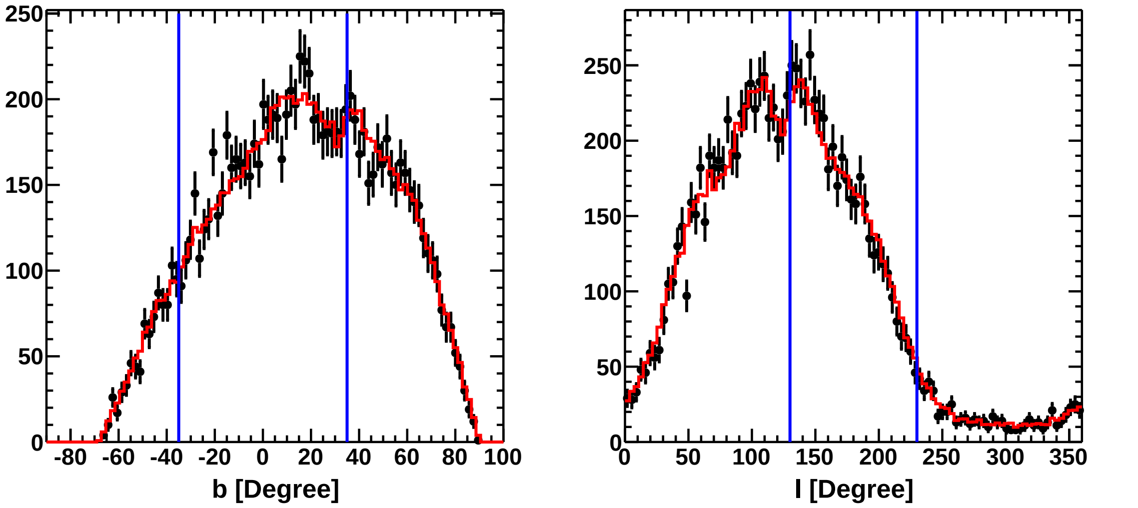

Figure 1: Histogram of TA surface detector data in galactic latitude, *b* (left) and galactic longitude, *l* (right). TA data is the black points with error bars, and the TA Monte Carlo simulation is the red histogram. The blue lines, at $\pm 35^{\circ}$ in the left panel, and at $\pm 50^{\circ}$ in the right panel, show where the enhancement in *b* and deficit in *l* are expected for galactic protons. Neither effect is seen in these data.

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