Evaluation of a wide-sky survey method for EAS experiments

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Abstract: Several ground-based Extensive Air Shower (EAS) experiments such as ASγ and Milagro have observed that CRs show large scale anisotropy in the TeV energy region with an amplitude of about 0.1%. As this phenomenon is very weak we have to deal carefully with potential errors introduced by analysis methods. In this paper, we discuss two methods for analyzing wide sky survey data, the Equi-Zenith angle method and a χ²-Iteration method. The simulation results show that the χ²-Iteration method can give accurate and reasonable results in the case of large scale anisotropy in data samples.

Keywords: EAS, anisotropy, Equi-zenith angle method, χ²-Iteration method, azimuth modification

1 Introduction

The galactic magnetic field strongly affects the trajectories of cosmic rays (CRs) with the result that cosmic rays as observed on Earth are highly isotropic. However, several ground extensive air shower experiments such as the ASγ array in Tibet [1] and the Milagro experiment [2] have observed that CRs in the TeV energy region present large scale anisotropy phenomenon with an amplitude of about 0.1%. The ARGO experiment (Yangbajing, Tibet) has also reported a similar result as shown in Figure 1 [3]. There are many possible modulation effects magnetic fields in space, the earth environments (e.g. pressure and temperature) and the dependency of the detector efficiency on time and direction. Therefore when we estimate the background from some direction or over some time period we must compensate during the data analysis, for these variations in efficiency. The most popular operation is embodied in the Equi-Zenith angle method and involves modifying the CRs uneven distribution caused by the modulation in azimuthal direction. However it is not clear how to understand this operation and whether it will introduce new problems which will influence the final results. Therefore, it is necessary to discuss the reliability of the analytical result after azimuth modification, especially for faint anisotropy phenomenon. In this work, we have generated three data samples which followed YBJ-ARGO experiment data characteristics with the same Modified Julian Date(MJD), zenith angle and counting rates, but with different azimuth angle distributions. The goal is to subject these data sets to careful analysis and attempt to extract the known anisotropy that have been artificially introduced. We denote the three data samples as:

1.) D1–isotropic events. This data set simulates a cosmic ray flux with little or no anisotropy;
2.) D2–anisotropy events. This data set simulates anisotropy modeled on that measured by ARGO experiment at $E_p = 3.9\text{TeV}$. The anisotropy follows the expression

$$I = A_1 \cos\left(\frac{2\pi (\Phi - \phi_1)}{360}\right) + A_2 \cos\left(\frac{2\pi (\Phi - \phi_2)}{180}\right)$$

with $A_1 = 0.00093, A_2 = 0.0005, \phi_1 = 34.1$ and $\phi_1 = 279.4$;

3.) D3–based on D2, but adding a sinusoidal modulation in the azimuthal direction with an amplitude of 2% in horizontal coordinate system which in order to simulate uneven distribution caused by the modulation in azimuthal direction.

In practice, we use only data for which the arrival direction within 45 of the zenith. Over the course of a day, therefore, the detector array scans the celestial sky in the declination band from -10° to 70° in the whole right ascension range $0^\circ - 360^\circ$. For each sample group, the total number of events (single particles are detected by the detector array) is about $7 \times 10^9$.

2 Techniques for wide-sky survey

Ground EAS experiments have the advantages of duty circle and wide-angle field of viewing, which make it continually observe the whole celestial sky. For these experiments,
LI TAO-LI et al. EVALUATION OF A WIDE-SKY SURVEY METHOD FOR EAS EXPERIMENTS

Figure 1: Sidereal time CRs intensity map for different energy ranges. Ep is the median energy of protons estimated by means of Monte Carlo simulations. The three smooth lines are fitted by the second-order cosine harmonics $1 + A_1 \cos(2\pi(x - \phi_1)/360) + A_2 \cos(2\pi(x - \phi_2)/180)$.

the azimuth distribution of events is usually uneven and most importantly very stable. In this paper we used two techniques based on Equi-Zenith angle Method for wide-sky survey. The Equi-Zenith angle Method is free from variations in time arising from atmospheric conditions and detector performance.

2.1 Equi-zenith Angle Method

We divide all the events detected by EAS experiments into different clusters according to their local sidereal time ($t$) and direction (zenith-$\theta$, azimuth-$\phi$) in the horizontal coordinate system. We approximately consider all the events clusters in the bin centered on $(t, \theta, \phi)$ as coming from the same direction, and use the average of $\sum_{\phi' \neq \phi} N_{off}(t, \theta, \phi')$ as the background of $N_{on}(t, \theta, \phi)$. (Here $\phi'$ means that we use other azimuth bins in the same zenith direction to calculate the background of $(t, \theta, \phi)$ except $N_{on}(t, \theta, \phi)$ itself.) We then convert the coordinates of $N_{on}$ and $N_{off}$ into equatorial coordinates and sum all events from different time bins and with different values of $\theta$ and $\phi$ corresponding to the same values of the Ra and Dec, the background $N_{bkg}(Ra, Dec)$ is treated in the same way. From the above discussion, we write

$$N(Ra, Dec) = \sum_{t,\theta,\phi} N_{on}(t, \theta, \phi)$$

(2)

$$N_{bkg}(Ra, Dec) = \sum_{t,\theta,\phi} \sum_{\phi' \neq \phi} N_{off}(t, \theta, \phi') / n - 1$$

(3)

(Here n is the number of azimuthal bins at zenith angle $\theta$.) The significance of the signal above the background exceed can be calculated using,

$$s = \frac{N(Ra, Dec) - N_{bkg}(Ra, Dec)}{\sqrt{N_{bkg}(Ra, Dec)}}$$

(4)

This method is direct and easy to deal with. Figure 2 shows that the result of D1 sample with the Equi-zenith angle method, the significance of isotropic CRs obey the standard normal distribution as expected. However as Figure 3 shows, when we analyze an anisotropic distribution as with D2 samples, the analytical result is different from the expected data. The main reason is that this method can not estimate the background correctly because it effectively integrates over the azimuth rather than estimating the background as a function of the azimuth. The prerequisite for the using Equi-Zenith angle method is therefor that the backgrounds are isotropic, so the intensities everywhere in a zenith belt are all the same and the differences come only from statistical errors. Therefore, the background estimated by Equi-Zenith angle method is far from being accurate when anisotropic phenomenon exist.

2.2 $\chi^2$ Iteration

The $\chi^2$ uses the same basic approach as does the Equi-Zenith approach, but calculates a value of $\chi^2$ based on the ratio of the observed values of $N_{on}(t, \theta, \phi)$ to the ideal values, $I$, of the CRs intensity as a function of $t$, $\theta$ and $\phi$. We define $I_{i,j}$ to be the CRs relative intensity for declination bin (j) and right ascension bin (i). With minor modifications for notational convenience, we then use $N_{i,j,\theta,\phi}$ and $N_{off,i,j,\theta,\phi}$ to express the number of events and background.
Finally, we constructed a $\chi^2$ equation:

$$\chi^2 = \sum_{t,\theta,\phi} \left( \frac{N_{t,\theta,\phi} I_{k}^{ij}}{I_{k}^{ij}} - 1 \right)^2 \sum_{\phi'=1}^{n_{\phi}'} \frac{N_{t,\theta,\phi',\phi}}{I_{k}^{ij'}} \right)^2$$

This expression was minimized by adjusting the values of $I_{k}^{ij}$, where $k$ represents the iteration times. In the actual calculation, the initial values of $I_{k}^{ij}$ were taken to be 1. After many iterations, we obtain a minimized $\chi^2$ value, and the values of $I_{k}^{ij}$ that provide this minimum. The error $\sigma_{I_{k}^{ij}}$ can then be readily obtained. Consequently, the significance for the direction $(i,j)$ can be calculated as follow:

$$s_{i,j} = \frac{I_{k}^{ij} - 1}{\sigma_{I_{k}^{ij}}}$$

There is a caveat that applies to the $\chi^2$ iteration technique. When the $\chi^2$ equation is set up for a given data set, if the number of events in $N_{\text{on}}$ is too small the $\chi^2$ equation will not be convergence properly, and will give an unreasonable value. That is to say, the experiment data selected for analysis must be sufficiently large with the result that this technique is most suited for dealing with long term observation data.

3 Azimuth Correction

As mentioned above, we know that there are a number of reasons leading to an uneven distribution of data in the azimuth and that this uneven distribution can be very stable as a function of time. For example, the azimuthal distribution of the YBJ-ARGO data shows an uneven distribution with an amplitude of about 2%. As yet, there is no clear explain for this distribution, but a consensus is that it is caused by either an uneven acceptance in the detector system and by the geomagnetic field. Nevertheless, we must correct this effect when we use equi-zenith angle technique. A serious question that then arises is whether or not a true large scale anisotropy in the data will be discernable after this correction to the azimuthal data is made. To answer this question, we analyzed the data sets D2 and D3 with the $\chi^2$ iteration technique. Figure 4 displays a two dimensional sky map of relative intensity with the anisotropy distribution from the D3 samples after the azimuth has been modified. The data have been smoothed using an angle of 5° in equatorial coordinates. Figure 5 shows the relative intensity, a function of right ascension form D3 samples. The smooth curve is the expected intensity function, and the dotted line is the result what we get from $\chi^2$ iteration technique after azimuth modification.

4 Summary and Discussion

EAS CRs array experiments, search for TeV gamma ray sources, have the advantage of wide angle scanning of the sky. EAS experiments also have the advantage of being able to study CRs’ large scale anisotropy. In this work we have studied, using simulated data, two techniques for scanning the sky based on the Equi-zenith angle method. Although the simple Equi-zenith angle method is direct and easy to deal with, it can not analyze the large scale anisotropy exactly. The $\chi^2$ iteration technique, however, is found to give accurate results. In addition, we have also shown that the azimuth modification commonly used to compensate for instrumental or environmental asymmetry can give reasonable result, even if there exists a large scale anisotropy in the CRs background. It also proved that the anisotropy CRs detected by ARGO experiments is not be introduced by analysis method but real exist.

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