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Correlations of Ultrahigh Energy Cosmic Rays with BL Lac Objects - Is there Evidence for Neutral Primaries ?

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The authors of a recent publication [1] have claimed significant correlations between BL Lacertae objects and ultra-high energy cosmic rays above 10 EeV observed by the High Resolution Fly's Eye (HiRes) experiment. Out of 271 HiRes events, ten events are observed within 0.8 degrees of BL Lacs, consistent with the HiRes angular resolution. If the BL Lacs are the sources of these events, the cosmic ray must travel most of its path as a neutral particle — a gamma ray, for instance. In this paper, we present a method to study the shower maximum distribution of the correlated events to put an upper limit on the fraction of gammas in the set.

1. Introduction

A recent publication [1] has suggested correlations between BL Lacs and ultra-high energy cosmic rays above 10 EeV observed by HiRes. The angular separations between these HiRes events and the cited BL Lacs are less than $0.8°$, which is significantly smaller than the expected angular deflection of charged particles in galactic magnetic fields. Hence, the authors inferred that the correlated events must be neutral particles originating from the BL Lacs. The correlations are discussed in detail in [2].

The purpose of this paper is to discuss a method that places an upper limit on the expected number of gammas to be observed by HiRes originating from these BL Lacs. The distribution of X_{max}, the atmospheric depth of shower maximum observed by the HiRes detector, will be used to distinguish the composition.

2. The Confidence Limit Calculation

In what follows, we will describe the method used to calculate an upper limit on the number of photon primaries in the sample of events correlation with BL Lac objects. We will use the term 'confidence limit' to refer an the upper bound on the number of events for some 'confidence level'. The confidence level is the probability that the true mean number of events expected from an experiment is below some confidence limit. To calculate an upper limit of gammas in the sample, we use a simple confidence limit calculation to evaluate the maximum mean number of gammas what would be expected in the sample.

To calculate the confidence limit, we divide the X_{max} distributions into N bins. If p_i (g_i) represents the mean number of hypothesized proton (gamma) events in the i^{th} bin, then

$$d_i = \epsilon_p \tilde{p}_i + \epsilon_f \tilde{g}_i = p_i + f_i \tag{1}$$

is the number of hypothesized data events in the i^{th} bin, where ϵ_p and ϵ_g are given by

$$\epsilon_p = \frac{p}{\sum_{i=1}^{N} P_i} \tag{2}$$

and

$$\epsilon_g = \frac{g}{\sum_{i=1}^{N} G_i}. \tag{3}$$

Table 1. List of parameters used in confidence limit calculation.

Parameter	Definition
N	$N = \left(\int_{g=0}^{\infty} dg \int_{p=0}^{\infty} dp \sum_{E^{-2},E^{-3}\ proton\ spectra} \prod_{i=1}^{MBins} \frac{d_i^{D_i} e^{-d_i}}{D_i!} \frac{\tilde{p}_i^{P_i} e^{-\tilde{p}_i}}{P_i!} \frac{\tilde{g}_i^{G_i} e^{-\tilde{g}_i}}{G_i!} \right)^{-1}$
$\tilde{d}_i$	Number of hypothesized data events in the i^{th} bin scaled to the luminosity in the Monte Carlo
D_i	Number of data events in the i^{th} bin
$\tilde{p}_i$	Number of hypothesized proton events in the i^{th} bin scaled to the luminosity in the Monte Carlo
p	Number of hypothesized proton events $= \sum_{i=1}^{N} p_i$
P_i	Number of Monte Carlo proton events in the i^{th} bin
$\tilde{g}_i$	Number of hypothesized gamma events in the i^{th} bin scaled to the luminosity in the Monte Carlo
g	Number of hypothesized gamma events $= \sum_{i=1}^{N} g_i$
G_i	Number of Monte Carlo gamma events in the i^{th} bin

The parameters ϵ_g, $\tilde{g}_i$, G_i, ϵ_p, $\tilde{p}_i$ and P_i are dependent on the proton and gamma energy spectra. Both $\tilde{p}_i$ and $\tilde{g}_i$ will be marginalized. The parent spectra are obviously unknown, so we marginalize the spectra by summing the probabilities of E^{-2} and E^{-3} proton and iron spectra. The number of gamma events (N_0) can be ruled out at some confidence level by finding N_0 through the equation

$$\text{Confidence Level} = N \int_{g=0}^{N_0} dg \int_{p=0}^{\infty} dp \sum_{E^{-2},E^{-3}} \sum_{proton\ spectra} \prod_{i=1}^{MBins} \frac{d_i^{D_i} e^{-d_i}}{D_i!} \frac{\tilde{p}_i^{P_i} e^{-\tilde{p}_i}}{P_i!} \frac{\tilde{g}_i^{G_i} e^{-\tilde{g}_i}}{G_i!}. \quad (4)$$

For reference, full list of parameters is given in Table 1. Since the gamma spectrum is unknown, the proton and gamma spectra are marginalized by summing over E^{-2} and E^{-3} spectra.

Since we will be calculating a confidence limit essentially using a Bayesian approach, we should be sure that our results are, in the least, conservative from a frequentist point of view.

To check our definition of confidence levels, we create statistically independent fake data sets using a parent X_{max} distribution of gammas generated with a E^{-2} spectrum and protons generated with an E^{-3} spectrum. Different spectra are used to ensure the method works if the proton and gamma spectra are different. We add the two distributions with various fractions of gammas and protons and the normalize the parent distribution to 10 events. We then fluctuate bin of the parent distribution according to Poisson statistics to produce one fake data set and calculate the 95% confidence limits for gammas using four likelihoods: that which (1) marginalizes the proton and gamma spectra, (2) assumes an E^{-2} gamma spectrum and marginalizes the proton spectra, (3) assumes an E^{-3} gamma spectrum and marginalizes the proton spectra, (4) assumes an E^{-2} gamma spectrum and E^{-3} proton spectrum. The number of times the true mean for gammas falls under the confidence limit is then divided by the total evaluated.

If we were to interpret the results from a frequentist perspective the quoted confidence level should be a lower bound on the calculated confidence level. The calculated levels asymptotically reach the Bayesian confidence level as the number of gammas increases, when it becomes less likely that the number of gammas will fluctuate to zero events.

3. Acknowledgments

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