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Limit On The Ultra High Energy Gamma Ray Flux Using HiRes Stereo Data

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Abstract: Measuring the cosmic gamma ray flux at super-GZK energies is of significance in both observing the GZK effect and putting constraints on more exotic models of the origin of UHECRs. At these energies, gamma ray primaries interact with the earth's magnetic field before they enter the atmosphere.

We have developed a simulation of gamma ray preshowers to study their effect on the profile on the extended air shower. By comparing the measured X_{max} distribution in the HiRes stereo data to both gamma ray and hadronic Monte Carlo simulations, it is possible to derive an upper limit on the gamma ray fraction measured.

Introduction

The chemical composition of the highest energy cosmic rays remains loosely determined after many years of measurement. Qualitative methods [1] have provided evidence of a shift in composition and suggest a light hadronic composition. For an air fluourescence detector such as HiRes[2], the principle window onto the primary composition is the observation of the extended air shower profile in the atmosphere. Heavier particles, with larger cross-sections, produce showers which develop high in the atmosphere. Lighter particles produce showers at greater atmospheric slant depth, X. Thus the general technique to discriminate between different candidate primary species of an observed cosmic ray shower is to compare the depth of shower maximum, X_{max} to the expected distribution of X_{max} for that species.

Since no pure samples of cosmic ray showers of known primary species exist, it is necessary to use computer simulations to provide the X_{max} distributions with which the data is to be compared. In the case of ultra-high energy gamma rays, the simulation should take into account the chance of interaction between the gamma ray and the earth's magnetic field, known as the geomagnetic preshower effect.

Gamma Ray Preshowers

Gamma rays incident on the geomagnetic field with energies above $10^{19.6}$ eV can interact via pair-production with a magnetic field photon. The resulting pair can emit hundreds of secondary photons via magnetic Bremsstrahlung before reaching the atmosphere. Even at primary energies of 3×10^{20} eV, the highest energy cosmic ray ever observed [3], the secondary photons are not likely to possess enough energy to pair produce again.

The production of many lower-energy photons via this mechanism is known as a preshower. Upon entering the atmosphere the preshower will trigger an extended air shower, which will develop faster than that produced by a single photon of equal energy. This change in shower development will manifest itself in a reduced $\langle X_{max} \rangle$.

Since the probability of pair production depends on the ratio $E_\gamma / B_\perp$, that is the ratio of the primary gamma ray energy to the transverse component of the magnetic field, the likelihood of a preshower occurring is direction-dependent. Near the threshold energy for this effect, only those gamma rays incident perpendicular to the magnetic field vector will produce a preshower. At higher energies, almost all directions will have a strong preshower probability, although gamma rays incident along the magnetic field vector would probably be unaffected. The directions of high $B_\perp$ will tend to produce the preshower further away from the atmosphere, and hence the preshower will consist of more particles than if the pair production happened close to the atmosphere.

Simulation Technique

The ACME Preshower Simulation

Gamma ray preshowers are simulated by a program called ACME. The simulation starts with a gamma ray of given energy at a (configurable) range of 6×10^9m, where the magnetic field of the earth is not strong enough to cause a preshower at the gamma ray energies we are considering. The gamma ray is moved in small steps over which the magnetic field can be assumed to be constant. For each step, the probability of a pair production event is calculated and then used in a Monte Carlo decision as to whether pair production actually occurs during that step.

In the event of pair production, the resulting electron/positron pair is followed, and for small steps along their path the probability of emitting a Bremsstrahlung photon is calculated and used in a Monte Carlo throw. Since the chance of Bremsstrahlung is much higher than that of the initial pair production, we must consider the possibility of multiple Bremsstrahlung emissions in each step. In fact, the simulation avoids this issue by reducing the step size according to electron energy and magnetic field strength, such that for any given step, the probability of multiple Bremsstrahlung emissions is negligible. For the highest energy electrons in the strongest magnetic fields near the earth, this results in the smallest simulation step size of tens of meters, for which there is a non-negligible probability of single Bremsstrahlung emission but no significant opportunity for multiple emission.

The actual Bremsstrahlung emission probability is an expensive calculation, involving a numerical integration over the Bremsstrahlung spectrum. In order to improve simulation preformance, a two-dimensional polynomial interpolation in electron energy and $B_\perp$ is precalculated and used. This results in a perfomance increase of several orders of magnitude.

The Simulation Chain

The ACME preshower simulation must be combined with an extended air shower simulation in order to produce a model of the shower profile in the atmosphere. The simplest method of doing this is to use the preshower simulation to follow the preshower up to the edge of the atmosphere (altitude 112km), then take all the particles in the preshower and use them as the initial state of an air shower simulation such as CORSIKA[4] or SENECA[5]. In this work, we have used CORSIKA with the GHEISHA electromagnatic generator. In CORSIKA, the preshower is loaded using the STACKIN directive.

Each preshower is developed as an extended air-shower and the longitudinal shower profile is saved. We then use the shower profile as input to our detector simulation. The shower is propagated through the detector simulation which includes the detector geometry effects, simulation of the atmosphere, simulated electronic noise etc.

In an event-by-event comparison, in which one would examine the probability that any given HiRes cosmic ray event was a gamma ray, we produce a sample of simulated gamma-induced showers which have the input parameters of the measured event. In this case we also provide the detector simulation with the atmospheric parameters that were measured at the observation of the event.

The final step of the event-by-event comparison is to take all of the showers which triggered the detector in the simulation and process them with the HiRes stereo reconstruction program. The resulting data provides an X_{max} distribution which is our best theoretical estimate of how a gamma ray matching the event paramters would be seen by the HiRes detector. The simulated gamma X_{max} distribution, along with a similar simulated proton distribution, may then be compared to the measured X_{max} for this event.

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