Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 2 (OG part 1), pages 309–312

Synchrotron radiation from primary cosmic ray electrons: Monte Carlo studies of event topologies and potential backgrounds at balloon altitudes

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Abstract: The balloon-borne Cosmic Ray Electron Synchrotron Telescope (CREST) experiment will measure the flux of cosmic ray electrons at energies greater than 2 TeV by detecting the x-ray component of the synchrotron radiation emitted as the electrons traverse the Earth's magnetic field. This method enhances the instrument acceptance to several times its geometric area. Monte Carlo simulations of electrons traversing the atmosphere were performed in order to calculate the acceptance of CREST and characterize synchrotron radiation patterns at balloon altitudes. The study results influence the design of CREST and potential future instruments using a similar detection technique.

Introduction

The goal of the balloon-borne Cosmic Ray Electron Synchrotron Telescope instrument is to measure the flux of cosmic ray electrons at energies greater than 2 TeV. The flux of these very high-energy electrons is indicative of the abundance of local acceleration sites in the galaxy. An Antarctic flight is planned for the austral summer of 2009/10. A detailed description of the instrument is given elsewhere in these proceedings [1].

The instrument does not directly detect the electrons, but instead detects the x-ray synchrotron photons from the electrons as they bend in the Earth's magnetic field. The use of synchrotron photons in this manner has been proposed previously [2, 3]. The technique takes advantage of the preferential emission of synchrotron radiation in a narrow forward cone. The result is a line of photons many hundreds of meters long at balloon altitudes whose average energy is a strong function of the energy of the primary electron.

The instrument consists of an array of 1024 BaF_2 crystals (5 cm diameter x 2 cm) viewed by photomultiplier tubes (PMTs). The crystals are surrounded by a plastic scintillator veto system to reject charged particle signals. The detection of a high energy electron is based on the observation of signals above a threshold of ~ 20 keV in multiple co-linear hits in the BaF_2 array, all occurring with the proper relationship in time, and in the absence of signals consistent with a through-going charged particle in the veto system. By indirectly detecting the electrons, the effective area A_{eff} of the instrument is larger than its physical dimensions. Simulations are necessary to understand the synchrotron event rate, instrument acceptance, and signal event topology in time and space.

Synchrotron radiation is emitted in a broad spectrum characterized by the critical energy E_c, defined as the energy above which half the power is radiated. For a 2 TeV electron propagating in a magnetic field with a component of 0.1 gauss perpendicular to the electron propagation direction, E_c = 27 keV. The critical energy scales linearly with the strength of the perpendicular component of the magnetic field $B_\perp$ and with the square of the Lorentz factor γ of the primary electron. A critical energy E_c = 40 keV in the same

$B_\perp$ as above corresponds to a primary electron energy around 2.5 TeV, while for a 50 TeV electron, $E_c = 16.6$ MeV.

Backgrounds to the signal events generated by ultra-high energy (UHE) electrons can arise due to a random coincidence of cosmic and atmospheric x-rays that satisfy timing and co-linearity requirements, as well as particle interactions and showers in the vicinity of the instrument and in the instrument itself. If the identification of an electron event requires a minimum number of co-linear coincident photons $n_\gamma = 4$, each with energy greater than 40 keV, all arriving within a 6 ns window in time, calculations show that roughly one background event of this type is expected over a 30 day flight. A full understanding of potential backgrounds due to atmospheric showers in the vicinity of the instrument requires a detailed simulation.

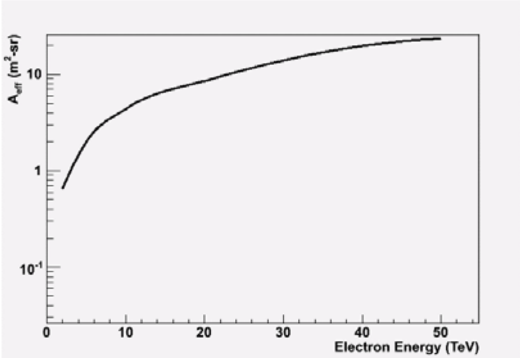

Figure 1: CREST effective area as a function of primary electron energy

Simulations of synchrotron radiation

Geometry and physics details

The simulation software designed to characterize the synchrotron events and determine the acceptance of CREST models a 400 km high flat atmosphere as a single layer without material. Primary electron tracking and synchrotron generation are extracted from GEANT3.2.1 particle physics simulation software. Electrons are generated at a single point with an isotropic distribution and tracked through to instrument depth. The electron tracking in the magnetic field is performed by the GEANT3 Runge-Kutta algorithm. The magnetic field model used in this study is based on the International Geomagnetic Reference Field (IGRF) for 2003 at the location of McMurdo Station, Antarctica. Photons are tracked in straight lines to instrument depth. A file is written containing details of photon creation heights, hit locations, energies, relative arrival times, and direction cosines for each event.

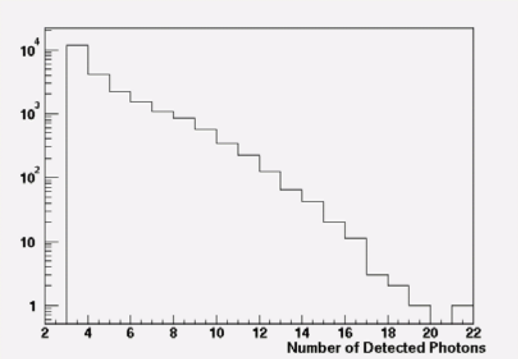

Figure 2: Distribution of number of detected synchrotron photons for a 20 TeV primary electron.

Analysis method

The output of the simulation is subsequently used to characterize the instrument acceptance, A_{eff}, which is calculated as a ratio of the number of potentially detectable events to the number of incident primary electrons multiplied by the physical area of the instrument. A potentially detectable event is defined as one, which meets the criterion of $n_\gamma \geq 4$, where only photons with energies greater than 40 keV are counted.

A post event-generation analysis performs the photon attenuation in the atmosphere and characterizes the detector response. A survival probability due to atmospheric absorption is assigned to each photon in an event. Pair production, Compton scattering, and photoabsorption are included. Scattered photons are assumed lost. Note that Rayleigh scattering is ignored, but this is always at least an order of magnitude smaller than the sum of the three included processes. To determine the detector response, the event is centered randomly on the CREST instrument. Each photon is then tested to see if it hits one of the crystals, and if so, the energy deposited in the crystal is calculated.

The number of potentially detectable events is determined by dividing up the atmospheric layer into equal area bins, each the size of the CREST instrument physical dimensions, then examining each bin to determine if these criteria are met using the results from the processing described above.

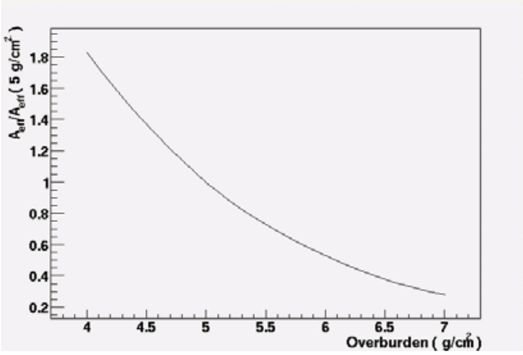

Figure 3: Relative effective area for CREST as a function of atmospheric overburden for a 5 TeV electron

Results

Several results of the simulation are pertinent to the design of detectors utilizing synchrotron radiation to detect UHE energy electrons. The simulations indicate that photons travel together, so that the time difference between arrival times is purely geometric. For CREST the maximum time expected for photons arriving on a horizontal area the size of CREST from a single primary is 6 ns. Their spatial arrangement is extremely linear. (This is also indicated by a full GEANT4 model of the atmosphere –still under development– with all charged particle tracking and photon physics included.) The mean zenith angle of incident photons is about 60°. This large average zenith angle is due primarily to the stronger $B_{\perp}$ at polar latitudes for grazing incidence. This high angle of incidence is taken advantage of by spacing the BaF_2 crystals in an open lattice, using the crystal sides as additional detection area.

Figure 1 shows the effective area A_{eff} plotted as a function of the incident electron energy for an instrument size of 2.3 m x 2.3 m. The increase of A_{eff} with energy is essential for the success of the CREST instrument. The number of photons per detectable event is an important trigger consideration for CREST, and is shown in Figure 2.

Since balloon-borne instruments are subject to fluctuations in the atmospheric overburden due to height variations over the course of the flight, the effective area is plotted as a function of depth in Figure 3. This indicates a preference for the highest possible flight altitude.

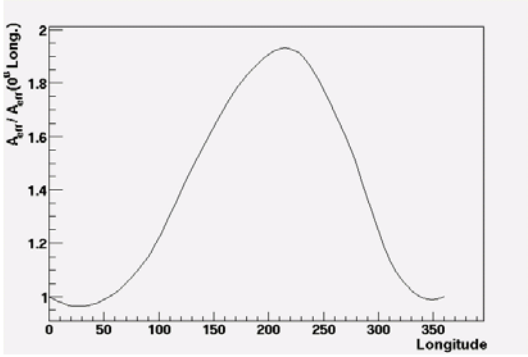

Figure 4: Variation of effective area with longitude.

The deviations in the Earth's magnetic field change the effective area as a function of position relative to the magnetic pole. At the latitude of the expected launch location of McMurdo Station, Antarctica, the dependence of effective area with longitude with respect to A_{eff} at a longitude of 0° is shown in Figure 4. Careful accounting of this effect is necessary in the data analysis.

The potential for reconstruction of the primary electron energy is demonstrated in Figure 5, in which the dependence of the average detected photon energy is presented as a function of the primary electron energy. The average photon energy of an event scales approximately as the square of the primary electron energy. There is roughly a factor of two uncertainties in the primary energy for a given event.

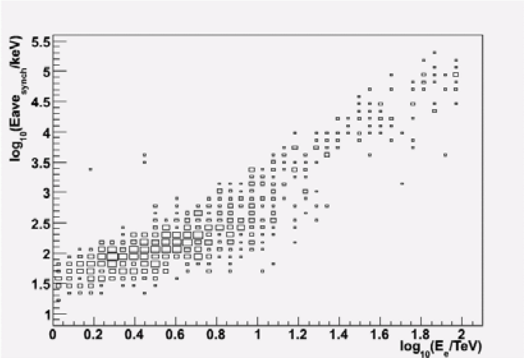

Figure 5: Scatter plot of the event-averaged x-ray signal versus the energy of the primary electron.

Conclusion

Detecting synchrotron photons from primary high energy electrons increases the instrument acceptance. Higher energy electrons are preferentially accepted. Characteristics of synchrotron photons, such as simultaneity and co-linearity, provide clear identification of an UHE electron event.

The resolution of the instrument's measurement of the primary electron energy is sufficient to determine the energy spectrum of UHE electrons. CREST will clearly see an energy cutoff in the spectrum, should it exist, by the absence of events with high average photon energies.

The background to the experiment is minimal. The largest background contribution is from the purely random x-ray flux. The requirement that candidate events have co-linear photons provides strong background rejection.

Acknowledgments

This work is supported under NASA contracts NNG04WC34G, NNG04WC32G, NG04WC36G, NNG04WC07G, and the Kentucky Space Grant. We would like to thank the Columbia Scientific Balloon Facility and the CSBF launch crews for their excellent support of balloon missions, and we acknowledge contributions from Mike Duvernois and J. Taylor Childers.

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