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A Direct Cerenkov Observatory for High-Energy Cosmic Rays

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Abstract: A design concept for a future ground-based cosmic-ray observatory using the Direct Cerenkov technique will be presented. This technique can provide high precision, largely model-independent measurements of the energy and charge of heavy cosmic-ray primaries in the region of the knee. It does so by exploiting the direct component of Cerenkov radiation emitted by these primaries prior to their first hadronic interaction in the atmosphere. The promise of the technique has recently been verified with measurements made by gamma-ray observatories.

Introduction

A long-standing goal of the cosmic-ray community has been to extend the energy reach of precise abundance measurements to at least the region of the knee. The challenges in achieving this are well-known: first, the cosmic ray particle flux drops very rapidly with energy - necessitating large detectors or long exposure times; second, the thickness of the atmosphere prevents the direct collection of the primary particles in ground-based detectors. As a result of this, cosmic ray studies have naturally evolved into two distinct styles: direct observations, wherein particle detectors are flown on balloons or spacecraft above the atmosphere to collect cosmic rays before they encounter the atmosphere; and indirect observations, where detectors at ground level examine the secondary (or tertiary) products of cosmic ray interactions in the atmosphere. From the properties of these secondaries, indirect techniques then infer the nature of the primary particles.

By leveraging the technology and instrumentation methods of high-energy physics, direct observations have, to date, produced the most precise measurements of cosmic rays that are available. The charge resolution (dZ/Z - RMS) of these detectors is typically better than 3%. The drawback to direct observations is that, for fiscal and logistical reasons, the size of these instruments is constrained to be relatively small, of order ~ 1 m^2. This severely limits their ability to target particles at the highest energie (e.g., E $> 10^{14}$ eV total energy).

Indirect observations, on the other hand, are able to take advantage of an interesting magnifying effect which occurs when cosmic rays interact in the atmosphere. After a particle interacts in the atmosphere, it produces an extensive air shower of secondary particles. These secondaries (which can be electrons, muons, and Cerenkov or fluorescence photons, etc) are spread out over a footprint which can extend for hundreds of meters. Any particle detector within this footprint can, therefore, "see" the primary particle. This leads to an effective area which can be many orders of magnitude greater than the actual physical size of the detector elements. In essence, for indirect studies, the atmosphere becomes part of the detector system. This methodology has been used for many years, for example, in gamma-ray astronomy, to estimate the energy of cosmic ray events by measuring the ground-level density of Cerenkov photons produced in the electromagnetic cascades of those events. Such techniques can typically achieve an energy resolution of better than 20% (see e.g., [1], or [2].)

From the point of view of cosmic ray abundance measurements, however, indirect methods are not ideal. Not only do they depend closely on hadronic interaction codes to interpret their observables, but

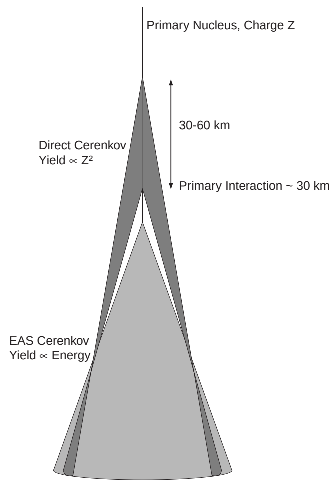

Figure 1: Schematic representation of the different Cerenkov light production regions in a cosmic ray-induced air shower. Taken from [3].

these observables themselves tend to be only logarithmically sensitive to the mass (or charge) of the primary particles. Thus, instead of clearly resolved charge peaks, the results of indirect measurements tend to be wide distributions of single parameters, to which different charge contributions must be fit.

A long-pursued goal in cosmic ray physics has been the combination of the precision of direct observations with the effective area of indirect measurements. As first reported by Kieda, Swordy, and Wakely [3], such a method might be possible by targeting the Cerenkov light produced directly (DC light) by the primary cosmic ray prior to its first interaction in the atmosphere.

Direct Cerenkov Light

High energy charged particles entering the atmosphere will generate Cerenkov light if they are above the Cerenkov threshold. This threshold varies with altitude, but occurs at a Lorentz factor, γ , of ~ 700 at an altitude of ~ 50 km. By combining a measurement of this direct Cerenkov light (which has, in fact, been measured at balloon altitudes [4, 5]) with a measurement of the Cerenkov light produced in the shower, a simultaneous determination of energy and charge of each primary particle can be made. Since the Cerenkov yield scales with the nuclear charge of the primary as Z^2, the intrinsic precision of the technique is superior to any of the other indirect methods. Furthermore, since it is produced at high altitudes, the DC light is spread over a large area at the earth, providing an enhancement in the effective area, as in other indirect methods.

Importantly, since the Cerenkov yield saturates at high energy, the DC yield is essentially independent of energy, for sufficiently high-energy particles. This stands in contrast to the shower Cerenkov light, which scales nearly linearly with the energy of the particle, and has only a weak dependence on the primary mass/charge. The principle difficulty in exploiting these two complementary forms of Cerenkov emission is in finding a way to separate the two components well enough to make an independent measurement of each. The key to achieving this can be found by recognizing the different production regions for these two kinds of Cerenkov light (See Figure 1).

Time and Angle Differentiation

The direct Cerenkov light is produced high up in the atmosphere (H > 30 km), where the atmospheric density and index of refraction are low. Hence, the maximum Cerenkov opening angle ($cos[\theta_C] = 1/n$) is small, of order 0.1 degrees. In contrast, the Cerenkov light associated with the air shower is produced lower in the atmosphere (typically H < 20 km), where the density is exponentially larger. As a result, the Cerenkov opening angle is roughly an order of magnitude larger, of order 1.0 degrees.

A second difference can be found in the arrival time of the photons. The DC photons, which are produced at the top of the atmosphere, must propagate at a velocity c/n to the ground, whereas the development of the shower proceeds at velocity c. Hence, Cerenkov photons produced in the air shower will arrive at the ground a few nanoseconds prior to the DC photons. These two differences, in time and angle, can be used to explore the possibility of doing DC light measurements from the ground.

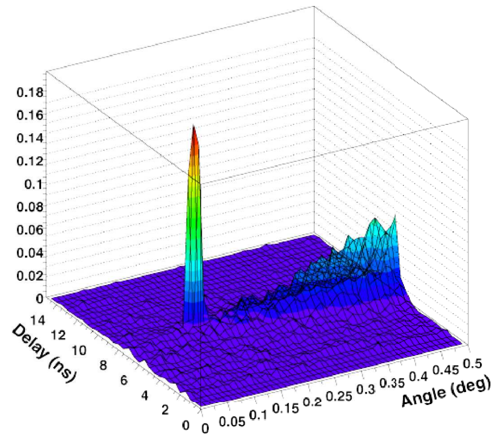

Figure 2: Simulation of Cerenkov light density (arbitrary units) produced by a vertically-incident 100 TeV cosmic ray iron nucleus. The large spike is due to DC production, while the smaller ridge to the right is due to air shower-produced Cerenkov.

Air Shower Simulations

Figure 2 shows the results of a CORSIKA [6] simulation of a single 100 TeV iron nucleus entering the atmosphere and interacting at $\sim$30km. What is shown is a 2D histogram of the ground-level photons density versus their arrival time and angular direction. The sharp spike at $\sim 0.15°$ and 8ns is the contribution of DC photons. The ridge to the right is the beginning of the air shower light, which continues off the plot, out to angles of 1.0 degrees or more. Clearly, the “signal to noise” of the DC/shower Cerenkov is excellent in the region of the spike (for iron nuclei, the DC contribution alone amounts to $\sim$100 photons/m^2), indicating that a high-resolution Cerenkov camera with adequate angular and temporal resolution ($\sim 0.05°$ and ~ 1 ns, respectively) could separate these components and make a simultaneous event-by-event determination of charge and energy.

Detector Technology and First Observations

The technology required to make direct Cerenkov observations currently exists - albeit in a simpler form - in the present generation of ground-based TeV gamma-ray detectors, such as VERITAS, MAGIC, and HESS. These instruments use large 12m imaging reflectors with fast photodetectors to map the angular scales of air shower Cerenkov events into 2D representations with angular pixelation of ~ 0.15 degrees. In these instruments, the angular and temporal resolution is roughly 2-3 times too coarse in time and angle to fully separate the DC component of Cerenkov light from the shower component. As a result when viewing a DC event, the shower emission will bleed into the region of the DC spike, washing it out. The expected response from such an instrument is simply a “hot” pixel located at the end of the shower ellipse. Events with exactly this topology have now been verified by two gamma-ray instruments[7, 8] and the DC technique has even been used to generate an initial spectrum of cosmic iron nuclei [9]. Figure 3 shows DC events as seen by the HESS and VERITAS gamma-ray telescopes.

Expected Performance

As detailed in [3], with a dedicated observatory of sufficient angular and temporal precision, DC technique could achieve charge and energy resolution approaching $\sim$15%. The effective area of such an observatory will depend on the number and configuration of individual telescopes deployed. Figure 4 shows the results of a simple optimization exercise in which a four-telescope array is allowed to vary in baseline. The figure shows that with a spacing of ~ 50m, a dedicated DC observatory would achieve $\sim 10^4$ m^{2}sr days of stereo exposure in 1 year of operation, assuming a 9% duty cycle. This is roughly 2 orders of magnitude more than the largest exposures thus far achieved on balloon platforms. The three-telescope exposure (which should yield the highest-quality events) is smaller, but still a very respectable 10^3 m^{2}sr days per year. The expected range of useability of the technique depends on the charge of the primary particle (see [3] for more details) being observed, but, for iron nuclei extends over several orders of magnitude to at least 1 PeV, and perhaps beyond. Studies are under way to explore this ultimate upper limit.

One very important aspect of the technique is that, because the Cerenkov yield depends purely on well-understood electromagnetic emission processes, the technique is largely free from the systematic uncertainties arising from hadronic model-

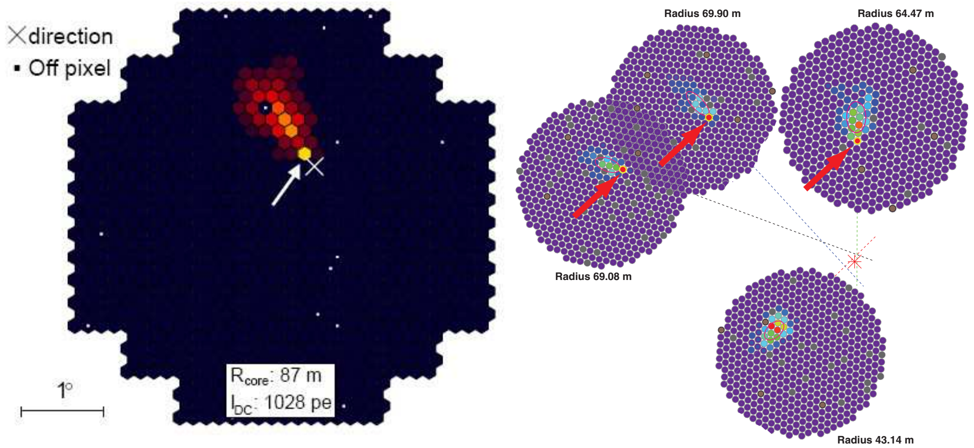

Figure 3: Cosmic ray events featuring DC emission, as seen in two gamma-ray telescopes. The left panel is an event seen in a HESS telescope. The right panel is an event seen by the VERITAS array. Here DC light is visible in 3 or the 4 telescopes. In both plots the DC pixels are indicated with arrows. See text for references.

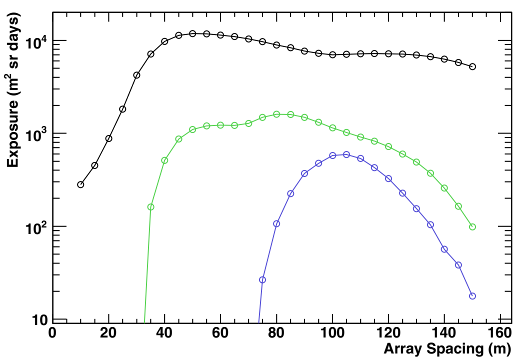

Figure 4: Optimization study of array spacing for a square array of DC telescopes. The 3 different lines correspond to the number of telescopes hit by the DC light in the event (from top to bottom, 2,3,4). The drop off at high spacing is due to the limited footprint of the DC light pool on the ground.

ing.

Conclusions

The Direct Cerenkov technique, a new method for doing cosmic ray research, has been presented. Featuring high precision and large effective area, it has the potential to allow new advances in high-energy cosmic ray measurements. Furthermore, because it offers an event-by-event determination of particle identity, free of dependencies on hadronic interaction codes, it actually has the possibility to calibrate those codes, if used in conjunction with traditional air shower techniques. The existence of DC light has now been confirmed, and even used to generate an initial spectra of heavy cosmic rays. Simple simulations indicate that a four-station array of instruments could achieve an exposure factor of $\sim 10^4$ m^2 sr days per year of operation. This is ~ 100 times larger than any existing direct measurement and is more than sufficient to extend precise elemental measurements of cosmic rays past the region of the knee.

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