

# Ground-based Observations of TeV Cosmic Rays using Direct Cerenkov Radiation

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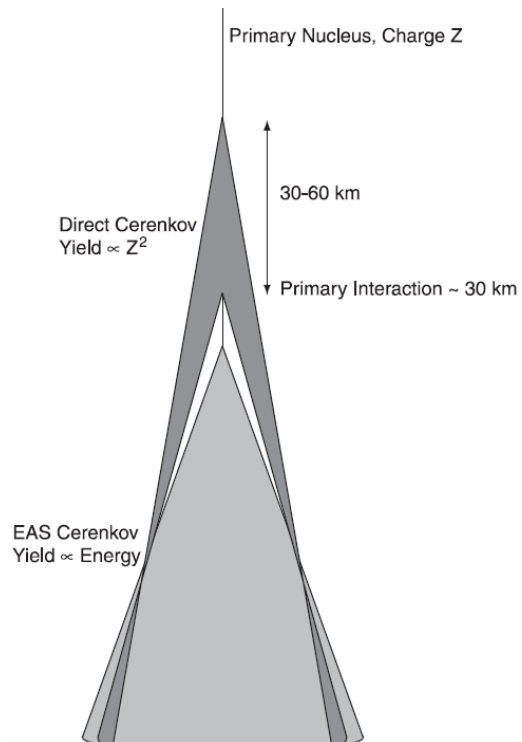
**Abstract.** A new method for making high-resolution ground-based measurements of the energy and charge of cosmic ray primaries in the region of the knee is presented. The method exploits the direct component of Cerenkov radiation emitted by cosmic ray nuclei prior to their first hadronic interaction in the atmosphere. A dedicated ground-based Direct Cerenkov detector could achieve model-independent charge and energy resolution as good as 15%, on an event-by-event basis.

## 1. Introduction

It has been long recognized that one of the keys to understanding the nature and origin of cosmic rays lies in extending high precision measurements of the particle flux to as high an energy as possible, preferably to at least the region of the cosmic ray “knee”, at  $\sim 3 \times 10^{15}$  eV. The impediment to this is twofold: first, the particle flux drops very rapidly with energy – necessitating large detectors or long exposure times at high energies; second, the thickness of our atmosphere ( $\sim 1000$  g/cm<sup>2</sup>) prevents the direct observation of primary particles from the ground.

As a result of this, cosmic ray studies have separated into two general styles of observation: direct observations, wherein particle detectors are flown (on balloons or spacecraft) above the atmosphere to collect cosmic rays; and indirect observations, where detectors at ground level examine the secondary products of cosmic ray interactions in the atmosphere, and from them infer the properties of the primary particles.

Direct observations have produced the most precise measurements of cosmic rays that are available; precisely because these detectors leverage the technology and instrumentation of the high energy



**Figure 1. Schematic representation of Cerenkov light production from a cosmic ray. Taken from [1].**

physics community. 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 limited to roughly  $\sim 1 \text{ m}^2$ . This severely limits their ability to target the highest energy ( $E > 10^{14}$  eV total energy) particles.

Indirect observations, on the other hand, are able to take advantage of the “magnifying” effect of cosmic ray interactions in the atmosphere. After a particle interacts in the atmosphere, producing an extensive air shower of secondary particles, these secondaries (which can be electrons, muons, or 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, producing an effective area which can be many orders of magnitude greater than the actual physical size of the detector element. In essence here, the atmosphere becomes part of the detector system, and by measuring the detailed properties of the secondary flux, the properties of the primary particle can be inferred. For example, this methodology has been used for many years to measure the energy of cosmic ray events by measuring the ground-level density of Cerenkov photons produced in the electromagnetic cascades they produce, typically with energy resolution of better than 20%. (This is the “air-Cerenkov” technique; for short but interesting review, see [2].)

From the point of view of hadronic cosmic ray measurements, however, indirect methods are not ideal. Not only do they depend on poorly-informed hadronic interaction codes to interpret their observables, but 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 single wide distributions, 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 [1], 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.

## 2. 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 roughly a Lorentz factor,  $\gamma$ , of  $\sim 700$  at an altitude of 50km.

By combining a measurement of this direct Cerenkov (DC) light with a measurement of the Cerenkov light from the shower, a simultaneous determination of energy and charge can be made. Furthermore, 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 indirect methods. Additionally, 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 with only a weak dependence on the primary mass. The principal difficulty is in finding a way to separate the two components well enough to make an independent measurement of each. The key to achieving this lies in identifying the different regions of production of the two kinds of Cerenkov light.

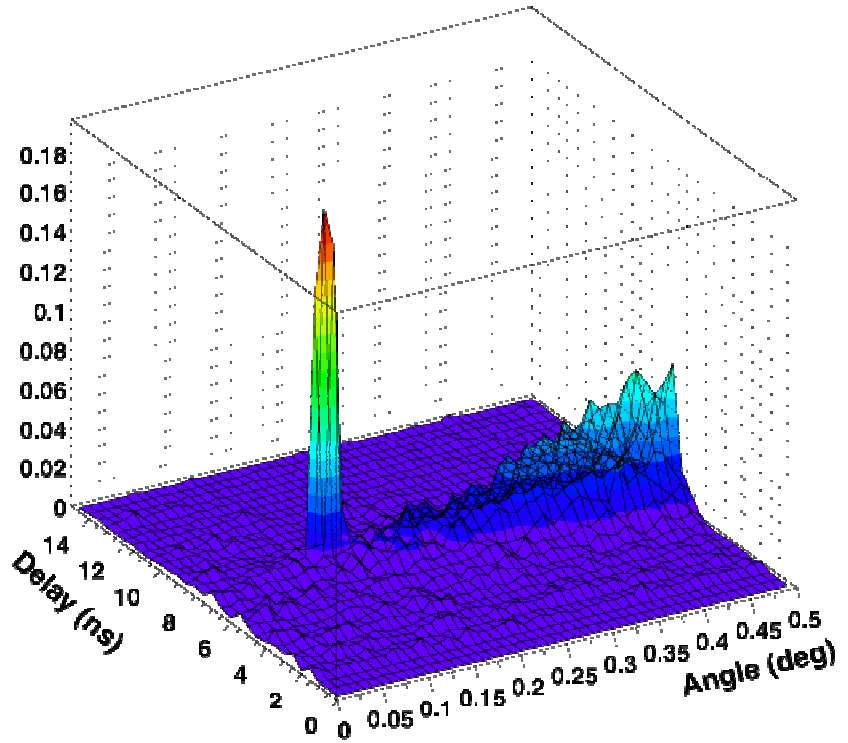
### 2.1. Time and Angle Differentiation

The DC light is produced high up in the atmosphere ( $H > 30\text{km}$ ), where the atmospheric density is low, and hence, the Cerenkov opening angle is small, of order 0.1 degrees. In contrast, the light produced by the shower Cerenkov is produced lower in the atmosphere (typically  $H < 20\text{km}$ ), where the density is exponentially thicker. 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. This gives two observables with which to explore a DC light measurement.

## 2.2. Simulations

Figure 2 shows the results of a CORSIKA [3] simulation of a single 100 TeV iron nucleus entering the atmosphere and interacting at  $\sim 30$  km. What is shown is a 2D histogram of the ground-level photons density versus their arrival time and angular direction. The sharp spike at  $\sim 0.15$  deg and 8 ns is the contribution of DC photons. The mound 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 amounts to  $\sim 100$  photons/m<sup>2</sup>), indicating that a detector with adequate angular and temporal resolution could separate these components and make a simultaneous event-by-event determination of charge and energy.



**Figure 2. Simulation of DC and shower Cerenkov produced by a vertically-incident 100 TeV cosmic ray iron nucleus.**

## 2.3. Detector Technology and First Observations

Fortunately, the technology for just such a detector currently exists – albeit in a simpler form – in the present generation of ground-based TeV gamma-ray detectors, such as VERITAS and HESS. These instruments use large 12m imaging reflectors with fast photodetectors to map the angular scales in air shower events into 2D representations with angular pixilation of  $\sim 0.15$  degrees. Some, such as VERITAS, also feature high-speed digitizing electronics which record the time development of the showers to 2ns precision.

In these instruments, the angular and temporal resolution is roughly 2-3 times too coarse to properly separate the DC component from the shower component. As a result, the shower emission will bleed into the DC spike, washing it out. The expected response from such an instrument is simply a “hot” pixel at the end of the shower ellipse. Even with this degraded response, however, it is possible to extract a lower-resolution measurement of the cosmic ray iron flux at energies near 100 TeV. Just such a measurement was recently announced by the HESS collaboration, which has declared DC light to be their “Source of the Month” for October 2006 [4]. Figure 3 is a plot from this result which shows the signal produced by a single high-energy heavy nucleus. The shower ellipse shows a signal in the DC region of 1028 photoelectrons. Similar results were obtained in the 3 other HESS telescopes for this event. This represents the first observation of DC light from the ground, and confirms the promise of the technique.

### 3. Predicted Performance

Monte Carlo studies indicate that a dedicated DC observatory, comprising perhaps 3 8m fixed-mount reflectors, could be employed to achieve a charge resolution of better than 15% RMS, coupled with an energy resolution of 10-15%. At the same time, the effective area of the technique would, conservatively, exceed 100s of  $\text{m}^2\text{sr}$ , at least 20 times larger than the largest direct cosmic ray detector ever flown. In a single observing season at a good site, a DC observatory could accumulate a high-precision exposure factor which is roughly 100 times larger than the largest direct exposure factor ever achieved.

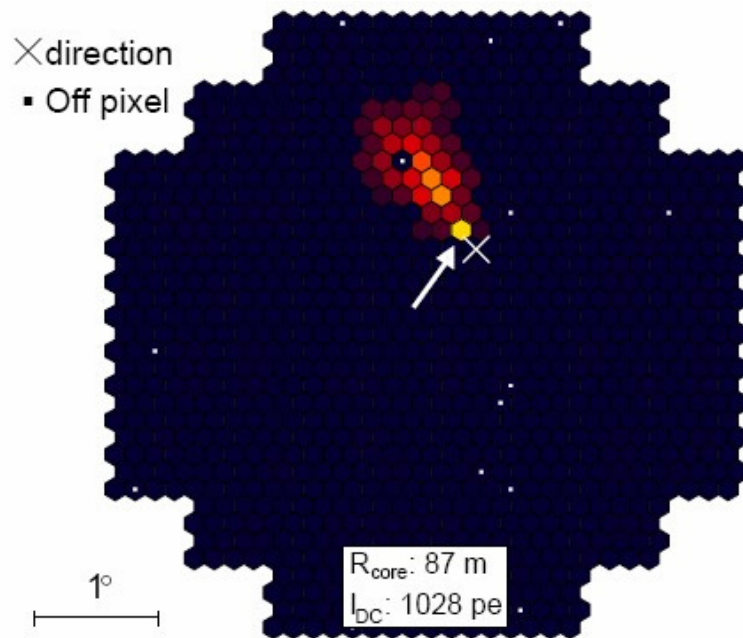
The energy range of the technique is set on the low-energy side by the threshold for Cerenkov production, while on the high-energy side it is determined by the scattering of shower light into the DC spike. These effects together produce a conservatively estimated energy window which increases with  $Z$ , reaching a span at iron of nearly 2 orders of magnitude, with an upper energy limit extending into the PeV range. Studies are underway to extend this upper limit further. For more details, see [1].

### 4. Conclusions

The observation of DC light can provide an unprecedented combination of excellent charge resolution with large effective area. By observing cosmic ray showers with sufficient angular and temporal precision, the achievable charge and energy resolution could approach  $\sim 15\%$  in an instrument with over  $100 \text{ m}^2\text{sr}$  of geometric factor. A very important aspect of this technique is that, because the Cerenkov yields depends purely on well-understood electromagnetic interactions, it is virtually free of the issues arising from hadronic model uncertainties which impact traditional air shower arrays. Finally, this technique has now been observed and used by the HESS collaboration to generate initial spectra of heavy cosmic rays, confirming that the DC is not only real, but capable of producing exciting new results in cosmic ray physics.

### References

- [1] Kieda, Swordy, Wakely, *Astroparticle Physics* **15**, 287 (2001)
- [2] Lidvansky, *Radiation Physics and Chemistry* **75**, 891 (2006)
- [3] <http://www-ik.fzk.de/corsika/>
- [4] [http://www.mpi-hd.mpg.de/hfm/HESS/public/som/Som\\_10\\_06.htm](http://www.mpi-hd.mpg.de/hfm/HESS/public/som/Som_10_06.htm)



**Figure 3. A high energy heavy cosmic ray nucleus, as observed by the HESS observatory, showing DC emission at the tail of the shower ellipse. See text for details.**