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Particle detection at PeV energies using direct Čerenkov light

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Abstract. We describe the potential use of the Direct Čerenkov light (DČ) observation technique for observing new cosmic ray and astrophysical phenomena. This technique may allow for high resolution charge measurements of cosmic ray nuclei in the PeV energy region as well as searches for exotic particle states. The same instrument might be used for an all-sky survey for TeV γ-ray sources. We detail the conceptual design of a wide field-of-view "Direct Čerenkov Observatory" for exploiting this technique, and describe several new science goals that can be addressed by this instrument.

1 Introduction

A recently proposed high resolution charge measurement technique for observing PeV cosmic rays (Kieda, Swordy, and Wakely, 2001; Wakely, Kieda, and Swordy, 2001) opens up the possibility for several new scientific inquiries. The technique exploits the unique angular and timing characteristics of Čerenkov light emitted by primary cosmic rays before the nucleus has suffered a nuclear interaction with air molecules in the Earth's atmosphere (Figure 1). This technique promises to provide high resolution charge measurements for cosmic rays in the TeV-PeV energy region.

The DČ light technique can only be exploited over a limited energy window. The lower energy bound is defined by the threshold for Čerenkov emission by the nucleus in the upper atmosphere, while the upper energy threshold is determined by the energy at which the secondary EAS Čerenkov light overwhelms the DČ light. This window expands like $\sim Z$ for heavy nuclei (Figure 2). A DČ measurement of Iron nuclei ($Z = 26$) is possible into the cosmic-ray "knee" region, around 1 PeV.

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2 Direct Čerenkov Observatory (DČO) Design

The conceptual DČO design uses a number of large (≥10 m diameter) telescopes located on fixed, vertical pointing mounts. The telescopes are separated by a distance of approximately 80 m (Figure 3). Each telescope consists of a 10 m diameter, a wide field-of-view optical concentrator, a highly-pixellated focal plane, and a photomultiplier readout plane (Figure 4). In the preferred implementation, the optical concentrator provides an isochronous surface to preserve the incoming wavefront timing to approximately 2 ns or better. This timing requirement provides additional separation between the DČ light and the secondary Čerenkov light. Possible optical concentrators include multiple UV transmitting Fresnel lenses currently being developed for the OWL satellite observatory (Lamb, 1999). Simulations of these optical systems indicate excellent imaging capabilities out to fields of view of 45° or more.

A highly pixellated focal plane images the Čerenkov light from the cosmic ray shower. The detector intercepts part of the Čerenkov light pool on the ground, the effective collection aperture is therefore far larger than the 10m diameter detector. In order to have sufficient resolution and signal-to-noise ratio for DČ light measurement, small pixels ($0.1°$) are necessary. For a $45°$ field of view camera, one would require more than 10^5 pixels to image the entire field of view. A possible design to reduce costs is shown in Figure 4. The individual pixels in the focal plane are optically multiplexed into a secondary optical readout plane which employs multi-anode photomultiplier tubes. The reduction in cost is traded for increased background light per photomultiplier tube pixel as well as increased optical loss. This will result in a commensurate increase in the energy threshold of the instrument. However, for observations of high-Z PeV cosmic rays, these compromises are acceptable. This DČO design should have energy resolution of about 15%, charge resolution of $\Delta Z/Z < 5\%$ for $Z > 10$, and an effective collection aperture of $\sim 2 \times 10^4$ m^{2}sr for events with shower cores which fall within 50-120m of a detector.

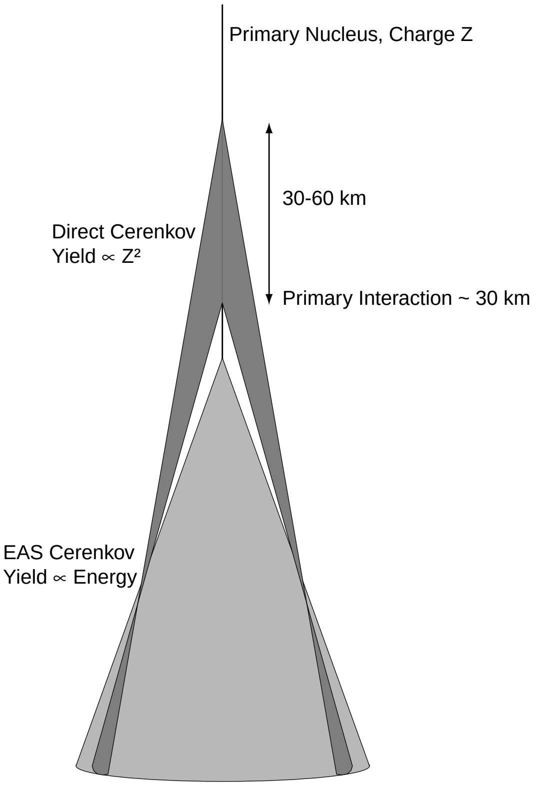

Fig. 1. Schematic Representation of the Čerenkov emission from a cosmic ray primary.

3 Science Goals

The DČO combination of high resolution charge measurement, sensitivity to cosmic rays in the PeV energy region, wide field-of view, and large detection aperture provides a wide range of new science opportunities.

3.1 Measurements of Cosmic Ray Nuclei ($Z < 30$)

For many years the origin of the “knee” in the cosmic ray intensity spectrum near 1 PeV has been the subject of much speculation. The existing paradigm for the origin of the bulk of the cosmic rays at lower energies is diffusive shock acceleration in supernovae remnants (SNR). The coincidence of the “knee” with the expected theoretical energy limit of SNR diffusive shock acceleration is intriguing, however the “knee” represents only a small change in the spectral slope of the overall flux, with the energy dependence changing from $E^{-2.75}$ below the “knee” to $E^{-3.0}$ above it. We are faced with the simple observational fact that the cosmic rays have an essentially continuous spectral slope for nearly 11 orders of magnitude. In principle, additional mechanisms could provide the cosmic ray flux at high energies. The power budget for “post-knee” cosmic rays is only a fraction of the total budget required, so there is some freedom in selecting models. However, to result in a smooth energy spectrum, these mechanisms would have to generate fluxes which are remarkably, perhaps implausibly, close to that of the SNR

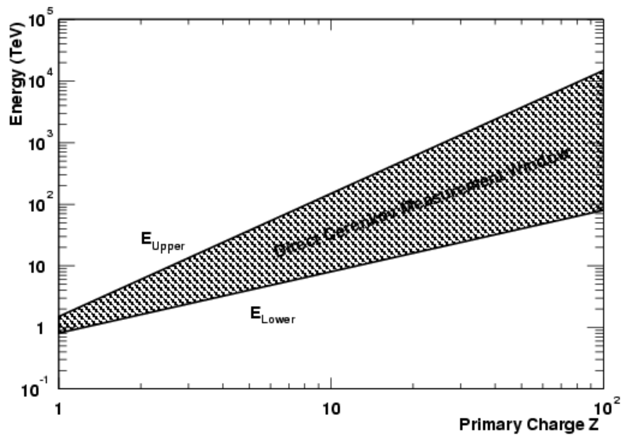

Fig. 2. Upper and lower threshold for detection of DČ light in cosmic ray air showers. The lower threshold is due to the Čerenkov photon emission threshold. The upper threshold is where secondary light density from the EAS has a strength equal to the DČ light density. Vertical Axis: Primary Energy (TeV). Horizontal Axis: Primary particle charge Z.

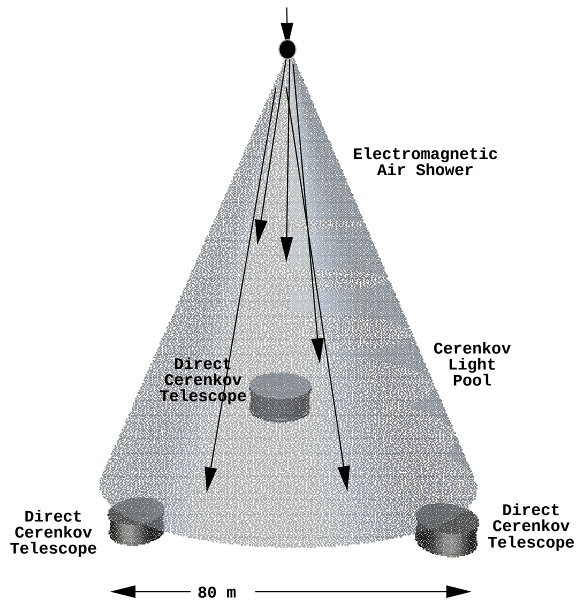

Fig. 3. Conceptual Direct Čerenkov Observatory General design. Each wide field of view (45-60°) DČO telescope observes the Čerenkov light pool from the cosmic ray air shower with 0.1° pixels. The telescopes are nominally separated by a distance of 80 m.

mechanism.

More reliable and accurate measurements in the “knee” region of traditional cosmic ray composition nuclei ($1 \geq$ Z

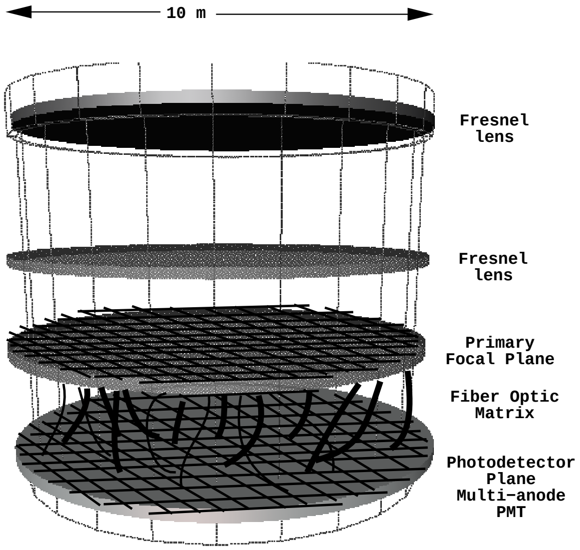

Fig. 4. Conceptual Direct Čerenkov Observatory telescope structure. The UV transmitting Fresnel lenses provide the wide field of view (45-60°) for the instrument. Pixels in the focal plane are optically multiplexed to the photomultiplier readout plane to reduce cost.

≤30) could drastically revise our current ideas. The accurate determination of the composition of cosmic rays has provided some of the key advances in this field at lower energies, where direct measurements are possible with detectors above the atmosphere. For example, the realization that the observed spectral slope of cosmic rays is significantly steeper than that produced in the cosmic ray sources themselves is based on measurements with sufficient elemental resolution to separate primary source cosmic ray elements from those produced in the interstellar medium at 10^{11} eV. The accurate identification of the fluxes of iron nuclei across the "knee" region will drastically improve our understanding of cosmic rays in this energy region. While existing air-shower techniques do not have sufficient charge resolution to make these measurements, a DČO should be able to make high quality measurements for $Z = 26$ from 10 TeV to a few PeV, as shown in Figure 2.

3.2 Measurement of Ultra-Heavy Nuclei ($Z \geq 30$)

Recent measurements of the abundances of cosmic ray elements and isotopes at lower energies have shown a striking similarity with the average abundances of material in our Galaxy. A plausible extrapolation of these abundances to higher energies can be made by source spectra which have the same power law dependence in magnetic rigidity. Accelerated cosmic rays propagate through the galactic magnetic field to the earth, with a propagation loss due to escape from the Galaxy and spallation reactions with interstellar material depending on the pathlength from the source to the observation point. A model using this form can be used to predict the observed energy spectra and mean elemental abundances from protons though iron up into the PeV energy regime.

The ultra heavy (UH) elements (i.e., $Z \geq 30$) can be expected to behave in a similar way to the more common elements. Although the fluxes of these elements have been measured at low energies their abundances are totally unknown in the PeV energy region due to the experimental difficulty in uniquely identifying these rare cosmic rays using traditional air-shower measurements and the very low flux of these elements. The presence of UH elements in the cosmic ray flux would provide direct evidence for the cosmic ray source material abundances persisting into the PeV region and the general validity of this rigidity-based model.

Figure 5 illustrates an estimate of the ultra-heavy nuclei flux based upon leaky-box model extrapolations of the lower energy HEAO-3 satellite measurements. At PeV energies, the UH flux is approximately 1/1000 of the iron flux. With a 2×10^4 m^2 sr detection aperture and 15% on-time, ~ 1000 UH nuclei/year above 10^{14}eV are expected to be collected with the DČO.

3.3 Exotic Particle States

The unique sensitivity of the DČO technique to respond to the apparent charge of the incoming nucleus can also allow a search for cosmic ray nuclei with exotic charge states (effective $Z > 92$) with high sensitivity. Some possible candidates for such a search are:

Strange Quark Matter Strange quark matter is a postulated stable form of baryonic matter which may have been formed in the early universe, or inside the cores of neutron stars (Witten, 1984; De Rújula, 1985). If quark matter is created in neutron star collapse or neutron star - neutron star collisions, some of this material may be ejected and accelerated to relativistic energies. There are several papers discussing the possible existence of strange quark matter in the cosmic ray flux (Kasuya, Saito, and Yasué , 1993; Banerjee et al., 1999, 2000). This state of matter may be uniquely identified in cosmic rays by the DČO through the observation of exotic charge states ($Z > 92$).

Magnetic Monopoles Relativistic magnetic monopoles have also recently been proposed as a source of super-GZK cosmic rays (Kephart and Weiler, 1996; Wick et al., 2000), as they may be easily accelerated above 10^{20} eV in the Galactic magnetic field. These particles possess a very large equivalent charge, making their DČ light extremely strong. Consequently, the DČ technique can provide a large exposure search for these relativistic monopoles based only upon its electromagnetic signature.

3.4 Other Applications of DČ Observations

We note that the next generation of imaging Čerenkov telescope arrays, including VERITAS, HESS, and CANGAROO all begin to approach the DČO design in terms of the angular

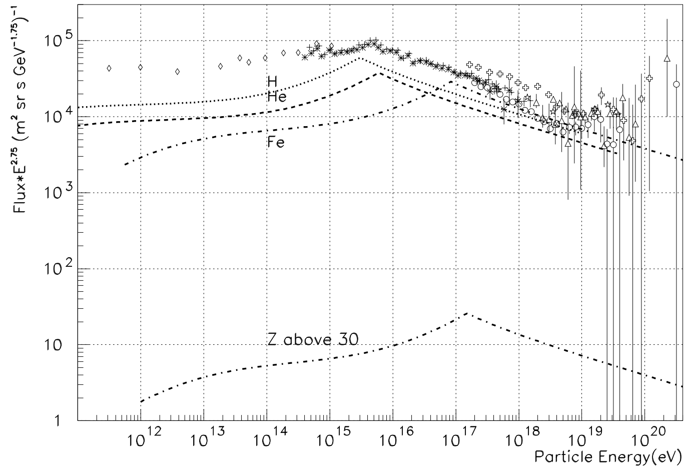

Fig. 5. Ultra Heavy (Z> 30) cosmic ray primary flux extrapolated from HEAO-3 satellite measurements (Binns et al., 1989) to the PeV energy range using a leaky-box propagation model (Swordy, 1995). Horizontal Axis: Primary cosmic energy (eV). Vertical Axis: Differential Cosmic Ray flux multiplied by $E^{2.75}$. Individual points: All particle flux measurements from various experiments (described in http://astroparticle.uchicago.edu archive section)

pixel size, trigger and timing. These experiments will likely be able to provide a first measurement of DČ light. An intriguing possibility is to use the DČ light to reject background in these experiments. The ability to distinguish between the Čerenkov signals produced by electrons and gamma rays in the $10-500$ GeV energy range is important for substantial improvement in the sensitivity of ground-based gamma-ray astronomy. In this energy range, protons and heavy nuclei do not produce secondary particles with sufficient energies to generate substantial Čerenkov light. The majority of the background events for gamma ray instruments in this region are produced by cosmic ray electrons, which also generate pure electromagnetic air showers, with EAS Čerenkov image characteristics identical to a gamma ray primaries. The capability to identify even a small fraction of the electron events from their DČ emission could improve the sensitivity of gamma-ray telescopes in this energy range.

The instrument shown in Figure 4 might also be capable of providing the beginnings of an all-sky survey for TeV gamma rays. In particular, recent flares of AGN sources in this energy region have produced the brightest TeV gamma sources in the sky as transients lasting for time-scales of days or hours. A sufficiently bright transient source might be directly observable with this instrument, which has the advantage of a very wide field of view.

4 Conclusions

The DČ light observation technique may provide a new capability for examining the cosmic ray flux at high energies with good charge resolution. A dedicated Direct Čerenkov Observatory possesses the capability for measurement of the cosmic flux of Ultra-Heavy (UH) nuclei ($Z > 30$) at energies above the spectral knee. These measurements can provide additional information that may lead to a sophisticated understanding of the cosmic ray origin and propagation in this energy region. The DČO can search for exotic charge states of matter; both relativistic magnetic monopoles and also 'quark matter' with charge $Z \gg 100$. A dedicated large aperture Direct Čerenkov observatory can serendipitously provide an excellent time-average and instantaneous all-sky sensitivity with a capability for looking for new transient sources of TeV gamma rays.

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