PROCEEDINGS OF SCIENCE

A New Method for Observing the Core of the Highest Energy Cosmic Rays Using Compact Detectors

Wakiko Takano* **and Kinya Hibino**

Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan.

E-mail: r201970105fg@jindai.jp

We propose a novel method to effectively observe the core region of ultra-high energy cosmic ray (UHECR) air showers. The measurement of the core region has been challenging due to saturation problems of surface detectors caused by the high particle density. However, simulations have shown the importance of collecting data from the core region for understanding UHECRs. To address this challenge, we propose to use compact and thin sensors, such as the CMOS camera image sensors commonly found in consumer devices. These sensors have the unique ability to accurately detect not only optical photons but also charged particles such as cosmic rays and environmental radiation. Due to their thinness, these CMOS have very small energy deposits, allowing high-density regions to be observed without causing saturation problems. In this study, we aim to construct a new observation model using small and thin sensors such as CMOS sensors and discuss the possibility of establishing a large-scale and cost-effective observation network for UHECRs through a simplified model. Our other related paper will further discuss the effective use of CMOS sensors for cosmic ray observations.

37th International Cosmic Ray Conference (ICRC 2023)
July 26th – Aug 3rd, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)410

1. Introduction

Ultra-high-energy cosmic rays (UHECRs) are cosmic rays with energies exceeding 10^{18} electron volts (eV), and understanding their origin and acceleration mechanisms remains a major challenge in astrophysics [1]. Gathering statistical data on UHECRs is important, but traditional methods is expensive and requires a large area. and long-term observation.

To overcome these limitations, we propose a novel observational model that exploits the potential of compact and thin sensors with low energy deposition, such as CMOS (Complementary Metal-Oxide-Semiconductor) camera image sensors. These sensors, commonly found in smartphones and other devices, not only detect visible light but also exhibit the ability to respond to charged particles [2].

We focus on developing a new observational model that specifically targets the core region of air showers induced by UHECRs. The core region is characterized by a remarkably high particle density with rapid density changes within a confined area. Traditionally, the core has been excluded from observations due to detector saturation caused by the particle density. However, by using small and thin sensors with low energy deposits makes it possible to observe the core even in areas of high particle density without encountering saturation problems.

We hypothesize that precise observations of the core region provide valuable information for determining the arrival characteristics of air showers based on core data alone. In this paper, we present our proposed method for observing UHECRs using compact and thin sensors, focusing on the core region of air showers. First, we describe the characteristics of the charged particles in the core region obtained from simulations of air showers produced by ultrahigh-energy cosmic rays. We then present a simplified model using an air shower array of three sensors arranged in a specific configuration to provide efficient and reliable observations.

2. The core region of ultra-high-energy cosmic ray (UHECR) air showers

According to Figure 2 of [3], the core of air showers produced by ultrahigh-energy cosmic rays has a very high particle density. For example, if the primary particle energy of the UHECR is 10^{20}eV at a distance of 10 meters from the core axis, the density can reach up to 1000 particles per square centimeter. The overall density distribution depends on the energy of the primary particles. In particular, it increases sharply as it approaches the core axis.

Figure 3 of [3] shows the mode and 50% values of the angular distribution of charged particles over 100 meters from the core axis. The modal value of the distribution is within 5 degrees and narrows further to 1 degree for particles within 10 meters of the core axis. There is also a slight improvement when the energy threshold is increased to 3 MeV, 5 MeV, and 10 MeV. In other words, when a large number of particles are observed and the arrival direction of the particles can be accurately reconstructed from the tracks, it becomes possible to estimate the arrival direction of primary cosmic rays from the mode of the angular distribution.

3. A simple observation model for detecting the core

Based on simulations of the core region in ultra-high energy cosmic ray (UHECR) air showers, we have developed a simplified observational model for detecting the core using compact and thin

PoS(ICRC2023)410

sensors such as CMOS camera image sensors. This model aims to use the knowledge gained from the simulations to identify the location of the core and to determine the energy of the primary particles in air shower events.

For example, assuming a sensor area of 1 cm^2, a detectable particle density for such small sensors will be larger than 10,000 particles per square meter, as indicated by the red dashed line in Figure 3. Examining the range of this density within the air shower, we find that at the primary particle energy of 10^{20} eV, it extends up to 200 meters from the core axis. It extends to 90 meters, 33 meters, and 6 meters at 10^{19} eV, 10^{18} eV, and 10^{17} eV, respectively. The detectable region forms a circular area centered on the core axis.

On the other hand, the effective observation area, where sensors will be placed, has a radius half that of the detectable region. Placing sensors within this area allows effective observation of the air shower. For example, at a primary particle energy of 10^{20} eV, where the detectable region extends up to 200 meters from the core axis, the effective observation area would be a circle with a radius of 100 meters. This radius is the region in which sensors will be positioned. If the core of the air shower falls within this effective observation area, all sensors will be within the detectable area.

Table 1 shows the distance from the core axis and the radius of the effective observation area for each primary particle target energy.

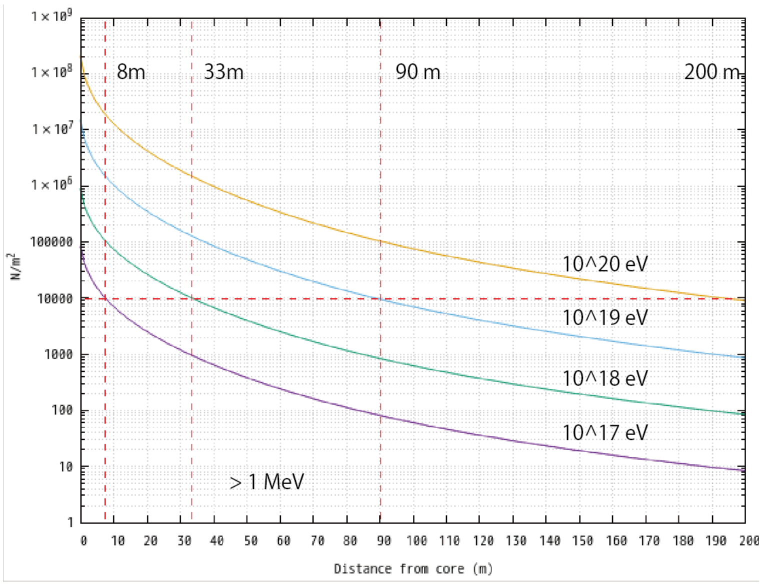

Figure 1: The detectable particle density using a 1 cm^2 sensor is larger than10,000 particles per m^2. With a primary particle energy of 10^{20}eV the detectable area extends up to 200 meters from the core axis.

4. Placement of the sensors

Once the effective observation area has been determined, the next step is to plan the placement of the sensors. We will use only three sensors to ensure efficient observation of air showers. The three sensors are in an equilateral triangle configuration as shown in Figure 2. In this case, the target

PoS(ICRC2023)410

Table 1: Range of detectability and radius of effective observation area for each target energy.

Target (eV)	Range from Core Axis	Effective Observation Radius
10^{20}	200 m	100 m
10^{19}	90 m	45 m
10^{18}	33 m	16.5 m
10^{17}	8 m	4 m

energy of a primary particle is 10^{20} eV, resulting in an effective observation area in the form of a circular region with a radius of 100 meters. The three sensors, arranged in an equilateral triangle, will be about 173 meters apart.

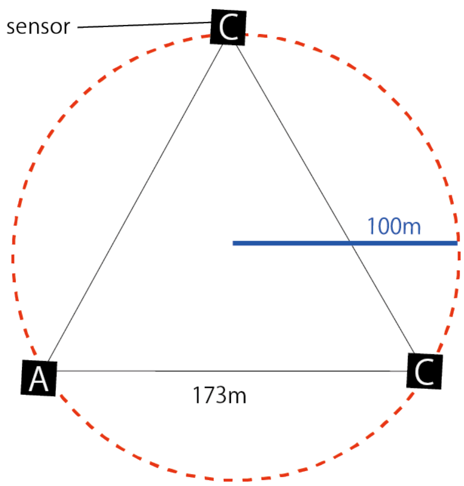

Figure 2: When observing air showers produced by 10^{20}eV cosmic rays, the sensors will be positioned in a configuration that forms an equilateral triangle touching the circular effective observation area with a radius of 100 meters. The distance between each sensor will be approximately 173 meters.

5. Reconstructions

Figure 3 shows an example of detecting an air shower produced by cosmic rays with an energy of 10^{20} eV using the three abovementioned sensors. When the core of the air shower reaches point O, which is within the effective observation area, the distances from the core to sensors A, B and C are determined to be 30 m, 153 m, and 160 m, respectively. Moreover, on average, the observed particle counts will be 200 particles, 2.5 particles, and two particles, respectively.

In actual observation, neither the positions of the core nor the energies of the primary particles are known, only the number of particles detected by each detector is known. Therefore, the next step is to see if it is possible to reconstruct them from the observed particle counts.

First, we examine the distances from each sensor to the core based on the observed particle counts. For example, if 200 particles are detected within an area of 1 cm^2, the corresponding density in Figure 4 indicates a distance of 30 meters from a core with an energy of 10^{20} or 6 meters from a core with an energy of 10^{19} eV. Similarly, the distances from the core to sensors B and C are estimated from the observed particle counts. A density of 200 particles in a 1 cm^2 sensor is not achievable for energies below 10^{18} eV, so these energy levels are excluded. Table 2 summarises the distances from each sensor to the core for primary particles with energies of 10^{20} eV and 10^{19} eV.

The distances are then used to determine the position of the core and the energy of the primary particles. The position of the core can be determined from the intersections of circles with radii corresponding to the distances from each sensor (see Figure 5). If the energy of the primary cosmic ray is 10^{19} eV, the calculated distances do not yield any intersection points between the three circles, thus excluding 10^{19} eV as a possible energy level. As a result, the reconstructed position of the core and the energy of the primary cosmic ray for the observed cosmic ray air shower are determined to be 10^{20} eV at point O.

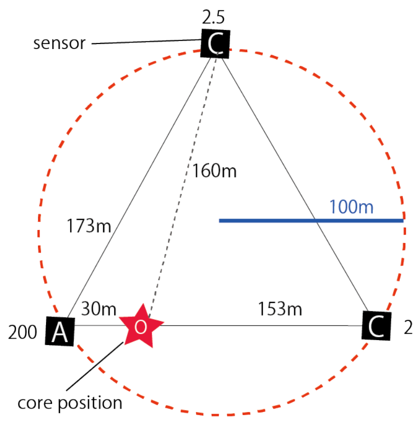

Figure 3: When the core of the air shower produced by cosmic ray with energy of 10^{20} eV reaches point O, which is within the effective observation area, the distances from the core to sensors A, B, and C are determined to be 30 m, 153 m, and 160 m, respectively. Moreover, the observed particle counts will be an average of 200 particles, 2.5 particles, and two particles respectively.

Table 2: Distances from the core to each sensor derived from the observed particle counts. Estimated distances for primary particles with energies of 10^{19} eV and 10^{20} eV.

Energy	Sensor A	Sensor B	Sensor C
10^{20} eV	30m	143m	160m
10^{19} eV	6m	63m	70m

6. Estimation of the number of arrays

The above is a simplified model for observing the core of Ultra-High-Energy Cosmic Ray (UHECR) air showers using an array of three sensors arranged in an equilateral triangle. Based on calculations, it is estimated that about 3200 such observation arrays would be required to effectively detect cosmic rays with energies of 10^{20}eV as targets once a year.

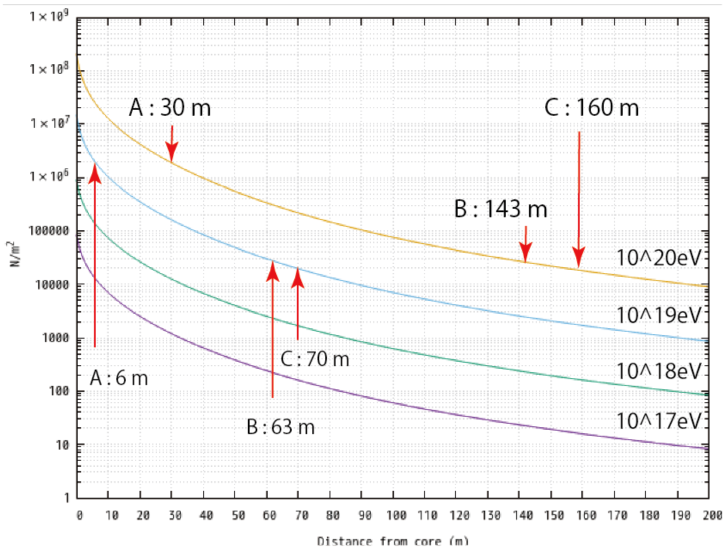

Figure 4: If 200 particles are detected within a 1 cm^2 area, the corresponding density indicates a distance of 30 meters from a core with an energy of 10^{20} eV, or 6 meters from a core with an energy of 10^{19} eV. Similarly, the distances from the core to sensors B and C are estimated from the observed particle counts.

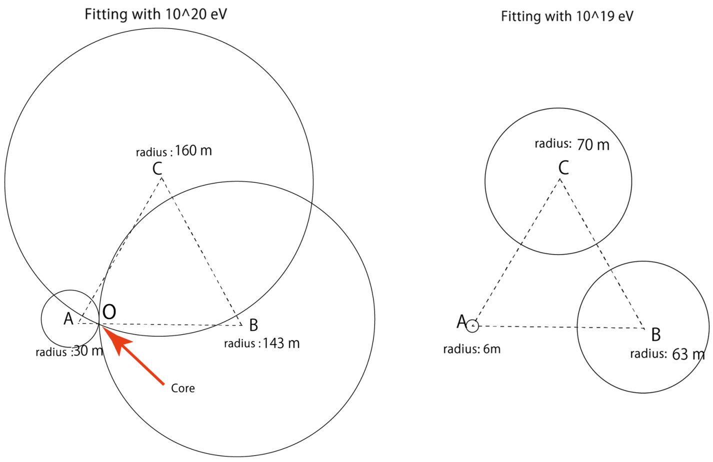

Figure 5: The position of the core is determined by identifying the intersections of circles with radii corresponding to the distances calculated by the three sensors. At the same time, the energy of the primary cosmic ray is reconstructed. In the case of an air shower produced by a cosmic ray with an energy of 10^{19} eV, the calculated distances do not give any intersection points between the three circles, thus excluding 10^{19} eV as a possible energy level. Consequently, the reconstructed position of the core and the energy of the primary cosmic ray for the observed cosmic ray air shower are determined to be 10^{20} eV at point O.

7. Summary

Although more detailed simulations are needed for realization, core observations have great potential to significantly expand the observation area at a low cost. In this context, we introduced an example of using a thin sensor that can observe particles without saturation even in high-density areas. Our other related paper has extensively discussed the effectiveness of CMOS camera image sensors and potential candidates for these sensors in cosmic ray observations [4].

References

[1] A. Coleman; et al. Ultra-High-Energy Cosmic Rays: The Intersection of the Cosmic and Energy Frontiers, Astroparticle Physics Volume 149, July 2023, 102819, https://doi.org/10.48550/arXiv.2205.05845

[2] J. J. Cogliati, K. W. Derr, J. Wharton, Using CMOS Sensors in a Cell- phone for Gamma Detection and Classification (2014). arXiv:1401. 0766.

[3] Takano, W.; Hibino, K. Observing Ultra-High Energy Cosmic Rays using Camera Image Sensors. In Proceedings of the 37th International Cosmic Ray Conference, Berlin, Germany, 12
UTF201323 July 2021.

[4] W. Takano; K. Hibino, Consumer Devices with CMOS camera image sensors as Pocket-Sized Particle Detectors, PO_E113 , ICRC(2023)