Characterising the Cosmic Rays in a CCD

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I. Introduction

I. Cosmic rays

Particles with extremely high energies (up to 10^{20} eV) have been detected. It is found that these particles originate from extraterrestrial sources, galactic as well as extra galactic. The bulk of these particles are composed of protons and atomic nuclei and are called cosmic rays. It is known that supernovae and active galactic nuclei are able to accelerate charged particles to extreme energies trough magnetic fields. Once these cosmic rays hit the atmosphere, their energy is converted into new particles including muons which are known as secondary cosmic rays. These secondary cosmic rays reach the ground and are easily detected. These particles can easily penetrate through solid matter because of their high energy and relatively low losses of energy per interaction.

II. CCD detection

Because of the fact that these are charged particles, charged coupled devices (CCD's) can be used to detect muons. As muons pass trough the CCD they will excite large amounts of electrons in pixels, therefore these events are easily identified. Events of cosmic rays in CCD's are characterized by [1]. They define an event as a group of connected pixels with counts above the background, with at least one pixel having a significantly higher number of counts. Muon tracks are characterized by straight lines and dots depending on the incoming angle. Wandering tracks are characterized as worms and are produced trough Compton-scattered gamma rays and beta emitters in the telescope.

II. Experimental overview

To detect cosmic rays using a CCD, the Gratama telescope was used. During the observation, the telescope was pointed at the zenith. First 100 bias frames were made, after this, dark images of 30 minutes exposure time were made. These dark images were then calibrated using the bias frames and IRAF. After this, the final images were obtained, which contained a large number of cosmic rays. Five dark frames of 30 minutes were taken. The analysis consisted of only 2 of these frames for general properties of cosmic rays like the number of cosmic rays per unit area per unit time and the fraction of the different types of cosmic rays. Furthermore, a look was taken at the angle dependence of the cosmic rays using only 1 frame of 30 minutes. The results will be compared with previous literature.

Table 1: *Properties of the CCD[2]*

Property	Value
CCD Type	KAF-6303E
Size CCD	2.77 cm $\times$ 1.85 cm
Pixels	3060 x 2040
Size pixel	9 μm $\times$ 9 μm
Height pixel	(77 ± 8) μm
Temperature	-20 °C

III. Number of cosmic rays and type

I. Method

For the first 2 frames, the number of cosmic rays was counted using Gaia, during the counting, distinction between muons and worms was made. This resulted in a total count of 624 muons and 77 worms. Using the following equation it is possible to calculate the flux of muons and worms:

$$\Phi = \frac{N}{\Delta t \cdot A_{CCD}}. \tag{1}$$

II. Results

Using the total integration time ($\Delta t = 60 min$) and area of the CCD (see table 1), a flux for the muons of $\Phi_{muons} = (2.03 \pm 0.09)$ min^{-1} cm^{-2} is obtained and for the worms this resulted in $\Phi_{worms} = (0.25 \pm 0.03)$ min^{-1} cm^{-2}. Furthermore using these counted events it is possible to calculate the fraction of muons compared to the total number of cosmic rays. This can be be simply calculated by dividing the number of muons by the the number of events. This means that 0.89 ± 0.05 of the cosmic rays detected originate from muons[1].

IV. Shape of cosmic rays

The events will be characterized according to the scheme developed by [1]. Various events have been observed including muons, worms and others. For the muons, straight tracks of varying length are observed, mainly circular events and oval shaped ones are observed however. Figure 1 shows some shapes of the observed muonic events. Muonic events that are observed are similar to the ones observed by [1]. However, muonic events that show side branches which are indicated by [1] are not present in the observations. A large diversity in worm events are observed, shapes range from long curved tracks to completely curved tracks and small asymmetric patches. Shapes of the worm events are similar in shape as the ones observed by [1]. Some observed worm events are shown in figure 2. In addition to muonic and worm events, different events with various shapes are encountered which are not indicated by [1]. Two of these observed events are shown in figure 3. Most of these events show two structures which are separated by a region which is not affected by this event. This means that these events have a different origin than the more common worms. These events could be produced by electron-positron annihilations of the positrons produced by beta decay.

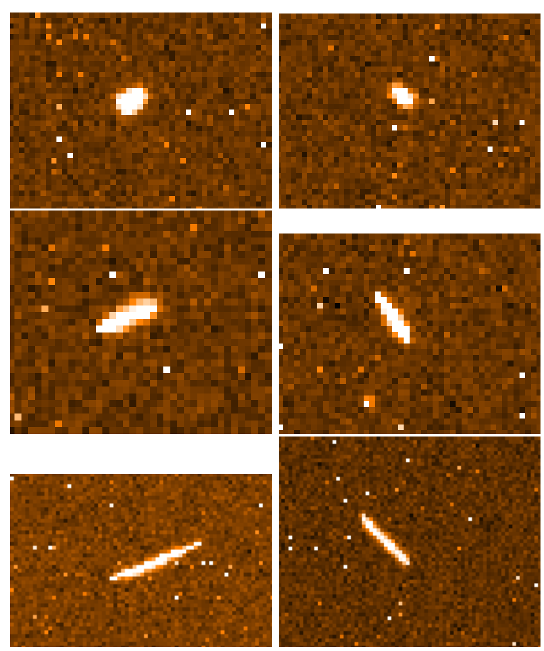

Figure 1: *Typical muon tracks in the detector*

[1]The calculated errors were simply calculated using poison statistics and simple error analysis

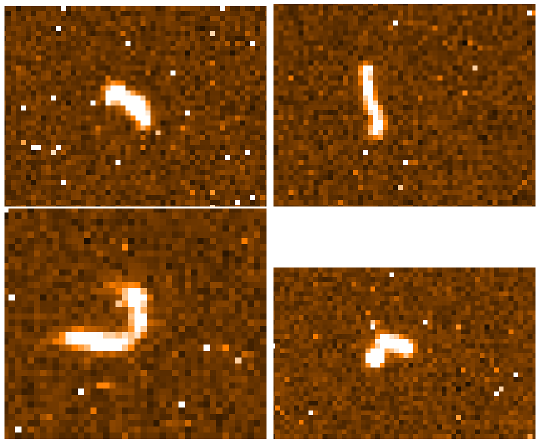

Figure 2: *Typical worm tracks in the detector*

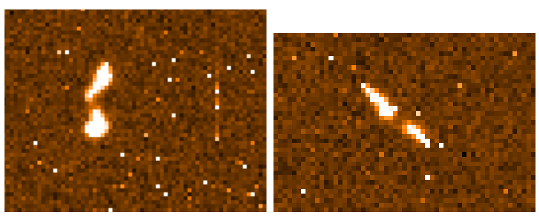

Figure 3: *Other tracks in the detector*

V. Angle dependence

I. Method

The observations clearly indicate that there are significant more shorter paths of cosmic rays than very long ones. This indicates that the cosmic rays are mainly coming from a small angle compared with the zenith. In order to verify this more quantitatively, a function was fit to our data (only muonic events). But before this, a closer look at our observations and the biases during the observation is needed. As can be seen in figure 4 cosmic rays at low angles θ have a bigger collective area than cosmic rays at high angles θ.

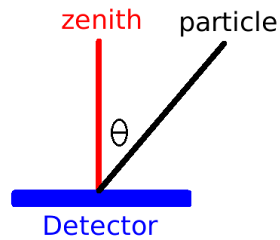

Figure 4: *Detector setup*

This means that we can rewrite the collecting area as,

$$A(\theta) = A_0 \cos\theta. \tag{2}$$

Furthermore as can be seen in figure 1, cosmic rays vary in shape e.g. they have a certain length and width in the detector. The width has been defined by λ_1 and the length by λ_2. However, if one would only use λ_2 to measure the angle, the incidence angle would be over estimated. This is because of the fact that cosmic rays excite extra pixels on the end and start of the track. To correct for this effect, the length that will be used to calculate the angle is $\lambda_2 - \lambda_1$[2]. With the thickness of the CCD, the incidence angle of the cosmic rays is calculated. The angle is then corrected by dividing the number of counts by the $A_0 \cos\theta$ which results in the corrected data for the biased angle. In this way, the number of cosmic rays as a function of angle is obtained.

[2] If we only would use λ_2 this would mean that a event with size 2x2, would have an angle, but because of symmetry it would come from a angle of 0°. This means that it is necessary to subtract λ_1 from λ_2 to get the actual angle.

II. Results

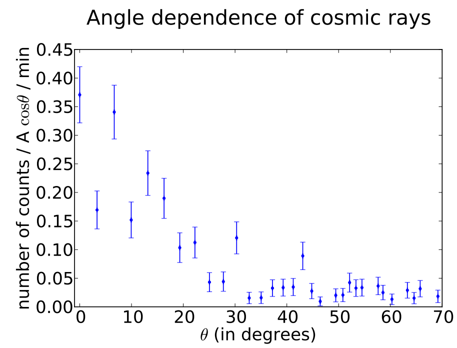

Figure 5: *Flux as function of angle*

When this method is used we obtain figure 5. Now the goal is to fit a function through these points. According to [1], the dependence of the flux on angle should be $\Phi \propto \cos^{\alpha}\theta$ with $\alpha \approx 2$. This means that the following function needs to be fitted:

$$\Phi = \Phi_0 \cos^{\alpha}\theta + \Phi_1. \tag{3}$$

`scipy.optimize.curve_fit` was used to fit this function, `curve_fit` uses the Levenberg-Marquardt algorithm to fit the function, the Levenberg-Marquardt algorithm is a non-linear least square fitting algorithm[3]. This failed for the equation 3 because the solution was not converging. In addition, an attempt was made to fit this function by means of the Taylor expansion of equation 3, this worked but resulted in a non-physical solution with $\Phi_1 \ll 0$. Because both attempts failed, an exponential of the following form was fitted:

$$\Phi = \Phi_0 \exp(-\alpha\theta) + \Phi_1. \tag{4}$$

This resulted in an good fit with the following values for the constants, $\Phi_0 = (0.34 \pm 0.03)$ min^{-1} cm^{-2}, $\Phi_1 = (0.1 \pm 0.2)$ min^{-1} cm^{-2}, $\alpha = 3.3 \pm 0.8$.

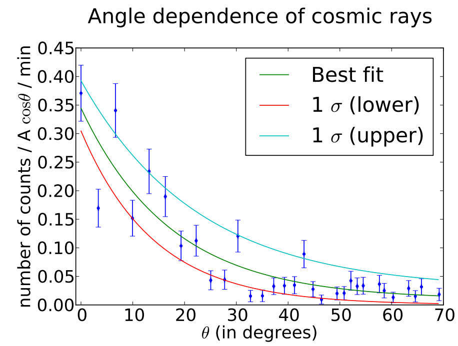

Figure 6: *Flux as function of angle with the best fit and the 1σ bounds on the functions.*

As can be seen in figure 6, the 1σ from the best fit give a very broad space for different functions, this means that using better fit algorithms different functions could be fitted.

VI. Discussion

Due to the large amount of data in the 5 frames, only two frames were analyzed (for time consuming reasons), of which one frame was analyzed more accurate. In future experiments, the analysis of the data should be extended to all frames. This will result in smaller errors and more statistically reliable data. Furthermore because fitting a non-linear function of the form $\cos^{\alpha}\theta$ seems to be difficult, future data reduction could use other non-linear least square fitting algorithms to fit this function.

VII. Conclusion

The CCD on of the camera on the telescope of the Blaauw observatory was used to detect cosmic rays. Several events have been observed, including muonic and worm like events with various shapes. Another type of event was noticed, which shows two separate structures, this could be produced by electron-positron annihilations. The results show that most of the muon cosmic rays originate from small incident angles. The dependence of the flux on the incidence angle was shown to be described by an exponential function. The key results are resembled in table 2.

Table 2: *Results*

Quantity	Value
Φ_{muons}	(2.03 ± 0.09) min^{-1} cm^{-2}
Φ_{worms}	(0.25 ± 0.03) min^{-1} cm^{-2}
fraction of muons	0.89 ± 0.05
$\Phi(\theta)$	$\Phi_0 \exp(-\alpha\theta) + \Phi_1$
Φ_0	(0.34 ± 0.03) min^{-1} cm^{-2}
Φ_1	(0.1 ± 0.2) min^{-1} cm^{-2}
α	3.3 ± 0.8

References

[1] D. Groom. Cosmic rays and other nonsense in astronomical ccd imagers. *Experimental Astronomy*, 14(1):45–55, 2002.

[2] Santa Barbara Instrument Group. Sbig operating manual. www.sbig.com.

[3] SciPy developers. Numpy and scipy documentation, 2015.