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East-West Effect of Cosmic Ray at 35 km Altitude in the GRAINE 2023 Balloon Experiment

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GRAINE (Gamma-Ray Astro Imager with Nuclear Emulsion) is large-aperture-area observation project of cosmic gamma rays in the GeV/sub-GeV for precise by long balloon flights of the nuclear emulsion telescope. Nuclear emulsion is a charged particle detector with the highest spatial resolution based on the principle of silver halide photography. Due to the high spatial resolution (submicron) of the three-dimensional trajectory, the angular resolution of nuclear emulsion is close to the principle kinematical limit (0.1° for 1 GeV gamma rays, 1.0° for 100 MeV) and polarization information can also be provided as well. We have conducted the balloon experiments (2011, 2015, 2018) and succeeded in imaging the highest resolution of Vela Pulser during the 2018 Australian balloon experiment. As a next step, we developed a telescope with a larger aperture area (6.5 times larger than in 2018) to 2.5 m^2 and performed a balloon experiment in Australia in April 2023. Furthermore, the altitude of the flight was 35-37 km, the flight time was 23.5 hours, and it succeeded in covered only the Vela Pulser but also the galactic center.

The GRAINE telescope consists of three major parts: a converter, which detects γ-ray pair creation reactions by stacking 90 nuclear emulsion films; a timestamper, which adds time information to the tracks by moving the nuclear emulsion films at a time-specific period; and an attitude monitor, which determines the telescope's direction by taking star images. The arrival direction of a track on the celestial sphere can be determined by adding time information by timestamper and attitude information by attitude monitor.

Since Nuclear emulsion records the tracks of all charged particles, many cosmic rays, not only those generated by γ-rays, are recorded in the flight data. We have attempted to directly measure the east-west effect at high flight altitude by analyzing mainly the minimum ionizing particles. In this presentation, I report the current analysis of the GRAINE 2023 timestamper and attitude monitor, and the east-west effect observed in the flight data at an altitude of around 35 km.

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1. Introduction

High-energy gamma rays are extremely important probes for elucidating high-energy phenomena in the universe and cosmic ray acceleration mechanisms. Unlike charged particles, gamma rays reach Earth without being affected by complex interstellar magnetic fields, enabling observations that preserve information from gamma-ray sources. Therefore, celestial objects that emit high-energy gamma rays are promising candidates as acceleration sources for cosmic ray protons. Additionally, when electrons are accelerated, gamma rays are expected to be emitted through bremsstrahlung, synchrotron radiation, and inverse Compton scattering, making them play an important role in exploring the origins of cosmic ray electrons. The all-sky observations by the Fermi-LAT detector launched in 2008 significantly advanced high-energy γ-ray observations, leading to the discovery of numerous γ-ray sources[1][2]. However, the angular resolution of these gamma-ray observations is an order of magnitude lower than observations at other wavelengths due to observational difficulties.

In response to this challenge, we are advancing a project to observe GeV/sub-GeV cosmic gamma rays with the world's highest angular resolution (0.08 degree @ 1-2 GeV) through long-duration balloon flights of a gamma-ray telescope using nuclear emulsion films (Gamma-Ray Astro Imager with Nuclear Emulsion: GRAINE project). Nuclear emulsion is a charged particle detector with the highest spatial resolution based on the principle of silver halide photography. It records three-dimensional trajectories of charged particles with sub-micron precision. Because it records three-dimensional tracks with high spatial resolution, the angular resolution of nuclear emulsion approaches the fundamental kinematic limit (0.1° for 1 GeV gamma rays (1.0° for 100 MeV))[3], and can also provide polarization information[4].

The GRAINE telescope consists of three major parts (Fig.1): a converter, which detects γ-ray pair creation reactions by stacking 90 nuclear emulsion films; a timestamper, which adds time information to the tracks by moving the nuclear emulsion films at a time-specific period; and an attitude monitor, which determines the telescope's direction by taking star images. The arrival direction of a track on the celestial sphere can be determined by adding time information by timestamper and attitude information by attitude monitor to the track.

We have conducted three balloon experiments so far (2011[5], 2015[6], 2018[7]), and succeeded in obtaining the world's highest-resolution image of the Vela Pulsar in the 2018 Australian balloon experiment [8] (Fig.2). Based on this success, we developed a telescope with an aperture area enlarged to 2.5 m², which is 6.5 times larger than the 2018 version, and conducted a balloon experiment in Australia from April 30 to May 1, 2023. Furthermore, we achieved a flight time of 23.5 hours, which is 1.6 times longer than the 2018 flight, successfully capturing not only the Vela Pulsar but also the galactic center within our field of view.

This flight data contains recorded tracks of all charged particles, not just γ-rays. In this study, focusing on this characteristic, we analyzed the east-west effect during the flight by examining atmospheric γ-rays, which constitute the major background for cosmic gamma rays, and He nucleus tracks.

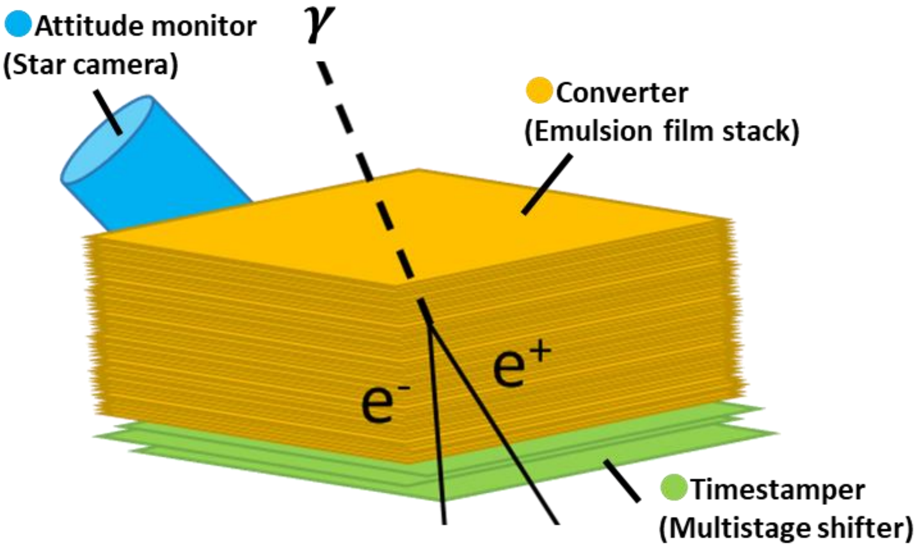

Figure 1: Main components of a gamma-ray telescope using nuclear emulsion. Converter is the part that reconstructs the angle of gamma rays by measuring the angle between electrons and positrons generated by the electron-pair creation caused by gamma rays. The Attitude monitor determines the attitude of the telescope by matching star images taken by the star camera with the star catalog. Timestamper adds time resolution to the track of the electron pair creation generated at converter.

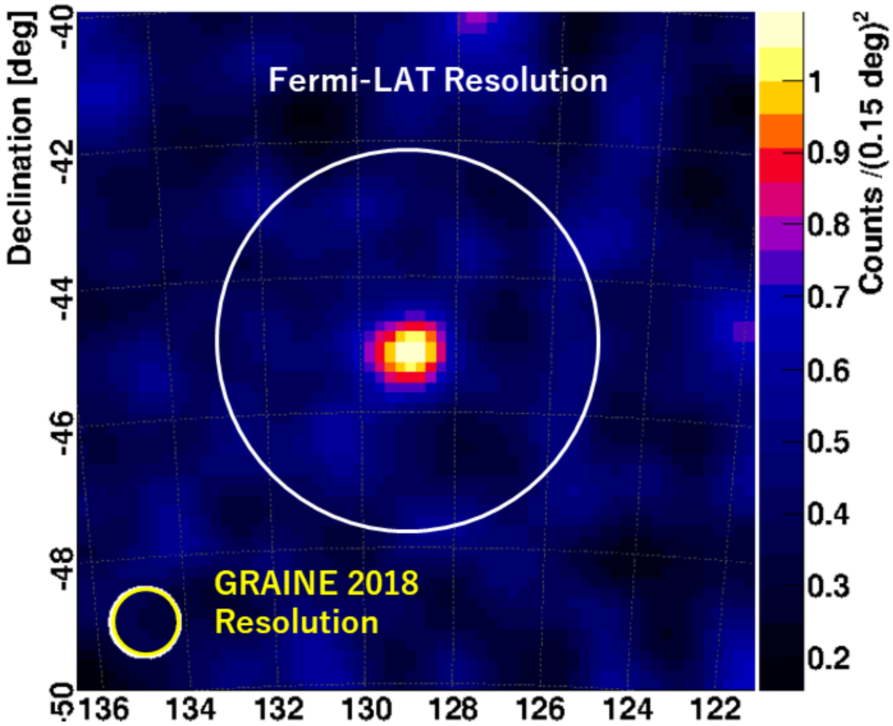

Figure 2: Imaging result of Vela pulsar by GRAINE2018 (100-400 MeV). Achieved nearly an order of magnitude improvement in resolution compared to Fermi-LAT in the same energy band [8].

2. Analysis Flow

2.1. Selection of γ-ray and α-particle events

After the flight, the films were developed and tracks were read using a Hyper Track Selector (HTS)[9]. This readout information contains the position, angle, and intensity of the tracks. Based on this information, γ-rays and α-particles were selected using the following methods.

2.1.1. Selection of α-particles

α-particles were selected based on track darkness information. α-particles have larger energy loss when penetrating through the film compared to minimum ionizing particles, resulting in darker tracks. Therefore, when track darkness is plotted on the horizontal axis, a cluster can be found at a certain darkness region (Fig. 3). α-particle tracks were selected by extracting this cluster.

2.1.2. Selection of γ-rays

γ-rays were selected based on topology by identifying tracks that originate within the film and branch into two tracks (Fig. 4).

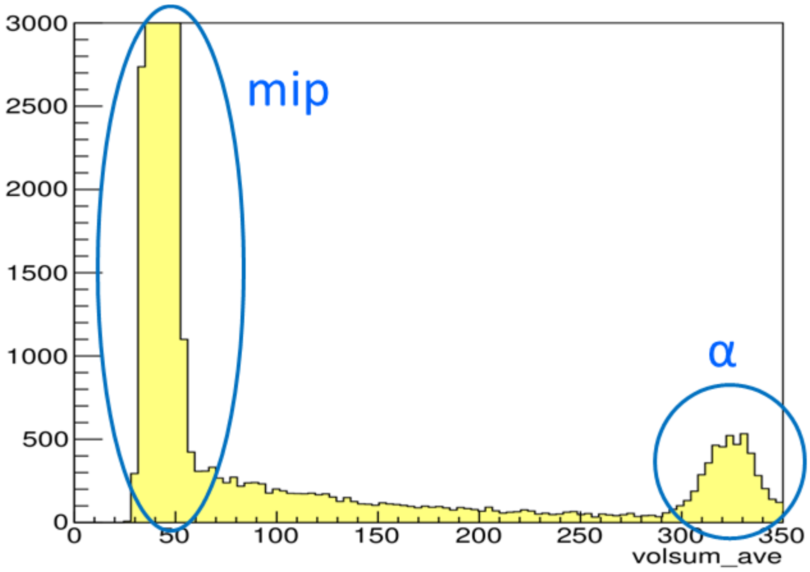

Figure 3: Relationship between track darkness and particle type in HTS scanning. The horizontal axis represents the track darkness index (pulse height volume), and the vertical axis represents the number of tracks. While minimum ionizing particles cluster around phv = 50, α-particles show phv = 300 or higher.

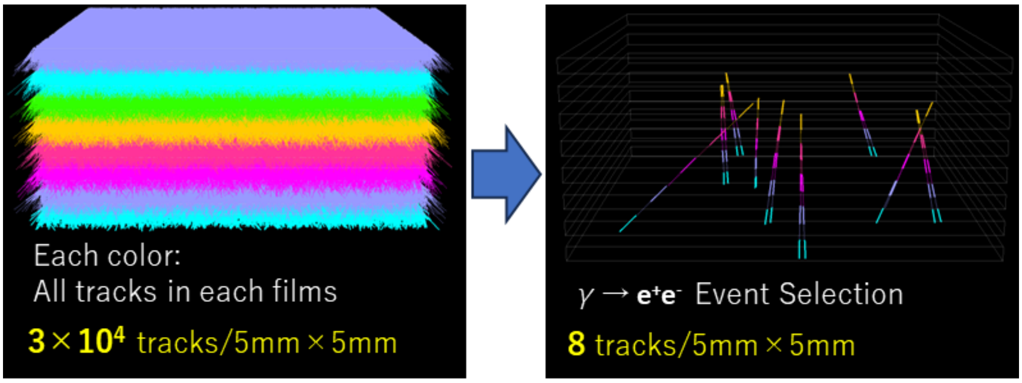

Figure 4: Selection of γ-ray tracks. First, track data from five layers were prepared, and the upstream two layers were used as veto to extract events that originate within the detector. Subsequently, γ-ray tracks were selected by extracting events with the characteristic structure of electron-positron pair production, where tracks branch into two from a common vertex.

2.2. Mapping Events on Celestial Coord.

2.2.1. Assignment of time information

Since tracks recorded in the film do not carry temporal information, a time stamper was used to assign timestamps. The time stamper is a mechanism that assigns temporal information by changing the relative positional relationship of tracks during flight, functioning like clock hands through positional shifts of tracks (Fig. 5). The time stamper provided timestamps for γ-rays and α-particles with a time resolution of 0.1 seconds.

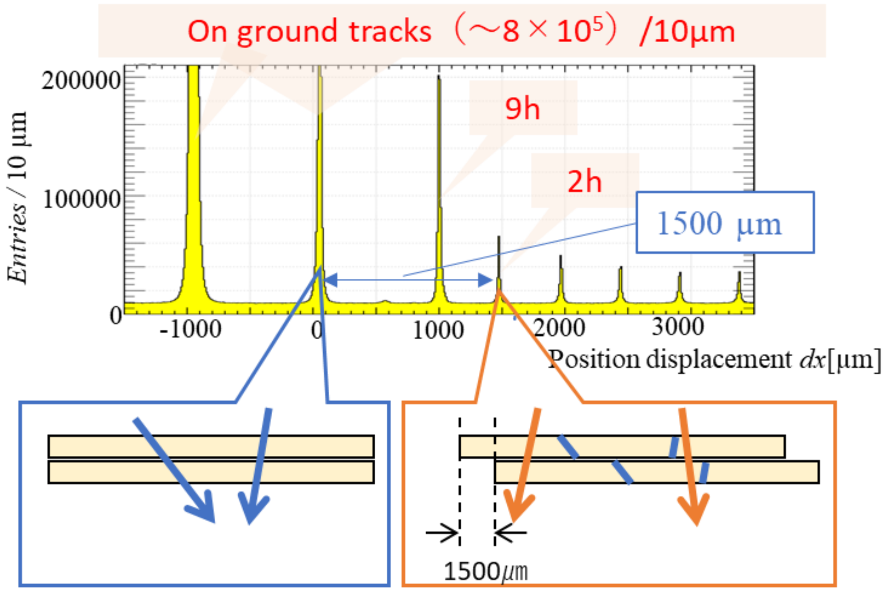

Figure 5: Mechanism of the time stamper and an example of actual flight data analysis. Timestamps are assigned to tracks by correlating the positional shift created by the time stamper with the actual positional shift of tracks. In this example, track populations are divided into 2-hour intervals. By performing the same analysis in four stages, track populations can be separated with time resolutions of 6 minutes, 15 seconds, and 0.1 seconds, respectively.

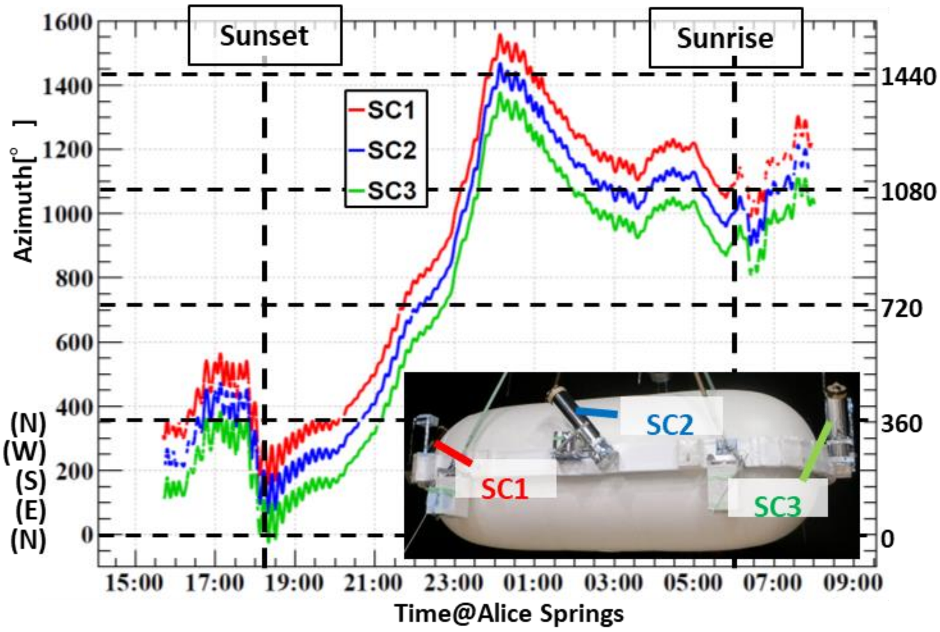

Figure 6: Azimuthal angle variation of star cameras during flight. It was confirmed that the azimuthal angle could be determined using all three cameras from daytime to nighttime.

2.2.2. Assignment of telescope attitude information

The telescope's orientation constantly changes during flight due to wind effects. GRAINE does not perform active control of the line of sight, and the viewing direction at each time is determined by attitude monitors. This was accomplished by capturing star images with three star cameras and matching them with star catalogs. Figure 6 shows the azimuthal angle variation of the telescope determined by the attitude monitor. It was confirmed that the line of sight could be determined using all three cameras.

2.2.3. Celestial sphere mapping by combining all analyses

By combining the time information assigned by the time stamper with the telescope direction information provided by the attitude monitor, γ-ray events were mapped onto the celestial sphere. Figure 7 shows the result of mapping γ-ray events in horizontal coordinates. Based on this analysis result, the east-west effect for γ-rays and α-particles was confirmed.

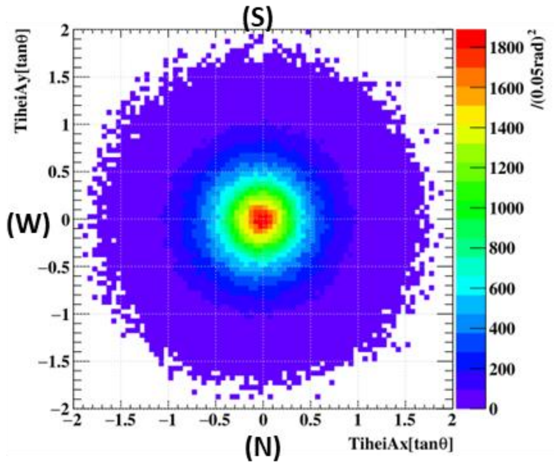

Figure 7: Arrival direction distribution of γ-rays in horizontal coordinates.

3. Temporal variation of the east-west effect

Among the obtained arrival azimuth angle distributions, those with elevation angles from 45° to 70° were divided into 4-hour intervals to create azimuth distributions. Figure 8(a) shows the azimuth distributions of γ-rays and α-rays from 16:00 to 20:00 Alice Springs time, along with the cutoff rigidity simulation results for the flight position during that time period. While anisotropy due to the east-west effect was confirmed for both γ-rays and α-particles, differences were observed between α-rays and γ-rays when the anisotropy was fitted with a cosine function. The temporal variation of this fit position is shown in Figure 8(b). While the phase of α-particles remained stable, the phase of γ-rays showed temporal variation. The altitude of the telescope during flight is shown in Figure 8(c), and the position in Figure 8(d). The altitude during flight did not change significantly. Although the flight moved eastward, there was no significant change in magnetic latitude except toward the end.

The cause of the different behaviors between γ-rays and α-particles is currently under investigation. Possible contributing factors include effects from cosine fitting and, in the case of gamma rays, a mismatch between the interaction point and the detector.

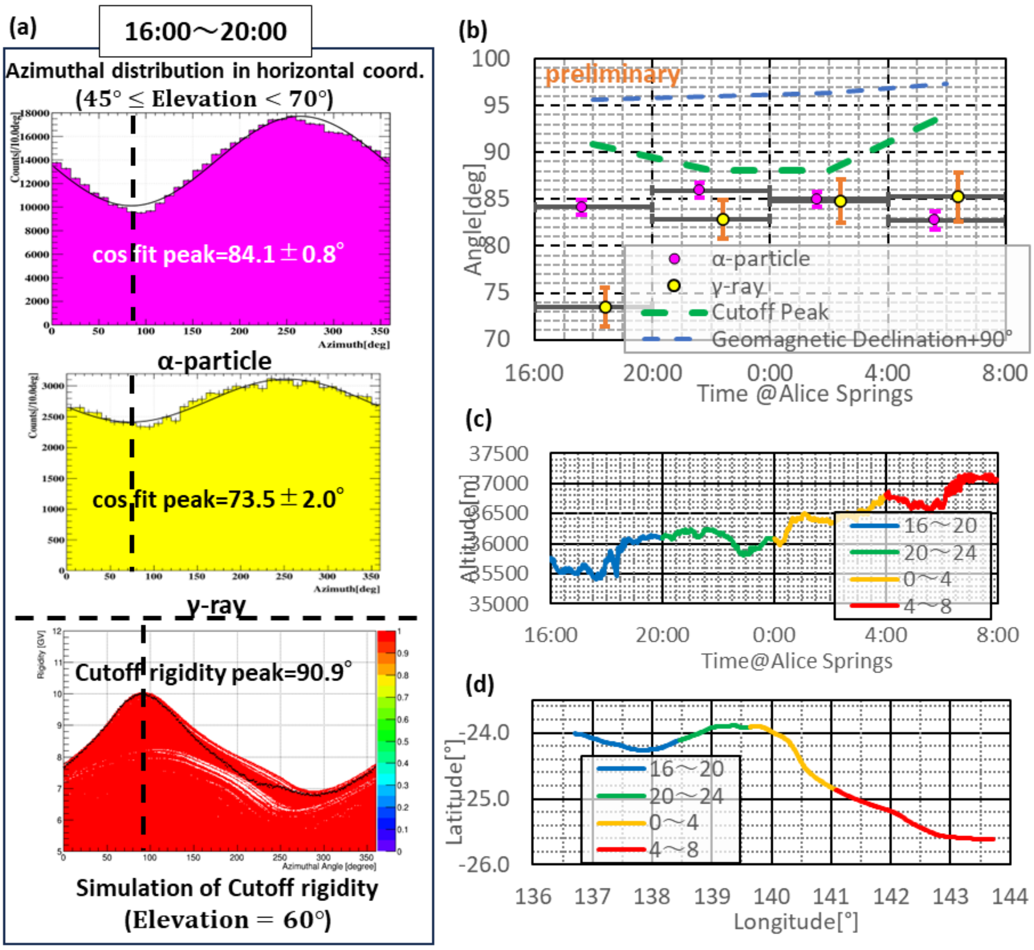

Figure 8: Analysis results of the east-west effect in flight data. (a) Azimuth angle distributions of γ-rays and α-particles from 16:00 to 20:00 Alice Springs time, along with cutoff rigidity simulation results. (b) Temporal variation of the east-west effect phase. (c) Altitude variation of the telescope during flight. (d) Flight path of the telescope during the mission.

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