PROCEEDINGS OF SCIENCE

GRAINE: Results of observations of gamma-ray sources from the 2023 balloon experiment

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We have been running the GRAINE project, a cosmic gamma-ray observation project covering the energy range from 10 MeV to 100 GeV, using nuclear emulsion detectors characterized with a high-angular resolution, polarization sensitivity and large aperture area. We conducted the fourth balloon experiment, GRAINE2023, in Australia with an aperture area of 2.5 m^2, for which we developed a new large-area telescope for scientific observations. We detected the Vela pulsar, thereby verifying the performance of the newly developed telescope. The measured angular resolution is $0.59^{+0.1}_{-0.07}$ ° for energies above 75 MeV, primarily in the 100–500 MeV range. We then measured the gamma-ray spatial distribution near the Galactic Center for energies above 75 MeV, and the obtained results are consistent with the expected models derived from Fermi-LAT observations. Because the angular resolution of Fermi-LAT is about 1° at 1 GeV, obtaining the flux within 1° of the Galactic Center in the sub-GeV energy range requires assumptions based on observational results at energies above 1 GeV. By contrast, we achieved a direct measurement of the flux within 1° of the Galactic Center, enabled by the high angular resolution of GRAINE. This represents a unique feature of the present study.

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1. Introduction

Observations of high-energy cosmic gamma rays play a crucial role in understanding non-thermal phenomena in the universe and the mechanisms of cosmic-ray acceleration. The most significant recent progress in the field was achieved with the Large Area Telescope on the Fermi Gamma-ray Space Telescope (Fermi-LAT) launched in 2008[1]. However, the angular resolution is orders of magnitude lower than that at other wavelengths, making studies of the spatial structure of sources difficult, particularly in regions with strong background emission such as the Galactic plane and the Galactic Center. Thus, observations with a higher angular resolution are essential to advance sub-GeV/GeV gamma-ray astronomy.

We have been running the GRAINE project, a cosmic gamma-ray observation project in an energy range of 10 MeV–100 GeV, using a balloon-borne telescope equipped with nuclear emulsion films [2]. The angular resolutions obtained with the nuclear emulsion film is very high for gamma rays (1° at 100 MeV and 0.1° at 1 GeV), which are 5–8 times higher than that with the Fermi-LAT (5° at 100 MeV and 0.8° at 1 GeV[3]). Furthermore, the emulsion film has high sensitivity for the polarization and we verified the performance in the polarized GeV gamma-ray beam experiment by decoding the precisely observed azimuthal-angle distribution of the produced pairs of electrons and positrons, which carries information of the polarizations of incident gamma-rays[4]. The GRAINE project plans to perform repeated observations with an aperture area of 10 m^2 with the flight duration of one week. We conducted several small-scale experiments for demonstration, and in the third balloon experiment, GRAINE2018, the emulsion gamma-ray telescope achieved the highest angular resolution ever reported in the sub-GeV energy band (>80 MeV).[5][6].

The fourth balloon experiment, GRAINE2023, was conducted in 2023 in Australia. Its aperture area was 2.5 m^2, 6 times larger than that in GRAINE2018. GRAINE2023 is the first step for scientific observation in the GRAINE project. The primary objectives of this experiment were to verify the performance of a new large-area telescope for scientific observations using the Vela pulsar, and to conduct the first observations of the Galactic Center region with our telescope. In this paper, we report the results of observations of gamma-ray sources from the 2023 balloon experiment.

2. GRAINE2023 balloon experiment

We began assembling our telescope at the balloon launch station in Alice Springs, Australia, at the end of February 2023, and the balloon was subsequently launched on 30 April. The level flight lasted 24 hours, covering the entire periods during which the target sources—the Vela pulsar and the Galactic Center—were within the $\pm 45^\circ$ field of view of the telescope (0° corresponds approximately to the zenith). We recovered the telescope the next day and sent all the films to Japan. We completed the photographic development of the 2000 films over the course of a month, and began scanning the recorded tracks in the films. In parallel with the selection of gamma-ray events from the large number of reconstructed tracks, we also carried out analyses of the time stamper and the attitude monitor, completing all data processing by the summer of 2025.

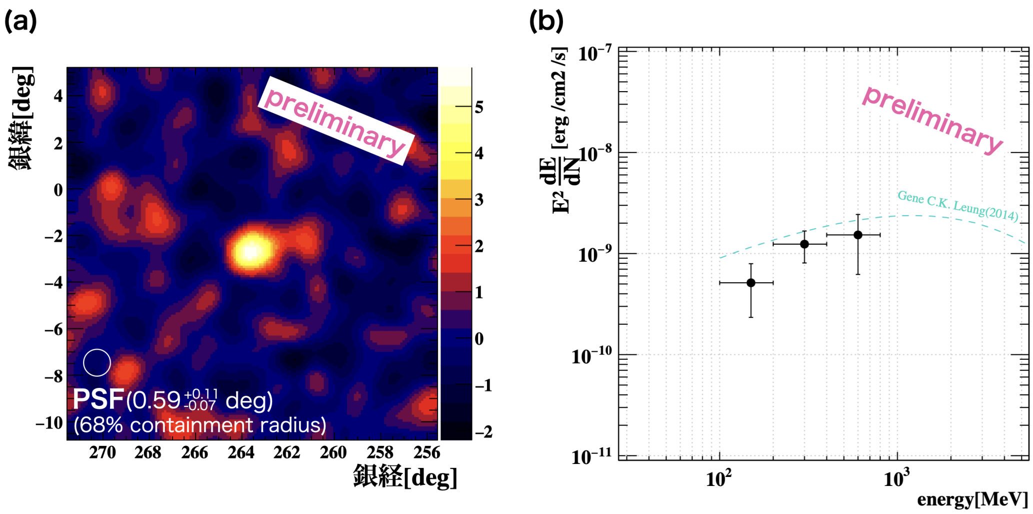

Figure 1: (a)The significance map of detected gamma rays (>75 MeV) around the Vela pulsar in Galactic coordinates。(b)The energy flux of Vela pulsar. Black points represent the GRAINE2023 results. The light-blue dashed line represents the fit to the results obtained by Fermi-LAT[7]. The vertical error bars represent statistical uncertainties, and the horizontal error bars represent the energy range.

3. Observation results

3.1 Vela pulsar

We observed the Vela pulsar, the brightest gamma-ray source in the energy band of the GRAINE experiment, to verify the performance of the newly developed telescope for scientific observations. Figure 1(a) shows the significance map of detected gamma rays (>75 MeV) around the Vela pulsar in Galactic coordinates. Background events from atmospheric gamma rays were subtracted based on the actual data, taking into account the time, azimuthal (due to the east-west effect), and energy dependence of the number of detected events, using all data including periods outside the Vela pulsar observation. We clearly detected the Vela pulsar with a PSF, defined as the 68%-events containment radius, of $0.59^{+0.1}_{-0.07}$ °, which is consistent with the expected performance in the main energy band of the observation, 100–300 MeV. Figure 1(b) shows the energy flux, which is consistent with the flux obtained by Fermi-LAT. These observations confirmed the sub-GeV gamma-ray observation performance of the newly developed large-area telescope.

3.2 Galactic Center

3.2.1 Observation of a wide region

Figure 2 shows Galactic latitude dependence of the number of detected gamma-ray events (>75 MeV) after subtraction of the atmospheric gamma-ray background, for Galactic longitudes(l) of 320° <l<360° or 0° <l<40°, and Galactic latitudes(b) of -35° <b<35°. We observed a 3.2σ excess in the region -5° <b<+5°, indicating the detection of predominantly Galactic diffuse gamma rays on the Galactic plane.

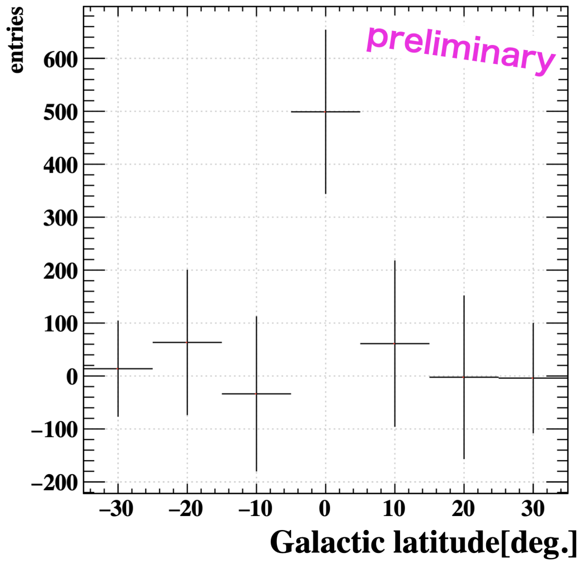

Figure 2: Galactic latitude dependence of the number of detected gamma-ray events (>75 MeV) after subtraction of the atmospheric gamma-ray background, for 320° <l<360° or 0° <l<40°, and -35° <b<35°. The vertical error bars represent statistical uncertainties determined by the event statistics before background subtraction, and the horizontal error bars represent the Galactic longitude range.

3.2.2 Observation of the central region

Figure 3 shows the observed gamma-ray spatial distribution near the Galactic Center (75 MeV–10 GeV) and the calculated values based on publicly available Fermi-LAT models and point source catalogs. Although the observed data cover energies above 75 MeV, the gamma-ray detection efficiency above 10 GeV is negligible with the current analysis method. Therefore, we compared the data with the expected values in the 75 MeV–10 GeV energy range. We calculated the region of interest (ROI) with a half-width R as (360-R)° <l<360° or 0° <l<R°, and -R<b<R. The obtained results are consistent with the expected values for 1° <R<10°, indicating the detection of cosmic gamma rays near the Galactic Center. Most importantly, we have directly obtained observational data within 1° in the sub-GeV band, which is a key achievement of this work. Because the angular resolution of Fermi-LAT is about 1° at 1 GeV, obtaining the flux within 1° of the Galactic Center in the sub-GeV energy range requires assumptions based on observational results in the energy range above 1 GeV. By contrast, as demonstrated by the observation of the Vela pulsar in the previous section, GRAINE achieves an angular resolution better than 1° in the sub-GeV energy range, enabling direct measurement of the flux within 1° of the Galactic Center. This result is not only an independent experimental result, but also a unique one enabled by the high angular resolution of GRAINE. Looking ahead, observations of regions with 1°<R using GRAINE's high angular resolution in the GeV band significantly suppress contamination from diffuse gamma ray backgrounds. This enables the study of gamma rays from astrophysical or dark matter origins without relying on diffuse gamma-ray models in the vicinity of the Galactic Center, thereby leading to unprecedented advances. This is one of the main targets of the next balloon experiment currently planned for 2028.

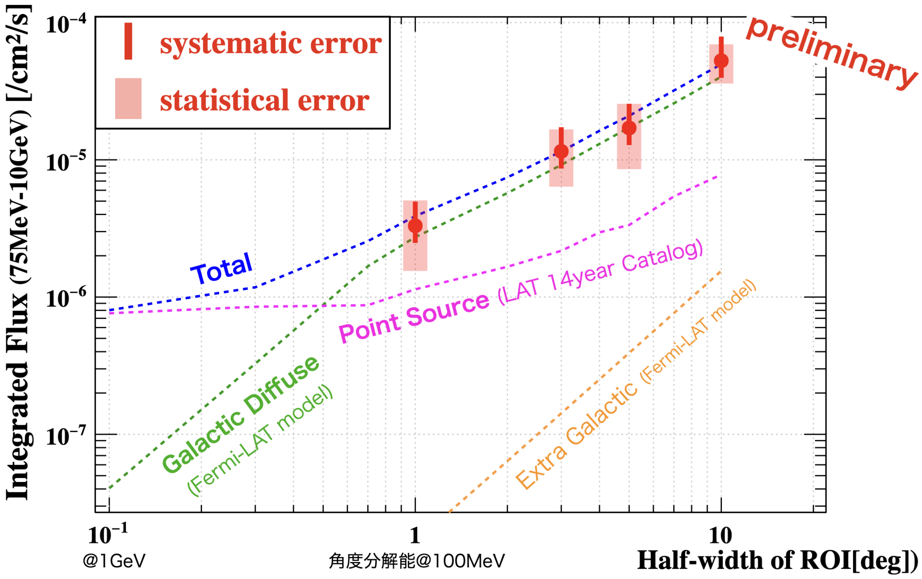

Figure 3: The observed gamma-ray spatial distribution near the Galactic Center. The observed gamma-ray spatial distribution near the Galactic Center. The horizontal axis represents the half-width R of the region of interest (ROI), and the vertical axis shows the integrated flux in the energy range of 75 MeV–10 GeV, calculated within the ROI as (360-R)° <l<360° or 0° <l<R°, and -R<b<R. Red plots represent the observed results with statistical and systematic uncertainties. The dashed lines represent calculated values based on publicly available Fermi-LAT models and point-source catalogs. The green line is calculated using the Galactic diffuse gamma-ray model (gll_iem_v07), the magenta line using the point-source catalog (gll_psc_v35), the orange line using the extragalactic gamma-ray model, and the blue line represents the sum of these three components[8][9][10].

4. Summary

We have been running the GRAINE project, a cosmic gamma-ray observation project in an energy range of 10 MeV – 100 GeV, using nuclear emulsion, characterized with a high-angular resolution, polarization sensitivity and large aperture area [2]. We conducted the fourth balloon experiment, GRAINE2023, in Australia. For this experiment, we developed a new large-area telescope for scientific observations, and the aperture area ($2.5\,\mathrm{m}^{s}$) is six times larger than that of our previous experiment. We completed the scanning of the recorded tracks in the films and all data processing by the summer of 2025. We detected the Vela pulsar, and the obtained angular resolution and energy flux are consistent with the expected values, verifying the performance of the newly developed telescope. Furthermore, we initially mapped the large-scale distribution of Galactic diffuse gamma rays, followed by a detailed study of the gamma-ray spatial distribution near the Galactic Center. The results obtained for regions of interest (ROIs) with half-widths R in the range 1° <R<10° are consistent with the expected models derived from Fermi-LAT observations. The direct measurement of the flux within 1° of the Galactic Center, enabled by the high angular resolution of GRAINE, is a unique feature. We plan the next balloon experiment in 2028 at the same scale as GRAINE2023, aiming to observe the vicinity of the Galactic Center in the GeV energy band to study the dark matter density profile and related topics.

References

[1] S. Abdollahi et al., Astrophys. J. **697** (2009) 1071.

[2] S. Takahashi et al., Adv. Space Res. **62** (2018) 2945.

[3] S. Abdollahi et al., Astrophys. J. Suppl. Ser. **247** (2020) 33.

[4] K. Ozaki et al., Nucl. Instrum. Meth. A **833** (2016) 165.

[5] S. Takahashi et al., Astrophys. J. **960** (2023) 47.

[6] Y. Nakamura et al., Prog. Theor. Exp. Phys. **2021** (2021) 123H02.

[7] Gene C. K. Leung et al., Astrophysical Journal letters **797**, L13 (2014).

[8] S. Abdo. et al., ApJS **260**, 53 (2022).

[9] S. Abdo. et al., ApJS **247**, 33 (2020).

[10] https://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_essentials.html.