PROCEEDINGS OF SCIENCE

GRAINE Project: High-resolution Imaging and Polarization Measurement of Sub-GeV/GeV Gamma Rays with Balloon-borne Emulsion Telescopes

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The Large Area Telescope onboard the Fermi Gamma-ray Space Telescope (Fermi-LAT) has surveyed the sub-GeV/GeV gamma-ray sky and achieved high statistics measurements since 2008. However, observation at low galactic latitudes remains difficult owing to the lack of the angular resolution, and new issues following the operation of Fermi-LAT have arisen. We devised a precise gamma-ray observation project, Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE), using balloon-borne emulsion gamma-ray telescopes to realize high angular resolution, polarization-sensitive, and large-aperture observations in the 0.01–100 GeV energy region. The main detector of the telescope, the nuclear emulsion, is a device that can track charged particles with sub-micron accuracy, and by measuring the angle of electron pair tracks and the emission azimuthal angle directly below the gamma-ray conversion point, it has a high angular resolution of 0.1 degrees in the 1 GeV band and the ability to measure polarization in the sub-GeV band. By combining the nuclear emulsion with a time stamper and launching it on a balloon, it is possible to achieve precision observations that would not be possible with satellite projects. GRAINE's initial targets are high-angular-resolution observations of the Fermi Galactic Center GeV Excess and the first polarization measurement of the Vela pulsar in the sub-GeV band by repeatedly launching balloons from Australia. In the 3rd balloon experiment conducted in 2018, imaging observations of the Vela pulsar in the 100 MeV band were achieved with the world's highest resolution using a small-size emulsion telescope. This talk comprehensively reports the latest observational results from the Vela pulsar and the Galactic center region from the 4th balloon experiment (conducted in April 2023) that launched a telescope with a 2.5-m^2 aperture area 6 times larger than the previous experiment, as well as the technical developments for high-angular resolution and polarization measurements using an emulsion telescope, and the preparation status towards further scientific observations using larger telescopes and long-duration balloon flights.

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1. Introduction

By observing gamma rays that can travel straight through space unaffected by the magnetic field, we can explore high-energy phenomena occurring in the universe. The insights cosmic gamma rays bring us span an extremely wide range of fields, including cosmic rays, astronomy, particle physics, and fundamental physics.

The Fermi Gamma Ray Space Telescope (Fermi-LAT), the latest sub-GeV to GeV gamma-ray detector, has continued its all-sky survey since its 2008 launch, providing unprecedented high-statistics gamma-ray data. While achieving various breakthrough results, including the detection of over 6,000 gamma-ray sources, new challenges have also emerged. The primary constraint preventing observation is insufficient spatial resolution (angular resolution). Understanding complex structures like the Galactic plane/central regions with dense concentrations of objects, or extended supernova remnants, requires more detailed data. Achieving high-resolution observations has thus become the critical improvement needed to advance gamma-ray astronomy to its next stage.

We have advanced the development of a gamma-ray telescope that achieves both high angular resolution and large aperture using nuclear emulsion technology developed by Japanese particle physics experimental researchers, and have promoted the balloon-borne observation experiment "GRAINE Project (Gamma-Ray Astro-Imager with Nuclear Emulsion)" [1]. Nuclear emulsion film [2], which achieves thin material layer (10^{-3} in units of radiation length) and sub-micron spatial resolution, is an optimal detector for measuring the direction of gamma rays. It can precisely measure the tracks directly below the gamma-to-electron-pair conversion point, enabling high-resolution precision observations that improve the angular resolution of Fermi-LAT by approximately one order of magnitude. Additionally, it possesses sensitivity to gamma-ray polarization. Figure 1 shows the configuration of the emulsion gamma-ray telescope. During the 2018 balloon experiment (GRAINE2018), our third balloon mission, we succeeded in detecting celestial sources, Vela pulsar, for the first time with the 0.4-square-meter emulsion telescope, demonstrating that balloon-borne nuclear emulsion film enables observation of sub-GeV gamma-ray sources with the world's highest resolution [3–6].

Since 2023, the GRAINE project has been conducting research using a 2.5-square-meter telescope mounted on a JAXA scientific balloon, working toward achieving its initial scientific goals, such as precise measurements of the Galactic center region. This paper describes the current status of the GRAINE project and the outlook for future balloon experiments.

2. GRAINE project and Scientific Targets

The GRAINE project aims to present qualitatively new cosmic-ray gamma-ray data and pioneer new physics by collecting data through repeated balloon flights using an emulsion telescope. This telescope possesses high-precision imaging and polarization measurement capabilities unattainable by current and future satellite-based GeV gamma-ray telescopes.

Dark matter, one of the unsolved problems in modern physics and astronomy, is expected to be densely distributed in the central regions of galaxies. There, collisions between dark matter particles are suggested to produce characteristic gamma-ray emissions. Searching for evidence of

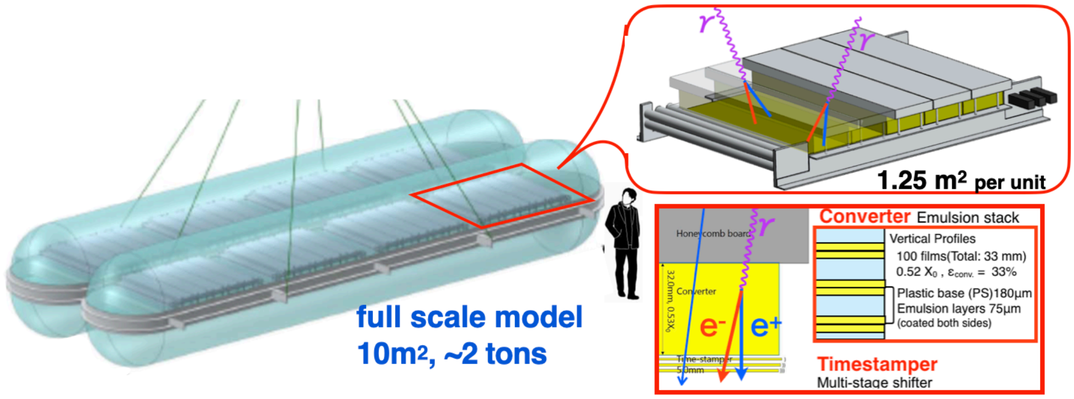

Figure 1: (Left) Full-scale model of the balloon-borne emulsion gamma-ray telescope with a 10-square-meter aperture. (Top right) Unit-type 1.25-square-meter emulsion telescope. (Bottom right) Cross-sectional configuration diagram of the telescope.

dark matter through cosmic gamma-ray observations complements underground and accelerator experiments.

Around 2014, multiple groups analyzing large statistical data sets accumulated by Fermi-LAT discovered an excess of gamma rays at the center of the Milky Way galaxy [7]. The "Fermi Galactic Center GeV Excess" could potentially be interpreted as a signal from dark matter annihilation, and the current understanding of high-energy phenomena at the Galactic center remains chaotic. The Galactic center region is not only densely populated with numerous celestial objects, but also exhibits a complex spatial distribution of Galactic diffuse gamma rays (a component generated by interactions between interstellar medium and cosmic rays). Observations by Fermi-LAT, which lacks sufficient angular resolution, inevitably suffer from background contamination, constituting the largest uncertainty in flux measurements.

Figure 2(left) shows the angular distribution of the excess GeV gamma-ray flux from the Galactic center. Fermi-LAT measurements align well with the simple dark matter distribution model (the NFW profile). If the model is correct, the flux rises sharply toward the center. Leveraging GRAINE's angular resolution enables the first-ever measurement of flux in the most central region ($< 0.1^\circ$), while suppressing the background of Galactic diffuse gamma-ray emission contamination to one-hundredth of conventional levels, providing crucial verification data.

Research on high-energy astrophysical objects has traditionally relied on measuring and refining the energy spectrum, spatial distribution, and time profile of incoming photons. However, in recent years, polarization has emerged as a new observational axis. Progress had been slow due to the technical challenges of observation, but experiments using polarization-sensitive telescopes like the IXPE satellite [9] and the balloon-borne XL-Calibur [10] have been conducted, opening new observational windows in the X-ray to hard X-ray range. Meanwhile, in the high-energy gamma-ray band (> tens of MeV), although radiation models with high polarization have been proposed for objects like pulsars, effective observational methods have yet to be established.

Nuclear emulsion film records the passage positions of charged particles in three dimensions with sub-micron spatial resolution. It enables the separation and measurement of two tracks while minimizing the amount of material passing directly below the pair-production reaction point, allowing significant measurement of the emission azimuthal angle of electrons and positrons carrying photon polarization information (principle demonstrated using a polarized gamma-ray beam [11]).

The Galactic center and the Vela pulsar are bright gamma-ray sources detectable by balloon experiments, and GRAINE has targeted these for its initial science observations. Figure 2(right) shows the dependence of the significance of GeV-band gamma-ray detection at the Galactic center (>1 GeV) and the minimum detectable polarization of the Vela pulsar (>0.1 GeV) on the amount of observation.

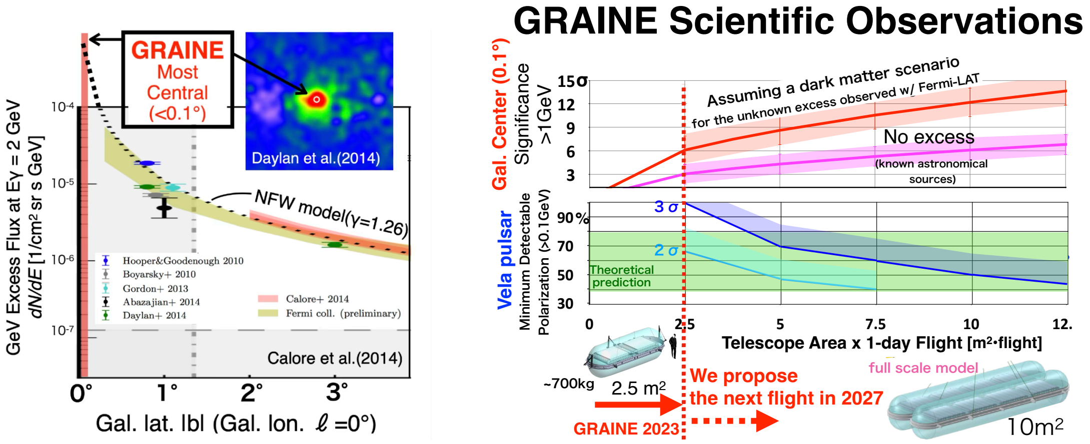

Figure 2: (left) Angular distribution of the GeV gamma-ray excess flux from the Galactic center and its predicted value from the NFW profile (dark matter density distribution) [8].(right) The dependence of the significance of GeV-band gamma-ray detection at the Galactic center (>1 GeV) and the minimum detectable polarization of the Vela pulsar (>0.1 GeV) on the amount of observation

3. Balloon experiment in 2023(GRAINE 2023)

The GRAINE2023 experiment was approved by JAXA for observation using two payloads (payload weight approx. 700 kg) each equipped with an emulsion telescope with an aperture area of 2.5 square meters, conducted over two flights. This aimed to take the first step toward scientific observation of GRAINE.

To realize an experiment expanding the observation scale to 13 times that of the previous experiment (GRAINE2018), a production facility capable of manufacturing 10 times the conventional amount of nuclear emulsion and nuclear emulsion film [12, 13]; A roller-driven multi-stage shifter enabling lightweight, large-area timestamping [14]; A 5-meter-long pressurized vessel gondola mounting two 1.25-square-meter telescope units; A Daytime Star Camera with improved low-temperature resistance and detection sensitivity; A solution physical developer that enhances the contrast of developed silver grains in nuclear emulsion film [15]; and a latest-generation track readout device that doubles the readout speed of tracks compared to a previous model [16]. As shown in Figure 3(left), two payloads were completed by December 2022. However, due to troubles occurring just before launch, such as soaring helium gas prices, the GRAINE payload capable of flight for the 2023 Australian experiment was forced to be changed to a single gondola flight.

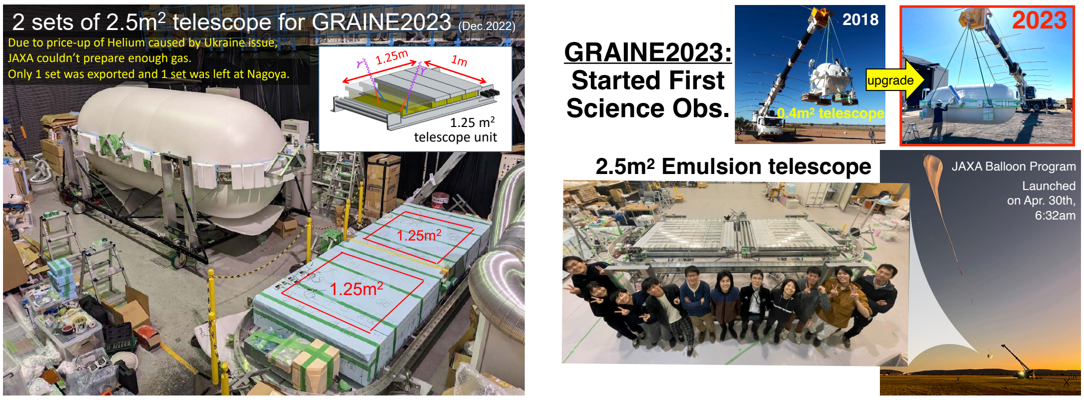

Figure 3: (left) Gondola #1 and #2 equipped with the 2.5-square-meter emulsion telescope, which completed its final tests in December 2022. (right) GRAINE2023 Australian Balloon Experiment: View of the nuclear emulsion film after installation at the launch site and during balloon release.

GRAINE2023 was conducted on April 30, 2023, achieving a 27-hour flight (Figure 3 (right)). During the first half of the observation period, we successfully conducted experiments to observe the Vela pulsar within the telescope's field of view, followed by the Galactic center region in the latter half, recording the track data from this time period onto nuclear emulsion film.[17].

The nuclear emulsion films brought back were developed over approximately two months at Gifu University. Data acquisition from the recovered nuclear emulsion film utilized the newly developed state-of-the-art emulsion scanning system, Hyper Track Selector-2, at Nagoya University for the first time in a full-scale experiment, digitizing track data at the fastest speed in the history of nuclear emulsion experiments. In parallel, we performed performance evaluation of the track data, identified the electron-positron pair production points, determined the energy, assigned arrival times, analyzed the attitude monitor data and determined the attitude. Combining these analysis data, we sequentially mapped the gamma-ray arrival directions onto the celestial sphere.

For results obtained up to July 2025, please refer to the presentations at this conference [18–20]. Through advanced flight data analysis, we confirmed the acquisition of valid astronomical observation data using the newly developed telescope unit in this experiment and successfully detected the Vela pulsar in the sub-GeV band, continuing the success of the previous experiment [18]. Furthermore, analysis in the Galactic center observation period progressed, achieving GRAINE's first detection of cosmic gamma rays in the vicinity of the Galactic center region and measuring their spatial distribution [18]. Additionally, using flight data, we are newly advancing the development of event selection and timestamp analysis methods targeting multi-GeV gamma-ray events [19], anticipating the publication of observational results in higher energy bands (the GeV range). The nuclear emulsion film data acquired by the balloon experiment records not only gamma-ray pair-production reactions but also the tracks of all primary and secondary cosmic ray charged particles. Furthermore, by combining timestamp analysis and attitude analysis, unique measurement data at balloon altitudes is being obtained. Currently, we are conducting a detailed comparison between the cutoff rigidity calculated from the geomagnetic field model for each observation location (altitude, latitude/longitude) and the measured arrival azimuth distributions of atmospheric gamma rays and alpha particles. As a byproduct of this research, we are compiling precise measurement results of the east-west effect of primary and secondary cosmic rays at an altitude of 35 km, which can only be measured by balloon experiments[20].

4. Next Balloon experiment in 2027(GRAINE 2027)

The primary objective of the next Australian balloon experiment scheduled for March-April 2027 is high-resolution observation of GeV-band cosmic gamma rays from the Galactic center. We retain one of the two payloads prepared for the 2023 experiment unused (#2) and aim to fly the payload #2 according to the original plan. Two roller-driven multi-stage shifters, three daytime star cameras, insulation, crash pads, and the pressurized gondola carrying these components have been manufactured with a design nearly identical to #1. This ensures they can operate without issue, including during night flights, as demonstrated in the 2023 experiment. Combining the observational results from GRAINE2023 (#1) with those from the emulsion telescope (#2) flying in the 2027 experiment, we will perform precise measurements of Galactic center gamma rays in the GeV band. If significant statistics are obtained in the GeV band, we can expect to measure the flux of point sources in the Galactic center and components of the Fermi Galactic Center GeV Excess, leveraging the high angular resolution of the emulsion telescope. We aim to achieve the first detection of GeV-band gamma-ray signals from the very center of the Milky Way Galaxy (within a 0.1-degree radius), one of our initial scientific goals.

As a second objective, GRAINE will conduct experiments through Japan-U.S. collaboration and develop new observation techniques in preparation for future expansion plans. Beyond the 2027 experiment, GRAINE will pursue increased flight opportunities, flight duration, and instrument area by establishing a new experimental framework and developing observation methods to realize NASA's large-scale balloon experiments. A prototype "hybrid emulsion telescope" capable of extended observation periods and high temporal resolution will be mounted on part of the gondola. This will enable the first verification of observation techniques at balloon altitudes, conducted jointly with U.S. researchers. Building on this foundation, GRAINE will proceed with designing scientific observation models and proposing future expansion plans.

The upper section of the hybrid emulsion telescope consists of the nuclear emulsion film part (γ-ray measurement and coarse time stamping via a single-stage emulsion shifter) handled by Japan, while the lower section comprises the scintillation fiber tracker (SFT) part (high-precision, high-efficiency time stamping) handled by the United States. The scientific observation model will be mounted on NASA's large balloon, aiming for long-duration flight observations. For example, a seven-day flight opportunity in Kiruna could enable groundbreaking science, such as measuring intergalactic magnetic fields through high-resolution imaging of Active Galactic Nuclei.

The Japan Group has taken the lead in initiating fundamental research toward practical application and design considerations for the new timestamp method. In August 19-21 2025, we transported nuclear emulsion films + SFT (repurposing a compact device developed around 2000) to the Norikura Cosmic Ray Observatory, Institute for Cosmic Ray Research, The University of Tokyo and conducted hybrid observation tests targeting atmospheric gamma rays and electrons at 0.1 GeV band (Figure 4). Aiming to confirm the principle and performance of the new method, we are conducting demonstration analyses of the emulsion scan data and SFT data, which will be fed back into the design study for the balloon-borne model.

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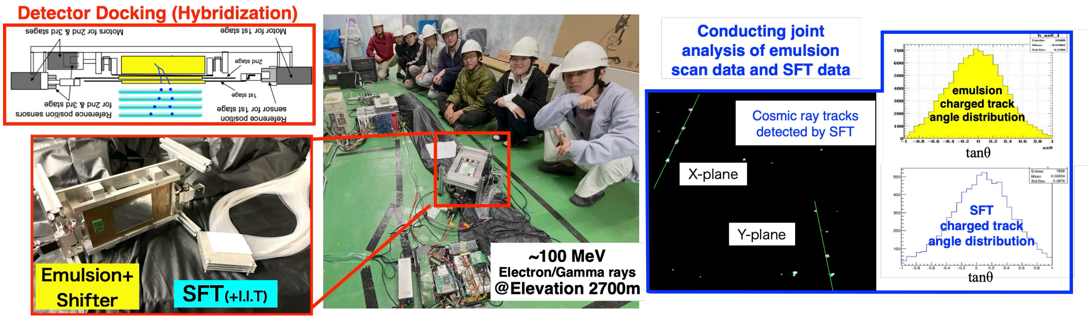

Figure 4: Test observations with the hybrid telescope conducted at the Norikura Cosmic Ray Observatory, Institute for Cosmic Ray Research, The University of Tokyo (August 2025)

5. Summary

We are advancing the GRAINE project for precision gamma-ray astronomy using balloon-borne emulsion telescopes. During the 2023 Australian balloon experiment, we successfully conducted observations with the first 2.5-square-meter emulsion telescope and acquired valid astronomical data. For the next 2027 Australian balloon experiment, we plan to advance scientific observations using the second telescope while conducting demonstration tests for future upgrades.

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