PROCEEDINGS OF SCIENCE

GRAINE project: gamma-ray observation with a balloon-borne emulsion telescope

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The Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) is a balloon-borne experimental project for the precise observation of cosmic gamma-rays. A next generation detector "emulsion telescope" for GRAINE consists of large area (∼10 m^2) nuclear emulsion plates, which are three-dimensional charged particle tracking devices with the submicron spatial resolution. The telescope has the higher angular resolution and the linear polarization sensitivity for 10 MeV–10 GeV gamma-rays than the Large Area Telescope on board the Fermi Gamma-ray Space Telescope (Fermi-LAT). In 2011, a technical flight was performed by employing a small-scale telescope (125 cm^2 aperture area), and the feasibility of each component of the detector was demonstrated. The next balloon flight, which will take place in Australia after 2014, is aimed at detecting and imaging the Vela pulsar. By the detection and subsequent imaging of the Vela pulsar, the brightest source in the high energy gamma-ray sky, we will verify the overall performance of the emulsion telescope. Here we report an overview and status of GRAINE.

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1. Introduction

Huge accelerators of charged particles exist naturally in space, such as black holes, pulsars, supernova remnants. Observations of the hard X-ray and gamma-ray emissions from such accelerators are effective in understanding such non-thermal phenomena. Observation of the gamma-ray emission is particularly important for studying the acceleration of cosmic ray protons. Accelerated protons interact with interstellar gases and produce neutral pions, which immediately decay into gamma-rays in the energy range from a few 10 MeV to a few GeV.

The Large Area Telescope on board the Fermi Gamma-ray Space Telescope (Fermi-LAT)[1], which has sufficient sensitivity in this energy range, has surveyed the entire sky since 2008 and has thus far detected about 2000 gamma-ray sources[2]. However, almost 30% of these sources are classified as “unassociated sources", which have no associations with other wavelength observations. Most unassociated sources lie in the galactic plane or the galactic center. Current observations at low galactic latitude are limited by confusion with background (galactic diffuse gamma-ray) emission and many sources. Improvements in detector performance, especially in angular resolution, are important for detailed observations at low galactic latitudes.

2. GRAINE project

The Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) project is a balloon-borne experiment project designed to observe gamma-ray sources precisely in the 10 MeV–10 GeV region[3]. Each detector consists of a nuclear emulsion plate, which is a three-dimensional charged particle tracking device with the submicron spatial resolution. Its angular resolution improves upon that of the Fermi-LAT by one order of magnitude via the precise measurement of track angles at the starting point of the interaction $\gamma \rightarrow e^{+} + e^{-}$. In addition, it makes the measurement of the azimuthal angle of e^{+} and e^{-} feasible and is sensitive to gamma-ray polarization. The performance of the emulsion telescope is described in Table 1. The emulsion gamma-ray telescope consists of the converter (100 sets of interleaved emulsion film and copper foil layers) for detecting gamma-rays and determining their directions precisely; the time stamper, referred to as “the multi-stage shifter,"[4] for assigning event arrival time; and, the calorimeter (several dozen sets of an emulsion film and Pb plates) for measuring energy via the shower counting or the multiple Coulomb scattering method. It is a dead-time-free, dead-space-free, and lightweight detector without an electronic counter. We started developing a large-area telescope (aperture area $\sim$10 m^2) and promoting long-duration balloon flights ($\sim$200 hours), similar to the JACEE or RUNJOB balloon-borne experiments, for scientific observation.

In June, 2011, as the first phase of the GRAINE project, we performed a technical balloon-borne experiment . A small-scale telescope (aperture area 12.5 $\times$ 10 cm^2) was launched at Taiki Aerospace Research Field in Japan, and its flight duration was 4.3 hours, flying for 1.6 hours of this time at a level altitude of 34.7 km. We analyzed the flight data by scanning the recovered films with the fully automated scanning system S-UTS at Nagoya University [5], and acquired

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[1] At nomal incident.

[2] Effective area was considered with 10 m^2 aperture area, transmittance at 5 g/cm^2 atmospheric depth, conversion efficiency at 0.54 radiation lengths and detection efficiency for each energy.

Table 1: Performance of the emulsion gamma-ray telescope

Energy range	10 MeV–10 GeV
Angular resolusion[1]	0.93°@100 MeV 0.1°@1 GeV
Polarization sensitivity	Yes
Energy resolution	10%–20%
Effective area[1] [2]	2.1 m^2@100 MeV 2.8 m^2@1 GeV
FOV	>2.2 sr
Time resolution	< 1 s
Dead time	No

following results: (1) the time resolution of the multi-stage shifter at the balloon altitudes was evaluated and it was 0.6 seconds [6]; (2) the first light of GRAINE was authorized [7]; and, (3) the flux of atmospheric gamma-rays, which is our main back ground, was measured [8]. Through this technical flight, the feasibility of GRAINE project was demonstrated.

3. Preparation status for next balloon-borne experiment

The aim of the next experiment in the GRAINE project is detecting and imaging a gamma-ray source in the 100 MeV region. We plan a middle duration (∼24 hours) balloon flight in Alice Springs, Australia, which is expected to observe the Vela pulsar, the brightest gamma-ray source in the GeV sky, for 6.5 hours within the field of view of the emulsion telescope. The status of each component of the experiment is reported in the following subsections.

3.1 Emulsion film

We manufacture an emulsion gel used as the raw materials for films utilized in the experiment. We succeeded in the development of the highly sensitive emulsion gel with an emulsion production machine present in our laboratory since 2010. The grain density – the average number per unit length – of the silver particles observed after chemical development of this new type of gel is two times higher than that of the typical gel.

A film production test was performed before introducing the new gel to the converter of the emulsion telescope. We constructed a temperature- and humidity-controlled pouring room to avoid cracking and curling the film. Over the course of four days, 1 m^2 of emulsion films was poured and the chamber, which has the same structure as the converter of the emulsion telescope, was constructed. We brought this chamber to the Norikura Observatory the Institute for Cosmic Ray Research (altitude 2700 m) and performed gamma-ray observation test in 100 MeV energy region. Figure 1 shows the incident angle dependency of track finding efficiency in a film scanned by S-UTS. While the efficiency of films employed in GRAINE 2011 was ∼80%, the efficiency of films coated with the high sensitive emulsion gel was drastically improved. Then, we reconstructed

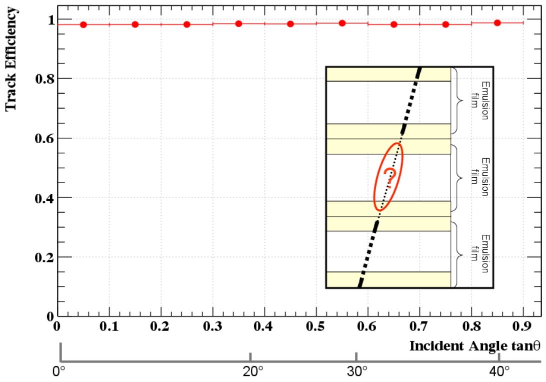

Figure 1: Angle dependency of track finding efficiency in a film coated with the new-type high sensitive emulsion gel.

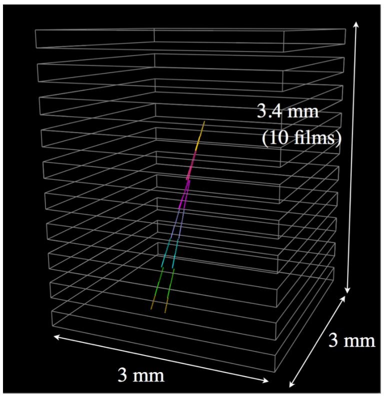

Figure 2: 3-D view of $\gamma \rightarrow e^{+}+e^{-}$ detected in the chamber employed in the obseration test at the Norikura observatory. The reconstructed energy of this event was 160 MeV.

tracks which penetrated multiple films and detected gamma-ray events with the e-pair topology (gamma-like events start in the middle of the chamber, penetrate downstream, and are accompanied by a partner track). Figure 2 shows a 3-D view of one of these candidates.

We will develop more effective and faster production methods and prepare $\sim$50 m^2 of films over a few months' time.

3.2 Time stamper

The multi-stage shifter adopted as the time stamper for the gamma-ray telescope determines the event arrival time with the subsecond resolution by sliding the multiple stages precisely during the observation period and analyzing the position displacements induced intentionally between tracks in the emulsion layers. The second flight model ,upon which 30 times larger emulsion films can be mounted compared with the first model, and its control module have been completed. Figure 3 shows a picture of the second flight model. The dimensions and the mass of the second flight model are 660 mm × 1450 mm × 100 mm and 70 kg, respectively. This model has three 1 mm thick stainless-steel stages. Each stage slides with a 10 mm stroke and is driven by a fine-scale pulsed stepping motor. We completed an operation test in an environmental chamber at the Scientific Balloon Laboratory at the Institute of Space and Astronautical Science (ISAS). At a temperature of -60°C and a pressure of 5 hPa, a stable operation over 24 hours was verified.

3.3 Star camera

The first daytime star camera mounted on GRAINE 2011 determined attitudes of the emulsion telescope at a working ratio of 74% during daytime observation periods[7]. For the Australia launch, we replaced the CCD camera with one that has a higher quantum efficiency. We performed a night-sky observation test on the ground and found that the number of stars detected within the field of view of the new camera (43 stars) substantially increased compared with the number of stars detected by the old camera (11 stars). Three independent cameras are mounted on the gondola in

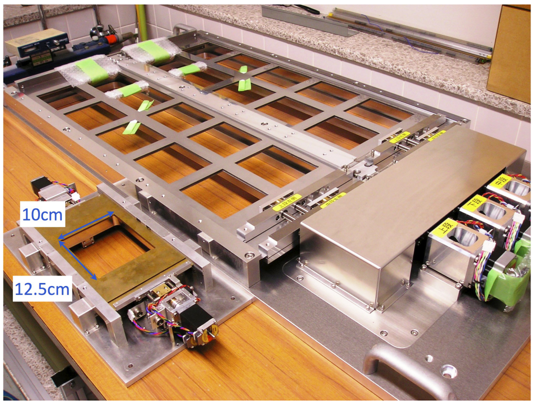

Figure 3: Picture of the multi-stage shifter first flight model (left) and second flight model (right).

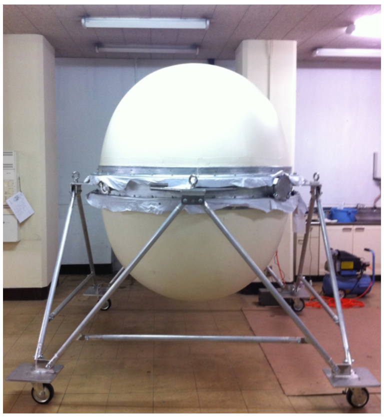

Figure 4: Picture of the balloon-style pressure vessel.

distinct directions. We estimate that the working rate of the three-camera system is ∼99% and the monitoring accuracy is < 0.1 milli-radians.

3.4 Pressure vessel

The entire emulsion telescope is contained in a pressure vessel pressurized to ∼0.2 atm to maintain the vacuum-packed emulsion chamber at balloon altitudes. This offers the following advantages: preventing deformation of the converter in a severe environment with the temperature variation; preventing the fading effect in case of long time taken for a recovery; and, shading and waterproofing to ensure recovery. Figure 4 shows a picture of the balloon-style pressure vessel, whose concept the ATIC group adopted[9] . It consists of aluminum rings, spherical plastic films for airtightness, and shells made of reinforced fibers. The diameter of the sphere and the mass, including the trussed structures, are 1.6 m and 100 kg, respectively.

4. Summary

GRAINE is a precise gamma-ray balloon-borne observation project with an emulsion telescope mounted. In the next balloon-borne experiment located in Alice Springs, Australia, we will employ a 0.6 m aperture telescope and demonstrate the performance of our detector, in particular its higher angular resolution, by detecting the Vela pulsar in the 100 MeV region. Preparations are progressing steadily and the flight is planned to take place after November 2014. In this stage of the experiment, we will extend the observation time and aperture area, and begin scientific observations with GRAINE.

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