PROCEEDINGS OF SCIENCE

Gamma-Ray Astro Imager with Nuclear Emulsion, Evaluation for timestamper emulsion film for the balloon experiment

Shogo Nagahara[a,*] **and GRAINE Collaboration**[a,b,c,d,e]

[a]*Kobe University,*
Kobe 657-8501, Japan
[b]*Aichi University of Education,*
Kariya 448-8542, Japan
[c]*Okayama University of Science,*
Okayama 700-0005, Japan
[d]*Gifu University,*
Gifu 501-1193, Japan
[e]*Nagoya University,*
Nagoya 464-8602, Japan

E-mail: nagahara@radix.h.kobe-u.ac.jp

We are developing the GRAINE (Gamma-Ray Astro Imager with Nuclear Emulsion) project for precise (0.08 degree @ 1 - 2 GeV) and large-aperture-area observations of cosmic gamma rays in the 10 MeV - 100 GeV by long balloon flights of the nuclear emulsion telescope. We have demonstrated the performance and feasibility of balloon-borne emulsion gamma-ray telescope experiments in 2011, 2015, and 2018. We succeeded in imaging the Vela pulsar at high resolution during our 2018 observations. We are preparing for observations in spring 2023 with an aperture area of 2.5 m^2, 7.5 times larger than in 2018. Since emulsion films have no time-resolution, time information is added using a mechanism called a timestamper. For the emulsion films used in this part, a new type of film suitable for large-scale production was adopted. In this study, the basic performance and long-term properties of this film were evaluated for suitability for the GRAINE experiment. First, we evaluated the sensitivity and noise level by using films cut to several centimeters and preparing samples under different conditions that affect film quality (humidity during vacuum packing, temperature during storage, and storage period). Next, we evaluated the sensitivity of the 10 cm x 12.5 cm films by scanning the tracks with the Hyper Track Selector. These evaluation results and the latest status of the films used in the balloon-borne experiment are presented.

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[*] Speaker

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1. Introduction

High-energy gamma rays are very important probes for understanding high-energy phenomena in space and cosmic ray acceleration mechanisms. Because gamma rays arrive at Earth without being influenced by the effects of interstellar magnetic fields, gamma rays keep information about the source. Thus, objects radiating high-energy gamma rays are candidates for cosmic ray proton acceleration sources. Gamma rays are also important in the search for cosmic-ray electron sources because gamma rays are also radiated when electrons are accelerated by Bremsstrahlung, synchrotron radiation, and inverse Compton scattering. High energy gamma-ray observations have made great progress with the discovery of many γ-ray sources by observations with the Fermi-LAT detector, which was launched in 2008[1][2]. On the othe hand, the angular resolution of these gamma rays is an order of magnitude lower than observations at other wavelengths due to the difficulty of observation.

In response to this, we are conducting a project to observe GeV/sub-GeV cosmic gamma-rays with the world's highest angular resolution by long balloon flights of a gamma-ray telescope using a nuclear emulsion film (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 the three-dimensional trajectory of charged particles with submicron accuracy. Due to the high spatial resolution 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)[3] and polarization information can also be provided as well[4]. We have demonstrated the performance and feasibility of balloon-borne emulsion gamma-ray telescope experiments in 2011[5], 2015[6], and 2018[7]. We succeeded in imaging the Vela pulsar at high resolution during our 2018 observations with a 0.38 m^2 aperture area and 17.4 hours flight. 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 flight time was 23.5 hours, 1.6 times longer than in 2018, and it succeeded in covered only the Vela Pulser but also the galactic center.

The telescope of GRAINE consists of three major components: the conveter, the attitude monitor, and the timestamper (Fig. 1). 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[8]. Nuclear emulsion film has no time resolution. By moving the relative positions of the films to create time-specific relative positions, Timestamper gives time information to the tracks that penetrate the continuous film.

Timestamper has developed a new model for the 2023 experiment to enable larger area telescope (Fig. 2)[9]. The nuclear emulsion film in Timestamper is also a new type of film suitable for large-scale production from the 2023 experiment due to its large area. In this study, the basic performance and long-term properties of this new type of film were evaluated for suitability for the GRAINE experiment.

These evaluation results and the latest status of the films used in the balloon-borne experiment are presented.

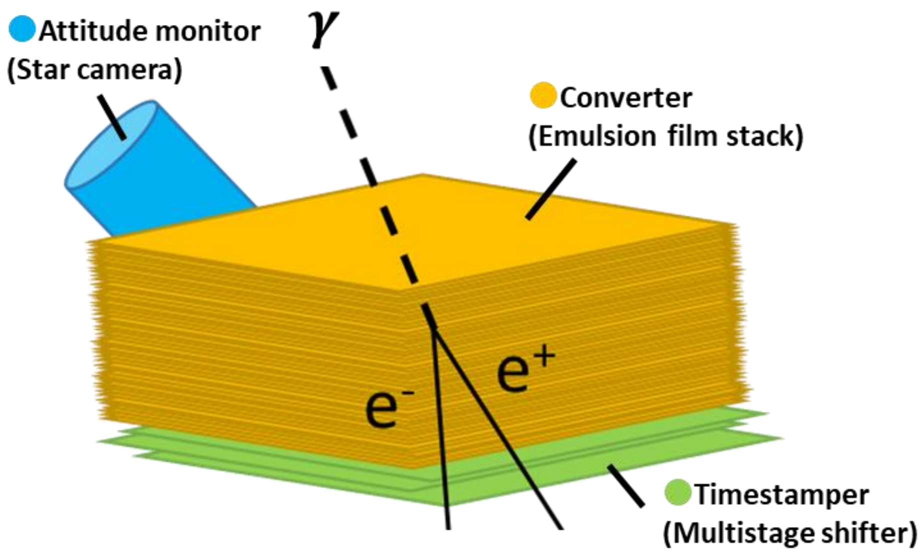

Figure 1: Main components of a gamma-ray telescope using nuclear emulsion. Converter is the part that reconstructs the angle of gamma rays by measuring the angle between electrons and positrons generated by the electron-pair creation caused by gamma rays. The Attitude monitor determines the attitude 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.

2. Evaluation for timestamper emulsion films

The quality of nuclear emulsion film decreases when stored at high temperatures for long periods of time. Grain counts in the tracks decrease and the random grain (fog) counts that are not related to the track increases when stored at high temperatures. The former leads to a decrease in signal intensity, and the latter leads to an increase in noise. These are known to depend on the temperature and humidity of the film. To evaluate their effects on the experiment, the following evaluation tests were performed.

2.1. Another section Evaluation of basic properties using small pieces

As a basic characteristic evaluation, we evaluated the sensitivity and noise level by using films cut to several centimeters and preparing samples under different conditions that affect film quality (humidity during vacuum packing, temperature during storage, and storage period).

Sensitivity was evaluated in terms of the number of grains per 100μm of beta-ray trajectory with known energy Grain Density: GD). The results are shown in Fig. 3. GD did not decrease significantly after 3.5 days, which was projected before the experiment. This was found to be sufficient for use in the experiment.

Noise level was evaluated by the number of random grains per 1000μm^3 (Fog Density: FD). The results are shown in Fig. 4. FD was found to be at a level sufficient to keep the problem beyond 6 months, which was projected before the experiment.

Both FD and GD were found to be independent of humidity in the range of 30 – 50% humidity.

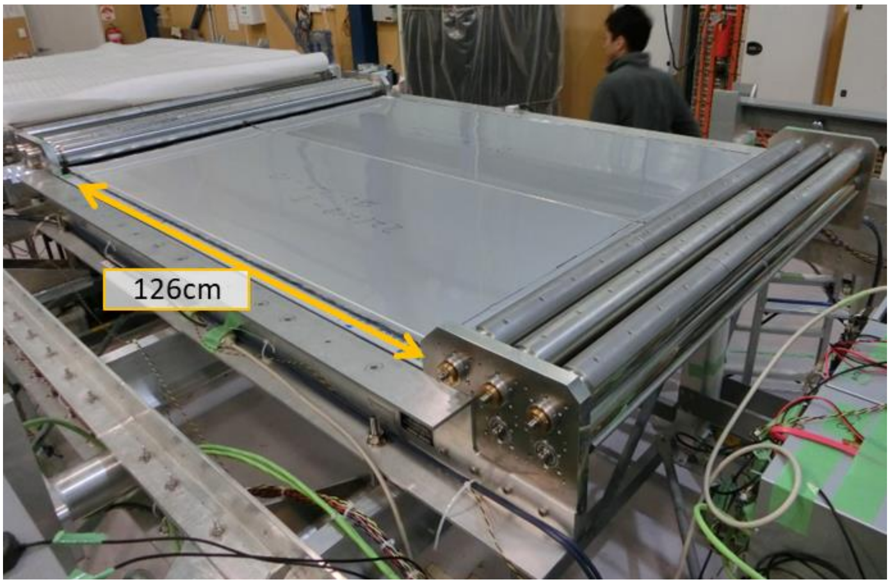

Figure 2: Timestamper used in 2023 experiment.

2.2. Evaluation of Practical Performance

Tracks recorded in emulsion film are read out using Hyper Track Selector (HTS)[10]. In order to estimate the efficiency of track detection in HTS, an evaluation using cosmic ray tracks was performed. The experiment was performed on three layers of film. Efficiency was defined as the probability of finding a track in the middle film if the tracks were connected in the first and third films. The results are shown in Fig. 5. The zenith angle dependence of efficiency is due to the optical properties of HTS. It is known that efficiency is significantly reduced in areas with large zenith angles when the signal level is low. Efficiency was decreased when the storage period after the observation was longer than 2 weeks. This shows that it is important to recover the film quickly after the observation.

3. Operational results of the time stamper film in the 2023 balloon experiment

Timestamper film operation schedule for 2023 experiment is shown in Fig. 6. Films were produced between October and November 2022. The film was vacuum-packed after a refresh process to erase existing tracks and fog from December 2022 to January 2023. In order to minimize film quality decrease, a low-temperature environment was kept as much as possible after packing. The film was installed on the telescope in early March. The flights then operated from April 30 to May 1, when winds and other conditions were favorable. After the observations, the films were stored in a cold storage unit by May 3. The film was then transported back to Japan, and by June 27, all films used at Timestamper had been developed.

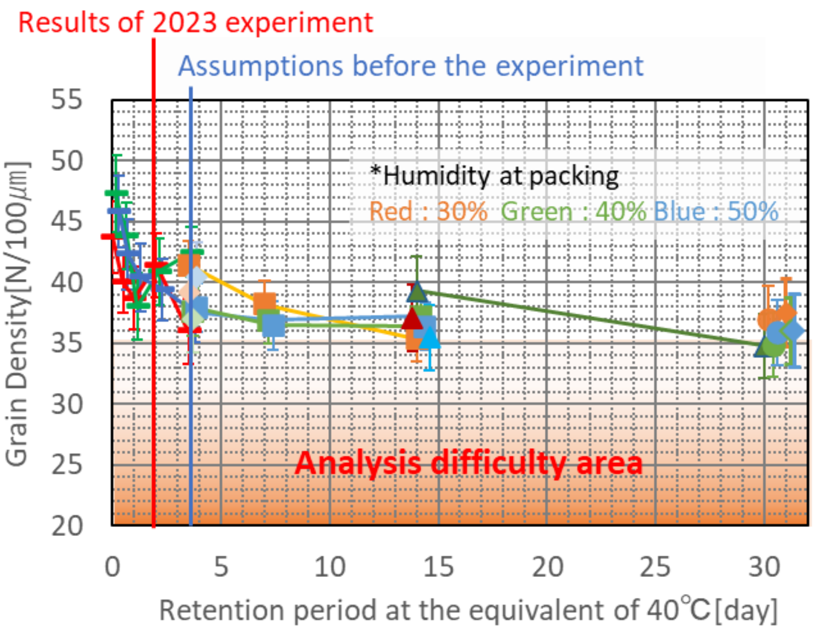

Figure 3: Relationship between Grain density and storage period of film at various humidity conditions. The horizontal axis is based on the assumption that the storage period is 40°C according to Arrhenius' law. The blue line is the storage period after the flight, which was assumed before the 2023 experiment (3.5 day). The red line is the storage period after the flight of the 2023 experiment (1.8 day).

Temperature logs between packing and development are shown in Fig. 7. Based on temperature logs, the 20°C equivalent storage time from packing to development was 85.7 days. As shown in Fig. 4, the 2023 experiment succeeded in developing the film in about half the time previously assumed. The 40°C equivalent storage period from observation to development was 1.8 days. As shown in Fig. 3, the 2023 experiment succeeded in developing the film in about half the time previously assumed.

The condition of the film after development was checked using a microscope. As a simple checking, the FD of the film was evaluated on three levels: 0<FD<4, 4<FD<6 and 6<FD (/1000μm^3). As a result, 67.5% of the films were 0<FD<4, 32.1% of the films were 4<FD<6 and 0.4% of the films were 6<FD. This is within the allowable range for the analysis.

The films are presently being prepared for readout by HTS.

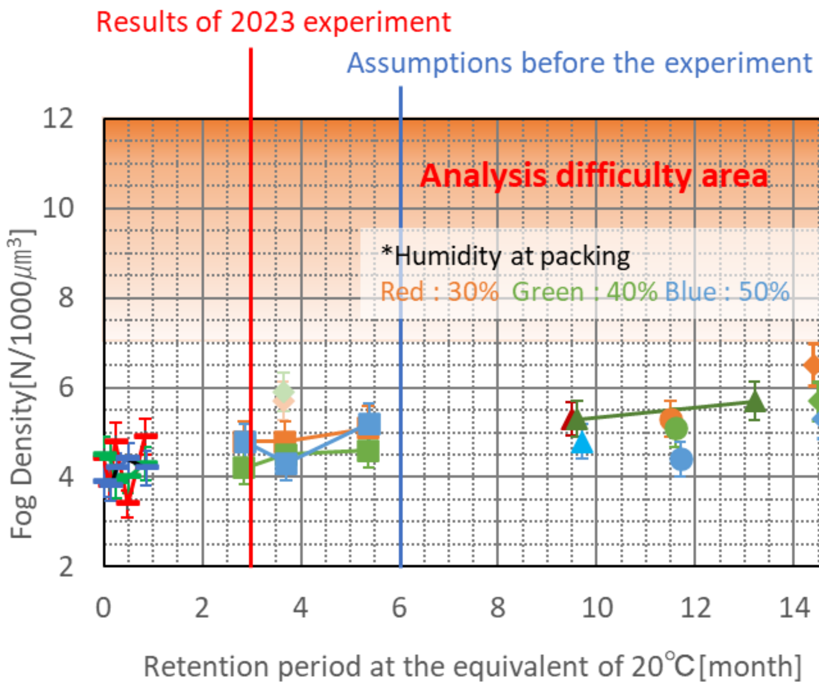

Figure 4: Relationship between Fog Density and storage period of film at various humidity conditions. The horizontal axis is based on the assumption that the storage period is 20°C according to Arrhenius' law. The blue line is the storage period after the flight, which was assumed before the 2023 experiment (6 month). The red line is the storage period after the flight of the 2023 experiment (3 month).

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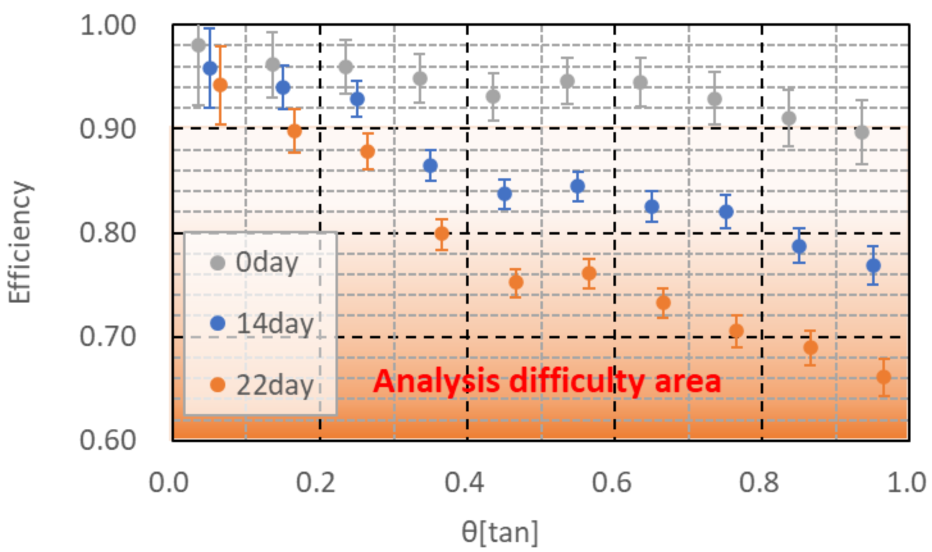

Figure 5: Relationship between zenith angle and efficiency. The horizontal axis is the zenith angle of the track relative to the film. The legend is based on the assumption that the storage period is 40°C according to Arrhenius' law.

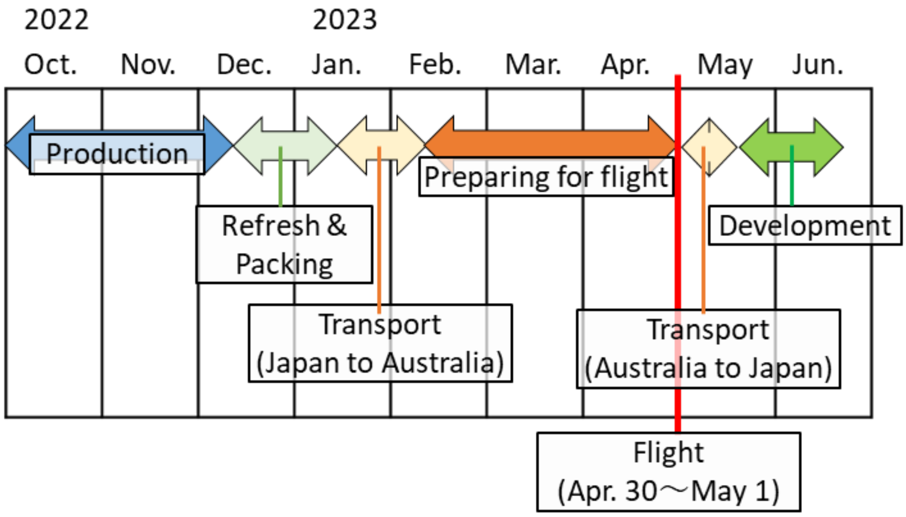

Figure 6: Timestamper film operation schedule for 2023 experiment.

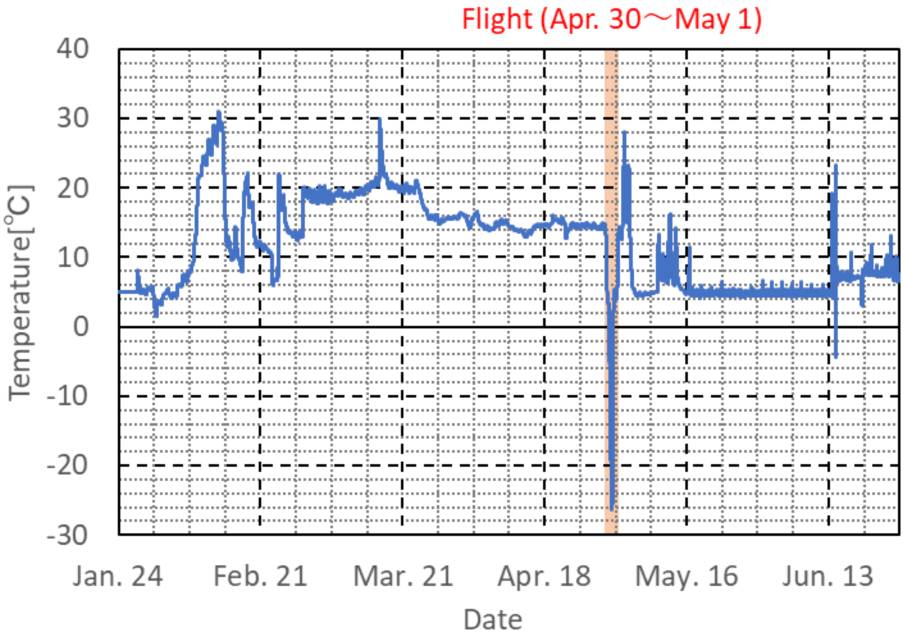

Figure 7: Temperature log of film after packing.

Full Authors List: GRAINE Collaboration

Shigeki Aoki[1], Takashi Azuma[1], Ayaka karasuno[1], Takumi Kato[1], Kenji Kuretsubo[1], Toshitsugu Marushima[1], Shota Matsuda[1], Takafumi Nakamura[1], Motoya Nakamura[1], Miyuki Oda[1], Kazuhiro Okamoto[1], Atsumu Suzuki[1], Satoru Takahashi[1], Mayu Yamashita[1], Shoma Yoneno[1], Kohichi Kodama[2], Atsushi Iyono[3], Kazuma Nakazawa[4], Masahiro Yoshimoto[4], Hirotaka Hayashi[5], Ryosuke Komatani[5], Masahiro Komatsu[5], Masahiro Komiyama[5], Hideyuki Minami[5], Kunihiro Morishima[5], Misaki Morishita[5], Naotaka Naganawa[5], Mitsuhiro Nakamura[5], Tomoaki Nakamura[5], Yuya Nakamura[5], Noboru Nakano[5], Toshiyuki Nakano[5], Akira Nishio[5], Hiroki Rokujo[5], Osamu Sato[5], Kai Shimizu[5], Amon Suganami[5], Kou Sugimura[5], Mayu Torii[5], Ikuya Usuda[5], Saya Yamamoto[5]

[1]Kobe University, [2]Aichi University of Education, [3]Okayama University of Science, [4]Gifu University, [5]Nagoya University