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GRAINE project, prospects for scientific balloon-borne experiments☆

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Abstract

We are pushing forward with the GRAINE project, a 10-MeV to 100-GeV cosmic γ-ray observation project that uses an emulsion telescope with high angular resolution (0.08° at 1 to 2 GeV) and polarization sensitivity, and a large aperture area ($\sim$10 m^2), by repeating long-duration balloon flights. Through various ground experiments, a balloon-borne experiment in 2011, and a balloon-borne experiment in 2015, the feasibility of cosmic γ-ray observations with a balloon-borne emulsion telescope was pioneered. Through scientific balloon-borne experiments, we can attempt to achieve the following: pioneering polarization observations for high-energy γ rays from pulsars, active galactic nuclei, flares, and γ-ray bursts; direct probing of proton acceleration by π^0 feature detection and approaching an emission mechanism with a spatial structure for supernova remnants; resolving GeV γ-ray excess at the galactic center region; probing new physics beyond the Planck scale by polarization observations with high-energy γ rays propagating over cos-

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mological distances; observing transient sources, e.g. γ-ray bursts and flares, with a high sensitivity, high photon statistics and polarization sensitivity. Developments in scientific balloon-borne experiments are ongoing.

Keywords: γ-ray astronomy; nuclear emulsion; cosmic ray; balloon-borne experiment

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1. Introduction

The observation of high-energy cosmic γ-rays provides direct information of high-energy phenomena in the universe. Currently, AGILE (Tavani et al., 2009) and Fermi-LAT (Atwood et al., 2009) together with the recently launched CALET and DAMPE are observing the γ-ray sky and are offering new insights into high-energy phenomena in the universe. However, past and current observations have some limitations. The angular resolution is of a lower order of magnitude than observations at other wavelengths, despite the critical importance to astronomy of γ-ray observations. In addition, despite its significance, the polarization of high-energy cosmic γ rays has never been measured. In order to overcome such limitations, we must improve the angular resolution of such measurements and introduce polarization measurements, which would open new perspectives to astronomy.

Nuclear emulsion plates are powerful tracking devices that can record the three-dimensional trajectory of charged particles with a precision of 1-μm or less. By detecting the beginning of the electron pair created by γ rays in a thin ($\sim 2.0 \times 10^{-3}$ radiation length) and precise ($\sim$submilliradian) emulsion film, the γ-ray direction can be precisely determined, and high-sensitivity γ-ray linear polarization can be achieved.

Several significant milestones have been reached using nuclear emulsions, e.g., the discovery of the π meson (Lattes et al., 1947), the discovery of the charmed particle (Niu et al., 1971), the first observation of tau-neutrino interactions (Kodama et al., 2001), and the discovery of the $\nu_\mu \to \nu_\tau$ appearance (Agafonova et al., 2015); and the measurement of the very high energy cosmic ray spectrum in the series of long duration balloon flights by the JACEE (Asakimori et al., 1995, 1998) and RUNJOB (Apanasenko et al., 2001) collaborations.

Recent years have seen significant progress in emulsion techniques. Nuclear emulsion plates have been very precise, quite uniform, refreshable, and mass-producible tracking devices (Nakamura et al., 2006). Development and production of emulsion films have been achieved in the laboratory (Naganawa & Kuwabara, 2010). Emulsion scanning has been automated, and the possible scanning speed has been exponentially increasing (Niwa et al., 1974; Aoki et al., 1990; Nakano, 1997; Nakano & Morishima, 2008; Morishima & Nakano, 2010). Multistage-shifter techniques allow a track-timing resolution of below ∼seconds with high reliability and high efficiency for large-scale and inaccessible emulsion experiments (Takahashi et al., 2010).

Several groups conducted high altitude balloon flights that utilized emulsions to produce results on cosmic ray protons and nuclei (Asakimori et al., 1995, 1998; Apanasenko et al., 2001) and also very high energy electrons and γ-rays (Nishimura et al., 1980; Kobayashi et al., 2012). In 2004, a new balloon-borne experiment with the latest emulsion techniques was performed to observe primary electrons (Kodama et al., 2004). Subsequently, the potential for a high-performance γ-ray telescope with a nuclear emulsion target became apparent. The latest emulsion techniques open the door to novel cosmic γ-ray observations.

Given these new technologies and the observational possibilities they engender, we are developing the GRAINE project (Aoki et al., 2012; Takahashi et al., 2013) to detect 10-MeV to 100-GeV cosmic γ rays using a precise (0.08° at 1 to 2 GeV) and polarization-sensitive (50% or better minimum detectable polarization for the Vela pulsar above 100 MeV) large-aperture ($\sim$10 m^2) emulsion telescope carried aloft in repetitive long duration balloon flights.

2. Emulsion γ-ray telescope

Figure 1 shows a schematic view of the emulsion γ-ray telescope, which consists of a converter, time-stamper, calorimeter and an attitude monitor. The converter comprises a stack of ∼100 emulsion films which have a total thickness of ∼3 cm and radiation length of ∼0.53 corresponding to a conversion efficiency of ∼0.34. The converter plays the role of a target and a detector for the incident γ-rays. The time-stamper consists of multi-stage shifter which has emulsion film stages moved with individual cycle to make independent position relations using the stages for each timing. By the track reconstruction across the stages, incident track timing can be reconstructed in the analysis. The time-stamper provides an accurate assignment of the time of arrival (or time-stamp) information for all tracks, and hence for γ-ray events observed in the emulsion chamber. The time-stamping of γ-ray events is essential for conversion of their incident directions into celestial sphere coordinates with attitude monitor data. Required timing resolution is a ∼second accuracy or below for a determination of the telescope attitude within the angular resolution of the emulsion γ-ray telesocpe with an attitude chainging of ∼mrad/second (∼sub-degree/second) due to a gondola rotation which is a dominant attitude changing of the balloon gondola. In addition, a ∼0.1 second timing resolution allows observations of γ-ray bursts. Moreover, a ∼milli-second timing resolution allows phase-resolved analyses of pulsars. By increasing stages of the multi-stage shifter with a shorter cycle (higher frequency), the timing resolution can be improved with several orders of magnitude. In a 2015 balloon-borne experiment described in section 3, we achieved a timing resolution of milli-second order of magnitude. For a chance coincidence at the track reconstruction of the multi-stage shifter, although the chance coincidence depends on a multi-stage shifter configuration, operation and track density, we aim to be the chance coincidence of a few % or below with a model for scientific balloon-borne experiments described in section 5. The attitude monitor consists of star cameras. γ-ray energy up to ∼10 GeV is reconstructed by measuring the momenta of an electron pair from multiple Coulomb scattering in the converter. The calorimeter, which consists of a stack of emsulion films and metal plates, is one of options for high energy extension above ∼10 GeV. Table 1 shows an expected performance of the emulsion γ-ray telescope. Figure 2 shows sensitivities of point like sources. Although the sensitivity is limited by an exposure time and atmospheric γ-ray background due to a balloon-borne experiment, a large aperture area and high angular resolution allow comparable sensitivity to Fermi-LAT's one at low galactic latitude by repeating long duration balloon flights. Particulary, a high sensitivity can be achieved in the energy region below 200 MeV and around GeV.

3. Ground experiments and balloon-borne experiments

We performed various tests on the ground. High angular resolution and polarization sensitivity were demonstrated with γ-ray beams by inverse Compton scattering [LEPS/SPring-8 (Dec. 2004), UVSOR (Mar. 2008), NewSUBARU (Nov. 2013)] (Figure 3 and 4) (Takahashi, 2011; Ozaki, 2016; Ozaki et al., 2016). Detectability of γ-ray events using electron pair topology was demonstrated with atmospheric γ rays at a mountain height [Norikura (July and Sept. 2007, July 2013)] (Takahashi, 2011). Energy measurements were

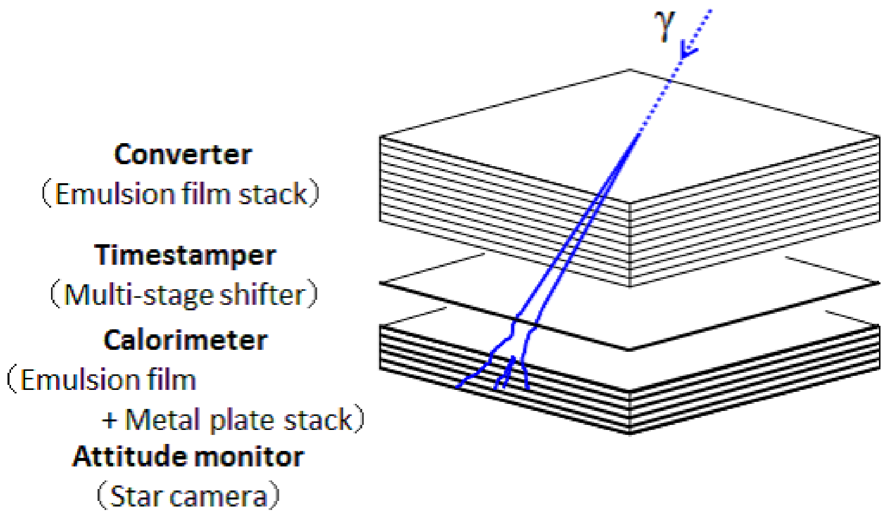

Figure 1: Schematic view of emulsion γ-ray telescope.

Table 1: Expected performance of emulsion γ-ray telescope

Energy range	10 MeV – 100 GeV
Angular resolution[a]	
100 MeV	1.0 degree (17 mrad)
1 GeV	0.1 degree (1.7 mrad)
Polarization sensitivity	Yes
Energy resolution	10 – 20%
Effective area[a,b]	
100 MeV	2.1 m^2
1 GeV	2.8 m^2
Field of view	> 2.2 sr
Time resolution	< 1 s
Dead time	Free

Notes.
[a] Normal incidence
[b] A 10 m^2 aperture area, transmittance at 5 g/cm^2 atmospheric depth, conversion efficiency with 0.53 radiation lengths and detection efficiency for each energy have been taken account into.

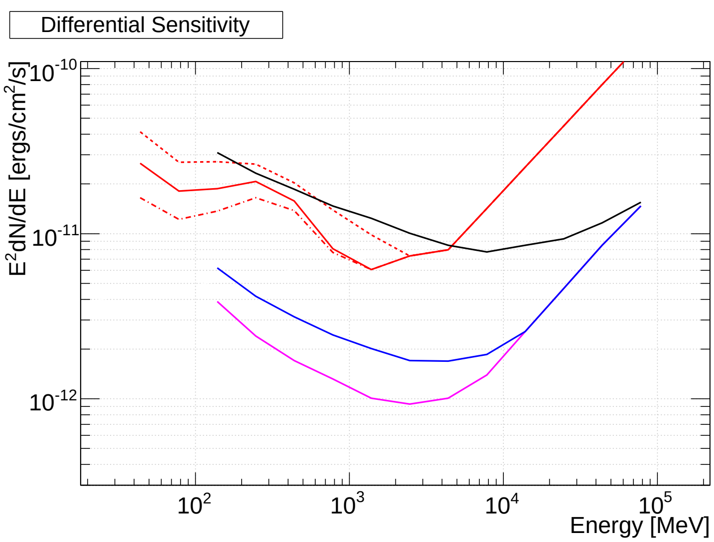

Figure 2: Sensitivities of point like sources as a function of γ-ray energy (a 5σ eauivalent detection, a minimum of 10 photons). (red) Sensitivities in emulsion γ-ray telescope with a 700 m^2-days (aperture area $\times$ flight days) in atmospheric γ-ray background (Kinzer et al., 1974) at a 11.5 GV (solid) and 4.5 GV (dashed) geomagnetic rigidity at a 5 g/cm^2 atmospheric depth. (chain) Additional precision angle measurements with grain by grain in the atmosperic γ-ray backgroud at a 11.5 GV geomagnetic rigidity at a 5 g/cm^2 atmospheric depth. Sensitivities in Fermi-LAT at Glactic center (0, 0) (black), intermediate latitude (0, 30) (blue) and north galactic pole (0, 90) (magenta) in galactic coordinates with 5 years.

investigated [Electron LINAC at Tokai-mura (Aug. 2012), NewSUBARU (Nov. 2013)] (Takahashi et al., 2013; Ozaki, 2016). Moreover, a multi-stage shifter for a time stamper was developed (June 2007 –) (Takahashi et al., 2010; Takahashi, 2011; Takahashi et al., 2015a; Mizutani et al., 2014). The emulsion chamber flatness has also been investigated [J-PARC μ-pit(Nov. 2014)] (Kawahara, 2015).

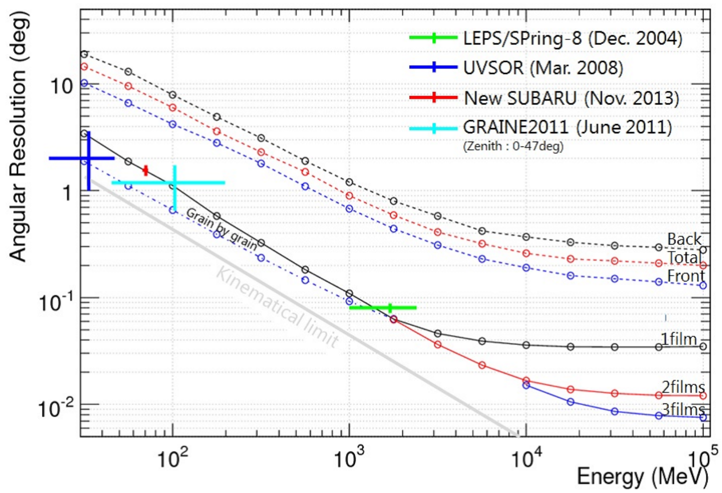

Figure 3: Angular resolution as a function of γ-ray energy (68% containments, normal incidence). Solid and chain lines show simulated angle resolution with emulsion γ-ray telescope. The chain line shows in additional precision angle measurements with grain by grain and a single film. The dots with error bars show experimental data of the emulsion γ-ray telescope. Dashed lines show angular resolution with Fermi-LAT (P7SOURCE_V6).

In June 2011, our group conducted its first successful balloon-borne γ-ray emulsion telescope experiment (GRAINE 2011) with a 125 cm^2 aperture telescope carried aloft for 4.3 h. By analyzing the flight data, we systematically detected γ-ray events down to a γ-ray energy of 50 MeV or lower and up to an incident γ-ray angle with respect to the zenith of 45° or larger with 97% or greater γ-ray-detection purity. We also developed a method to calibrate the γ-ray direction, timing, energy, polarization, and detection efficiency using flight data and demonstrated high angular resolution (1.0° around 100 MeV) and sufficient timing resolution (0.21 s). By detecting γ-ray events, time-stamping, and combining attitude data, we established a procedure to determine the direction from which the γ rays arrive in celestial coordinates.

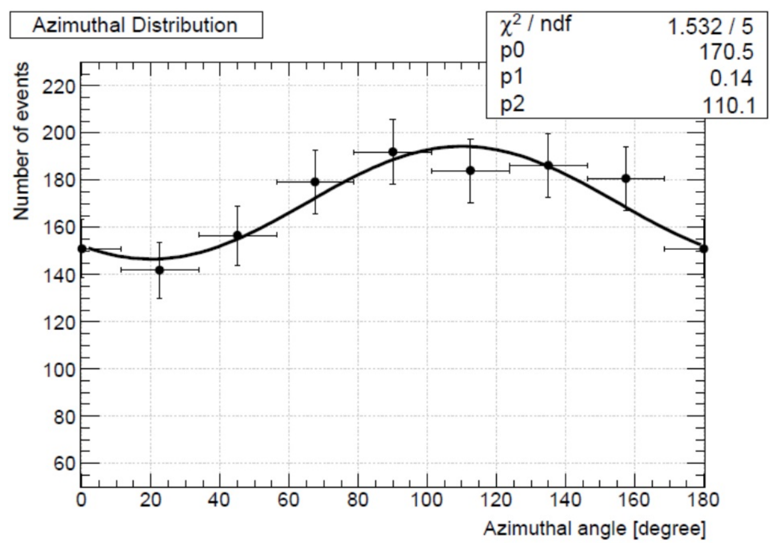

Figure 4: Azimuth distribution of electron pairs converted from a linear polarized γ-ray beam [a 2.4 GeV maximum energy, LEPS/SPring-8 (2004)]. The dots with error bars show experimental data. Solid line shows a fitted curve with $N(\omega) = p0\{1 + p1 \cdot \cos 2(\omega - p2)\}$ where $N(\omega)$ is a number of events, ω is an azimuth angle of an electron pair, $p0$ is a base line, $p1$ is an amplitude and $p2$ is a polarization direction.

Moreover, the instrumental background and atmospheric γ-ray background were clarified for the first time. (Takahashi et al., 2015b; Rokujo et al., 2013)

Based on the experiences and achievements of GRAINE 2011, we designed, improved, and prepared a balloon-borne experiment in 2015 (GRAINE 2015). In May 2015, a Japan-Australia JAXA collaborative balloon experiment was launched from the Alice Springs balloon-launching station with a 3,780-cm^2-aperture telescope and was held aloft for 14.4 h. The goal of this experiment was to demonstrate the overall performance of the γ-ray emulsion telescope. An operation of a multi-stage shifter was performed with a time resolution of millisecond-order magnitude for a study of pulsar phase-resolved analysis. A balloon experiment scheme was established in Australia. (Takahashi et al., 2016; Ozaki et al., 2015)

We pioneered the feasibility of cosmic γ-ray observations with a balloon-borne emulsion telescope.

4. Prospects for scientific balloon-borne experiments

A balloon experiment in Australia is an unique and hopeful site. Day-scale balloon experiments can be performed in Australia. Since Australia is located in the southern hemisphere, it is hoped that γ-ray sources in the southern sky can be observed (e.g., Vela, W44, and the galactic center). Due to the high geomagnetic rigidity at mid-latitudes, the charged particle background (as well as the neutral particle and γ-ray background) can be suppressed.

The 2015 balloon experiment was the first balloon experiment in Australia conducted by the current JAXA balloon group. The JAXA balloon group successfully performed the balloon experiment, and we performed a precursor experiment. The JAXA balloon group had a plan to continue the Australia balloon campaign. By enlarging the aperture area and flight duration, we attempt to start a scientific balloon experiment.

Due to its difficulty, the polarization of high-energy cosmic γ rays has never been observed. This is a frontier in high-energy astrophysics. Pioneering research can be performed by an emulsion γ-ray telescope. We pioneer the polarization observation of pulsars, active galactic nuclei (AGNs), flares, and γ-ray bursts (GRBs), and approach the development of an emission mechanism and a structure of a magnetic field. Moreover, new physics searches can be performed beyond the Planck scale. Figure 5 shows the polarization sensitivity for a Vela pulsar. Significant observation exceeding 100% polarization can be started from around one transit (number of transits of a source in the field of view of the telescope with diurnal rotation (roughly corresponding to flight days)). By accumulating exposure, high polarization sensitivity can be achieved. Figure 6 shows the accumulated polarization sensitivity as a function of source flux. The Vela pulsar can be observed to degree of polarization of nearly 10%. Polarization observation of other bright sources, pulsars, AGNs, flares, and GRBs, can also be achieved.

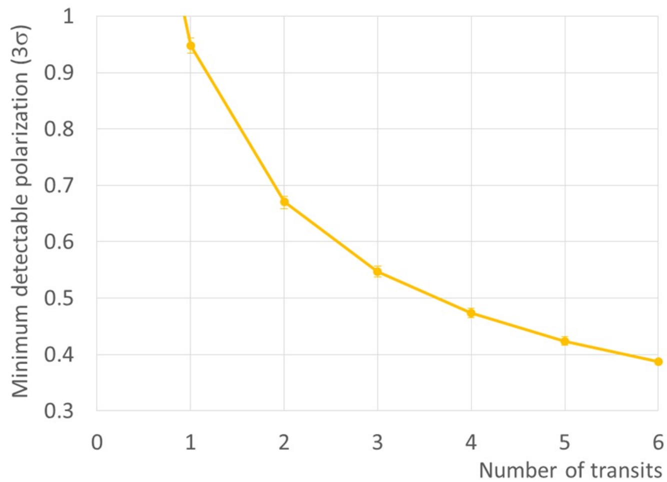

Figure 5: Polarization sensitivity for Vela pulsar (> 200 MeV) as a function of the number of transits of a source in the field of view of the telescope with diurnal rotation (roughly corresponding to flight days). Aperture area:10 m^2, atmospheric depth: 5 g/cm^2, at Alice Springs.

π^0 feature detection provides us with direct evidence of proton acceleration. Figure 7 shows the spectral energy distribution of supernova remnant (SNR) W44 observed by Fermi-LAT (Ackermann et al., 2013a). By detecting a decline below 200 MeV, the π^0 feature can be detected. The π^0 feature detection was reported as a Fermi-LAT collaboration. However, current measurements have a large systematic error below 200 MeV. The major factor was due to the uncertainty of the contamination of galactic diffuse γ rays with an insufficient angular resolution below 200 MeV. Through observation using an emulsion γ-ray telescope with a high angular resolution, the contamination of galactic diffuse γ rays can be drastically reduced ($<\sim 1/10$). Thus, precise spectral measurements that can suppress systematic errors can be performed (Figure 7 (red points with error bars)). Precise validation of

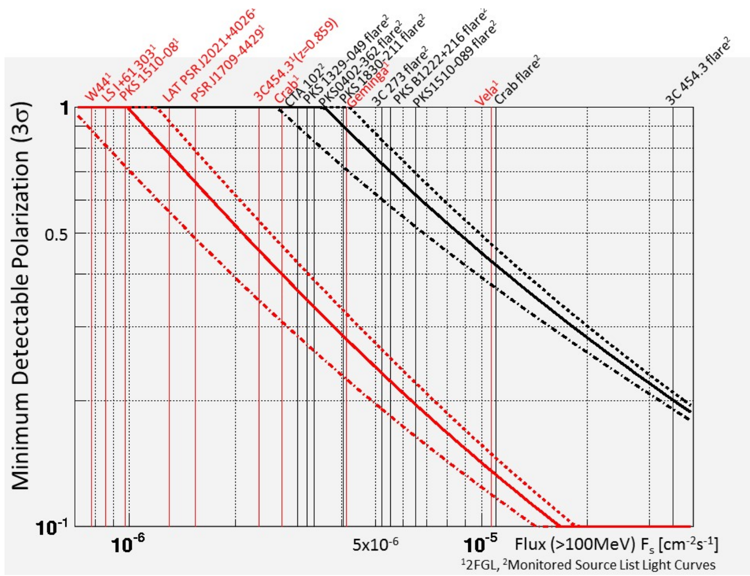

Figure 6: Polarization sensitivity as a function of source flux (> 100 MeV). Black curves indicate the polarization sensitivity for 70 m^2-days (aperture area × flight days (roughly corresponding to a number of transits)) accumulation. Red curves indicate the polarization sensitivity for 70 m^2-days (aperture area × flight days) ×10 accumulation. The atmospheric depth is 5 g/cm^2. Dashed lines indicate a geomagnetic rigidity of 4.5 GV, and solid lines indicate a geomagnetic rigidity of 12 GV. Chain lines indicate a geomagnetic rigidity of 12 GV with grain-by-grain precise measurement.

the π^0 feature for W44 can be performed. Systematic study of other SNRs is also possible. Moreover, precise low-energy measurements are expected to reveal new components, e.g., electron-induced components. In addition, by clarifying a spatial structure with a higher angular resolution, above 200 MeV, the emission mechanism can also be approached. Figure 8 shows the detection sensitivity for W44. Significant observation can be started from around two transits.

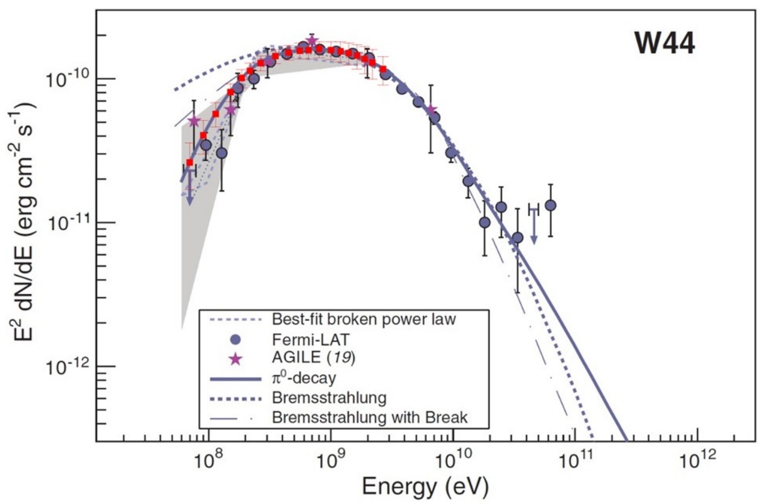

Figure 7: Spectral energy distribution of supernova remnant W44 (Ackermann et al., 2013a). Red points with error bars indicate simulated observations by the emulsion γ-ray telescope (accumulated: exposure 70 m^2-transits (aperture area $\times$ number of transits) $\times$ 10, atmospheric depth: 5 g/cm^2, at Alice Springs).

The GeV γ-ray excess at the galactic center region has been reported by many groups using public data of Fermi-LAT. The GeV γ-ray excess was well explained as γ-ray-annihilating dark matter particles. On the other hand, the possibility of dense γ-ray sources at the galactic center region was considered. The GeV γ-ray excess was also explained as γ-ray sources unresolved with the angular resolution of Fermi-LAT. Figure 9 shows simulations of GeV γ-ray excess at the galactic center region with high angular resolution. The GeV γ-ray excess coming from the annihilation of dark matter particles or unresolved sources can be judged by the γ-ray intensity profile with a high angular resolution. Figure 10 shows the detection sensitivity for the galactic center region. Significant observation can be started from around one transit.

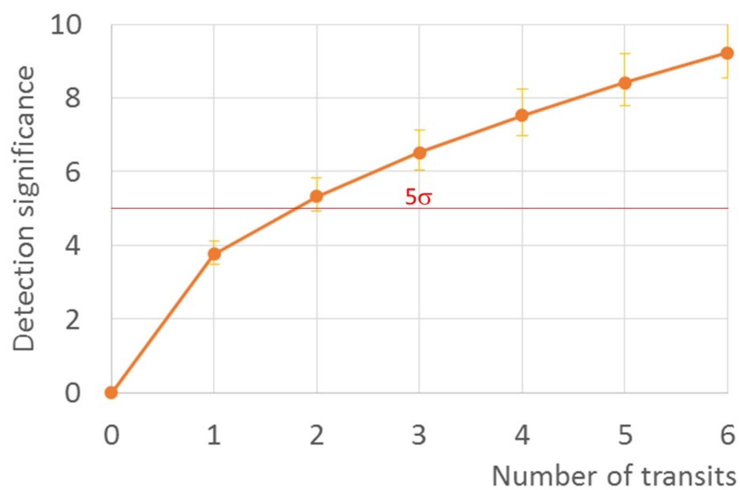

Figure 8: Detection sensitivity for supernova remnant W44 (>200 MeV) by emulsion γ-ray telescope (aperture area: 10 m^2, atmospheric depth: 5 g/cm^2, at Alice Springs) as a function of the number of transits of a source in the field of view of the telescope with diurnal rotation (roughly corresponding to flight days).

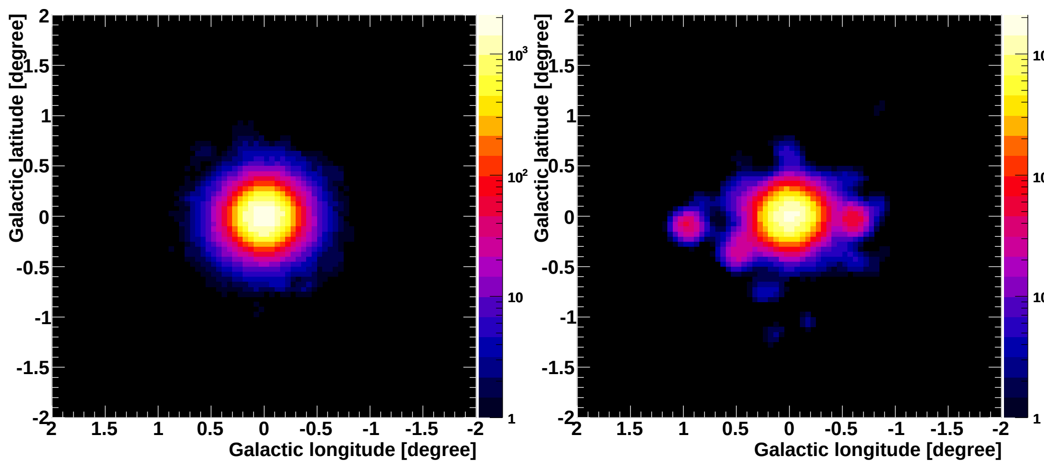

Figure 9: Simulations of the GeV γ-ray excess (>1 GeV) at the galactic center region (color scale: counts / $(0.05\ \text{degree})^2$) with a high angular resolution (0.1 degree at 68% containment (corresponding to the angular resolution of the emulsion γ-ray telescope at 1 GeV), 4,200 m^2-hours). (Left) Scenario of the annihilation of dark matter particles (spatial distribution of γ-ray intensity $\propto$ (distance from galactic center)$^{-2.4}$, γ-ray energy spectrum (Daylan et al., 2016)). (Right) Scenario of unresolved sources (luminosity function of the millisecond pulsar (Hooper & Mohlabenga, 2016), spatial distribution of γ-ray sources $\propto$ (distance from galactic center)$^{-2.4}$).

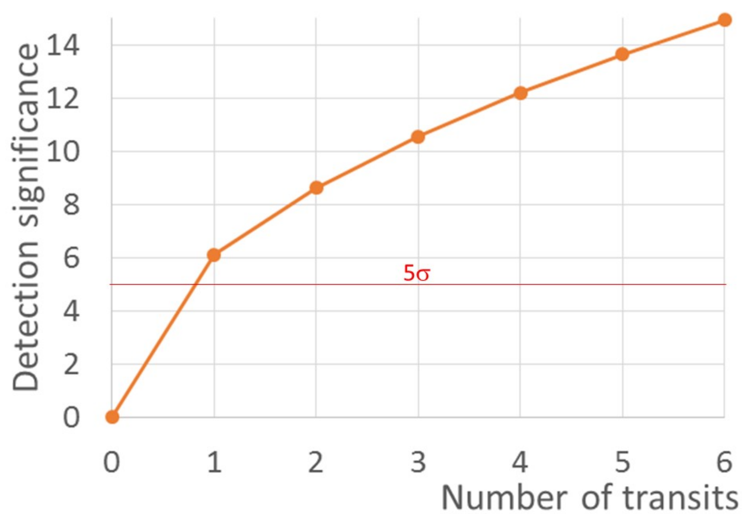

Figure 10: Detection sensitivity for the galactic center region (> 1 GeV) by emulsion γ-ray telescope (aperture area: 10 m^2, atmospheric depth: 5 g/cm^2, at Alice Springs) as a function of the number of transits of a source in the field of view of the telescope with diurnal rotation (roughly corresponding to flight days).

Using γ rays propagating over cosmological distances, a new physics search can be performed beyond the Planck scale. Quantum gravity theories predict a violation of Lorentz invariance. The validation of fundamental symmetries beyond the Planck scale provides us with observational constraints for quantum gravity theories. By checking the energy dependence of the arrival timing of γ rays from GRBs by Fermi-LAT, Lorentz invariance was proven around the Planck scale (Abdo et al., 2009). By polarization observation from GRBs by GAP (70 to 300 keV), CPT invariance was proven beyond the Planck scale (Toma et al., 2012). The degree of CPT violation (here, the rotation angle of the polarization vector) is proportional to the square of the photon energy. By polarization observation from distant AGNs and GRBs with high-energy γ rays (e.g., > 100 MeV) by emulsion γ-ray telescope, very precise (five orders of magnitude better) validation can be performed.

Transient sources, e.g. GRBs and flares, can be observed by emulsion γ-ray telescope with a large collection area (high photon statistics), wide field of view (above 2.2 sr (17.5% of all sky)), high angular resolution, polarization sensitivity and dead time free. Figure 11 shows sensitivities to transient sources by emulsion γ-ray telescope. Emulsion γ-ray telescope can observe an unexplored region with a duration below several tens seconds. The sensitivity with a duration above several tens seconds can be performed to be comparable to Fermi-LAT's one. Observed rate of transient sources by Fermi-LAT was 638 transient sources per year (mainly flares). 1.7 transient sources per flight day can be observed by emulsion γ-ray telescope with high statistics measurements of energy spectrum, time variation and polarization-sensitive observations.

5. Developments for scientific balloon-borne experiments

In order to achieve a 10 m^2 aperture area, units of the emulsion γ-ray telescope are deployed. The allowable balloon-borne payload is $\sim$2 tons. In a 10 m^2 aperture area deployment, the weight of the emulsion films (100 stacked films) is 1 ton. The multi-stage shifter in GRAINE 2015 (open area: 2,500 cm^2, weight: 65 kg) has a weight of 2.6 tons in a 10 m^2 aperture area deployment. This is not acceptable for a balloon-borne experiment. Thus, drastically lightening of the multi-stage shifter is essential in order to achieve a 10 m^2 aperture area. In addition, in order to achieve a flight duration with more than one transit, a long-duration capability is needed for the

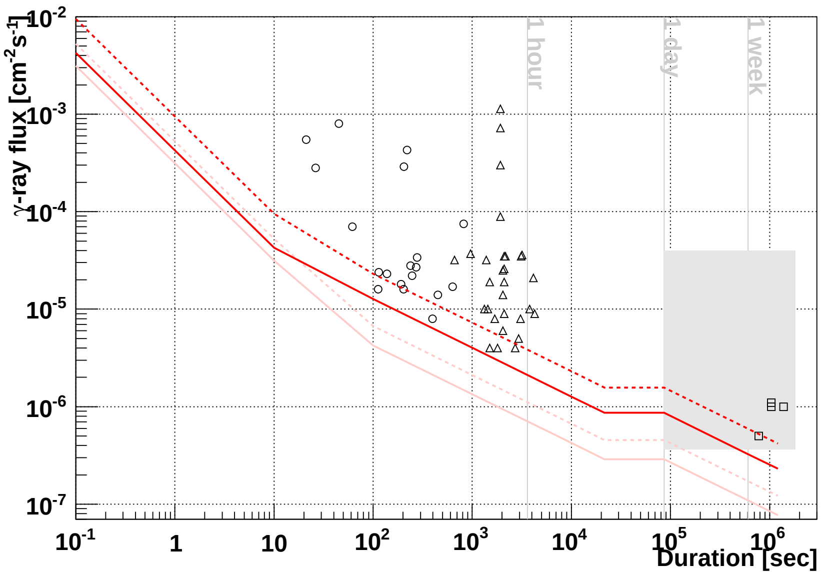

Figure 11: Flux sensitivities to transient sources by emulsion γ-ray telescope as a function of a duration (10 m^2 aperture area, 5 g/cm^2 atmospheric depth, above 5σ significance, above 5 photons). Red lines show sensitivities above 100 MeV. Pink lines show sensitivities above 200 MeV. Solid lines show a normal incidence. Dashed lines show a 45 degree zenith incidence. Each symbol and shaded area show transient sources detected by Fermi-LAT (circle: GRB (2008 Aug – 2011 Aug, 100 MeV – 10 GeV, $T_{90,LAT}$) (Ackermann et al., 2013b), triangle: solar flare (2008 Aug – 2012 Aug, 100 MeV – 10 GeV) (Ackermann et al., 2014a), square: nova (>100 MeV) (Ackermann et al., 2014b), shaded area: flare (2FAV, 7.4 years, 4547 flares, 100 MeV – 800 MeV) (Abdollahi et al., 2016)).

multi-stage shifter. Long-duration capability requires narrow gaps between a higher number of stages.

In order to achieve a large aperture area and long duration capability, a conventional model of a multi-stage shifter (stage-plate-driven model) was reviewed on a zero basis, and a model with a new mechanism (roller-driven model) was invented (Figure 12). A roller-driven model has no stage plates or guide rail, so it is lighter. Moreover, as a result of the embedded structure (IRECO structure), narrow gaps between stages and an increasing number of stages can be realized. In addition, it is easy to enlarge the aperture area in a unit. Thus, the number of deployed units can be reduced while maintaining the total aperture area in the deployment. As a result, the total weight can be reduced.

Based on the invention, a prototype of the roller-driven model was constructed by Mitaka Kohki Co., Ltd. from August 2014 (Figure 13). Currently, working and performance tests are ongoing and a required accuracy of within 1 μm is being obtained. In addition, a 10 m^2 aperture area in the deployment based on the prototype has a weight of 0.4 tons, which is 6.5 times lighter that the conventional model (2.6 tons), resulting in a drastic weight reduction.

For an emulsion analysis with a large area [A 10 m^2 aperture area corresponds to a $\sim$1000 m^2 emulsion area (10 m^2 $\times$ $\sim$100 films).], a latest emulsion scanning system, Hyper Track Selector, achieved a 0.5 m^2/hour scanning speed (Yoshimoto et al., 2017). Moreover, a faster scanning system is being developed with a 2.5 m^2/hour scanning speed. A data processing will follow the emulsion scanning.

Acknowledgment

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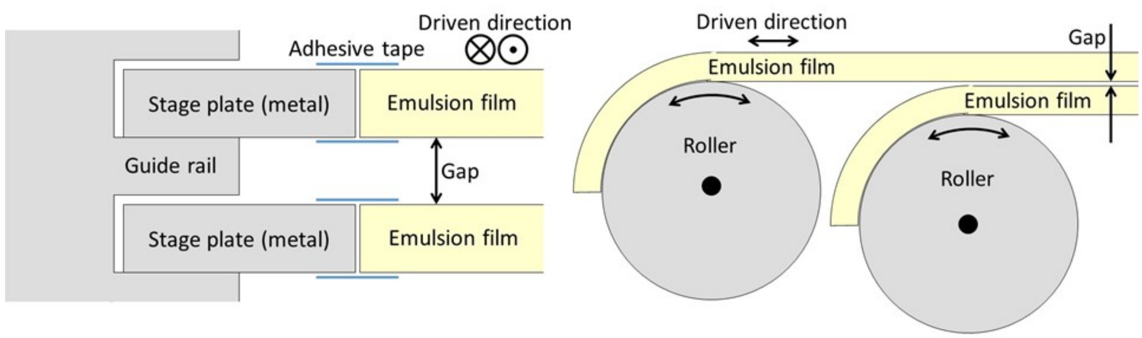

Figure 12: (Left) Conventional model (stage-plate-driven model). (Right) New model (roller-driven model).

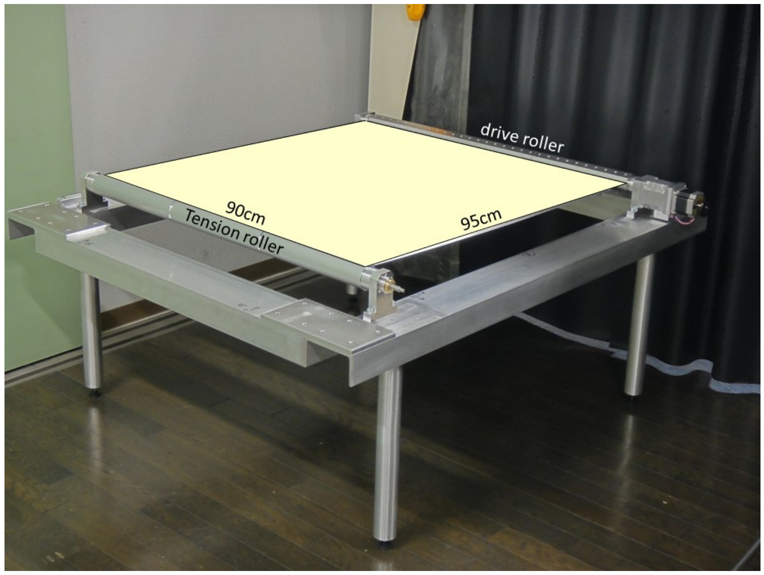

Figure 13: A prototype of the new model (roller-driven model).

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