GRAINE project and first results on 2018 balloon-borne experiment

Precise observations of high-energy $\gamma$-rays by a balloon-borne emulsion telescope with a high angular resolution, polarization sensitivity and large-aperture-area

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BG photo: GRAINE2011, JAXA scientific ballooning (taken by NHK)
All-sky map by Fermi Gamma-ray Space Telescope using nine years of data collected from 2008 to 2017

>5000 sources (FL8Y)

Image credit: NASA/DOE/Fermi LAT Collaboration
Nuclear emulsion

Cross sectional view of an emulsion film

- Intrinsic position accuracy of ~50nm
- Precisely tracking beginning of e-pairs
  - High angular resolution
  - Polarization sensitive
- Suppressed multiple Coulomb scattering
- Large scalability
- Automatic large-area-analysis technique
- Timestamping technique

Novel \( \gamma \)-ray telescope
**GRAINE** 
Emulsion γ-ray telescope 
Repeated long-duration balloon flights

- **Highest angular resolution**
- **First polarization sensitivity**
- **Largest aperture area**

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**Gamma-Ray Astro-Imager with Nuclear Emulsion**

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<table>
<thead>
<tr>
<th></th>
<th>Fermi LAT</th>
<th>GRAINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular resolution @100MeV</td>
<td>6.0deg (105mrad)</td>
<td>1.0deg (17mrad) x1/6</td>
</tr>
<tr>
<td>@1GeV</td>
<td>0.90deg (16mrad) x1/9</td>
<td>0.1deg (1.7mrad) x1/9</td>
</tr>
<tr>
<td>Energy range</td>
<td>20MeV – 300GeV</td>
<td>10MeV – 100GeV</td>
</tr>
<tr>
<td>Polarization sensitivity</td>
<td>----</td>
<td>Yes x8</td>
</tr>
<tr>
<td>Effective area @ 100MeV</td>
<td>0.25m²</td>
<td>2.1m² * x3</td>
</tr>
<tr>
<td>@ 1GeV</td>
<td>0.88m²</td>
<td>2.8m² * x3</td>
</tr>
<tr>
<td>Dead time</td>
<td>26.5 μ sec (readout time)</td>
<td>Dead time free</td>
</tr>
</tbody>
</table>
K. Ozaki, S. Takahashi et al., NIMA (2016)

**Angular resolution**

![Angular resolution graph]

**Energy range**

Atmospheric γ-ray @Mt. Norikura (July, Sep. 2007, July 2013), and others

![Energy range graph]

**Polarization sensitivity**

LEPS/SPring-8 (Dec. 2004)

$E_\gamma, \text{Max.} = 2.4 \text{GeV}$

$N(\omega) = p_0 \{ 1 + p_1 \cdot \cos 2(\omega - p_2 - 90^{\circ}) \}$

Significant and consistent result

$<P> = 66\%$, modulation factor $= 0.21^{+0.11}_{-0.09}$

K. Ozaki, S. Takahashi et al., NIMA (2016)

**Flatness study**

J-PARC ν beam line μ-pit (Nov. 2014)

RMS $< 1.8\text{mrad}(0.10\text{deg})$

**Timestamper**


~sea level 12 hours 2 stages

**Efficiency** 98%

**Reliability** 97%

**RMS** 1.58

**Data** 70.8±30% MeV/c

**MC** 70.4±26% MeV/c
GRAINE 2011
First balloon-borne emulsion γ-ray telescope experiment

JAXA scientific ballooning
Taiki Aerospace Research Field (Hokkaido, Japan)

June 8th, 2011
4.3 hour flight duration
(1.6 hours @34.7km)

12.5cm × 10cm aperture
GRAINE 2011 Flight data analysis

γ-ray event detection

- Low energy threshold (<50MeV)
- Large incident angle (>45deg)
- High reliability (>97%)

Angular resolution

1deg@100MeV

Time resolution

RMS: 0.21[sec]
Reliability: 99%

GRAINE First Light

Feasibility demonstration

S. Takahashi et al., PTEP 043H01 (2015); H. Rokujo et al., NIM A 701, 127 (2013)
Launched, 6:33 12th May 2015
Design, various improvements & preparations
Establishment of a scheme & flow of the experiment in Australia
Demonstration of the telescope performance

Flight duration: 14 hour 22 min
(11 hour 32 min \(x 7\))
\(@36.0\)-37.4 km
almost covered
Vela w/in 45 deg zenith

Image © JAXA

S. Takahashi et al., PTEP 073F01 (2016); K. Ozaki et al., JINST 10 P12018 (2015)
Summary of GRAINE 2015

- 3780cm² aperture (x30, new-type emulsion films, total 48m²)
- 14.4hour flight duration (11.5hour(x7)@36.0–37.4km)
- Establishment of a scheme & flow of the experiment in Australia
- Emulsion track read-out, total 41m² w/ HTS
- Emulsion film S/N ratio x~20, data size ~1/20
- Track finding inefficiency in a single film ~1/10
- Data reduction load for γ-ray event detection ~1/200
- Data processing of all active area, 2830cm² aperture (total 30m²)
- γ-ray PSF ~1.0deg@100MeV
- Time resolution, 9.8 msec (~1/10)
- Star camera sensitivity, magnitude of 6.1 → 7.5

Significant progress from GRAINE 2011

Prospects for enlarging effective area x time and BG reduction

- Robustnized star camera systems $\rightarrow x_{1.77}$ eff. time
  - Redundant data storages, Recoverable system from errors
- Stabilized emulsion films $\rightarrow x_{1.33}$ eff. area
  - Established optimal parameters for production & processing
- Established multi-stage shifter setup $\rightarrow x_{1.33}$ eff. area x time
  - Optimized emulsion film mounting
- Corrected multi-stage shifter operation $\rightarrow x_{1/2}$ BG

Total $x_{6.3}$ improvements. ($x_{5}$, effectively)

Overall performance demonstration
Imaging resolution aimed w/i 1deg above 100MeV
Flight duration: 17.4h (21%↑)
Level flight @38.1 – 35.4 km: 14.7h (28%↑)
Fully covered Vela pulsar in 45 deg zenith (10%↑)

- Stably operated (Multi-stage shifter, 3 star cameras, Pressure vessel)
- Recovered (Apr 27 to Longreach)
- Developed (Apr 29 – May 13 @U Sydney)

Aperture of 3780cm²

Various developments, improvements, preparations

Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus

GRAINE 2018, JAXA Scientific balloon
@BLS Alice Springs Australia, 6:30AM 26th April (ACST)
GRAINE 2018, Converter, γ-ray event detection

- Surface treatment
- Scanning by HTS
- Thickness tuning

Surface treatment tuning

- May 28 – July 23 – Dec 10
- Weeks

- # of processed films
- Thickness tuning
- Scanning by HTS

-grays from hadron interactions in the converter

- 0.57deg (10mrad)

- γ-rays from a launching plate above the telescope (incl. attitude info.)
  - U3, 4

- 3deg (50mrad)
Simultaneity of the hadron event tracks

RMS: 0.51 sec

Timestampable for high resolution γ-ray imaging

Track rate dist. (U3A7, U4A6)

Vela obs. operation (3rd stage: 10μm/s)

Local time (UTC+9.5)

1° imaging resolution (w/ 0.3°/s attitude change)

Good enough timing resolution for 1° imaging resolution

1° imaging resolution (w/ 0.3°/s attitude change)
GRAINE 2018, Flight data analysis, Attitude monitor

Complementary attitude monitoring by the three star cameras w/ each 90 deg azimuth.

For Vela pulsar observation:
Attitude determination: 98.9%
Accuracy: 0.022deg in azimuth.

Horizontal coordinates [deg]

Galactic coordinates
Zenith & 45 deg zenith

Determined attitude (telescope coordinates)
GPS (horizontal coordinates)

Vela pulsar
All sky coverage
GRAINE 2018: >51% (>2.0\pi [sr])
24h flight duration: >65% (>2.6\pi [sr]) incl. GC

Attitude-determinable for high resolution \(\gamma\)-ray imaging.

Survey Map

Local time (UTC+9.5)
GRAINE 2018, Converter+Timestamp+Attitude monitor

$\gamma$-ray arrival direction reconstruction

in galactic coordinates

All sky map

(Aitoff projection)

$>80\text{MeV}$

Before exposure correction

Accumulating data (14%)
Search for galactic diffuse emission

>80MeV
After exposure correction & BG subtraction

First indication of astrophysical gamma-rays for the emulsion gamma-ray telescope
Progress of data processing for Vela pulsar observation

- **Attitude monitor**
- **Converter**
- **Timestampper**
- **Combined**

GRAINE 2015 scale
GRAINE Scientific observation roadmap

Apr 2018, Demonstration
Alice Springs
0.39m² aperture
17.3 hours flight duration
3 – 5 g/cm² altitude

Improvements

Vela pulsar detection, Imaging, phase resolved analysis
Galactic diffuse & Geminga detection/indication

Vela pulsar
Polarization observation (<50%)

SNR W44 (<200MeV, >200MeV)
Precise spectrum measurement
High resolution imaging

Galactic Center
Obs. with ~arcmin resolution

Test of fundamental symmetries beyond the Planck scale

Transients sources
Obs. w/ high sensitivity & high photon stats

Search for γ-ray correlation with Giant Radio Pulses from pulsars
Search for GeV γ-ray Pair Halo → Constraints on IGMF

Pioneering polarization observation for high energy γ-rays

Studying cosmic ray sources

Resolving GeV γ-ray excess at galactic center

Studying transient sources & w/ ones

Imaging resolution aimed w/ 1 deg above 100 MeV

PS3-255: Gamma-ray Imaging Performance of Nuclear Emulsion Telescope in GRAINE-2018 Balloon Experiment
Hiroki Rokujo

Takahashi, Aoki et al., ASR 62 (2018) 2945
Developments for scientific balloon-borne experiments

**Pressure vessel gondola**
- Conceptual design
- Light, Thin, 0.3atm
- 5m² (4units) aperture area w/ a single pressure vessel gondola (~0.3ton weight)

< ~2 ton payload (aimed) w/ a 10 m² aperture

**Timestampmer, Multi-stage shifter**
- New multi-stage shifter (prototype) Co-developed w/ Mitaka Kohki

**Evolution of the Scanning Speed**
- ~2500m²/year
- ~500m²/year

**Table**

<table>
<thead>
<tr>
<th></th>
<th>2018</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size [m²]</td>
<td>1.5 x 0.7</td>
<td>2.0 x 1.5</td>
</tr>
<tr>
<td>Aperture [m²]</td>
<td>0.38</td>
<td>1.25</td>
</tr>
<tr>
<td># of stages (w/o fixed stag.)</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Gap [mm] (with surrounding)</td>
<td>1 (0.5)</td>
<td>0.5</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>65</td>
<td>107</td>
</tr>
<tr>
<td>Weight w/ 1.25m²-ap [kg]</td>
<td>214</td>
<td>107</td>
</tr>
</tbody>
</table>

A 1/2 weight of conventional model per aperture