GRAINE project:
Cosmic Gamma-ray Observation with Balloon-Borne Emulsion Telescope

Shigeki Aoki for GRAINE collaboration

(1)Kobe University, (2)ISAS/JAXA, (3)Nagoya University, (4)Okayama University of science, (5)Aichi University of education, (6)Utsunomiya University
Fermi two-year all-sky map ($E_\gamma > 1\text{GeV}$)

**What has Fermi found: The LAT two-year catalog**

- **Unknown**: 31%
- **Blazars**: 57%
- **Non-blazar active galaxies**: 1%
- **Supernova remnants**: 4%
- **Globular clusters, high-mass binaries, normal galaxies and more**: 1%
- **Pulsars**: 6%

**1873 sources**

**SNR W44**
Abdo et al., Science, 2010
Color: 2-10GeV gamma-ray (Fermi LAT)
Contour: IR (Spitzer)

**Crab**
INTEGRAL

Credit: NASA/DOE/Fermi/LAT Collaboration
Detection principle of high energy gamma-ray

Arrival direction, timing, energy, polarization
**Nuclear emulsion**

- Powerful tracking device
  - High spatial resolution: ~1 micron
  - Small radiation length: 0.002X₀

- Cross-sectional view of an emulsion film
- Microscopic view: 10 micron

- Gamma-ray interaction with emulsion
  - Emission of e⁺/⁻ and e⁻/⁺

- High angular resolution for gamma-ray
  - Sensitive to gamma-ray polarization
## GRAINE

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

### Components
- **Converter**
  - Emulsion + Copper foil
- **Timestamper**
  - Multi-stage shifter
- **Calorimeter**
  - Emulsion + metal plate
- **Attitude monitor**
  - Star camera

### Performance

<table>
<thead>
<tr>
<th></th>
<th>Fermi LAT</th>
<th>GRAINE</th>
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<tbody>
<tr>
<td>Angular resolution</td>
<td>6.0deg (105mrad)</td>
<td>0.93deg (16mrad) x1/7</td>
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<tr>
<td>@100MeV</td>
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<td>0.10deg (1.7mrad) x1/9</td>
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<tr>
<td>@1GeV</td>
<td>0.90deg (16mrad)</td>
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<tr>
<td>Energy range</td>
<td>20MeV – 300GeV</td>
<td>10MeV – 100GeV</td>
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<tr>
<td>Polarization sensitivity</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Effective area @ 100MeV</td>
<td>0.25m²</td>
<td>2.1m² * x8</td>
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<td></td>
<td>2.8m² * x3</td>
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<tr>
<td>Dead time</td>
<td>26.5 μsec (readout time)</td>
<td>Dead time free</td>
</tr>
</tbody>
</table>

* 10m² * trans * conv * det
Angular Resolution

PSF at normal incidence

Emulsion (data)  Emulsion (MC)  Fermi-LAT (data)

1 Film  Total
2 Films  Front
3 Films  Back

0.13deg (2.2mrad) @ 1GeV
0.08deg (1.4mrad) @ 2GeV

Kinematical limit

* http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
High resolution imaging

GRAINE (Simulation)

W44
Abdo et al., Science, 2010
Color: 2-10GeV gamma-ray (Fermi LAT)
Contour: IR(Spitzer)

- 3 flights (41.7m² days)
- $>1$ GeV
- Smearing IR(Spitzer) distribution with 0.08 deg (1.4 mrad)
- Considering atmospheric gamma-ray ($>1$ GeV) as BG
Polarization measurement

Cross-sectional view of OPERA film

emulsion

TAC base

emulsion

e^-
e^+

293 \mu m
0.002Xo

\gamma

Microscope image

1micron
Polarization sensitivity

\[ N(\omega) = p2 \times \{1 + p0 \times \cos(2(\omega - p1 - 90^{\circ}))\} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>(p0)</td>
<td>0.14 ± 0.03962</td>
</tr>
<tr>
<td>(p1)</td>
<td>20.12 ± 9.506</td>
</tr>
<tr>
<td>(p2)</td>
<td>170.5 ± 5.089</td>
</tr>
</tbody>
</table>

\(\chi^2 / \text{ndf} = 1.532 / 5\)

Consistent with expected

preliminary
Atmospheric gamma-ray @ Mt. Norikura
Event ID: 131 3741965
E=150±38-15[MeV]
$p\beta_1=50±12-7[\text{MeV/c}]
$p\beta_2=100±36-13[\text{MeV/c}]

LCS gamma-ray beam @ UVSOR
Event ID: 221 2314379
E=28±6-4[MeV]
$p\beta_1=13±4-2[\text{MeV/c}]
$p\beta_2=15±4-3[\text{MeV/c}]

Atmospheric gamma-ray @ SPring-8

Atmospheric gamma-ray @ balloon flight (MSC)

Energy range

1713µm
74µm

10MeV 100MeV 1GeV 10GeV 100GeV
Momentum Measurement by MCS

Angular Method

\[ \frac{1}{p\beta} = \frac{\theta_{RMS}}{13.6\text{MeV/c}} \left[ \frac{z}{X_0} \left( 1 + 0.038\ln \left( \frac{X}{X_0} \right) \right) \right]^{-1} \]

- 0.8 GeV/c \( \pi^- \)
- 1.5 GeV/c \( \pi^- \)

K. Kodama et al.
$dE/dx$ measurement (p-id)

"OPERA film" × KEK-PS 1.2 GeV/c beam (29 films)

\begin{align*}
\pi & (\beta = 0.99, \\
& \quad dE/dx = 1.08 \text{ MIP }) \\
\rho & (\beta = 0.79, \\
& \quad dE/dx = 1.23 \text{ MIP })
\end{align*}
$dE/dx$ measurement (Z-id for nuclei)

“desensitized” operation (98% RH 3days)

45°C  38°C  30°C

no “desensitized” operation

He  Li  Be  B  C

Pulse height in sheet-D (counts)

Pulse height in sheet-B (counts)

T. Toshito et al.,
GRAINE roadmap

- 8th/June/2011, TARF, JAXA Scientific Ballooning, 
  12.5cm x 10cm aperture area, 4.3hours (1.6hours@35km) flight duration 
  - Working test for each element 
  - Connection test between elements 
  - Measurement of atmospheric gamma-rays

- 2014(Planned), Alice Springs, JAXA International Scientific Ballooning 
  2500cm² aperture area, 1 day flight duration 
  - Overall test by detecting known gamma-ray source 
  - Observation with highest imaging resolution

- 2015- 
  10m² aperture area, 7days flight duration 
  - Starting scientific observation
GRAINE roadmap

- **8th June, 2011, TARF, JAXA Scientific Ballooning**
  - 12.5cm x 10cm aperture area, 4.3 hours (1.6 hours @ 35km) flight duration
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Taiki Aerospace Research Field

Airstrip (L 1,000m)

Sliding Launcher on Rails (L 460m)

Meteorological Equipments

Handling Area (ø140m)

Balloon Operation Building

Hangar (W30m, H35m, L83m)
Multi-stage shifter (time stamper)

Converter

Shifter (1)

Shifter (2)

Shifter (3)

Simple
Compact
Light
HV free
Low power consumption
Dead time free

S. Takahashi et al.
Multi-stage Shifter (Time Stamper)

Co-developed with Mitaka Kohki Co., Ltd.

Weight: 5 kg
Power Cons.: 20 W
Reproducibility: $1 \mu m$

Gap of stages: $2 \text{mm}$

Pulse motor
Photo sensor
1.3m

Star camera

Emulsion chamber

Pressure meter

GPS

Battery
TARF
8th June 2011
5:05

Level flight
Duration: 4.3 hours
Level: 1.6 hours

Flight path
Level flight (34.7 km)
7:14~8:50

20 km

Duration: 4.3 hours
Level: 1.6 hours
Emulsion chamber
Aperture area : 12.5cm x 10cm

- **Flatness compensation films**
- **Converter**
  - 102 emulsion films, 91 copper foils (50μm)
  - 1.1kg, 35.0mm, 0.54X0 (ε_{conv} = 34%)
  - OPERA film x 10 (go-ban part)
  - OPERA film x 88 + Copper foil x 88
  - New type gel film x 4 + Copper foil x 3

- **Timestamper**
  - 1st : OPERA film x 2
  - 2nd : OPERA film x 2
  - 3rd : OPERA film x 2
  - New type gel film x 1

- **Calorimeter**
  - 32 emulsion films, 10 (0.5mm) & 17 (1mm) lead plates
  - 3.2kg, 31.9mm, 4.0X0 (Shower Max.@ a few GeV)
  - OPERA film x 5 (go-ban part)
  - (OPERA film + lead plate(0.5mm))x10
  - (OPERA film + lead plate(1mm))x17
Automated Emulsion Scanning System

“S-UTS”

Nagoya Univ.
Number of tracks: $8.0 \times 10^8$

$|\tan \theta_{proj}| < 1$

Film#67, 1st
Track reconstruction

Number of tracks

- Raw: \( 10^9 \)
- Clustering: \( 10^8 \)
- Both sides: \( 10^7 \)
- Between films: \( 10^6 \)
- Bottom
- Top

Reconstructed tracks (film#1-16): \( 8.7 \times 10^7 \) (overlap)
Connection accuracy

- **Pos diff X**: $\sigma_{dx} = 0.75\text{micron}$
- **Pos diff Y**: $\sigma_{dy} = 0.76\text{micron}$
- **Ang diff X**: $\sigma_{d\theta x} = 4.2\text{mrad}$
- **Ang diff Y**: $\sigma_{d\theta y} = 4.6\text{mrad}$
Track efficiency

Honeycomb board

Low energy \( \gamma \)

High energy \( \gamma \)

e+  e-  e+  e-

Emulsion film
Emulsion film
Emulsion film
Track efficiency

Film#5
(5mm)^2 \times 10 \text{films} \times 2 \times 10^4 \text{tracks}
153 events
Reliability 97%
One of gamma-ray events

Event : 71 6923485
Start : #7
$\theta_{\text{incident}}$ : 9.748 [deg]
$(p\beta)_{\text{left}}$ : 60 $^{+20}_{-12}$ (25%) [MeV/c]
$(p\beta)_{\text{right}}$ : 32 $^{+9}_{-6}$ (22%) [MeV/c]
$E_{\gamma}$ : 92 $^{+22}_{-13}$ (+24% -14%) [MeV]

$0.077\text{mm}$
Detection efficiency (MC)

- Normal opening angle (current)
- Normal & Large opening angle
- High track efficiency film

Detection efficiency

Gamma-ray energy (MeV)

Geant4.9.5
Normal incident
7 films
Scanning response
Reconstruction program
Atmospheric gamma-ray flux @35km

- Preliminary

- Thompson, 1974, 10-5g/cm²
- GRAINE2011, 6.6g/cm²
Establishment of timestamp technique


"Multi-stage shifter" 1st model

Track rate measurement @ 35 km

- Detection of hadron events

- Aperture area: 12.5 x 10 cm²

- Correct operation during whole observation time
- Giving time info. to all penetrating tracks
- Detection of hadron shower tracks by timing and 3-D spatial analysis
- Time resolution: 0.15 sec

Graph showing excess (6.6σ) count rate over time.
Ev : 2438038  
7:18:34.5 (JST)  
Δt=+-0.5s  
1.2cm x 1.2cm  
x 16films

Pointing accuracy
Δθ_{space} : 0.65deg (0.0114rad)  
E_γ : 45+33-10 [MeV]  
θ_γ : 46.61 [deg]
• **Optics Filter**  
  Schneider Optics B+W091

• **Camera Lens**  
  Nikon AF Nikkor 85mm F1.4D  
  - diameter: 60.7mm  
  - focal length: 85mm

• **CCD Camera**  
  HAMAMATSU C3077-79  
  (near-IR camera)  
  - pixels: 640 × 480

• **CPU board**  
  ADVANTECH PCM-3362  
  - CPU: Intel Atom N450 1.66GHz

• **Video Capture board**  
  Sensory Frame Grabber Model 311  
  - ADC: 8bit  
  - Frame rate: 30FPS

• **SSD (128GB)**  
  TOSHIBA SSDN-ST128H

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**Optics filter cut-on below 610nm**

![Graph showing the optical spectrum with cut-off at 610nm.]

- : Daytime sky BG (Dietz et al., 2002)
- ■: Star spectrum (M-type: 3200K)

**Field of View:**  
5.9deg(H) × 4.5deg(V)  
Limiting magnitude: 6  
Monitoring accuracy: 0.16mrad

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Image data on Level Flight

time: 8:11:00.16 (@Altitude 34.6km)

Because of stray light reflected on hood, outer region was saturated.
Image data on Level Flight

time: 8:11:00.16 (@Altitude 34.6km)

6 stars were detected.
Attitude analysis

Daytime star camera view

Star catalog data

8:11:00(JST) @35km

Working rate: 74 %
Monitoring accuracy: < mrad
Elevation < 0.25mrad
Azimuth < 0.44mrad

Rotation speed of the balloon

95% time during level flight was \( \omega < 0.15 \text{deg/sec.} \)

It is important to decide telescope attitude to celestial coordinate better than emulsion angular resolution(0.08deg).

We confirmed attitude decision accuracy was \( \omega \sigma_t < 0.02 \text{deg.} \)

K. Ozaki et al.,
Proc. of Balloon Sympo.,
isas12-sbs-022
GRAINE
First Light

Event: 111 2986322
Start: #11 up
θ_{incident}: 26.64deg (0.5016rad)
θ_{open}: 0.0059rad
E_γ (θ_{open}): 340MeV
JST: 8:24:44.0±0.44
Altitude: 34.6km
Atm. depth: 6.6g/cm²
Gal. Ion.: 112.06deg
Gal. lat.: -6.86deg
GRAINE roadmap

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  10m² aperture area, 7days flight duration
  - Starting scientific observation
Flight model of multi-stage shifter

1st model
Aperture area: 2500 cm²

2nd model

12.5 cm
10 cm

Co-developed with Mitaka Kohki Co., Ltd.
Emulsion production

Fuji Janet Co., Ltd., Nagoya Univ.

Gelatin1/4, Na type, Fe x 2, MIP (XAA, 20deg, 40min)

New type
GD=86.1±4.7
FD=2.9±0.9

OPERA type
GD=34.8±0.6
FD=3.7±0.4

Incident angle Tracking efficiency
97.7±0.25 [%]
Evaluated by K. Kamada (Kobe Univ.)

AgNO₃ aq KBr, KI aq
Ag⁺ Br⁻ I⁻
Mix
Gelatin + Hot water

Emulsion production efficiency [%]
Automated emulsion read-out system (Nagoya Univ.)

Evolution of the Scanning Speed

**Speed in cm²/h**

- **TS(TTL) E653** (1983): ~0.003 m²/Year
- **NTS(CPLD) CHORUS** (1994): ~0.082 m²/Year
- **UTS(FPGA) DONUT** (1998): 1 m²/Year
- **SUTS(FPGA) OPERA** (2006-): 72 m²/Year
- **HTS(GP/GPU) Future Exp.** (2011-2012): 9000 m²/Year

~2000 m²/Year

~20 m²/Year

~0.02 m²/Year
Automated emulsion read-out system (Nagoya Univ.)

Hyper-TS: Next Generation Read-out system

Scanning speed 9000 cm²/h (design)
Flight duration ~1 day
Vela

Alice Springs  2014/May/15, Culmination 17:09(NT), In FOV 6.5 hours (13:53-20:24) (-0:30(JST))

Lat.: -23° 40’
Lon.: 133° 50’ E
Significance vs. Exposure Time

Vela flux: $1.068 \times 10^{-5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (2FGL, >100MeV)
Remaining Air (vertical): 5g/cm²

Significance $\sigma$

- Taking into account the variation of zenith angle
- transmission efficiency of cosmic gamma-ray
- atmospheric gamma-ray
- detector aperture and effective thickness

4.7$\sigma$ significance from 6.5 hour observation
Significance vs. Remaining Air Thickness

Vela flux: $1.068 \times 10^{-5} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (2FGL, $>100\text{MeV}$)

6.5 hour observation

Taking into account the variation of zenith angle
- transmission efficiency of cosmic gamma-ray
- atmospheric gamma-ray
- detector aperture and effective thickness

The less remaining air shall brings the higher significance.
### 2013

<table>
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<tr>
<th>Jan</th>
<th>Feb</th>
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<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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<th>Sep</th>
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<tr>
<td><strong>Emulsion film</strong></td>
<td>Established 2nd flight model</td>
<td><strong>Film production</strong></td>
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<tr>
<td><strong>Multi-stage shifter</strong></td>
<td>Low T&amp;P test, Assembling, Flight ready</td>
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<tr>
<td><strong>Star camera</strong></td>
<td>Design, Test, Assembling, Flight ready</td>
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### 2014

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<tbody>
<tr>
<td><strong>Stacking &amp; Assembling</strong></td>
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</table>

- Sep/2013, emulsion film for 2nd flight model will be established.
- Sep/2013, multi-stage shifter will be ready for the flight.
- Sep/2013, star camera will be ready for the flight.
- Feb-Apr/2014, stacking and assembling
- May/2014, 2nd flight model will be ready for the flight.
Subject

- Galactic cosmic-rays origin, acceleration and propagation
- Galactic high energy objects
  - Pulsar, PWN, SNR, Magnetar, X-ray binary, Globular cluster
- Extragalactic cosmic-rays origin, acceleration and propagation
- Extragalactic high energy objects
  - AGN, GRB, cluster of galaxy, starburst galaxy
- Cosmological research by using gamma-rays from AGNs and GRBs
- Search for gamma-rays from annihilation/decay of dark matter from galactic center and dwarf galaxy
Summary and Outlook

• Promoting GRAINE project
• Performed balloon experiment in 2011
• Demonstrated emulsion gamma-ray telescope with flight data
• Measured atmospheric gamma-ray

• Preparing for planned balloon experiment at Alice Springs in 2014
backup
Momentum measurement with multiple coulomb scattering for gamma-ray energy reconstruction

35MeV electron LINAC @Tokai-mura

35.2±6.5-7.4 [MeV/c]

Absolute: 1.8% (34.6MeV/c@incident)
Relative: 20% (15films)

→ 14%@E_γ=70MeV (even case)
→ 20%@E_γ=35MeV (uneven case)
放射起源に迫る上で200MeV以下が重要

M. Ackermann et al.
Science 339, 807 (2013);
DOI: 10.1126/science.1231160