SMILE-2+:
The 2018 balloon observation of MeV gamma-ray telescope in Australia

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photo: Just before Launching @ Alice Springs, Australia, April 7th 2018
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MeV Gamma-ray Astronomy

- **Nucleosynthesis**
  Supernova Remnants
  Galactic Plane($^{26}$Al, $^{60}$Fe, …)

- **Particle Acceleration**
  Jets in AGNs, GRBs
  Supernova Remnants

- **Early Universe**
  GRBs of the First Stars
  and so on

MeV Sky Map

GeV Sky Map

Requirements for
the next-generation observation:

- Wide-band detection
- Large Field of View
- High Quality Image
Electron-tracking Compton Camera : ETCC

- **Gaseous TPC**: Scattering Target
  track and energy of recoil electron

- **Scintillator**: Absorber
  position and energy of scattered gamma ray

measure all the parameters
of Compton-scattering kinematics

- 1 photon → direction and energy
- Large field of view
- Compton kinematical test
  with $\alpha$ angle
- Particle identification with $dE/dx$ ratio
- No heavy veto system around ETCC

Conventional image (without $e^{-}$ track info.)

ETCC image (with $e^{-}$ track info.)
### SMILE project

**Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiment**

| SMILE-I | Sep. 2006 | • 10 cm cubic, Xe + Ar 1 atm
|         |          | • Confirmation of operation at high altitude
|         |          | • Observation of diffuse cosmic/atmospheric gamma rays

| SMILE-2+ | Apr. 2018 | • 30 cm cubic, Ar 2 atm
|          |          | • Effective area: a few cm\(^2\) @ 300 keV
|          |          | • Half Power Radius: ~10° @ 662 keV
|          |          | • Observation of bright celestial sources

| SMILE-3 | Early 2020 | • 30 cm cubic, CF\(_4\) 3 atm
|         |            | • Effective area: ~10 cm\(^2\) @ 300 keV
|         |            | • Half Power Radius: ~5° @ 662 keV
|         |            | • Scientific observation

| Satellite |            | • 50 cm cubic x 4, CF\(_4\) 3 atm
|           |            | • Effective area: ~200 cm\(^2\) @ 1 MeV
|           |            | • Half Power Radius: ~2° @ 662 keV
|           |            | • All sky survey with sensitivity of sub-mCrab

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32nd ISTS & 9th NSAT, Fukui, 6/21/2019
Balloon Experiment: SMILE-2+

**Aim**: certificate imaging spectroscopy of ETCC using celestial objects

**Targets**: $e^\pm$ annihilation line from the galactic center region (511 keV)

- Crab nebula

**Requirements for detections above the significance of $\sim 5\sigma$**

- Altitude: $\sim 39$ km (atmospheric depth $\sim 3.5$ g/cm$^2$)
- Half Power Radius (HPR): $\sim 10$ degrees
- Effective area: a few cm$^2$
- Energy Range: 0.3 – 1.5 MeV
Ground Performance of SMILE-2+ ETCC

Two type event analysis

- fully contained $e^-$ event
- escaped $e^-$ event

Source: $^{137}$Cs

Imaging check for various angles using $^{137}$Cs

Preliminary experiment simulation

Effective area

[cm$^2$]

Counts

$^{137}$Cs energy spectrum Zenith ~0°

Preliminary
In this presentation, we show only fully-contained $e^-$ events.
Flight Overview of April 7 – 9, 2018

April 7 (local time)
- 2:47-3:09  power on sequence
- 3:09  start of data acquisition
- 6:24  launching
- 8:44  start of level flight

April 8
- 10:45  end of data acquisition
- 10:45-10:53  power off sequence
- 11:07  cut off
- 11:40  landing

April 9  recovering

level flight ~26 hours
- crab nebula ~6 hours
- galactic center ~8 hours

~150 m
- 5 x 10^5 m³

JAXA ← gondola

We succeeded in the balloon flight as planned.
Small noises did not degrade data acquisition so far. Our detector was stable at the balloon altitude as planned.
Our gas detector succeeded in getting charged particles. We could select electrons fully-contained in the gas detector.
Gamma-ray candidate events

We selected gamma-ray candidate events.

- level flight: 4/7 8:45 - 4/8 4:05
- livetime: 5.8 x 10^4 sec
- Raw: 1.7 x 10^7 events

Energy Spectra:
- single track
- single scintillator hit
- background reduction
- fully-contained e- events
- gamma-ray candidate

Energy level:
- 511 keV

gamma-ray candidate rate [events/sec]

elevation angle [degree]

Sun, Crab nebula, Galactic Center

start of the level flight

Raw          1.7 x 10^7 events

fully-contained e- events

4/7 8:45 - 4/8 4:05

livetime 5.8 x 10^4 sec

511 keV
Analysis for the Crab nebula

- rough imaging selection
- $30^\circ < \text{elevation angle} < 60^\circ$
- $-22.5^\circ < \text{azimuth angle} < 22.5^\circ$
- North = azimuth angle $0^\circ$

ON – OFF = residual

Quick check:
the excess with $3\sigma$ level in 200-1500 keV
Analysis for the Galactic Center Region

gamma-ray elevation angle of the ETCC > 60°

ON region: include the galactic center region
OFF region: not include the galactic plane

Quick check:
5.5σ @ 460 – 560 keV
10.0σ @ 100 – 3000 keV

preliminary

ON 4/8 04:00-06:30
OFF 4/7 11:00-13:00
residual

galactic map
Comparison with INTEGRAL/SPI

- **SMILE-2+**

  ![](chart.png)
  
  Quick check:
  - $10^{-3}$ - $10^{-2}$ events/cm²/sec
  - $5.5\sigma$ @ 460 – 560 keV

- **INTEGRAL/SPI**

  recent major satellite telescope in this energy band

  ![](graph.png)
  
  Siegert et al. 2016
  
  ~$2.5 \times 10^{-3}$ ph/cm²/sec
  
  65$\sigma$ (the same energy range)

Assuming the ETCC has the same observation time of INTEGRAL:

\[
\sim 5\sigma \times \sqrt{\frac{1.6 \times 10^9 \text{ cm}^2 \text{ sec}}{75 \text{ cm}^2}} \div \frac{6.4 \times 10^3 \text{ sec}}{6.4 \times 10^3 \text{ sec}} = \sim 295\sigma
\]

ETCC can improve the significance dramatically.
Future Work

1. **SMILE-2+ data analysis**
   - detail analysis, using unfolding method with the response matrix, and so on

2. **SMILE-3 and satellite observation**
   - $e^\pm$ annihilation line map
   - INTEGRAL model
     - one point source
     - three 2D gaussians
   - Too simple?

   • **SMILE-3**
     - Effective area: $\sim 10 \text{ cm}^2$
     - HPR: $\sim 7^\circ$
     - 30 days observation

   • **Satellite**
     - Effective area: $\sim 200 \text{ cm}^2$
     - HPR: $4.5^\circ$
     - 1 year observation

ETCC with sharp HPR and efficient background rejection enables us deep sky survey.
Summary

• The aim of SMILE-2+ is to certificate imaging spectroscopy of ETCC using celestial objects.

• We succeeded in the balloon flight in Australia in April 2018.
• The level flight continued during 26 hours at altitude of 38.4-40.5 km.
• Observation time:
  - Crab nebula ~6 hours
  - Galactic Center Region ~8 hours

• Success of bright object detection in the Quick Check
  - Crab nebula 3σ in 200-1500 keV
  - Galactic Center Region 5σ in 511 keV band

• A balloon observation of an ETCC can improve the detection significance of celestial objects dramatically.
• We are analyzing the SMILE-2+ data in detail.
• In the future, the observation of an ETCC satellite will reach the sensitivity of sub-mCrab.
Noises of gas detector

- Gamma-ray candidate rate [events/sec]
- Ratio of the active pixels
- Gas detector pixel map
- Sun, Crab nebula, Galactic Center

Graphs showing:
- Start of the level flight
- Preliminary!

Time in ACST:
- 4/7 03:00, 9:00, 15:00, 21:00
- 4/8 03:00, 9:00

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Comparison of flux with INTEGRAL/SPI

SMILE-2+ Quick check
- bin including 511 keV: 460 - 560 keV
- effective area: ~1 cm² @ 511 keV
- flux: $10^{-3} - 10^{-2}$ events/cm²/sec

INTEGRAL/SPI model

Siegert et al. 2016
bulge FWHM 20.55°

energy spectrum

e+e- 511 keV line: $0.96 \times 10^{-3}$ ph/cm²/sec
ortho positronium: $\sim 1.5 \times 10^{-3}$ ph/cm²/sec
total: $\sim 2.5 \times 10^{-3}$ ph/cm²/sec

The flux of SMILE-2+ quick check is roughly consistent with the flux of INTEGRAL/SPI observation
Method of Flight Data Analysis

Two type of event analysis
Here we present
only fully contained e\(^-\) event.

Event selection
1. single scintillator hit
2. fully contained electron selection
3. certification of Compton kinematics
   using α angle selection
   • Only simple selection
   • No gamma-ray veto