Effectiveness and Performance of a Full Ray-Tracing Sub-MeV Compton Imager

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Sub-MeV/MeV gamma-ray astronomy

Treasure box of Interesting Science
- Nucleosynthesis
  SNR, Galactic plane
- Particle acceleration
  Relativistic Space Jet
- Strong gravitational potential
  Blackhole, accretion disk
- Evolution of the Universe
  Most-distant GRB
- Others
  Solar flare, Gamma-ray pulsar

All-sky MeV map
1–30 MeV

CGRO/COMPTEL
~30 objects/10 years

V. Schönfelder+ (A&AS, 2000)

Unrevealed last wide window for Astronomy

Requirements for the next generation telescopes
- Large Field of View
- High quality image
- Wide-band detection
Difficulty of MeV gamma-ray imaging

Compton scattering dominates in MeV cross section

Principle of Compton Imager

\[
\cos \phi = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)
\]

Radioactivation by cosmic rays -

- Huge background in space

- Improvement of imaging
- Background suppression

are two big tasks in MeV
Electronic Tracking Compton Camera (ETCC)

Observed Ray track samples

- Electron
- Muon
- Pair-creation candidate
- Shower

- 30 cm
Effectiveness of Ray-Tracing information

Three additional parameters

1. **SPD**, Direction of scattering plane
   \(\rightarrow\) Event by event arrival direction

2. **dE/dx**, Energy deposit rate of particle
   \(\rightarrow\) Background rejection by particle identification

3. **\(\alpha\)**, Angle between scattered gamma and recoil electron
   \(\rightarrow\) Background rejection by kinematics test

Image of three $^{137}$Cs (662 keV) sources with/without ray tracing info.

Ray-Tracing info. enables us to detect the sources by factor $\sim 3$ in significance.
ETCC for 2\textsuperscript{nd} balloon exp. (SMILE-II)

**Aim:** Confirmation as a sub-MeV telescope

\[\rightarrow\text{ Imaging of Crab/Cyg X-1}\]

\>(>3\sigma\text{ detection, ~40 km, one-day flight})

**Required Performances**

- Effective area: \(>0.5\ \text{cm}^2\) (@300 keV)
- Angular resolution: \(<10^\circ\) (@600 keV)

**SMILE-II flight model**

- SMILE-III sim. \((30\ \text{cm})^3\ \text{Xe} \ 3\ \text{atm}, 3\ \text{R.L. scintillator}\)
- \(0.7\ \text{cm}^2\) (@300 keV)

**Clear the requirements!!**

**Effective Area [cm\(^2\)]**

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**ARM (FWHM) [degree]**

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**SMILE-II Measured values**

- GSO: \(5.3^\circ\) (@662 keV)
- LaBr\(_3\): 5.3°
Other Performances of SMILE-II FM

Energy resolution

\[ \frac{\Delta E}{E} [\%] = 10.7 \times \left( \frac{E}{662 \text{ keV}} \right)^{-0.5} \]

Imaging check for large zenith angles

\(^{137}\text{Cs} (662 \text{ keV}, 0.7 \text{ MBq})\) at 2 m distance from ETCC

SMILE-II flight model ETCC has large FoV \(\sim 2\pi \text{ str}\)
ETCC in intense radiation field

Balloon/Satellite altitude has intense background radiation

Can ETCC image a gamma-ray source in such field?

ETCC has imaging capability in intense BG

We generate factor ~5 more intense field than expected BG

662 keV
ETCC as a gamma-ray polarimeter

Simulation

- 100% polarized gamma rays

- Polarization

- Azimuth angle $\Phi$ [deg]

- Normalized counts

- Modulation Factor (MF) = \( \text{max} - \text{min} \) / \( \text{max} + \text{min} \)

Experiment

- Paraffin (10x10x5 cm$^3$)
- Lead (5 cm)
- $^{133}\text{Ba}$ (1.7 MBq)
- $\leq 320$ keV

$^{133}\text{Ba}$ is set at $\Phi=90^\circ$

- ETCC

- SMILE-II

- Azimuth angle [deg]

- Normalized counts

- Polarization

- ETCC has large MF which can detect low S/N polarization

- MF vs. Energy (@ 0 deg.)
  - MF = 0.5
  - 400 keV

- MF vs. Incident angle (@ 200 keV)
  - MF = 0.5
  - 60°
Summary

- Ray-Tracing info. brings big benefits for Compton imager
  - High quality/contrast imaging (SPD)
  - Efficient background rejection (dE/dx, \(\alpha\))

- SMILE-II ETCC fulfills the requirement performances
  - Effective area: \(0.7 \, \text{cm}^2\) (@ 300 keV)
  - Angular resolution: 5.3 deg. (@ 662 keV)
  - Energy resolution: \(10.7\% \times (E/662 \, \text{keV})^{-0.5}\)
  - Wide Field of View: \(\sim 2\pi \, \text{str}\) (@662 keV)

- Imaging capability in intense radiation field

- As a background-suppressed imaging polarimeter
  - Modulation Factor: \(>0.5\) (E < 400 keV, Zenith angle < 60\(^\circ\))

SMILE-II ETCC can detect Crab (>3\(\sigma\), several hours)

Negotiation with NASA/GSFC for balloon flight(s) @ fort sumner is ongoing
Thank you for your attention!!

Please visit to the SMILE project web page

http://www-cr.scphys.kyoto-u.ac.jp/research/MeV-gamma/index_e.html