Imaging detection for GRBs & SNe with high sensitivity and good polarimetry by Electron Tracking Compton camera

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3) Research Inst. for Sustainable Humanosphere, Kyoto Univ.
MeV Astronomy Sky survey

**SN, GRB→ 1-150keV**

<table>
<thead>
<tr>
<th>Point Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>25-50keV 173</td>
</tr>
<tr>
<td>50-100keV 79 (&gt;3.5σ)</td>
</tr>
<tr>
<td>100-200keV 30 (&gt;2.5σ)</td>
</tr>
<tr>
<td>200-600keV 12</td>
</tr>
<tr>
<td>&gt;600keV 4</td>
</tr>
</tbody>
</table>
Main reasons of Difficulty

1. Huge BG of gammas & fast neutrons
2. Obscurity of imaging by circular direction
   If no BG, severalx10cm² => a few mCrab@10⁶sec

V. Schönfelder (2004) Suggestion
Low background is most important for next MeV detector

2. Redundancies (TOF, Kinematics, dE/dx)
3. Measurement of electron direction (SPD)
4. Low-z material and light weight
5. Short timing gate
Advanced Compton Camera

- Crab 4σ (8hrs) with MLEM meth.
  - Ge detector with BGO VETO
  - FoV 3str, ΔARM 7.3° (FWHM)
  - 0.3-1.5MeV Eff.A 6cm²
  - Simulation 3800 γ detection 667 γ
  - B.G. in Crab view~29000(S/N~0.02)
- Liquid Xe TPC 2000
  - No VETO
  - 0.1-10MeV Expected eff.A ~ 20cm²
  - No. detection for Crab

Priority: good energy res.

Aprile et al. (2004)

Priority: Large effective Area large

Liquid Xe TPC 2000
- No VETO
- 0.1-10MeV Expected eff.A ~ 20cm²
- No. detection for Crab

priority: Large effective Area large
Electron Tracking Compton Camera (ETCC)

Goal: High sensitivity for Continuum gammas with > ~50 better than COMPTEL

Strong BG rejection & clear imaging are needed

1. Electron tracking for imaging,
   Kinematics ($\alpha$)+dE/dx (multi redundancies)

2. Large FoV. ~3str & No Veto counter

$50cm$-cubic $3atm$ CF4 gas $\sim110cm^2@1MeV$
10cm-cube $\mu$-TPC & ETCC

Timing Projection Chamber (TPC)

GSO:Crystal

$\mu$-PIC

Micro Pixel Chamber

400$\mu$m

11\%@ 662 keV (FWHM)

spd ~160°
**Sub-MeV γ-ray Imaging Loaded-on-balloon Exp. (SMILE-I)**

- **Test flight using 10cm cube ETCC to measure**
- **Diffuse Cosmic and Atmospheric gamma rays in 0.1-1MeV**
- **3hours observation @35km**

- **All Trigger # 2.3x10^5 (3hours)**
- **Signal ⇒ ~420(down going) +500(up)**
- **Simulation ⇒ ~400 (diffuse cosmic)**

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**SMILE-I Flight Data (CR + γ)**

- **Event Selection**
- **MIPs**
- **e**

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**Diffuse Cosmic γ**

- **Marshall et al. (1980, HEAO A2)**
- **Kistler et al. (1999, HEAO A2)**
- **Kappadath et al. (1997, COMPTEL)**
- **Wichnade et al. (1999, SMM)**
- **Churazov et al. (2007, INTEGRAL)**

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Improvement of SMILE-II

Crab Observation for $10^4$s with $5\sigma$ detection

From SMILE-I,
Effective area $1\,\text{cm}^2$  $\Delta\text{ARM} 10^\circ$

But SMILE-I= $1\,\text{mm}^2$ $\rightarrow$ x100 Improvement

① Physical process
- Recoil e stopping in TPC
- Scattered gamma absorbing

② Reconstruction Inefficiency; $\sim10\%$ in SMILE-I

If Recont. Eff. $\rightarrow 100\%$ SMILE-II

$(30\,\text{cm})^3$ TPC $\times 20$ times of SMILE-I
Reconst. Eff. $\Rightarrow X 10$ Angular Res. $20^\circ \Rightarrow 5.3^\circ$
Imaging Test in 30cm ETCC

Noise reduction by Energy loss rate $\frac{dE}{dx}$

$^{137}\text{Cs}(\sim 0.85 \text{MBq})$

- $\phi_{\text{kin}}$
- $\phi_{\text{geo}}$
- Recoil $e^-$
- Scattered $\gamma$
- Cosmic $\mu$
- Escaped $e^-$
- Compton $e^-$

$\Rightarrow$ Continuum fully gamma events selected by $\frac{dE}{dx}$ cut

$\frac{dE}{dX}$

Energy Cut

$\phi_{\text{kin}}$ vs $\phi_{\text{geo}}$

Data
Performance in 30cm-cube ETCC

$^{137}$Cs ($\sim$0.85MBq) 2m

137Cs BG

$^{137}$Cs

Field of View (3str)

Preliminary

Gamma + Noise

Continuum Gamma

662keV Gamma

dE/dX Cut

Energy Cut
Angular Resolution & Energy band in 30cm-cube ETCC

Angular Resolution (FWHM) @ 662 keV

Energy Resolution (FWHM)

- 18% @ 166 keV
- 11% @ 662 keV

Multi energy sources

LaBr₃ (simulation)
GSO (simulation)

SMILE-II 30cm ETCC

0.85 MBq
0.63 MBq
0.16 MBq

137Cs
22Na
133Ba

> 300 keV @ 2 m
30°
60°

0.63 MBq
0.16 MBq
Imaging Improvement by SPD

Legacy

Advanced (SPD=200°)

Legacy Compton Imaging

Advanced Compton Imaging

$^{137}$Cs × 3
3.2MBq
0.85MBq
0.74MBq

⇒ ($\sim$4times better contrast image)
Detection Efficiency & Effective Area

Further improvement

$\Rightarrow$ CF$_4$ + 3atm Eff. Area $\sim$ 10cm$^2$
+ double of Scintillator $\Rightarrow$
Total $\sim$20 cm$^2$ @ SMILE-II

Simulated Effective Area

Present Eff. Area $\sim$ 1cm$^2$
Compton electrons in TPC $\Rightarrow$ 100% detection

Similar effective area to COMPTEL
But 3str FoV, Low background, Clear Imaging in SMILE-II
Weak source detection such as Crab

- RI: $^{22}\text{Na}$
  - Zenith = 26°.
  - $z = 2\text{m, } 31\ \text{kBq}$

1/4 of total system operation

- $S/N = 0.019$
  - A few times stronger source than crab for SMILE-II

S/N = 0.019

A few times stronger source than crab for SMILE-II
Performance Test under intense radiation condition using 140MeV proton beam 2013-Oct.

ETCC operation under intense MeV Gammas & Neutrons from water target

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Trigger rate 300-500Hz
Balloon trigger rate 60Hz

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ETCC operation under intense MeV Gammas & Neutrons from water target
Modulation Factor in SMILE-II in Simulation

Preliminary

Un-polarized, $\cos \theta < 0.7$

<table>
<thead>
<tr>
<th>#Event</th>
<th>Max</th>
<th>Min</th>
<th>MF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un polarized</td>
<td>5.33e5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0^\circ$, 100%</td>
<td>4.69e5</td>
<td>1.4</td>
<td>0.35</td>
</tr>
<tr>
<td>$45^\circ$, 100%</td>
<td>4.83e5</td>
<td>1.45</td>
<td>0.35</td>
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</table>

$MF = (\text{max}-\text{min})/(\text{max}+\text{min})$
New Balloon Exp. (SMILE-II & III)

**SMILE-II (in USA)**
- Collaboration with Goddard (now planning)
- 30cm ETCC with 1~4cm²
- Detection Crab, CygX-1 at >5s
- Polarization

**SMILE-III (Polar region)**
- Upgrade to ~15cm² X2 ETCCs
- Deep Survey for galactic plane
<table>
<thead>
<tr>
<th></th>
<th>S-ETCC (4unit)</th>
<th>ACT</th>
<th>GRIPS</th>
<th>CAST</th>
<th>MEGA</th>
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<tbody>
<tr>
<td>Scatt, material</td>
<td>gas</td>
<td>Si</td>
<td>Si</td>
<td>Si</td>
<td>Si</td>
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<tr>
<td>Absorber</td>
<td>GSO/LaBr$_3$</td>
<td>Ge</td>
<td>LaBr$_3$</td>
<td>CdTe</td>
<td>CsI</td>
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<tr>
<td>$\gamma$ VETO</td>
<td>nothing</td>
<td>BGO/CsI</td>
<td>nothing</td>
<td>BGO</td>
<td>nothing</td>
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<tr>
<td>Tracking</td>
<td>○</td>
<td>×</td>
<td>△</td>
<td>×</td>
<td>△</td>
</tr>
<tr>
<td>Eff. Area</td>
<td>40x4 cm$^2$</td>
<td>~10$^3$ cm$^2$</td>
<td>190m$^2$</td>
<td>10-30 cm$^2$</td>
<td>20 cm$^2$</td>
</tr>
<tr>
<td>ARM</td>
<td>2.3° @ 1 MeV</td>
<td>1.2° @ 1 MeV</td>
<td>1.8° @ 1 MeV</td>
<td>2.5° @ 1 MeV</td>
<td>2.0° /5.5° @ 1 MeV</td>
</tr>
<tr>
<td>FoV</td>
<td>3 str</td>
<td>3 str</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>4.4e-6 @ 0.5 MeV, 6.5e-6 @ 1 MeV, 4.7e-5 @ 5 MeV</td>
<td>1e-5 @ 1 MeV</td>
<td>3e-5 @ 1 MeV, 7e-4 @ 5 MeV</td>
<td>6e-5 @ 1 MeV</td>
<td></td>
</tr>
</tbody>
</table>
Crab & CygX-1 fluxes (SMILE-II)

Crab polarization above 200keV
(Integral/IBIS)
P=0.46±0.3-0.19
(Integral/SPD)
P=0.4±10-10%

Cyg X-1 above 400keV
P=67±30-30%

IBIS M=0.3 SPI were not calibrated on the ground as a polarimeter.

$E>100\text{keV}$, $1\text{cm}^2$ ETCC 1300 gamma /10hrs from Crab
$BG$ 6500 gamma /10hrs $MPD=28/M\%\quad 4\text{cm}^2$ $MPD=12/M$
$10\text{cm}^2\quad 28/3.3=8.5/M\%$

$M$: modulation factor $M>0.6$ expected for ETCC (Low background compared to IBIS due to real imaging)
Precise measurement of MeV CMB

- 0.1-10MeV Dominant contribution is unclear
- Seyfert or FSRQ?
- SMILE-III Polar flight

Polar Flight (∼10^6 sec) ⇒ >10^6 events
⇒ precise spectrum of CMB
Anisotropy
⇒ >10^5 events is enough for separation of
Seyfert and FSRQ with 5σ
GRB Detection with Swift

Trigger bias looks to appear above for long GRB with $z>4$

Salvaterra et al. 2008

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Band</th>
<th>Field of view</th>
<th>$P_{\text{lim}}$</th>
<th>$z_{\text{max}}$ at $z \geq 6$</th>
<th>$z_{\text{max}}$ at $z \geq 10$</th>
<th>GRBs per year at $z \geq 6$</th>
<th>GRBs per year at $z \geq 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift</td>
<td>15–150</td>
<td>1.4</td>
<td>0.4</td>
<td>6.3–7.5</td>
<td>1.3–4</td>
<td>0.09–0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.25</td>
<td>7.0–8.3</td>
<td>2–7</td>
<td>0.16–0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td>7.5–9.9</td>
<td>3–16</td>
<td>0.3–0.9</td>
<td></td>
</tr>
<tr>
<td>INTEGRAL/IBIS</td>
<td>20–200</td>
<td>0.1</td>
<td>0.2</td>
<td>3.8–5.2</td>
<td>0.1–0.5</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td>GLAST/GBM (on-board)</td>
<td>50–300</td>
<td>9</td>
<td>0.7</td>
<td>6.2–6.3</td>
<td>1.2–1.5</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>GLAST/GBM (ground)</td>
<td></td>
<td></td>
<td>0.47</td>
<td>6.8–6.9</td>
<td>1.8–2.4</td>
<td>0.05–0.12</td>
<td></td>
</tr>
<tr>
<td>SVOM</td>
<td>4–50</td>
<td>2</td>
<td>1.0</td>
<td>6.7–7.4</td>
<td>2–4</td>
<td>0.1–0.13</td>
<td></td>
</tr>
<tr>
<td>EDGE</td>
<td>8–200</td>
<td>2.5</td>
<td>0.6</td>
<td>6.9–8</td>
<td>2–6</td>
<td>0.18–0.23</td>
<td></td>
</tr>
<tr>
<td>EXIST</td>
<td>10–600</td>
<td>5</td>
<td>0.16</td>
<td>9.7–11.3</td>
<td>11–56</td>
<td>0.9–2.8</td>
<td></td>
</tr>
</tbody>
</table>
Imaging GRB Trigger in Sub-MeV

Imaging ability for each photon
Even $10^\circ \times 10^\circ$ -> 1/100 B.G. of 1 str Detector

$\rightarrow$ Imaging Trigger photon by photon in ETCC

GRB detection limit
$\sim 70$ ph. $>100$keV in $4^\circ \times 4^\circ$ $\@ \sim 100\text{cm}^2$ in $10^3$ sec ($8\sigma$)

Point Accuracy for GRBs
$<0.2^\circ$ for $300\gamma$, $0.5^\circ$ for $30\gamma$
GRB Cosmology

\(~650\) GRBs/one year & 10 with \(z>10\) /10years from GRIPS proposal

Expected \(\gamma\) in S-ETCC for GRB @\(z=20\) & \(E_{\text{iso}}=10^{52}\) erg \(\rightarrow\) a few \(\times100\) ph.

ETCC could detect weak flux long duration GRB efficiently

At least relativistic dilation effect \((x\sim10)\)

40cm-cube ETCC

GRB of \(10-2\times10^{-10}\) erg/cm\(^2\)s \((900M_{\text{solar}})\)

Eff. Area 40cm\(^2\)

- \(10^3\)s 200\(\gamma\) B.G. 35\(\gamma\) in 4x4\(^o\) S/N \(~18\sigma\)
- \(10^5\)s 2x10\(^4\)\(\gamma\) B.G> 3.5x10\(^3\)\(\gamma\) S/N =330\(\sigma\)
- 5\(\sigma\) detection during \(10^5\)s \(\rightarrow\) \(~300\)\(\gamma\)
a few 10 \(M_{\text{solar}}\) Super long bursts OK!
GRB detection in SMILE-III

Observations
1. GRB 021206: 80+-20% (Coburn & Boggs 03)
2. GRB 930131, GRB 960924: > 30% (Willis et al. 05)
3. GRB 041219a: 96+-40% (Kalemci et al. 07; McGlynn et al. 07)
4. GAPS 27+- 11%, 84+16-28%, 70+-22% Yonetoku et al. 2011

- SMILE-III GRB~ No background Calibration by Crab!
- ETCC M > 0.6 FoV 3str, Eff. Area 30cm²@200 keV
  GRB 10⁻⁶ erg/cm²s ~250 photon/s T₉₀=40s 250x40s ~10⁴
  MDP = 4.3/M % (3σ) (M > 0.6 )  7% polarization OK!
  GRB 10⁻⁷ erg/cm²s  24% polarization
  a few GRBs (10⁻⁶ erg/cm²s) ~10 (10⁻⁵ erg/cm²s) with one-month
  & low fluence and long duration GRB

- Satellite ETCC~160cm² (Sensitivity~1mCrab@10⁶sec)
  10⁻⁷ erg/cm²s GRB MDP = 5/M % (>100 GRB/year)
  10⁻⁶ erg/cm²s GRB MPD = 2/M % (several 10 GRB/year)
MeV Gammas from SNe

- SMILE with LaBr$_3$ dE/E $\sim$3%@900keV (FWHM)
- Sensitivity for line $\gamma$ $\sim$5x10$^{-6}$ $\gamma$/cm$^2$s (SMILE=III Eff. Area 30cm$^2$)
  $\sim$5x10$^{-7}$ $\gamma$/cm$^2$s (Satellite-ETCC: Eff. Area $\sim$160cm$^2$)


SN 1a $\sim$20 /several years observation within 20Mpc
Collapse type SNe $\sim$5 from GRIPS proposal
Galactic lines of SMILE-III

511keV, 1804keV(Al-26), 4MeV (C-12)

Polar Flight (SMILE-II 10 cm², 10^6 sec) ⇒ > 10^3~10^4 event/pixel
More detailed map of 511keV due to point-like direction of gamma rays
In addition, survey for galactic plane ⇒ possible detection of new sources
due to low background and point-like directional imaging of ETCC
The effects of cosmic rays on the ISM

Vincent Tatischeff, MPE, Oct. 20-21, 2009

Narrow lines: e.g. $^{12}$C(p,p)$^{12}$C$^{*}_{4,439}$, $^{12}$C(p,2pn)$^{10}$B$^{*}_{0,718}$

Broad lines: e.g. $^1$H($^{12}$C, $^{12}$C$^{*}_{4,439}$)$^1$H

$^4$He($\alpha$,n)$^7$Be$^{*}_{0,429}$ and $^4$He($\alpha$,p)$^7$Li$^{*}_{0,478}$

Solar modulation

Protons

$E_{\gamma}(\pi)$

$\gamma$-ray lines

Ionization

Heating

Astrochemistry

Nucleosynthesis

Diffuse $\gamma$-ray emission

- $40^\circ < \theta < 40^\circ$

$\gamma$-ray lines

$\pi^0$ decay

$F_{\gamma}$ (photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$)

$E_{\gamma}$ (MeV)

$E_p$ (MeV)
ETCC have obtained both strong background rejection abilities and high contrast imaging by direction of recoil electron.

ETCC has nearly one order better sensitivity than usual CC with similar effective area.

ETCC also is a good polarimeter with MF>0.6 in sub-MeV region.

SMILE-II having 1-4cm² @0.3MeV effective area will be planned in USA in 2014, 15 for the observation of Crab and Cyg.X-1 with one-day flight. (>5sigma detection, and Polarization)

SMILE-II will be improved to SMIEL-III having > 10cm² (several times better sensitivity of COMPTEL) in 2016.

In the long duration flight around the Polar cap, SMILE-III will measure ~10 Celestial objects, MeV-Cosmic Background and several GRBs with polarization.