ASTRO-H
Soft Gamma-ray Detector

Hiro Tajima
KIPAC, Stanford University
for ASTRO-H/SGD team

Outline

❖ Introduction
❖ SGD Design
❖ Expected Performance
❖ Technology Development
❖ Summary
ASTRO-H/SGD Team

- KIPAC, Stanford University
- ISAS, JAXA
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- Saitama University
  - Y. Terada
- Aoyama-gakuin University
  - K. Yamaoka
- Kanazawa University
  - D. Yonetoku
- CEA/DSM/IRFU
  - F. Lebrun, O. Limousin, P. Laurent
**ASTRO-H Mission**

- **Next Generation of Japanese X-ray Satellite Mission**
  - Successor to Suzaku (Astro-E2)

- **Recovery of Calorimeter Science**
  - Lost due to failure of calorimeter onboard Suzaku

- **Major Science Objectives**
  - New probes of super-massive black holes
    - General Relativity effects near BHs
    - Obscured AGNs
  - Detailed Understanding of galaxy clusters
    - Better determination of cluster mass and other properties
    - Structure formation history of Universe
    - Properties of Dark Energy
  - Cosmic-ray accelerators
* Simultaneous of observations of sources by 4 instruments
  - Soft X-ray Spectrometer (SXS)
    - Soft X-ray telescope + X-ray micro-calorimeter
  - Hard X-ray Imaging System (HXI)
    - Hard X-ray telescope + hard X-ray imager
  - Soft X-ray Imaging System (SXI)
    - Soft X-ray telescope + CCD
  - Soft Gamma-ray Detector (SGD)
    - Narrow field-of-view Compton camera
From Suzaku/HXD to ASTRO-H/SGD

**Focusing optics**
- Better sensitivity
- Imaging

**Suzaku/HXD**
- 2-mm thick Si PIN
- GSO

**SGD**
- Compton camera
  - Better sensitivity
  - Wider energy band

**ASTRO-H Soft Gamma-ray Detector**
SPIE Astronomical Telescopes and Instrumentation, JUN 30, 2010, San Diego
SGD Concept and Requirements

* **Concept**
  - Narrow FOV (field-of-view) Compton camera
    - Compton kinematics to suppress backgrounds
  - Si scatterer for smaller Doppler broadening, lower energy threshold

* **Mission Requirements**
  - Spectral measurement down to 1mCrab sources @100 ks
    - Energy band: 10 – 600 keV
    - 1mCrab in 2-10 keV band with photon index ~1.7
  - Energy resolution good enough to identify activation BG lines

* **Extra success**
  - Measurements of gamma-ray polarization in celestial objects
SGD Science Drivers

*More than 10 objects*
- Seyfert, radio quiet QSO, High-z QSO (Blazar)
- X-ray pulsar, Magnetar
- CXB

*Less than 10 objects*
- TeV Blazar
- ULX, LMXB, gamma-ray binary
- Rotation-powered pulsar
- SNR
- GC, Galactic ridge

*High impact*
- 511 keV from GC, SNR, BHC, LMXB or AXP
- Non-thermal Bremsstrahlung from Cas-A
- Polarization in BHC, pulsar or TeV blazar

\[ \Gamma = 1.7 \pm 0.17 \]

Nakazawa (Tokyo)
AGN

- Spectral Measurements for ~100 AGNs (1 mCrab)
- Detect >500 AGNs (0.2 mCrab) with 100 ks observation

SGD sensitivity @100ks

1 mCrab @100ks

$\Gamma = 1.7 \pm 0.17$

Mushotzky

Swift/BAT 2year survey

Nakazawa
Non-Thermal Bremsstrahlung in Cas A

- First detection of non-thermal Bremsstrahlung by SGD
  - Characteristic $\Gamma \sim 1$ spectrum determined by Coulomb loss
  - New probe for cosmic-ray acceleration
    - Energy budget in sub-GeV cosmic rays
    - Interstellar medium heating
- Prime candidate: Cassiopeia A
  - X-ray variability yields $B \sim 0.5$ mG
    - Inconsistent with leptonic model for Fermi data

---

**Energy budget in sub-GeV cosmic rays**

**Interstellar medium heating**

**Characteristic $\Gamma \sim 1$ spectrum determined by Coulomb loss**

**New probe for cosmic-ray acceleration**

**Prime candidate: Cassiopeia A**

**X-ray variability yields $B \sim 0.5$ mG**

**Inconsistent with leptonic model for Fermi data**

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**Uchiyama**

**Synchrotron**

**Brems**

**π^0 decays**

**Leptonic model**

**Hadronic model**

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**B = 0.3 mG**

**B = 1.0 mG**

**SGD 100 ks**

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**B = 0.1 mG**

**B ~ 0.12 mG**

**B > 0.12 mG**

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**SGD (1mCrab)**

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**Uchiyama**

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**Suzaku PIN**

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**Tuesday, June 29, 2010**
Non-thermal Bremsstrahlung from Magnetar

- $e^+e^-$ pairs created around Magnetar are accelerated along magnetic field
- $e^+e^-$ pairs emit non-thermal Bremsss when reaching the pole and Compton scatter at Magnetar surface
- $e^+$ should emit 511 keV

Gravitational redshift!
Polarization: New Frontier

* Geometrical information on magnetic field & accretion disk
  - Pulsar emission model, cyclotron resonance
  - AGN jet
  - BHB reflection

* Constraints on Lorentz invariance violation
  - Any positive detection from cosmological sources

- 3.5% $\sqrt{10^4/t_{\text{obs}}}$ (1 Crab)
- 3.6% $\sqrt{10^5/t_{\text{obs}}}$ (0.1 Crab)
- 4.3% $\sqrt{10^6/t_{\text{obs}}}$ (0.01 Crab)

3σ Minimum Detectable Polarization

Analytical calculation

Mkn501 flare, 20% polarization

1σ=2.7%@100ks
Polarization: New Frontier

- Geometrical information on magnetic field & accretion disk
  - Pulsar emission model, cyclotron resonance
  - AGN jet
  - BHB reflection

- Constraints on Lorentz invariance violation
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The 3σ Minimum Detectable Polarization (MDP) as a function of observation time is depicted in the graph. The analytical calculation by Takeda (ISAS) is shown alongside Monte Carlo (G4) simulations. The apparent polarization is 3.2±1.7%. The data is synthesized from orthogonal polarization data.

- Constraints on Lorentz invariance violation:
  - Any positive detection from cosmological sources

- Analysis for various sources:
  - 3.5% $\sqrt{10^4/t_{\text{obs}}}$ (1 Crab)
  - 3.6% $\sqrt{10^5/t_{\text{obs}}}$ (0.1 Crab)
  - 4.3% $\sqrt{10^6/t_{\text{obs}}}$ (0.01 Crab)
* Spectral measurement of 1 mCrab sources up to 600 keV
  - Effective Area > 20 cm$^2$ @ 100 keV
    ✦ Detection Efficiency > 10% @ 100 keV
    ✦ Geometrical Area > 200 cm$^2$
  - Field of view < 0.6° @ E = 150 keV
    ✦ Minimize source confusion
  - Requirement verification by simulations
    ✦ Realistic component performance measured using EM (engineering models)

* Identification of activation lines
  - Energy resolution < 2 keV (FWHM) @ 0 keV
BGO Active Shield
- Narrow FOV ~ 10°
- Modular structure
  - Mechanical rigidity
  - Easier to assemble than monolithic design
- APD (Avalanche Photo Diode) readout
  - Compact photon detector

Fine Collimator
- Suppress CXB to be less than NXB
  - Coverage up to ~200 keV is required
- FOV ~ 0.5 – 1°

2 units of 4x1 Compton cameras due to spacecraft constraint
- 4-fold (90°) rotational symmetry is violated
- Design optimization: 3x1 option
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Compton Camera Design

- **Compton Camera Baseline Design**
  - 32 layers of 0.6 mm thick single-sided pixellated Si sensor
  - 8 layers of 0.75 mm thick bottom-CdTe (single-sided pixellated)
  - 2 layers of 0.75 mm thick side-CdTe (single-sided pixellated)
  - 2 layers/module to reduce # of mechanical elements

- **Placement of ASICs to maximize hermeticy of CdTe sensors**
  - 4-fold (90°) rotational symmetry is conserved

![Graph showing incident energy vs fraction for different angular ranges](image)

- **Graph Details**
  - $135° > \theta > 45°$
  - $\theta < 45°$
## Pixel Size Optimization

### Contributions to angular resolution @ 662 keV (68% containment)

<table>
<thead>
<tr>
<th></th>
<th>662 keV</th>
<th>122 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>incident energy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>pixel size</strong></td>
<td>1.6 mm</td>
<td>3.2 mm</td>
</tr>
<tr>
<td><strong>Doppler broadening</strong></td>
<td>1.5°</td>
<td>1.5°</td>
</tr>
<tr>
<td><strong>Geometrical error</strong></td>
<td>1.8°</td>
<td>2.4°</td>
</tr>
<tr>
<td><strong>Energy resolution</strong></td>
<td>0.7°</td>
<td>0.7°</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.3°</td>
<td>3.9°</td>
</tr>
</tbody>
</table>

### Diagram

- 1.6 mm
- 3.2 mm

### Graph

- Δθ (degree) vs. Counts

- 53.9 mm
SGD Performance is verified using simulation
- Use component level test results for component performance
- Estimates of NXB based on Suzaku/HXD-PIN data
  - BG in HXD-PIN is understood to 5% level
  - Neutron BG dominant in HXD
  - Heavily suppressed in SGD according to full simulation studies
- Full simulation of activation BG estimate still in progress
Expected Sensitivity

• SGD sensitivity is one order of magnitude better than existing observatories
• As good as or better than ASTRO-H/HXI for diffuse sources
• Mostly photon statistics limited
  ✦ Better sensitivity by longer exposure

Point source sensitivity

Diffuse source sensitivity
Development of Key Technologies

CdTe 1.4 mm pixel
0.75 mm thick
@ -20°C, -400V
+ custom ASIC (VATA450)

Watanabe (ISAS)

— no correction
— on-chip noise reduction
— off-line noise reduction

Tuesday, June 29, 2010
Development of Key Technologies

Si 3.2 mm pixel
0.6 mm thick
@-15°C, 250V
+ custom ASIC
(VATA450)

CdTe 1.4 mm pixel
0.75 mm thick
@-20°C, -400V
+ custom ASIC
(VATA450)

Tanaka (KIPAC)

Watanabe (ISAS)
Development of Key Technologies

Si 3.2 mm pixel
0.6 mm thick
@-15°C, 250V
+ custom ASIC (VATA450)

— best channel
— worst channel

Tanaka (KIPAC)

— measured
— expected improvement

ASTRO-H Soft Gamma-ray Detector

SPIE Astronomical Telescopes and Instrumentation, JUN 30, 2010, San Diego

CdTe 1.4 mm pixel
0.75 mm thick
@-20°C, -400V
+ custom ASIC (VATA450)

— no-correction
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Watanabe (ISAS)
Requirements

- Survival of vibrations during launch
- Thermal gradient within Compton camera < 5°C
- Size: 10 cm x 10 cm x 12 cm (H)

Baseline mechanical design completed
- Mechanical model passed component-level vibration test
  - Resonance frequency > 160 Hz

New design with improved cooling capability and easier assembly
Requirements

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**New design with improved cooling capability and easier assembly**
Currently in detailed design phase after successfully completing PDR (preliminary design review)

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<tbody>
<tr>
<td>phase-A</td>
<td>Preliminary design</td>
<td>Detailed design</td>
<td>Flight model fabrications and tests</td>
<td>Integration and tests</td>
<td>Launch</td>
<td></td>
</tr>
</tbody>
</table>

- SDR: System Design Review
- PDR: Preliminary Design Review
- CDR: Critical Design Review
SGD will bring rich science on soft gamma-ray sources such as AGNs, neutron stars, BHs, SNR, 511 keV sources

Key Technologies for SGD

- Most component @TRL (Technical Readiness Level) 5
  - Component validation in laboratory environment

ASTRO-H became an official JAXA in September 2008
- SGD (ASTRO-H) will be launched in 2014
Backup slides

- ASTRO-H science
- ASTRO-H instruments
- SGD science
- GRB polarization
- Detector development
Strong gravity required to heat up to X-ray temperature.

- Most prominent X-ray sources in the sky.
  - Extended sources: Clusters of galaxies.
  - Point sources: Black holes
Non-Thermal High-Energy Electrons

- Synchrotron radiation.
- Compton up-scattering.
  - CMB (Cosmic Microwave BG)
  - Synchrotron light

![Diagram showing energy flux distribution]

Energy Flux

- Radio
- Infra-red
- X-rays
- \( \gamma \)-rays

Energy

\[ E^{1/3} \]

\[ \frac{U_B}{U_Y} \]
Mystery of 511 keV Emission

✶ Origin is not well known for 30 years.
  • Sgr A*: Totani 2007
  • SN Ia: Knodlseder 2005
  • LMXB (low-mass X-ray binary): Weidenspointner et al. 2008
  • Low-mass dark matter

✶ Recent INTEGRAL measurement indicates spatial asymmetry
  • Correlation with distribution of LMXBs

Weidenspointner et al. 2008
511 keV Annihilator with SGD

- Competitive against OSSE and INTEGRAL
  - Low BG due to narrow FOV (10° x 10°)
    - Good sensitivity: $10^{-5} \text{ cts/s/cm}^2$
  - Imaging with Compton reconstruction within FOV
    - Could be useful to identify signal against flat BG
  - Energy resolution: ~ 5 keV
    - probe condition of emission site

Nakazawa

Watanabe

511 keV image within SGD FOV

GC $10^{-3} \text{ cts/s/cm}^2$ @ 100 ks
SGD Observation of Cas A

* Constraints on:
  - Electron spectrum
  - Magnetic field
    ✦ Equipartition: $B = 0.3$ mG
    ✦ Synchrotron cooling: $B = 0.5$ mG
  - sub-GeV electron/proton population

![Cas A Suzaku spectra][102]

100-200 keV excess w. GSO ??
1% of NXB ..

$B = 0.1$ mG

(Maeda+ in prep.)

![Normalized counts/sec/keV vs energy (keV)][103]

Uchiyama

SGD 100 ks

B = 0.1 mG

B = 0.3 mG

B = 1.0 mG
511 keV from Cygnus X-1

- 2.5σ (stat) evidence by Suzaku/HXD (Makishima et al. 2008)
  - Difference between bright/faint period by XIS
  - Systematic error due to BG is canceled to <1%
- Origin of 511 keV @ GC?
- Emission mechanism?

Suzaku 17 ks

SGD 100 ks

Peak @492±17 keV
Line flux: $10^{-3}$ cts/s/cm²
Polarization Measurement with SGD

\[
\frac{\partial \sigma}{\partial \Omega} \propto \left( \frac{E_\gamma'}{E_\gamma} \right)^2 \left( \frac{E_\gamma'}{E_\gamma} + \frac{E_\gamma}{E_\gamma'} - 2 \sin^2 \theta \cdot \cos^2 \phi \right) 
\]

AVG \cdot (1 + Q \cos 2(\phi - \chi_0))

100% polarization
Q = 49±1%
1σ sensitivity: 2.0%
@ 1Crab x 5 ks
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Si/CdTe Hybrid Design

- Low-Z sensor (Si) is a good scatterer:
  - Compton scattering dominant for Si at lower energies
  - Diamond (C) is even better if low energy threshold possible
  - Smaller Doppler broadening effect
- High-Z sensor (CdTe/CZT/Ge) is a good absorber
  - Photon absorption is dominant to 300 keV

![Diagram showing single-layer interaction probability with different processes and angles.](image-url)

- Photo-absorption
- Compton scattering
- Pair creation

- Si: $\sigma = 1.4^\circ$ (Si)
- CdTe: $\sigma = 2.9^\circ$ (CdTe)

@662 keV
Detector Configuration

- **Single sensor type**
  - Simpler structure, readout

- **Hybrid type**
  - Low-Z scatterer and high-Z absorber
  - Simple stacking or sounding absorber
  - Photons tend to be scattered horizontally

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Nuclear Compton Telescope
GRIPS

Some of Advanced Compton telescope options

ASTRO-H/SGD

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![Graph showing fraction vs. incident energy](image-url)

- Incident Energy (keV)
- Fraction
- 135° > θ > 45°
- θ < 45°
Development of Key Technologies

Key Technologies with high technical readiness (TRL 5)

- Si sensor
  - Many particle physics experiment, PMELA, AGILE, Fermi
  - Reliable manufacturer: Hamamatsu Photonics (HPK)
- CdTe sensor
  - Long development history, well understood
  - Very uniform detector response: critical for calibrations
  - Flight heritage: INTEGRAL
- Front-end ASIC (improved VIKING architecture ASIC)
  - Final version out of foundry (Previous design also usable)
  - Flight heritage: Swift, PAMELA, AGILE
- BGO (APD) readout
  - APD technology is well developed and manufactured by HPK
  - Flight heritage with Japanese small satellite

Still in Development

- Compact assembly
APD (Avalanche Photo-Diode) readout to reduce the size of photon sensor.

- Developing larger APD arrays to readout long BGO.
- APD placement in SGD support structure.

**Figure:**

- **BGO 30.0x4.8x0.3 cm³**
- **BGO 1.0x1.0x1.0 cm³**
- **HPK S8664-1010N 1.0x1.0 cm²**

**T. Ikagawa, et al. NIM 2004**

- **-15 °C**
  - 662 keV 20.9% (FWHM)
  - 60 keV

- **-20 °C**
  - 32 keV
  - 662 keV 7.1% (FWHM)

**Minimum detectable Energy: 11 keV**
VATA: Low Noise Front-end ASIC

- **Low noise and low power consumption**
  - Front-end MOSFET geometry optimized for small capacitance.
  - VA32TA: 2 mW/channel, shaping time 2 $\mu$s
  - VA32TALP: 0.2 mW/channel, shaping time 4$\mu$s, 110 $e^-$ @ 6 pF.
  - VA64TA1: 0.2 mW/channel, shaping time 4$\mu$s
  - VA32TA5: VA64TA1 + integrated ADC
  - Common mode noise detection.

- **Fast shaper for self-trigger.** (75–600 ns)

- **Internal DAC** (4-bit trim DAC, bias).
- **Radiation hard to 20 MRad** (due to 0.35 $\mu$m process).
- **SEU** (single event upset) tolerant design. (>70 MeV/$\mu$m$^2$)

\[
\frac{45 + 19 \times C}{\sqrt{\tau}} \ [e^-] \text{ (RMS)}
\]

\[
\frac{76 + 24 \times C}{\sqrt{\tau}} \ [e^-] \text{ (RMS)}
\]
High integration of functions to reduce electronics components inside of BGO shield
- Integrated Wilkinson-type ADC
- Common mode noise detection
- Zero-suppression with digital threshold

Integrated ADC with on-chip common mode noise detection

Al-pixel/CdTe/Pt
1.4 mm pixel
0.75 mm thick
@-20°C, -400V

Watanabe (ISAS)

241Am

$\Delta E \sim 1.3-1.4$ keV (FWHM)
Front-end ASIC Development

- **Low noise**
  - Fine energy resolution, low threshold
  - Good angular resolution, background rejection

- **High integration of functions to reduce electronics components inside of BGO shield**
  - Integrated ADC
  - Zero-suppression in final version

- **Low power**
  - 0.3 mW/channel.
  - Total # of channels: ~85k (~1/10 of Fermi)
  - 5 W/camera

- **Flight heritage**
  - Swift, PAMELA, AGILE

---

Al-pixel/CdTe/Pt
1.4 mm pixel
0.75 mm thick
@-20°C, -400V
# Si Sensor Energy Resolution

## Double-sided Si-Strip Detector (DSSD)
- 2.56x2.56 cm²
- 0.4 mm pitch
- 0.3 mm thick

<table>
<thead>
<tr>
<th>Energy</th>
<th>Resolution (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.9 keV</td>
<td>1.1 keV</td>
</tr>
<tr>
<td>14.4 keV</td>
<td>1.1 keV</td>
</tr>
<tr>
<td>60 keV</td>
<td>1.3 keV</td>
</tr>
<tr>
<td>122 keV</td>
<td>1.3 keV</td>
</tr>
</tbody>
</table>

### Operation temperature
- -20 ~ 0 °C

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**Fukazawa, et al. SPIE 2004**

- 14.4 keV
- 122.1 keV

**H. Tajima, et al. SPIE 2002**

- 13.9 keV
- 17.6 keV
- 21.0 keV
- 26.3 keV
- 59.5 keV

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*ASTRO-H Soft Gamma-ray Detector*

SPIE Astronomical Telescopes and Instrumentation, JUN 30, 2010, San Diego
Experimental Test of Compton Camera

ASTRO-H Soft Gamma-ray Detector
SPIE Astronomical Telescopes and Instrumentation, JUN 30, 2010, San Diego

Watanabe (ISAS) 38/21

Tuesday, June 29, 2010
Experimental Test of Compton Camera

Obtained with the first prototype

Two $^{57}$Co, 122keV events

Before Compton constraint

$\Delta E/E \sim 3\%$ (not calibrated)

$^{22}$Na, 511keV events

JAEA/Gunma Univ/JAXA/RIKEN

Watanabe (ISAS)
Experimental Test of Compton Camera

JAEA/Gunma Univ/JAXA/RIKEN

364 keV

ΔE/E ~ 3%
(not calibrated)

After Compton constraint

Watanabe (ISAS)
Angular Resolution of Compton Camera

Scattering angle resolution @ 122 keV

Experimental angular resolution is dominated by Doppler broadening.

Energy dependence

+ Data
– MC (G4)

Energy resolution
pixel size

Good enough

Fukazawa et al., SPIE 2004

Watanabe (ISAS)
Experimental Validation of Modulation

- Geant4 MC simulation in agreement with experimental data
  - Validate modeling of detector geometry & response
- Modulation factor
  - 82.9±0.8% (Experimental)
  - 85.6±2.7% (MC)

Takeda (ISAS)

![Data vs. MC comparison graph]

- Observed Events/bin
- Azimuth angle [degree]
- Corrected Events/bin
- Instrument response

ASTRO-H Soft Gamma-ray Detector
SPIE Astronomical Telescopes and Instrumentation, JUN 30, 2010, San Diego

Tuesday, June 29, 2010
GRB 021206 with Hypothetical SGD

RHESSI Observation

\[ 80 \pm 20\% \]

Coburn & Boggs

Good timing resolution

\[ P = 78 \pm 2\% \ (\text{input: } 80\%) \]

1 unit SGD w/o collimator

\[ P = 11 \pm 2\% \ (\text{input: } 10\%) \]

5\(\sigma\) limit