The Advanced Compton Telescope

Vision Mission Concept Study (3/04)

“to uncover how supernovae and other stellar explosions work to create the elements”
-SEU Roadmap 2003

Steve Boggs for the ACT Team
University of California, Berkeley
GLAST 2007, Stanford University

Witness to the Fires of Creation
ACT Overview

Enable high sensitivity $\gamma$-ray spectroscopy

Life Cycles of Matter
- Supernovae & nucleosynthesis
- Supernova remnants & interstellar medium
- Neutron stars, pulsars, novae

Black Holes
- Creation & evolution
- Lepton vs. hadron jets
- Deeply buried sources

Fundamental Physics & Cosmology
- Gamma-ray bursts & first stars
- History of star formation
- MeV dark matter

• 100× sensitivity improvement for spectroscopy, imaging & polarization (0.2-10 MeV)
• Advanced 3-D positioning $\gamma$-ray spectrometers, 25% sky field-of-view
• LEO equatorial orbit, zenith-pointing survey mode (baseline mission), 80%/orbit
Cosmic High Energy Laboratories

*Why MeV gamma-rays?*

**COMPTEL 1-30 MeV Source Catalog**

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**Unique 0.2-10 MeV Science**
- nuclear lines
- e-/e+ mass, annihilation
- peak emission: AGN, BHs, GRBs
- polarization

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<table>
<thead>
<tr>
<th>Sources (5 yr)</th>
<th>COMPTEL</th>
<th>ACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supernovae</td>
<td>1</td>
<td>100-200</td>
</tr>
<tr>
<td>AGN</td>
<td>15</td>
<td>200-500</td>
</tr>
<tr>
<td>Galactic</td>
<td>23</td>
<td>300-500</td>
</tr>
<tr>
<td>GRBs</td>
<td>31</td>
<td>1000-1500</td>
</tr>
<tr>
<td>Novae</td>
<td>0</td>
<td>25-50</td>
</tr>
</tbody>
</table>

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“(Schönfelder et al. 2000)”

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“…to explore the profound mysteries of life, space, time and the workings of the universe.”

-NASA Space Science Enterprise Strategy 2003
Type Ia Supernovae

Cosmic Yardsticks, Alchemists

Goal: study $^{56}\text{Ni}$ & $^{56}\text{Co}$ emission from the core of Type Ia supernovae.

1. Standard candles -- characterize the $^{56}\text{Ni}$ production, relation to optical
2. Explosion physics -- uniquely distinguish explosion physics
3. SNe Ia rate, local & cosmic -- direct rates unbiased by extinction

We define the science requirements in terms of the following objective:

*ACT must be able to strongly distinguish typical deflagration models from delayed detonation models, even if the supernovae distances are unknown.*

Leading to instrumental requirements:
- broad (3%) line sensitivity at 847 keV: $\sim7\times10^{-7}$ ph/cm$^2$/s
- spectral resolution: $\Delta E/E < 1$
- wide field of view: 25% sky

….these lead to 40-50 detections/year (5 @ 15$\sigma$)!
Primary science requirement: systematic study of SNIa spectra, lightcurves to uniquely determine the explosion mechanism, $^{56}$Co (0.847 MeV) abundances.
**Standard Candle**

characterize $^{56}$Ni production

Requirements: measurement of $^{56}$Ni production in >100 SNe at >5$\sigma$ levels.

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**Explosion Physics**

flame propagation, dynamics

Requirements: high sensitivity (>15$\sigma$) lightcurves and high-resolution spectra ($\Delta E/E<1\%$) of several SNe Ia events of each subclass over the primary 5-year survey.
Compton Telescopes: Then & Now

CGRO/COMPTEL
• ~40 cm³ resolution
• ΔE/E ~ 10%
• 0.1% efficiency

ACT Enabling Detectors
• 1 mm³ resolution
• ΔE/E ~ 0.2-1%
• 10-20% efficiency
• background rejection
• polarization, wide FoV
Baseline ACT Instrument

D1: 27 layers 2-mm thick Si
  • 10x10 cm², 64x64 strips
  • 3888 det., 248,832 chns
  • -30° C, Stirling cycle cooler

D2: 4 layers, 16-mm thick Ge
  • 9.2x9.2 cm², 90x90 strips
  • 576 det., 103,680 chns
  • 80 K, Turbo-Brayton cooler

BGO: 4-cm thick shield
ACD: plastic scintillator

ACT Apples/Oranges Envelope:
  • 1850-kg instrument (w/o margin)
  • 2000 W instrument (w/o margin)
  • Delta IV shroud (~4m dia.)
• full science goals
• detailed performance
• mission design & readiness
• technology recommendations
ACT Collaboration

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Where do the chemical building blocks of life, planets, stars originate?

How do the chemical elements evolve?

What powers supernovae explosions?

Resolved spectroscopy and flux of nuclear lines from the heart of supernovae

What is the physics at the edge of a black hole?

How do matter & antimatter behave in extreme environments?

Spectroscopy, polarization, and timing of photons from black holes, neutron stars, and novae

When did the first stars form?

Can gamma-ray bursts measure the geometry of the Universe?

Gamma-ray burst localization, spectroscopy, polarization and timing
Backup Slides
ACT Mission Configuration

- **Instrument**
  - (1.42 x 1.42 x 0.75 envelope)

- **Ø1.5m antenna**
- **Solar Array**
  - 34 m² (shown)

- **Bus Structure and sub-system layout**
  - similar to GLAST bus design

- **Thermal radiator**
  - End panels deploy
  - (22 m² shown)
  - Propulsion Tank
  - 0.58m x 1.02m
  - 309 kg capacity
  - 2 each

- **Cryo-cooler (not visible)**
  - Reserve envelope included in design Ø1.0m x 0.6m

- **Battery Box**
  - (green)
  - 2 each

**Delta IV 4m fairing**
Alternate ACT Designs

Tracking Si/CdZnTe calorimeter (UCR) → e⁻ tracking, room T
limit: power (#strips)

Ge/BGO shield (UCB) → high spectral resolution
limit: power (cooling), mass (BGO)

Thick Si (NRL) → reduce Doppler broadening, minimal cooling

LXe (Rice, Columbia) → fast timing, good stopping power
limit: mass (detector)

Gaseous Xe/LaBr₃ (GSFC/UNH) → e⁻ tracking
limit: mass, power (#chns?)

LaBr₃ (UNH) → fast timing (modern COMPTEL)
limit: mass (LaBr₃)
ACT Technology Recommendations

1. **Germanium detectors**: enabling technology development
   - electrode optimization
   - environmental testing
   - mfg large numbers

2. **Thick Si detectors**: enabling technology development
   - basic development for thicker detectors
   - mfg large numbers

3. **LXe detectors**: laboratory demonstration
   - optimized spectral performance
ACT Technology Recommendations (Cont.)

4. Readout electronics: basic development
   • ~1 mW/chn readout
   • 0.1 mW preamps

5. Cryogenics: study and development
   • detailed technical study
   • enabling development of scaling

6. Passive materials: study and development
   • low-Z structure
   • minimal cryostats

7. Simulation toolset: basic development
   • integrated simulation package
   • tested environmental inputs
   • data and imaging analysis software

→ Plus, balloon demonstrations of all ACT technologies.
ACT Enabling Technologies

The ACT Vision Mission study identifies the most promising detectors and highest priority technology developments.

**Recommendations:**
- Ge, thick Si, (LXe)
- low-power readouts
- cryogenics, materials, sims

<table>
<thead>
<tr>
<th>Property</th>
<th>Si Strip</th>
<th>Ge Strip</th>
<th>Liquid Xe</th>
<th>CZT Strip</th>
<th>Xe µWell</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔE/E (1 MeV)</td>
<td>0.2-1%</td>
<td>0.2%</td>
<td>3%</td>
<td>1%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Spatial Resol.</td>
<td>&lt;1-mm³</td>
<td>&lt;1-mm³</td>
<td>&lt;1-mm³</td>
<td>&lt;1-mm³</td>
<td>0.2-mm³</td>
</tr>
<tr>
<td>Z density</td>
<td>14</td>
<td>32</td>
<td>54</td>
<td>48</td>
<td>54 (3 atm)</td>
</tr>
<tr>
<td></td>
<td>2.3 g/cm³</td>
<td>5.3 g/cm³</td>
<td>3.0 g/cm³</td>
<td>8.3 g/cm³</td>
<td>0.02 g/cm³</td>
</tr>
<tr>
<td>Volume (achvd.)</td>
<td>60 cm³</td>
<td>130 cm³</td>
<td>3000 cm³</td>
<td>4 cm³</td>
<td>50 cm³</td>
</tr>
<tr>
<td>Operating T</td>
<td>-30° C</td>
<td>-190° C</td>
<td>-100° C</td>
<td>10° C</td>
<td>20° C</td>
</tr>
</tbody>
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### ACT Baseline Science Instrument Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy range</td>
<td>0.2-10 MeV</td>
</tr>
<tr>
<td>*Spectral resolution</td>
<td>0.2-1%</td>
</tr>
<tr>
<td>*Field of View</td>
<td>~1°</td>
</tr>
<tr>
<td>Sky coverage</td>
<td>80% per orbit</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>~1°</td>
</tr>
<tr>
<td>Point source localization</td>
<td>5’</td>
</tr>
<tr>
<td>Detector area, depth</td>
<td>~12,000 cm², 47 g/cm²</td>
</tr>
<tr>
<td>Effective area</td>
<td>~1000 cm²</td>
</tr>
<tr>
<td>*3% broad line sensitivity (10^6s)</td>
<td>1.2×10^-6 ph/cm²/s</td>
</tr>
<tr>
<td>Narrow line sensitivity</td>
<td>5×10^-7 ph/cm²/s</td>
</tr>
<tr>
<td>Continuum sensitivity</td>
<td>(1/E)×10^-5 ph/cm²/s/MeV</td>
</tr>
<tr>
<td>GRB fluence sensitivity</td>
<td>3×10^-8 erg/cm²</td>
</tr>
<tr>
<td>Data mode</td>
<td>Every photon to ground</td>
</tr>
</tbody>
</table>

*Primary science requirement driven by Type Ia supernovae.*
**ACT Mission Overview**

- **Instrument Synthesis & Analysis Laboratory (ISAL), September 2004**
- **Integrated Mission Design Center (IMDC), November 2004**

<table>
<thead>
<tr>
<th>Systems</th>
<th>Current</th>
<th>Heritage</th>
<th>ACT</th>
<th>ACT TRL</th>
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<tbody>
<tr>
<td>DC Power</td>
<td>2 kW</td>
<td>AQUA</td>
<td>3.8 kW</td>
<td>TRL-9</td>
</tr>
<tr>
<td>Data Bus (Spacewire)</td>
<td>32 Mbps</td>
<td>SWIFT</td>
<td>60 Mbps</td>
<td>TRL-7</td>
</tr>
<tr>
<td>TDRSS Ku-band</td>
<td>1 Gbps</td>
<td>GLAST</td>
<td>625 Mbps</td>
<td>TRL-8/9</td>
</tr>
<tr>
<td>Cryocooler (80K)</td>
<td>300 W</td>
<td>NICMOS</td>
<td>600 W</td>
<td>TRL-9</td>
</tr>
<tr>
<td>Cryocooler (-30° C)</td>
<td>100 W</td>
<td>RHESSI</td>
<td>300 W</td>
<td>TRL-9</td>
</tr>
</tbody>
</table>

“Baseline ACT” for ISAL & IMDC:
- D1: 32 layers SiDs 2-mm thick each
- D2: 3 layers, GeDs 16-mm thick each
- 1.2 m² area, 144 detectors/layer
ACT in NASA’s Strategic Plan

- Selected in March 2004 for a NASA Vision Mission concept study

- 2005 NASA Universe Strategic Roadmap identifies the Nuclear Astrophysics Compton Telescope as a Pathways to Life Observatory

- Space Science strategic objective 5.12 – understand the development of structure and the cycles of matter and energy in the evolving universe (2003)

- ACT identified in the 2003 SEU Roadmap under *Cycles of Matter and Energy* (“will be undertaken after Beyond Einstein has begun”)

- Nuclear astrophysics was identified by the Gamma-Ray Astrophysics Working Group (GRAPWG) in 1999 as the ‘highest-priority science goal’, and ACT as the ‘highest priority major gamma-ray mission’