# THE ADVANCED COMPTON TELESCOPE MISSION

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## ABSTRACT

The Advanced Compton Telescope (ACT) has been identified as the next major step in gamma-ray astronomy. It will probe the nuclear fires creating the chemical elements by enabling high resolution spectroscopy of nuclear emission from supernova explosions. During the past two years, our collaboration has been undertaking a NASA mission concept study for ACT[1]. This study was designed to (1) transform the key scientific objectives into specific instrument requirements, (2) to identify the most promising technologies to meet those requirements, and (3) to design a viable mission concept for this instrument. We present the results of this study, including scientific goals and expected performance, mission design, and technology recommendations.

Key words: nucleosynthesis, supernova Ia, Compton telescope, ACT.

## 1. INTRODUCTION

One of the fundamental questions modern astrophysics is faced with is a detailed understanding of the origin of the elements. The amounts of different radioactive isotopes created through nuclear burning during different stages of stellar evolution constitute a sensitive probe of the "cauldrons in our cosmos" [6]. Nuclear lines from radioactive decays of these isotopes provide a direct measure of their quantity; observing them requires high sensitivities to nuclear lines at MeV energies, where Compton interactions dominate over both photoelectric absorption and pair creation.

The Advanced Compton Telescope (ACT) has been the focus of long-term planning in the US gamma-ray astrophysics community since 1999 when the Gamma-Ray Astrophysics Working Group (GRAPWG) identified ACT as the "highest-priority major gamma-ray mission."

NASA's Structure and Evolution of the Universe roadmap in 2003 called for measurements that would "uncover how supernovae and other stellar explosions work to create the elements" — a mandate for an observatory capable of nuclear-line astrophysics observations. Supernovae (SNe) of type Ia play a special role as standard candles for cosmology, in addition to being significant contributors of metals to our universe. The primary science goal for ACT was defined as follows: A systematic study of SNe Ia spectra and lightcurves with the goal to uniquely determine the explosion mechanism and $^{56}$Co abundances (see [3, 4]). To achieve this, ACT must be able to detect several SNe Ia events of each subclass (luminous, superluminous, underluminous) in their 847 keV line from $^{56}$Co decay with at least $15\sigma$ significance over a 5-year survey.

In 2004, ACT was selected by NASA for a "Vision Mission Concept Study." The goals of this study included the transformation of ACT's key science objectives into specific instrument requirements, identification of the most promising detector technologies, design of a viable mission concept, and formulation of technology development recommendations.

[1]The full ACT study report is available on the www at http://www.ssl.berkeley.edu/act/ and as astro-ph/0608532.

*Table 1. Technology Readiness Level (TRL) evaluation of key ACT mission components, for a 2015 launch.*

| Systems | Current | Heritage | ACT | ACT TRL |
|---|---|---|---|---|
| DC Power | 2 kW | AQUA | 3.8 kW | TRL-9 |
| Data Bus (Spacewire) | 32 Mbps | Swift | 60 Mbps | TRL-7 |
| TDRSS Ku-band | 1 Gbps | GLAST | 625 Mbps | TRL-8/9 |
| Cryocooler (80 K) | 300 W | NICMOS | 600 W | TRL-9 |
| Cryocooler (-30°C) | 100 W | RHESSI | 300 W | TRL-9 |

## 2. THE ACT BASELINE INSTRUMENT AND MISSION

**ACT Baseline Instrument** The ACT study "baseline instrument" is a hybrid of thick Si-strip detectors and Ge-strip detectors. It constitutes a promising combination of a low-Z (and low-Doppler-broadening) scattering detector (Si) and a higher-Z (and high stopping power) "calorimeter" detector (Ge). The baseline instrument was originally conceived in fall 2004, early in the study, for design studies of the instrument at NASA's Instrument Synthesis & Analysis Laboratory (ISAL) and of the mission at NASA's Integrated Mission Design Center (IMDC). The chosen baseline encompasses the key challenges of different ACT instrument technologies: cooling (to 80 K for Ge) and a large number of instrument channels. The baseline instrument was slightly modified later in the study to optimize its scientific performance (less Si, more Ge, addition of BGO rear shield). Fig. 1 shows the optimized ACT baseline instrument.

**ACT Mission** The requirements for an ACT mission given as constraints to the IMDC included a low-earth (near-) equatorial orbit at $\sim$550 km or below and a 5–10 yr mission lifetime. Primary observatory mode will be zenith-pointed to obtain the best sky exposure with a large-FoV instrument, but pointed observations will be possible. Fig. 2 shows a sketch of the ACT spacecraft; it easily fits into a Delta 4 shroud. Very conservative rough estimates for telemetry requirements were used for the IMDC mission assessment — detailed simulations later in the study showed that $< 10$ Mbps average telemetry are required for the Si-Ge baseline with BGO. Power, data bus, telemetry, and cooling requirements of an ACT mission were all found at technology readiness levels (TRLs) of 7–9 (1–9 scale) for a launch in 2015 (see Tab. 1) — today's *mission* technology is ready for ACT.

## 3. PERFORMANCE OF THE ACT BASELINE INSTRUMENT

A space-based instrument operating in the energy range of nuclear lines — such as ACT — is subject to complex backgrounds generated by cosmic rays, earth albedo radiations, trapped particles, and diffuse gamma rays; typically measurements are significantly background-dominated. Therefore accurate, detailed simulations of the background induced in the instrument and spacecraft, and the exploration of event selection and reconstruction techniques for the reduction of these backgrounds, are crucial to predictions of instrument performance. The ACT study's approach to this simulation challenge, including the space environment model used and the approach to a detailed yet flexible instrument model, is described in [7]. The study leveraged heavily off of previously existing tools such as MGGPOD [8] and MEGAlib [9], both of which were enhanced significantly during this study. For the primary science goal of ACT, the characterization of SN Ia, the relevant performance parameters are the instrument's sensitivity to a 3% broadened 847

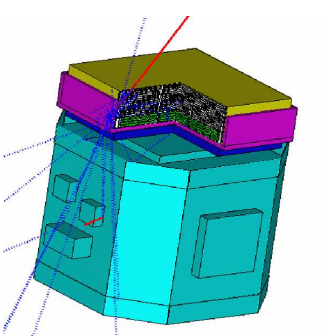


*Figure 1. The optimized baseline ACT instrument on a spacecraft bus. Partial cutaway view, simulated interaction of a cosmic-ray electron shown.*

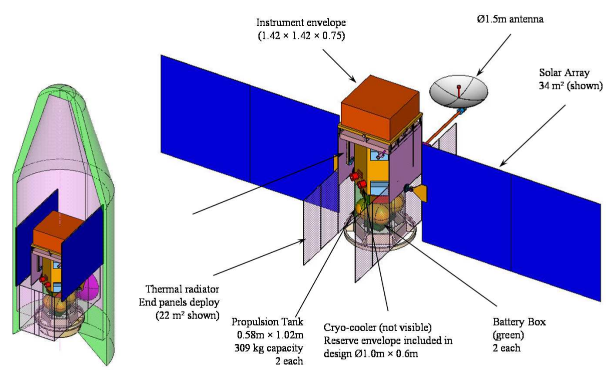


*Figure 2. The ACT spacecraft studied at the IMDC in a Delta 4 shroud and with solar and radiator panels unfolded.*

*Table 2. Predicted performance of the optimized Si-Ge baseline ACT instrument. (Sensitivities for 3$\sigma$, $10^6$ s.)*

| | |
|---|---|
| Energy range | 0.2 – 10 MeV |
| Spectral resolution | 0.2 – 1% |
| Field of View | 25% sky (zenith pointer) |
| Sky coverage | 80% per orbit |
| Angular resolution | $\sim 1^\circ$ |
| Point source localization | 5' |
| Detector area, depth | $\sim$12000 cm$^2$, $\sim$50 g cm$^{-2}$ |
| Effective area | $\sim$1000 cm$^2$ |
| 3% broad line sensitivity | $1.2\times10^{-6}$ ph cm$^{-2}$s$^{-1}$ @ 847 keV |
| Narrow line sensitivity | $5\times10^{-7}$ ph cm$^{-2}$s$^{-1}$ |
| Continuum sensitivity | $\sim$ (1/E)$\times10^{-5}$ ph cm$^{-2}$s$^{-1}$MeV$^{-1}$ |
| Data mode | every photon to ground |

keV line ($1.2\times10^{-6}$ ph cm$^{-2}$s$^{-1}$), its energy resolution at 847 keV (3.3 keV FWHM), and its Field-of-View (45° HWHM sensitivity at 847 keV). Fig. 3 shows the narrow-line sensitivity achievable with the optimized baseline ACT in a staring observation; Fig. 4 illustrates the angular resolution of the instrument. Tab. 2 gives a summary of the optimized baseline instrument's performance.

## 4. ALTERNATE INSTRUMENT CONCEPTS

Several different detector technologies are potential candidates for an ACT instrument, ranging from semiconductors to liquid scintillators to gas microwell detectors. One of the primary goals of the ACT study was to identify the most promising approaches. Given the different properties of these detectors, and the widely varying requirements they would place on a mission, a common "apples/oranges envelope" for instrument mass, power, and volume was derived from the IMDC study to serve as a constraint for the various concepts: 1850 kg, 2 kW (both w/o margins), and the dimensions of a Delta 4 shroud.

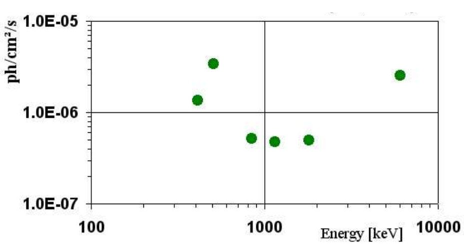


*Figure 3. Narrow-line sensitivity of the optimized Si-Ge baseline ACT instrument (3$\sigma$, $10^6$ s observation).*

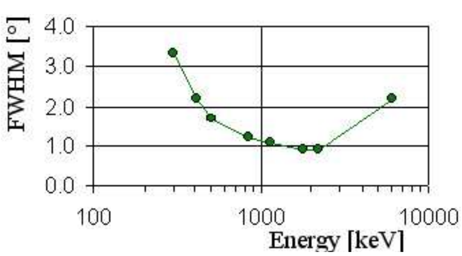


*Figure 4. Angular resolution (customarily given in terms of the Angular Resolution Measure, or ARM, for Compton telescopes) of the optimized Si-Ge baseline ACT instrument.*

The alternate concepts, along with the motivation for their conception and the aspect of the "envelope" that constrained them, are listed in Tab. 3. The performance of the instruments was compared in the 2-D parameter space most relevant to ACT's primary science goal of distinguishing SNe Ia: sensitivity to 3% broadened 847 keV emission, and energy resolution. ACT must clearly distinguish between delayed-detonation, deflagration, and sub-Chandrasekhar models of SN Ia explosions. The $^{56}$Ni lightcurves of the first two are the most similar, thus distinguishing them places the most stringent requirements on ACT performance. The significance at which an ACT with a given sensitivity and energy resolution could distinguish between a typical delayed-detonation model and a typical deflagration model for a SN Ia explosion at 20 Mpc is shown in Fig. 5 for both precisely known SN distance and uncertainties typical of today's observations ($\sim$ 10%, see e.g. [2] compared to [5]).

## 5. TECHNOLOGY RECOMMENDATIONS

The ACT vision mission study resulted in a list of technology development recommendations:

- Ge detectors: enabling technology development (electrode optimization, large numbers)
- thick Si detectors: enabling technology development (basic development of thicker detectors, large numbers)
- liquid Xe detectors: laboratory demonstration of optimized spectral performance
- readout electronics: basic development of low-power ASICS and preamplifiers
- cryogenics: study and development
- passive materials: study and development of low-Z structure and minimal cryostats
- simulation toolset: development of an *integrated* simulation package, tested environmental inputs, and improved data and imaging analysis software

## 6. SUMMARY AND CONCLUSIONS

The Advanced Compton Telescope's primary science goal is a systematic study of SN Ia. ACT will distinguish the explosion mechanism, characterize the relation of $^{56}$Ni production to optical emission of these explosions used as standard candles, and determine local and cosmic SN Ia rates (the latter from SN Ia line contributions to the cosmic diffuse background). An ACT capable of achieving this primary goal will enable significant

*Table 3. Alternate instrument concepts for an Advanced Compton Telescope.*

| Alternate Concepts | Motivations | Apples/Oranges Envelope Limit |
|---|---|---|
| tracking Si / CZT calorimeter | electron tracking, room temperature | power (# of strips) |
| Ge / BGO shield | high spectral resolution | power (cooling) & mass (BGO) |
| thick Si | reduce Doppler broadening, minimal cooling | power (# of ch.) & mass (det) |
| liquid Xe | fast timing, good stopping power | mass (detector) |
| gas Xe / $LaBr_3$ | high-resolution electron tracking | mass ($LaBr_3$) & power (# of ch.) |
| low-Z-scintillator / $LaBr_3$ | fast timing ("modern COMPTEL") | mass ($LaBr_3$) |

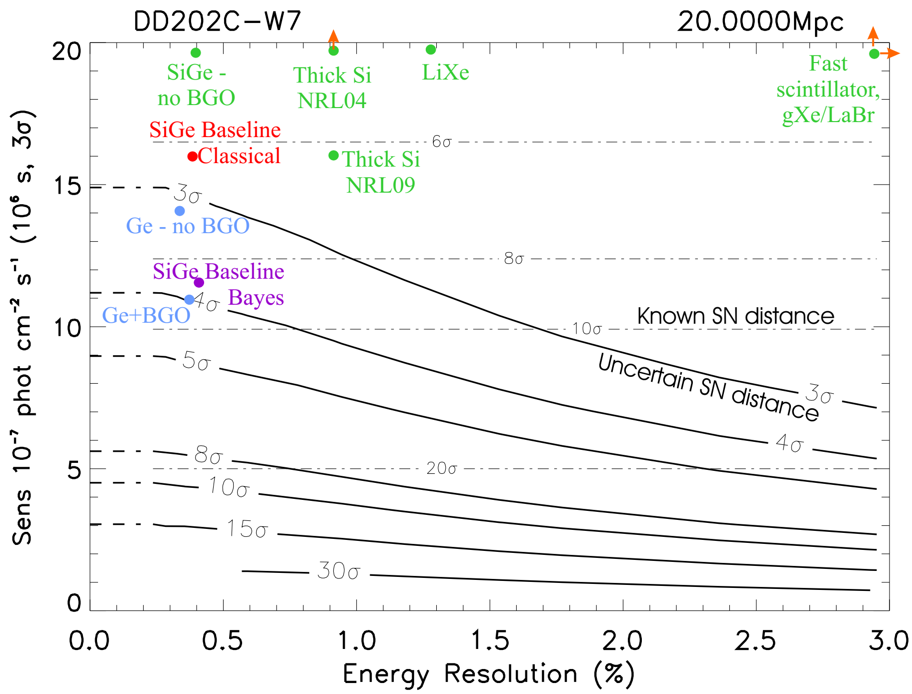


*Figure 5. Comparison of candidate instrument performances in the 2-D performance space for distinguishing SN Ia models: sensitivity to 3% broadened 847 keV line emission, and energy resolution. Lines denote significance of discrimination between delayed detonation and deflagration models for a SN Ia at 20 Mpc. With typical uncertainties in the SN distance, the required sensitivity is related to the instrument's energy resolution. Blue and purple marks denote Bayesian analysis methods, green and red marks denote "classical" analysis methods (see [1, 10] for details).*

advances in our understanding of cosmic accelerators and sites of nucleosynthesis in general through a roughly 100-fold improved sensitivity in the nuclear line regime over previous missions, a wide field-of-view, and good temporal, energy, and spatial resolution. The ACT concept study has shown that from a technological standpoint, an Advanced Compton Telescope could be ready for launch as early as 2015, and has identified the areas where additional technology developments are required in preparation for a large-scale satellite instrument.

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