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The Advanced Compton Telescope mission

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For the ACT Study Team (Thanks to C. Wunderer for presenting this paper).

Abstract

The Advanced Compton Telescope (ACT), the next major step in γ-ray astronomy, will probe the fires where chemical elements are formed by enabling high resolution spectroscopy of nuclear emission from supernova explosions. ACT requires two orders of magnitude improvement in sensitivity over current gamma- ray observatories to achieve this goal, and will operate primarily in survey mode – covering 80% of the sky on every orbit. ACT will also enable new classes of compact object and GRB observations, including all-sky monitoring for transients and rapid localizations, high resolution spectra, high sensitivity to positron annihilation emission and other line features, and novel sensitivity to polarization. ACT was chosen by NASA for a 1-year Vision Mission concept study, with the primary goals of identifying the key technologies and developing the detailed mission concept. We discuss the scientific goals and capabilities of ACT, and an overview of the science mission.

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1. Overview

The formation of stars and planets, and the development of the chemistry of life, can be understood only in the context of the creation and evolution of the elements. The nucleosynthesis products are interesting as signposts of our origins, as well as diagnostics of the poorly understood supernova explosion mechanisms. The direct observations of nucleosynthesis products in diverse environments, including individual new supernovae as well as supernova remnants, will yield deep new insights.

The unique and substantial astrophysical information carried by γ-ray photons with energies near one MeV has long been clear. Nuclear γ-ray line transition energies are practically unique, identifying individual isotopes. In the case of nuclear levels populated by radioactive decay, we

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also infer the ages of these isotopes to within a few half-lives. At the electron rest-mass energy (0.511 MeV) the annihilation of electron–positron pairs can be studied in numerous high-energy sources, and the onset of relativistic effects in photon production and interaction processes produces distinctive spectral shapes. Gamma-ray photons are highly penetrating, easily traversing entire galaxies and escaping from supernova ejecta on timescales of weeks. Gamma rays provide probing diagnostics of many astrophysical sources, in some cases the only accessible means of understanding the physics of those sources.

The greatest challenge for γ-ray astronomy has always been small photon fluxes and large backgrounds, so instrument sensitivities are paramount. The *Advanced Compton Telescope* (ACT), tasked to overcome this challenge, has been identified in the NASA roadmap as the next major step in γ-ray astronomy. Its main goal is to probe the nuclear fires creating the chemical elements. For example, thermonuclear supernovae (SN Ia) are used as standard candles across the Universe, yet even those near us are poorly understood. ACT will detect and measure nuclear species produced in those explosions, providing otherwise unattainable information on the dynamics of SN nuclear burning. Supernovae, novae, and stellar winds populate our Galaxy with fresh nuclei. ACT will measure the radioactive γ-ray and positron emitters among them across the entire Milky Way, mapping our galaxy in a broad range of nuclear line emissions from radioactive decays (^{22}Na, ^{26}Al, ^{44}Ti, ^{60}Fe), nuclear de-excitations (^{12}C, ^{16}O, ^{56}Fe) and e^+e^- annihilations.

2. Science objectives

ACT is driven in its instrumental performance by some of the most pressing astrophysical questions of our age, the observations of distant Type Ia supernovae and their role in the production of the most abundant heavy element, Iron. The understanding of SNe Ia explosion physics is of critical importance for cosmology, astrophysics, and nucleosynthesis, and places the most stringent sensitivity requirements on ACT (Fig. 1). Therefore, we spent substantial effort studying this requirement (Boggs et al., 2006). Most of the other science objectives will follow naturally from the ACT improvements in line and continuum sensitivity (Table 1).

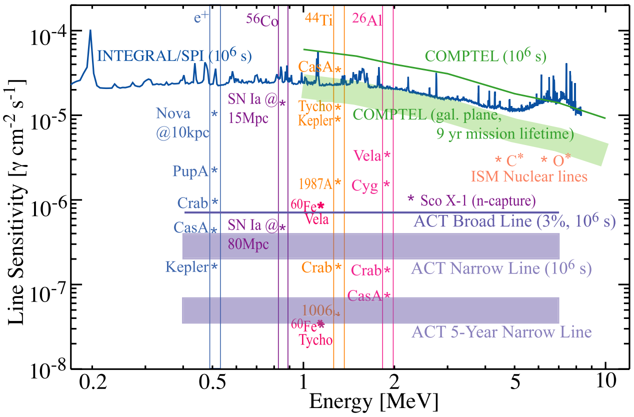

Fig. 1. The ACT target sensitivity at the start of this study, which was driven by the study of 3%-broadened 0.847-MeV ^{56}Co emission from SNe Ia. (Courtesy of M. Leising, C. Wunderer.)

Table 1
ACT baseline instrument performance

Energy range	0.2–10 MeV
Spectral resolution	0.2–1%
Field of view (FoV)	25% sky
Sky coverage	80% per orbit
Angular resolution	$\sim 1°$
Point source localization	$5'$
Detector area, depth	12,000 cm^2, 47 g cm^{-2}
Effective area	$\sim$1000 cm^2
3% broad line sensitivity	$1.2 \times 10^{-6}\ \gamma$ cm^{-2} s^{-1}
Narrow line sensitivity	$5 \times 10^{-7}\ \gamma$ cm^{-2} s^{-1}
Continuum sensitivity	$(1/E) \times 10^{-5}\ \gamma$ cm^{-2} s^{-1} MeV^{-1}
GRB fluence sensitivity	3×10^{-8} erg cm^{-2}
Data mode	Every photon to ground

Nuclear γ-ray lines from SNe Ia hold the key to solving their mysteries. ACT has three primary science goals for studying SNe Ia, and these goals are the primary drivers of ACTs instrumental performance requirements (broad-line sensitivity, spectral resolution, FoV).

ACT's SNe Ia goals are aggressive:

1. *Standard Candles.* Characterize the ^{56}Ni production distribution for SNe Ia, and correlate with the optical lightcurves to determine the relationship between empirical absolute magnitude corrections and ^{56}Ni production (Fig. 2).
   Requirements: measurement of ^{56}Ni production in >100 SNe Ia at >5σ levels.
2. *Explosion Physics.* Clarify the nuclear flame propagation and ejecta mass and kinematics for a key handful of SNe Ia, to uniquely distinguish among (or reject) current models of SNe Ia explosions.
   Requirements: high sensitivity (>15σ) lightcurves and high-resolution spectra ($\Delta E/E < 1\%$) of several SNe Ia events of each subclass over the primary 5-year survey.
3. *SN Ia Rate – Local and Cosmic.* Measure the SN Ia rates in the local universe, unbiased by extinction and solar constraints, and the cosmic SNe Ia history.
   Requirements: all-sky survey of SNe Ia, sensitive to distances beyond the Virgo cluster and measurement of the cosmic γ-ray background spectrum with sufficient energy resolution to separate the contributions from SNe Ia and AGN.

While optimized for SNe Ia observations, ACT will be a powerful observatory for many different classes of nuclear line observations. Diffuse line emissions from interstellar radionuclides, electron–positron annihilations, and nuclear excitations by accelerated particles afford us the opportunity to study stellar evolution, the ongoing production of the elements, and the most energetic processes throughout

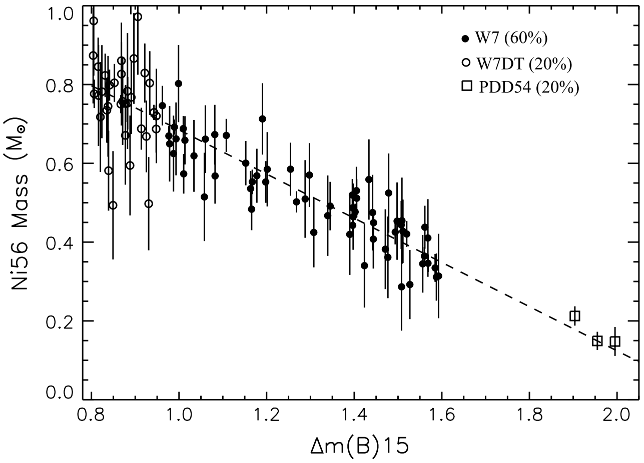

Fig. 2. This figure shows an example of how ACT studies can quantify the relationship between SNe Ia ^{56}Ni production and the optical lightcurve variations. Shown is a 5-year cumulative measurement of ^{56}Ni from all SNe Ia detected above 5σ, assuming a ratio of SN explosions of 60:20:20 between normal (W7), superluminous (W7DT), and subluminous (PDD54) SNe Ia. It is assumed for this simulation that the ^{56}Ni mass is correlated with the optical magnitude correction by the relation $M_{56} = 1.24 - 0.56 \times \Delta m_{15}(\mathrm{B})$ (dashed line). (Courtesy of P. Milne.)

the Milky Way Galaxy. The decay of ^{26}Al shows directly a million years of massive star and supernova activity (Plüschke et al., 2001). Given its wide FoV, ACT will accumulate deep exposures on persistent sources over its 5-year survey ($>2 \times 10^{7}$ s), reaching narrow-line sensitivities below 10^{-7} cm^{-2} s^{-1}, enabling a detailed study of the production of ^{44}Ti, ^{26}Al, and ^{60}Fe in various types of supernovae. With greatly improved sensitivity and angular resolution, we expect these apparently diffuse emissions to be resolved, at least in part, into hundreds of distinct regions, which can be understood in terms of individual massive-star groups visible at other wavelengths. At least 16 known massive-star remnants in our Galaxy and Local Group are expected to be detectable in at least one line assuming a five-year mission lifetime (Fig. 1).

3. Science instrument

The most promising instrument design for fulfilling these science requirements is a Compton telescope (von Ballmoos et al., 1989) utilizing recent advances in detector technologies to achieve significant improvements over the Compton Telescope (COMPTEL) on CGRO (Schönfelder et al., 1993). COMPTEL employed a design with two widely separated (1.6 m) scintillator detector arrays, with moderate 2-D position resolution ($\sim$1 cm^{2}) and energy resolution ($\Delta E/E \sim 10\%$). The large separation of the detectors enabled time-of-flight (ToF) measurement, and thus helped reduce background, but resulted in a small efficiency ($<$0.3%) and relatively small FoV (9% of the sky). COMPTEL achieved its success not with large effective areas, but with ToF measurements and other event-acceptance criteria which enabled suppression of the intense background in this energy range.

Modern 3-D position sensitive γ-ray detectors, arranged in a compact, large-volume configuration, will improve efficiency by two orders of magnitude, provide a powerful new tool for background rejection, and utilize high spectral resolution to dramatically improve sensitivity.

There are two required and two potential advances in detector technologies that will dramatically improve ACT sensitivity over COMPTEL: fine 3-D position resolution (1 mm^{3}), high spectral resolution ($<$1%), potentially tracking of the initial recoil electron for photon energies throughout the nuclear line range (0.5–2 MeV), and potentially very fast timing (sub-nanosecond) of interactions. There are a number of promising detector technologies for achieving these performance advancements. The final ACT instrument could be composed of a single detector type, or include combinations of these technologies to optimize performance.

A number of different instrument designs were considered in detail for this concept study (Boggs et al., 2006). For detailed comparison, we selected a "baseline" instrument for the study that was designed both to be a promising option scientifically, and to encompass a variety of the challenges an ACT instrument might pose. This baseline concept was chosen as a hybrid Si-Ge array, consisting of a 27-layer array of 2-mm thick silicon (low Z) detectors, situated immediately above a 4-layer array of 16-mm thick germanium (high Z) detectors. Scientifically, this hybrid design represented a promising choice because it combines the higher intrinsic angular resolution achievable by having a first scatter in the low-Z silicon (less Doppler broadening) with the better stopping power of the high-Z germanium for higher efficiency. Both of these technologies assumed the excellent spatial resolution ($<$1 mm^{3}) and excellent spectral performance ($\sim$0.2% at 1 MeV) that has been achieved in the laboratory. Neither detector array assumed any electron-tracking or fast-timing capabilities. Simulated performance capabilities for this baseline instrument are presented in Table 1.

4. Mission overview

The ACT mission consists of a single instrument composed of a large array of position-sensitive detectors, surrounded by anti-coincidence shields and mounted on a zenith-pointing spacecraft (S/C) (Fig. 3). From the mission perspective, ACT could be launched as early as 2015 from Kennedy Space Center (KSC) on a Delta IV 4240 vehicle. The Delta IV 4240 can deploy ACT into its baseline 550 km, 8° inclination circular orbit. A 5-year minimum (10-year desired) lifetime is required to meet the primary science goals of the mission. ACT is a wide FoV instrument (25% of sky), surveying the entire sky by maintaining a zenith-pointed orientation and sweeping out the sky over the course of its orbit. Pointing attitude (±1°) and aspect ($\pm 1'$) are fairly relaxed. Extensive mission details can be found in the ACT concept study (Boggs et al., 2006).

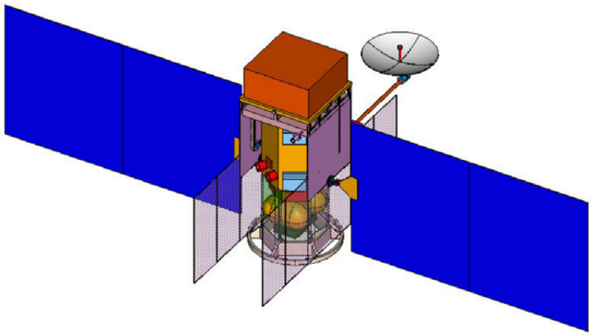

Fig. 3. ACT science instrument (orange) on its spacecraft bus, with solar panels (blue), thermal radiators (transparent grey), and high-gain TDRSS antenna deployed. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

5. Conclusion

Our primary goals of the ACT Concept Study were to (1) transform the key scientific objectives into specific instrument requirements, (2) identify the most promising technologies to meet these requirements, and (3) design a viable mission concept for this instrument (Boggs et al., 2006). To this end, we developed technology recommendations that identify the detector and readout requirements and lay out goals for their development, demonstration, and implementation. Furthermore, we developed a baseline ACT mission concept, including mission requirements. The primary findings of our mission design studies are that (1) the SNe Ia science goals are readily achievable with the ACT baseline design, and (2) all of the primary mission architecture requirements are achievable with technologies readily available for a 2015 launch (Boggs et al., 2006).

References

Boggs, S.E. et al., in press. AIAA.

Plüschke, S. et al., 2001. Exploring the Gamma-Ray Universe. ESA SP-459, 91.

Schönfelder, V. et al., 1993. ApJS 86, 657.

von Ballmoos, P. et al., 1989. A& A 221, 396.