The Advanced Compton Telescope

Steven E. Boggs, for the ACT Team

Department of Physics, University of California, Berkeley, CA 94720-7300, U.S.A.

Abstract. The Advanced Compton Telescope (ACT), NASA's next major step in gamma-ray astronomy, will probe the fires where chemical elements are formed by enabling high-resolution spectroscopy of nuclear emission from supernova explosions. During the past several years, our collaboration has been undertaking a NASA mission concept study for ACT. 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 will present the results of this study, including scientific goals, instrument design, and mission requirements.

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INTRODUCTION

Since the gravitational collapse of matter into stars and galaxies a few hundred thousand years after the Big Bang, much of the visible matter in the Universe has been through the slow but spectacular lifecycle of matter: stellar formation and evolution ending in novae or supernovae, with the ejection of heavy nuclei back into the galaxy to seed a new generation of stars. The unstable balance between gravitational and nuclear forces produces a cycle in which the death of stars leads to the birth of others, maintaining a rich, dynamic story of life, death, and rebirth on the galactic stages of our Universe.

Nuclear gamma-ray astrophysics is the study of emission from radioactive nuclei as tracers of this cycle of creation. Nuclear decays are "fingerprints" of the isotopes, and the gamma rays emitted characterize their quantities, speeds, and depths in their environments. The unstable nuclei provide a direct means of quantifying the underlying processes of nuclear burning in supernovae, novae, and hydrostatic stars. They carry unique information about the otherwise hidden, extreme conditions under which they were produced. These nuclei allow us to see to the very core of a supernova explosion, revealing critical information about the underlying nuclear ignition, structure, and dynamics of these events that affect the evolution of our Galaxy.

Because of this potential, the Advanced Compton Telescope (ACT) has been identified as the next major step in gamma-ray astronomy in NASA's roadmap. 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 (^{56}Ni, ^{56}Co), 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 gamma-ray and positron emitters among them across the entire Milky Way, mapping our galaxy in a broad range of nuclear line emissions (Fig. 1) from radioactive decays (^{22}Na, ^{26}Al, ^{44}Ti, ^{60}Fe), nuclear de-excitations (^{12}C, ^{16}O, ^{56}Fe) and e^+e^- annihilations.

As additional objectives, gamma rays from accretion of matter onto galactic compact objects and massive black holes in AGN will test accretion disk and jet models and probe relativistic plasmas. Gamma-ray polarization will be used to study the emission processes in GRBs, pulsars, AGN, and solar flares -- opening a new dimension in diagnostic phase space. The origins of the diffuse cosmic MeV background will be identified.

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Previous γ-ray missions began to address this science, but the key to real advancement is a dramatic improvement in sensitivity. The optimal approach for achieving this improvement is an imaging Compton telescope using advanced detector technology. The technology enabling ACT is the development of 3-D position-sensitive detectors with excellent energy resolution. They resolve interaction sites and energies as photons Compton scatter throughout the instrument, providing a powerful new tool for background rejection, Compton imaging, and polarization studies. The excellent position resolution of these detectors facilitates compact Compton telescopes, increasing the detection efficiency by up to two orders of magnitude over COMPTEL on CGRO. The combination of improved efficiency and improved background rejection will yield 50 times better sensitivity than any previous or current γ-ray spectrometer or imager. The large field-of-view achievable with compact designs is also a major improvement, enabling the discovery and monitoring of transient sources, and long exposures of steady-state sources. We restricted this study to instruments designed to attack the SN Ia problem, as opposed to broad MeV scientific objectives. We made this tough choice despite the demonstrated success of multi-instrument missions, e.g., CGRO.

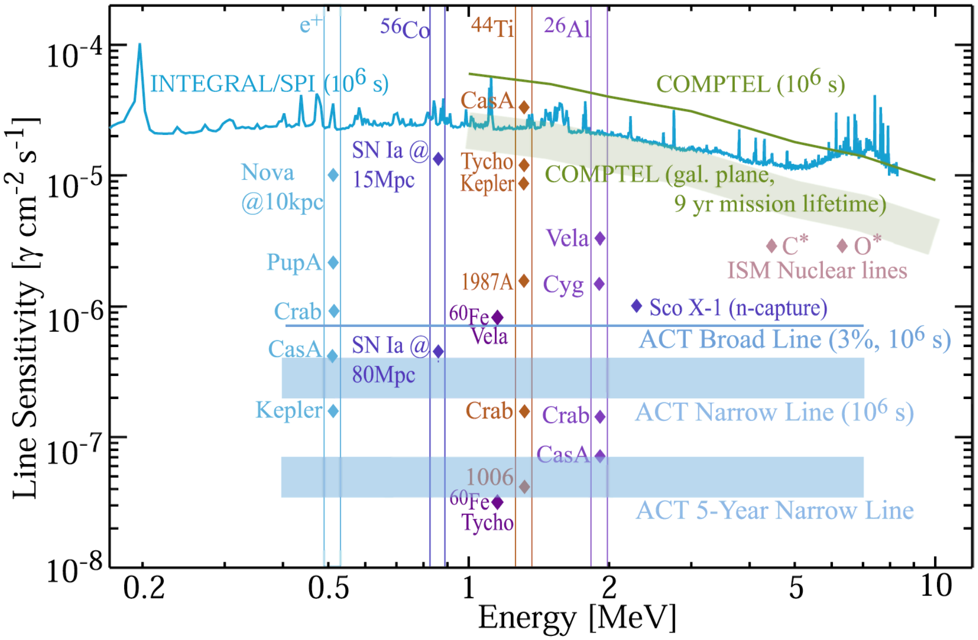

FIGURE 1. The ACT target sensitivity at the start of this study, which was driven by the study of 3%-broadened 0.847-MeV 56Co emission from SNe Ia. The ACT baseline already comes close to this goal, achieving the sensitivity required to systematically study SN Ia, while also achieving major improvements in all-sky sensitivity to narrow lines, γ-ray emission from compact objects and GRBs, and novel sensitivity to polarization.

INSTRUMENT OVERVIEW

While we investigated in detail a number of different instrument concepts for ACT during this study, there are several design parameters that are nearly universal. The optimal ACT design consists of at least 2m^2 arrays of position-sensitive spectroscopy detectors in order to achieve effective areas of ~1000 cm^2. The depth of the sensitive volume for stopping MeV gamma rays must be 35-50 g/cm^2, with a weak dependence on the detector materials. Detectors must be reliable, uniform, and radiation hard. All designs require a surrounding charged-particle anticoincidence detector (ACD), composed of thin scintillator plastic, surrounding the detector array to veto cosmic ray and trapped particle backgrounds. In addition, we have determined that in LEO, the dominant background component for all designs studied is Earth albedo gamma rays. A massive bismuth germanate (BGO) scintillator shield beneath the detector array in the baseline model helps suppress this background.

Early in the study we selected a "baseline" instrument for reference 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 was subsequently optimized for overall sensitivity, staying within the mission envelope (mass, power size) established in the one-week run through the Instrument Synthesis & Analysis Laboratory (ISAL) at Goddard Space Flight Center in September 2004. This optimized baseline concept consists of a hybrid Si-Ge array, consisting of a 27-layer "D1" array of 2-mm thick silicon (low Z) detectors, situated immediately above a 4-layer "D2" 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 (~0.2% at 1 MeV) that has been achieved in the laboratory. Neither detector array assumed any electron-tracking or fast-timing capabilities. This hybrid design seemed especially appropriate for the ISAL run because it combined the technical challenges of cooling a large array of Ge detectors to 80 K with that of powering a large number of readout channels with moderate cooling for the Si detectors (~250,000 channels, -30° C). A 4-cm thick BGO shield surrounds the instrument's bottom and sides.

The ultimate incarnation of ACT will be the result of detailed scientific and technology trades that we have only begun in this concept study. Toward this end, however, we have studied competing technologies that could either augment or supplant those chosen for the baseline design. These include thin Si, liquid Xe (LXe), CdZnTe, LaBr scintillator, and gaseous Xe (GXe) detectors. Each of these detectors possesses capabilities that could potentially improve the performance over the baseline instrument—in terms of electron tracking (thin Si, GXe), fast timing (LXe, LaBr, GXe), or room-temperature operation (CdZnTe, LaBr). However, these benefits currently come with a performance hit in other areas including efficiency (thin Si, GXe), spectral resolution (LXe, GXe, CdZnTe, LaBr), and overall power (thin Si, GXe). None of these detector enhancements improved the SNe Ia sensitivity over the ACT baseline (some degraded sensitivity considerably). With the caveat of the limited resources available for this study, and the limited time for optimizing the individual designs, it is still clear that the baseline Si-Ge geometry remains a promising design to pursue for ACT, and most of the alternate designs will have to strive to reach its performance. In addition, we studied two additional instruments composed of all Ge detectors and all thick Si detectors similar to those used in the baseline. The all-Ge instrument is the only design with comparable sensitivity to the Si-Ge baseline.

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). From the mission perspective, ACT could be launched 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. Launch later than 2015 may require a slightly higher orbit, depending on the phase of the solar cycle. ACT is a wide field-of-view 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 (±1') are fairly relaxed. In normal operational mode, the detectors must be cooled while observations are conducted. A low-inclination orbit will allow the instrument to operate with a nearly 100% duty cycle while remaining out of the South Atlantic Anomaly (SAA) with its intense radiation. All photon data will be passed through a simple filtering routine in the science instrument processor to identify candidate events. For the selected events, energy, position, and timing data, together with instrument aspect data, will be packaged and stored in the S/C 100-Gbyte solid-state data recorder for telemetry to the ground.

Much more detailed information on the science goals, instrument design and performance, and the mission design is provided in the ACT Concept Study Report [1].

ACKNOWLEDGMENTS

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REFERENCES

1. S. E. Boggs et al., "The Advanced Compton Telescope, NASA Vision Mission Concept Study Report", astro-ph/0608532.