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Semiconductor Compton Imager and Polarimeter (SCIP)

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Abstract: A Semiconductor Compton Imager and Polarimeter (SCIP) is the only instrument capable of achieving 50-100 times better sensitivities than the Compton Gamma Ray Observatory and INTEGRAL missions in the energy range of 150 keV-10MeV. These sensitivities are required for new discoveries in γ-ray line emission from radioactive nuclei as tracers of the cycle of galactic creation. SCIP will enable detailed study of Type Ia supernovae, gamma ray bursts, diffuse galactic nuclear lines, positron astrophysics, active galactic nuclei, solar physics, and a menagerie of different galactic sources. Technology development on CdTe, CdZnTe, silicon, and germanium detectors, the semiconductor types proposed for SCIP, is necessary for a New Start in 2020 and must focus on: increasing detector dimensions, reducing pixel size, improving energy resolution, and producing high performance ASICS.

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Overview

1. Scientific Accomplishments: A Semiconductor Compton Imager and Polarimeter (SCIP) will provide 50-100 times better sensitivities compared to the Compton Gamma Ray Observatory (CGRO) and INTEGRAL missions. This is a larger advance than those missions have made over the very first space-based γ-ray missions. SCIP, a version of an Advanced Compton Telescope (ACT), is a square meter class instrument that will provide high-resolution observations of γ-ray lines using semiconductor detectors (Si, Ge, and/or CdTe/CZT). SCIP will provide excellent locations (a few arc-minutes) for sources over a very large FoV (up to 3 steradians), allowing extensive monitoring of a large number of Galactic and extragalactic sources. Major accomplishments will be the capability to detect up to 100 thermonuclear (Type Ia) supernovae per year in the γ-ray lines from the decay of ^{56}Ni and ^{56}Co and to measure the distribution of the radioactivity within them. This will clarify the ignition and propagation of the nuclear flame in those still poorly understood standard candles of cosmology. In addition, SCIP will provide excellent γ-ray studies of nearby core collapse supernovae (Types II, Ib, and Ic) and their possible jets, γ-ray bursts to great distances, diffuse galactic nuclear lines from ^{26}Al and ^{60}Fe across the Galaxy, ^{44}Ti in several galactic supernova remnants, positron annihilation radiation from throughout the Galaxy, including the mysterious emission from near the galactic center, Active Galactic Nuclei (AGN), compact stars in the Galaxy (accreting neutron stars and black holes, pulsars, and classical novae), and high-significance detection of γ-rays from solar flares. Especially the uniform and frequent exposure enabled by the large FoV and scanning operation (similar to Fermi) will enable transient detection/monitoring and deep all-sky surveys.

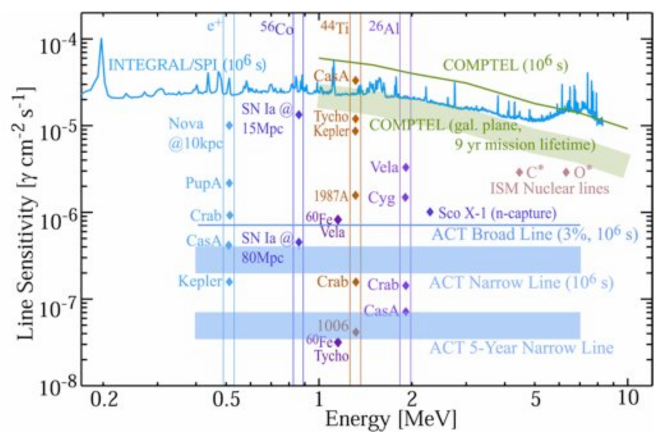

Figure 1. The SCIP target sensitivity, which was driven by the study of 3%-broadened 0.847-MeV ^{56}Co emission from SNe Ia. Simulations of a Si-Ge SCIP already come close to this goal, achieving the sensitivity required to systematically study SN Ia.

2. Instruments/Detectors: The main motivation of the original ACT study[i], on which SCIP is based, is the quest to understand the origin of the elements via observation of γ-ray lines. Taking maximum advantage of the information encoded in line profiles and shifts requires an instrument with very good (<1% required, ideally <0.5%) energy resolution. The logical approach is thus to build a SCIP from the highest energy-resolution detectors available in larger volumes – semiconductor detectors. The baseline ACT/SCIP utilized a combination of Si-Ge detectors, but also included other potential instruments including thin silicon devices, liquid xenon time projection chambers, gaseous xenon instruments, and fast plastic and lanthanum-bromide scintillator arrays. The energy resolutions of these other instrument concepts are not as good as one designed with Si, Ge and/or CdTe/CZT, so we are not including them in this proposal. The development of a m^2-class instrument using Si, Ge and/or CdTe/CZT requires significant increase in size over existing instruments, so we are proposing support for improvements in these devices that can result in a planned launch in about 15 years, and a mission that would last 5-10 years.

3. SCIP Sensitivities: The sensitivities for the proposed mission, shown in Fig. 1, will dramatically improve the number of sources observed in the 150 keV to 10 MeV energy range, and thereby significantly improve our scientific understanding of the wide variety of sources ob-thereby significantly improve our scientific understanding of the wide variety of sources observed, especially the understanding of Type 1a supernovae and distant GRBs.

Scientific Goals

Mark Leising *et al.* and Mark McConnell *et al.* submitted detailed ASTRO2010 Science White Papers that cover the science that SCIP will enable in much greater detail and clarity. The following provides a summary of key SCIP science:

1. Type Ia Supernovae: SNe Ia, the thermonuclear explosions of degenerate white dwarfs, are profoundly radioactive events. As much as one-half of the white dwarf mass is fused to ^{56}Ni ($\tau_{1/2}$ =6.1d). After a short time, the decays of this nucleus and ^{56}Co ($\tau_{1/2}$ =77d) power the entire visible display. Most of this power originates in γ-ray lines, which begin to escape after several days and are the most direct diagnostic of the dominant processes in the nuclear burning and explosion.

Fundamental questions about these explosions remain unanswered. We do not understand the physics behind the empirical calibration of their absolute magnitudes that allows them to be used as standard candles for measuring acceleration of the Universe; the nature of the progenitor systems[ii]; how the nuclear flame propagates, how it proceeds as fast as it does, if, or where, it turns into a shock[iii]; and to what extent instabilities break spherical symmetry, or whether their effects are wiped out by subsequent burning.

Thermonuclear supernovae are grand experiments in reactive hydrodynamic flows. Fundamental uncertainties in the combustion physics lead directly to differences in ^{56}Ni yields and locations[iv], which in turn are directly observable with a sensitive γ-ray telescope. Previous attempts to detect ^{56}Co emission have been unsuccessful due to the instrument sensitivities and supernova distances.

Nuclear γ-ray lines from SNe Ia hold the key to solving these puzzles. Two primary goals of these studies are:

> ***A. Standard Candles.*** *Characterize the ^{56}Ni production distribution for SNe Ia, and correlate with the optical light curves to determine the relationship between absolute magnitude corrections and ^{56}Ni production.*
>
> ***B. Explosion Physics.*** *Clarify the nuclear flame propagation by measuring total and ^{56}Ni masses and their kinematics for a handful of SNe Ia, to distinguish among current models of SNe Ia explosions.*

SCIP will allow direct correlation for over 100 SNe Ia between the optical properties and the ^{56}Ni production, which is likely to be the underlying factor in the optical light curve variations. SCIP is also sensitive to other possible variations, such as ^{56}Ni distribution in velocity (through spectroscopy), and total ejecta mass (through light curve monitoring), which can be distinguished from the total ^{56}Ni mass explanation. Such measurements will allow us to directly probe the underlying physical mechanisms driving the variations in the optical curves. Coupled with SCIP's ability to uncover the explosion mechanism and dynamics, a much better understanding of how SNe Ia evolve with redshift will be possible, including their use as standard candles to high redshift. Only a sensitive, wide-field instrument can achieve all these objectives.

2. Gamma Ray Burst (GRBs): *SCIP will provide rapid localizations (5') over a wide FoV (25% sky), broad spectral coverage (0.15-10 MeV Compton imaging, 10 keV – 10 MeV spectra), a minimal detectible fluence ~3×10^{-8} erg cm^{-2}, accurate timing (1 μs or better), and novel capabilities for measuring polarization.* Given its broad spectral coverage (50 keV – 10 MeV), excellent timing (μs), high spectral resolution, and sensitivity to polarization, SCIP is an outstanding instrument for studies of prompt emission processes in GRBs. The non-thermal spectra of bursts are commonly interpreted as synchrotron and inverse Compton radiation from electrons accelerated to ultra-relativistic energies in internal shocks. To address the open issue of whether classical synchrotron radiation or modified processes operate during the prompt GRB phase, SCIP will provide high signal-to-noise hard X-ray spectra with good time resolution to study the temporal hard-to-soft evolution and determine the spectral shape below the peak.

Polarimetric information will probe the GRB geometry and emission mechanism. Detections of high polarization (>40%) strongly argue for the synchrotron mechanism and suggest that field tangling can only arise on scales larger than the synchrotron coherence length.

3. Diffuse Galactic Nuclear Lines: *SCIP will provide a deep all-sky exposure over its 5-10 year survey, with two orders of magnitude improvement in narrow-line sensitivity and high spectral resolution (<1% with 0.5% as the goal).* Diffuse line emissions from interstellar radionuclides, electron-positron annihilation, and nuclear excitations by accelerated particles afford the opportunity to study stellar evolution, the ongoing production of the elements, and the most energetic processes throughout the Milky Way Galaxy. Given its wide FoV, SCIP will accumulate deep exposures on persistent sources over its 5-10 year survey (>2-4×10^7 s), reaching narrow-line sensitivities below 10^{-7} cm^{-2} s^{-1}, and enabling a detailed study of the production of ^{44}Ti, ^{26}Al, and ^{60}Fe in various types of supernovae, and ^{26}Al in stellar winds. The current global galactic maps will resolve into hundreds of distinct regions and individual objects.

A. ^{26}Al-Decay: The proton-rich isotope ^{26}Al ($\tau_{1/2}$=0.7 My) decays to the first excited state of ^{26}Mg at 1.809 MeV. In the CGRO COMPTEL map, we see a line flux of ~3×10^{-4} cm^{-2} s^{-1} from the central Galaxy (longitude ±30°), and smaller fluxes from a handful of other star-forming regions[v]. With SCIP's wide FoV and greatly improved sensitivity, this map will display hundreds of regions of high significance. We therefore will see ^{26}Al 1.809 MeV emission from nearby clusters, OB associations, and individual supernova remnants. We can thereby study global galactic nucleosynthesis, the massive star content and evolution of associations, the nucleosynthesis yields of individual objects, and the dynamics of supernova remnants.

B. ^{60}Fe-Decay: The neutron-rich isotope ^{60}Fe ($\tau_{1/2}$=1.5 My) is exclusively ejected from core-collapse supernovae. RHESSI and INTEGRAL have detected[vi] line emission from its daughter ^{60}Co. The total flux is an order of magnitude smaller than ^{26}Al, but SCIP will measure it in a number of distinct regions and individual sources, as well as from the central galactic plane. The total galactic production as well as individual source yields of ^{60}Fe and ^{26}Al will provide unprecedented constraints on core collapse supernova nucleosynthesis calculations. If the nuclear flame proceeds slowly in the initial burning in thermonuclear supernovae, a significant older stellar population could also be represented in ^{60}Fe emission. The spatial differences between these two radionuclides will describe the nucleosynthesis of both classes of sources.

4. Positron Astrophysics: SCIP will provide a deep all-sky exposure to positron annihilation, with two orders of magnitude improvement in narrow-line sensitivity, high spectral resolution, and nearly continuous all-sky monitoring for transient and variable sources. The bright positron annihilation line and triplet-state positronium continuum delineate the escape of positrons from extreme environments over the past ~My. The bright bulge positron emission component remains a mystery. Interstellar positrons entrained in galactic magnetic fields will provide part of the complex 511 keV map, which will also feature individual supernova remnants and stellar and compact object wind nebulae, and possibly the galactic center black hole. Given the energy resolution goal of ~0.5% at 511 keV, the conditions in the various annihilation media will be revealed through the line profile and the annihilation physics.

Despite the fact that the 511 keV line is the brightest γ−ray line in the sky, the dominant source of the Galaxy's positrons remains a puzzle. Investigations of this puzzle include the spatial distribution, the line profile, and the fraction of positron-electron annihilations that occur after the temporary formation of the positronium. Potential sources include hypernovae, SNe Ia radioactivity, pulsar winds, LMXBs[vii], and annihilation or decay of low-mass dark matter particles. For each of these potential sources, the contribution to the population of galactic positrons is determined by the yield from the production mechanism, the survival/escape of positrons from the source, the fraction of positrons retained by the Galaxy, and the population of the source in the Galaxy. SCIP will provide a significant improvement to our understanding of all of these phenomena.

5. Active Galactic Nuclei (AGN): The *CGRO, INTEGRAL and FERMI* show that nuclear activity in galaxies produces powerful and rapidly variable fluxes of γ-rays. This results from a supermassive black-hole at the center of the galaxy that generates this emission. The AGNs detected at γ-ray energies fall into two distinct classes. The first class includes radio galaxies and Seyfert AGNs with redshifts $z < 0.1$ and >50 keV luminosities between 10^{40} -10^{45} ergs s^{-1}. The OSSE and COMPTEL instruments on CGRO provided strong evidence for a spectral softening above 100 keV for these AGNs. Blazars comprise the second class of γ-ray emitting AGNs, and include BL Lac objects, core-dominated flat-spectrum radio quasars, and highly polarized and variable quasars. Blazars detected at γ-ray energies have a wide range of redshifts peaking near $z \sim 1$ and reaching to $z \sim 5$.

A precise characterization of the high-energy continuum radiation in Seyfert galaxies is important for testing the unification scenario for AGNs. Seyfert 1 and 2 galaxies differ primarily by the orientation of the observer with respect to the axis of the accretion disk. OSSE and INTEGRAL observations suggest that Seyfert 2 AGNs have lower high-energy cutoffs than Seyfert 1 AGNs. More sensitive observations with SCIP can test this idea by comparing the measured spectra of Seyfert 2 galaxies with calculations of Compton-scattered Seyfert 1 radiation spectra. Knowledge of the high-energy radiation of AGNs will help establish the contribution of blazar jet radiation and the hard tails of Seyfert galaxies to the cosmic diffuse γ-ray background. Fermi will only cover this down to 100 MeV and the low energy contribution can be constrained by SCIP.

6. Black Holes, Neutron Stars, Pulsars, Classical Novae: Results from CGRO and INTERGAL show that galactic BH sources are bright at MeV γ-ray energies, and display a wide range of spectral states and undergo transitions from the bright, soft X-ray states to dimmer, hard γ-ray states. The improved sensitivity of SCIP will map black hole spectral states to test disk models for black holes accreting near the Eddington limit, and at low Eddington ratios where advection effects may play an important role. The SCIP large FoV will ensure the necessary coverage to observe many of these sources.

Because black-hole X-ray binaries reach flux levels of 10^{-2} ph cm^{-2} s^{-1} MeV^{-1} at 511 keV, SCIP will be able to search for broadened annihilation line features that are expected to surround accreting black holes. SCIP will also search for narrow and broad annihilation lines in the "microblazars" such as 1915+105 and 1655-40. Also, observation of polarized soft γ-rays from binaries can probe the orientation of the accretion disk.

Neutron stars and accreting and radio pulsars are known to be strong continuum sources above 100 keV. Combining SCIP data with that collected by Fermi will help unravel the particle acceleration and photon production mechanisms in pulsar magnetospheres. SCIP will be particularly suited to studying high-field pulsars such as PSR 1509-58, and perhaps magnetars with their newly-discovered hard components. Also, neutrons produced by nuclear reactions in the accretion disks can be ejected in all directions and can be captured in the atmosphere of the secondary star producing 2.2 MeV line emission. Fluxes for the closest XRB's will be detected by SCIP if accretion rates are large enough.

Classical Novae are explosions occurring on the surface of accreting white dwarfs in close binary systems as a consequence of explosive H-burning. Gamma-rays are expected from positron-electron annihilation (^{13}N and ^{18}F, as well as by ^{22}Na) and nuclear lines from ^{7}Be and ^{22}Na. ^{13}N and ^{18}F are produced in all nova types, whereas ^{7}Be (^{22}Na) is mainly from CO and ONe white dwarfs. In addition, γ-ray lines at 478 keV and 1275 keV, are expected to last a couple of months and years, respectively. SCIP would enable detection for the 1275 keV line to 4-5 kpc, and one nova per year at this distance is guaranteed with high confidence. *The large FoV of SCIP is crucial*, since the positron annihilation γ-ray emission happens before the nova is discovered optically.

7. Solar Physics: Gamma-ray lines in flares reveal the energy spectrum, composition, and angular distribution of the accelerated particles and the ambient abundance where these particles interact. There are three kinds of line emission in the SCIP energy range: nuclear de-excitation, neutron capture (2.2 MeV), and positron annihilation (0.511 MeV). Since each excited nuclear state has a different threshold energy for the ion stimulating it, relative line strengths constrain the accelerated-particle energy spectrum. The neutron-capture and positron-annihilation lines represent the effects of higher-energy ions. The shape of the annihilation line and flux in the associated lower-energy continuum constrains the density, temperature, and ionization state of the medium where the positrons annihilate.

Because de-excitation typically occurs on 10^{-12} sec timescales the lines are Doppler-broadened and red-shifted due to nuclear recoil, providing information on the angular distribution of interacting ions. *The broadening of lines is ~1%; thus energy resolution at this level is necessary for SCIP.* The relative strengths of these lines also provide information on solar abundances; e.g. the abundance of Ne can be directly measured only in this way. Spectroscopy of broader lines from heavy-ion interactions with H and He yields the accelerated ion composition, which can be compared with Solar Energetic Particles. SCIP will have ten times the effective area of previous solar γ-ray experiments and thus will measure ambient abundances and accelerated ion spectra and compositions with unparalleled precision.

8. Polarization: A compact design will make SCIP a sensitive γ-ray polarimeter. Individual nuclear reactions are polarized, but the total emission from a homogenous and isotropic source is unpolarized due to symmetry. Anisotropy is expected for many of the astrophysical sources described above and therefore, measuring the polarization of the emitted radiation will tell us the preferred direction of emission. Determining the preferred direction yields information about the underlying source geometries and emission mechanisms for sources such as: radio pulsars, accreting x-ray pulsars, galactic black hole binaries, gamma-ray bursts, and solar flares. INTEGRAL has recently measured the polarization of the CRAB over the same energy range as SCIP, 0.1-1 MeV, showing that the high-energy electrons responsible for the polarized radiation are produced in a organized structure near the pulsar[viii].

Table 1. SCIP science derived instrument requirements and goals at 10^6 seconds.

Energy range	0.15-10 MeV
Spectral resolution	0.2-1%
Field of view (FoV)	25% sky
Angular resolution	~1°
Effective area	~1000 cm^2
3% broad line sensitivity	1.2×10^{-6} γ cm^{-2} s^{-1}
Narrow line sensitivity	5×10^{-7} γ cm^{-2} s^{-1}
Continuum sensitivity	$(1/E)\times10^{-5}$ cm^{-2} s^{-1} MeV^{-1}

SCIP Instrument Requirements

Compton scattering is the dominant photon interaction mechanism in matter in the few hundred keV to several MeV energy band.

Consequently, an instrument capitalizing on the multi-site nature of the photon interaction process to obtain maximum information about each incident photon is the logical choice for a sensitive detector covering this nuclear-line energy band so rich in unique information about our universe. Table 1 summarizes the science requirements derived from the above discussion.

Compton Telescopes

A Compton telescope operates by Compton scattering an incident γ-ray one or more times before fully absorbing the final γ-ray due to photo-electric interactions. The detectors compromising the instrument record the location and energy deposited at each interaction. The incident γ-ray energy is determined by summing the energy depositions in the instrument. In the case of partial energy absorption, it is possible to reconstruct the event given three or more interactions in the instrument. The direction of the incident γ-ray can be constrained to a cone centered on the vector connecting the first two interactions (r_1, r_2) with an opening angle θ

$$\cos\theta = 1 + \frac{m_e c^2}{E_\gamma} - \frac{m_e c^2}{E_\gamma - E_1}$$

given E_γ, the incident γ-ray energy, and E_1, the energy deposited by the γ-ray at the first interaction site (see Fig 2). If one can track the direction of the recoil electron in the first interaction one can reduce the direction of the incident γ-ray to an arc of the cone.

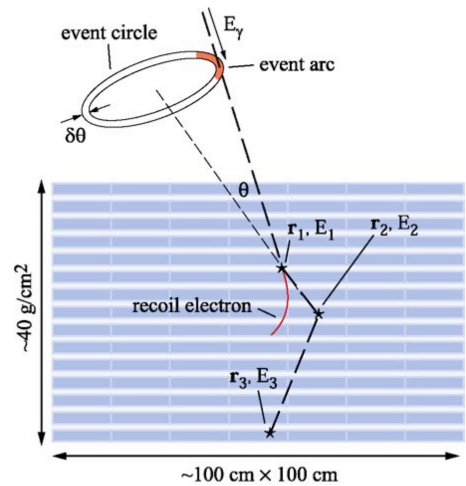

Figure 2. By measuring the position and energy of each photon interaction, the initial photon direction can be determined through the Compton scatter formula to within an annulus (event circle) on the sky. Measuring the recoil electron direction further constrains the event to an arc.

Two uncertainties due to the detectors contribute to the effective width of the event circle: the uncertainty in θ due to the detector's energy resolution, and the uncertainty in the direction between the first two interaction sites due to the detector's position resolution. Both of these uncertainties contribute to the uncertainty (effective width) of the event circle δθ. There is also a fundamental limit on the width of the event circle set by Doppler broadening due to Compton scattering on bound electrons, which is higher for high-Z materials.

A compact Compton telescope is also a highly sensitive polarimeter due to the fact that linearly polarized γ-rays have a higher probability of Compton scattering perpendicular than parallel to their polarization vector. This scattering property can be used to measure the intrinsic polarization of radiation from astrophysical sources by measuring a modulation in the distribution of azimuthal scatter angles in the instrument. Compact designs maximize the efficiency for photons scattered at θ~90° – which are the most highly modulated, resulting in high sensitivity to polarized emission.

The properties of a Compton instrument make it clear that an instrument design with the required sensitivity as shown in Table 1 must have:

1) a material likely to Compton scatter incident γ-rays in the energy range of interest (low-Z),
2) a material likely to absorb the remaining γ-ray energy (high-Z),
3) very good energy resolution throughout the instrument,
4) fine position resolution throughout the instrument,
5) low-power electronics that maintain the intrinsic energy and position resolution of the materi-

als in the instrument while staying within the power budget of a satellite,
6) compact, low-mass, and low-Z passive material within the instrument's detection volume (structural support, col-located electronics, etc.) that could scatter the interacting γ-ray.

Planar germanium, silicon detectors[ix], cadmium zinc telluride (CZT)[x] and cadmium telluride (CdTe)[xi] have demonstrated energy resolution well below 1 keV FWHM at 60 keV. The position resolution in all of the semiconductor detectors has been demonstrated at pitches smaller than 1 mm[ix,x,xi]. And silicon provides an excellent low-Z Compton scatterer while germanium with its intermediate-Z works well as a scatterer and absorber, and CZT and CdTe both provide excellent high-Z energy absorbing materials. Semiconductor detectors are currently the only materials that can satisfy requirements 1-4 at the same time.

Technology Development

Semiconductor detectors have come a long way, but before they are ready for the m^2-class SCIP necessary for γ-ray science, additional development is needed as detailed below for each technology.

Development is also needed to fulfill requirements 5 and 6 that affect all of the detector technologies. The power budget for the satellite is driven by the readout electronics and the operational temperature of the detectors. Highly integrated readout ASICs exist for CZT, germanium, and silicon[xii], but their power requirements will need to be further reduced (~1 mW/ch) while maintaining their resolution, large dynamic range, and timing needs to meet the science goals for SCIP. The other major impediment to the science goals facing all detector technologies is passive material. This refers to dead material within the detectors themselves, as well as to the structural supports to hold the detectors and the readout electronics. The instrument is designed to minimize the amount of material inside the active volume, but development work is needed to produce innovative mechanical designs.

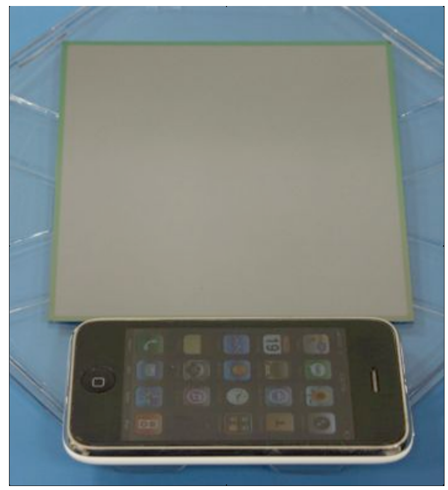

Figure 3. A detector from a 200 mm diameter wafer that is 0.7 mm thick with an active area of 200 cm^2.

1. Silicon Detectors: Silicon is the best semiconductor detector material for Compton scattering and nearly all designs use a silicon scatterer with a germanium or CdTe/CZT calorimeter. SCIP could utilize thin silicon detectors (0.2-0.25 mm thick) to allow electron tracking from layer to layer which helps to reduce the Compton cone to an arc. However, this increases the number of detector readout channels by a factor of 4-5, which increases the amount of passive material and power consumption by the same factor. Another path would utilize electron tracking inside of a silicon detector with high spatial and energy resolution which has recently been demonstrated[ix] using a specialized detector (3x1 cm^2 and 0.5 mm thick, 120 μm pixels) and high-speed (also high-power) readout electronics.

Using the current state of the art in thick silicon detectors, 2-mm thick double-sided strip detectors with 100 cm^2 active area, nearly 4000 are required for the scattering section of SCIP. In order to enable SCIP, work is needed in three areas:

A. Reduce the room temperature leakage current: The current 2-mm thick detectors are commercially available, use intrinsic high-resistivity silicon, are fabricated using standard CMOS processing, and have leakage currents <=10 nA/cm^2 at room temperature which translates to the necessary resolution at temperatures >= 0^o C. Reducing the leakage current by an order of magnitude would allow true room temperature operation with increased energy resolution.

B. Increase the detector thickness: Thicker detectors help to reduce the detector count, amount of passive material, number of electronics channels, and power requirements. Simulations show that a thickness of 0.5-1 cm is ideal at 1 MeV. The thickness of the detector is limited by the bias voltage needed to deplete it and by the machinery to handle the wafers (the commercial line is limited to 3 mm). However, NRL has recently shown that a wafer bonding technique may enable thicker detectors. Another technique is being pursued at NRL using deep trenches in the silicon to deplete the detector from trench to trench rather than from face to face. This makes the bias voltage needed to deplete the detector a function of trench spacing rather than detector thickness and one can make thicker detectors from the same quality material.

C. Increase the detector area: Larger detectors have the same benefits as thicker detectors, but the limitations are based on the availability of high-resistivity intrinsic silicon. Currently, the largest boule used commericially is 150 mm in diameter. NRL is currently testing a detector from a 200 mm diameter wafer (see Fig. 3) that is 0.7 mm thick with an active area of 200 cm^2.

2. Germanium Detectors: Compared to other semiconductor detectors, germanium has the advantage of combining a high stopping power with fairly fast timing, fine 3D detector voxelization, as well as high material uniformity, and unsurpassed energy resolution. Large cross-strip germanium detectors with 2mm pitch and 1 mm^3 voxel size (Fig. 4) have been successfully flown on the Nuclear Compton Telescope (NCT) balloon prototype, and the Ge detectors considered during the 2005 ACT study are nearly identical in geometry and readout to today's NCT detectors. This makes large-volume cross-strip Ge detectors a comparatively mature option for SCIP. An optimized, Ge-based SCIP requires technology development in these areas:

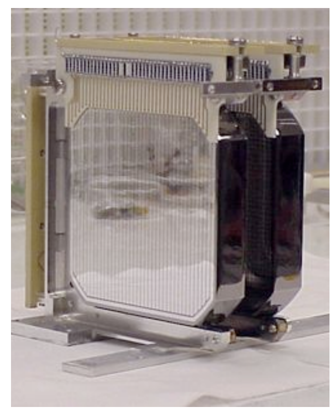

Figure 4. Two NCT detectors (8x8x1.5 cm each), wire-bonded in their cryostat mounting.

A. Smaller Voxel Size: The Ge detectors considered during the 2005 ACT study are nearly identical in geometry and readout to the NCT balloon detectors. Detailed studies of Compton event reconstruction in NCT's detectors have shown that event reconstruction (angular resolution, and consequently background rejection and ultimately sensitivity) could be significantly improved by smaller detector voxels. This can be achieved either by reducing strip pitch by a factor of 2-4, a development currently underway in the context of the solar GRIPS balloon (at the cost of more readout channels for the same detector volume), or alternatively – without increased number of channels – through inter-strip interpolation. Detailed laboratory investigations of the achievable benefits of inter-strip interpolation are needed for reliable predictions of the potential sensitivity increase beyond what's discussed in the 2005 ACT report.

B. Detector Geometry: Further development is also needed to minimize passive and veto-only material within the Ge individual detectors themselves: electrode and guard ring geometries need to be optimized to minimize guard ring widths (already instrumented for vetoing in NCT). Detectors could be made somewhat larger by cutting the germanium boule lengthwise. Furthermore, detailed radiation damage testing and verification of ruggedness for these detectors is needed.

C. ASIC: To be feasible on a space mission, a SCIP-size semiconductor array requires low-power ASIC readout (on the order of 1mW/ch). Combining the required low noise, large dynamic range, and fast (<10 ns) triggering, while not exceeding the power envelope, necessitates additional development beyond currently available ASICs. A suitable chip should be developed and tested with Ge-strip detectors.

D. Cooling: While cryocooled Ge detectors (their operational temperature is ~100 K) have successfully flown in space (RHESSI, INTEGRAL/SPI), the cooling of a SCIP Ge array with thousands of readout channels needs ~ 20x larger heat lift than RHESSI. In 2004, The ISAL study of the SCIP instrument recommended using a Turbo Brayton mechanical cooler scaled up from HST NICMOS, possibly combined with cooling loops. Enabling technology development and a detailed technical study of the SCIP-scale cryogenic system, including design, optimization, and redundancy, are needed.

3. CdTe-CZT Detectors: CdTe and CdZnTe (CZT) are the most developed high-Z room temperature semiconducting detectors available. They are very well suited as the secondary detector in a Compton telescope because of their position resolution, high stopping power and good energy resolution at room temperature. Room temperature operation might be the only feasible mode of operation because of the high power density required for the many channels of spectroscopy electronics.

Remarkable progress in high-quality single-crystal production of CdTe by the Traveling Heater Method (THM) and CdZnTe by the High Pressure Bridgman (HPB) technique was made in the 1980s and it dramatically changed the situation of high-resolution room-temperature detectors. In addition, various electrode technologies have been developed to overcome poor carrier transport in the device[xi].

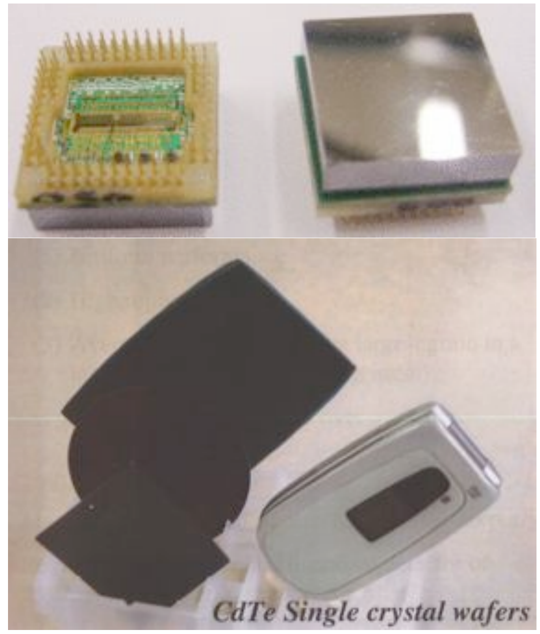

Figure 5. Top: CdZnTe detector developed for the EXIST program. Bottom: CdTe single crystal wafers manufactured from 4-inch boules by Acrorad of Japan.

The BAT instrument on SWIFT was based on this technology, as is the proposed EXIST mission (see Fig. 5). However, the energy range of a proposed SCIP mission is more than an order of magnitude higher than SWIFT. This implies an effective thickness increase of more than an order of magnitude, to ~30g/cm^2.

To achieve the optimal area and thickness for SCIP, hundreds of thousands of SWIFT-sized CZT crystals would be required, making the endeavor impractical. Even using the latest crystal size available (4 cm^2), more than ten thousand crystals would be necessary. Fortunately, there is a major push toward larger crystals from the homeland security community. Sufficient funding should be made available for the space community to keep up with the latest developments in CZT crystal growth and detector development and apply them to astrophysics missions.

Interestingly, CdTe crystals can be grown into large single crystals. Highly-uniform single crystals with a diameter of 10 cm are routinely grown by Acrorad of Japan. ISAS/JAXA has succeeded in making high resolution CdTe diode detectors up to 1 mm thick. The Si/CdTe Compton Camera and Hard X-ray Imagers onboard ASTRO-H mission are based on this thin and uniform CdTe diode technology[xiii]. Using deep trenches to collect the charge from within the semiconductor, as discussed above for silicon, could allow the implementation of large area (> 50 cm^2), thick (5 mm) CdTe detectors. A primary focus of the SCIP new technology plan effort should therefore be the development of thick position sensitive CdTe detectors.

In addition to the detectors, low power spectroscopy electronics are required to achieve the SCIP goals. The ASICs required for CZT or CdTe detector readout, while clearly demanding custom designs to match capacitance, charge collection time and signals amplitude, generally follow along similar lines to the silicon and germanium requirements.

Table 2. SCIP technology areas with their level of effort and time scale.

Technology	Level of Effort (FTE/yr)	Time (years)
ASIC/Readout	2	2-3
Mechanical	2-3	2-3
Cooling (near room temp)	2	2-3
Cooling (cyrogenic)	2	5-6
Silicon Development	1-2	6-7
Germanium Development	1-2	5-6
CdTe/CZT Development	1-2	6-7

4. Milestones: Table 2 summarizes the major areas that need development to enable the science goals. All detector technologies need mechanical and structural design, and cooling whether the detector technology allows near room temperature or cryogenic operation. *To enable SCIP's γ-ray line science, semiconductor detectors need development work in order to: increase detector dimensions, reduce pixel size, improve energy resolution, and produce higher performance ASICS with lower power requirements.* In order to propose a New Start in 2020, these milestones must be met: demonstrate a working low-power ASIC by 2014, provide lab/balloon ready instruments by 2015, decide on room temperature or cryogenic operation by 2016, choose semiconductor materials by 2016, specify detector dimensions by 2017, select a final mechanical design by 2018, and create a final cooling design by 2019.

Conclusions

The large FOV, 50-100 times improved sensitivity, and excellent source locations provided by the Semiconductor Compton Imager and Polarimeter will enable a very significant improvement in the detection and understanding of the variety of γ-ray objects in the 150 keV- 10 MeV energy range. The detection of a large number of Type 1a SN events, through the ^{56}Ni and ^{56}Co lines, (about 100/yr) will provide a unique and powerful tool to better understand these explosions. The many other scientific objectives described above, will also provide greatly improved understanding of the low-energy γ-ray spectra emitted by sources throughout the universe.

This white paper supports the extensive development of high-resolution semiconductor detectors and associated technology to enable a large-scale Compton imager, that will provide 2 orders of magnitude improvement in sensitivity, excellent energy resolution, and extremely large field-of-view with excellent position resolutions to enable leaps of progress in our understanding of the processes at work in the creation of the elements in the vicinity of black holes, and in our sun – as well as enable what often leads to scientific 'revolutions' : unexpected discoveries.

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