Lunar Occultation Observer (LOCO)

A Nuclear Astrophysics All-Sky Survey Mission Concept using the Moon as a Platform for Science

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Summary

The long-term goal of our program is the development of a next-generation mission capable of surveying the Cosmos in the nuclear regime (~0.02-10 MeV). The *Lunar Occultation Observer* (LOCO) [1-3] is a new γ-ray astrophysics mission concept having unprecedented flux sensitivity, high spectral resolution, excellent spatial resolution, and very uniform sky coverage. It meets or exceeds the capabilities required of the next-generation nuclear astrophysics mission, and is therefore capable of addressing multiple high-priority science goals.

LOCO will be a pioneering mission in high-energy astrophysics: the first to utilize the moon as a scientific platform, and the first to *successfully* employ occultation imaging as the *principle* detection method. This is a powerful, yet relatively simple, approach to imaging in regimes where traditional imaging approaches are inappropriate, complex, or cost prohibitive. Specifically, LOCO will utilize the *Lunar Occultation Technique* (LOT) - the temporal modulation of source fluxes as the are repeatedly occulted by the Moon - to detect and image both point- and extended-sources. Astrophysics observations from lunar orbit, based on the LOT, maximize performance relative to other Earth-orbit endeavors.

Occultation imaging eliminates the need for complex, position sensitive detectors, in contrast to the coded-aperture [4] or Compton [5] telescopes that traditionally operate in the hard X-ray or nuclear γ-ray regime. Instead, LOCO will incorporate a large-area scintillator-based spectrometer array to achieve the required flux sensitivity and spectral resolution. The relative simplicity of this implementation extends previous spaceflight heritage, minimizes technology development and risk, and is cost effective.

In previous work, we have demonstrated occultation imaging performance for both point- and extended sources [6,7}, developed new analysis techniques that address previous shortcomings of the technique (e.g. position resolution, source confusion, etc.), and evaluated top-level mission performance and design. A configuration, placed into lunar orbit, that meets all performance requirements is appropriate for a MIDEX-class mission [1-3].

Open issues relate primarily to *implementation* rather than *development*, and are the focus of our current efforts. Ongoing development tasks include refinements to analysis techniques, detector prototyping and design, as well as spacecraft and mission architecture planning. These efforts will enable improved estimates of science return, mitigate mission risk, and lead to more robust mission lifecycle cost estimates.

Science Motivation

A nuclear astrophysics mission spanning the energy regime from hard X-ray to γ-ray (~0.02-10 MeV) energies will probe astrophysical processes and objects in the transition regime between the thermal and non-thermal Universe, as well as nuclear processes. With excellent spectroscopic resolution and flux sensitivity, a nuclear astrophysics all-sky survey will enable a variety of investigations including, but not limited to, the following [4,5]:

- **Star Formation Rates** Cosmic nucleosynthesis takes place in stars whose lives end in supernovae or novae. Mapping the Galactic distributions (e.g. Figure 1) of the radioactive signatures from these events - including nuclear lines (e.g. ^{22}Na, ^{44}Ti, ^{60}Fe, ^{26}Al), nuclear de-excitations (^{12}C, ^{16}O, ^{56}Fe), and e^+e^- annihilations - will enable detailed investigations of galactic event rates, models of cosmic and galactic evolution, probes of extreme environments, and the underlying dynamic processes shaping the Galaxy.

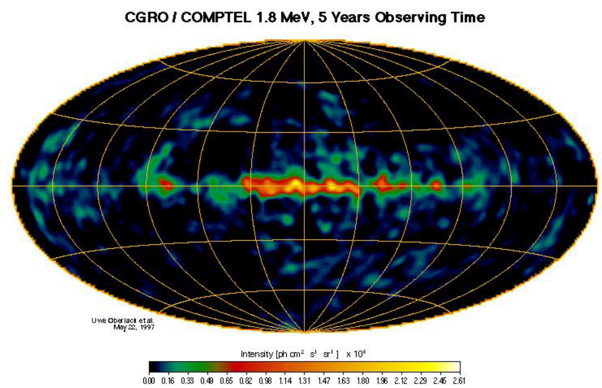

Figure 1. Galactic ^{26}Al emission (1.8 MeV) obtained with the COMPTEL instrument aboard the *Compton Gamma-Ray Observatory* [3].

- **Novae & Supernovae** While Galactic nucleosynthesis can be studied by mapping long-lived isotopic signatures distributed as diffuse emission, short lived isotopes generated and decaying during the early phases of these events can be used to probe their dynamics and structure. Of paramount importance is the understanding of Type Ia supernovae. Issues related to their progenitors, nuclear propagation, shocks and other instabilities could have significant relevance in astrophysical and cosmological contexts.

- **Black Hole Census & Compact Objects** A large fraction of black holes (BHs) are obscured by gas and dust. These BHs span a wide range of masses, from stellar mass objects in our local neighborhood, to supermassive BHs that exist in the nuclei of other galaxies. The emission of these obscured BHs peaks in the hard X-ray regime (~few hundred keV). A survey will provide information relevant to cosmological structure formation as well as the evolution of galaxies and stellar objects. Accretion onto compact object other than BHs (e.g. neutron stars, etc) can also be used to probe extreme processes and environments.

- **Dark Matter-Annihilation Radiation** The origin of the observed Galactic 511 keV emission is unclear. Competing models include supernovae, unresolved point sources, or dark matter signatures. Improved spectral and spatial resolutions are required for further analysis.

- **Multiwavelength Correlation Studies** The nature of processes powering Active Galactic Nuclei (AGN) requires near-simultaneous observations that span X-rays through TeV gamma-rays. These multiwavelength observations can give insight into the processes responsible for emission from the central engine (BH), as well as shed light on the spectra of the cosmic diffuse infrared and MeV radiations.

- **Lunar Science** As successfully demonstrated by NASA's Lunar Prospector mission, gamma-rays from planetary objects can be used to study the composition of planetary surfaces. Most orbital geochemistry missions have concentrated on the regime >500 keV with modest sensitivity. New studies can be facilitated by measuring characteristic gamma-ray line and continuum emission in the 10-250 keV range. In addition, of critical importance is the potential for detection of a 2.2 MeV line indicative of neutron capture on Hydrogen at the lunar poles, a key goal of ongoing lunar exploration efforts.

These top-level science goals have consistently ranked high in NASA and National Research Council studies (e.g. [8-10]), and there is a strong consensus within the astrophysics community that these are the appropriate objectives for a space-based astrophysics mission. To address these goals an astrophysical observatory must employ science instrumentation having: 1) ***large sensitive detector area*** to reach the required flux sensitivities, 2) ***wide field-of-view and uniform exposure*** to effectively monitor and truly survey the sky, 3) ***excellent spatial resolution*** to minimize source confusion and characterize extended source morphologies, and 4) ***good spectral resolution*** to identify both broadband and nuclear line spectra.

Lunar Occultation Observer (LOCO)

The *Lunar Occultation Observer* (LOCO) mission concept is a viable, highly cost-effective approach for a next-generation nuclear astrophysics investigation capable of meeting these requirements. Fundamental benefits derive from both the imaging approach (occultation) as well as its orbit (lunar).

The concept is based on proven fundamentals [11,12], eliminates the need for a complex position-sensitive science instrument, requires no long-term technology demonstration program, and removes the need for complex triggering, background rejection, or event recognition schemes. These features are in contrast to other nuclear astrophysics approaches [4,5,13]. ***These benefits will translate into robustness, risk mitigation, and cost effectiveness. The requirement for balloon-based proof-of-principle efforts is eliminated.***

Occultation imaging requires astrophysical sources to be repeatedly eclipsed by a natural or artificial object, with the temporal modulation effectively encoded on the acquired data. The fundamental data element is a count rate time-series encoded with occultation features. Each time-series datum corresponds to a known spacecraft position.

Given the ephemerides of the occulting object and detector, images are generated by projecting the limb(s) of the occulting body onto the celestial sphere (Figure 2). Sources are subsequently identified using advanced image analysis and statistical techniques [3,4], and can be subsequently analyzed to obtain parameters such as source intensity, variability, and spectrum. A detailed description of the geometry of occultation imaging can be found elsewhere (e.g. [11,12]).

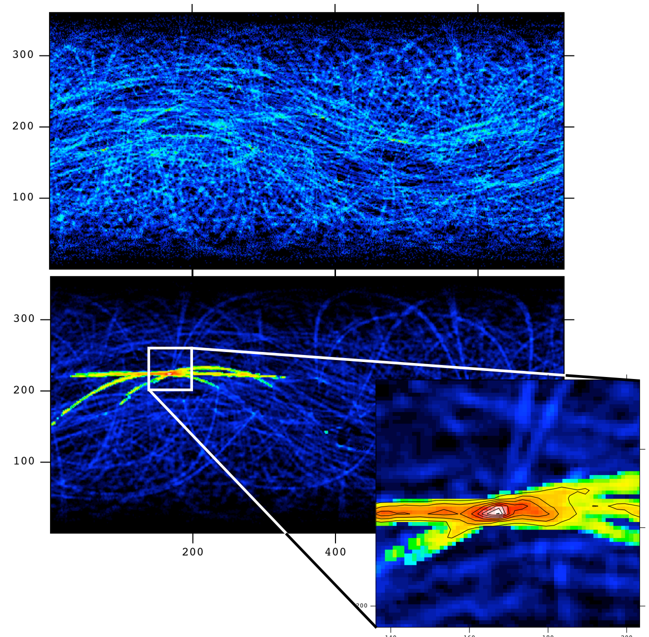

Figure 2. Occultation image generated for baseline LOCO configuration. Shown are the lunar limb projections (top), a likelihood weighted image, and the image of a hypothetical astrophysical source at the position of the Crab Nebula (inset).

The Case for the Moon

The Moon is a unique location for experimental astrophysics and it's beneficial characteristics can be brought to bear on the challenges of high-energy astrophysics. ***The benefits of this concept derive from the innovative imaging technique and the lack of a lunar atmosphere & magnetosphere***.

The Lunar Occultation Technique (LOT) is conceptually similar to the EOT but will lead to increased performance capabilities due to the following factors:

- **Dense Regolith** is an optimal occultation medium leading to sharp (fast) occultation features, translating directly into excellent spatial resolution.

- **Lack of Lunar Atmosphere** eliminates energy dependent attenuation of incident γ-rays prior to occultation (unlike Earth), translating into improved spatial and spectral resolution relative to the EOT.

- **Lack of Lunar Magnetosphere** eliminates the systematics imposed by activation & dynamic backgrounds experienced by Earth-orbiting spacecraft.

Backgrounds at the Moon consist of well characterized and/or easily monitored components such as primary cosmic rays, diffuse γ-ray emission [14,15], as well as the lunar albedo [16,17]. Except for periods of high solar activity, background systematics vary on time scales of days to months, and are easily monitored and accounted for using techniques similar to those pioneered by the *Lunar Prospector* team [17].

Baseline Mission Overview

Since intrinsic imaging capability is not required, the heart of LOCO is a large-area spectrometer comprised of ***an array of modest spectrometer modules***. Each spectrometer module will incorporate an inorganic scintillator crystal, associated readout technology, and front-end electronics. Baseline configurations/parameters derived from a mission feasibility study include:

- **Spectrometer Area:** 4-5 m^2 total area, necessary to achieve required flux sensitivity.

- **Spectrometer Geometry:** A cylindrical geometry maximizes sensitive area in the direction of the lunar limb (astrophysical sources), while simultaneously minimizing area to the nadir (lunar albedo background). Baseline geometry is cylinder, with instrumented outer surface.

- **Spectrometer & S/C Mass:** Instrument mass ultimately depends on the choice of scintillator material, opto-electronic readout, and associated sub-systems. An instrument mass of 250 kg (750 kg) is estimated for the baseline spectrometer geometry of 1 cm (3 cm) thickness.

- **Calibration:** The spectrometer will use the 6.13 MeV γ-rays from lunar albedo ^{16}O de-excitation (and other prominent lunar albedo lines); this line also serves as a proxy for monitoring cosmic-ray variations. This approach was proven with the *Lunar Prospector* Gamma-Ray Spectrometer [17].

- **Orbit:** lunar near-polar, circular assumed (other options under study). With reasonable orbital precession rates, LOCO will survey >90% of the sky per orbit.

- **Telemetry Requirements:** Data transfer rates to Earth depend on the acquisition cadence and spectral bandwidth. These are design parameters under study, but conservative estimates suggest that telemetry rates will be consistent with those to be achieved with NASA's *Lunar Reconnaissance Orbiter* (LRO).

- **Pointing Requirements:** Because the LOCO spectrometer does not have an intrinsic imaging capability there is no formal pointing requirement. The spectrometer will maintain an orientation ~normal to the lunar surface. Pointing *knowledge* with degree level accuracy is required and proven achievable.

The LOCO approach to nuclear astrophysics imaging & spectroscopy simplifies the mission implementation strategy and minimizes cost and risks relative to other methodologies.

Expected Performance

Preliminary performance measures can be estimated using the baseline configuration described above. Additional parameters include the assumption of a Lanthanum Bromide (LaBr3:Ce) based spectrometer with a total instrumented area of 4 m^2 and 1 cm thick. *This is a baseline only and does not represent a final configuration*. Figure 3 shows the flux sensitivity for this baseline configuration in 10^6 seconds[1], in comparison to other missions. It is important to note that LOCO achieves this sensitivity over the entire sky (highly uniform coverage) during the observation period, in contrast to the other missions. Initial estimates suggest that LOCO is approximately as sensitive, yet more cost effective than the ACT concept.

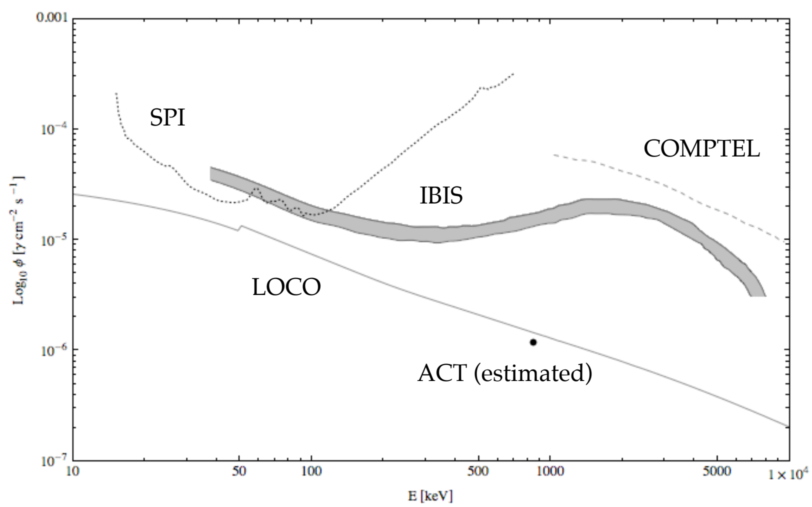

Figure 3. Flux sensitivity for baseline LOCO configuration corresponding to 10^6 seconds of elapsed time.

LOCO is also synergistic with NASA's *Vision for Space Exploration*, and is an excellent example of a mission drawn to the Moon for its scientific advantages as a research outpost. As such, ***the***

[1] This is elapsed time, not on-axis or on-source time.

National Research Council's recent report Scientific Context for the Exploration of the Moon [20] noted the LOCO concept's creativity and well-motivated use of the lunar environment for high-energy astrophysics - the only high-energy astrophysics mission concept to be so identified.

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