Xenon Compton Telescopes at Columbia: the post LXeGRIT phase

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Sensitivity Goals for An Advanced Compton Telescope

~$10^{-7} \text{ ph cm}^{-2} \text{s}^{-1} (3\sigma)$ for narrow lines and

~$10^{-6} \text{ ph cm}^{-2} \text{s}^{-1} (3\sigma)$ for broad lines

Do we have what it takes to make such a big step?

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A Visionary Mission According to NASA Roadmap

What can we do to change this?

• So far we do not have one telescope concept which „has it all“ and it is essential to continue the development and demonstration of different technologies for Compton imaging of MeV gamma-rays.

• It may well be that to fully realize the science of MeV lines and continuum emission will take a multi-instruments Observatory or a suite of missions with different telescopes, emphasizing complementary aspects of the Compton measurement.

• Nothing however will be more effective to turn an ACT mission from vision to reality than new scientific results at MeV energies, clearly within reach at ~10 x COMPTEL sensitivity and at much better angular resolution.

Intermediate missions, within this decade, will also be vital to train and maintain the next generation of scientists needed for a future mission.
At Columbia we have focused on the Liquid Time Projection Chamber concept for Compton imaging. Detection efficiency is dramatically increased by using one homogeneous material as both D1 and D2. With 3D position sensitivity and good energy resolution, the complete event interaction history is recorded thus dramatically enhancing background reduction through event reconstruction. High probability to fully contain the scattered photon energy when using a good stopping material such as Liquid Xenon.
Technology demonstrated with LXeGRIT

Flight Proven Technology
LXeGRIT: 1st Prototype

$$(x_1, y_1, x_2, y_2) \rightarrow \text{scatter direction } (\chi, \psi)$$

$$E_i \rightarrow \text{total energy and scatter angle } \varphi$$

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Key Questions in Gamma-ray Astrophysics

What is the origin and nature of gamma-ray bursts?

How does matter behave in extreme conditions like those in Neutron Stars, Supernovae and Active Galactic Nuclei?

What is the nature of the jets from BH and AGN and how are the particles accelerated?

What is the nature of the unidentified high energy $\gamma$-ray sources?

How do supernovae work?

What are the progenitors and explosion mechanisms?

What has been the rate in the last several hundred years?

Where are the sites of nucleosynthesis?

What and where are the sites of cosmic ray acceleration?

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The MeV Gamma-Ray Band (0.1 – 10 MeV)

Holds the key to many answers...

**continuous γ-ray spectra** from sites of high-energy particle acceleration, i.e. Neutron Stars, Black Holes, Supernovae, AGNs, GRBs. The luminosity of these objects is maximum in the MeV region.

**γ-ray lines** from cosmic radioactivity, probing nucleosynthesis and elements formation. The energy of many nuclear lines are around 1 MeV ($^{56}$Co, $^{60}$Fe, $^{56}$Co, $^{44}$Ti, $^{22}$Na, $^{26}$Al..)

Field largely unexplored: low fluxes and large background combined with the difficulty of imaging MeV photons
Advantages of LXe

- High detection efficiency
  \[ \rho = 3.06 \text{g/cm}^3, Z = 54 \]
- Short radiation length
  \[ L_{rad} = 2.6 \text{cm} \]
- High ionization yield for good \( \Delta E/E \)
  \[ W = 15.6 \text{eV/pair}, F = 0.04 \]
- Sub millimeter spatial resolution
  \[ D < 80 \text{cm}^2/\text{s}, \text{ high } \mu, \text{ saturated } v_d \]
- Excellent scintillator with fast decay time
  \[ N_{ph} = 4 \times 10^4 / \text{MeV} \]
- Three-dimensional localization in large, homogeneous volume
  With TPC mode of operation
A LXeTPC for Compton Imaging

\[ \cos \varphi = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1} \right) \]
The Post LXeGRIT Vision:

A Compton Telescope as Explorer Class Mission on a LDB (ULDB?): proposal in 2004

Instrument Wish List:

- Much Larger Area
- Better Energy Resolution
- Lower Energy Threshold
- Minimal DAQ Dead time
- Energy Sensitive Trigger
- Time of Flight
Columbia Advanced Compton Telescope Concepts

LXeTPCs
UNEX Proposal in 1998

Si-CdTe
SR&T Proposal in 2001

XeTPCs – Gas
SR&T Proposal in 2000

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Baseline Concept

- Upper TPC
- Lower TPC
- PMTs
- Cathode Plane (Upper Drift)
- X Induction Wires (Upper)
- Anode Strips (Double Sided)
- Induction Wires (Lower)
- Cathode Plane (Lower Drift)
Concept Studied as UNEX Mission

- XENA Detector Housing
- Detector Vessel Support Pad Assembly (3 PI)
- Girth Ring
- LN$_2$ Vessel Support Pad Assembly (3 PI)
- 100 Liter LN$_2$ Support Vessel
- Cryostat Housing Assembly
- Support Straps (3 pl)
- Support Cage Assembly
Mission Characteristics and Sensitivity

Geometrical Area: 2500 cm²
Depth of Converter: 3 cm
Depth of Calorimeter: 20 cm
Separation for TOF: 10 cm

Energy resolution @ 2 MeV: 4% FWHM
Angular Resolution @ 2 MeV: 2° FWHM
Field-of-View: 120 degree

Sensitivity (3σ in 4x10⁵ s):
- Narrow Lines: 6x10⁻⁶ cm⁻² s⁻¹ (1.8 MeV)
- Continuum (1 - 3 MeV): 1.7x10⁻⁸ cm⁻² s⁻¹ keV⁻¹

Polarization: 10% (Crab in 10 h)
Very Large Efficiency

18% or ~500 cm² effective area @ 2MeV
Xenon Compton Telescope Mission on Long Duration Balloon

**Exposure Map for a 14 days flight from Southern sky:**
**Exceptional coverage**
1st Class Science even with a LDB Mission

Novae ($^7\text{Be}, ^{22}\text{Na}, e^+ e^- \text{ Ann.})$

Supernovae Ia ($^{56}\text{Ni}, ^{56}\text{Co}, ^{57}\text{Co}$)

young SNR ($^{44}\text{Ti}$)

Blazars

Pulsars

Gamma Ray Bursts

Solar Flares: continuum and lines

Simulated Spectrum of inner Galaxy for a 4.6 days exposure, assuming $^{60}\text{Fe}$ emission traces COMPTEL $^{26}\text{Al}$ distribution, at ~1/7 line flux ratio, so total flux in each line taken as $5 \times 10^{-5}/\text{cm}^2/\text{s}$
Excellent Polarimetry

Simulations based on 39 x28x10 cm$^3$ LXe volume
Background estimate assumes only atm and CDG components, as verified with LXeGRIT

Compton Scattering Kinematics

Solid lines for a constant $\theta$

Dashed lines: constant $h\nu$
Liquid Xenon as Scintillator

Light from Complicated Set of Atomic Processes

Direct excitation:

\[ \text{Xe}^* + \text{Xe} \Rightarrow \text{Xe}_2^* \]
\[ \text{Xe}_2^* \Rightarrow 2\text{Xe} + h\nu \]

Recombination:

\[ \text{Xe}^+ + \text{Xe} \Rightarrow \text{Xe}_2^+ \]
\[ \text{Xe}_2^+ + e \Rightarrow \text{Xe}^{**} + \text{Xe} \]
\[ \text{Xe}^{**} \Rightarrow \text{Xe}^* \]
\[ \text{Xe}^* + \text{Xe} \Rightarrow \text{Xe}_2^* \]
\[ \text{Xe}_2^* \Rightarrow 2\text{Xe} + h\nu \]

- \( W_{\text{ph}} = 24 \text{ eV} \)
  (\( W_{\text{ph}}(\text{NaI}) = 17 \text{ eV} \))
- \( t_{\text{fast}} = 4.2 \text{ nsec (singlet)} \)
- \( t_{\text{slow}} = 22 \text{nsec (triplet)} \)
- \( \lambda = 175 \text{ nm} \)
Xe Light Signal Ideal as Event Trigger

Drift time measured w/r to fast light pulse and known $v_d$ give gamma-ray depth of interaction $\rightarrow$ Z-coordinate

- 662 keV Photoabsorbed $\rightarrow$ single-site event
- 662 keV Compton scattered and Photoabsorbed $\rightarrow$ two-site event
New PMT for LXe (HAMAMATSU R9288)

- quartz window for Xe light
- bialkali photocathode
- Q.E. at 175 nm: 20%
- Gain: $10^6$ (12 stages)
- Metal Channel Dynode
- Compact Size (2'', 3.2 cm long)
- Transit Time Spread: 750 psec/pe (factor of 2 improvement expected)
- Operating T: -110°C to +50°C
- tested up to 5-atm pressure
- Custom HV base on ceramic
PMT Development Phases

1st ver.
R6041

2nd ver.
R6041-mod

3rd ver.
R9288

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Aluminum Strip PMT (3rd Version)

- The previous models used a Mn layer to keep the surface conductivity of the PC at low temperature.
- The new model uses Al strip instead of the Mn layer.
- QE is improved and PMT production is more constant in quality.

HAMAMATSU R9288

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Excellent Time Resolution

A Study by University of Tokyo group for $\mu \rightarrow e\gamma$ Experiment

http://meg.psi.ch
**Time Resolution improves as \( \sim 1/\sqrt{N_{pe}} \)**

\[
N_{pe} = \frac{E_\gamma \cdot Q_f}{W_{ph}} \times P_{ce} \times Q_e
\]

\(~200 \text{ pe for } 662 \text{ keV}\)

- W-value for Light in LXe: \( W_{ph} = 23.7 \text{eV} \)
- Field Quenching Factor : \( Q_f = 0.4 \)
- Quantum Efficiency of the PMT: \( Q_e = 15\% \)
- Attenuation Length of UV photons: 30cm
- Teflon reflectivity: 90%

For LXeGRIT With 12 PMTs

Light Collection Simulation
Tests in LXe Chambers at Columbia

- Tests with Bi-207 source
- 1 cm drift gap
- Good coupling of sensitive LXe volume with PMT
- Amplitude and timing readout of charge and light
Another New Development in PMTs

- HAMAMATSU R8520
- Total Area: 25.7 x 25.7 mm$^2$
- Total length: 35 mm
- Bi-alkali photocathode
- UV quartz window.
- Metal Channel, 11 stages
- Gain=$10^6$
- QE at 175 nm: 24%
- Easily tiled, low profile, excellent time resolution.
And one more, for even faster timing

- BURLE 2” flat panel microchannel plate PMT
- Bi-alkali cathode on quartz faceplate.
- *Easily tiled, low profile, photon counting, excellent time resolution, multi-anode*, but more R&D required
LXe Charge and Light Anti-Correlation

![Graph showing LXe charge and light anti-correlation.](image)

- **Yield (a.u.)** on the vertical axis.
- **Drift Field (kV/cm)** on the horizontal axis.
- Two data sets are plotted:
  - ▲ Ionization
  - ▼ Scintillation

Graph indicates a decreasing trend in yield with increasing drift field for both ionization and scintillation.
Better Energy Resolution

Goal: 60 keV FWHM @ 1 MeV

Drift Field (kV/cm)

Resolution (σ%)

σc Aprile (1991)
σc Conti (2003)
σmin Conti (2003)

Na-22 Spectrum

511 keV
1.274 MeV
Test Pulse
Liquid Argon?

A very attractive alternative:

→ Better Energy Resolution;
→ Much easier to purify;
→ Lower Z;
→ Lower cost
Summary

Balloon missions of long duration (> 10 days) can advance MeV gamma-ray astrophysics, if one can realize a new COMPTEL which can truly yield results on such short observation time. It might be the best way we have to get to an ACT in space!

The TPC imaging technology is ready to be applied for such a mission and we plan to propose it through the next Explorer AO. A strong collaboration is needed to realize such an instrument and not just to satisfy the NASA politics!

We might be looking for Dark Matter WIMPs but we are not WIMPS! Come and join us.