The Design of the Lynx X-ray Microcalorimeter (LXM)

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– on behalf of the LXM sub-group of the Lynx instrument working group
Lynx X-ray Microcalorimeter

~ 100,000 pixels!
**Main Array**
- 1” pixels, 5’ FOV, 50 µm pixels, hydra-25
- $\Delta E = 3$ eV
- Up to 7 keV
- 86,400 pixels

**Enhanced Main Array:**
- 0.5” pixels, 1’ FOV, 25 µm pixels, hydra-25
- $\Delta E = 2.0$ eV
- Up to 7 keV
- 12,800 pixels

**Ultra-Hi-Res Array**
- 1” pixels, 1’ FOV, 50 µm single pixels
- $\Delta E = 0.4$ eV
- Up to 0.8 keV
- 3,600 pixels

- Study of metallicity in galaxy clusters to $z=3$ as probe of galaxy formation processes near peak of cosmic star formation
- Determine effects of AGN energy feedback on ISM & determine physical state of gas near SMBH sphere of influence in nearby galaxies
- Study of plasma physics effects related to dissipation of energy from AGN outflows.
- Will spatially & spectrally resolve starburst-driven winds in low-redshift galaxies
Gold absorber: 45 µm x 45 µm x 4.2 µm, $T_c \approx 60$ mK under bias

- Energy resolution = 0.70 eV [FWHM] at 1.5 keV
- Best achievable resolution at low energies with this design $\sim 0.4$ eV
- For Ultra Hi-Res array, absorber 4 times thinner $\Rightarrow$ 2 times better energy resolution.

$\Rightarrow$ < 0.4 eV possible
Multi Absorber TES “Hydras” - 1 TES, 4 absorbers

Exponential decay after spatially variant equilibration

Also works with MCCs
Hydras with 3x3 array of 65 µm absorbers, 5.0 µm thick

$\Delta E_{rms} = 2.4 \text{ eV (FWHM)}$ at 6 keV, Mn-Kα
Main Array Development: 10 Kilo-pixel array fabricated with 3x3 hydrazas

96x96 array (9216 pixels) - fully wired within array – absorbers on 75 µm pitch
- 32x32 array of 3x3 Hydrazas
Main Array Development: 20 Absorber Hydras

- Combined spectrum from all 20 hydra pixels for Cr Kα1 X-rays give $\Delta E = 3.36$ eV (FWHM).
- Also showed good performance for 1.5 keV and 277 eV X-rays, where most pixel populations could still relatively easily be discriminated from rise-time.
• Will require pixels on a 25 μm pitch.
• Below is an example of a 10 x 10 array of pixels on a 35 μm pitch.
• Each absorber cantilevered above substrate on a single 1 micron diameter “stem”

LXM Prototype arrays using TESs

- High-yield, high-density, buried multi-layered wiring underneath pixels (MIT/LL).
- Superconducting microstrip wiring & ground planes integrated
  ⇒ Hydras pixels easily fabricated on nice flat surface

- About two thirds of the full sized LXM array
- This is a TES microcalorimeter version, MMC one also being developed and currently being fabricated.
8” wafers, currently being cored down into 4” wafers
Microwave SQUID Multiplexing

- Circuit diagram for high-resolution X-ray microcalorimeter readout using microwave SQUID multiplexing
- TESs couple to unique microwave resonator
- SQUIDs built into microwave resonator
- Current in input coil modulates resonance frequency

Microwave SQUID resonator chips developed at NIST:
Microwave SQUID Multiplexing

- Measuring 32 TES multiplexed at GSFC through resonators spaced by 6 MHz, with frequencies around ~ 5.5 GHz
- Now achieved ~ 2.67 eV [FWHM] at 6 keV, with integrated NEP = 2.58 eV. Max. slew rate ~ 0.4 A/s.

SOA: Spacing of resonators can be ~ 2 MHz.
- 128 resonators with a 6 MHz spacing.
- Now demonstrated with 128 microcalorimeters attached with no degradation of performance.
## LXM Focal Plane Layout

**Baseline, January 2018**

T<sub>c</sub>=65 mK

<table>
<thead>
<tr>
<th>Arrays</th>
<th>FoV</th>
<th>Pixel size</th>
<th>Thickness</th>
<th>DF</th>
<th># of sensors</th>
<th>Hydra</th>
<th># of pixels</th>
<th>Max slew rate for max E</th>
<th>Energy range (keV)</th>
<th>Samp. rate (MHz)</th>
<th>Res.</th>
<th># of res.</th>
<th>Margin at max energy</th>
<th># of HEMTs</th>
<th>Round up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main array</td>
<td>5'</td>
<td>5x5 hydras</td>
<td>1&quot;</td>
<td>4</td>
<td>3 eV</td>
<td>3,456</td>
<td>25</td>
<td>86,400</td>
<td>1.7</td>
<td>6</td>
<td>0.5</td>
<td>10</td>
<td>400</td>
<td>2.5</td>
<td>8.6</td>
</tr>
<tr>
<td>Enhanced Main Array</td>
<td>1'</td>
<td>5x5 hydras</td>
<td>0.5&quot;</td>
<td>4</td>
<td>1.5 eV</td>
<td>576</td>
<td>25</td>
<td>14,400</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>40</td>
<td>100</td>
<td>2.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Ultra-Hi-Res Array</td>
<td>1'</td>
<td>Single pixels</td>
<td>1&quot;</td>
<td>1</td>
<td>0.3 eV</td>
<td>3,600</td>
<td>1</td>
<td>3,600</td>
<td>0.85</td>
<td>1</td>
<td>0.3</td>
<td>6</td>
<td>667</td>
<td>2.1</td>
<td>5.4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7,632</td>
<td>104,400</td>
<td></td>
</tr>
</tbody>
</table>

**Enhancement option to be considered later**

<table>
<thead>
<tr>
<th>Extended array</th>
<th>20'</th>
<th>Single pixel</th>
<th>5&quot;</th>
<th>0.5 1 eV</th>
<th>54,000</th>
<th>1</th>
<th>54,000</th>
<th>7.168</th>
<th>2</th>
<th>2.8</th>
<th>56</th>
<th>71</th>
<th>2.3</th>
<th>5.9</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2: 2 eV Extended Array</td>
<td>20'</td>
<td>Single or 2x2 hydra</td>
<td>5&quot;</td>
<td>0.5 2 eV</td>
<td>13,500</td>
<td>1 or 4</td>
<td>13,500</td>
<td>7.168</td>
<td>2</td>
<td>0.9</td>
<td>178</td>
<td>2,250</td>
<td>9.5</td>
<td>6.0</td>
<td>6</td>
</tr>
</tbody>
</table>
• 4 temperature stages (55 mK / 4 K / 20 K / 300 K)
• 2-stage HEMT at 4.5 K, ~ 1 mW/HEMT with low enough noise temp. and sufficient gain
• Split 4GHz bandwidth to four 1GHz bandwidth blocks
  • 1GHz BW block consists of LO, I/Q modulator, I/Q demodulator, baseband amplifiers, dual-channel 1Gsps DAC and dual-channel 1Gsps ADC
• Use 2 FPGA to handle four 1GHz BW blocks
LXM block diagram
Lynx telescope basic design

- Optical Cone
- Magnetic Broom
- Grating Readout (not on translation table)
- Translation Table
  - Micro-Calorimeter
  - High Definition X-Ray Imager (HDXI)

- Spacecraft Bus
- Grating Arrays
- Aft Door
- Post-Collimator
- Pre-Collimator
- Aspect Camera
- Outer Door

Dimensions:
- 4.5 m
- 9.475 m
- 12 m
- 10 m
- 2.85 m
Lynx National Aeronautics and Space Administration

Lynx Translation Table Configuration

- Micro-Calorimeter Dewar
- HDXI Electronics
- ISIM Mounting Plate
- Translation Table
- Micro-Calorimeter Electronics
- Micro-Calorimeter Cryo-Cooler
- Optical Bench

Aft View

- XGS Radiators
- Translation Table Enclosure (and Radiators) not shown
- Translation Table Motion
Inside the cryostat

- Diameter = 70 cm
- Length = 143.2 cm

- Support struts
- Cryocooler – 4-stage pulse tube cooler
- Multi-stage continuous adiabatic demagnetization refrigerator
- 4.5K Support ring
- Focal plane assembly
- Aperture assembly (series of infrared blocking filters)
Filter wheel and calibration sources

Rotatable filter “paddles”
Notional Focal Plane Assembly Design

- Cryoperm shield
- Niobium shield
- Thrust cones (T300, 3 layers, 0.68 mm thick) to support lowest temp. stages
- Mech. analysis – will survive launch loads, no buckling

Focal plane array – 10 m to optics
4-Stage Stirling-Type Pulse Tube Cryocooler currently baselined for design purposes

- **4-Stage Cryocooler:**
  - 4.5K (50 mW)
  - 15K (65 mW)
  - 40K (180 mW)
  - 80K (3.6 W)

- Mass: ~23 kg (Compressor ~ 16 kg)

- Heat pipes to remove compressor & cold head heat dissipation

- **Vibration** (<100Hz): ~ 10mN with soft mounting

- **Electronics:**
  - Power available: 800+ W, Power needed: 507 W
  - Reliability > 98.5%
## 5-stage Adiabatic Demagnetization Refrigerator

### Stage Details

<table>
<thead>
<tr>
<th>Stage</th>
<th>Details</th>
<th>T range</th>
<th>Max Avg cooling power*</th>
<th>Nom Avg cooling power</th>
<th>Avg heat rejection</th>
<th>Peak heat rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>150 g GLF, 3 T</td>
<td>1.35-4.6 K</td>
<td>1.41 mW</td>
<td>1.00 mW</td>
<td>4.0 mW</td>
<td>~20 mW</td>
</tr>
<tr>
<td>4</td>
<td>200 g CPA, 2 T</td>
<td>0.54-1.5 K</td>
<td>0.66 mW</td>
<td>0.25 mW</td>
<td>0.68 mW</td>
<td>0.31 mW</td>
</tr>
<tr>
<td>3</td>
<td>60 g GLF, 1 T</td>
<td>0.6 K</td>
<td>0.31 mW</td>
<td>0.25 mW</td>
<td>0.25 mW</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>100 g CPA, 0.5 T</td>
<td>0.045-0.3 K</td>
<td>0.012 mW</td>
<td>0.006 mW</td>
<td>0.050 mW</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100 g CPA, 0.1 T</td>
<td>0.05 K</td>
<td>0.012 mW</td>
<td>0.006 mW</td>
<td>0.006 mW</td>
<td></td>
</tr>
</tbody>
</table>

Meets cooling requirements (3 µW @ 0.05 K, 124 µW @ 0.6 K) with required 100% margin
**LXM Development Milestones**

<table>
<thead>
<tr>
<th>Life-Cycle Phases</th>
<th>Pre-Phase A: Concept Studies</th>
<th>Phase A: Concept &amp; Tech Development</th>
<th>Phase B: Prelim. Design &amp; Tech Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life-Cycle Gates</td>
<td></td>
<td>KDP-A 10/1/24</td>
<td>KDP-C 10/1/28</td>
</tr>
<tr>
<td>Project Life-Cycle Reviews</td>
<td>SOTA TRL: 3-4 03/18</td>
<td>KDP-B 11/1/26</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>▲ MCR 8/1/24</td>
<td>▲ PDR 7/1/28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▲ SRR 7/1/26</td>
<td></td>
</tr>
</tbody>
</table>

**Total Mass Estimate: 468 kg**
- Cryostat: 164 kg
- Electronics boxes: 146 kg
- Harnesses: 34 kg
- Thermal: 72 kg
- Other: 52 kg

**Total Power Estimate: 1,832 W**

Cost: CBE~ $380M (FY20), just completing second round of costing.
Conclusions / Co-authors from the Lynx IWG
LXM sub-group

• The LXM instrument has a well-established baseline design.
• Technology development is advancing rapidly.
• Meeting of LXM requirements appears very feasible on required time-line.

1. Simon Bandler - GSFC - Co-chair
2. Enectali Figueroa-Feliciano - Northwestern - Co-chair
3. Kazuhiro Sakai - GSFC
4. Megan Eckart - GSFC
5. Stephen Smith - GSFC
6. Wonsik Yoon - GSFC
7. Mike DiPirro - GSFC
8. Joel Ullom - NIST
9. Doug Bennett - NIST
10. Dan Swetz - NIST
11. Ben Mates - NIST
12. Kent Irwin - Stanford
13. Jeffrey Olson - Lockheed Martin
14. Dan McCammon - Wisconsin
15. Doug Swartz - NASA/MSFC
16. Ben Zeiger - Luxel
17. Kevin Ryu - MIT Lincoln Labs.
Back-up
Detailed parts of FPA design:

Side panels with:

1. Microwave SQUID resonator multiplexing chips for reading out the TESs
2. Shunt/nyquist inductors chips for TES bias circuit
Lynx 3 main science pillars

2. THE INVISIBLE DRIVERS OF GALAXY FORMATION AND EVOLUTION

- Lynx will map hot gas around galaxies and in Cosmic Web.
- The assembly, growth, and state of visible matter in cosmic structures is largely driven by violent processes that produce and disperse large amounts of energy & metals into surrounding medium as hot ionized baryons.
- Will characterize all significant modes of energy feedback including:

  **BH feedback:**
  - spectro-imaging of SMBH spheres of influence
  - density diagnostics in AGN winds
  - extended narrow emission line regions
  - AGN-inflated bubbles in elliptical galaxies
  - plasma physics

  **Galactic winds feedback:**
  - Spatially and spectrally resolve hot phase of galactic winds