Off-Plane Grating Developments

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- James Tutt
- Andrew Holland, et al

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- Thomas Rogers
- Ann Shipley, et al

Industry partners
- LightSmyth Technologies
- Nanonex Corp.
- XCAM/e2v
- NGAS

Importance of grating spectroscopy

IXO X-ray Science
(as accomplished by missions in the X-ray Study)

<table>
<thead>
<tr>
<th>Science</th>
<th>IXO</th>
<th>AXSIO</th>
<th>N-CAL</th>
<th>NXGS</th>
<th>NWFI</th>
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<tbody>
<tr>
<td>Strong Gravity</td>
<td>orbiting Fe Kα</td>
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<tr>
<td>SMBH Growth</td>
<td>spin survey</td>
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<td>Evolution of LSS</td>
<td>WHIM</td>
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<tr>
<td>Feedback</td>
<td>cluster imaging</td>
<td></td>
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<tr>
<td>High density matter</td>
<td>NS spectra</td>
<td></td>
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<td></td>
<td>NS timing</td>
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Legend:
- IXO Science Goal is
  - Fulfilled
  - Partially fulfilled
  - Not fulfilled
  - Not Applicable

- Missing baryons
- Galactic feedback
- Stellar coronae
- Charge exchange
- Supernova remnants
Off-Plane X-ray Grating Spectrometer (OP-XGS)

Off-Plane X-ray Grating Spectrometer (OP-XGS)

Field of View: 7.5 Deg

Focal Surface

4 Nested Hyperboloids

Doubly Reflected X-rays

X-rays

10 meters

Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

N-XGS

Mirror modules

Grating modules

Readout detector arrays

Readout Detector Arrays

Grating & Mirror Modules
Off-plane geometry and technical challenges

1. Radial profile to control aberration
2. Blazed profile to increase S/N in plus or minus orders
3. Alignment to ensure spectral overlap

$\sin \alpha + \sin \beta = n \lambda / d \sin \gamma$
A new grating fabrication technique

- e-beam lithograph a mask (high density radial pattern)
- Reduction DUV immersion photolith into Si
- Results in a “Pre-master” (left)
- Etch to get a blaze (below)
- Replicate(?)

1. Spin coat resist onto nitride coated Si wafer
2. Nanoimprint pre-master into resist
3. Reactive ion etch residual resist and nitride
4. Rinse resist with acetone
5. Wet etch Si with KOH
6. Nitride tab removal with HF
Diffraction Efficiency

- Measure at BESSY PTB
- Allows 2-D sampling of focal plane

BESSY PTB's EUV Reflectometer

<table>
<thead>
<tr>
<th>Axis</th>
<th>Range</th>
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<tbody>
<tr>
<td>θ</td>
<td>-30° to 95°</td>
</tr>
<tr>
<td>Tilt</td>
<td>-10° to 10°</td>
</tr>
<tr>
<td>Φ</td>
<td>0° to 360°</td>
</tr>
<tr>
<td>X</td>
<td>-90 mm to 90 mm</td>
</tr>
<tr>
<td>Y</td>
<td>-10 mm to 300 mm</td>
</tr>
<tr>
<td>Z</td>
<td>-15 mm to 140 mm</td>
</tr>
<tr>
<td>Det. X</td>
<td>0 mm to 120 mm</td>
</tr>
<tr>
<td>Det. R</td>
<td>150 mm to 550 mm</td>
</tr>
<tr>
<td>Det. Ψ</td>
<td>0° to 180°</td>
</tr>
<tr>
<td>2θ</td>
<td>-5° to 190°</td>
</tr>
</tbody>
</table>

Accuracy: 10 μm or 0.01°

Samples:
- up to 50 kg in weight
- up to 550 mm in diameter

Diameter: 2 m
Length: 2.1 m
Weight: 3 t
Efficiency Results

- $\alpha = 0$; higher orders at lower energies in evanescence
- Low duty cycle causes groove well/top interference
- Blaze should 1) remove latter, 2) take power from 0 order, 3) provide flatter efficiency response over energy – all shown theoretically/empirically
Spectral Resolving Power Tests at MSFC

a) Installation

b) GSFC Optics
   TDM

a) Optics + Gratings

a) CCD + stages
Resolution results

- Mg-Kα fluorescence line @ 0.925 keV
- Detected at ±1\textsuperscript{st}, ±2\textsuperscript{nd}, and ±3\textsuperscript{rd} orders
- Resolution ≈ 900, 1300, 1300, respectively

![Graph showing resolution results](image)
Zero order focus results: Black diamonds - focus run on Day 1 with Manson electron beam current at 0.16 mA; Red crosses - focus run on Day 2 with Manson beam current at 0.5 mA; Cyan asterisks - focus run on Day 3 with Manson beam current at 0.16 mA; Green and Blue diamonds - focus checks on Day 4 with Manson beam at 0.5 mA and 0.16 mA, respectively; Orange diamonds - focus check on Day 5 with Manson beam at 0.16 mA.
Grating alignment and module design

$\Delta x = L(\alpha_{m,1} / \beta_{m,1}) - L(\alpha_{m,0} / \beta_{m,0})$  

$\Delta y = L_{\perp} f \tan[\arcsin(y_{m,1})] - L_{\perp} i \tan[\arcsin(y_{m,0})]$  

<table>
<thead>
<tr>
<th>DOF</th>
<th>2.35 $\sigma$</th>
<th>2.35 $\sigma$</th>
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<tbody>
<tr>
<td>X</td>
<td>-317 $\mu$m</td>
<td>+317 $\mu$m</td>
</tr>
<tr>
<td>Y</td>
<td>-124 $\mu$m</td>
<td>+124 $\mu$m</td>
</tr>
<tr>
<td>Z</td>
<td>-1.56 mm</td>
<td>+1.56 mm</td>
</tr>
</tbody>
</table>

Harvey & Vernold (1998)

Allured & McEntaffer, 2013, in prep
Grating alignment and module design

Picomotors
Alignment Module
Gratings

Sample
Beam Expander
Beam Concentrator
Laser
Spatial Filter
Shack-Hartmann Sensor

Direct View of Beam

Figure of Si Wafer

Angular Step Demonstration
Grating Module Rev 2
Accomplishments and plans

- Radial, high density grating fabricated
- Measured high efficiency over relevant energies
- Measured high spectral resolving power matching theoretical expectations at first order
- Higher order resolving power limited by facility issues
- Alignment metrology and methodology consistent with achieving tolerance requirements

- Blaze grating (recently ~successful)
- Measure high efficiency on blazed gratings
- Measure high spectral resolving power on blazed gratings
- Limit source size or increase beam length
- Design, fabricate, and test aligned modules of blazed gratings (a new SAT... hopefully)
NASA - APRA

- 5-year suborbital rocket program
- Off-plane Grating Rocket Experiment (OGRE)
- Increase flight readiness of gratings as well as optics and CCDs...
  - Optics supplied by Goddard Space Flight Center
  - Gratings ,+++ at Iowa
  - CCD camera supplied by Open University + e2v Technologies
OGRE performance
Capella

[Graphs and charts showing data analysis results]
Payload

Launch 2017!
Summary

• Grating spectrometers are critical to future X-ray science goals
• Off-plane gratings provide a method for obtaining high throughput and spectral resolving power
• A new fabrication method has been identified.
  • Initial steps have been taken to produce a high density, radially ruled groove profile
  • Initial performance results are consistent with requirements
  • Blazing processes are understood and underway
  • Alignment tolerances are identified
  • Alignment methodologies and module mounts have been implemented with a development plan in place
• Technology development programs have accelerated grating studies and provided a well defined path until a mission is identified
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  • NNX12AF23G, …?
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  • NNX13AD03G

• Thank you for your attention!
Back-up slides
Total flux (0.3–1.0 keV) = 1.82 x 10^{-11} ergs/cm^2/s
Model tbabs*pegwrlw, N_H = 1 x 10^{22} cm^{-2}, photon index = 2.0
WHIM absorption lines:

<table>
<thead>
<tr>
<th></th>
<th>Width (mÅ)</th>
<th>λ (Å)</th>
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</thead>
<tbody>
<tr>
<td>NeIX Kα</td>
<td>1.5</td>
<td>13.8</td>
</tr>
<tr>
<td>OVI Kβ</td>
<td>1.8</td>
<td>19.11</td>
</tr>
<tr>
<td>OVI Kα</td>
<td>4.1</td>
<td>19.18</td>
</tr>
<tr>
<td>OVI Kα</td>
<td>1.8</td>
<td>19.48</td>
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<tr>
<td>OVI Kα</td>
<td>3.0</td>
<td>21.85</td>
</tr>
</tbody>
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AGN Outflow
Total flux (0.3–1.0 keV) = 1.0 x 10^{-12} ergs/cm²/s
Model tbabs+diskbb+gaussian 60 ksec
N_H = 3 x 10^{21} cm⁻², kT = 3 keV
Absorber velocities (km/s) (4 mA widths)
1454  860  316
1294  674  214
1010  536  96
Weak Emission Line Source

Total flux (0.3–1.0 keV) = 9.36 \times 10^{-13} \text{ ergs/cm}^2/\text{s}

Model tbabs*(apec+apec), \( N_H = 1 \times 10^{20} \text{ cm}^{-2} \)

\( kT_1 = 0.2 \text{ keV}, kT_2 = 0.8, F_2/F_1 = 2.3 \)