High-Resolving-Power Soft X-ray Transmission Grating Spectrometers for the Arcus (MIDEX) and Lynx (X-ray Surveyor) Missions

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INTRODUCTION: A number of high priority questions in astrophysics can be addressed by a state-of-the-art soft x-ray grating spectrometer, such as the role of Active Galactic Nuclei in galaxy and star formation, characterization of the Warm-Hot Intergalactic Medium and the “missing baryon” problem, characterization of halos around the Milky Way and nearby galaxies, as well as stellar coronae and surrounding winds and disks.

An Explorer-scale, large-area (~ 500 cm² or greater), high resolving power (R = \( \lambda / \Delta \lambda \approx 2,500 \) or greater) soft x-ray grating spectrometer is highly feasible based on Critical-Angle Transmission (CAT) grating technology. Still significantly higher performance can be provided by CAT grating spectrometers on an X-ray Surveyor/Lynx-type mission. CAT gratings combine the advantages of blazed reflection gratings (high efficiency, use of higher diffraction orders) with those of conventional transmission gratings (low mass, related alignment tolerances and temperature requirements, transparent at higher energies) with minimal mission resource requirements. They are high-efficiency blazed transmission gratings that consist of freestanding, ultra-high aspect-ratio grating bars fabricated from silicon-on-insulator (SOI) wafers using advanced misoriented dry (DRIE) and wet (KOH)etch techniques. Blazing is achieved through grating-incidence reflection off the smooth grating bar sidewalls. The reflection properties of silicon are well matched to the soft x-ray band. Nevertheless, CAT gratings with sidewalls made of higher atomic number elements allow extension of the CAT grating principle to higher energies and larger dispersion angles.

Using Al K\( \alpha \) radiation at the NASA MSFC Stray Light Facility, we have demonstrated resolving power \( R = 3,000 \) with 52 mm-wide Si CAT gratings bonded into a 9th order with a 12 m focal-length ATHENA-like silicon optic, and \( R = 10,000 \) in an 8th order with Pr-coated CAT gratings and slumped glass x-ray mirrors from the NASA GSFC x-ray optics group.

Currently fabricated silicon CAT gratings are highly efficient in the soft x-ray band, have passed environmental testing, and are capable to support attractive mission concepts today. We recently have increased grating size by a factor of 3 to ~32x32 mm² while maintaining record-high diffractive efficiency > 30% (sum of blazed orders). With the still existing significant room for improvement the expected scientific yield from CAT-grating-based soft x-ray spectroscopy missions or instruments will increase further in the near future.

Best of Both Worlds (transmission vs. blazed reflection):

Blazed Transmission Grating Design for Soft X Rays

Record Diffraction Efficiency (~ 34%) with Room for Improvement

Large-Area Freestanding Transmission Gratings with Integrated Supports

Three CAT gratings being tested at beam line 6-3.2 at the Lawrence Berkeley National Lab Advanced Light Source. Monochromatic x-rays are incident from the left and detected on the right after diffraction.

X-ray Surveyor/Lynx

X-ray Surveyor mission concept is being studied for the 2020 Decadal. A potential CAT-grating spectrometer (MIDEX) addresses high resolving power (\( R = 10,000 \)), high effective area (\( > 2000 \) cm²) soft x-ray science that will not be covered by any other planned mission. A transmission spectrometer (CATXGS) combines ultra-high dispersive power with high-resolution with minimal resource requirements, simultaneously providing higher possible resolution over the 0.5 – 10 keV band with maximum effective area. Reference: Efficiency weighted resolving power from initial focus ray trace studies (Morris et al., Proc. SPIE 9905, 1X (2016)).

Preliminary analysis strongly suggests that the tested CAT gratings, illuminated across 30 mm width, are not a limiting factor in the design and construction of blazed transmission grating spectrometers with resolving power on the order of \( R = \lambda / \Delta \lambda \approx 10,000 \).

Expected Performance from Today’s CAT Gratings and Prospects for the Future

The table below uses performance, dimensions, and blockage factors from silicon CAT gratings for \( \lambda = 0.3-2.5 \) nm from 2015. Future performance is based on theoretical predictions for 6 \( \mu \)m deep gratings with reasonably reduced blockage factors. Resolving power is based on ray-trace models using sub-apertured Wolter-I mirrors.

<table>
<thead>
<tr>
<th>GRATING</th>
<th>MIDEX</th>
<th>Probe-AMS/ACGS</th>
<th>X-ray Surveyor</th>
</tr>
</thead>
<tbody>
<tr>
<td>focal length</td>
<td>(~ 10 ) m</td>
<td>(~ 10 ) m</td>
<td>(~ 10 ) m</td>
</tr>
<tr>
<td>PSF/subaperatured LSF</td>
<td>10%/50%</td>
<td>10%/50%</td>
<td>0.5%/0.5%</td>
</tr>
<tr>
<td>mirror effective area (covered by gratings) [cm²]</td>
<td>3600</td>
<td>6000</td>
<td>&gt; 10,000</td>
</tr>
<tr>
<td>Grating effective area (today’s hardware) [cm²]</td>
<td>600</td>
<td>1400</td>
<td>&gt; 2300</td>
</tr>
<tr>
<td>Grating effective area (future) [cm²]</td>
<td>&gt; 1000</td>
<td>&gt; 2000</td>
<td>&gt; 4000</td>
</tr>
<tr>
<td>Resolving power (Detector/OBF losses are neglected)</td>
<td>&gt; 3500</td>
<td>&gt; 3500</td>
<td>&gt; 5000</td>
</tr>
</tbody>
</table>

Acknowledgments:

We are very grateful to Will Zhang, Ryan McClelland, Kao-Wing Chan, Itron Mneumez, and Mark Schafferfield (all NASA GSFC) for their help in lending us a mirror TDM with exquisite angular resolution. We thank James Carter and William Jones for support at the Marshall SFL. Cores Research and Valley Borde for lending of the SPI. Eric Guillotin (LBNL) for support at the ALS. Ritvik Bhatia (Ultratech) for DRIE+KOH (Samples 1, 3, 6) and K. D. Matheson et al., Proc. SPIE 990556 (2016).

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References: