International X-ray Observatory (IXO)

# Critical-Angle Transmission Grating Spectrometer for IXO

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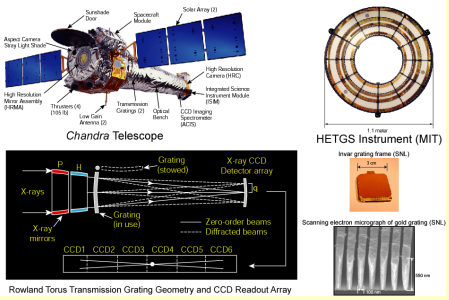
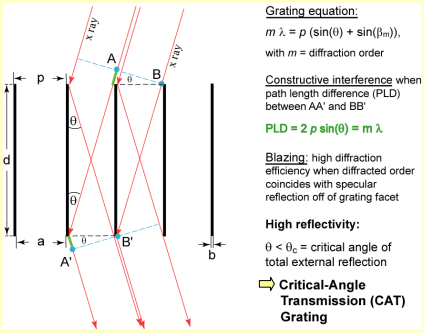
**ABSTRACT:** We present a high-resolution soft x-ray grating spectrometer for IXO that meets or exceeds the requirements for effective area (> 1000 cm² for E < 1 keV) and spectral resolution (E/ΔE > 3,000). Building on Chandra and XMM-Newton heritage, the spectrometer is based on novel high-efficiency blazed transmission gratings.[1-4] These critical-angle transmission (CAT) gratings combine the advantages of traditional transmission gratings (very low mass, extremely relaxed alignment and flatness tolerances) with those of X-ray reflection gratings (high efficiency over a broad band due to blazing).
We have micro-fabricated 200 nm-period silicon CAT gratings with the required bar dimensions (~ 6 micron tall, ~ 40 nm wide, aspect ratio 150), optimized for the 0.3 to 1.0 keV energy band. X-ray tests show blazing behavior up to 1.28 keV in accordance with predictions. Finite element analysis and ray tracing have confirmed the suitability of the mechanical and optical designs.
The CAT grating spectrometer works in tandem with IXO focal-plane detectors: only a fraction of the mirror aperture is covered with CAT gratings and, even so, high-energy x-rays pass through the gratings to the focal-plane focus. The CAT spectrometer extends IXO's highest resolving powers to energies below 1 keV, including lines of C, N, O, Ne and Fe ions, central to many science topics, e.g., coronal emission from stars, studies of the ISM and WHIM, and warm absorption and outflows in AGN (see also posters by Huenemoerder and Schulz).

[1] R. K. Heilmann, *et al.*, "Development of a Critical-Angle Transmission Grating Spectrometer for the International X-Ray Observatory", *Proc. SPIE* **7437**, 74370G (2009).
[2] R. K. Heilmann, M. Ahn, E. M. Gullikson, and M. L. Schattenburg, "Blazed High-Efficiency X-Ray Diffraction via Transmission through Arrays of Nanometer-Scale Mirrors", *Opt. Express* **16**, 8658 (2008).
[3] R. K. Heilmann, M. Ahn, and M. L. Schattenburg, "Fabrication and Performance of Blazed Transmission Gratings for X-Ray Astronomy", *Proc. SPIE* **7011**, 701106 (2008).
[4] M. Ahn, R. K. Heilmann, and M. L. Schattenburg, "Fabrication of 200 nm-Period Blazed Transmission Gratings on Silicon-on-Insulator Wafers", *J. Vac. Sci. Technol. B* **26**, 2179 (2008).

## *Chandra* Heritage: High Energy Transmission Grating Spectrometer (HETGS)

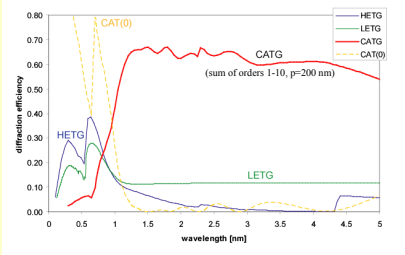



## Blazed Transmission Grating Design for Soft X Rays



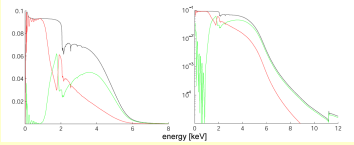

Strawman parameters (Si): p = 200 nm, θ = 1.5°, d ~ 6 µm, b ~ 40 nm

## Silicon CAT Grating Efficiency Predictions

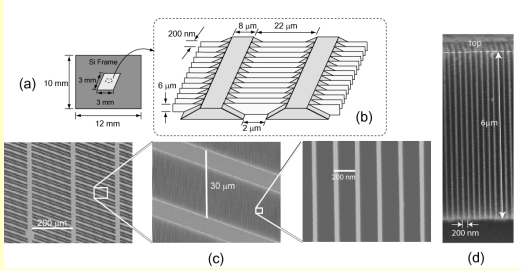



## Impact on Effective Area at Focus

Black: mirror effective area fraction covered by grating array
Green: area fraction transmitted through gratings to focus, contributing to effective area at focus
Red: area fraction lost at focus (difference between black and red curves)
(Slumped glass FMA)

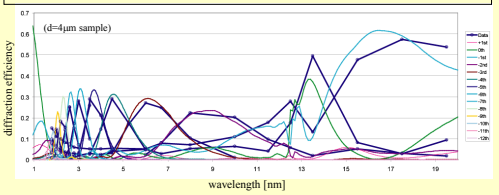



## 200 nm-period CAT Grating Fabrication Results



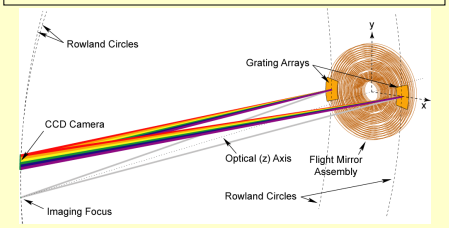

Scanning-electron micrographs of prototype CAT grating fabrication results. (a) Depiction of CAT grating "chip." (b) Depiction of CAT grating (white) and Level 1 support mesh (gray). (c) Successive magnifications of top views of CAT gratings: (left) 200 µm-pitch Level I support mesh, (middle) 30 µm-pitch Level I support mesh, and (right) 200 nm pitch CAT grating bars. (d) Cross section of a cleaved CAT grating. IXO strawman design parameters have been achieved.

## Preliminary Efficiency Results (200 nm period)



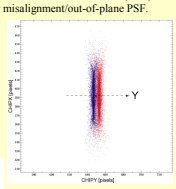

Comparison of theoretical and measured ("Data") diffraction efficiencies

## Blazed Transmission Grating Spectrometer Optical Design

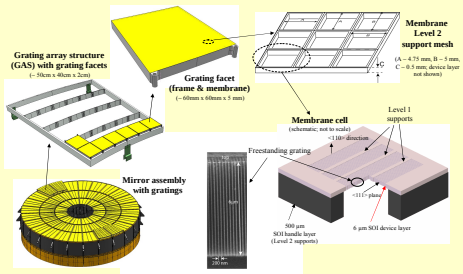



- Blazing eliminates need for camera on one side of focus.
- Gratings highly transparent at higher energies.
- Gratings highly polarization insensitive.
- Camera CCDs sort orders.
- Maximize spectral resolution by placing gratings as far from focus as possible (max. dispersion distance). Leads to R > 2100 *without any sub-aperturing*.
- Sub-aperturing increases R to > 3000.
- Can tolerate reasonable amount (~ 2") of mirror misalignment/out-of-plane PSF.

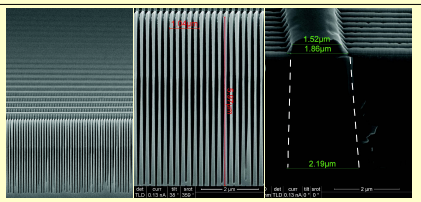
Scatter plot of two spectral lines on a camera CCD with wavelengths of 35.000 and 35.005 Å in 3rd order (p = 200 nm) from a raytrace model of the above optical design with a simplified 4.1 arcsec mirror PSF, resulting in a spectral resolution of ~15,000. Various error terms that have not been included yet will lead to a reduction in spectral resolution. (Estimates predict R ~ 3000 – 5000.)




## Grating Assembly Structural Hierarchy (slumped glass version)

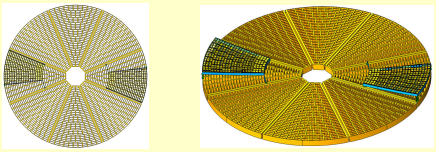



## Recent Dry Etch Results




It is difficult to achieve narrow support bars with KOH etch. Solution: Dry etch first, then follow with short KOH polish. Left and center: SEM cross section of CAT gratings with integrated Level 1 supports after 12 min. dry etch. Right: Cross section through support bar, showing only slight widening. Next steps: KOH polish, mask removal, etc.

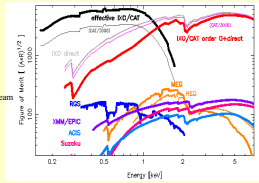
## Grating Array Layout for Silicon Pore Optics (SPO)



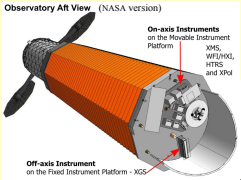
## Comparison with other Missions

Order of Magnitude Improvement in Figure of Merit for Soft X-Ray Spectroscopy (full coverage)

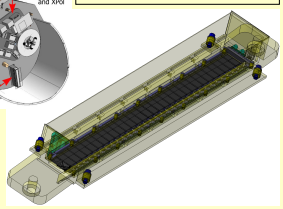
Black "Effective IXO/CAT": ~ 10,000cm² option
Gray "CAT/3000": 3,000 cm² option
Gray "IXO direct": XMS with no gratings
Magenta "CAT/3000": XMS with 3,000 cm² opt. in the beam
Red "IXO/CAT order 0 + direct": XMS with 10,000 cm² option in the beam
XMS: X-ray Microcalorimeter Spectrometer at focus
A: effective area
R: resolution




## Observatory Aft View (NASA version)




## Camera

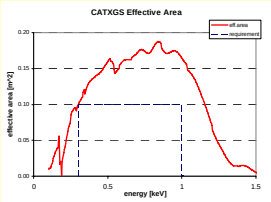


- Linear array of 32 modified CCID41 CCDs (Chandra, Suzaku heritage)
- placed off-axis on fixed instrument platform
- can operate simultaneously with any of the focal plane instruments

## Effective Area

Inputs:

- SPO effective area
- Grating coverage
- Grating efficiencies
- Structural losses (10% Level 1, 10% Level 2, 1.6% GAS)
- Filter transmission (30 nm Al/10 nm $Al_2O_3$ deposited on CCDs)
- CCD efficiencies




**Future Plans:**
- Fabricate and test larger CAT gratings with hierarchy of support structures and higher throughput.
- More detailed ray-tracing of CAT Grating Spectrometer

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See also http://space.mit.edu/home/dph/ixo/ (IXO/CATXGS Development)
http://snl.mit.edu/ (Space Nanotechnology Laboratory)