High-resolution soft x-ray grating spectrometer for IXO with blazed transmission gratings:
The critical-angle transmission grating spectrometer (CAT-GS)

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Critical-Angle Transmission Grating Spectrometer (CAT-GS)

• Mission requirements:
  – Effective area > 1000 cm² (0.3 – 1 keV)
  – Spectral resolution \( E/\Delta E > 3000 \) (FWHM)

• Implementation:
  – CAT grating array aft of mirrors (< 6 kg)
  – Linear CCD detector array (32 CCDs) on instrument bus (< 40 kg)
Transmission Grating Spectrometer Heritage:

NASA *Chandra Observatory* X-ray Telescope
High Energy Transmission Grating Spectrometer (HETGS)

*Chandra Telescope*

Rowland Torus Transmission Grating Geometry and CCD Readout Array
Diffraction Gratings for X-ray and EUV Spectroscopy

Transmission Gratings
- 1st order

- Relaxed alignment & surface flatness tolerance
- Low diffraction efficiency (absorption, etc.)

Blazed Reflection Gratings

- High diffraction efficiency
- Requires precise alignment, flat & smooth surface

Grating Equation

\[ m\lambda = p(\sin \alpha + \sin \beta_m) \]

- \( m \): diffraction order
- \( \lambda \): wavelength
- \( p \): grating period
- \( \alpha \): incident angle, \( \beta_m \): diffracted angle
Alignment sensitivity: Transmission Grating vs. Reflection Grating

\[ m\lambda/p = \sin\theta - \sin\beta_m \]
Alignment sensitivity: Transmission Grating vs. Reflection Grating

\[ m \lambda / p = \sin \theta - \sin \beta_m \]
Critical-Angle Transmission Grating Spectrometer (CAT-GS)

**Improvements over Chandra HETGS:**
- Optimized for soft x-ray band (0.3 - 1 keV) => higher efficiency
- Blazed transmission gratings
  => detector needed on one side (+ OR - orders) only
  => enable use of higher diffraction orders => higher resolution
- transmission gratings transparent at higher energies where other detectors have better energy resolution
- sub-aperturing increases resolution
Diffraction efficiency comparison bw. Chandra and CAT gratings
Mirror only (12.5” HPD)

Observatory (15.0” HPD)

Effect of sub-aperturing on resolution

( Courtesy Andrew Rasmussen)

$\lambda/\Delta\lambda \sim 2200$

$\lambda/\Delta\lambda \sim 1350$
Short history of the Space Nanotechnology Laboratory at MIT

- Fabricated 200 (HEG) and 400 (MEG) nm-period Au transmission phase gratings for Chandra HETGS (> 500 gratings, > 1in², 1995-96)

- SNL gratings flown on other missions:
  - SOHO (1995)
  - IMAGE (2000)

- Developed advanced high-precision grating patterning and nanofabrication tools and techniques
MIT Nanoruler
Scanning-Beam Interference Lithography Tool

- Uses phase-locked, scanning beams to pattern large substrates (up to 300 mm)
- Tight control of grating phase & duty cycle (< 3 nm)
- Can pattern up to 5000 l/mm
- Recently demonstrated “spatial frequency division” which enables patterning up to 20,000 l/mm

Nanoruler with 300 mm silicon wafer

91 cm x 42 cm pulse compression grating

Plymouth Grating Laboratory
Diffraction Gratings for X-ray and EUV Spectroscopy

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How do you go from a blazed reflection grating to a blazed transmission grating?
Critical-Angle Transmission Gratings

Oblique incidence, normal grating bars

Normal incidence, tilted grating bars

(a)  (b)
Critical Angle Transmission (CAT) Grating

Constructive interference when:
path length difference (PLD) between A' and B'

$$\text{PLD} = 2 \, p \, \sin(\theta) = m \, \lambda$$

Blazing: high diffraction efficiency when diffracted order coincides with specular reflection off of grating facet

Refractive index and critical angle for x-ray and EUV:

$$\begin{align*}
n &= 1 - \delta + i\beta, \ &\delta \ll 1, \ \beta \ll 1, \ \beta \neq 0 \\
\theta_c &= (2\delta)^{1/2} : \sim 1 \sim 2^\circ
\end{align*}$$

High reflectivity when:

$$\theta < \theta_c, \ \text{total external reflection}$$

⇒ Critical-Angle Transmission (CAT) Grating
Critical-Angle Transmission (CAT) Grating

The CAT grating is a transmission grating, NOT a reflection grating!

0th transmitted order (PLD = 0) consists of photons that are not deflected but penetrate the grating bars and go to the telescope focus. There is NO 0th order in the direction of specular reflection.

Diffraction is enhanced in the mth order for wavelengths where \( \beta_m \) is close to \( \theta \). Diffraction is strongly suppressed on the other side of the 0th order.

Rotation of the grating around the normal to the plane of incidence by a small angle \( \gamma \) results in a shift of the blaze condition relative to the incident beam by \( 2\gamma \), while the directions of the diffracted orders change by only \( \gamma (m\lambda/p)^2 \sim \gamma m^2 \times 10^{-3} - 10^{-4} \).
CAT Grating Design Issues

Design Parameters (IXO)

• Period, $p = 200$ nm (large dispersion)
• Duty cycle $(b/p) = 0.2$ (high throughput)
• Critical angle, $\theta = 1.5^\circ$ (high reflectivity)
• $d = a/\tan\theta = 6$ µm (optimum “filling”)
• Sidewall roughness < 1 nm (high reflectivity)

Fabrication Challenges

• High aspect ratio ($d/b \sim 150$)
• Thin grating bars ($b = 40$ nm)
• Freestanding structure
• Smooth sidewalls (roughness < 1 nm)
• Fine period gratings ($p = 200$ nm)

Initial prototype: $p = 574$ nm, $d = 10$ µm
Recent 200 nm-period CAT grating fabrication results

- Smaller period
- Smaller sidewall angle
- Higher etch anisotropy
- Larger process latitude
- Larger open area (> 45%)

Scanning electron micrographs:
(a) Top view
(b) Bottom view
(c) Cross section (destructive)

As of January 2009: IXO design parameters achieved: \( d = 6 \, \mu m, \, <b> = 40 \, nm \)
X-Ray Results:

- Blazing
- High Diffracted Orders
First x-ray data from 200 nm-period CAT gratings

- strong blazing
- reduced blazing for \( \lambda \) with \( \theta_c(\lambda) < \alpha \)
- 0\(^{th}\) order transmitted at shortest wavelengths (CAT grating becomes weak phase grating)

\[ \alpha = 2.6 \text{ deg} \]
(blaze 5.2 deg from 0\(^{th}\) order)

**Raw data**
(not normalized)

Heilmann et al.
Diffraction Efficiency: Theory and Experiment

$p = 200$ nm, $\theta = 2.6$ deg (blaze at 5.2 deg. from $0^{th}$ order)

Normalized Diffraction Efficiency

Wavelength [nm]
Model calculations:
Silicon CAT grating
\( p = 200 \, \text{nm} \)
\( \theta = 1.5 \, \text{deg} \)

20 m focal length:
78 cm CCD array
(32 CCDs)
The CCD array covers a range of \( m^*\lambda = 7.2 \text{ nm to 15 nm} \)

\[
m\lambda = p(\sin \alpha + \sin \beta_m)
\]
Order Sorting Capability of CAT-GS detector read-out

![Graph showing energy difference between neighboring orders and ACIS energy resolution (FWHM)]
Baseline CCD for CAT

- MIT/Lincoln, 1024 x 1024, 24-micron pixels, 4 outputs
- High-performance backside treatment
- On-chip binning for nominal ~50 fps readout rate
- Chandra/Suzaku heritage:
  - ~100 CCD-years on-orbit & counting
Detector Array

Linear array of 32 CCDs (25 mm x 25 mm, 24 μm pixel size)

Mass:
- Camera: 25-40 kg (depending on shielding requirement)
- Detector electronics and power supply (DEA): 22 kg
- Digital processor: 14 kg

Power:
- Camera: 5 W (thermal control)
- DEA: 28 W
- Digital processor: 20 W

Courtesy David Robinson
Resolution (FWHM):
black – CAT-GS \(<R> \sim 3000\)
red – XMS (\(\Delta E = 2eV\))

BUT: for \(A = 1000\) cm\(^2\) subaperturing provides \(R = 4500\)

Figure of Merit \(\sqrt{AR}\): 
black – CAT-GS \(<R> \sim 3000\)
\(A = 3000\) cm\(^2\)
red – XMS (\(\Delta E = 2eV\))
green – no gratings

For more detail and response files go to 
http://space.mit.edu/home/dph/ixo/ixo.html
Summary

- CAT grating spectrometer easily meets & exceeds IXO requirements
- CAT gratings combine advantages of transmission and blazed reflection gratings (low mass, relaxed alignment tolerances, high resolution, polarization insensitive)
- CAT-GS opens window into high-resolution soft x-ray spectroscopy

Technology development:
Increase open area (pre-etch techniques, etc.)
Increase grating size (hierarchical support structures)

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