The Three Decades of the Chandra High Energy Transmission Grating (HETG)

Claude R. Canizares, MIT

Chandra’s First Decade of Discovery
September 2009
NASA Chandra X-ray Observatory
High Energy Transmission Grating Spectrometer (HETGS)
Key features needed for an HETG design:

• **HIGH SPECTRAL RESOLUTION (R~1000):**
  - ~5000 lpmm (p=0.2 μm, bar thickness=0.1 μm)
  - fabrication of hundreds of identical grating elements to tolerances of ~100 ppm

• **HIGH EFFICIENCY:** over 1.5 decades of energy (0.4 - 8 keV)
  - ~0.5-1.0 μm tall (>5:1 aspect ratio grating bars)

• **HIGH RELIABILITY:** gratings rugged enough to withstand launch and space environment

Order of magnitude beyond previous gratings
HETG Timeline: the first decade

1979  Beginning of transmission grating development for AXAF (CRC, Mark Schattenburg with H. I. Smith)

1983  AXAF RFP issued (launch date 1991-2)

• Proposal selected for Phase B study

(1986 Challenger disaster)

1988  AXAF approved for “phased new start”

1989  HETG Accepted for AXAF (launch date 1995-6)
Proposed Fabrication Method: X-ray Lithography

Replicate a Master (thin grating mask fabricated via UV lithography) into many thick, phased gratings with the same period using X-ray lithography.
Invention of Micro-gap X-ray Nanolithography

Mask (thin grating)

a) CONTACT X-RAY NANOLITHOGRAPHY

b) MICROGAP X-RAY NANOLITHOGRAPHY
AXAF Gold Transmission Grating

0.1μm
X-ray Lithography Station

Soft X-ray (Cu L line)

Exposure time ~24-36 hrs per grating!

We (and industry) needed a high intensity X-ray machine

Only supplier was Hampshire Instruments
HETG Timeline: the second decade

1989  HETG Accepted for AXAF
3     AXAF Restructured to AXAF-I and AXAF-S;
4     HETG Systems Requirements Review (SRR)
HETG Timeline: the second decade

1989  HETG Accepted for AXAF
3    AXAF Restructured to AXAF-I and AXAF-S;
4    HETG Systems Requirements Review (SRR)

2    Hampshire Instruments ceases operations;
     X-ray lithography no longer viable

HOW COULD WE POSSIBLY BUILD
~700 NEAR-PERFECT GRATINGS ??
Key breakthrough by Schattenburg:

For each exposure, lock UV interference pattern to standard grating (on wafer) using Moire pattern

MLS demonstrates repeatability to less than ~200 ppm (within few weeks!)

Thinks he can achieve high aspect ratio by plasma etching rather than X-ray lithography

Now the masks have become the gratings
Simplified HETG Fabrication Process

Dozens of technological innovations by Schattenburg and his team; several key patents for processes now widely in use by VLSI industry
Gold Transmission Grating Fabrication Process

Benefit of anti-reflection coating (ARC).

Reflectivity from Resist/IL Boundary

ARC Thickness (nm)

- Resist
- Ta₂O₅
- ARC
- Silicon

200 nm period
λ = 351.1 nm
TE polarization

Grating after interference lithography.

Grating after oxygen plasma RIE of ARC.

Grating after gold plating and resist stripping.
History of HETG Grating Fabrication

Number of Gratings in NE80 vs Time (year - 1900)

- 5/18/95
- 9/12/96
HETG Timeline: the second decade

1989  HETG Accepted for AXAF
3    AXAF Restructured to AXAF-I and AXAF-S;
4    HETG Systems Requirements Review (SRR)

1993  Hampshire Instruments ceases operations; X-ray lithography abandoned

8    Preliminary Design Review (PDR)
1995  Critical Design Review CDR

1996  Deliver & Calibrate Completed HETG
1999  Chandra Launch!
With profound admiration and gratitude for the HETG Team

Tom Markert
1948-1996
SNR E0102-72

- Oxygen $8$
- Ly alpha

- Neon $9$
- Res

- Neon $10$
- Ly alpha

- Magnesium $11$
- Res

Direct image,
all energies

- $1800 \text{ km s}^{-1}$
- $900 \text{ km s}^{-1}$
- $-900 \text{ km s}^{-1}$
- $-1800 \text{ km s}^{-1}$

O VIII Ly $\alpha$

Flanagan et al.
Disk Winds in Black Hole X-ray Binaries

GROJ1655-40

Magnetic Fields Drive Disk Winds

GRS 1915+105

Disk Winds Suppress Jets
Environments of Active Galactic Nuclei

MCG-6-30-15  Lee et al.

NGC 1068  Evans et al. 2009
914 analysis ready observations
308 distinct objects:
623 HETG/ACIS
91 LETG/ACIS
200 LETG/HRC

Verification & Validation (V&V):
All products manually examined for zeroth order position, extraction region, & confusing sources.
Recently reprocessed to apply CALDB 4.1

Search, sort, select, preview, plot, download, ...
SN 1996cr w/HETG (485 ks) circa 2009 (PI: F.E. Bauer)

Flux increased years after explosion: bubble-shell CSM structure. Line shapes w/o red-shifted emission: SN core blocks backside.

Model at 2009. Dia.~0.01" @ 3.7 Mpc

Cyg X-1 Disk & Atmosphere Viewed with HETG ...

... and the best CCDs (Suzaku)
Understanding the Atmosphere
Crucial for Constraining the Physics

Magnetic driving? Transitions from Disks to Jets?
1996 TMA Objective Grating Assembly (TOGA) test at MSFC/XRCF

Twelve years after initial proposal, the first real evidence that grating assembly would perform as expected!!

“[expletive deleted]!!! I might even use the gratings!” --- Leon van Speybroeck
Environments of Active Galactic Nuclei

NGC 3783  Kaspi et al. 2002

NGC 1068  Evans et al. 2009