Nanometers to Megaparsecs: The Inside Story Behind the Making of the Chandra HETG

Claude R. Canizares
Chandra Fellows Symposium
October 2004
Chandra HETG Schematic

X-rays

X-ray mirrors

Grating (stowed)

Grating (in use)

X-ray CCD Detector array

Zero-order beams

Diffracted beams

S0  S1  S2  S3  S4  S5
NASA Chandra X-ray Observatory
High Energy Transmission Grating Spectrometer (HETGS)

HETGS instrument.

Invar grating frame.

Scanning electron micrograph of gold grating.

1.1 meter

3 cm

550 nm

100 nm
HETG Timeline

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1986  Challenger Disaster

1988  Congress approves “phased new start” of AXAF optics;
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1999  Chandra Launch!
“To Disperse or Not To Disperse”
That is THE Question
(wave-particle duality in X-ray spectrometers)

\[ E = h\nu \]

Non-Dispersive
\[ \Delta E \sim \text{fixed} \]
Resolving Power \( \sim E/\Delta E \)

Instruments
- Prop Counters \( \rightarrow \) IPC
- Gas Scint PC \( \rightarrow \) IGSPC
- Si(Li) \( \rightarrow \) CCD
- \( \mu \)Calorimeter
- STJ/TES

\[ \lambda = c/\nu = hc/E \]

Dispersive
\[ \Delta \lambda \sim \text{fixed} \]
Resolving Power \( \sim 1/E \)

Instruments
- Bragg spectrometers
- Transmission Gratings
- Reflection Gratings
Einstein Observatory 1978-1981

Spectrometers

- Focal Plane Crystal Spectrometer (FPCS)
- Objective Grating Spectrometer (OGS)
- Solid State Spectrometer (SSS)
HEAO-2 (Einstein Obs)
Objective Grating Spectrometer (OGS)

1000 lpmm (p=1 micron)
Thin wires
Support structure
Fabricated at Utrecht
HETG Timeline

1979-80  CRC & Mark Schattenburg begin collaboration with Henry I. (Hank) Smith (MIT EECS Dept)

~ 1979 CRC discovers (by chance) that Hank Smith in EECS is expert in micro-fabrication of X-ray gratings and zone plates

Attempts several zone plate and grating design schemes with grad student Mark Schattenburg; settles on HETG concept

Smith very reluctant to collaborate until diminished funding makes him eager to have additional grad student

~ 1980/81 Schattenburg begins working in Smith Nanotstructures Lab to develop improved transmission gratings
Key features needed for an HETG design:

• ~5000 lpmm (p=0.2 micron) gratings

• high efficiency over 1.5 decades of energy (0.4 - 8 keV) => high aspect ratio to enable phased grating

• gratings rugged enough to withstand launch

• fabrication of hundreds of identical grating elements to tolerances of ~100 ppm
INTERFERENCE LITHOGRAPHY

\[ p = \frac{\lambda}{2 \sin \theta} \]
Single-sided grating efficiency (as built)

2500 lpm (0.4 micron period)  5000 lpm (0.2 micron period)
HETG observation of Capella
X-ray Lithography

Key technology for replicating a “thin” grating “mask” into many thick, phased gratings with the same period.
Invention of Micro-gap X-ray Nanolithography

Mask (thin grating)

a) CONTACT X-RAY NANOLITHOGRAPHY

b) MICROGAP X-RAY NANOLITHOGRAPHY
X-ray Lithography Station

Soft X-ray (Cu L line)

Exposure time ~ 24-36 hrs per grating!

We (and industry) needed higher intensity X-ray machines…

But, note prophetic statement:

“X-ray lithography is the technology of the future… and it always will be!”

-- Mark Schattenburg
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Key Proposal Strategy issue:

How can we (MIT/CSR) propose for 3 instruments ???

- CCD camera (aka ACIS),
- Bragg Crystal Spectrometer (building on Einstein FPCS)
- And HETG ????
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Strategy: Propose for even more!!!

CCD -- collaborate with Penn State (Garmire) as PI (became ACIS)

Then propose not two, but three instruments in one proposal for High Resolution X-ray Spectroscopy Investigation: BCS, HETG and an “optional” LETG (expecting [hoping] to lose the low energy grating)
Proposal for High Resolution X-ray Spectroscopy Investigation

Teamed with Ball Aerospace and GSFC (Bruce Woodgate) for BCS

“We propose to use AXAF to perform moderate and high resolution X-ray spectroscopy of point and extended celestial objects including stars, X-ray binaries supernova remnants, galaxies, clusters of galaxies, quasars, and interstellar and intergalactic material.”

“We propose two complementary dispersive spectrometers [BCS & HETG]… we … offer an LEG only as an option…”
Professor Claude R. Canizares  
Department of Physics and  
Center for Space Research  
Building 37-501 
Massachusetts Institute of Technology 
Cambridge, MA 02139 

Dear Dr. Canizares:

We have completed the review and evaluation of proposals for the Advanced X-ray Astrophysics Facility (AXAF) mission. I am pleased to inform you that the proposal "High Resolution X-ray Spectroscopy Investigation for the AXAF Mission" submitted by you and your colleagues has been accepted, in part, for definition study on AXAF. The low energy grating option, which you proposed, is not being selected. You are also appointed to the AXAF Science Working Group (SWG). Final selection for the mission will be contingent upon the definition study results and the approval of AXAF as a spacecraft new start.

The instrument definition study will parallel and be integrated with spacecraft definition studies presently being conducted by two mission contractors and should result in a clear understanding of scientific and technical requirements of the mission. During the definition study, we expect you to work closely with the NASA AXAF Definition Team and mission definition contractors to specify mission requirements and spacecraft interfaces and to develop a detailed schedule for instrument test and delivery. We will also develop a Project Data Management Plan (PDMP).

The initiation of the development phase will depend upon, among other factors, the estimated total cost of AXAF and the confidence that the program can be completed within this estimate. During the definition study, we will estimate the cost
AXAF 1984

- 6 mirrors
- 4 focal plane instruments
- Low earth orbit
- Shuttle servicing
- “just like HST”
- launch ~1991

**AXAF remained 7-8 yrs away from launch for the next 8 years!**
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NASA Space & Earth Sciences Advisory Committee Report 1986/7

The Crisis in Space and Earth Sciences
March 17, 1988

The Honorable Donald W. Riegle
Chairman
Subcommittee on Science, Technology, and Space
105 Dirksen Senate Office Building
Washington, D.C. 20510

Dear Don:

I am writing to express my strong support for AXAF. Advanced X-ray Astrophysics Facility, which has been included in the President’s 1989 budget request. AXAF constitutes a major step forward in reassessing America’s leadership in space science and its inclusion in this year’s authorization is critical.

The space science of X-ray Astronomy was pioneered by the United States in the 1960’s and 1970’s. While numerous countries have profited from our efforts and have X-ray Astronomy missions flying at present, we do not. The Einstein Observatory, which was launched in 1978 and then under study for a decade now by NASA, the scientific community, and industry, is the follow-on to highly successful Einstein. To meet its mid-1980’s date AXAF must be funded this year.

Due to its tremendous scientific potential, AXAF is listed as the most important single recommendation for the national Academy of Sciences Astronomy Survey Committee and it continues to gain full support of scientific community. But, current estimates alone, over 1000 astronomers from 100 institutions will be involved with AXAF data and 10-20 per year will complete their thesis research during AXAF fifteen-year lifetime.

The cost of AXAF development this year is $27 million and $15 in current year dollars over 5 years. It represents a significant investment. The design of the telescope and placement of the entire observatory in space is an investment in our national technological base.

Despite its relative youth, this space-based science, X-ray astronomy, has already made a very significant contribution to the technological base. Technology advances taken from instrumentation developed for X-ray astronomy have been used in a variety of important products from Medical CAT scanners to airport X-ray detectors. Other X-ray related breakthroughs in crystallography and precision optics hold promise for extraordinary advances in a number of areas.

This is an extremely important time for astronomy. A number of technological advances and unique phenomena in the universe provide an opportunity for extraordinary scientific advances. The promise of those advances will not only increase human knowledge, it will help us maintain an outstanding group of astronomers and recruit the next generation of scientists. Our scientists are our greatest edge in economic competitiveness today and we can not afford to lose these people.

The planning for AXAF is completed. The tests required have all been accomplished. The budget is well understood. The project can be done and it will have an immediate payoff for all of science.

I believe that AXAF’s designation as a new start in the Space Science budget is a cornerstone of a new pride in space science and I ask for your support.

Sincerely,

John F. Kerry

JFK/nrd
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“Re-proposal” was the written portion, followed by ~3 hr “stand-up oral exam” by CRC (with Bill Mayer) before AXAF deselection review board (chair: B. Margon)

CRC is optimistic

….but not for long!!
• In a hallway discussion at Jan 1989 Boston AAS meeting, unnamed, usually reliable source tells CRC that review board has “deselected” BCS to save cost/complexity

• CRC reaches Charlie Pellerin (NASA Astrophysics Director) that evening at AAS Hotel; asks for breakfast meeting next morning; spends sleepless night wondering what to tell him

• CRC asks Pellerin for “stay of execution” to allow proposal of revised BCS as “insurance” against problems with XRS; Pellerin agrees

• By Sept 1989 MIT/Ball team submits new proposal for revised BCS that complements XRS -- presented to Len Fisk (yet another oral exam) and accepted

• And the politics continues, year after year.....
May 20, 1991

Professor Claude R. Canizares
Professor of Physics
Director
Massachusetts Institute of Technology
Center for Space Research
Cambridge, Massachusetts 02139

Dear Professor Canizares:

Thank you for your recent letter supporting the funding for continued development of the Advanced X-ray Astrophysics Facility (AXAF).

On May 14, the Committee on Commerce, Science, and Transportation met to consider the FY 1992 NASA authorization bill. I am pleased to report that the Committee approved, without objection, the Subcommittee’s proposal to fully fund AXAF for the coming fiscal year. I expect our authorization bill to be ready for Senate consideration in early June.

Sincerely,

AL GORE
Chairman
Subcommittee on Science, Technology, and Space

AG:spb
HETG Timeline (continued)

1989 BCS deselected; revised BCS proposed & accepted

1992  AXAF Restructured to AXAF-I and AXAF-S; BCS dies final death; team focuses on HETG for AXAF-I; AXAF-S eventually dies also
AXAF Restructuring -- 1992

*(the pictures but not the pain...)*

Weiskopf 2003
So, the BCS ws dead but we still had the HETG

… until disaster struck again!
So, the BCS was dead but we still had the HETG … until disaster struck again!

• We had subcontracted with Hampshire Instruments, a start-up company building high-intensity X-ray sources for microchip lithography, for ~$3.5M machine

• After $1.7M of progress payments, Hampshire president asks for further, accelerated payment to meet payroll

• CRC declines and exercises backup option for delivery of another, existing Hampshire machine

• Hampshire ceases operations and N.Y. State financing agency seizes all assets, including backup machine

• X-ray lithography is no longer possible, but miraculously, Schattenburg develops alternate based on precision production of multiple X-ray masks
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!!*
• By the next quarterly review at NASA/MSFC, CRC announces Hampshire failure, presents recovery plan and **pledges delivery of HETG on schedule and on budget**; even NASA (A. Diaz) is amazed (though not as amazed as CRC himself!)

• After ~ 1 year effort, MIT lawyers unsuccessful in obtaining any recompense from liquidation; U.S. government concurs that MIT has acted responsibly and closes matter

• President of Hampshire Instruments commits suicide
But now, we need significant facilities for large-scale production of hundreds of gratings

- Plan devised for stand-alone Class 100-1000 clean-room facilities in CSR building to permit production of HETG facets
- Requires several $M investment by MIT
- Provost Mark Wrighton reviews request and denies it
- By phone (from NASA HQ) CRC asks for “stay of execution” and chance to appeal
- CRC makes personal appeal to Provost, who reverses decision
- CSR facility is constructed at cost of ~$3M and loaded with ~$5M of specialized equipment
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

- 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.
GRATING AFTER INTERLAYER ETCH

resist

interlayer

ARC

0.2 μm
a) SiO$_2$ Interlayer

b) Ta$_2$O$_5$ Interlayer
11) Spin-Etch Wafer
   etch in acid(s)
   rinse & dry

Before Spin Etch

12) Mount
   period map baseline (optional)
   clean frames
   apply glue to frames
   align & join frames to membrane
   soft-cure glue (time)
   cut out frames
   oven hard-cure glue (optional)
   optical inspection
   period map final

After Backside Spin Etch

Clean Invar Frame

Apply Adhesive

Align and Join Frame to Membrane

Cure and Cut Away
(a) High Energy Grating (HEG).

(b) Medium Energy Grating (MEG).
Fabricating hundreds of gratings is only part of the job

Dozens of scientists, engineers, technicians and students invented a whole host of new ways to measure, hold, calibrate, test, protect, model, etc. the grating spectrometer

Here are just a few examples:
How do we map grating periods to <100 ppm across grating and from one grating to another for ~1000 gratings? Use automated laser reflection system (Dewey)

How do we test each grating’s efficiency? Test some gratings at synchrotron facilities, test all gratings in automated X-ray test system at MIT (Flanagan, Elder, …)

How do we align gratings? Use polarizing property of gratings for white light (Levine)

HETG Test/Alignment Facilities
Bldg NE80 (Draper)
How do we assure gratings will withstand launch?  *Perform individual and system level acoustic, shake, and thermal-vac tests (McGuirk, Dewey)*

How do we know if gratings are humidity sensitive?  *Dip one in a glass of water at a Science Working Group meeting*

How do we hold gratings in torroidal “Rowland Circle” geometry to required tolerance?  *Design precision HETG Support Structure (HESS) fabricated by numerically-controlled milling machine (Pak)*

How do we avoid thermal/mechanical stresses from distorting gratings?  *Use INVAR frames held to HESS by a single screw (Pak, Manino)*

How do we know if HETG will survive truck shipment to MSFC?  *Send truck on dry run with shipping container instrumented with accelerometers*

How do we know if our gratings will achieve the required resolution?  *Test them with the “test mirror assembly (TMA)” in the MSFC X-ray Cal facility (Galton, Dewey)*
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
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1996  Deliver & Calibrate (XRCF) Completed HETG

1999  Chandra Launch!!! (only 20 years had passed)
High Energy Transmission Grating

336 grating facets aligned to <1 arc min tolerance

HEG: inner two rings

MEG: outer two rings
Tom Markert
1948-1996
With deep gratitude to the Incomparable HETG (and BCS) Team

HETG Instrument Team:
Daniel Dewey
Kathryn Flanagan
Allen Levine
Thomas Markert
Mark Schattenburg
Henry I. Smith

Engineers
Eugene Galton (Proj Mgr)
William Mayer (Former PM)
Michael McGuirk (Dpty PM)
Richard Aucoin
Len Bordzol
George Czernienko
Richard Elder
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Don Humphries
Christopher Pak
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Irena Porro
Norbert Schulz
Michael Wise

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Mario Jimenez
Julia Lee
Sera Markoff
Patrick Ogle
Patrick Wodjowsky

BCS Scientist & Engineers
Bruce Woodgate (GSFC)

Graduate Students
David Buote
Kathleen Early
Yao-Ching Ku
Taotao Fang
Maya Farhoud
Rob Gibson
Amalia Hicks
Una Hwang
Tesla Jeltema
Joshua Migliazzo
Alberto Moel
Gabrielle Owen
Mark Schattenburg
Michael Stage
David Um

Plus a dozen undergraduate UROP & senior thesis students…
The AXAF Science working Group
HEG Spectrum of Capella at Mg XI

Now which ones of you are going build a truly high resolution spectrometer!!