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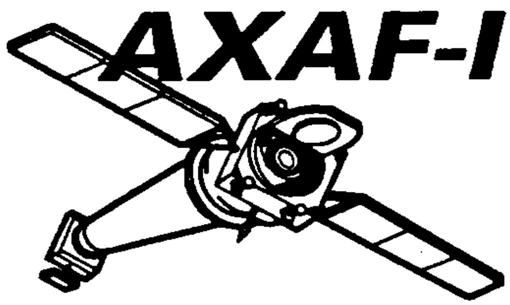
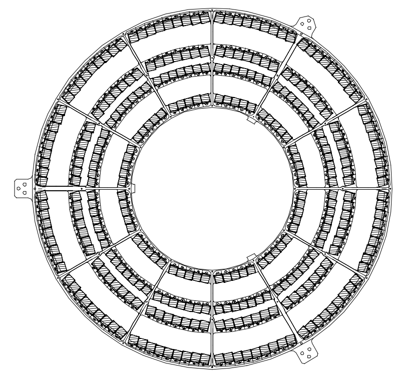



**Advanced X-ray Astrophysics Facility**

***HETG***



**High Energy Transmission Grating**

# HETG Phase C-D Contract Final Report

Submitted to:
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812

Submitted by:
Center for Space Research
Massachusetts Institute of Technology
Cambridge, MA 02139

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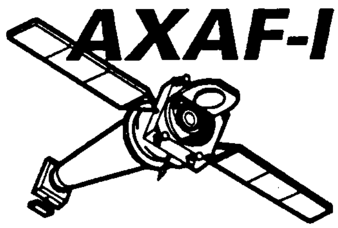
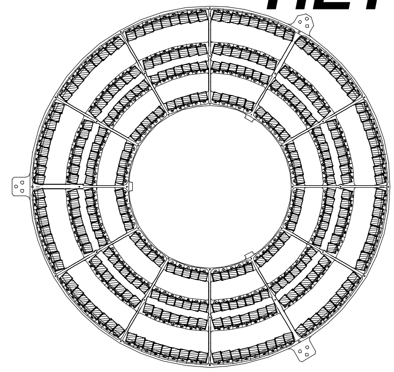



**Advanced X-ray Astrophysics Facility**

**HETG**



**High Energy Transmission Grating**

# HETG Phase C-D Contract Final Report

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# Table of Contents

# 1. Introduction and Summary

The High Energy Transmission Grating (HETG) Contract Phase C/D, NAS8-38249, ran from July 13, 1990 to February 28, 2002. MIT's Center for Space Research (CSR) designed, built, and integrated a spectrographic instrument into the Advanced X-ray Astrophysical Facility (AXAF) satellite, later called Chandra. MIT also supplied the necessary scientific support for the first 31 months of highly successful on-orbit operation of the HETG Spectrometer (HETGS). MIT will support HETGS through the planned 89+ months of continued operations. The success of HETGS is shown by its high on-orbit reliability, and by the number and quality of the scientific results published. The refereed papers documenting these scientific results are so numerous, that a simple bibliographic listing forms a major part of this report.

The key milestones in developing the flight hardware were:

- System Requirements Review 5/10/93
- Preliminary Design Review 5/23/94
- Critical Design Review 1/17/95
- Mass Model Delivery to Eastman Kodak (EKC) 7/27/95
- TMA Objective Grating Assembly (TOGA) Delivery 6/30/96
- Instrument Delivery to X-Ray Calibration Facility (XRCF) 10/1/96

The key post-Acceptance milestones for the flight hardware were:

- Delivery from XRCF to EKC 6/1/97
- Telescope Delivery, EKC to TRW 9/1/97
- AXAF Launch 7/23/99
- HETGS First Light 8/28/99
- Contract End 2/28/02

To successfully meet each one of these milestones, efforts were expended at MIT/CSR. These efforts were guided and monitored by the AXAF (Chandra) Program Office and the Science Working Group at the Marshall Space Flight Center (MSFC). The HETG is one of four Science Instruments (SI) on AXAF-I, a space based observatory for performing studies of X-ray emission from every class of astrophysical emitter. The AXAF-I project objectives are detailed in key documents; the definitive statements of AXAF Requirements are AXAF-101,"AXAF Program Requirements Document, Level 1", and MSFC-SPEC-1836B, "AXAF Level II Project Requirements Document". The AXAF "Observatory To Science Instrument Interface Control Document (ICD)" TRW Document IF1-20, also known as CM07a, describes and defines the interfaces between the Observatory and the HETG.

This report is a compilation of the accomplishments and documentation in the successful completion of this contract. It refers to many of the documents that were delivered to MSFC during the program as well as those retained at CSR. It summarizes system studies, calibration, contamination control, design, process development, facility development, fabrication, testing, observation planning, program support, and post launch data analysis and publication efforts during these eleven years. This contract was preceded by the Phase A/B studies under contract NAS8-36748, and the data analysis and program support is being continued under contract NAS8-01129.

# 2. HETG Management and Engineering Process

Chandra in many ways set the pace for NASA Programs in the 1990's. Chandra met the cost, and performance goals set before Program start. There was some schedule slippage due mostly to additional reviews held in the wake of the two Mars mission failures. HETG set the pace among the Chandra contracts. Partly because of the elegant simplicity of the instrument, and partly because of the performance of the team, HETG met the cost and schedule objectives set before the program start and exceeded the key science performance goals for Diffraction Efficiency and Resolving Power by 20%. The outstanding performance of the HETG instrument is reflected in the number and quality of the scientific papers based on HETG observations carried out by many scientists and groups; the subset of these papers directly produced by the HETG group are listed in section 12.

The HETG management and engineering processes followed the proven approaches developed by NASA over the years and documented in NASA management instructions, specifications and standards. The result is an HETG Science Instrument which is giving robust performance on orbit. The engineering knowledge generated in developing HETG is captured in a set of physical documents archived in the MSFC library, among other places. Many of these documents are available on the MSFC local area network on the G-drive of the fileserver "CHANDRA".

# 3. System Requirements Review

The initial HETG efforts defined the system requirements through a process of negotiation between the astrophysicists who are the end users of the instrument and the scientists who developed the fabrication process. The knowledge developed through this negotiation is captured in the 8 documents in the System Requirements Review data package submitted to MSFC and TRW on May 10, 1993.

Those documents include:

| Title | DPD 729 Identifier |
|---|---|
| HETG Project Management Plan | SMA 01 |
| Work Breakdown Structure and Dictionary | SMA 02 |
| HETG Contract End Item Specification, | SCM 02 |
| Ground Support Equipment Specification. | SCM 03 |
| HETG Verification Plan | SVR 01 |
| Verification Requirements and Specifications Document | SVR 02 |
| Product Assurance and Safety Plan | SPA 01 |
| Safety Compliance Data, and the | SSA 02 |

Each document was submitted both in paper form, and in the format of Microsoft Word documents which were loaded on the Observatory Projects Office file server at MSFC. The documents are available over the internet using the "file transfer protocol" function of Internet

Explorer. An account on the OPO server (username and password) is required to access these documents, but that is easily obtained by anyone who should have access.

# 4. Interface Working Groups (IFWG)

The interface working groups developed the interface definitions among all the instruments and the spacecraft. The interface knowledge was captured in the minutes of the IFWG meetings, and the TRW document CM04, AXAF to Science Instrument Preliminary ICD. TRW recorded and published minutes of the IFWG meetings, sending copies to all participants.

The final form of the interfaces is recorded in the TRW document IF 1-20, MSFC DPD692 CM07a, Observatory to Science Instrument ICD. The primary mechanical interfaces for HETG are defined in TRW drawing 301331, in Appendix G of IF 1-20.

# 5. Preliminary Design Review

After establishing the Requirements and developing Interface Specifications, a strawman design was created. The Preliminary Design Review gave all interested parties the opportunity to evaluate the strawman design. The following documents were submitted for the Preliminary Design Review:

| Title | DPD 729 Identifier |
|---|---|
| HETG Project Management Plan | SMA 01 |
| HETG Contract End Item Specification, | SCM 02 |
| Ground Support Equipment Specification. | SCM 03 |
| HETG Operations Handbook | SOP 01 |
| Technical Review Documentation (PDR) | SCM 04 |
| Materials and Process Selection Plan | SHF 01 |
| Materials and Process Specification List | SHF 02 |
| Material Identification and Usage List | SHF 03 |
| Fabrication Plan | SHF 05 |
| Contamination Control Plan | SHF 06 |
| Verification Plan | SVR 01 |
| Verification Requirements and Specifications Document | SVR 02 |
| Verification Test and Assessment Reports | SVR 04 |
| Product Assurance and Safety Plan | SPA 01 |
| Failure Mode and Effects Analysis (FMEA) | SPA 04 |
| Critical Items List | SPA 05 |
| Data, Safety Compliance | SSA 02 |
| Technical Analyses and Models | SSE 03 |
| List of Drawings and Specifications | SSE 04 |
| Drawings | SSE 05 |
| Fracture Control Plan | SSE 08 |

The "Work Breakdown Structure and Dictionary", SMA 02, was not resubmitted because it required no changes between SRR and PDR.

# 6. Critical Design Review

The HETG Critical Design Review Data Package consists of the following documents:

| Title | DPD 729 Identifier |
|---|---|
| Contract End Item Specification | SCM02 |
| Ground Support Equipment Specification | SCM03 |
| Spares List | SCM07 |
| Materials and Process Selection and Verification Plan | SHF01 |
| Materials and Process Specification List | SHF02 |
| Material Identification and Usage List | SHF 03 |
| Fabrication Plan | SHF05 |
| Contamination Control Plan | SHF06 |
| HETG Project Management Plan | SMA01 |
| HETG Operations Handbook | SOP01 |
| Product Assurance and Safety Plan | SPA01 |
| Failure Mode and Effects Analysis (FMEA) | SPA04 |
| List, Limited Life Items | SPA11 |
| Safety Compliance Data | SSA02 |
| System and Subsystem Technical Analysis and Models | SSE03 |
| List of Drawings and Specifications | SSE04 |
| Drawings | SSE05 |
| Fracture Control Plan | SSE08 |
| Verification Plan | SVR01 |
| Verification Requirements & Specification Document | SVR02 |
| Verification Requirements & Specification Compliance Report | SVR06 |
| Technical Review Documentation (CDR) | SCM04 |

All of these documents shipped January 13, 1995, except the last item, SCM 04, which was hand carried to the review January 19, 1995.

# 7. Mass Model Delivery to Kodak

The HETG Mass Model was delivered to Kodak on June 30, 1996.

The HETG Mass Model was fabricated from the residual hardware from the first attempt to machine the HETG Element Support Structure. The interface features, including all the mounting and alignment features, were accurately machined and identical to the flight unit. The Alignment Reference Mirror and its interface support structure were delivered along with the Mass Model. This permitted use of the Mass Model for handling and alignment procedure development and rehearsal, as well as for mechanism life testing and overall weight and balance proofs.

There was an error in the CNC tape that took a several square inch chunk out of the part in a non-critical area. The missing mass was replaced by adding a weight at the location of the missing material.

The 336 grating facets were mounted using the same type hardware as the flight unit. The facets were simulated by aluminum rectangles having the same mass and center of gravity as the facets themselves. So the mass and center of gravity of the Mass Model were identical to the flight unit.

The Mass Model was used at MIT prior to delivery to rehearse the mass and center of gravity measurement procedures.

# 8. Flight Hardware Acceptance with DD-250 and Report

On Sept. 17, 1996, prior to HETG flight hardware delivery, an Acceptance Data Package consisting of four volumes was reviewed at MIT by personnel from MIT, MSFC and TRW.

## 8.1. SCM05 Volume I Table Of Contents

1. Configuration Identification List (Top Level)
Equipment Log Books (DR SCMI0
    1.1. XGEF logbook
    1.2. Alignment Logbook
2. Limited Life Items (DR SPAll)
3. Mass Properties Report (DR SMA03)
4. Shipping Documents (DD250, Form 11
5. Certificate of Qualification (DR SP A09)
6. Work planned, but not completed
7. Work planned to be completed at the next site
8. Nonconformance Reports List and Status
9. Hardware Shortages and Rationale/Recovery Plan
10. Waivers and Deviations
11. Packaging, Handling and Transportation Record (MSFC Form 362)

## 8.2. SCM05 Volume II Table Of Contents

13. List of Installed Nonflight Hardware
14. Special Handling and Storage Procedures (DR SCM09)
15. Assembly Dwgs. and Interface Schematics, Installation Dwgs.
16. Radioactive Source License
17. Summary of Materials and Cleanliness Verification Data
    17.1 MSFC-SPEC-1238
    17.2 MSFC-SPEC-1443
    17.3 NHB 8060.1
    17.4 MIL-Sill-1246, Level 350A
18. MUA List and Status
19. Handling Equipment Proof-load Certificates
20. Nonconformance Reports (DR SP A06)

## 8.3. SCM05 Volume III Table Of Contents



## 8.4. SCM05 Volume IV Table Of Contents

# 9. Calibration Support at MIT

MIT collected several gigabytes of detailed calibration data on each HETG grating facet produced. A database is available which associates every measurement data file with the serial number of the grating frame. Each grating frame had a serial number machined into the frame at the time of the frame manufacture. The database associates the frame serial number with the wafer serial number, so the entire fabrication process data is traceable.

The active area used in flight varied for each grating facet, depending on where it was mounted. Measurements of absolute grating period were recorded as a function of location on each grating, and filed by measurement date and serial number. Measurements of diffraction efficiency were recorded as a function of X-ray energy and location on the grating.

This measurement data was used in an overall model of the instrument to predict compliance with the Level I performance requirements prior to assembly and prior to the end-to-end calibration of the Chandra instruments at MSFC's X-Ray Calibration Facility (XRCF). The energy scale calibration, resolving power and diffraction efficiency of each flight grating were input to the model and weighted by the HRMA effective collecting area appropriate for the facet location and X-ray energy. The model prediction agreed very well with the XRCF measurement.

The raw and processed data from every measurement was recorded on a hard drive on the MIT Center for Space Research network, and archived on two duplicate magnetic tapes. One copy of each tape is stored at MIT, and the other copy is stored (as of January 2002) at the SAO CXC office on Garden Street in Cambridge, MA. There are hundreds of tapes in each data set. The tapes are labeled by test date, and there is a database which associates every grating facet with all the tests performed and with the date the test was performed.

## 9.1 Laser Reflection Period Measurement

MIT developed an instrument to measure grating period which uses a laser beam reflected and diffracted from the "grating facet under test". The grating equation relates two angles (between the surface normal and the reflected beam and between the surface normal and the diffracted beam) to the period of the grating at the location where the laser beam illuminates it. The instrument, called the "LR" for short, measures the average grating period within the 2 mm diameter illuminated area. The precision of the period measurement with this instrument is .001 nanometer, about 1/50 of the typical spacing between atoms.

Every grating produced for HETG had an LR map produced at least once. The map typically consists of a 10 x10 or denser grid. Gratings which initially meet the absolute period and period uniformity specifications are subjected to thermal cycling and simulated launch vibration environments, and have the period mapped again after each environmental exposure. This repeated mapping gave great confidence in both the fabrication process and the stability of the gratings to environmental influences.

The LR instrument was calibrated by measuring special transfer standard gratings produced by MIT and measured by NIST. The transfer standards were the same as the flight gratings except for being on silicon substrates, rather than the 0.5 or 1.0 micron thick polyimide substrates used for flight. The silicon substrate provided the temporal and thermal stability required for a dimensional standard.

## 9.2 XGEF Diffraction Efficiency Measurement

Diffraction efficiency is defined as the ratio of the photon counts within a diffraction spot or line to the number of incident photons at that energy. Diffraction efficiency is a function of both photon energy and subaperture location within a grating element.

MIT developed a facility called the "X-Ray Grating Evaluation Facility" (XGEF) to measure the diffraction efficiency of grating facets as a function of X-Ray energy and position on the grating.

XGEF uses an X-Ray source with a slit collimator to simulate a star and the HRMA. The grating under test is located in the collimated beam. The grating to detector distance is 8.6 m, simulating the on-orbit use condition. Two detectors are available: a position sensitive proportional counter (PSPC), and a Lithium doped Silicon detector, each of which are sensitive to single photons. Each grating element is mounted so that its dispersion axis is aligned with the PSPC high resolution axis during the measurement. A monitor detector located at the source is used to measure source intensity fluctuations.

The diffraction efficiency of each of the 336 HETG flight grating elements was measured using XGEF. The overall HETG diffraction efficiency was predicted using a computer model which included the predicted efficiency of each HRMA shell, the mounting location of each grating element, and the XGEF measurements of the grating element diffraction efficiency. The model predicted that HETG would exceed the Level I requirement for diffraction efficiency by approximately 20%.

The computer model was verified by the end-to-end calibration at Marshall Space Flight Center's X−Ray Calibration Facility (XRCF), using the actual HRMA and flight detectors. The measurements agreed well with the prediction.

## 9.3 Synchrotron Studies

Dr. Tom Markert initiated and led a program of testing select gratings at synchrotron light source facilities to verify our analytical models of the grating response to X-rays. SAO's Dale Graessle helped Dr. Markert's team to perform tests at Brookhaven National Laboratory's National Synchrotron Light Source (NSLS). Lower energy tests were also carried out at the radiometry laboratory of the Physikalish-Technische Bundesanstalt (PTB). Dr. Kathryn Flanagan used this data to improve the accuracy of the internationally accepted Tables of the Optical Constants of gold and polyimide, which are critical input data to the model of the grating diffraction efficiency. The improvements to the Tables were hailed by the international X-ray physics community as a significant science result from Chandra even before launch. Using the new optical constants, Dr. Dan Dewey's analytical models give excellent agreement with the measured HETG grating X-ray diffraction efficiency.

# 10. Calibration Support at MSFC

The calibration of the HETG spectrometer was performed at MSFC as part of the overall Chandra calibration. The calibration took place in stages, with the HRMA being measured first using a special ground calibration detector called the XDA, the XRCF Detector Assembly. Then HRMA/flight-detector (ACIS or HRC) combinations were measured, and finally HRMA/OTG/flight-detector combinations.

The entire calibration process was rehearsed using the 16 inch diameter Technology Mirror Assembly (TMA) as a HRMA surrogate, a "two chip ACIS" as the ACIS surrogate, and the XDA, the XRCF Detector Assembly, as itself. The rehearsal allowed debugging of the procedures and data processing using live data. The OTG surrogate was called the TMA Objective Grating Assembly. The rehearsal provided a testbed for the control system timing, and for the distribution of data processing tasks among the 30 computers in the XRCF Control Room and the at the Instrument Scientist's analysis stations.

## 10.1 TOGA

The TMA Objective Grating Assembly (TOGA) is matched in size to the Technology Mirror Assembly (TMA), an AXAF polishing readiness demonstrator. The TOGA Objective Grating Support Structure held flight spare HETG grating facets and LETG grating modules in the clear aperture of the TMA, which acted as the objective element of an X-ray telescope.

The TOGA contained eight Medium Energy Grating facets, and eight high Energy Grating facets, as well as ten LETG grating modules, all aligned as in Chandra. This provided for real data to be used in checkout of the data processing system, and in determining the robustness of the algorithms for locating the lines of grating dispersion.

MIT supplied:

- TOGA Objective Grating Support Structure
- HETG flight spare grating facets (qty = 16)
- Intermediate Support Structure
- Mounting and alignment of the gratings and Intermediate structures
- Protective covers for the TOGA, and
- Drawings and documentation of the TOGA design

All TOGA hardware was supplied in a MIL-STD-1246 level 350A cleanliness condition for compatibility with the XRCF, and for compatibility with the flight hardware.

In addition to the first demonstration of the quality of the HETG and LETG gratings, several bugs were located in the procedures and data processing software during the rehearsal. The bugs were corrected prior to the actual test runs with flight hardware. The net result was a greater awareness of the grating instruments' operation and a substantial savings to the Program in cost and schedule.

## 10.2 XRCF

MIT supported the calibration at XRCF throughout the months of preparation, data collection and interpretation, and packaging and shipment to TRW for assembly into the Chandra satellite.

MIT helped to develop the handling plans to assure the cleanliness and safety of HETG throughout its stay at XRCF. MIT supported the installation of HETG into XRCF during the week of December 3 through 10, 1996.

MIT scientists remained on-site at XRCF throughout the data collection period, interpreting the data collected and adjusting the measurement sequence as needed to accommodate hardware and software anomalies. Data collection was a 24 hour/day, 7 days/week operation, and the scientists worked in shifts to provide continuous coverage.

One anomaly in the HETG instrument was discovered at XRCF. A few grating facets on HETG were out of alignment in roll, with the result that photons diffracted by those facets were displaced to pixels adjacent to the nominal line formed by the majority of the grating facets. The anomaly produces no degradation in resolving power, and only a very slight reduction in diffraction efficiency. The error was caused by a tooling problem during grating fabrication which resulted in unusual stress in the polyimide substrates of one fabrication lot. HETG was flown with no corrective action required.

The resolving power and diffraction efficiency measurements on the end-to-end flight system showed that HETG met its Level I performance requirements by a large margin. The measurements agreed well with the values predicted by the computer model.

Details of the HETG ground calibration and analyses are provided in the HETG Ground Calibration Report, available through the Chandra web site.

# 11. Chandra Integration Support

MIT supported the integration of HETG into the Chandra satellite at TRW June 5 through 18, 1997. The integration was planned for only a few days, but took significantly longer because of errors in installation tool design and in machining and installation of mounting shims. The errors were all corrected eventually, and HETG was mounted on the Aft HRMA Structure within its alignment and contamination specifications.

# 12. Pre-Ship Reviews

NASA requested an unplanned pre-shipment review by an independent panel of experts. MIT supported this Independent Assessment by presenting a complete review of how the HETG design met the Level I performance requirements, and how the verification activities confirmed that the flight article realized the design.

MIT supported the AXAF-I Acceptance Review at TRW, August 4-6, 1998. The part of the review related to this contract covered simply the HETG Acceptance Data Package, Waivers and Nonconformances.

# 13. Orbital Activation and Calibration

The HETG project office supported operations efforts for HETG and LETG initial insertion and retraction and the establishment of an on-orbit operations baseline. The HETG project office also supported planning and analysis of focus and calibration observations during the initial months of HETG operation. Key calibration parameters were updated from on-orbit data and supplied to CXC for data processing.

The HETG project office also provided critical support throughout the recovery from and resolution of two insertion anomalies. The HETG project office identified both the cause of the anomalies and work-around processes which allow the mission to proceed with no loss of science capability.

# 14. HETG Engineering Knowledge Captured

The "HETG specific" process knowledge is captured in the procedures written for the technicians to follow in manufacturing the grating elements and in assembling the elements onto the mount. This knowledge is so specific that it is not likely to be useful for any other purpose. Nevertheless, the procedures are available as part of the Acceptance Data Package described in section 7.

The principles and methods discovered in developing the HETG manufacturing process are recorded in Papers in archival journals, in Presentations, which are usually published in conference proceedings, and in student theses and dissertations, which are available from University Microfilms.

The next three subsections list the documents and bibliographic data which capture the new manufacturing or engineering principles discovered during the HETG engineering effort.

## 14.1 Papers

**1992**

"X-ray nanolithography- the clearest path to 0.1 μm and sub-0.1 μm ULSI," M. L. Schattenburg and H. I. Smith, *Japan J. of Applied Phys. Series 5, Proc. of 1991 Intern. Micro Process Conference*, eds. S. Namba and T. Tsurushima (Japan Journal of Applied Physics, Tokyo), 63-70 (1992).

"The spectral archive of cosmic x-ray sources observed by the *Einstein Observatory* Focal Plane Crystal Spectrometer," K. S. K. Lum, C. R. Canizares, G. W. Clark, J. M. Coyne, T. H. Markert, P. J. Saez, M. L. Schattenburg, and P. F. Winkler, *Astrophys. J. Suppl.* **78**, 423-503 (1992).

"An anti-reflective coating for use with PMMA at 193 nm," A. Yen, H. I. Smith, M. L. Schattenburg, and G. N. Taylor, *J. Electrochem. Soc.* **139**, 616-619 (1992).

"A proposed method for fabricating 50 nm-period gratings by achromatic holographic lithography," A. Y. Yen, M. L. Schattenburg, and H. I. Smith, *Applied Optics* **31**, 2972-2973 (1992).

"Fabrication of 50 nm line-and-space x-ray masks in thick Au using a 50 keV electron beam system," W. Chu, H. I. Smith, S. A. Rishton, D. P. Kern, and M. L. Schattenburg, *J. Vac. Sci. Technol. B* **10**, 118-121 (1992).

"Diffraction in proximity x-ray lithography: comparing theory and experiment for gratings, lines, and spaces," K. Early, M. L. Schattenburg, D. B. Olster, M. I. Shepard, and H. I. Smith,

*Microelectronic Engineering* **17**, 149-152 (1992); also in *Microcircuit Engineering 91-Proceedings of the International Conference on Microlithography, September 17-19, 1991, Rome, Italy*, ed. A. Tucciarone (Elsevier, Amsterdam), 149-152 (1992).

"Low-stress gold electroplating for x-ray masks," W. Chu, M. L. Schattenburg, and H. I. Smith, *Microelectronic Engineering* **17**, 223-226 (1992); also in *Microcircuit Engineering 91-Proceedings of the International Conference on Microlithography, September 17-19, 1991, Rome, Italy*, ed. A. Tucciarone (Elsevier, Amsterdam), 223-226 (1992).

"An achromatic holographic configuration for 100 nm-period lithography," A. Yen, E. H. Anderson, R. A. Ghanbari, M. L. Schattenburg, and H. I. Smith, *Applied Optics* **31**, 4540-4545 (1992).

"Lithography for manufacturing at 0.25 micrometer and below," H. I. Smith and M. L. Schattenburg, in *Crucial Issues in Semiconductor Materials and Processing Technologies*, eds. S. Coffa, F. Priolo, E. Rimini, and J. M. Poate (Kluwer Academic Publishers, Dordrecht, The Netherlands), 153-166 (1992).

"Why bother with x-ray lithography?," H. I. Smith and M. L. Schattenburg, in *Electron-Beam, X-Ray, and Ion-Beam Submicrometer Lithographies for Manufacturing II* (*Proc. SPIE* **1671**), ed. M. Peckerar (SPIE, Bellingham, WA), 282-298 (1992).

"Large-area, free-standing gratings for atom interferometry produced using holographic lithography," J. M. Carter, D. B. Olster, M. L. Schattenburg, A. Yen, and H. I. Smith, *J. Vac. Sci. Technol. B* **10**, 2909-2911 (1992).

"Conductance quantization in a GaAs electron waveguide device fabricated by x-ray lithography," W. Chu, C. C. Eugster, A. Moel, E. E. Moon, J. A. del Alamo, H. I. Smith, M. L. Schattenburg, K. W. Rhee, M. C. Peckerar, and M. R. Melloch, *J. Vac. Sci. Technol. B* **10**, 2966-2969 (1992).

"Modeling and experimental verification of illumination and diffraction effects on image quality in x-ray lithography," S. D. Hector, M. L. Schattenburg, E. H. Anderson, W. Chu, V. V. Wong, and H. I. Smith, *J. Vac. Sci. Technol. B* **10**, 3164-3168 (1992).

"Fabrication of parallel quasi-one-dimensional wires using a novel conformable x-ray mask technology," R. A. Ghanbari, W. Chu, E. E. Moon, M. Burkhardt, K. Yee, D. A. Antoniadis, H. I. Smith, M. L. Schattenburg, K. W. Rhee, R. Bass, M. C. Peckerar, and M. R. Melloch, *J. Vac. Sci. Technol. B* **10**, 3196-3199 (1992).

**1993**

"X-ray lithography, from 500 to 30 nm: x-ray nanolithography," H. I. Smith and M. L. Schattenburg, *IBM J. Res. and Dev.* **37**, 319-329 (1993).

"Mask technology for x-ray nanolithography," M. L. Schattenburg and H. I. Smith, in *Materials Aspects of X-ray Lithography* (*Materials Research Society Symposium Proceedings* **306**), eds. G. K. Celler and J. R. Maldonado (MRS, Pittsburgh, PA), 63-68 (1993).

"Fabrication of flip-bonded mesa masks for x-ray lithography," M. L. Schattenburg, N. A. Polche, H. I. Smith, and R. Stein, *J. Vac. Sci. Technol. B* **11**, 2906-2909 (1993).

"Simultaneous optimization of spectrum, spatial coherence, gap, feature bias, and absorber thickness in synchrotron-based x-ray lithography," S. D. Hector, H. I. Smith, and M. L. Schattenburg, *J. Vac. Sci. Technol. B* **11**, 2981-2985 (1993).

**1994**

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## 14.2 Presentations

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"Why bother with x-ray lithography?," H. I. Smith and M. L. Schattenburg, presented at the *SPIE Conference on Electron-Beam, X-Ray, and Ion-Beam Submicrometer Lithographies for Manufacturing II*, San Jose, California, March 8-9, 1992 (*paper 1671-08*).

"The MIT high resolution x-ray spectroscopy instruments on AXAF," C. R. Canizares, D. Dewey, E. B. Galton, T. H. Markert, H. I. Smith, M. L. Schattenburg, B. E. Woodgate, and S. Jordan, presented at the *American Institute of Aeronautics and Astronautics Space Programs and Technologies Conference,* Huntsville, Alabama, March 24-27, 1992 (*paper AIAA-92-1469*); (*manuscript appears in unpublished conference proceedings*).

"Spatially coherent, large-area, free-standing gratings of 200 and 100 nm period for atom interferometry produced using holographic lithography," J. M. Carter, D. Olster, M. L. Schattenburg, S. D. Hector, and H. I. Smith, poster presented at the *36th International Symposium on Electron, Ion and Photon Beams (EIPB'92),* Orlando, Florida, May 26-29, 1992 (*paper C57*).

"Observation of conductance quantization in a GaAs electron waveguide device fabricated by contact x-ray lithography," W. Chu, C. C. Eugster, A. Moel, E. E. Moon, J. A. del Alamo, H. I. Smith, M. L. Schattenburg, K. W. Rhee, M. C. Peckerar, and M. R. Melloch, poster presented at the *36th International Symposium on Electron, Ion and Photon Beams (EIPB'92),* Orlando, Florida, May 26-29, 1992 (*paper C58*).

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"Proximity x-ray nanolithography- current performance and theoretical limits," H. I. Smith and M. L. Schattenburg, presented at the *American Vacuum Society 39th National Symposium and Topical Conferences*, Chicago, Illinois, November 9-13, 1992 (*invited paper J12-ThM6*).

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"Fabrication of transmission gratings for x-ray/EUV spectroscopy and polarization," M. L. Schattenburg, poster presented at the *MIT Astronomy & Astrophysics Workshop*, Cambridge, Massachusetts, January 24, 1994 (*paper 006*).

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"Fabrication and testing of x-ray transmission gratings for the Advanced X-ray Astrophysics Facility," M. L. Schattenburg, *Lawrence Livermore National Laboratory- Advanced Microtechnology Program Seminar*, Livermore, California, June 24, 1994 (*invited*).

"Fabrication of high energy x-ray transmission gratings for AXAF," M. L. Schattenburg, R. J. Aucoin, R. C. Fleming, I. Plotnik, J. Porter, and H. I. Smith, presented (by R. J. Aucoin) at the *SPIE Conference on EUV, X-ray, and Gamma-Ray Instrumentation for Astronomy V*, San Diego, California, July 24-29, 1994 (*paper 2280-17*).

"Maskless single-sided wet etching process for the fabrication of ultra-low distortion polyimide membranes," M. L. Schattenburg, R. I. Fuentes, G. Czernienko, R. C. Fleming, and J. Porter, poster presented at the *1994 Materials Research Society Fall Meeting Symposium- Thin Films: Stresses and Mechanical Properties V,* Boston, Massachusetts, November 28-December 2, 1994 (*paper B2-3.14*).

"The High Energy Transmission Grating Spectrometer for AXAF," T. H. Markert, C. R. Canizares, D. Dewey, M. McGuirk, C. Pak, and M. L. Schattenburg, presented at the *SPIE Conference on EUV, X-ray, and Gamma-Ray Instrumentation for Astronomy V*, San Diego, California, July 24-29, 1994 (*paper 2280-19*).

"Efficiency measurements and modelling of AXAF high energy transmission gratings," C. S. Nelson, T. H. Markert, Y. S. Song, H. L. Marshall, M. L. Schattenburg, D. E. Graessle, K. A. Flanagan, R. L. Blake, J. Bauer, and E. M. Gullikson, presented at the *SPIE Conference on EUV, X-ray, and Gamma-Ray Instrumentation for Astronomy V*, San Diego, California, July 24-29, 1994 (*paper 2280-18*).

**1995**

"The HETG spectrometer on AXAF," M. L. Schattenburg, private briefing for NASA Chief Administrator Daniel Goldin and staff, Cambridge, Massachusetts, March 6, 1995.

"Optically-matched tri-level resist process for nanostructure fabrication," M. L. Schattenburg, R. J. Aucoin, and R. C. Fleming, presented at the *39th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Scottsdale, Arizona, May 30-June 2, 1995 (*paper C75*).

"X-ray and XUV transmission gratings," M. L. Schattenburg, *University of Southern California-*

*Department of Aerospace Engineering Seminar*, Los Angeles, California, June 15, 1995 (*invited*).

"Achromatic-interferometric lithography for 100 nm-period gratings and grids," T. A. Savas, S. N. Shah, M. L. Schattenburg, J. M. Carter, and H. I. Smith, poster presented at the *39th International Conference on Electron Ion and Photon Beam Technology and Nanofabrication*, Scottsdale, Arizona, May 30-June 2, 1995 (*paper C53*).

"Fabrication and applications of nanometer periodic structures," T. A. Savas, *Max Planck Institute Special Seminar*, Göttingen, Germany Aug. 9, 1995 (*invited*).

**1996**

"The HETG Spectrometer," M. L. Schattenburg, *MIT Center for Space Research Friday Lunch Seminar*, Cambridge, Massachusetts, September 20, 1996 (*invited*).

"A research program leading to a 1 arcsec foil mirror x-ray telescope," M. L. Schattenburg and C. R. Canizares, presented at the *Structure and Evolution of the Universe Technology Workshop*, College Park, Maryland, December 2-3, 1996.

"A research program leading to a 1 arcsec foil mirror x-ray telescope," M. L. Schattenburg and C. R. Canizares, *Harvard-Smithsonian Astrophysical Observatory Seminar*, Cambridge, Massachusetts, December 6, 1996 (*invited*).

"Analysis of distortion in interferometric lithography," J. Ferrera, M. L. Schattenburg, and H. I. Smith, poster presented at the *40th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Atlanta, Georgia, May 28-31, 1996 (*paper C8*).

"Large-area achromatic interferometric lithography for 100 nm-period gratings and grids; with novel applications," T. Savas, M. L. Schattenburg, J. M. Carter, and H. I. Smith, presented at the *40th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Atlanta, Georgia, May 28-31, 1996 (*paper A3*).

"A diffractive-optic telescope for x-ray astronomy," D. Dewey, T. H. Markert, and M. L. Schattenburg, presented at the *SPIE Conference on Multilayer and Grazing Incidence Xray/ EUV Optics III*, Denver, Colorado, August 4-9, 1996 (*paper 2805-29*).

"Iridium and gold optical constants from foil transmission measurements over 2,00-12,000 eV," B. Harris, D. E. Graessle, J. J. Fitch, J. Juda, R. L. Blake, E. M. Gullikson, and M. L. Schattenburg, poster presented at the *SPIE Conference on Multilayer and Grazing Incidence X-ray/EUV Optics III*, Denver, Colorado, August 4-9, 1996 (*paper 2805-44*).

"A one-dimensional demonstration of spatial-phase-locked electron-beam lithography," J. Goodberlet S. Silverman, J. Ferrera, M. Mondol, M. L. Schattenburg, and H. I. Smith, presented at the *International Conference on Micro- and Nano-Engineering 96*, Glasgow, Scotland, September 22-25, 1996 (*paper K.3*).

"Super-smooth x-ray reflection grating technology," A. Franke and M. L. Schattenburg, poster presented at the *High Throughput X-ray Spectroscopy Workshop*, Cambridge, Massachusetts, September 30-October 1, 1996.

"Interferometric Lithography and its Applications," J. Carter, M. Farhoud, J. Ferrera, A. Franke, T. Savas, M. L. Schattenburg, and H.I. Smith, poster presented at the *50th Anniversary Celebration of the MIT Research Laboratory of Electronics*, Cambridge, Massachusetts, November 1, 1996.

"Super-smooth x-ray reflection grating technology," A. Franke and M. L. Schattenburg, poster presented at the *Structure and Evolution of the Universe Technology Workshop*, College Park, Maryland, December 2-3, 1996.

**1997**

"Interferometric lithography: techniques and applications," M. L. Schattenburg, *1997 IEEE-LEOS Spring Short-Course Series: Optical Grating Technology and Applications*, Lexington, Massachusetts, March 18, 1997 (*invited*).

"Spatial-phase locked electron beam lithography using a global fiducial grid," G. Goodberlet and M. L. Schattenburg, *Etec Corporation Seminar*, Hayward, California, June 10, 1997 (*invited*).

"Fabrication of super-smooth x-ray reflection gratings," A. Franke and M. L. Schattenburg, poster presented at the *MIT Microsystems Technology Laboratories Annual Review*, Dedham, Massachusetts, January 17, 1997.

"Super-smooth x-ray reflection grating fabrication," A. E. Franke and M. L. Schattenburg, poster presented at the *41st International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Dana Point, California, May 27-30, 1997 (*paper C59*).

"An inverted x-ray mask configuration compatible with pellicle protection," M. H. Lim, M. L. Schattenburg, and H. I. Smith, presented at the *41st International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Dana Point, California, May 27-30, 1997 (*paper J5*).

"Comparison of iridium optical constants derived by transmission and reflection methods from 50-1000 eV," B. Harris, J. J. Fitch, D. E. Graessle, D. A. Schwartz, R. L. Blake, E. M. Gullikson, and M. L. Schattenburg, presented at the *SPIE Conference on Grazing Incidence and Multilayer X-Ray Optical Systems*, San Diego, California, July 27-29, 1997 (*paper 3113-05*).

"Magnetic storage media defined by submicron lithography," M. F. Farhoud, H.I. Smith, M. Huang, D. Twisslemann, C. A. Ross, M. L. Schattenburg, J. M. Bae, and K. Youcef-Toumi, poster presented at the *MIT Materials Processing Center "Materials Day" Symposium*, Cambridge, Massachusetts, October 20, 1997.

"Interferometric Lithography and its Applications," J. Carter, M. Farhoud, J. Ferrera, A. Franke, T. Savas, M. L. Schattenburg, and H.I. Smith, poster presented at the *50th Anniversary Celebration of the MIT Research Laboratory of Electronics*, Cambridge, Massachusetts, November 1, 1997.

"Patterned Magnetic Media for Ultra High Density Data Storage," M. S. Farhoud, *University of Aachen- RWTH Institute*, Aachen, Germany, July 3, 1997 (*invited*).

"Fabrication of freestanding gratings for the MENA atom imager," J. van Beek, *Center for Space Research Seminar*, Cambridge, Massachusetts, October 31, 1997 (*invited*).

**1998**

"The Road to Nanoaccuracy in Lithography," H. I. Smith, J. G. Goodberlet, and M. L. Schattenburg, *Defense Advanced Research Projects Administration- Advanced Lithography Program Review*, San Antonio, Texas, January 27, 1998 (*invited*).

"Accuracy and precision for the sub-100 nm domain: laying the foundation with optical interference," J. Ferrera, T. Savas, J. Goodberlet, M. Mondol, J. Carter, M. L. Schattenburg, and H.I. Smith, poster presented at the *Microsystems Technology Laboratories Student Research Review*, Cambridge, Massachusetts, January 12, 1998 (*paper 7*).

"Fabrication of large area nanostructured magnets by interferometric lithography," M. F. Farhoud, M. Hwang, J. M. Bae, M. L. Schattenburg, H. I. Smith, K. Youcef-Toumi and C. A. Ross, presented at the *7th Joint MMM-Intermag Conference*, San Fransisco, California, January 6-9, 1998.

"Fabrication of large area nanostructured magnets by interferometric lithography," M. F. Farhoud, M. Hwang, J. M. Bae, M. L. Schattenburg, H. I. Smith, K. Youcef-Toumi and C. A. Ross, poster presented at the *Microsystems Technology Laboratories Student Research Review*, Cambridge, Massachusetts, January 12, 1998 (*paper 28*).

"Nano-scale freestanding gratings for UV blocking filters," J. van Beek, R. C. Fleming, P. S. Hindle, J. D. Prentiss, S. Ritzau, and M. L. Schattenburg, poster presented at the *42nd International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Chicago, Illinois, May 26-29, 1998 (*paper NFP2*).

"Analysis and modeling of anomalous scattering in the AXAF HETGS," J. E. Davis, H. L. Marshall, D. Dewey, and M. L. Schattenburg, presented at the *SPIE Conference on X-ray Optics, Instruments, and Missions,* San Diego, California, July 19, 1998 (*paper 3444-07*).

"100 nm gate aperture field emitter arrays," D. G. Pflug, M. L. Schattenburg, A. I. Akinwande, and H. I. Smith, poster presented at the *International Vacuum Microelectronics Conference,* Asheville, North Carolina, July 19-24, 1998 (*paper P42*).

"100 nm aperture field emitter arrays for low voltage applications," D. G. Pflug, M. L. Schattenburg, H. I. Smith, and A. I. Akinwande, presented at the *IEEE International Electron Device Meeting*, San Francisco, California, December 6-9, 1998 (*paper 32-1*).

**1999**

"Scanning beam interference lithography," P. Konkola, P. Everett, and M. L. Schattenburg, poster presented at the *Microsystems Technology Laboratories Student Research Review*, Dedham, Massachusetts, January 11, 1999 (*paper A12*).

"Sub 100 nm metrology via interferometric lithography," M. L. Schattenburg, *Defense Advanced Research Projects Administration- Advanced Lithography Program Review*, Washington, D.C., April 15, 1999 (*invited*).

"Sub-100 nm metrology using interferometrically produced fiducials, M. L. Schattenburg, presented at the *43rd International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Marco Island, Florida, June 1-4, 1999 (*invited paper AMT4*).

"A Holographic Phase-Shifting Interferometer Technique to Measure In-Plane Distortion," M.H. Lim, J. Ferrera, K.P. Pipe and Henry I. Smith, *43rd International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Marco Island, Florida, June 1-4, 1999 (*paper AMTP1*).

"Fabrication of 200 nm period nanomagnet arrays using interferometric lithography and a negative resist," M. Farhoud, J. Ferrera, A.J. Lochtefeld, M. L. Schattenburg, C. A. Ross, and H.

I. Smith, poster presented at the *43rd International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Marco Island, Florida, June 1-4, 1999 (*paper NFP2*).

“Fabrication of patterned media for high density magnetic storage,” C. A. Ross, H. I. Smith, T. Savas, M. L. Schattenburg, M. Farhoud, M. Hwang, M. Walsh, M. C. Abraham, and R. J. Ram, presented at the *43rd International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication*, Marco Island, Florida, June 1-4, 1999 (*invited paper ND3*).

“Segmented x-ray mirror development for Constellation-X,” R. Petre, C. Chen, L. Cohen, D. Content, R. J. Harms, O. Mongrard, G. Monnelly, T. Saha, M. L. Schattenburg, and W. Zhang, presented at the *SPIE Conference on X-Ray Optics, Instruments, and Missions II,* Denver, Colorado, July 18, 1999 (*paper 3766-02*).

“Large-area reflection grating spectrometer for the Constellation-X mission,” S. M. Kahn, F. B. Paerels, J. R. Peterson, A. P. Rasmussen, M. L. Schattenburg, G. R. Ricker, Jr., M. W. Bautz, J. P. Doty, G. Y. Prigozhin, J. A. Nousek, D. N. Burrows, J. E. Hill, W. C. Cash, presented at the *SPIE Conference on EUV, X-ray, and Gamma-ray Instrumentation in Astronomy X,* Denver, Colorado, July 21, 1999 (*paper 3765-11*).

“Fabrication of patterned media for high density magnetic storage,” C. A. Ross, H. I. Smith, T. Savas, M. L. Schattenburg, M. Farhoud, M. Hwang, M. Walsh, M. C. Abraham, and R. J. Ram, presented at the *25th International Conference on Micro- and Nano-Engineering*, Rome, Italy, September 21-23, 1999 (*invited as ‘best paper’ from EIPBN-99 conference*).

“Initial Results from the *Chandra* High Energy Transmission Grating Spectrometer,” C. Canizares, D. S. Davis, D. Dewey, K. Flanagan, J. Houck, D. Huenemoerder, H. Marshall, and M. L. Schattenburg, N. Schulz, and M. Wise, presented at the *Atomic Data Needs for X-ray Astronomy Meeting*, NASA Goddard Space Flight Center, Greenbelt, Maryland, December 16-17, 1999 (*invited*).

**2000**

“Nanometrology,” M. L. Schattenburg, presented at the *MIT Nanogathering*, Cambridge, Massachusetts, January 6, 2000.

“Space Nanotechnology Laboratory,” M. L. Schattenburg, private briefing to Lt. Gen. Spence (Sam) M. Armstrong, NASA Associate Administrator, Cambridge, Massachusetts, March 22, 2000.

“Microcomb design and fabrication for high accuracy optical assembly,” C. Chen, O. Mongrard, L. Cohen, R. Heilmann, P. Konkola, G. Monnelly, and M. Schattenburg, poster presented at the *MIT Microsystems Technology Laboratories Student Research Review,* Dedham, Massachusetts, January 10, 2000.

“Spectral line imaging observations of E0102-72,” D. S. Davis, K. A. Flanagan, J. C. Houck, G. E. Allen, N. S. Schulz, D. Dewey, M. L. Schattenburg, and C. R. Canizares, presented at the *AAS 195th Meeting*, Atlanta, Georgia, January 13, 2000 (*paper 43.06*).

“*Chandra* HETG observations of the supernova remnant E0102-72,” J. C. Houck, K. A. Flanagan, D.S. Davis, G.E. Allen, N. Schulz, D. Dewey, M. L. Schattenburg, and C.R. Canizares, presented at the *AAS 195th Meeting*, Atlanta, Georgia, January 15, 2000 (*paper 112.09*).

"Beam steering system and spatial filtering applied to interference lithography," P. Konkola, C. G. Chen, R. Heilmann, and M. L. Schattenburg, poster presented at the *44th International Conference on Electron, Ion and Photon Beam Technology & Nanofabrication*, Palm Springs, California, May 30-June 2, 2000 (*paper P7-1*).

"Microcomb design and fabrication for high accuracy optical assembly," C. Chen, L. Cohen. R. Heilmann, P. Konkola, O. Mongrard, G. Monnelly, and M. L. Schattenburg, presented at the *44th International Conference on Electron, Ion and Photon Beam Technology & Nanofabrication,* Palm Springs, California, May 30-June 2, 2000 (*paper 16-4*).

"Relativistic corrections in displacement measuring interferometry," R. Heilmann, P. Konkola, C. Chen, and M. L. Schattenburg, presented at the *44th International Conference on Electron, Ion and Photon Beam Technology & Nanofabrication,* Palm Springs, California, May 30-June 2, 2000 (*paper 16-5*).

"High resolution spectroscopy of the supernova remnant E0102-72," K. A. Flanagan, C. R. Canizares, D. S. Davis, D. Dewey, J. C. Houck, and M. L. Schattenburg, presented at the *AAS 196th Meeting*, Rochester, New York, June 7, 2000 (*paper 34.09*).

"First Medium Energy Neutral Atom Imager results from the IMAGE mission," J.-M. Jahn, K. Asamura, M. M. Balkey, J. L. Burch, M.-C. Fok, H. O. Funsten, M. Grande, M. Gruntman, M. Lampton, D. J. McComas, T. Mukai, C. J. Pollock, S. Ritzau, M. L. Schattenburg, E. Scime, R. Skoug, and P. Valek, poster presented at the *NSF: Geospace Environment Modeling (GEM 2000)- Snowmass Summer Workshop,* Snowmass Village, Colorado, June 19-23, 2000.

"Magnetospheric ENAs observed with the IMAGE/MENA imager," J.-M. Jahn, C. Pollock, J. Burch, D. McComas, M. Gruntman, E. Scime, T. Mukai, H. Funsten, M. Grande, M. Lampton, S. Ritzau, M. L. Schattenburg, R. Skoug, P. Valek, and M. Wuest, presented at the *33rd COSPAR Scientific Assembly,* Warsaw, Poland, July 16-23, 2000 (*paper D3.3-0047*).

"High-accuracy x-ray foil optic assembly," G. P. Monnelly, D. Breslau, N. Butler, C. C. Chen, L. Cohen, W. Gu, R. K. Heilmann, P. T. Konkola, O. Mongrard, G. R. Ricker, and M. L. Schattenburg, presented at *SPIE's 45th Annual Meeting, Exhibition and Education Program,* San Diego, California, July 30-August 4, 2000 (*paper 4138-23*).

"Precision assembly station for high-resolution segmented optics," L. M. Cohen, H. Bergner, M. L. Schattenburg, and G. Monnelly, presented at *SPIE's 45th Annual Meeting, Exhibition and Education Program,* San Diego, California, July 30-August 4, 2000 (*paper 4138-20*).

"Progress toward meeting the Constellation-X performance goals using segmented x-ray mirrors," R. Petre, L. M. Cohen, D. A. Content, J. Hein, T. T. Saha, M. L. Schattenburg, and W. W. Zhang, presented at *SPIE's 45th Annual Meeting, Exhibition and Education Program,* San Diego, California, July 30-August 4, 2000 (*paper 4138-06*).

"Ionization and Velocity Structure in the Supernova Remnant E0102-72," K. A. Flanagan, C. R. Canizares, D. S. Davis, D. Dewey, J. C. Houck, and M. L. Schattenburg, presented at *X-Ray Astronomy 2000,* Mondello (Palermo), Italy, Sept. 4-9, 2000 (*poster 4.2*).

"Spectral line imaging observations of 1E0102.2-7219," D. S. Davis, K. A. Flanagan, J. C. Houck, G. E. Allen, N. S. Schulz, D. Dewey, M. L. Schattenburg, and C. R. Canizares, poster presented at the *Eleventh Annual October Astrophysics Conference in Maryland-- Young Supernova Remnants*, College Park, Maryland, October 16-18, 2000.

"Ionization structure and the reverse shock in E0102-72," K. A. Flanagan, C. R. Canizares, D. S. Davis, D. Dewey, J. C. Houck, and M. L. Schattenburg, poster presented at the *Eleventh Annual October Astrophysics Conference in Maryland-- Young Supernova Remnants*, College Park, Maryland, October 16-18, 2000.

"High resolution spectroscopy of two oxygen-rich SNRs with the Chandra HETG," C. R. Canizares, K. A. Flanagan, D. S. Davis, D. Dewey, J. C. Houck, and M. L. Schattenburg, presented at the *Eleventh Annual October Astrophysics Conference in Maryland-- Young Supernova Remnants*, College Park, Maryland, October 16-18, 2000.

"The shocking story of E0102-72," K. A. Flanagan, C. R. Canizares, D. S. Davis, D. Dewey, J. C. Houck, and M. L. Schattenburg, *Harvard-Smithsonian Center for Astrophysics-- High Energy Astrophysics Division Lunch Talk*, Cambridge, Massachusetts, October 25, 2000 (*invited*).

"Spectral Line Imaging Observations of E0102-72," D. S. Davis, K. A. Flanagan, J. C. Houck, G. A. Allen, N. S. Schulz, D. Dewey, M. L. Schattenburg, and C. R. Canizares, presented at the *American Astronomical Society- High Energy Astrophysics Division Meeting*, Honolulu, Hawaii, November 9, 2000 (*paper 32.05*).

"High Resolution Spectroscopy of Supernova Remnants with *Chandra*," K. A. Flanagan, C. R. Canizares, D. S. Davis, J. C. Houck, G. E. Allen, D. Dewey, M. L. Schattenburg, and N. S. Schulz, presented at the *American Astronomical Society- High Energy Astrophysics Division Meeting*, Honolulu, Hawaii, November 10, 2000 (*paper 40.01*).

"Interference lithography for space optics, nanometrology and integrated optics," M. L. Schattenburg, *MIT EECS/RLE Seminar Series on Optics and Quantum Electronics*, Cambridge, Massachusetts, November 29, 2000 (*invited*).

"Alignment and control architecture for scanning beam interference lithography" C. Chen, P. Konkola, R. Heilmann, and M. L. Schattenburg, poster presented at the *MIT Microsystems Technology Laboratories Student Research Review*, Dedham, Massachusetts, January 9, 2001.

## 14.3 Student Theses

### 14.3.1 Bachelor's Theses

Flora S. Tsai, *Characterization of Mechanical and Optical Properties of X-ray Mask Membranes*, B.S.E.E.C.S. 1991 (won departmental award for excellence). (*RLE Tech. Report 564*)

James Monie Bauer, *Ray Tracing the Bragg Crystal Spectrometer*, B.S. Physics 1991.

Harry Isaac Teplitz, *X-Ray Fresnel Diffraction Through a Collimating Slit*, B.S. Physics 1991.

David B. Olster, Refining the Process of Achromatic Holographic Lithography, B.S.E.E.C.S. 1992.

Satyen N. Shah, *A White Light Interferometer for Improved Achromatic Holographic Lithography*, B.S.E.E.C.S. 1993.

Christie S. Nelson, *Synchrotron Studies of an X-ray Transmission Grating*, B.S. Physics 1994.

### 14.3.2 Master's Theses

David Tae Sang Um, *Structural Analysis of Microdefelctions in AXAF Grating Elements Due to Attachment Mechanism Geometry, and the Design of More Efficient Mechanisms for Attachment*, B.S. Mech. Eng. 1993.

Gabrielle M. Owen, *Optical and Mechanical Characterization of Thin Membranes for x-ray Lithography*, M.S.E.E.C.S. 1994 (won departmental award for excellence). (*MTL Memo 94- 748*)

Satyen N. Shah, *Free Standing 100 nm Period Gratings Produced by Achromatic Holographic Interferometry*, M.S.E.E.C.S. 1995. (*MTL Memo 95-777*)

Andrea E. Franke, *Fabrication of Extremely Smooth Nanostructures using Anisotropic Etching*, M.S.E.E.C.S. 1997.

Maya F. Farhoud, *Interferometric Lithography and Selected Applications*, M.S.E.E.C.S. 1997. (*MTL Memo 97-883*)

Carl Gang Chen, *Microcomb Fabrication for High Accuracy Foil X-ray Telescope Assembly and Vector Gaussian Beam Modeling*, M.S.E.E.C.S. 2000.

Michael E. Walsh, *Nanostructuring Magnetic Thin Films Using Interference Lithography*, M.S.E.E.C.S. 2000.

### 14.3.3 Ph.D. Dissertations

Dr. Mark L. Schattenburg, *Astronomical X-ray Spectroscopy: Studies of the Crab Nebula and Development of Ultra-Fine Transmission Gratings*, Physics 1984.

Dr. Erik H. Anderson, *Fabrication and Electromagnetic Applications of Periodic Nanostructures*, E.E.&C.S. 1988.

Dr. Yao-Ching Ku, *Fabrication of Distortion-Free X-ray Masks Using Low Stress Tungsten*, E.E.&C.S. 1991. (*MTL Memo 91-643*)

Dr. Kathleen Early, *Experimental Characterization and Physical Modeling of Resolution Limits in Proximity Printing X-ray Lithography*, E.E.&C.S. 1991. (*MTL Memo 91-638; RLE Tech. Report 565*)

Dr. Anthony Yen, *Fabrication of Large-Area 100 nm-Period Gratings Using Achromatic Holographic Lithography*, E.E.&C.S. 1991. (*MTL Memo 91-642*)

Dr. Alberto M. Moel, *An Aligner for X-ray Nanolithography*, E.E.&C.S. 1993.

Dr. Ray Ghanbari, *Physics and Fabrication of Quasi-One-Dimensional Conductors*, E.E.&C.S. 1993.

Dr. William Chu, *Inorganic X-ray Mask Technology for Quantum-Effect Devices*, E.E.&C.S. 1993.

Dr. Scott D. Hector, *Optimization of Image Formation in X-ray Lithography Using Rigorous Electromagnetic Theory and Experiments*, E.E.&C.S. 1994. (*MTL Memo 96-812*)

Dr. David J. D. Carter, *Sub-50 nm X-ray Lithography with Application to a Coupled Quantum Dot Device*, E.E.&C.S. 1998.

Dr. Juan Ferrera, *Nanometer-Scale Placement in Electron-Beam Lithography*, E.E.&C.S. 1999.

Dr. Thomas E. Murphy, *Design, Fabrication and Measurement of Integrated Bragg Grating Optical Filters,* E.E.&C.S. 2000.

Dr. Maya Farhoud, *Fabrication and Characterization of Nanostructured Magnetic Particles for Applications in Data Storage*, E.E.&C.S. 2000.

# 15. HETG Science Knowledge Captured

The primary objective of HETG, and the entire Chandra mission, is to expand human knowledge of the origin and evolution of the Universe. The scientists who use the Chandra Observatory have been extraordinarily productive. Chandra data has strongly influenced astrophysicists models of how the universe has evolved and is evolving.

Scientists who helped develop HETG under this contract were guaranteed by NASA access to a certain percentage of the available observing time. These scientists are known as Guaranteed Time Observers (GTO). The HETG group and collaborating scientists have selected and submitted GTO observations for Cycles 1, 2, and 3. Data have been received and analyzed for the 37 targets observed in Cycles 1 and 2; these objects include stars, neutron star and black hole systems, supernova remnants, galaxies, clusters of galaxies, quasars and active galactic nuclei.

The data has often been so startling that press releases which merited coverage in major newspapers and magazines have been issued. This report does not include those news releases.

Science is recorded for scientists through papers in archival journals or presented at meetings of technical specialists. The sections below provide a bibliography of the formal scientific record of the achievements of the HETG group and collaborating scientists under this contract. Since Chandra is primarily a guest observer facility this is only a fraction of all HETG instrument results.

The bibliographic data presented below is collected from a number of sources, so there are some small variations in format. The data are as complete as possible as of March 2002.

## 15.1 CY 2002 HETG GTO Science Publications

Huenemoerder, David P., Canizares, Claude R., and Tibbetts, Kevin J., "X-ray Spectra and Light Curves of AR Lac: Temperature Structure, Abundances, and Variability", ASP Conference Series, TBD, Cool Stars, Stellar Systems, and the Sun, **12**, (in press).

Huenemoerder, David P., Schulz, Norbert S., Houck, John C., and Canizares, Claude R., "Coronal Spectroscopy with Chandra/HETG R.S", ASP Conference Series, **223**, Cool Stars, Stellar Systems, and the Sun", **11**, CD-1091.

Kastner, Joel H., Huenemoerder, D.P., Schulz, N., Canizares, Claude R., and Weintraub, David, "Evidence for Accretion: High-Resolution X-ray Spectroscopy of the Classical T Tauri Star TW Hydrae", ApJ, in press, 2002.

Taotao Fang, Greg L. Bryan, and Claude R. Canizares , “Simulating the X-ray Forest”, ApJ., **564**, 604, 2002.

Taotao Fang, David S. Davis, Julia C. Lee, Herman L. Marshall, Greg L. Bryan, Claude Canizares, “Chandra Observation of the Quasar H 1821+643 and its Surrounding Cluster”, Ap.J., **565**, 86, 2002.

Marshall, H.L., Canizares, C.R., and Schulz, N.S., “The High Resolution X-ray Spectrum of SS 433 using the Chandra HETGS”, Ap.J., **564**, 941, 2002.

Marshall, H.L., Miller, B.P., Davis, D.S., Perlman, E.S., Wise, M. Canizares, C.R. Harris, D.E., Biretta, J.A. , “A High Resolution X-ray Image of the Jet in M 87”, Ap.J., **564**, 683, 2002..

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## 15.2 CY 2001 HETG GTO Science Publications

Davis, D.S., Houck, J.C., White, III, R.E., Wise, M.W., and Canizares, C.R., "Chandra Observations of Elliptical Galaxies", Two Years of Science with Chandra, Washington, D.C., September 2001.

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