HETG Follow-on Science Instrument Contract Final Report NAS8-01129

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1 Introduction and Summary

The High Energy Transmission Grating (HETG) Follow-on Science Instrument Contract, NAS8-01129, ran from March 1, 2002 to September 30, 2004; this covers roughly the second 2.5 years of HETG flight operations as part of NASA's Chandra X-Ray Observatory. During this period MIT's Center for Space Research (CSR) provided instrument and scientific support and continued scientific participation in the Chandra Guaranteed Time Observer (GTO) program. Our GTO observations with the HETG cover a wide range of astrophysical systems including stars, x-ray binaries (XRBs), supernova remnants (SNRs), active galactic nuclei (AGN), and the inter-stellar and inter-galactic media.

Some of the main activities during this contract period include:

- Support to the CXC:
  - Provided inputs for POG[1], Chandra Newsletters, threads.
  - Attended Quarterlies, IARs, Calibration Workshops, etc.
  - Contributed to monitoring and calibration of the HETG.
- Ground Test Activity:
  - Re-tested/monitored spare gratings.
- GTO Science Program:
  - Presented results at conferences and workshops.
  - Published science results from GTO Cycles 1–4.
  - Provided GTO inputs for Chandra Cycles 4, 5, and 6.
  - Supported students and post-doc.s doing HETG science.
- Updated HETG web pages, http://space.mit.edu/HETG
- Submitted monthly reports, http://space.mit.edu/HETG/reports.html

Brief specifics of these activities and relevant web pages are provided in the sections of this report below.

For reference and perspective, this contract is the follow-on to the HETG Phase C-D Contract, NAS8-38249; its final report is available at
http://space.mit.edu/HETG/papers/HETG_Final_Report.pdf .
This follow-on contract is succeeded by a contract with the Smithsonian Astrophysical Observatory to the CSR for continued HETG support of and GTO program involvement in the Chandra X-Ray Observatory during its next 5 years of operation and science discoveries.

2 Support to the CXC and Community

2.1 Documentation and Meetings

Our activities during this contract period are given in a set of HETG monthly reports available on-line at:

http://space.mit.edu/HETG/reports.html

The material in this final report is a condensed overview of these monthly reports.

HETG personnel participated in Chandra-supporting meetings including Chandra Calibration Workshops and their Executive sessions, Quarterlies in Cambridge and at MSFC, and annual Independent Review meetings. HETG also supports the Chandra peer reviews. In addition, we have been involved in NASA's road mapping activities and in Con-X science (e.g., attending the Con-X Spectroscopy Workshop, May 2003; participating in Con-X FST meetings) and technology discussions, especially regarding grating design, in order to transfer our HETG experience and science into future NASA mission(s).

2.2 Monitoring and Calibration

The complete HETG spectrometer on Chandra involves several components: the High Resolution Mirror Assembly (HRMA), the HETG proper, and the Advanced CCD Imaging Spectrometer (ACIS.) Monitoring and calibration of these systems is carried out by working with CXC personnel as well as members of the ACIS instrument team. The calibration of the HETG is captured in the CXC data products and reports and papers, e.g., Marshall, Dewey, and Ishibashi[2], as well as notes on the web, e.g., see:

http://space.mit.edu/HETG/technotes.html .

We have recently submitted a paper to PASP entitled "High Energy Transmission Grating: Design, Fabrication, Ground Calibration and Five Years in Flight" by Canizares et al., which is a summary of the main ground activities carried out in making the HETG and summarizes current flight calibration status and prospects; it should be in print in the first half of 2005. Some of the main calibration items worked by HETG personnel in the past years are outlined in the following paragraphs.

HRMA FWHM Monitoring The exquisite performance of the HRMA is a key ingredient to the high resolution obtained by the HETG gratings. For the five years in flight we have monitored the FWHM of the streak in bright HETG observations, Figure 1. The FWHM has remained very stable over the 5 years showing no clear trends. This stability of the telescope is a

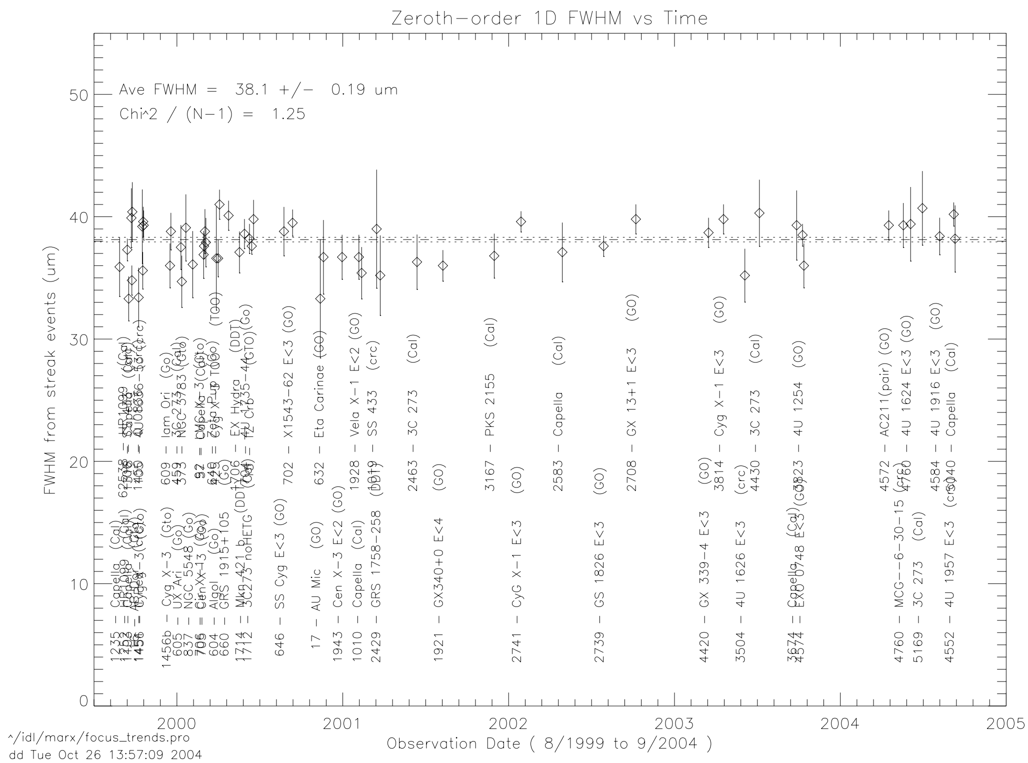


Figure 1: Plot of the FWHM of the HRMA-ACIS-S3 over 5 years of flight showing a very stable FWHM and hence stable HETG response.

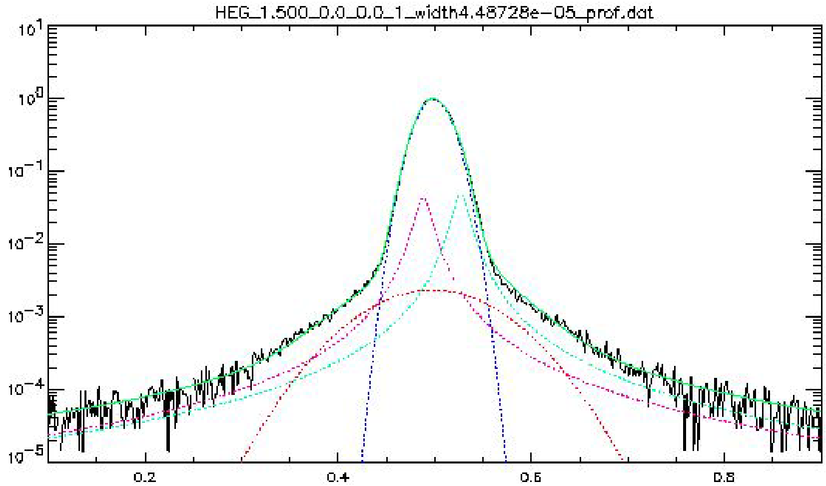


Figure 2: The Components of the modeled HETG Line Spread Function.

key characteristic of Chandra.

Line Spread Function Extensive work was carried out to improve the HETG LSFs and resulting RMFs which are used in HETG data analysis. In recent work, the HETG LSFs are parameterized by two Gaussian plus two Lorentzian components, Figure 2. These responses agree well with high-statistic observations of narrow and blended lines.

"Fluffium" The ACIS is used as the main readout detector for the HETG spectra and so the performance of the ACIS is relevant to HETG observation analysis, in particular the build up of a thin contamination layer on the ACIS[1]. HETG personnel were involved in attempts to reconcile various calibration data on the contamination and proposed a model of the contaminant that reconciled current measurements. This model's effect was implemented by introducing an additional edge-less absorbing component to the contaminant, the "fluffium" curve of Figure 3. The study of the contamination and it's spatial and time dependence is an on-going activity at this time which we continue to follow.

ACIS-S Geometry and HEG/MEG Periods Adjustment of the calibration of the geometry of the ACIS-S CCD chips was made to a level of less than 0.2 pixel in order to improve the accuracy of the HETG-measured wavelengths. Figure 4 shows an exaggerated schematic of the actual ACIS CCD chip geometry as now included in calibration data. With the geometry

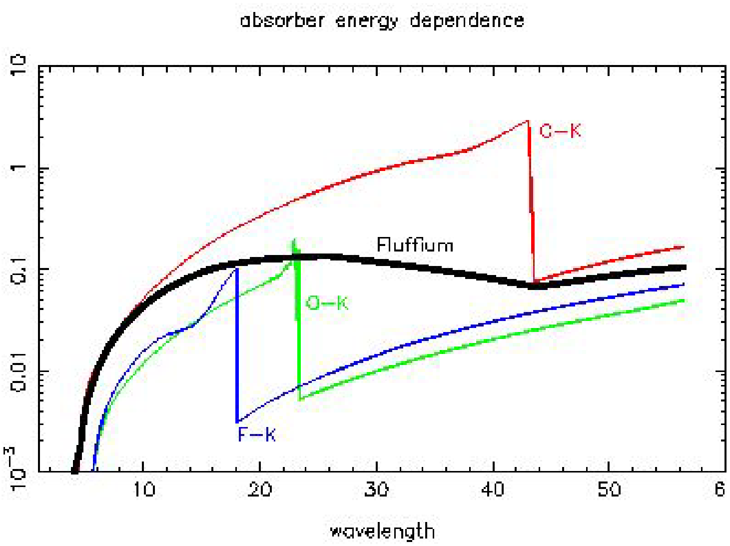


Figure 3: Components included in the ACIS on-orbit contamination model. The curve labeled "fluffium" was added to reconcile calibration data and is based on a simple model.

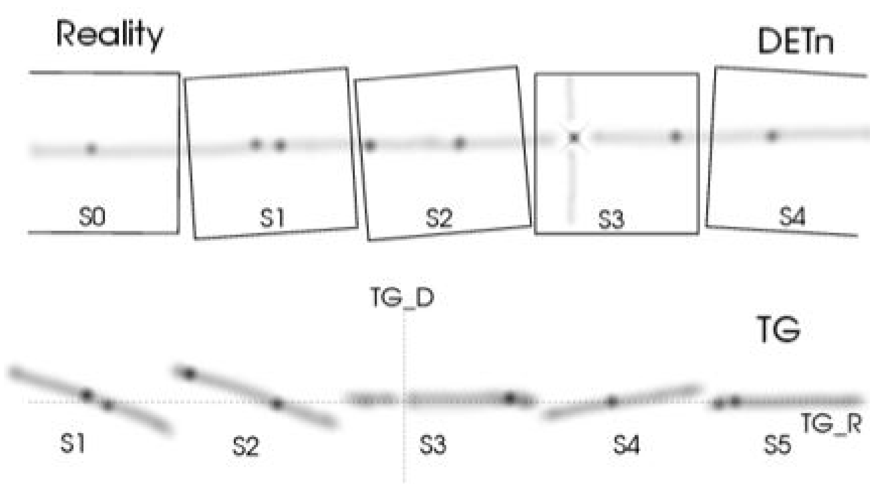


Figure 4: An exaggerated diagram of the ACIS-S chip rolls and offsets which have been accurately calibrated as part of HETG wavelength calibration efforts.

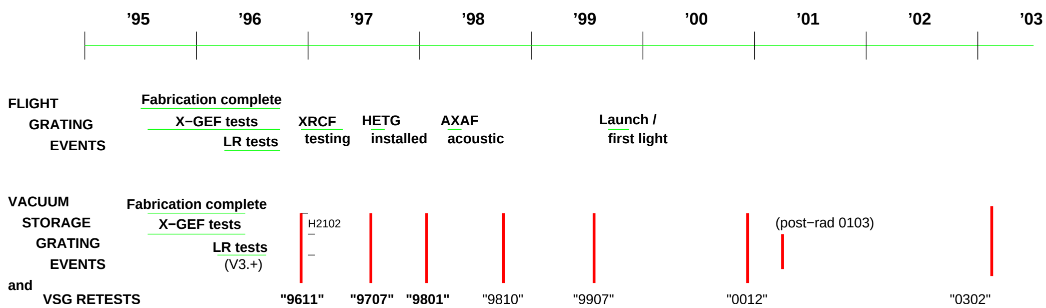


Figure 5: Time line showing the testing of spare gratings over 7+ years from initial fabrication to well into the flight mission.

accurately set we could then compare HEG and MEG grating-derived wavelengths; this resulted in a calibration adjustment of the MEG period from 4001.41 Å to 4001.95 Å. These changes are set to be included in the CXC's "re-pro[cessing] three" and will be made available to users in CALDB in the first half of 2005. This calibration study also demonstrated that the HETG wavelengths are stable to this 0.2 pixel level *from observation to observation* over five years of flight.

3 System Engineering and Ground Tests

During this contract period HETG system engineering was available to help resolve any hardware anomalies related to the HETG in flight. In addition we also supported "Knowledge Capture" and failure modes (risk) activities initiated by the project.

3.1 Spare Grating Testing

A key engineering activity was continuing a program to monitor spare HETG vacuum stored gratings (VSG) with our dedicated test equipment with the goal of alerting us to any evolution of grating properties that may then show up in the flight gratings. Figure 5 presents a time line covering the roughly seven years from the pre-launch fabrication of gratings through the various ground tests on the VSG gratings. The results of testing are summarized in the April 2003 monthly report: the measured efficiencies have remained stable at the <10% level during the past four years of storage.

3.2 Radiation Effects Evaluation

Previously, working with MSFC, we'd tested HEG and MEG spare gratings that were exposed to a proton beam and looked for any radiation-induced diffraction efficiency performance changes. Details are at

http://space.mit.edu/HETG/rad_anal/rad_anal.html .

We also supported assessing ACIS optical blocking filter radiation effects by doing acoustic tests on the radiation-exposed HETG spare gratings– the gratings remained intact.

3.3 Disposition of Test Equipment

Now, with five years of flight operation and calibration, the HETG itself is the best source of HETG performance information and so we have closed out our ground test equipment activities with the conclusion of this contract; this was agreed to in discussions with MSFC and CXC. Specifically, the following test setups created specifically for the HETG program are no longer available: Visual Inspection, Grating Storage (e.g., spares), Acoustic/vibration, Laser Reflection (for period), X-ray Grating Evaluation Facility (X-GEF, for efficiency), Alignment (facets to HESS), and S/C-as-installed video inspection equipment.

4 GTO Science Program Summary

> *"We have decided that Chandra is best served by the current [GTO program] policy."* - Paul Hertz, 8 October 2002.

4.1 HETG GTO Observations

The HETG Instrument Principle Investigator is granted Guaranteed Time Observer (GTO) time in the Chandra observation cycles, typically ≈700 ks in recent cycles. A search of the Chandra archive,

http://cda.harvard.edu/chaser ,

setting "PI Name" to "Canizares" yields a list of all of our GTO observations, 96 in cycles 1–6 (some of these are multiple observations of the same target.)

4.2 GTO Science Themes

Our HETG GTO observations and analyses cover a wide range of astrophysical targets and phenomena as described in the "Science Theme" sections of our monthly progress reports. This material is available on the web at:

http://space.mit.edu/HETG/gtoscience.html .

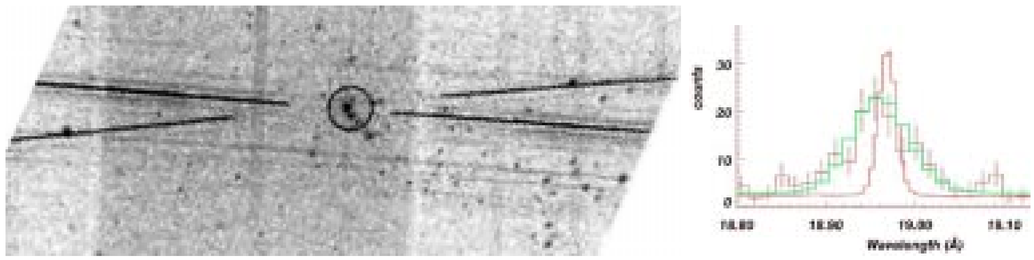


Figure 6: HETG observation of the bright, hot stars in the Orion Trapezium. The HETG/ACIS image is shown at left with the spectral tracks from the bright sources visible as long parallel lines. At right, the observed Oxygen line (green) from the source Θ^1 Ori C is broadened by ≈850 km/s over the instrumental profile (red.) (Figures adapted from Schulz et al.[3].)

Two examples from recently published papers are shown in Figures 6 and 7 and briefly described in their captions.

4.3 Software Development, Evaluation, and Support

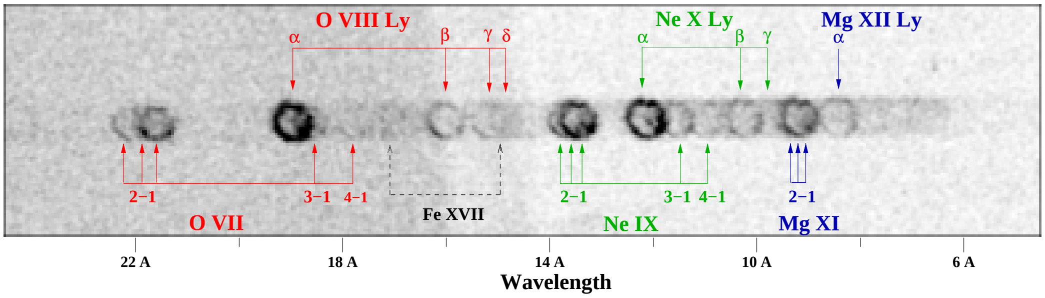
In the process of carrying out GTO analyses we use a variety of software – both CXC provided and custom software. With a close connection to the CXC we are able to provide generally informal input to improve CIAO, especially regarding the HETG and spectroscopy. Our in-house codes usually go beyond the CIAO range of software, for example spatial-spectral analysis, absorption line fitting with improved atomic information, distributed emission measure (DEM) determination, etc. These in-house efforts have and will inform future CXC software for HETG analysis.

4.4 Science Presentations, Meetings, and Publications

HETG personnel regularly attended many scientific meetings, both general, e.g.,, AAS, HEAD, COSPAR, and more unique, e.g., "4 Years of Chandra" (Huntsville AL), "Concordance Cosmology" (Cambridge UK), the Cas A very large project team meeting (NRL), etc. In addition to refereed publications, presentations at meetings are generally indexed in the NASA Astrophysical Data System abstract service,

http://adsabs.harvard.edu/abstract_service.html .

For example, using the ADS, a search for [co-]author "Canizares, C.R." from March 2002 to September 2004 (this contract's 31 month period) results in ≈30 conference items and 17 refereed publications. In all, our monthly reports for this period list ≈80 presentations (talks and posters) at meetings



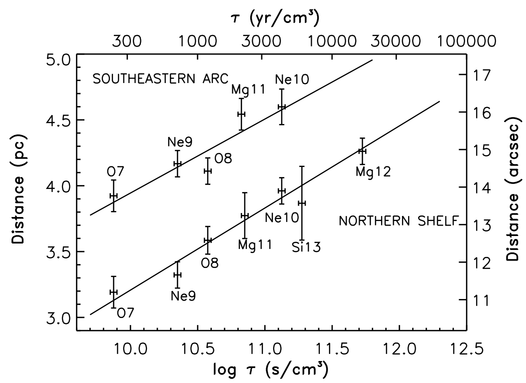


Figure 7: Supernova remnant science example. The upper image shows the dispersed MEG spectrum of the SNR E0102 with discrete lines from Oxygen, Neon, and Magnesium. The lower plot shows the variation in the distance (radius) of maximum intensity for the various ions as a function their optimal $\tau = n_e t$ value. The correlation demonstrates the process of reverse-shock ionization in the SNR. (Figures from Flanagan et al.[4].)

and almost 50 publications, all of which involve HETG GTO data and/or researchers.

4.5 Students, Post-Docs, and Fellows

Over the contract period we have supported for one or more years a total of five post-docs, 6 graduate students, and several undergraduates; the specifics are reported each year to the CXC and were listed in the HETG monthly reports for June'04, June'03, and May'02. In addition, several fellows (Chandra, Jansky, NSF) have chosen to take their fellowships in our group at MIT to be engaged with HETG science activities and researchers.

5 Continued Efforts in FY05–FY09

Our efforts will continue in FY05 and following years via a contract from SAO to CSR arranged at NASA's request and described in a letter from FD03/Keith Hefner (Oct.9'02):

> ...
> Procuring continued Instrument Principle Investigator (IPI) and Science Instrument (SI) support through the CXC follow-on contract should not be construed as a means of reducing the identity, autonomy, or importance of the IPI and SI teams. Nor is it intended to impair or limit the ability of the IPI and SI teams to interface and work issues with the Program Office and with the Project Scientist. This procurement arrangement is the most expedient and efficient contractual means through which the Program can continue the critical and important support provided by the IPI and SI teams.
> ...

We are looking forward to Chandra and HETG's second five years of remarkable observations and results.

Thanks to MSFC

> *I would like to make sure the MSFC folks understand that we feel very good about the roughly 20 years under their management... they really have done an outstanding job.* – C.R. Canizares

References

[1] "The Proposers' Observatory Guide", CXC Web page: http://cxc.harvard.edu/proposer/POG .

[2] Marshall, H.L., Dewey, D., and Ishibashi, K., Proc. SPIE, 5165, 457 (2004); http://xxx.lanl.gov/abs/astro-ph/0309114 .

[3] "X-Ray Modeling of Very Young Early-Type Stars in the Orion Trapezium: ...", Schulz et al., ApJ, 595, 365 (2003)

[4] "Chandra High-Resolution X-Ray Spectrum of Supernova Remnant 1E 0102.2-7219", Flanagan et al., ApJ, 605, 230 (2004)