CHANDRA
HIGH-RESOLUTION SPECTRA

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OUTLINE

GOAL: EXTRACT AND ANALYZE CHANDRA GRATING SPECTRA

1. Theory

   • Braggs’ Law, Rowland Circle, Orders

2. Hardware

   • [LETGS\|HETGS]+[ACIS-S\|HRC-\[SI\]]

3. Pipeline

   • tgdetect, tg_resolve_events, tg_create_mask, tgextract

4. Analysis
1. THEORY
BRAGGING ON THE X-WAVES

\[ n\lambda = 2d \sin \theta \]
1. THEORY

ROWLAND CIRCLE

Concave reflection grating
radius = 2 × Rowland

Rowland circle

small angles; YY’ assumed negligible

Source S

dispersed $\theta \propto \lambda$

$0^{th}$ order

$\alpha$ $\alpha$ $\alpha$

S

P

Q

P'

YY' assumed negligible

radius = 2 × Rowland

Concave reflection grating

Small angles; YY’ assumed negligible

Rowland circle

Source S

$0^{th}$ order

$\alpha$ $\alpha$ $\alpha$

$\theta$

$\theta$

$\theta$

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$\theta$
1. THEORY
TRANSMISSION GRATING GEOMETRY

Flanagan et al. 2007, Proc.SPIE 6688, 66880Y
1. THEORY
ORDERS AND DISPERSION RELATION

- You can measure the distance of a photon from the zeroth order in the detector plane and translate that distance to $n\lambda$
- If there is enough intrinsic energy resolution in the detector, you can separate the orders and remove the degeneracy in $\lambda$
- In the small angle approximation at which most gratings operate, distance along the detector,

\[
\text{dispersion distance } \propto \delta \theta \propto \lambda
\]

- Resolution is limited by the size of the 0th order image, with

\[
\delta \theta \propto \text{PSF-width } \propto \delta \lambda
\]

Along the Rowland circle, this is fixed, so

\[
\delta \lambda \approx \text{constant } \Rightarrow \text{Resolution } \lambda/\delta \lambda \uparrow \text{ as } \lambda \uparrow\]
2. HARDWARE
HETGS

• High-Energy Transmission Grating Spectrometer
  • Two gratings in one: Medium Energy Grating (MEG) for outer mirror shells, and High Energy Grating (HEG) for inner shells
  • The facets are tilted (+4.7° MEG, –5.2° HEG), leading to two arms which intersect at the 0th order
  • The MEG period is ≈2× HEG’s, so wavelength coverage of MEG is double that of HEG, with half the resolution
• Primary detector is ACIS-S, optionally also HRC-I (but as yet unsupported)
• Chandra POG Chapter 8:
  http://cxc.harvard.edu/proposer/POG/html/chap8.html
HETG facets and bars

https://space.mit.edu/HETG/hetg_info.html

(Mike Nowak)
HETGS schematic and footprint on ACIS-S
2. HARDWARE

LETGS

• Low-Energy Transmission Grating Spectrometer

• The Low Energy Grating (LEG) period is \( \approx 2.5 \times \text{MEG}'s \), so resolution is lower, but wavelength coverage is larger

• Primary detector by usage is HRC-S, optionally also ACIS-S and HRC-I

• Chandra POG Chapter 9:
  
LETG being integrated into the optical bench (chandra.harvard.edu)
LETG close up (chandra.harvard.edu)
LETG gratings: wires, coarse, and fine support

https://www.sron.nl/experimenten-50-jaar-ruimteonderzoek-2820/i-letg
2. THE HARDWARE

ACIS-S

[Diagram of ACIS focal plane array with labeled parts]

- Door in open position
- Internal Cal & LED Location
- Spectroscopy Array
- FP Alignment Mirror
- DH Alignment Mirrors (2 plc)
- FID Light Mounting Locations (6 plc)
- Frame Store Shield (3 plc)
- Imaging Array

ACIS focal plane array (chandra.harvard.edu)
2. THE HARDWARE
HRC-S & HRC-I

HRC focal plane array (chandra.harvard.edu)
Looking into the HRC Vacuum Housing
2. HARDWARE

HETGS+ACIS-S

Capella ObsID 1235
2. HARDWARE
LETGS+ACIS-S

XTE J1118+480 (accretion disk around BH)

chandra.harvard.edu

Fine support
diffraction

Readout streak

Coarse support
diffraction

vlk: CIAO Workshop AS235/Honolulu 2020 Jan 3-4
2. HARDWARE

LETGS+HRC-S

Capella ObsID 1248
Figure 9.5: The front surfaces of the HRC-S detector segments and their relationship to the Rowland circle are shown schematically. The scalloped line beneath them is the difference between the detector surface and the Rowland circle.
2. HARDWARE

LETGS+HRC-I

Cyg X-2 ObsID 87
2. HARDWARE
HETGS+HRC-I

Capella ObsID 19837
Figure 1: Expected spectral resolving power for HETG/HRC-I for different focus offsets based on MARX ray-trace simulations.
3. SOFTWARE
EXTRACT DATA USING CIAO

https://cxc.harvard.edu/ciao/threads/gspec.html

- Find the 0\textsuperscript{th} order
- Fix the regions from which to extract dispersed spectra
- Assign wavelengths
- Extract into standard format files
- Create redistribution matrix (RMF) and ancillary response (ARF) files
3. SOFTWARE
WHERE IS THE SOURCE?

• Must first locate the 0\textsuperscript{th} order

• Use \texttt{tgdetect} or \texttt{tg\_findzo}, or \texttt{tgdetect2} to automatically choose between them

• \texttt{tgdetect}: uses \texttt{celldetect} to find and centroid 0\textsuperscript{th} order sources, works with either ACIS or HRC data

• \texttt{tg\_findzo}: for ACIS, when 0\textsuperscript{th} order is piled up, uses readout streaks and dispersion axis to pinpoint the intersection
Where is my source?

tg_detect

This will fail if the source is piled up, or if the zeroth order image is blocked!

tg_findzo

This will fail if the source is too faint!

Accuracy can be as good as 0.1 pixels
3. SOFTWARE
MAP TO WAVELENGTH

Distance from 0th order gives you wavelength
\[ m\lambda = m\frac{hc}{E} = p\sin\beta \approx p\beta \]

Greater Distance = Higher Resolution
Resolution Limited by CCDs & Gratings Accuracy
\[ m\lambda = m\frac{hc}{E} = p\sin\beta \approx p\beta \]

**LETG**

**HETG**

Greater Distance = Higher Resolution
Resolution Limited by CCDs & Gratings Accuracy

(Mike Nowak)
3. SOFTWARE
MAP TO WAVELENGTH

• OSIP (Order Sorting Integrated Probability) Tables for ACIS

• The ratio of CCD energy to inferred energy, $R_0 = E_{CCD}/(mhc/\lambda)$ can be used to separate the orders
  
  • "Standard" — pre-calculated $R_0$
  
  • "Flat" — set a fixed ratio for range of $R_0$, e.g., 0.8-1.3
unix%> ds9 acisf11044N002_evt2.fits.gz &
Order Sorting Plot

- HEG
- Constant Energy
- MEG
- Escape Peak!
3. SOFTWARE

MAP TO WAVELENGTH

- OSIP (Order Sorting Integrated Probability) Tables for ACIS

- The ratio of CCD energy to inferred energy, $\mathcal{R}_0 = \frac{E_{\text{CCD}}}{(mhc/\lambda)}$ can be used to separate the orders

  - "Standard" — pre-calculated $\mathcal{R}_0$

  - "Flat" — set a fixed ratio for range of $\mathcal{R}_0$, e.g., 0.8-1.3

- You can't do this on the HRC because there is very little intrinsic energy resolution

- Must construct grating RMFs using `mkgrmf` for several orders, and use this Sherpa thread to use them during fitting

  http://cxc.harvard.edu/sherpa/threads/grating_hrcsletg/
3. SOFTWARE

WATCH OUT: TIME FILTERING

• At this stage you have a Level 1.5 file, or the so-called evt1a file.

• There is a bug in dmcopy where if you apply additional time filtering to this file, the GTI block gets corrupted and the EXPOSURE value in the header becomes incorrect.

• To work around, do something like this:
  • `cp -p evt1a old_evt1a`
  • `dmcopy old_evt1a"[time=@filter_spec]" evt1a clobber=yes`
  • `dmappend old_evt1a"[region][subspace -time]" evt1a`

• NOT a problem if you run chandra_repro
3. SOFTWARE

WATCH OUT: HRC-S BACKGROUND REDUCTION

• HRC-S does not have the intrinsic spectral resolution to do order sorting. This means that the background tends to be higher.

• There is a wavelength and PI based filter that can be applied to remove a large fraction of the particle background at minimal cost to the source counts,

  $\text{CALDB/data/chandra/hrc/tgpimask2/letgD1999-07-22pireg_tgmap_N0001.fits}$

• HOWEVER: recently, because of the gain drop in the HRC, this filter is working less efficiently.

• If you are working with very soft sources $\lambda > 44\text{Å}$, it is better to not apply this filter.
3. SOFTWARE
TG_CREATE_MASK

- Picks out sky spatial region into which the photons are dispersed
- fraction of enclosed energy is put into RMF
3. SOFTWARE

EXTRACT SPECTRA

- `tgextract` to make `pha2` files that can be read in and analyzed with Sherpa
  - Extraction efficiencies for adopted widths go into RMF, not ARF
- `mkgarf` to make effective area files, which includes detector spatial information (including QE uniformity, bad pixels, etc.), and the effect of dither
- `mkgrmf` to make RMFs
- XSPEC compatibility: `tgextract2` to make separate Type1 pha files, `tgsplit` to convert `pha2` into `pha`, `tg_bkg` to create separate background files
Bowtie extraction region in \((tg_r, tg_d)\) for HRC-S/LETG

also see [http://cxc.cfa.harvard.edu/cal/letg/LetgHrcEEFRAC/](http://cxc.cfa.harvard.edu/cal/letg/LetgHrcEEFRAC/) for optimized, narrower, bowtie
optimized, narrower bowtie

http://cxc.cfa.harvard.edu/cal/letg/LetgHrcEEFRAC/
Extraction efficiencies for various half-widths [LETGS+ACIS-S]
3. SOFTWARE

WATCH OUT: CONTINUOUS CLOCKING

- Image is collapsed into one dimension
- But MEG 2nd orders are suppressed, so HEG 1st order is always assumed
- Extraction width assumed to be 100%
- OSIP assumed flat (~0.8-1.3)
- For best results, put MEG –1 and HEG +1 off the chip
3. SOFTWARE

WATCH OUT: EXPOSURES

• Different chips can have different exposures

• event files will have the mean exposure of all the chips

• Effective Area files will have the mean exposure of the chips associated with that detector

• Be careful when making light curves!
3. SOFTWARE

VARIABLES

- Arrays of interest in evt1a/evt2
  - `tg_r`, `tg_mlam`, `tg_lam` — coordinates along dispersion axis
  - `tg_d` — coordinate along cross-dispersion axis
  - `tg_part`, `tg_m` — marker for grating type and order

- Arrays of interest in pha2
  - `tg_part`, `tg_m` — marker for grating type and order
  - `tg_srcid` — source identifier
  - `bin_lo`, `bin_hi` — wavelength grid
  - `counts` — counts from source area
  - `background_up`, `background_down` — counts from background areas
    (look for header keywords BACKSCUP and BACKSCDN)
3. SOFTWARE

COMPLICATIONS

• No more global fits because most models are just not good enough

• pileup on ACIS, background in HRC can become important

• Chip and plate gaps, and mismatches between Rowland circle and detector plane require careful observation setups

• HETGS+HRC-I not yet supported in CIAO

• evolving calibration: contamination on ACIS, degap and gain drop on HRC
4. ANALYSIS

HIGH-RESOLUTION SPECTRA

Capella ACIS-S/LEG [119 ks]

Capella HRC-S/LEG [607 ks]
4. ANALYSIS
WHAT CAN YOU DO?

HEG model of density sensitive Ne IX triplet (contaminated by Fe) overlaid on MEG (top) and LEG (right)

Figure 5: A portion of the HETGS spectrum of Cyg X-1 from ObsID 11044 (Miškovičová et al (2016, [11])). The data were divided by a model consisting of a power law absorbed by cold gas. Several lines show P Cygni profiles, such as Mg Lyα, Ne Lyα, and even Ne Lyβ. The observation is from inferior conjunction, where the disk wind is observed most clearly. Components of He-like Mg x1 are readily discerned, providing density diagnostics.
**FIGURE 11:** The bright continuum radiation shows the imprint of the ISM along the line of sight. The absorption features are seen in MEG spectra from neutral and doubly ionized oxygen, O II and O III. The energy range shown is roughly 0.558 keV to 0.60 keV. 


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**Fig. 2 — Residuals from a fit of the 500 ks LETG+HRC-S spectrum of the blazar 1ES 1553+113 to a continuum model. Galactic O I and C II are detected, as well as lines due to C V and C VI in different filaments of the WHIM. From Nicastro et al. (2013).**
Fig. 3 — Spectra of selected lines from LETGS observations of α Cen A. The use of strong primary colors is designed to separate out behavior of the K star (shaded yellow and red dots) from that of the G star (blue dots). Delicate pastels indicate 1σ photometric errors for B in orange and A in green. Approximate line formation temperatures are listed. Note the dramatic differences between the two stars at the shortest wavelengths (< 20 Å) compared to the rather similar fluxes at the longest wavelengths (> 170 Å). From Ayres (2014).
4. ANALYSIS

RESOURCES

- Chandra Proposers’ Observatory Guide
  - HETG (Chapter 8) http://cxc.harvard.edu/proposer/POG/html/chap8.html
  - LETG (Chapter 9) http://cxc.harvard.edu/proposer/POG/html/chap9.html

- Chandra Cal Pages
  - HETG — https://space.mit.edu/CXC/calib/hetg_user.html
  - LETG — http://cxc.harvard.edu/cal/letg/detailed_info.html

- CIAO Science Analysis Threads — http://cxc.harvard.edu/ciao/threads/gspec.html

- Sherpa Threads — http://cxc.harvard.edu/sherpa/threads/fitting.html

- D. Huenemoerder’s Analysis Guide — https://space.mit.edu/ASC/analysis/AGfCHRS/AGfCHRS.html

- TGCAT — http://tgcat.mit.edu