High Resolution X-ray Spectroscopy

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What Do We Mean by High Resolution?

- CCD Spectral Resolution (Suzaku):
  \[ \frac{E}{\Delta E_{\text{FWHM}}} \sim 18 \text{ @1 keV, } \sim 46 \text{ @6.4 keV} \text{ (scales as } E^{0.5}) \]

- Gratings Spectral Resolution:
  - \[ \frac{E}{\Delta E_{\text{FWHM}}} \sim 314 \text{ @1 keV } \text{ (XMM-RGS)} \]
  - \[ \frac{E}{\Delta E_{\text{FWHM}}} \sim 1350 \text{ @1 keV, } \sim 214 \text{ @6.4 keV } \text{ (Chandra-HETG)} \]

- Scales as \( E^{-1} \) (explanation coming up...)

- To date, X-ray High Resolution Means Gratings – Chandra-Low/High Energy Transmission Gratings & XMM-Reflection Gratings Spectrometer

- Near future, X-ray Calorimetry with Micro-X, XARM,
  \[ \Delta E_{\text{FWHM}} \sim 5-7 \text{ eV, } \frac{E}{\Delta E_{\text{FWHM}}} \sim 1000 \text{ @6.4 keV } \text{ (scales as } E) \]
High/Low Res Comparison

XMM-RGS

Photons cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\)

Wavelength (Å)

Chandra-HETG

keV Photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\)

Energy (keV)

Suzaku

Photons cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\)

Wavelength (Å)

(Simulation)

Photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\)

Energy (keV)
High/Low Res Comparison

νF_ν (ergs cm$^{-2}$ s$^{-1}$)

Energy (keV)

χ

$10^{-10}$ $10^{-9}$ $2 \times 10^{-9}$ $5 \times 10^{-9}$
Gratings

Gratings Equation:

\[ m \lambda = m \frac{hc}{E} = p \sin \beta \approx p \beta \]
Chandra-HETG
A Wistful Dream...

Lynx? (X-ray Surveyor)
\[ m\lambda = m \frac{hc}{E} = p \sin \beta \approx p\beta \]

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

**HETG**

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Greater Distance = Higher Resolution
Resolution Limited by CCDs & Gratings Accuracy
- 0th order shows diffraction from coarse support structure
- “Whiskers” are diffraction from fine support structure
Chandra HETG
Chandra HETG

Readout Streak

Pileup
Chandra HETG

- Readout Streak
- Dust Scattering Halo
- Pileup
- Line Spread Function (LSF) & Readout Streak
Order Sorting (aka Banana Plots)

- Multiple orders land on the same detector location
- CCD resolution is sufficient to separate these!
- Plotting $E_{\text{CCD}}$ vs. $m\lambda$ should show “bananas”
- Or we can plot $m\lambda$ vs. $E_{\text{CCD}} m\lambda/hc$
- $E_{\text{CCD}} m\lambda/hc$ is the “order”
unix%> ds9 acisf11044N002_evt2.fits.gz &
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Order Sorting Plot

HEG Order

MEG

Sky X (shifted)
Order Sorting Plot

Sky X (shifted)

HEG Order

MEG

Escape Peak!
Data Extraction Tasks

- All these can be accomplished with CIAO tools
  - (Select time intervals, “clean” the data)
- Where is my source?
  - tg_detect – or – tg_findzo – or – “by hand”
- What regions should be assigned orders?
  - tg_create_mask
- Which events should be assigned to which orders?
  - tg_resolve_events
- What region (width) should I extract?
  - tg_extract
- Create Response (RMF and ARF files)
  - mkgrmf, asphist & mkgarf – or – fullgarf
Time Intervals & Data Cleaning

• “Event Files” come in three varieties:
  • Event0 – Only us at Chandra see this
  • Event1 – You get this. It has “bad pixels”, “streak events” (S4), etc.
  • Event2 – You also get this. Bad pixels & streaks removed. You can start here if you aren’t choosing time intervals!

• There is a bug within the gratings tools where you need to do time slices on the Event1 files.
You can do a time slice with `dmcopy`:

```
dmcopy "evt1_file[stdevt][time=5.1096500e8:5.1098000e8]"
```

```
evt1_new
```

You can then run the `chandra_repro` script on this new file, and proceed from there:

- Removes bad pixels
- Applies Good Time Intervals (GTI)
- Removes “streaks” (S4 Chip)
- Selects “Good Grades”
Where is my source?
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This will fail if the source is piled up, or if the zeroth order image is blocked!
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This will fail if the source is too faint!
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
tg_create_mask

Hierarchy: 0\textsuperscript{th} Order > MEG > HEG

CIAO defaults are a bit too wide, so MEG “clips” HEG high energy for “Continuum” Sources

These are the \textit{Potential} Gratings Events
“Resolving” Events

\[ \frac{|m \lambda| E}{h c} \]

\[ m \lambda = TG_{-MLAM} \]

\[ E = ENERGY \]

Fraction of RMF is the “Order Sorting Integrated Probability” (OSIP) and is incorporated into ARF
Order Sorting

- For Chandra, there are two choices:
  - “Standard” (which varies with wavelength) with a pre-calculated OSIP
  - “Flat”, with the user choosing a fixed ratio, e.g., $E_{\text{CCD}} \text{m}\lambda/\text{hc} = 0.8–1.3$ and OSIP assumed to be 1
- Flat is usually the choice for “Continuous Clocking” mode
- To be a gratings photon, it has to be at the right place with the expected energy
- Greatly reduces background!
Orion Star Cluster
Before providing a sampling of highlights from the past few years to demonstrate the quality of the Chandra science, we provide some metrics for the mission which provide insight into its usage by the community and its scientific productivity.

Figure **: a) (upper left) Deep exposure of the Orion Nebula Cluster, color-coded by energy. This is 800 ks from the Chandra Orion Ultradeep Project (cite xxx). b) (upper right) A 300 ks composite image of High Energy Trans-mission Grating observations showing detail in the core along with the multiple grating traces, also color-coded with CCD energy. c) (bottom) The High Energy Grating spectrum of the brightest star in the cluster, showing a wealth of emission lines on a strong continuum (see section *** for interpretation).
tg_extract_events

Isolated Source, Defaults are Fine

Fraction of LSF is Incorporated in RMF
Narrower is Sometimes Necessary
Orion Star Cluster
Orion Star Cluster

Figure **: a) (upper left) Deep exposure of the Orion Nebula Cluster, color-coded by energy. This is 800 ks from the Chandra Orion Ultradeep Project (cite xxx). b) (upper right) A 300 ks composite image of High Energy Trans-mission Grating observations showing detail in the core along with the multiple grating traces, also color-coded with CCD energy. c) (bottom) The High Energy Grating spectrum of the brightest star in the cluster, showing a wealth of emission lines on a strong continuum (see section *** for interpretation).
Response Matrices & ARF

- If you’ve extracted the standard width, the standard RMF is sufficient
- ARF (effective area file) has to incorporate spatial information about the detector. Not only chip gaps, but also bad pixels & columns
- There’s also a “hidden” parameter – fractional exposure vs. wavelength
- Standard tools: mkgrmf, asphist & mkgarf, fullgarf
Sample Gratings ARF

![Graph of cm$^2$/photon vs. Energy (keV)](image)
And Now Analysis Begins!

- You have extracted spectra and created response matrices/effective area files
- Analyze in any standard program: ISIS, XSPEC, Sherpa, SPEX
- The standard is to extract 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd} (+/-) orders
  - Higher orders have less flux, and less accurate responses – difficult to use for continuum
- Line dominated sources, good for separating blends of lines
Complex Cases

- Pileup – Less likely to happen, but it can ...
- ISIS model (could write for Sherpa, not XSPEC[?])
- Continuous Clocking Mode (CC-mode)
- Sources with spatial structure
- Sources with spatial structure and CC-mode
Pileup in Gratings Spectrum

Most Significant in MEG (Higher Effective Area, Less Dispersion)
Continuous Clocking

- Image collapsed to one dimension
- But, MEG 2\textsuperscript{nd} orders are suppressed, so HEG 1\textsuperscript{st} order is always assumed
- Extraction width is assumed to be 100%, and OSIP is chosen to be flat (~0.8–1.3) and assumed 100%
- No source is piled up in this mode – we’ve looked at Sco X-1! (The Chandra team was *not* happy!)
- But, there are still issues at the few % level...
- We recommend putting MEG -1 and HEG+1 off the chips
A Note About Exposures

- Different Chips Can Have Different Exposures
- Especially True for Bright Sources with Data Loss
- Data 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
- None of these numbers may actually be the “true” exposure at a specific wavelength region
- The issues are incorporated into the ARF
- But might not be adequate when doing lightcurves
I’ll get back to you on this one ...
Other Resources

- TGCat: www.tgcat.mit.edu
- Spectral plots (counts & flux corrected), diagnostics, fluxes, variability plots
- Standard data products – spectra & responses
- Extraction scripts – all Chandra gratings modes
Science

GX 301-2

(Watanabe et al. 2004)
While the 0.66–1 keV (non-dip) spectrum at 200–300 km/s, the spectrum was softer and the flux was more than twice as high. However, the recent observation at 0.5–10 keV count rate (c/s) displays P Cygni-shaped Lyα and Lyγ lines. While many additional strong absorption lines can provide density and temperature diagnostics, the dip events seem to become shorter with distance from the donor.

ObsID 3815, the apparent softening in the spectrum was softer and the flux was more than twice as high. The dipole-allowed and forbidden lines, which can provide density and temperature diagnostics, are detected at 0.5–10 keV count rate (c/s). The 1s2s/1s2p transitions of an He-like ion form the core of the dip event.

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Si Kα lines (House, 1969)
Science

NGC 3783 from the TGCat Catalog

AGN Warm Absorbers
Magnetized Accretion Disk Winds

(GRO J1655-40)