Chandra Source Catalog Review

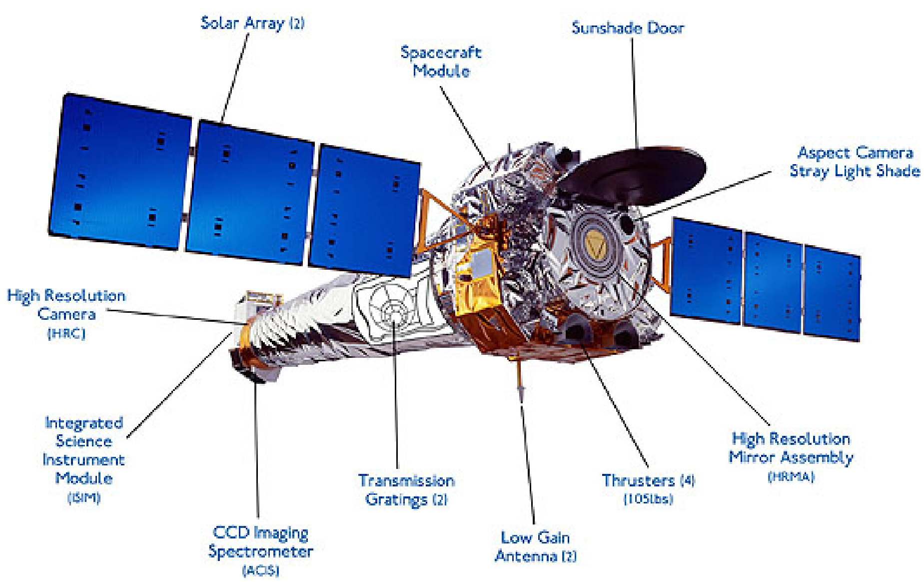
Instrumentation/Data Overview

Frank Primini

- Brief Review of Chandra Instrumentation and data
- Challenges for Source Catalog

1

Principal Components of Scientific Instrumentation



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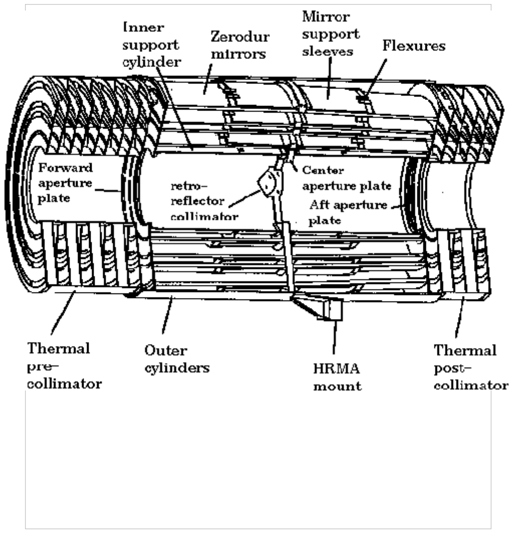
High Resolution Mirror Assembly (HRMA)

- 4 nested Wolter Type I mirror pairs
- Zerodur glass with Iridium coating
- ~30′ Field of View
- ~10 meter Focal Length
- ~1000 cm² on-axis geometric area
- ~½″ FWHM on-axis angular resolution



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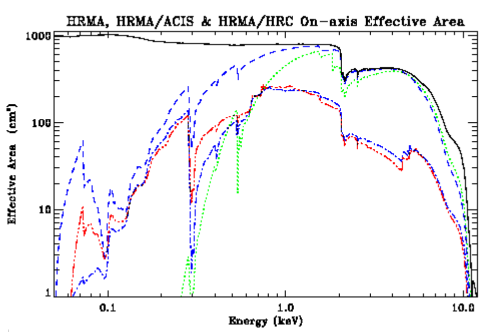
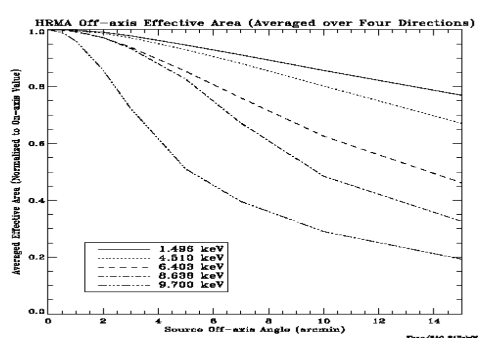
HRMA Effective Area

- HRMA Area varies with both energy and off-axis angle
- Detector Efficiency also depends on energy and detector position
- HRMA Area combined with detector efficiency → Effective Area





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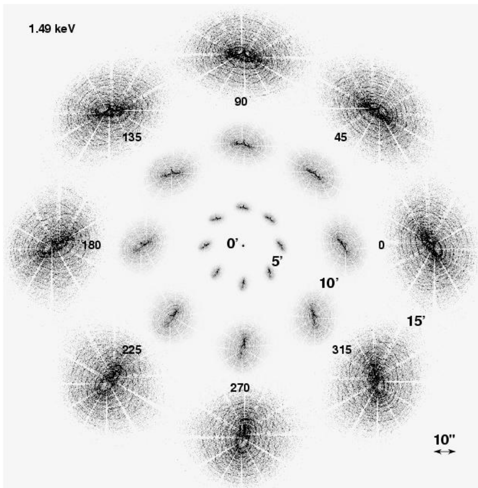
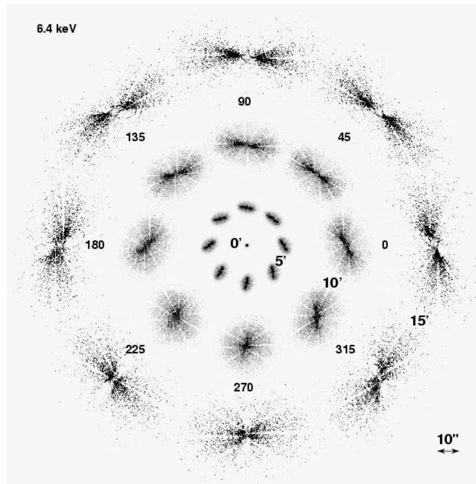
HRMA Point Spread Function (PSF)

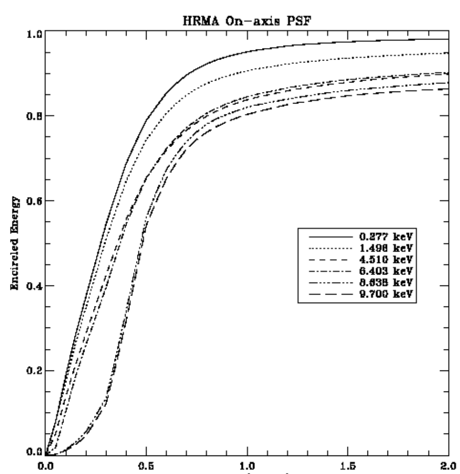
- PSF varies with both energy and off-axis angle

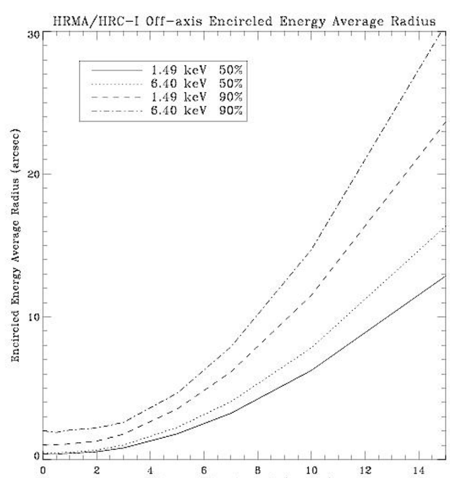




HRMA Encircled Counts Fraction (ECF)

- Simple Parameterization of PSF – circular apertures of same area as region encompassing given fraction of PSF
- Useful for aperture photometry but circular approximation can lead to errors





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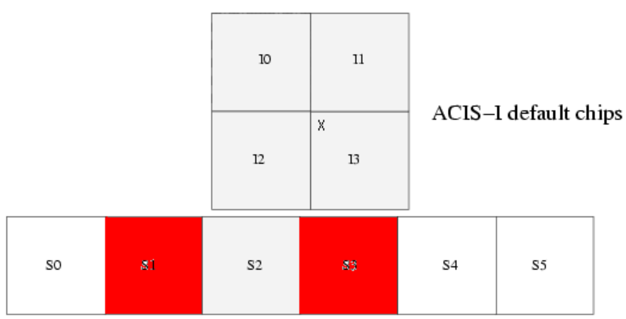
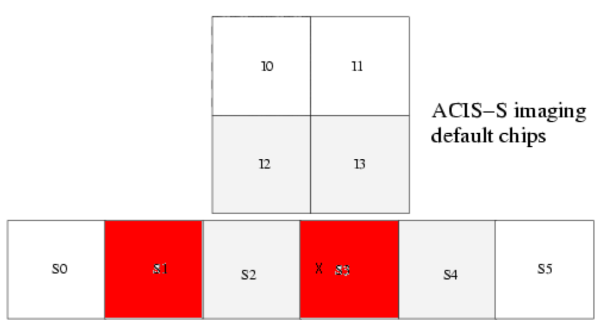
Advanced CCD Imaging Spectrometer (ACIS)

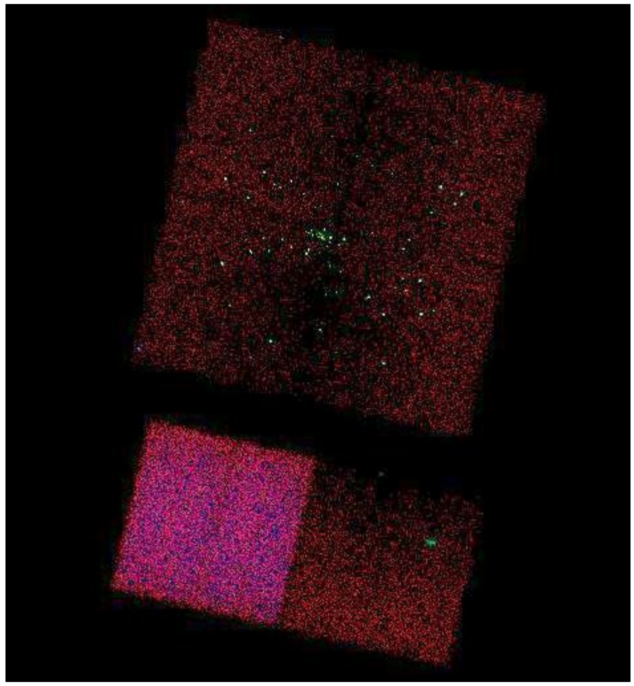
- 10 1024x1024 ~½″ pixel x-ray CCDs (~8′x8′ FOV per chip)
- Energy Range ~0.2 – 10 keV
- E/ΔE ~10-20 @ 1 keV
- Time resolution depends on operating mode (usually 3.2 s.)
- Two types of chip
  - Front-illuminated (low background, poor low energy response)
  - Back-illuminated (better low energy response, higher background)
- Two aimpoints
  - ACIS-I, follows focal surface
  - ACIS-S, follows Rowland Circle of gratings
- Various operating modes
- Typically select (any) 6 chips per observation

ACIS Chip Layout





An ACIS-I Observation of M31 (Full Field)



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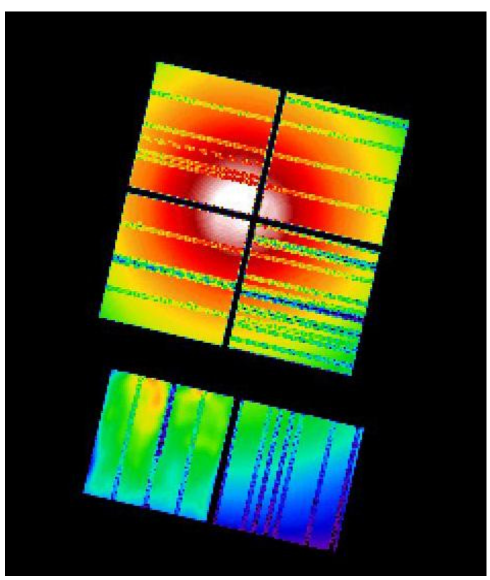
Example of an Exposure Map



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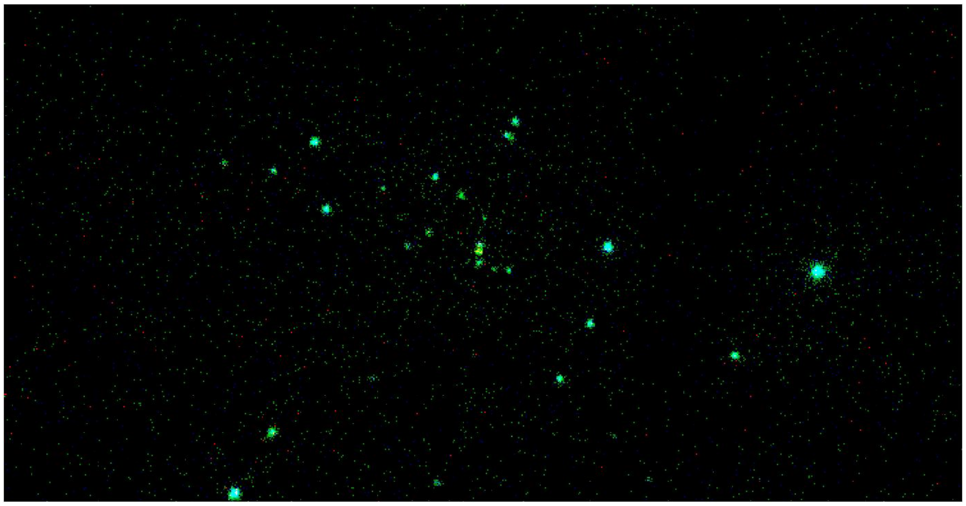
An ACIS-I Observation of M31 (Full Resolution)



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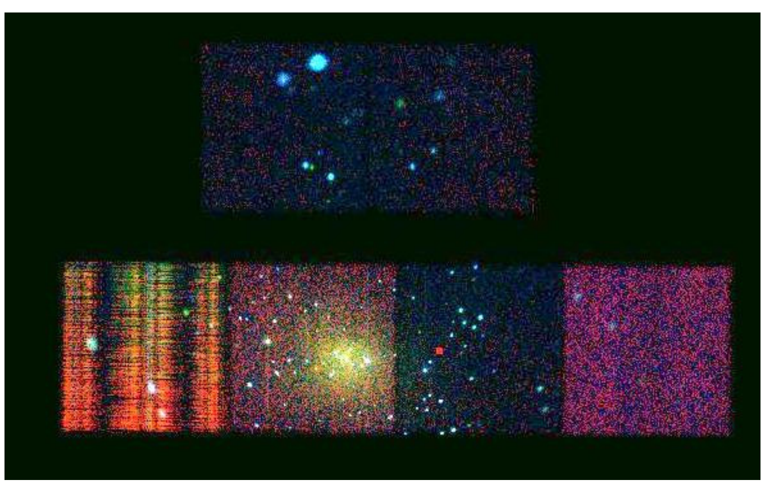
An ACIS-S Observation of M31 (Full Field)



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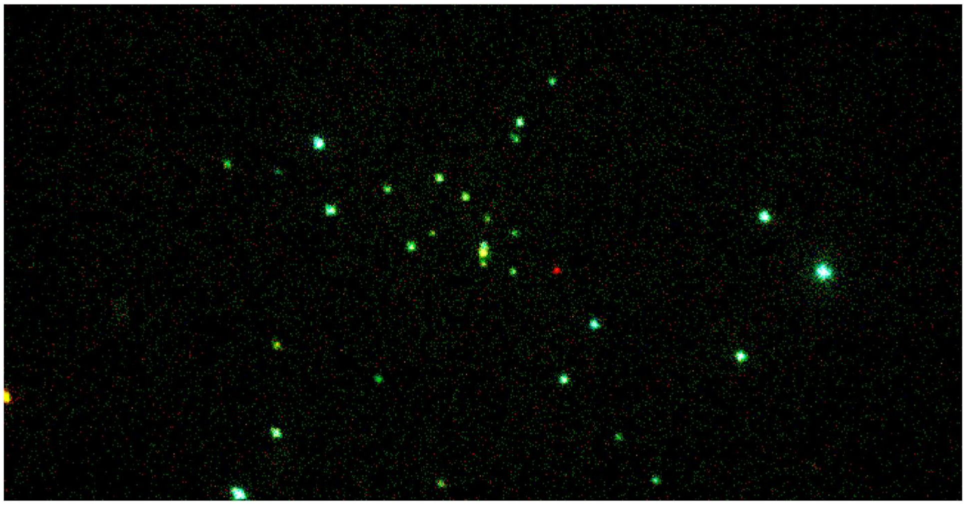
An ACIS-S Observation of M31 (Full Resolution)



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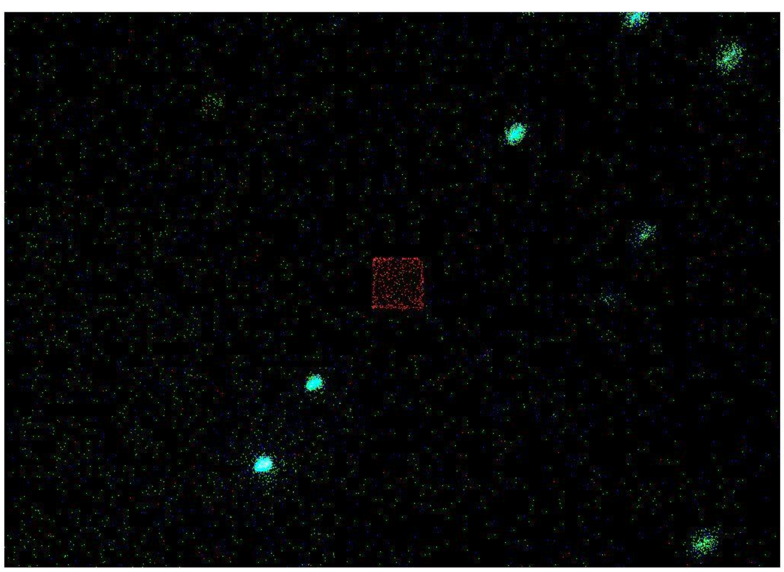
An Unscreened Hot Pixel Illustrates the Dither Pattern



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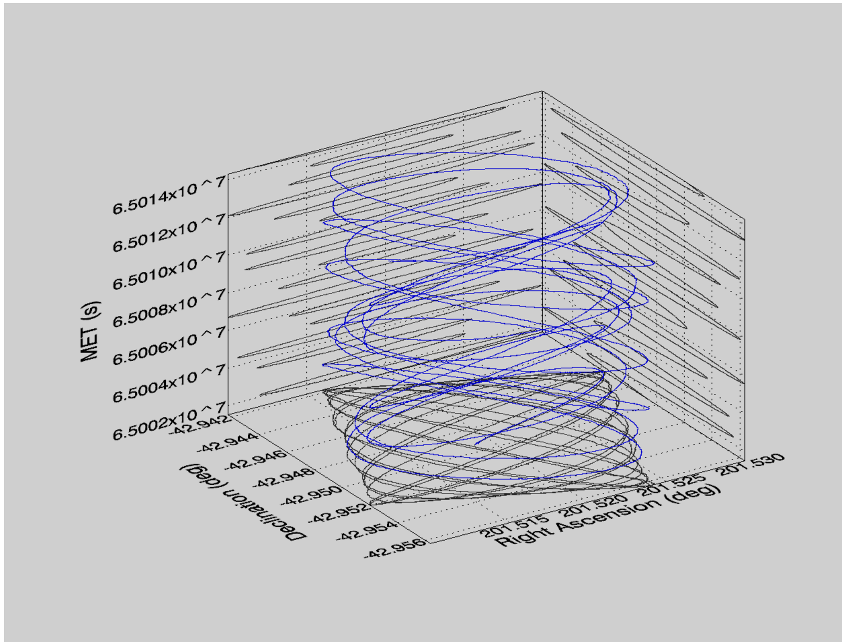
Example Aspect Solution



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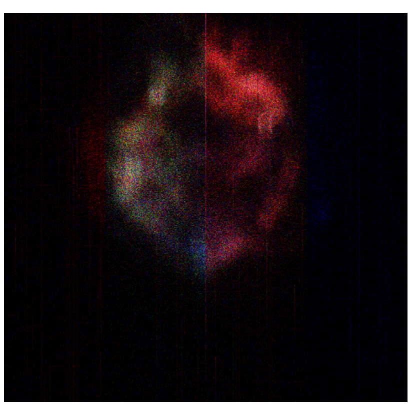
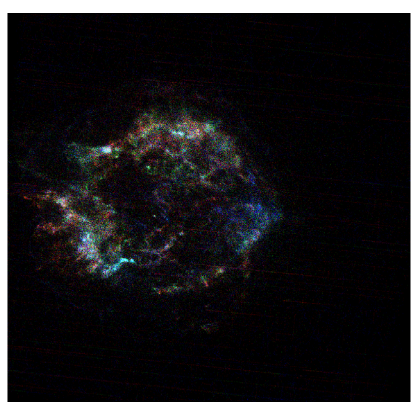
Example ACIS Level 1 Processing

ACIS Level 1 Example (ObsId 05162: SNR Cassiopeia A)

- Left figure shows photon event data input to the ACIS level 1 pipeline
  - Blurring is due to uncorrected spacecraft dither
  - Gross color variations occur because of variations of gain across the detector
- Right figure shows the result of ACIS level 1 processing
  - Aspect solution deblurs the image and correctly orients it on the sky
  - Gain correction allows actual photon energy dependence to be seen readily





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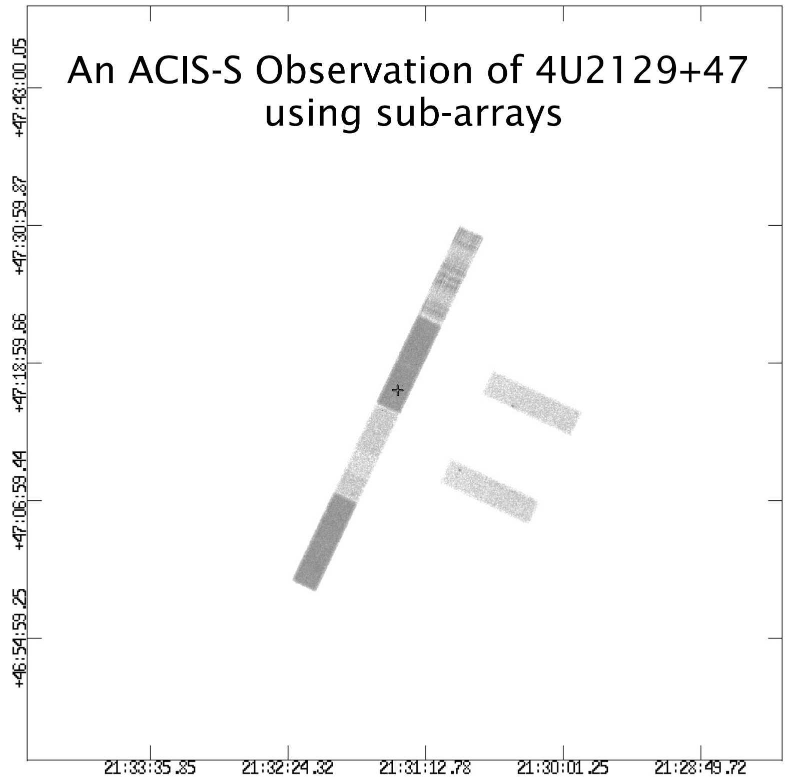
An ACIS-S Observation of 4U2129+47 using sub-arrays



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Spectroscopy with ACIS

- Non-dispersive Spectroscopy – amplitude of signal proportional to energy of incident x-ray (or x-rays)
- Telescope/detector effective area depends on off-axis angle
- Detector efficiency, energy resolution, and gain depend on source location on detector
- Energy resolution also depends on time during mission
- Need to generate two source- and observation-specific products
  - RMF: probability that x-ray of given energy will be detected in given pulse height, as a function of energy
  - ARF: telescope/detector effective area at source location
- Fold model spectrum through RMF and ARF to predict pulse height distribution; adjust model parameters to match actual distribution

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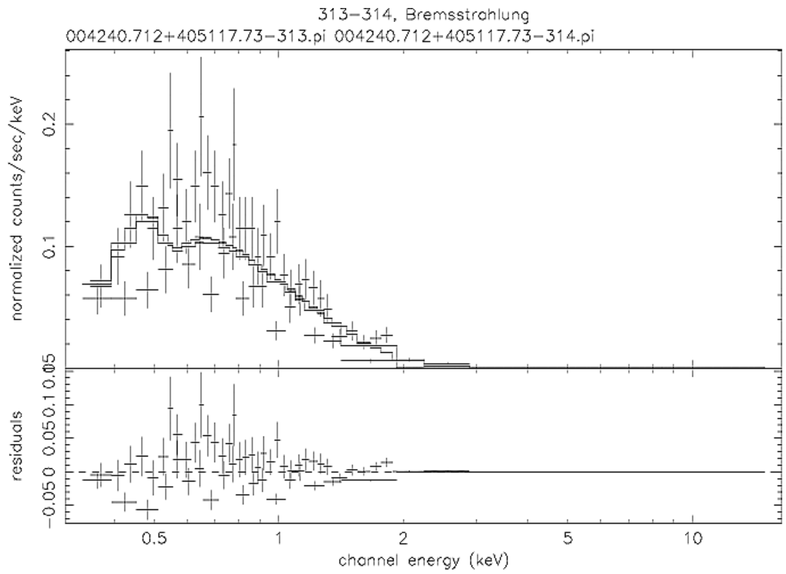
Spectroscopy with ACIS



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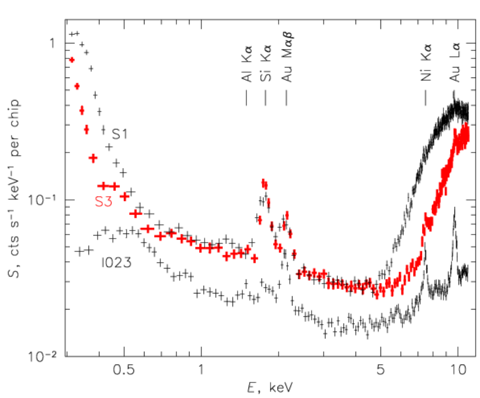
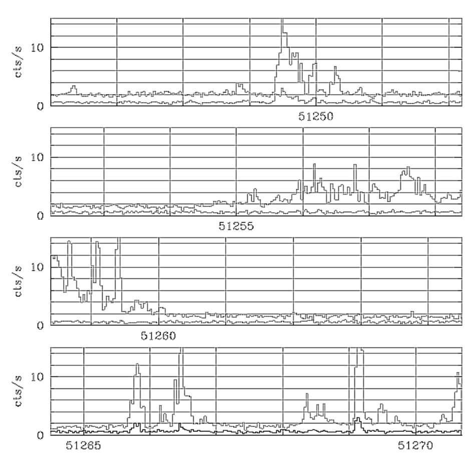
ACIS Background

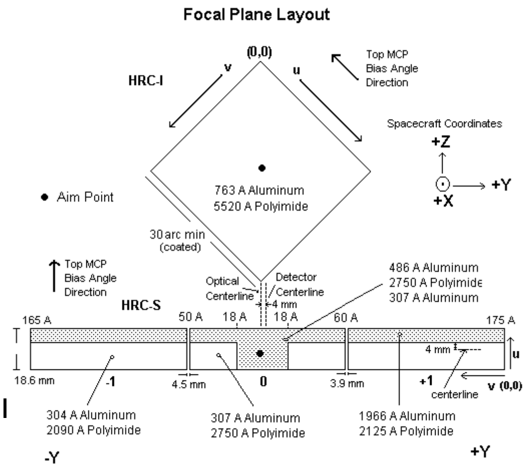
- ~0.3 c s^{-1} chip^{-1} for front-illuminated chips, ~2-5 times higher for back-illuminated chips
- Non-x-ray background significant (dominant at some energies) and variable





High Resolution Camera (HRC)

- Two CsI-coated micro-channel plate (MCP) detectors
- ~⅛″ pixels
- Energy Range ~0.2 – 10 keV
- E/ΔE ~1 @ 1 keV
- ~16 μs time resolution*
- Two aimpoints
  - HRC-I (~30′x30′ FOV)
  - HRC-S (~6′x99′ FOV)
- Background:
  - ~10^{-5} counts s^{-} arcsec^{-2} HRC-I
  - ~2×10^{-4} counts s^{-} res. el.$^{-}$ HRC-S



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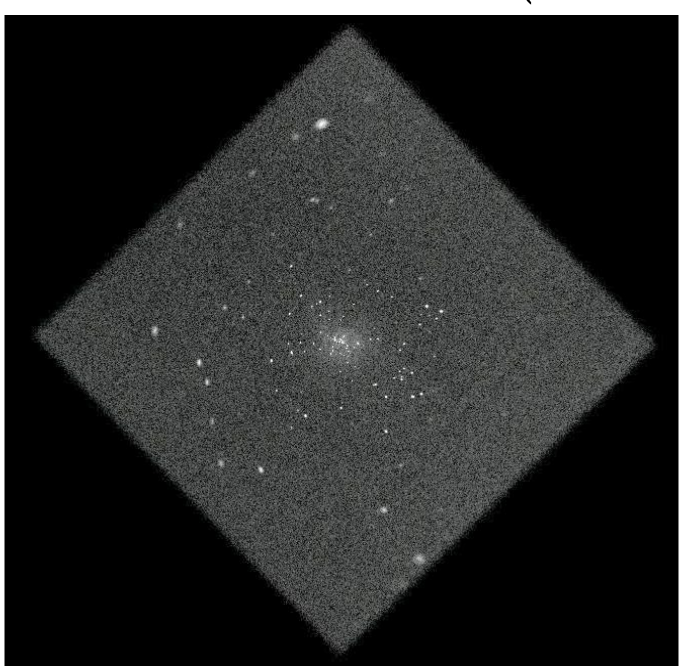
An HRC-I Observation of M31 (Full Field)



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An HRC-I Observation of M31 (Full Resolution)

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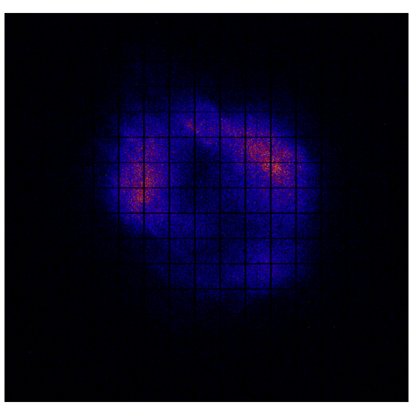
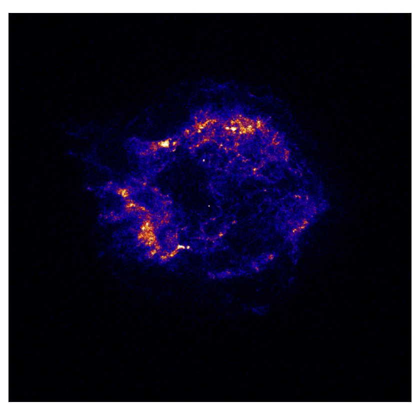
Example HRC Level 1 Processing

HRC Level 1 Example (ObsId 05164: SNR Cassiopeia A)

- Left figure shows photon event data input to the HRC level 1 pipeline
  - Blurring is due to uncorrected spacecraft dither
  - Regular pattern of gaps is present because degap correction has not been applied
- Right figure shows the result of HRC level 1 processing
  - Aspect solution deblurs the image and correctly orients it on the sky
  - Degap correction locates photon events correctly in image space





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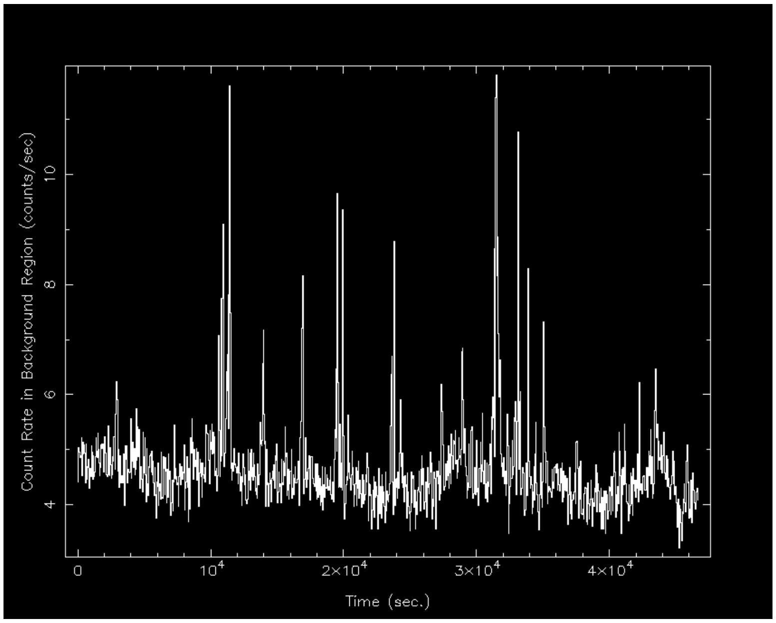
HRC Background Variability



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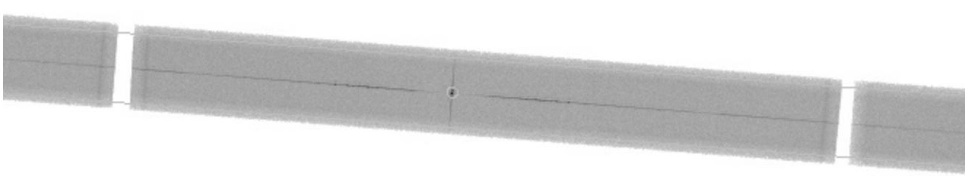
An HRC-S/LETG Observation of AB Doradus



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Low Energy Transmission Grating (LETG)

- High spectral resolving power at low energies
- Typically used with either HRC-S or ACIS-S
- Wavelength Range:
  - 1.2 – 175 Å (70 – 10000 eV) HRC-S
  - 1.2 – 60 Å (200 – 10000 eV) ACIS-S
- Resolving Power E/ΔE :
  - ≥1000 (50 – 160 Å)
  - 60 – 1000 (3 – 50 Å)

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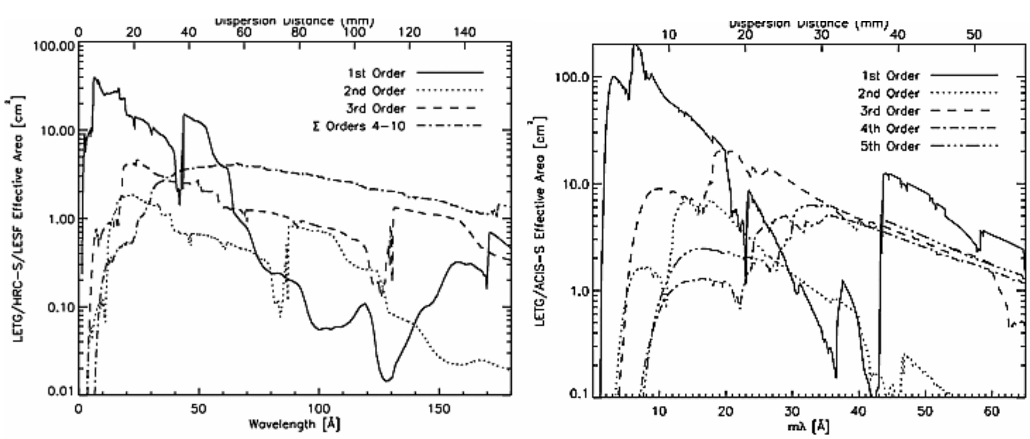
LETG Effective Areas



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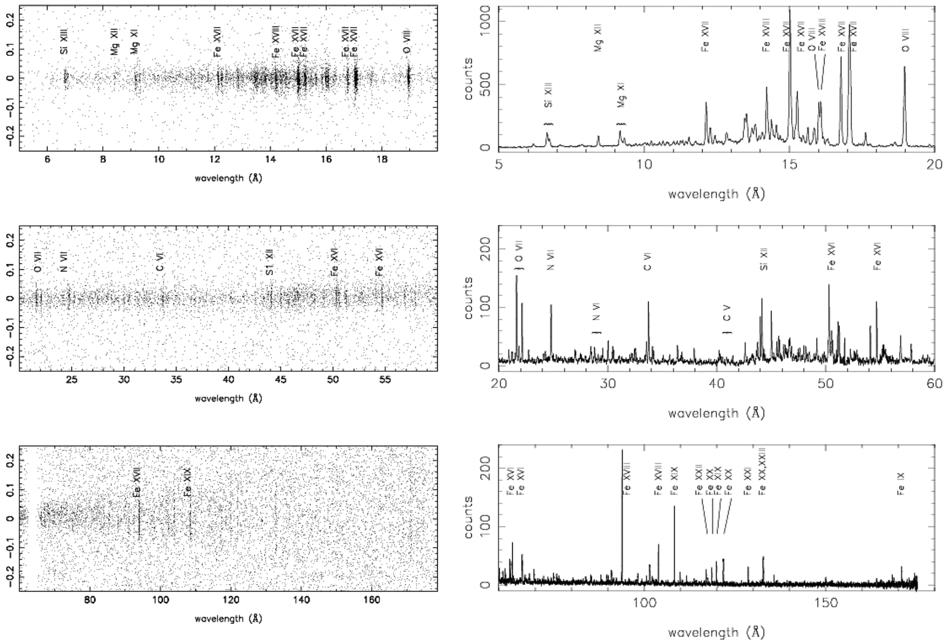
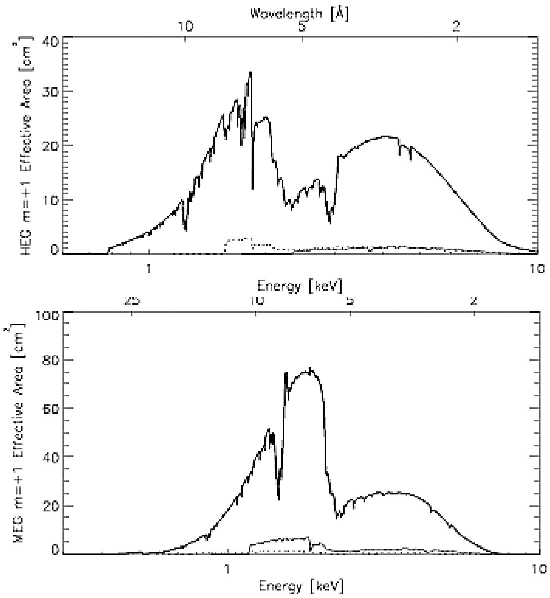
LETG/HRC-S Observation of Capella



High Energy Transmission Grating (HETG)

- Two grating systems, typically used with ACIS-S:
  - High Energy (HEG)
    - 1.2 – 15 Å (0.8 – 10 keV)
    - E/ΔE ~1000 @ 1 keV
  - Medium Energy (MEG)
    - 2.5 - 31 Å (0.4 – 5 keV)
    - E/ΔE ~660 @ ~0.8 keV

HETG Effective Areas



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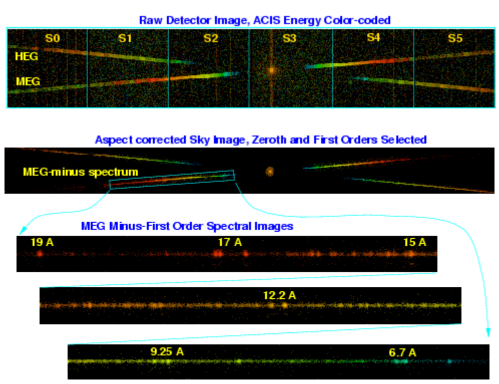
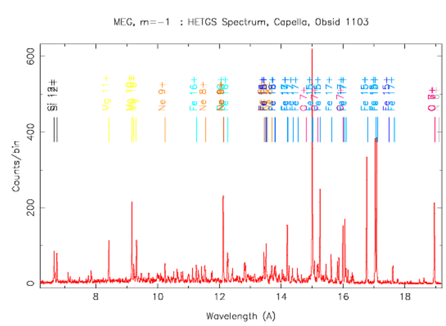
HETG/ACIS-S Observation of Capella





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Challenges for L3 Source Catalog

- Issues intrinsic to data
  - Operating mostly in Poisson regime
  - Multi-scale analysis required due to large data space and PSF
  - Data artifacts complicate analysis
- Analysis Issues
  - Estimating fluxes in overlapping sources
  - Combining observations
  - Estimating background and sensitivity
- Calibration limitations
  - PSF
  - Background

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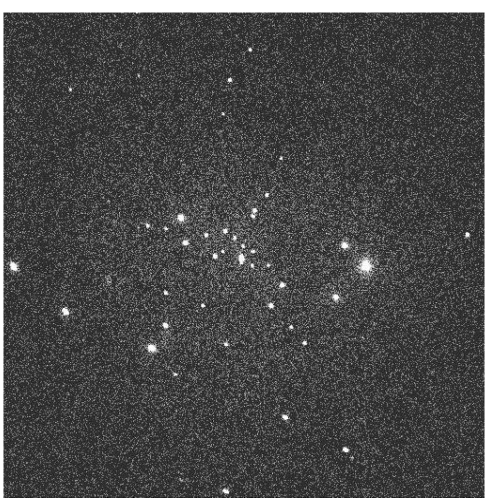
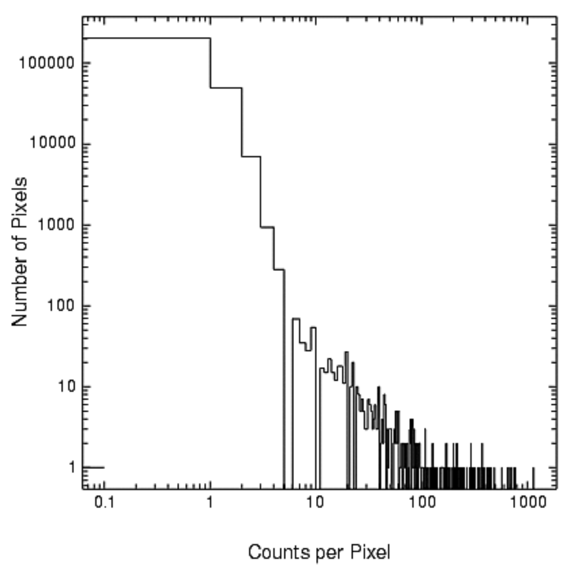
X-ray Pixels Are Mostly Empty





L3 Solutions to Low Counts

- Fly 100 Chandras
- Use source detection tool (wavdetect) designed for use with Poisson Statistics
- Use figures of merit appropriate to Poisson statistics in model fitting
- Use Bayesian tools (Gregory-Loredo) for variability analysis of event data

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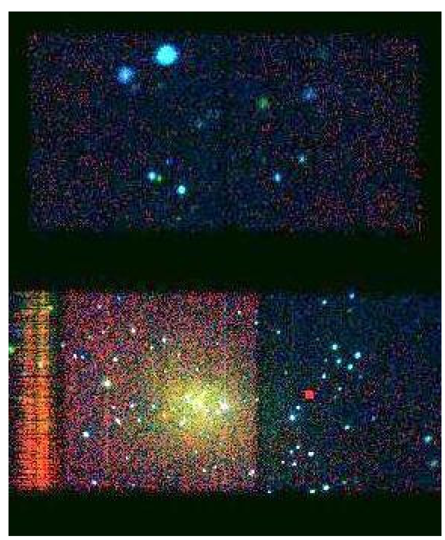
Multi-scale Analysis is Required

- A point source on-axis looks very different from a point source far off-axis
- Data space is too large to analyze at full resolution in a single pass
- An individual source is likely to be detected more than once in a single observation
- Extended sources can have complex structure and/or fill entire chip(s) field-of-view



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L3 Solutions to Multi-Scales

- Generate multiple images at different blocking factors to cover entire FOV
- Run wavdetect on each image using appropriate scales and merge source lists
- Use blank-sky data to estimate background for large extended sources
- Use vtpdetect to detect and characterize sources with complex structure

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Data Artifacts in Images

- Unscreened hot pixels trace out dither pattern with bright corners which can be detected as sources
- Readout streaks from bright sources can lead to multiple sources aligned with CCD columns
- Pile-up in bright sources affects the PSF and in extreme cases can deplete the core of the PSF, leading to multiple sources in a ring about the true source
- Pile-up in bright sources affects spectra
- PSF structure off-axis can make a single source appear as two sources

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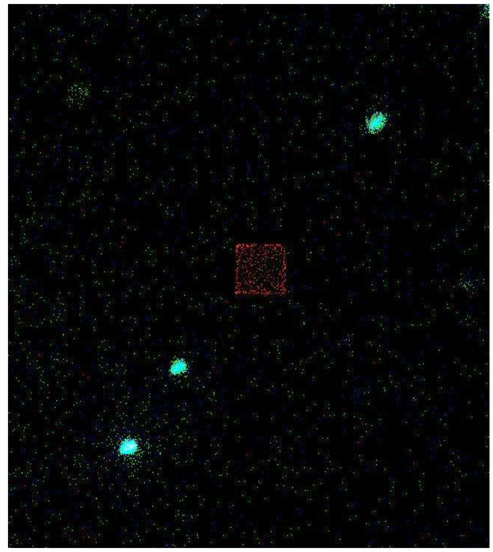
Unscreened Hot Pixels Can Lead to Spurious Sources

- New hot pixels can occur in any observation
- They won't appear in any CALDB list and must be detected and filtered out
- Unfiltered hot pixels trace the dither pattern
- corners of the pattern are enhanced and lead to detection of sources



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L3 Solution to Hot Pixels

- Generate bad pixel list for each observation using new (CIAO3.2) ACIS hot pixel tools
- No action required for HRC

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ACIS Readout Streaks

- CCDs are still accumulating data during readout
  - 3.2 s. data accumulation per frame
  - 40 msec. Readout (40 μsec. Per row)
- Each pixel in a column samples regions in all pixels in the column
- Bright sources appear as “trailed” images or readout streaks

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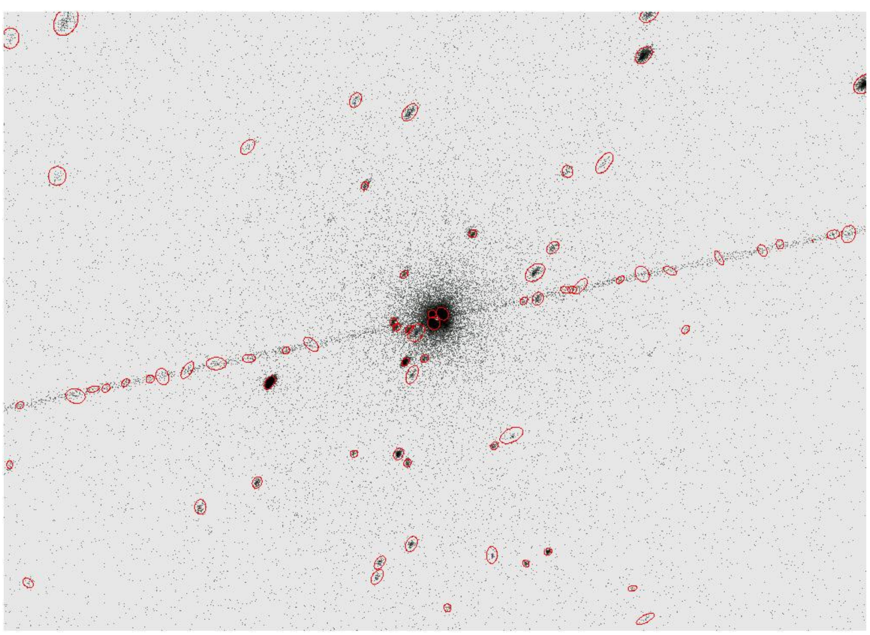
Readout Streaks Lead to Spurious Sources



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Possible L3 Solutions for Readout Streaks

- Filter sources along column after detection
  - May eliminate real sources
- Build streak into background map
  - Initial tests promising; still working on implementation

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ACIS Pile-up

- CCDs typically accumulate for 3.2 s.
- At sufficiently high source rates, two or more x-rays may be detected in a single pixel in the same frame and are interpreted as a single event
  - Event energies overestimated
  - Count rate underestimated
  - Pulse height saturation leads to event rejection

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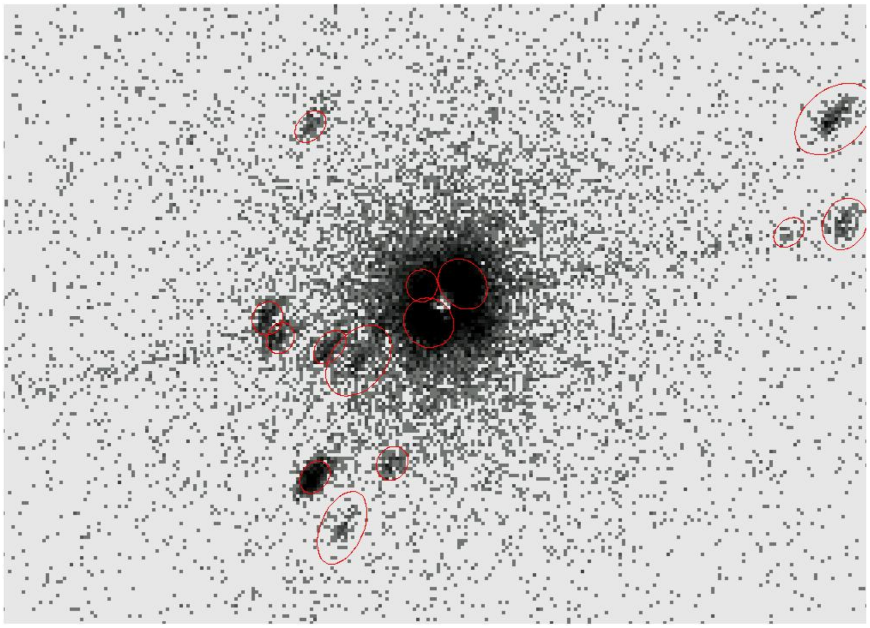
CCD Pile-up Leads to Spurious Sources



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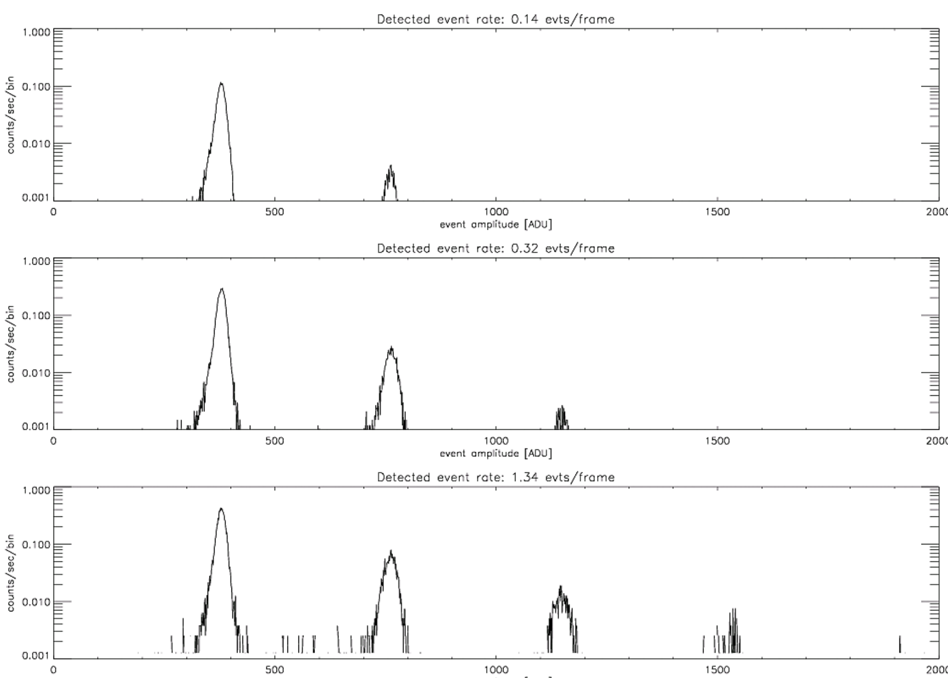
CCD Pile-up Affects Spectra



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L3 Solutions to Pile-up

- Better characterization of pile-up effects in PSF required
- Better characterization of pile-up effects in spectra required
- Recognize when observations/sources where pile-up is likely to be a problem
  - Identify “ring” sources
  - Flag piled spectra

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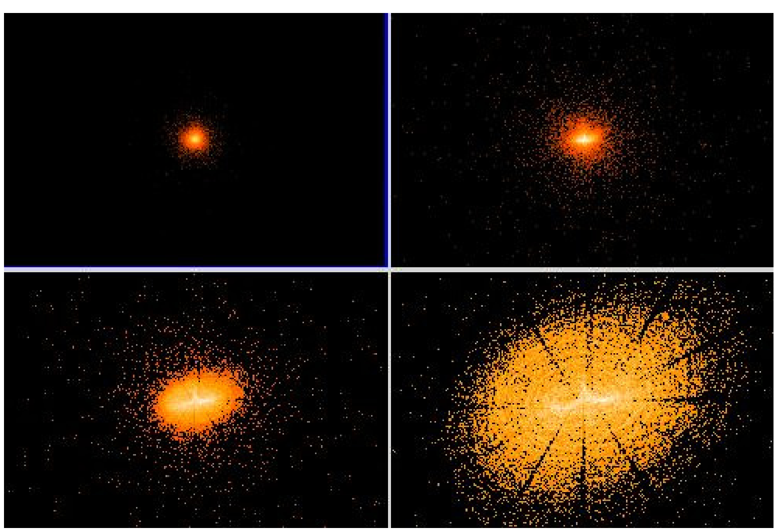
Off-axis PSF Has Complicated Structure

on-axis 2' off-axis



5' off-axis 10' off-axis

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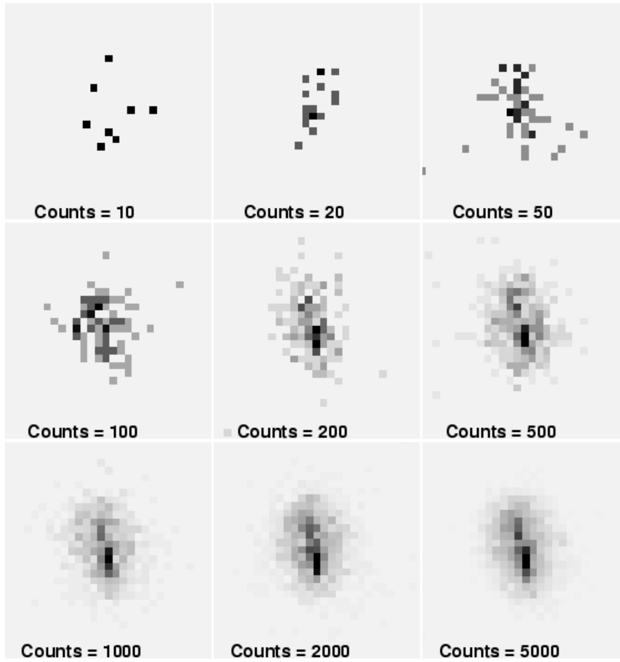
PSF Structure Can Lead to Multiple Sources



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L3 Solutions to PSF Structure

- Use SAOSAC raytrace simulations to generate PSF at each source location
- 2-D spatial fitting to determine source properties
  - Resolve sources
  - Fit for source intensities, positions, and extent

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Challenges in Analysis:

Estimating fluxes and spectra in closely separated sources

- Source and background apertures contaminated by other sources
  - complicated regions must be constructed to exclude contaminating data
- Restricted spectral extraction regions reduce effective area
  - Fraction of total PSF in "stopped-down" aperture < 1
  - Fraction is a function of energy

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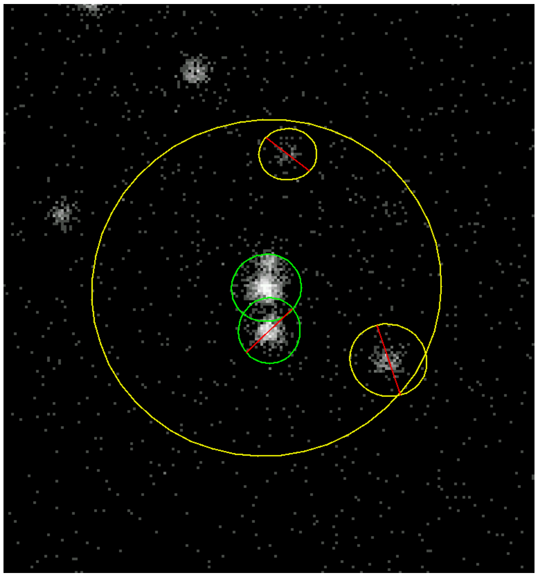
Closely Separated Sources



- Source region of centered source is the intersection of the included and excluded green regions
- Corresponding background region is the intersection of the included and excluded yellow regions and excludes the green regions
- Central source appears to be double, but "upper" source was not identified in detected source list
- 2-D spatial fitting may recover such sources

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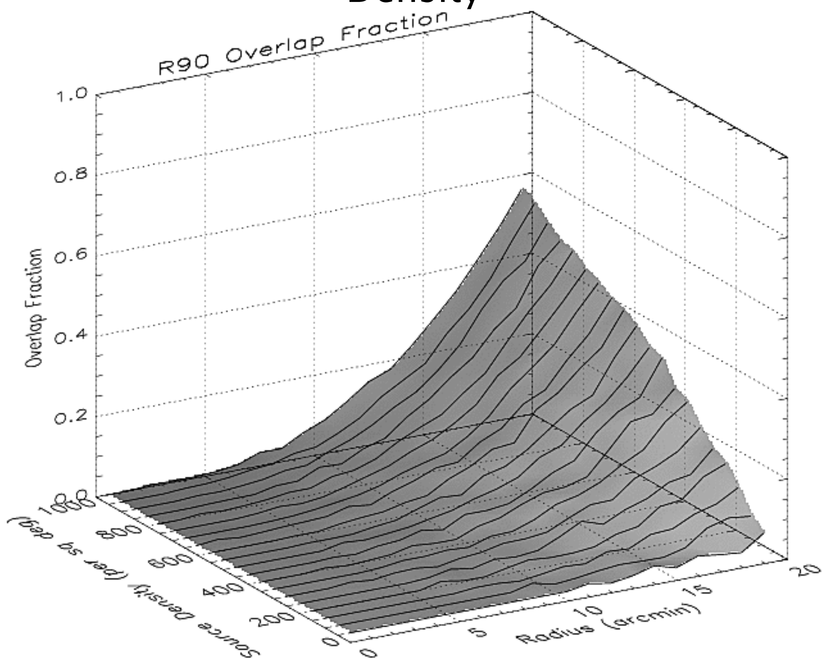
Fraction of Overlapping Sources vs Source Density



L3 Solutions for Closely Separated Sources

- Use SAOSAC raytrace simulations to generate PSF at each source location
- 2-D spatial fitting to determine source properties
  - Resolve sources
  - Fit for source intensities, positions, and extent
- Use estimates PSF ECF vs. Energy in stopped-down spectral extraction apertures to correct ARFs

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Challenges in Analysis:

Combining Observations

- Multiple observations of same source in different detectors, different off-axis angles
- Single off-axis source resolved into two sources on-axis
- Detecting sources in combined data where none detected in individual observations

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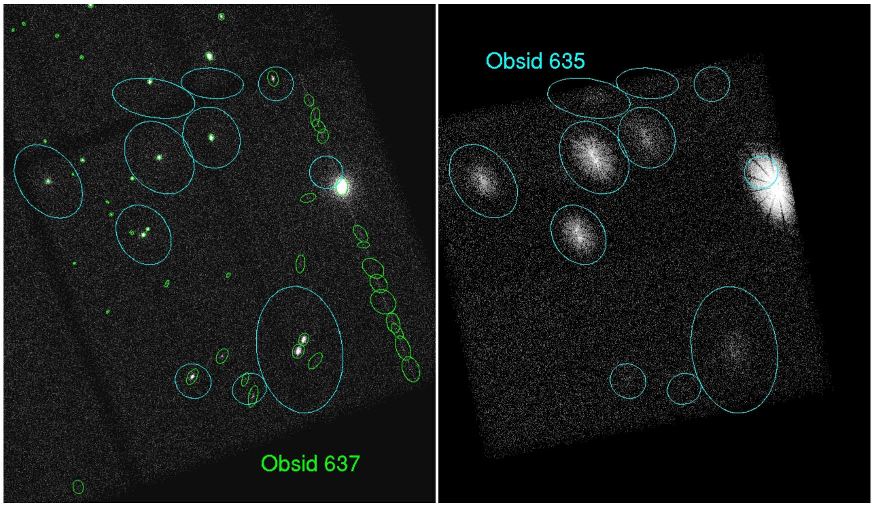
Combining Observations at Different Off-axis Angles



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L3 Solutions for Multiple Observations

- Merge source lists from individual observations
  - Need to test merging rules
- Additional source detection step on combined images and exposure maps
  - Probably not possible for all combinations of off-axis angle

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Challenges in Analysis:

Estimating Background and Sensitivity

- Background maps required for estimating detection sensitivity
  - cf. Einstein:
    - $Net/\sqrt{(var(Net+B)+var(B))} = snr$:
    - $Net = snr^2(1+\sqrt{(1+4(B+var(B))/snr^2)})/2$
  - cf. Chandra Extended Deep Surveys (Lehmer *et al*. 2005, ApJS, 161, 21)
    - $\log(Net) = \alpha + \beta \log(B) + \gamma [\log(B)]^2 + \delta [\log(B)]^3$
  - Input background map in wavdetect → output correlation maps yield sensitivity information
- Background maps required for detecting and characterizing large, complex extended sources

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L3 Solutions for Background Maps

- Generate maps from data themselves:
  - Source exclusion
  - Fitting background image with few counts
  - Choice of background scales
- Use ACIS blank-sky data:
  - May need to reprocess to match calibration profile of individual observations
  - Overall normalization
  - Additional location-dependent SXRB component
  - Need to generate HRC equivalent

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Calibration Limitations

- PSF
  - Estimating systematic and statistical errors in HRMA PSF simulations (SAOSAC raytraces); important for estimates of source extent
  - Incorporating aspect dither and blur in PSF simulations
  - Incorporating detector effects in PSF simulations
    - Position reconstruction errors (degap) in HRC
    - Effects of pile-up in ACIS
- Background
  - Modeling background flares
  - Lack of blank-sky background data for HRC
  - Use of blank-sky background data below ~2 keV for ACIS

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Summary
Source Catalog Challenges

Challenge	**Solution or Plan of Attack**	**Done**	***In Work***	***Rel 2+***
Low X- ray Counts	wavdetect; fitting techniques appropriate to Poisson Statistics	X		
Multi- scale Problems	wavdetect with multiple blocking factors and scales; merge source lists	X		
Hot Pixels	Generate observation- specific bad pixel lists	X		
Read- out Streaks	Build streaks into background map		X	
Pile- up (identification)	Identify piled observations from frame rates		X	
Pile- up (estimate effects)	Improved PSF calibration; implement pile- up spectral models			X
PSF Structure	PSF simulations and 2- D spatial fitting	X		
Overlapping Sources (fluxes)	PSF simulations and 2- D spatial fitting	X		
Overlapping Sources (spectra)	Generate energy- dependent ECF corrections to ARFs		X	
Multiple Observations (existing sources)	Merge lists of sources detected in individual observations	X		
Multiple Observations (new sources)	Source detection on combined images			X
Background maps (compact sources)	Generate from data		X	
Background maps (large extended sources)	Generate from blank- sky data			X

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