Calibration of the Chandra PSF Wings

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HRMA On-Axis PSF

- core
  - sub-arcsecond imaging
  - quasi-specular reflection from low spatial frequency surface errors

- wings
  - faint diffuse halo extending to large angles
  - diffract off surface microroughness
  - energy-dependent
  - azimuthally averaged profile is approximately powerlaw \((\theta^{-\gamma})\) with \(\gamma \sim 2\)

Detailed knowledge of this scattering halo as a function of energy and radius is needed for interpretation of observations with faint structure adjacent to bright sources. For example:

- X-ray scattering halos from cosmic dust along the line of sight
- extraction of faint sources adjacent to bright sources
- detecting faint structure (e.g., cosmic ray precursors) ahead of shocks in supernova remnants
Schematic of the PSF

- CORE
  - quasi-specular reflection from low-freq surface errors

- WINGS (\( \sim \theta^{-2} \))
  - diffraction from surface microroughness

\( \log_{10} \theta \) (arcsec)

\( \log_{10} \text{SB} \)
The HRMA PSF

The aim:

full on-axis PSF radial profile: core ↔ near wings ↔ far wings
spatial/spectral problem: want PSF as function of energy.

The Chandra PSF core is very narrow, the wings very faint ⇒ huge dynamical range

Detector limitations:

- **HRC**: limited energy resolution; high background
- **ACIS**: limited dynamical range (pileup, count rate limits); background
  - **PSF core**: need low count rate
    - long integration times needed
    - lose wings in background
  - **PSF wings**
    - high count rate needed to get above background
    - core heavily piled up
Limitations: ACIS pileup and background

\[ \log_{10} \text{SB} \]

\[ \log_{10} \theta \ (\text{arcsec}) \]
The HRMA PSF

One approach: combine observations with different count rates (and pileup).

- overlap unpiled portions of profiles
- profiles steeply decreasing radially outward $\Rightarrow$ statistics worse outward
Wings of the *Chandra* PSF

Conservative principle: avoid building astrophysics into the calibration, *e.g.*:

- intervening cosmic dust column ⇒ dust scattering halo.
  - increases with $N_H$ column.
  - most important at lower energies: total scattered power scales roughly as $E^{-2}$; at fixed angle, very roughly as $E^{-1}$
- diffuse structure, *e.g.* galaxy or cluster emission (AGN), or PWN (pulsars)
- companion objects

⇒ match deep PSF wings observation with fainter sources (probe the near wings and the core)

### Data Sets

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Object</th>
<th>Exposure</th>
<th>Frame Time</th>
<th>θ</th>
<th>$N_H$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far wings</td>
<td>3662</td>
<td>Her X-1 (high state)</td>
<td>50 ks</td>
<td>3.1 s</td>
<td>45&quot;</td>
</tr>
<tr>
<td>Core</td>
<td>2749</td>
<td>Her X-1 zero order</td>
<td>50 ks</td>
<td>3.2 s</td>
<td>8&quot;</td>
</tr>
</tbody>
</table>

- Her X-1 obsid 3662: Main High state; high count rate and good statistics for far wings; reasonable energy resolution, but inner wings heavily piled up.
- Her X-1 obsid 2749: low state; grating zero order data. $\sim 9000$ cts (0.5–8 keV; within 10") ⇒ limited statistics.
ACIS Pileup

Complications:

- Energy error: event energies too large; spectral distortion
- Grade morphing and loss:
  - grade 0 events → worse grades, (e.g. grade 0 → grade 6)
  - grade 0 fraction decreases, grade 6 fraction increases
  - good grades → bad grades; events lost entirely.
  
  reduction of QE!

Estimating pileup:

- estimate based on count rate (Poisson statistics); assume uniform photon distribution (wings), or photons within a single pixel (core).
- grade morphing: use profile of grade 6 and grade 0 as fractions of ASCA good grades (0,2,3,4,6). Pileup is indicated by increasing g6 fraction and decreasing g0 fraction.
Wings of the Chandra PSF

Her X-1 Observation (obsid 3662; derolled)
(Frame store is toward the top)

ACIS transfer streak

strut shadows
Strut Shadows

The lines at $\sim 30^\circ$ intervals are shadows cast by the mirror support struts. Implications:

- halo: predominantly mirror scattering (in-plane), not a diffuse astrophysical halo
- strut shadows: surface brightness lower by a factor of $\gtrsim 3.5$
  $\Rightarrow$ strict limit on any contribution from a cosmic dust scattering halo
Powerlaw Index (Her X-1 obsid 3662)

Simultaneous fit to obsid 3662 (powerlaw+background) and blank sky background
Wings of the *Chandra* PSF

Anomalous Diffuse (Al Kα?) Feature

source=red  background=black

Her X–1, transfer streak

Her X–1, 160–220 arcsec annulus

Her X–1, 220–280 arcsec annulus

Her X–1, 280–340 arcsec annulus
To avoid the Al line artifact in the Her X-1 high state observation, the 1.4-1.6 keV band was interpolated from adjacent bands.
Profile Fit and Normalization

- simultaneously fit radial surface brightness profiles for Her X-1 obsids 3662 ("wings" observation) & 2749 (grating zero-order)
- use 1 keV bins; sum Her X-1 (obsid 3662) narrow energy slices to get 1 keV wide bins.
- Fit: \( \psi(\theta) + \text{constant background} \) where

\[
\psi(\theta) = A_\beta \left/ \left[ 1 + (\theta / 1\text{''})^2 \right]^{\nu/2} \right.
+ \text{gaussian}(\text{FWHM} \sim 1\text{''})
+ \text{gaussian}(\text{FWHM} \sim 2 - 5\text{''})
\]

- Resulting model profile (and datasets) are normalized:

\[
\psi_{\text{norm}}(\theta) = \psi(\theta) \left/ \left[ 2\pi \int_0^{\theta_{\text{max}}} d\theta \theta \psi(\theta) \right] \right.
\]

- \( \text{NOTE: The fit procedure forces obsid 3662 and 2749 to match at overlap. 3662 and 2749 profiles are rescaled to match at the overlap.} \)
Profiles: 1.0-2.0 keV
Her X-1 data normalized using profile-matching

Normalized surface brightness, $\psi(\theta)$

- Her X-1 (wings)
- Her X-1 (0-order)
- Fit (without dust)
- Dust halo model

$\theta$ (arcsec)
Comparison to AR Lac (HRC-I)

AR Lac (obsid 1385)

- HRC-I observation early in the mission; no gratings
- 17'' off-axis;
- exposure time 18.8 ksec; 124000 source cts.
- data “corrected” to remove a blur from residual errors in the HRC event position reconstruction (Jerius et al. 2003, SPIE 5165-43)
- soft source; appropriate comparison is low-energy ACIS profile

Compare the low energy 1.0–2.0 keV ACIS observations to the HRC-I AR Lac data.

- normalization:
  - AR Lac: by area-weighted sum out to 15''
  - Her X-1: by area-weighted integral of fit out to 300''

- AR Lac HRC-I profile systematically below Her X-1 profile for \( \theta \geq 1'' \)!
Comparison to AR Lac (HRC-I)
Her X-1 data normalized using profile-matching

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chandra-psf-2003-10-27-her-x-1-data-normalized-using-profile-matching}
\caption{Normalized surface brightness, $\psi(\theta)$ vs. angle $\theta$ (arcsec).}
\end{figure}

- Her X-1 (wings)
- Her X-1 (0-order)
- AR Lac (HRC-I)
Alternative Her X-1 Normalizations

- Her X-1 obsid 2749 (grating zero-order): normalize by source spectrum integrated over 10″ radius region
- Her X-1 obsid 3662 (“wings” observation): normalize using transfer streak spectrum

⇒ relative offset between “core” dataset and “wings” dataset!

- better agreement of wings data with AR Lac HRC-I data
  - detector artifact? ACIS or HRC?
  - low-level grating artifact in zero-order data?

Tentative conclusion:

- normalization of wings dataset by transfer-streak is currently probably more reliable than profile-matching with zero-order grating data.
- However: the response during frame transfer is relatively uncalibrated.
  - slope of the gain curve differs by at least a few percent.
  - effective QE uncertain.

⇒ Consider powerlaw fits to wings data (obsid 3662) normalized by the ACIS transfer streak.
Profiles: 1.0-2.0 keV

Her X-1 wings data normalized using transfer streak
Wings of the Chandra PSF

Profiles: 3.0-4.0 keV

Her X-1 wings data normalized using transfer streak

![Graph showing normalized surface brightness vs. angle (arcsec). The graph includes data points for Her X-1 (wings) and Her X-1 (0-order), along with a fit line for wings only.]
Profiles: 6.0-7.0 keV

Her X-1 wings data normalized using transfer streak

\[ \psi(\theta) \]

- + Her X-1 (wings)
- + Her X-1 (0-order)
- Fit (wings only)

\[ \theta \text{ (arcsec)} \]

\[ 10^{-9} \rightarrow 10^{-8} \rightarrow 10^{-7} \rightarrow 10^{-6} \rightarrow 10^{-5} \rightarrow 10^{-4} \rightarrow 10^{-3} \]

Normalized surface brightness, \( \psi(\theta) \)
Powerlaw Index; Her X-1 wings

Simultaneous fit to obsid 3662 (powerlaw+background) and blank sky background
(1.4-1.5 keV and 1.5-1.6 keV fits not included.)
Powerlaw Normalization (at 10″); Her X-1 wings

Simultaneous fit to obsid 3662 (powerlaw+background) and blank sky background
(1.4-1.5 keV and 1.5-1.6 keV fits not included.)
Wings of the Chandra PSF

Summary

- Significant progress toward understanding the on-axis PSF at large angles;
  - PSF Shape is well constrained for $10'' \lesssim \theta \lesssim 6'$, and for $1 \text{ keV} \lesssim E \lesssim 8 \text{ keV}$.
- Profiles unreliable below 1 keV (low energy QE uncertainties)
- Wings shape fit reasonably well by a powerlaw out to $\sim 6'$. Residuals indicate slight steepening of the profile outward
- Differences between HRC-I and ACIS-S grating zero order data $\Rightarrow$ transfer-streak normalization likely better than profile-matching with available non-piled data (grating zero-order datasets)
- Normalization may be uncertain at level of a factor of $\sim 1.25$ or 1.5 (in addition to statistical errors); systematic errors:
  - transfer streak gain error
  - transfer streak effective QE
- Difference in near wings profile between HRC-I (AR Lac) and ACIS/grating zero-order not yet understood. ACIS or HRC artifact? Grating artifact?
- Reasonably detailed investigation of the angular ($\phi$) distribution of the wings can also be pursued.