XRT Point Spread Function

- Conclusion of spectral and spatial studies involving EPIC data from MCG-6-30-15, 3C 273,…
  - New XRTn_XPSF_000n.CCF files
  - Comparisons of PSF files

- Extreme low-Energy features

- King+Gaussian PSF profiling
MCG-6-30-15

Very bright point source – ~ 300 ks, low pile-up, low-BG, singles spectra (2-10keV) extracted from different annuli

Power-law index

vs. Radius

Normalization

vs. Radius

Andy Read (amr30@star.le.ac.uk)
EPIC CAL/OPS Meeting
Vilspa, Spain 23-24/03/04
King PSFs in the CCF

\[ \text{PSF}_{\text{KING}}(r) = \frac{A}{1 + (r/r_0)^2} \alpha \]

- Analysis of King Profile PSF in CCF
- Core Radius R0 and slope alpha show strong energy dependence

APPROACH 1

- Redo entire spectral analysis using altered King profiles with various R0-E and Alpha-E dependencies
- Initial results suggested a far flatter energy dependence is required
MOS 2

ON-AXIS

low-theta

high-theta

Energy (keV)

R0 [Param 1]

PN

ON-AXIS

low-theta

high-theta

Energy (keV)

R0 [Param 1]
Alpha vs R

MCG-6-30-15

PSF = CCF(KING)

Norm. vs R

Rev 0301

MOS1

MOS2

PN

Rev 0302

Rev 0303
Alpha vs R

MCG-6-30-15

PSF=CCF(HIGH-ACC)
(no energy dependence)

Norm. vs R

Rev 0301

Rev 0302

original boundary!

Rev 0303

Rev 0302
MCG-6-30-15

APPROACH #1

- Exploration of parameter space in King profile R0- and Alpha-dependence
  --- Alter CCF files (XPSF, extension 70 [King], just on-axis values)
  --- Redo entire analysis (3 observations, 3 instruments, 8 spectra/ARFs)
  --- Re-alter CCF files (XPSF) and repeat…

- Number of these searched-for (S) PSF dependencies give good results
  e.g.
  MOS1 R0=4.5 (constant with E)   alpha=1.45-1.36 (decreasing with E)
  MOS2 R0=4.5 (constant with E)   alpha=1.45-1.36 (decreasing with E)
  PN      R0=5.0 (constant with E) alpha=1.65-1.38 (decreasing with E)
  …(also more complex dependencies can give even better results…)
Alpha vs R

MCG-6-30-15  PSF=Best-S\textsuperscript{(earched)} Norm. vs R

\[ \text{Power-Law Index} \]

\[ \text{Normilation} \]

Rev 0.301
- MOS1
- MOS2
- PN

Rev 0.302
- MOS1
- MOS2
- PN

Rev 0.303
- MOS1
- MOS2
- PN

XMM EPIC MOS

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University of Leicester
Alpha vs R

MCG-6-30-15

PSF=S(earched)

Norm vs R

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University of Leicester
Alpha vs R

MCG-6-30-15 PSF=CCF(King) Norm vs R

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Vilspa, Spain 23-24/03/04
MCG-6-30-15

APPROACH #2

- Data of sufficient quality to calculate PSFs in small energy bands
- Development of software to fit King profiles to images
- See how these King profiles compare to those in the CCF
- Use these King profile PSFs in the spectral analysis
Examples of King profile fits to narrow-band images

MCG-6-30-15

MOS1
Rev 303
6 keV

PN
Rev 301
3 keV
PSF King-profile fitting results - MGC06 MOS1

Exposure-weighted

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EPIC CAL/OPS Meeting
Vilspa, Spain 23-24/03/04
Alpha vs R

PSF=AMR1

Norm. vs R
3C273 18 M1/M2 SW Obs.

Power-law index vs radius

Radius (1.1” pixels)

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3C273

PSF=CCF(King)  PSF=AMR1

Normalization vs radius

Radius (1.1" pixels)

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Testing new PSFs  
(Distributed 17/12/03)

Independent study [RDS]

PKS 0558-504 [Rev 84]  inner 5”[MOS], 10”[PN] excluded

<table>
<thead>
<tr>
<th></th>
<th>SASccf</th>
<th></th>
<th>AMR1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2-2 keV</td>
<td>2-10 keV</td>
<td>0.2-2 keV</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>Flux</td>
<td>Slope</td>
</tr>
<tr>
<td>M1</td>
<td>3.08</td>
<td>2.07</td>
<td>1.95</td>
</tr>
<tr>
<td>M2</td>
<td>3.07</td>
<td>2.13</td>
<td>1.95</td>
</tr>
<tr>
<td>PN</td>
<td>3.05</td>
<td>1.90</td>
<td>2.04</td>
</tr>
</tbody>
</table>

AMR1 fluxes agree better for both energy ranges

χ² better for low-E fit

High-E still not too good, though may be due to non-PSF effects
Testing new PSFs

Independent study [RDS]

Very bright transient, inner 20” excluded

<table>
<thead>
<tr>
<th></th>
<th>SASccf</th>
<th>AMR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-9 keV</td>
<td>Slope</td>
<td>1-9 keV</td>
</tr>
<tr>
<td></td>
<td>Flux</td>
<td>Slope</td>
</tr>
<tr>
<td>M2</td>
<td>1.62</td>
<td>9.57</td>
</tr>
<tr>
<td>PN</td>
<td>1.74</td>
<td>8.45</td>
</tr>
<tr>
<td>Diff</td>
<td>0.12</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>11%</td>
</tr>
</tbody>
</table>

Massive improvement in slope fit

Still a normalization problem (though perhaps a non-PSF effect)
Testing new PSFs

Independent study [RDS] – Mkn205

<table>
<thead>
<tr>
<th>Radii</th>
<th>PN Slope</th>
<th>PN Flux</th>
<th>M1 Slope</th>
<th>M1 Flux</th>
<th>M2 Slope</th>
<th>M2 Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>1.72±0.02</td>
<td>5.47±0.13</td>
<td>1.75±0.06</td>
<td>6.05±0.58</td>
<td>1.85±0.04</td>
<td>5.98±0.27</td>
</tr>
<tr>
<td>0-20</td>
<td>1.70±0.02</td>
<td>5.54±0.12</td>
<td>1.75±0.05</td>
<td>6.17±0.59</td>
<td>1.78±0.05</td>
<td>5.95±0.50</td>
</tr>
<tr>
<td>0-40</td>
<td>1.70±0.02</td>
<td>5.54±0.12</td>
<td>1.73±0.05</td>
<td>6.18±0.52</td>
<td>1.80±0.04</td>
<td>6.00±0.21</td>
</tr>
<tr>
<td>0-60</td>
<td>1.72±0.02</td>
<td>5.53±0.09</td>
<td>1.73±0.05</td>
<td>6.26±0.53</td>
<td>1.82±0.04</td>
<td>6.03±0.22</td>
</tr>
<tr>
<td>0-120</td>
<td>1.70±0.02</td>
<td>5.82±0.14</td>
<td>1.72±0.04</td>
<td>6.45±0.24</td>
<td>1.77±0.04</td>
<td>6.46±0.25</td>
</tr>
<tr>
<td>5-40</td>
<td>1.72±0.02</td>
<td>5.52±0.15</td>
<td>1.73±0.06</td>
<td>6.02±0.69</td>
<td>1.78±0.05</td>
<td>5.77±0.28</td>
</tr>
<tr>
<td>10-60</td>
<td>1.71±0.03</td>
<td>5.53±0.24</td>
<td>1.72±0.06</td>
<td>6.33±0.52</td>
<td>1.72±0.07</td>
<td>6.20±0.65</td>
</tr>
<tr>
<td>20-80</td>
<td>1.73±0.09</td>
<td>6.09±1.19</td>
<td>1.72±0.10</td>
<td>6.48±0.83</td>
<td>1.86±0.09</td>
<td>6.61±0.63</td>
</tr>
</tbody>
</table>

Slopes consistent (except perhaps for M2 0-10")

Fluxes OK (except for 0-120'' - poor BG subtraction or faint extended emission)
Comparison of PSFs: Enclosed Energies

- Enclosed energy versus energy @ 25”
- SASccf PSFs
Comparison of PSFs: Enclosed Energies

- Enclosed energy versus energy @ 25"
- AMR1 PSFs

Enclosed Energy

Energy (keV)

M1
M2
PN

idlout_sasccf+141103_t0r25.dat b1 b2 b3

AMR1
Comparison of PSFs: Enclosed Energies

- Ratio of enclosed energy (AMR1/SASccf) versus energy @ 25″
Comparison of PSFs: Enclosed Energies

- Ratio of enclosed energy (AMR1/SASccf) versus energy @ 45°
Comparison of PSFs: Enclosed Energies

- Ratio of enclosed energy (AMR1/SASccf) versus energy @ 70°
Reducing the PN EE?

- Choose the high end of the $R_0$ values (~6.0) and the low end of the $\alpha$ values (~1.56)
- Gives rise to lower EE (80-81% @25'')
- Are the spectral results still OK? …
Alpha vs R

MCG-6-30-15

PSF=260204

Norm. vs R

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EPIC CAL/OPS Meeting

Vilspa, Spain 23-24/03/04
Extreme Low-Energy Features

- Analysis of low-E (<250eV M1/M2 spectra in radial annuli (0-30 pixels [1 pixel=1.1”])
- Annulus 1 [6-12]
  2 [12-18]
  3 [18-24]
  4 [24-30]
  + comparison with centre
- Centres obtained via Gaussian fitting to images
Variation of spectrum with radius

Rev 0094 (3C273)

MOS1

R=0-6

Ann.1
6-12/0-6

Ann.2
12-18/0-6

Ann.3
18-24/0-6

Ann.4
24-30/0-6

- Relatively fewer low-E events at larger radius

MOS2

Ann.1
6-12/0-6

Ann.2
12-18/0-6

Ann.3
18-24/0-6

Ann.4
24-30/0-6

Flux=0.4684x10^{-3} \ HRO=0.927188 \ HRtot=1.10320

Flux=0.38745x10^{-3} \ HRO=2.08232 \ HRtot=2.08523

[Graphs showing normalized spectrum ratios for different annuli and radii]
Variation of spectrum with radius

Rev 0303 (MCG06-30-15) MOS1 MOS2

- M1 [soft] shows effect more than M2 [hard]

R=0-6
Ann.1 6-12/0-6
Ann.2 12-18/0-6
Ann.3 18-24/0-6
Ann.4 24-30/0-6

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- Rel. fewer low-E events at large-R
- M1 [soft] effected more than M2 [hard]

**Hardness ratio [HR] versus Rev for Annuli 1-4**

- Value 1: spectrum same as at centre
- Relative deficit in extreme low-E photons seen to increase with radius
- Effect appears less prominent at later revolution number
Hardness ratio [HR] versus Rev for Annuli 1-4 for one source (3C273)

- Again, effect less prominent at later revolution number
Hardness ratio [HR] versus central hardness ratio [HR0] for Annuli 1-4

- Value 1: spectrum same as at centre
- Just the soft spectrum sources (low HR0) that show the relative deficit of low-E photons effect
- These are mainly M1
- Very soft sources have lots of direct extreme low-E photons (i.e. small %age of redistributed photons).
- Low-E photons in hard sources may be nearly all redistributed
- Likely a PSF effect that is the cause – (e.g. a more compact ex.low-E M1 PSF)
Ratio of M1 central hardness ratio [HR0] to M2 central hardness ratio versus Rev

- i.e. effect of very different spectral shapes (e.g. Rev0094 3C273)
- Difference appears to get less at later revolutions
- Explainable if redistribution is getting worse with rev – Increasing redistribution is diluting the effect of different ex.low-E PSFs – At later Revs, relatively more <160eV photons are redistributed, rather than arriving directly.
Ex. Low-E PSFs for M1 & M2

- Using stacked 0301-0303 MCG06-30-15 observations
- < 160 eV and 160-250 eV
- M1 < 160 eV PSF is indeed more compact!

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>R0</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 160 eV</td>
<td>5.1</td>
<td>1.8</td>
</tr>
<tr>
<td>160-250 eV</td>
<td>4.9</td>
<td>1.6</td>
</tr>
<tr>
<td>M1</td>
<td>4.0</td>
<td>1.5</td>
</tr>
<tr>
<td>M2</td>
<td>4.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Effects of low-E changes?

- Added ex.low-E changes to AMR1 PSF (shown left [M1, theta=0])
- Effects (e.g. spectral) expected only to appear at very low energies (<250eV)
- However, large effects observed at large energies (2keV, 5keV)!
Effects of low-E changes?

- Analysis shows that spline fitting to points has gross effects far from low energy regions.
- High-energy effective area values subsequently effected.
Effects of low-E changes?

- Tiny changes to individual point values can lead to sensible spline fits
- No changes above ~250 eV
- General warning that interpolations may not be giving what we expect
- Also CAL interpolation may be different from e.g. my interpolation
PSF King+Gaussian [KG] Fitting

- King fits sometimes underestimate the PSF profile at the very centre

\[
\text{PSF}_{\text{KG}}(r) = \frac{A}{\left[1+(r/r_0)^2\right]^\alpha} + B e^{-Cr^2}
\]

\[\uparrow \quad \uparrow\]

KING + GAUSSIAN

- Would require new software [CAL, arfgen etc...] to access it
PSF King+Gaussian [KG] Fitting
- e.g. M1 100 eV
- Large Gaussian component required
(ratio of normalizations 25±1%)
**PSF King+Gaussian [KG] Fitting**

- e.g. PN 3000 eV
- Very small (~0) Gaussian component required (ratio of normalizations 1±1%)
- PN’s larger pixels insensitive to the very core of the PSF
PSF King+Gaussian [KG] Fitting

- Ratio of normalizations [Gauss/King] versus Energy
- M1/M2 : Significant Gauss component allowed, especially at low/medium-E – [no Gauss component required at high-E]
- PN : No Gauss component required (except perhaps at lowest-E [1.8±0.6%])
PSF King+Gaussian [KG] Fitting

- Comparison of AMR1 PSF and KG PSF

- M1 100eV

- Effective area @ 25" increases by 0.5%
PSF King+Gaussian [KG] Fitting

- Comparison of AMR1 PSF and KG PSF

- M2 3000eV

- Effective area @ 25" increases by 0.8%

[1] EE @ 25": 0.806753

[2] EE @ 25": 0.813336
PSF King+Gaussian [KG] Fitting

- Comparison of AMR1 PSF and KG PSF

- PN 3000eV

- Effective area @ 25" decreases by 0.9%

- Unsure as yet as to changes to any spectral analysis results (using arfgen)