Empirical effective area calibration of RGS using blazar spectra

Jelle Kaastra, Cor de Vries, Jan-Willem den Herder, Jelle de Plaa
Introduction & motivation

- Deep Mrk 509 study in 2011 revealed wiggles in RGS1/RGS2 effective area.

- SAS 13.5.0 contains many improvements in a.o. wavelength binning.

- In 2015, follow-up study of RGS effective area.

Mrk 509, Kaastra et al. (2011)
Two data sets

- Data set for RGS-pn comparison (840 ks)
  PKS 2155-304
  3C 273
  H 1426+428

- Data set for RGS analysis (4.1Ms)
  Mrk 421
  PKS 2155-304
  3C 273
  H 1426+428
RGS data analysis

- SAS version 13.5.0
- Make spectral fits (SPEX) using power law and ‘hot’ absorption model
- Convert count spectra into fluxed spectrum using best fit model
- Bin fluxed spectra into 1 A bins

PN Analysis

- 1: Power-law fit + hot in 0.3-2.5 keV range
- 2: Spline fit in 0.3-10 keV range
- Converted to fluxed spectra
RGS1/pn trend over time

<table>
<thead>
<tr>
<th>RGS1 band (Å)</th>
<th>a</th>
<th>b</th>
<th>n</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9–10</td>
<td>0.989±0.010</td>
<td>$(−12 \pm 7) \times 10^{-6}$</td>
<td>47</td>
<td>112.0</td>
</tr>
<tr>
<td>15–16</td>
<td>0.990±0.008</td>
<td>$(7 \pm 6) \times 10^{-6}$</td>
<td>47</td>
<td>113.5</td>
</tr>
</tbody>
</table>
Trend in RGS2/RGS1 in 26-27 Å band.
Fitting trends to all RGS bands

Table 6: Fits to ratio $R(t)$ of RGS2 over RGS1 flux. Values given are averages over all 28 wavelength bins used. $H(x)$ is the Heaviside function ($H = 0$ for $x < 0$ and $H = 1$ for $x > 0$).

<table>
<thead>
<tr>
<th>Model</th>
<th>$R(t) = a$</th>
<th>$R(t) = a + bt$</th>
<th>$R(t) = a + uH(t - 1408)$</th>
<th>$R(t) = a + bt + uH(t - 1408)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$</td>
<td>55.5</td>
<td>52.3</td>
<td>51.0</td>
<td>49.4</td>
</tr>
<tr>
<td>d.o.f.</td>
<td>44.6</td>
<td>44.5</td>
<td>44.4</td>
<td>43.6</td>
</tr>
<tr>
<td>$a$</td>
<td>$0.987\pm0.003$</td>
<td>1.011±0.004</td>
<td>0.996±0.003</td>
<td>1.006±0.004</td>
</tr>
<tr>
<td>$b/10^{-5}$</td>
<td>–</td>
<td>$-2.3\pm0.3$</td>
<td>–</td>
<td>$-1.4\pm0.4$</td>
</tr>
<tr>
<td>$u$</td>
<td>–</td>
<td>–</td>
<td>$-0.031\pm0.004$</td>
<td>$-0.015\pm0.005$</td>
</tr>
</tbody>
</table>
Fitting parameters trend and jump
High-Resolution fitting

Improvements of the models:

- Including dust absorption in absorption models
- Include spectral curvature in power-law models

Conclusion:
RGS1 is stable with respect to EPIC pn, but RGS2 is not (although within 5%).
Empirical correction for time dependency

For each 0.05 Å wide bin, we determine the fit residuals for each individual observation relative to the best-fit broken power-law model described in the previous section. We then fit these residuals as a function of time to a simple analytical expression. This is done for first and second order spectra independently.

If the observation epoch is denoted by $t$, expressed in units of 1000 orbits, then we use the following parameterisation:

- $t < 0.538$: $f = p_1 + (t/0.538)p_2$
- $0.538 < t < 1.408$: $f = p_1 + p_2 + p_6 + ((t - 0.538)/0.870)p_3$
- $1.408 < t < 2.112$: $f = p_1 + p_2 + p_3 + p_6 + p_7 + ((t - 1.408)/0.704)p_4$
- $2.112 < t < 2.816$: $f = p_1 + p_2 + p_3 + p_4 + p_6 + p_7 + ((t - 2.112)/0.704)p_5$
Scatter reduction before and after correction

\[ \sigma_{\text{tot}} / \sigma_{\text{noise}} \]

\[ \sigma_{\text{pop}} \]

\[ \sigma_{\text{tot}} \]
Stacked residuals in bands
Possible hydrazine contamination?

N = (4±1) x 10^{20} \text{ N}_2\text{H}_4 \text{ atoms m}^{-2}

![Graph showing spectral lines and data points representing possible hydrazine contamination.](image-url)
Conclusions

- Effective area of RGS is generally stable within 5%.
- RGS1 is more stable with respect to PN than RGS2.
- Using empirical fits to time dependent behavior of RGS, we can correct the calibration and reduce systematic scatter to 1-2%.
- Indications for contamination of Hydrazine detectable near 30-31 A.