The Chandra Source Catalog: X-ray Aperture Photometry


1Smithsonian Astrophysical Observatory; 2MIT Kavli Institute for Astrophysics and Space Research
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The Chandra Source Catalog (CSC) represents a reanalysis of the entire ACIS and HRC imaging observations over the 9-year Chandra mission. We describe here the method by which fluxes are measured for detected sources. Source detection is carried out on a uniform basis, using the CIAO tool wavdetect. Source fluxes are estimated post facto using a Bayesian method that accounts for background, spatial resolution effects, and contamination from nearby sources. We use γ-function prior distributions, which could be either non-informative, or in case there exist previous observations of the same source, strongly informative. The current implementation is however limited to non-informative priors. The resulting posterior probability density functions allow us to report the flux and a robust credible range on it. We first set up the problem (§1) and describe the classical solution that usually applies in the high counts regime (§2). We then develop the general Bayesian solution (§3). Some advantages and disadvantages of this method are discussed in §4. Example output is shown below in Figure 3.

2. CLASSICAL CASE

The standard practice in X-ray aperture photometry has been to ignore the Poisson nature of the problem (Equation 2) and to compute the maximum likelihood estimates of the source and background intensities β and δβ by solving the algebraic equations

\[ n_0 = \frac{f}{h} \delta g + \delta b; \quad n_g = \frac{g}{f} \delta b, \tag{4} \]

Solving Equation 4 for \( \delta g \) and \( \delta b \),

\[ \delta g = \frac{n_0 - n_g}{f - g}; \quad \delta b = \frac{f n_g - g n_0}{f - g}, \tag{5a} \]

with errors propagated under a Gaussian assumption,

\[ \sigma^2_{\delta g} = \sigma^2_{\delta b} = \frac{f^2 n^2_g - g^2 n^2_0}{(f - g)^2}, \tag{5b} \]

The classical case is a useful approximation in the high counts regime, when \( n_0, n_g, n_{r0} \gg 1 \) and when \( f \approx 1, g \approx 2 \). However, this condition is usually not met for the majority of X-ray sources, and the estimates and uncertainties derived thus become unreliable (Figure 2).

Figure 1: A typical Chandra image, showing an aperture centered on the source and an annular aperture around it that is dominated by the background. The inset figure displays a ChaRT simulation of a point source appropriate for this location, with the same regions overlaid. Note that a considerable fraction of the source counts fall into the putative background aperture. Accounting for this (via \( f \) and \( g \), see Equation 1) is an important factor in the analysis.

Figure 2: Comparison of classical approximation with Poisson. The Bayesian posterior density function pdf(Data) (Equation 9) is shown as the red curve, compared with the Gaussian density function in black. The former is defined only over the non-negative number line, whereas the latter is not. The shaded regions represent the 68% equal-tailed interval, and the solid horizontal line represents the classical 2σ level interval (Equation 5). The upper plot is for the high counts regime, and the lower plot is for the low counts case (\( n_0 = 81 \)). In both cases the same background (\( n_0 = 200 \)) and PSF fractions \( f = 1, g = 0 \) were used. Notice that the Gaussian approximation is reasonable for high counts, but is invalid in the low counts regime.

2.1 Bayesian Analysis

A number of Bayesian calculations have previously estimated the probability density of source intensity given a background measurement (e.g. Longo, 1990, Longo et al. 2002, Kashyap et al. 2006). However, these calculations, of pdf(\( p_{\beta |n} \)) (see Equation 2), do not account for the contamination of the counts in the background aperture. We can compute the posterior probability density function using Bayes’ Theorem, which allows inclusion of a counts-to-flux conversion factor without loss of generality. In practice, \( \beta \) is a parameter that takes a value or samples of values as a distribution, pdf(Data).

\[ n_0 - \text{Point} (\beta) - n_g = \text{Point} (\beta), \tag{2a} \]

with \( 0 \leq f \leq g \leq 1 \), and \( r = 2f / g \).

In Bayesian analysis, it is customary to denote the probability density function of a variable \( x \), conditional on another variable \( y \), as pdf(\( y | x \)). The probability of a hypothesis \( H \), generally a single number, is denoted as pdf(\( H | y \)). A posterior pdf(\( H | y \)) that takes a value or samples of values as a distribution, pdf(Data).

\[ \text{pdf(Data)} = \text{pdf(after)} \times \text{pdf(before)}, \tag{6} \]

where any of the terms in the numerator is the prior and the second term, the likelihood.

In general, we may write function priors for both \( \beta \) and pdf(\( H | y \)).

\[ \text{pdf}\left(\frac{\beta}{\beta_0} | H \right) = \frac{1}{\beta_0} \text{pdf}(\beta | H), \tag{7} \]

where the parameters set to a form that is non-informative, \( \beta_0 \) is the 1/2 percentile level of the posterior probability density function of \( \beta \). The likelihood is taken to be Poisson.

\[ \text{pdf}\left(\frac{H}{H_0} | H \right) = \frac{1}{H_0} \text{pdf}(H | H), \tag{8} \]

with the parameters set to a form that is non-informative, \( H_0 \) is the 1/2 percentile level of the posterior probability density function of \( H \).

The likelihood is taken to be Poisson.

\[ \text{pdf}(\beta | H) = \frac{1}{H_0} \text{pdf}(H | H), \tag{9} \]

where the parameters set to a form that is non-informative, \( \beta_0 \) is the 1/2 percentile level of the posterior probability density function of \( \beta \).

\[ \text{pdf}(H | H) = \frac{1}{H_0} \text{pdf}(H | H), \tag{10} \]

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REFERENCES


Figure 3: A display of the CSC viewer tool showing example results of the X-ray aperture photometry. The quantities listed for each source ID are:

- source cell area [arcsec²];
- background cell area [arcsec²];
- \( n_0 \); [cts];
- \( n_g \) [cts];
- \( g/2f \) [cts];
- and the 68% equal-tail uncertainty interval on \( g/2f \) [cts], based on the 44.6% and 55.4% percentile levels of the posterior probability density function pdf(Data).

The PSF fractions are \( f = 0.9 \) and \( g = 0.1 \) in all cases.

vkashyap@cfa.harvard.edu

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