Fig. 1. Diagram of the annulus spectral fitting. The input parameters (ovals) are given to the tool (rectangles) that produce the files (ellipse).

Fig. 2. CF of different annular radii of an on-axis source. The CF (vertical axis) is plotted against incident X-ray energy (keV; horizontal axis) for the annulus regions of 5 sets of \( r_{\text{in}} = r_{\text{out}} \). The unit of radius is pixel.

Fig. 3. Diagram of the annulus spectral fitting. The input parameters (ovals) are given to the tool (rectangles) that produce the files (ellipse).

Fig. 4. (a) Radial profile of a MARX-simulated unpiled-up on-axis source. (b) Best-fit \( N \) and \( \Gamma \) of the fitting at each annulus. The dashed-and-dotted lines represent the input parameter values of the simulation.

Fig. 5. (a) Radial profile of a MARX-simulated unpiled-up on-axis source. (b) Best-fit \( N \) and \( \Gamma \) of the fitting at each annulus. The dashed-and-dotted lines represent the input parameter values of the simulation.

Fig. 6. shows an example of the spectra and light curves of the annulus and the total PSF regions.

Sources on ACIS for Spectral and Temporal Analysis


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1. Introduction

The X-ray CCDs realize energy resolution capability by counting the number of electrons produced by photo-electric absorption of an X-ray photon by the device medium and subsequent ionization, where the number of electrons in a detection cell is proportional to the incident X-ray energy. This assumes that any multiple X-ray photons land on a single cell within a readout time frame. If two photons with the energy of \( E_1 \) and \( E_2 \) land on the same detection cell in the same frame, we have no measure to distinguish it from a single photon with the energy of \( E_1 + E_2 \). The phenomenon, known as pile-up, causes distortion in the spectrum and the PSF, and underestimate of event rates.

Davis (2001, ApJ, 562, 575) developed a method for the X-ray spectral analysis of piled-up sources. He used a non-linear modification to the standard integral equation implementation, he uses a non-linear modification to the standard integral equation relating the observed pulse height histogram and the source spectrum. This method is effective in analyzing the spectrum of mildly piled-up sources.

2. Methodology

2.1 Overview

The basic idea is to use only the events in the annular region (\( r_{\text{in}} \), the inner radius; \( r_{\text{out}} \), the outer radius) in the outskirts of PSFs of piled-up sources. We discard all events in the central core that are spectrally and spatially distorted by pile-up. Because most of the piled-up sources are bright enough, this still leaves us sufficient photons to characterize features of these X-ray sources.

We have to construct an appropriate set of RMF and ARF for the annulus event analysis. For RMF, we can use the RMF created at the center of the source, because the spatial dependence of RMFs is negligible in a scale of a PSF size. The ARF, on the other hand, should be tailored for a given annulus region since the effective area (EA) depends on the photon accumulation region and the incident X-ray energy. We developed an IDL code (mkannuarf), in which we calculate the correction factor (CF) between EAs in the ARF files of the annulus region and the whole PSF at each energy bin and compare with a RMF file for the annulus analysis. Figure 1 shows the diagram of the analysis.

2.2 Creating Annulus ARFs

CF is a function of the incident X-ray energy (\( E \)), \( r_{\text{in}} \) and \( r_{\text{out}} \), and is expressed as \( \text{CF}_{\text{annulus}} \left( E, r_{\text{in}}, r_{\text{out}} \right) = \text{CF} \left( E \right) \text{CF}_{\text{annulus}} \left( r_{\text{in}}, r_{\text{out}} \right) \). \( \text{CF}_{\text{annulus}} \left( r_{\text{in}}, r_{\text{out}} \right) \) and \( \text{CF} \left( E \right) \) are EAs of the annulus and the whole PSF regions. We take a practical approach to determine CF. First, we simulate an event file with a very good statistics (\( \sim 10^6 \) counts) using MARX at the same position on the detector with the source of interest. Second, we count the number of events included in the annulus and the whole PSF regions in the simulation event file. The ratio of events at each energy bin roughly gives the CF (\( \text{CF} \left( E \right) \)) in the input spectrum for the MARX simulation is a flat spectrum, \( (2) \text{the RMF is a unit matrix,} \text{and the effective area (EA) depends on the photon accumulation region and the incident X-ray energy.} \text{We developed an IDL code (mkannuarf), in which we calculate the correction factor (CF) between EAs in the ARF files of the annulus region and the whole PSF at each energy bin and compare with a RMF file for the annulus analysis. Figure 1 shows the diagram of the analysis.} \text{We next checked that the annulus spectra reproduce the input spectrum in case of more realistic spectral shapes; power-law with \( E > 30 \text{ keV} \)} \text{and thin-thermal plasma (mekal) with \( E < 30 \text{ keV} \), where blue circles indicate piled-up profile and red circles indicate the profile if there was no pile-up. We sliced the events along the radius with 0.5 pixel bin to obtain annulus spectra and fit them with the pile-up model implemented in sherpa. The best-fit parameters of the fittings; the pile-up fraction \( \text{P.F.}, \Gamma \), and \( E_\text{break} \) are summarized in Fig. 5 (a) and (b).} \text{In the innermost part of the profile (the radius less than ~4 pixel), we see the result is unsatisfactory, where the normalized value is far below the input value and even the pile-up fraction is not derived properly. In the outer part, on the other hand, we see a satisfactory result with the best-fit parameter values of N and \( \Gamma \) consistent with the input value and the pile-up fraction of less than ~2%. The pile-up fraction of 2% corresponds to the surface brightness of ~1.2x10^{-2} s^{-1} pix^{-1}, which are represented with the dashed lines in Fig. 5 (a) and (b).} \text{We use this surface brightness value as the criterion to determine \( r_{\text{in}} \) first, i.e., the first radius along decreasing radius that attains this surface brightness should be set \( r_{\text{in}} \) and all the events with \( r < r_{\text{in}} \) should be discarded from spectral fittings. This is a simple and model-independent quantity that we can calculate for any sources. This can be applied to sources of any brightness by taking a larger annulus radius as the source brightness increases. Moreover, we can use the same criterion for sources at any off-axis angles because, regarding pile-up, the same effect can be expected for the same value of count rate per pixel whatever off-axis angle or whatever distance from the center of the source the pixel is located.}

3. Application

We applied our pile-up analysis to the brightest X-ray sources detected in the ~850 ks Chandra observation on ONC (see also the oral presentation by E. D. Feigelson and the poster presentation by K. Getman). Among ~1,600 X-ray detections, we picked up 65 sources that show no pile-up effects, and we set the total number of counts exceeding (or) the maximum count rate per pixel in their light curve above 0.003 s^{-1} pix^{-1}. Fig. 6 shows an example of the spectra and light curves of the annulus and the total PSF regions.