A PILE-UP CORRECTION TECHNIQUE FOR DISPERSED SPECTRA

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The effectiveness of the Chandra X-ray Observatory's High Energy Grating Spectrometer (HETGS) for determining the spectrum of a bright X-ray source, or a source with bright lines, can be severely limited by the effects of pile-up in the CCDs. In such cases, the standard technique for flux-correction breaks down, producing false absorption and emission features in the spectra. A new method for flux-correcting grating data affected by photon pile-up will be discussed. The usefulness of the model will be illustrated using the Chandra HETGS observation of 4U 1636-53, a bright X-ray binary system.

1. Introduction

Photon pile-up in a Charge Coupled Device (CCD) is a consequence of its finite spatial and temporal resolution. The CCD is unable to resolve the individual photons that have participated in the same spatial and temporal resolution element, causing a single, usually higher energy, event to be recorded. As a result, pile-up results in a lower count rate and an observed pulse-height (PHA) spectrum that is distorted toward higher energies. This can be a significant problem for bright sources.

Previously[1], a general method for correcting the effects of pile-up in imaging (non-grating) observations was given by the author. Here, a model applicable to grating observations is discussed, and applied to the Chandra HETGS observation of the X-ray binary 4U 1636-53.

2. The Standard Flux-Correction Technique

In the absence of pile-up, the relationship between $\bar{C}_i$, the number of expected first order events in the ith diffraction bin, and the incident source flux $s(\lambda)$ is given by

$$\bar{C}_i = (N\tau) f(\lambda_i) A(\lambda_i) s(\lambda_i) \Delta\lambda, \tag{1}$$

where λ_i represents the wavelength associated with the ith bin as given by the diffraction equation, and $\Delta\lambda$ specifies the width of the bin. The quantity $A(\lambda_i)$ gives the effective area for a diffracted first-order photon of wavelength λ_i, and $f(\lambda_i)$ represents the cross-dispersion encircled energy fraction encompassed by extraction region at the wavelength λ_i. The total exposure time is given by $N\tau$, where N represents the number of CCD frames, and τ is the length of each frame.

In addition to events generated by first order photons, the ith bin may also contain contributions from from higher order, higher energy photons. If the CCD has enough intrinsic energy resolution, as does the Chandra's Advanced CCD Imaging Spectrometer (ACIS), then the correlation between the energy of a photon and the pulse-height of the event that it produces can be exploited to extract events from a specified diffraction order. Let C_i represent the number of such events for the first order in the ith bin. The so-called "flux-corrected" spectrum may be determined by replacing the expected number of counts $\bar{C}_i$ in Equ. 1 by the observed number C_i and then solving for $s(\lambda_i)$, i.e.,

$$s(\lambda_i) = \frac{C_i}{(N\tau) f(\lambda_i) A(\lambda_i) \Delta\lambda}. \tag{2}$$

In this equation, $A(\lambda_i)$ is assumed to contain the effects of the pulse-height filter used in the order sorting process[2].

Equ. 2 works quite well for the spectral analysis of observations not affected by pile-up. However, it falls short for those that are, as is clearly illustrated in Fig. 1, which shows the results of its application to the Chandra observation of the bright X-ray binary 4U 1636-53. The most notable feature in this figure is the mismatch between the flux-corrected MEG and HEG first order spectra. The flux obtained from the MEG first-order events appears to be more heavily absorbed than that of the flux obtained from the HEG events. This is a direct consequence of the

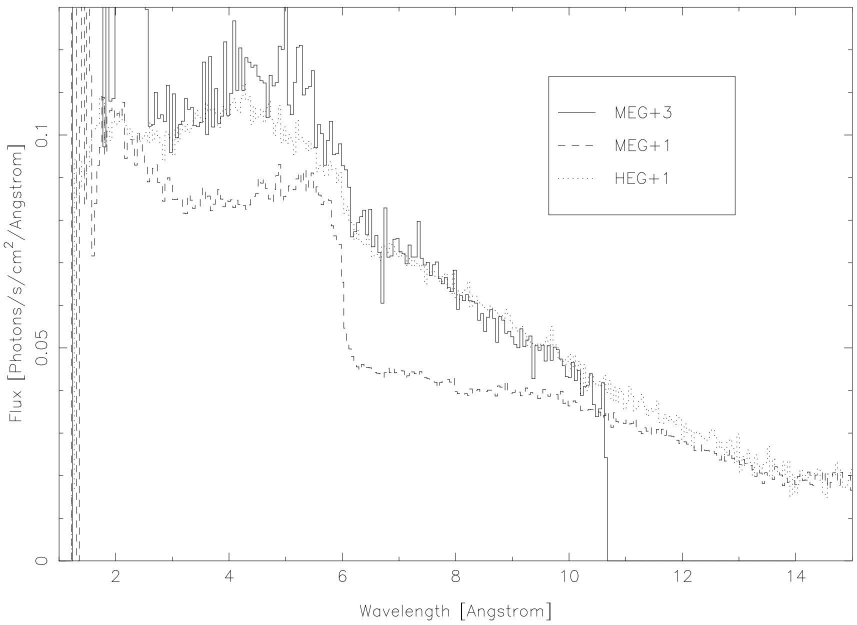

Figure 1. Figure showing the results of flux-correcting the 4U 1636-53 data using the standard flux correction technique based upon Equ. 2. As can be plainly seen, the standard approach fails to correct the MEG first order spectrum over much of the displayed wavelength band.

increased effective area of the MEG over the HEG leading to more pile-up effects in the MEG spectrum.

3. A Dispersive Pile-up Model

In this section, a model applicable to grating pile-up is presented. Since lack of space precludes the full mathematical details of the model to be given, only the main ideas underlying the model are discussed. The interested reader is referred to [3] for a more complete treatment.

As stated in the introduction, pile-up is a consequence of the finite spatial and temporal resolution of the detector. The temporal resolution is the easier of the two to characterize since it is set by the integration time between successive readouts, i.e., the frame-time τ. The spatial resolution of the CCD is primarily governed by the size of the charge cloud created by the photon as it interacts with the CCD. Because the charge cloud usually extends beyond the boundaries of the pixel where it originated, event detection algorithms involve the examination of pixels around the central pixel of the candidate event. For the Chandra ACIS CCDs, the event detection scheme involves the examination of 3 by 3 pixel regions. Such a region is called an event detection cell.

Following [1], the model assumes that the pulse-height of a multi-photon event is the sum of the pulse-heights of corresponding events in the absence of pile-up. Now consider the pile-up of two first-order diffracted photons, each with an energy E. Then the total energy of the event will be something like $2E$, or $hc/(\lambda/2)$. Hence, an order-sorting process based upon the examination of the pulse-height will characterize the event as one originating from a second order diffracted photon of half the wavelength. In other words, order-sorting also has the effect of removing piled events from first order.

As a result, the observed count-rate for the first order diffracted spectrum will be lower than expected in the absence of pile-up. Hence, a pile-up model for the correction of the first order spectrum can be constructed by simply computing the probability of getting a single, unpiled first order event. For if pile-up did occur, such an event would not appear in the order-sorted first order spectrum.

There are two channels for pile-up to deplete events from first order. The dominant channel is through the pile-up of other first order diffracted photons. The second channel is through the pile-up of a first order photon with other higher order, higher energy photons. The relative importance of the latter channel with respect to the first is given by

$$\frac{\sum_{m>1}(1/m)A^{(m)}(\lambda/m)s(\lambda/m)}{A(\lambda)s(\lambda)}, \quad (3)$$

where the sum is over diffraction orders, and $A^{(m)}(\lambda)$ represents the effective area associated with the mth such order. This ratio is plotted in Fig. 2 for two forms of $s(\lambda)$— a power-law and a constant, using effective areas for the Chandra MEG. As the figure shows, the effect of higher order pile-up is important only at longer wavelengths, and only then if the flux in that part of the spectrum is large enough for pile-up to be an issue. This is rarely the case for most astrophysical sources; hence, the model assumes that the second channel involving pile-up with higher-order photons can be neglected.

The last important ingredient of the model is the assumption of Poisson-distributed photon arrival times. The resulting model[3] is a highly non-linear relationship between the incident source spectrum and the expected counts spectrum. The general form of non-linearity in the model may be seen in Fig. 3. For small values of the incident flux, it shows that the count-rate increases linearly with the flux. This behavior is consistent with Equ. 1, which is applicable for small fluxes. As the flux increases, the non-linear terms in the model start to become important. At some critical flux, the count rate starts decreasing with increasing flux. When this happens, the central region of the cross-dispersion profile will start to develop a hole. Once the core of the cross-dispersion profile has "burned out", the count-rate will start to increase again as counts in the wings of the profile become important.

4. Application to 4U 1636-53

The bright X-ray binary 4U 1636-53 was observed September 20, 1999 by the Chandra X-ray Observatory using the High Energy Transmission Grating (HETG) in conjunction with the ACIS-S CCD detector. The total duration for the observation was 32270 seconds using a 3.2 second frame-time.

Data were processed using standard CXC pipeline tools in the CIAO 2.2 release, supplemented by custom software. Level 1 files were used with standard grade filtering applied. However, events that were flagged as so-called cosmic ray afterglow events were kept because of their misidentification for even moderately bright sources. Data were extracted for the MEG±1, MEG±3, and HEG±1 orders.

The ISIS [4] spectral analysis program was used to analyze the data using an implementation of the pile-up model described in the previous section. The data used for the encircled energy fractions were obtained from the Chandra LSF calibration data products.

Fig. 1 shows a plot of the MEG+1 and HEG+1 spectra corrected using Equ. 1. Also shown on this plot as the solid curve is the MEG plus third order spectrum, which is believed to be free of pile-up for wavelengths greater than 4 angstroms. Most of the MEG third order data below 3Å are a result of 3 photon pile-up from MEG first order. Note that the HEG+1 flux-corrected spectrum appears to be consistent with the MEG third order spectrum beyond 6Å. However, the MEG first order spectrum does not agree with either of the other spectra over much of the wavelength range.

Flux-correction using the pile-up model produces spectra that are in much better mutual agreement as shown in Fig. 4. As the figure shows, the MEG+1 and MEG+3 spectra agree quite well above about 5.5Å. Note that the pile-up correction has also increased the HEG first order spectrum so that it is systematically larger that the other two spectra above 6Å. It is easy to see that such an increase should be expected from a simple statistical argument. About 8 percent of the CCD frames contained an event in an event detection cell centered upon 8Å in the HEG+1 dispersion arm. This rate represents the fraction of observed single photon events, and does not include events due to multiple photons. From the application of Poisson statistics, it follows that the actual rate should be 8.7 percent in the absence of pile-up– a value that is about 9 percent larger.

5. Conclusion

In this paper a method of flux-correction applicable to grating data affected by pile-up was described and applied to the Chandra HETGS

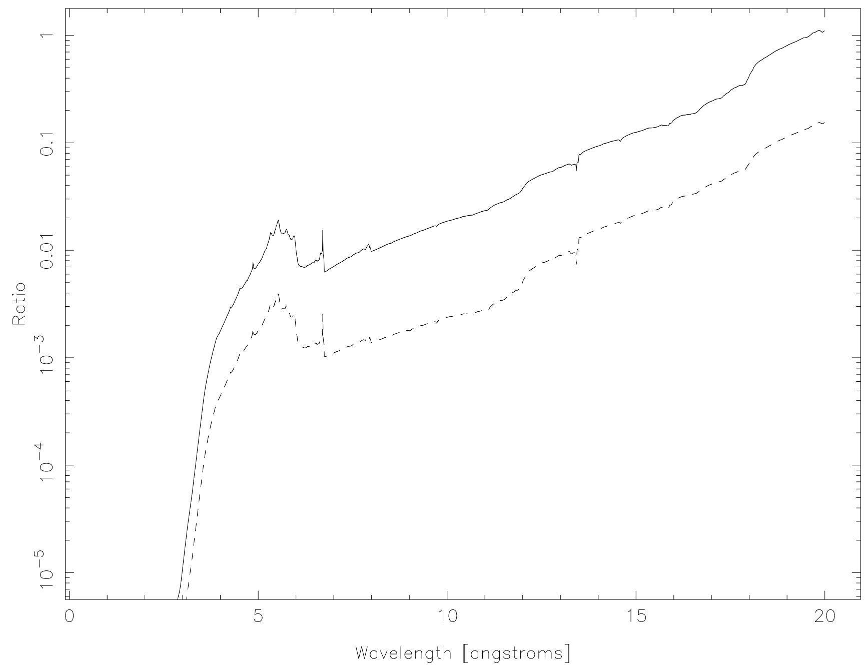

Figure 2. Figure showing the ratio of Equ. 3 of the expected count rate of higher-order events in a pixel, to the rate of first order events in the same pixel computed assuming no pileup. The solid curve shows the ratio evaluated for a constant value of $s(\lambda)$ using effective areas appropriate for the Chandra MEG. The dashed curve was generated assuming a power-law with a spectral index of 2.

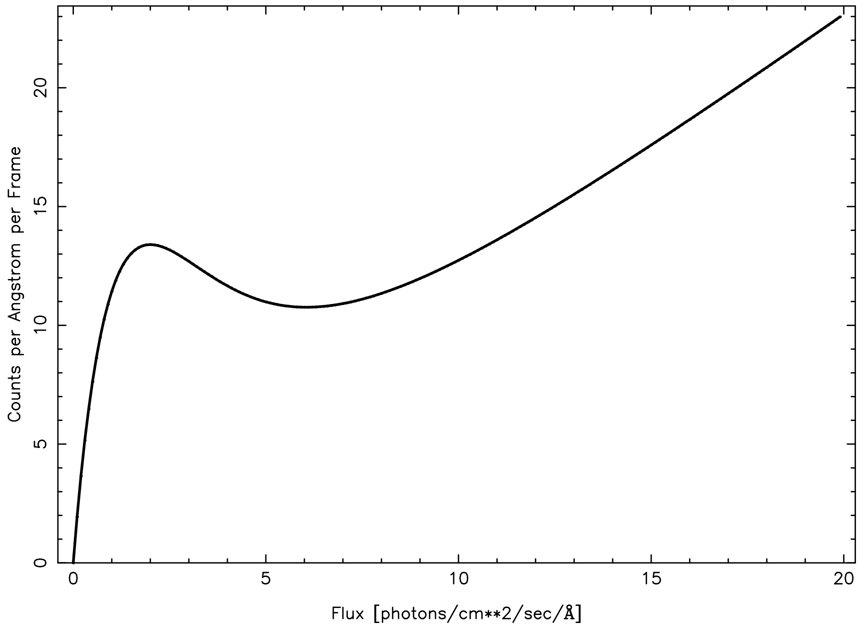

Figure 3. Figure showing the relationship between the incident source flux and the expected count rate at 2.0 keV for the MEG first order as predicted by the pileup model.

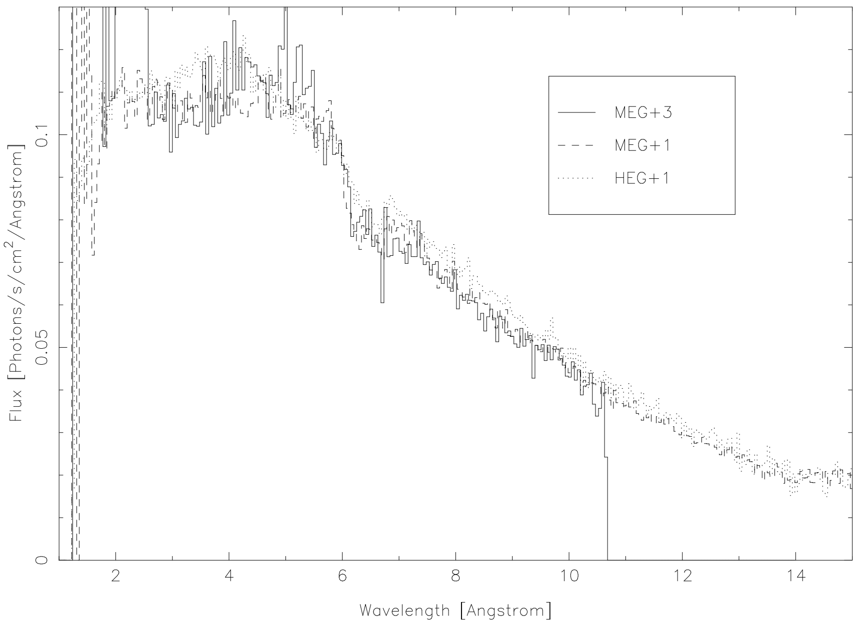

Figure 4. Figure showing the results of flux-correcting the 4U 1636-53 data using the pile-up model. The flux-corrected HEG first order spectrum is systematically larger than the other two spectra. It is believed that this discrepancy is due to uncertainty in one or more of the calibration parameters.

observation of 4U 1636-53.

The grating pile-up model has been implemented in the ISIS spectral modeling program. As such, in addition to simple flux-correction, one can use the pile-up model within ISIS to fit a spectral model to grating data affected by pile-up.

More work still remains to be done. For example, it appears that the model works better for parts of the spectrum that fall on the frontside ACIS chips than those parts that fall on the backside chips. Currently there is nothing in the model that distinguishes between the various chips apart from the effective area. Despite this shortcoming, the model appears to be an improvement over that of Equ. 1, and should be applicable to a wide range of sources.

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