Accounting for Pileup in Chandra ACIS Spectra

Y. Yu, D. van Dyk,
A. Siemiginowska, P. Freeman, Z. Zezas, V. Kashyap, and A. Connors

yu@stat.harvard.edu
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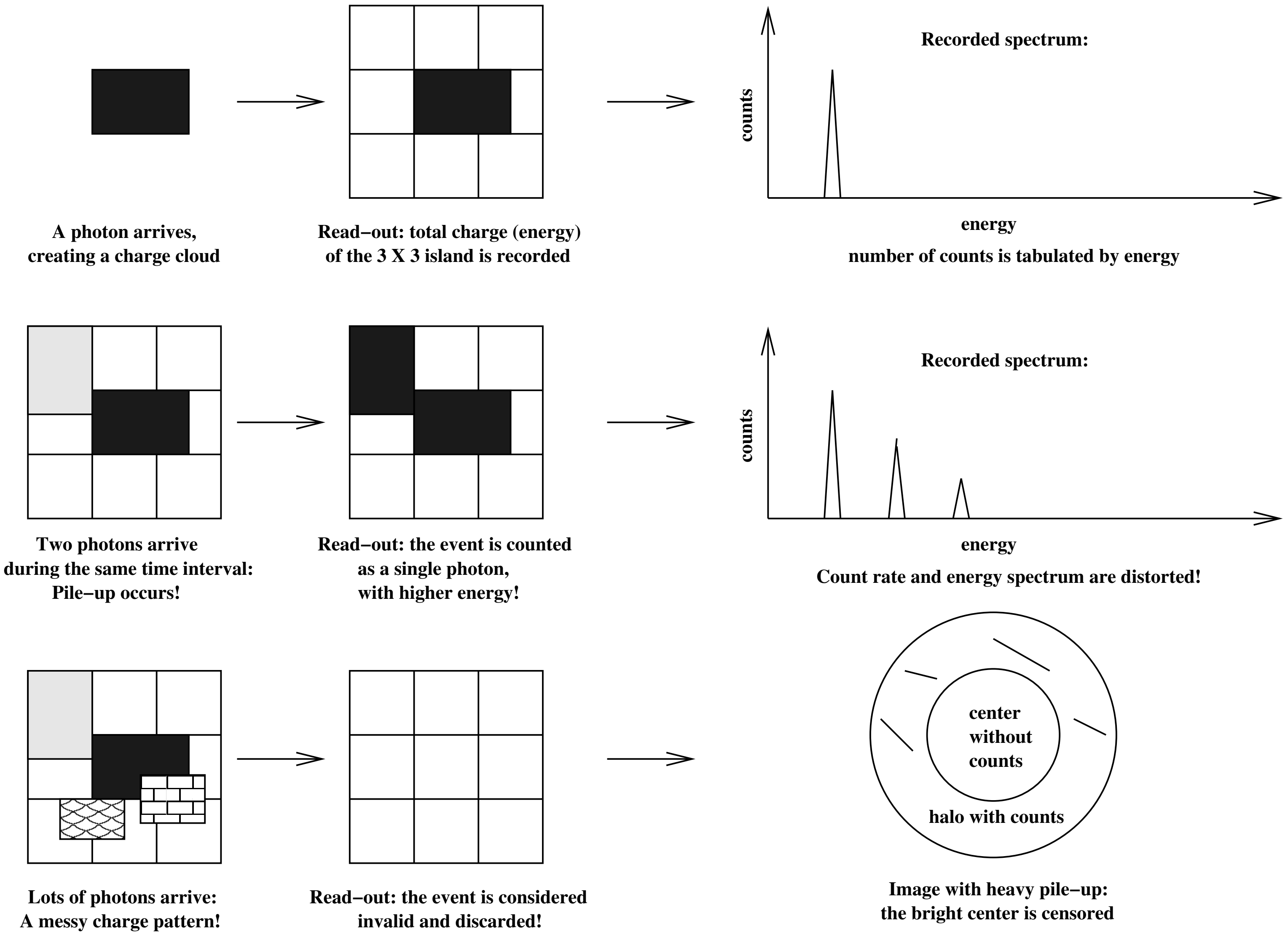
Abstract

CCD detectors such as Chandra's ACIS suffer from the problem of event pileup when observing bright sources. When multiple photons arrive at the same location on the detector within a frame readout time, the detector electronics cannot distinguish them as separate events, and consequently they are counted as a single event of higher energy, or discarded because of a non-standard charge pattern, or lost altogether if the total energy goes above the on-board discriminators. Thus, for bright sources pileup can seriously distort both the count rate and the spectrum in an irreversible way. However, while the changes are non-deterministic, they can be dealt with within a statistical framework. We have developed a highly structured statistical model that directly incorporates the mechanism of the instrument that results in pileup. We adopt the Bayesian approach and use state-of-the-art computing algorithms such as MCMC (Markov chain Monte Carlo) algorithms. This formulation allows us to incorporate the pileup model in a general spectral model that takes into account various source features, such as continuum, emission lines, interstellar absorption, as well as the effective area of the instrument, instrument response, and background contamination. We can also handle the spatial dimension of the problem by simultaneously fitting counts from several detection islands that suffer varying degrees of pileup. This strategy allows us to include data from regions of the detector with low pileup in our analysis. Even when the counts in these regions are relatively low, these data can be quite informative as to the shape of the spectrum, and thus, as to the amount of pileup in more heavily piled regions of the detector. We present results of our method for spectral analysis of the X-ray point source PKS2126. Residual plots for counts in several detection islands are used to check the self-consistency of the analysis.

Event pile-up in CCDs



Incorporating Pile-up in a Highly-structured Spectral Model

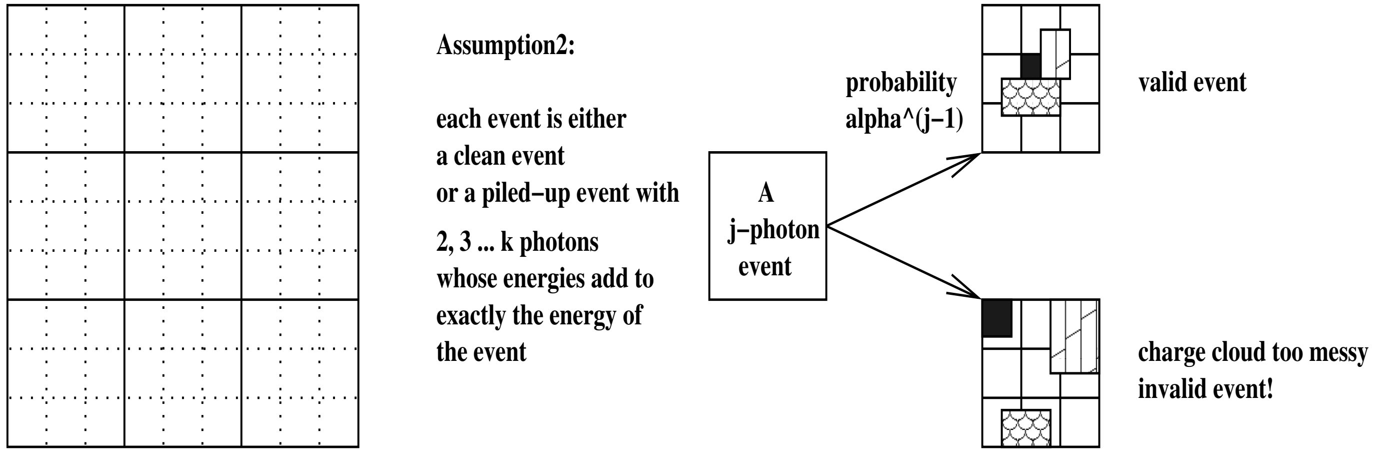
- Within a Bayesian framework, we design models (Van Dyk, Connors, Kashyap, and Siemiginowska, ApJ, 2001) that include

  1. a Poisson process for photon arrivals,
  2. stochastic instrument response via an RMF matrix,
  3. absorption of photons and varying effective area of the telescope,
  4. a generalized linear model (GLM) for the continuum, and
  5. several Gaussian emission line profiles.

  Model fitting is accomplished using EM and/or the Gibbs sampler.

- These algorithms allow us to add pile-up easily. Just consider a completely specified spectral model. We only need to split events stochastically into photons of lower energy.

Model Assumptions for Pile-up (and Complications)



Assumption 1: relevant region of the CCD can be partitioned into non−overlapping event detection islands

Assumption3: a j−photon event has probability alpha^(j−1) of being valid and kept

Note on the assumptions:

1. In reality, the locations of detection islands are not fixed, but depend on where photons land.
2. In reality, the energy of the piled-up event may only be approximately equal to the sum of energies of the individual photons.
3. This probability model for valid events is suggested by Davis 2001. $(0 < \alpha < 1.)$ A clean event (an event with only one photon) is always valid.

A Pile-up Model

Suppose the source spectrum during a single time interval can be specified by $\xi(E_l)$ for energy bins $l = 1, 2, \ldots, L$.

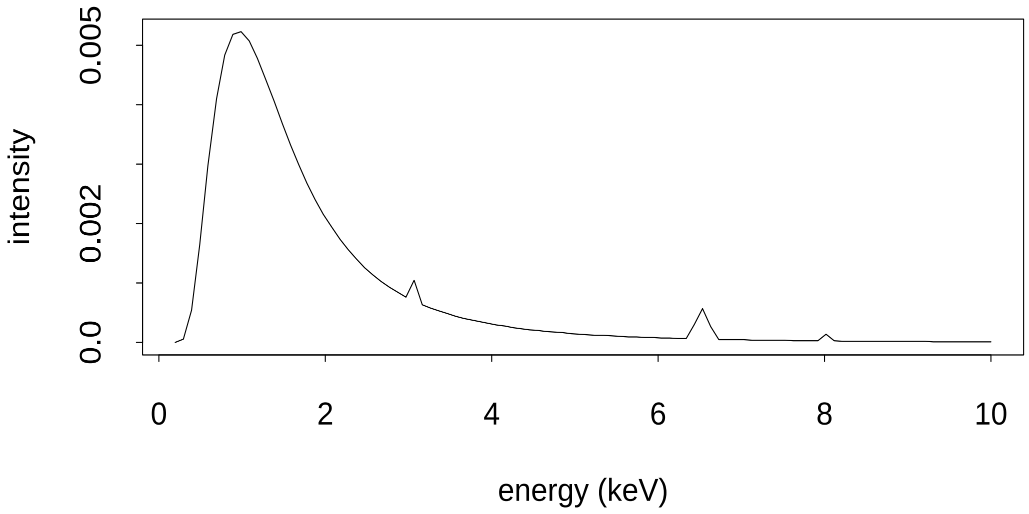


Fig. 1. A power law continuum with absorption and three emission lines.

Consider a recorded event with energy E, that is composed of a number of individual photons, n_l of which correspond to energy E_l, for $l = 1, \cdots, L$. The energy, E, of the observed event satisfies $E = \sum_{l=1}^{L} n_l E_l$. The total number of photons that pile-up into the event is $n = \sum_{l=1}^{L} n_l$. The probability of such a configuration in a valid event during a single time interval within a specific detection island is therefore

$$P(n_1, n_2, \cdots, n_L|\alpha) = \alpha^{n-1} \prod_{l=1}^{L} \frac{\xi(E_l)^{n_l} e^{-\xi(E_l)}}{n_l!}. \quad (1)$$

The factor α^{n-1} takes into account the probability of an event being valid.

For time intervals with no events, there are two possibilities: one is that indeed there are no photon arrivals during the time interval in this detection island, which has probability

$$P(\emptyset) = \prod_{l=1}^{L} e^{-\xi(E_l)}. \quad (2)$$

Another possibility is that there are n_l photons with energy E_l, $l = 1, \cdots, L$, but the resulting event is invalid and discarded. This is associated with probability

$$P(n_1, n_2, \cdots, n_L|\alpha) = (1 - \alpha^{n-1}) \prod_{l=1}^{L} \frac{\xi(E_l)^{n_l} e^{-\xi(E_l)}}{n_l!}. \quad (3)$$

In these equations we always condition on $\xi(E_l)$, $l = 1, \cdots, L$, the spectral intensities.

Based on equations (1), (2), and (3), it is easy to write down the posterior probability of the number of photons and the individual energies of these photons for a detected event. Suppose a 10 keV event is made up of two photons:

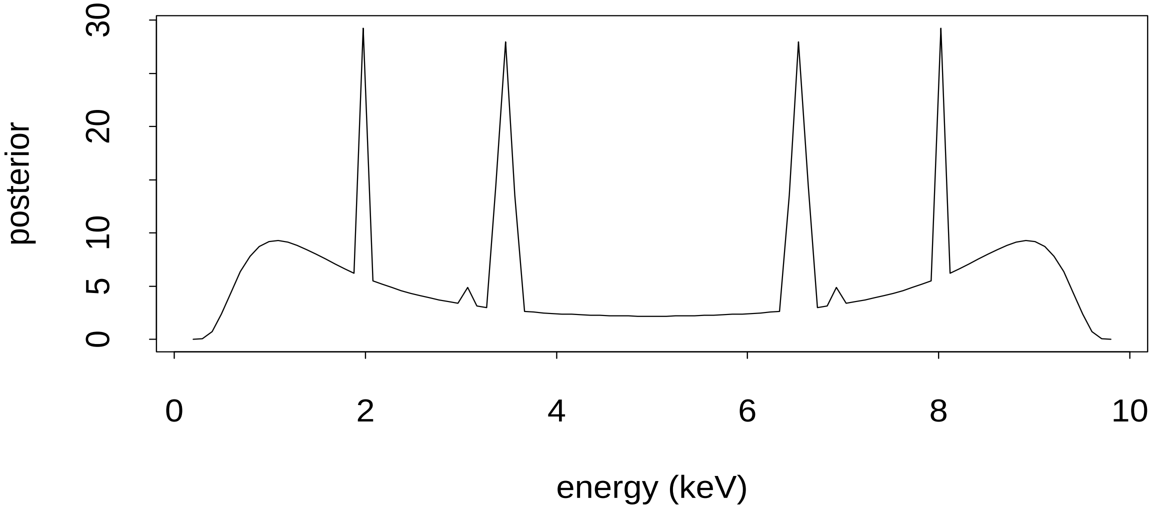


Fig. 2. The posterior density of the energy of one of two photons with energies summing to 10 keV with source spectrum given in Fig. 1.

Allowing More Than Two Photons to Pile-up

The difficulty lies in computation. Tabulating the posterior probabilities of all possible pile-up configurations: $O(N \log(L^{k-1}) + L^k)$ running time and $O(L^{k-1})$ storage.

- k is the maximum number of photons that can pile-up,
- L is the number of energy channels, and
- N is the total number of observed counts.

Impractical even for moderate values of k!

Fortunately, we found a sampling method that scales linearly in k.

As an example, we again consider the spectrum in Fig. 1. The following table shows the posterior distribution of the number of photons that produce an event of energy 10keV (take $\alpha = 1$):

	Number of Photons			
	1	2	3	4
Probability	61%	29%	8%	1%

Suppose a 10 keV event actually consists of three photons:

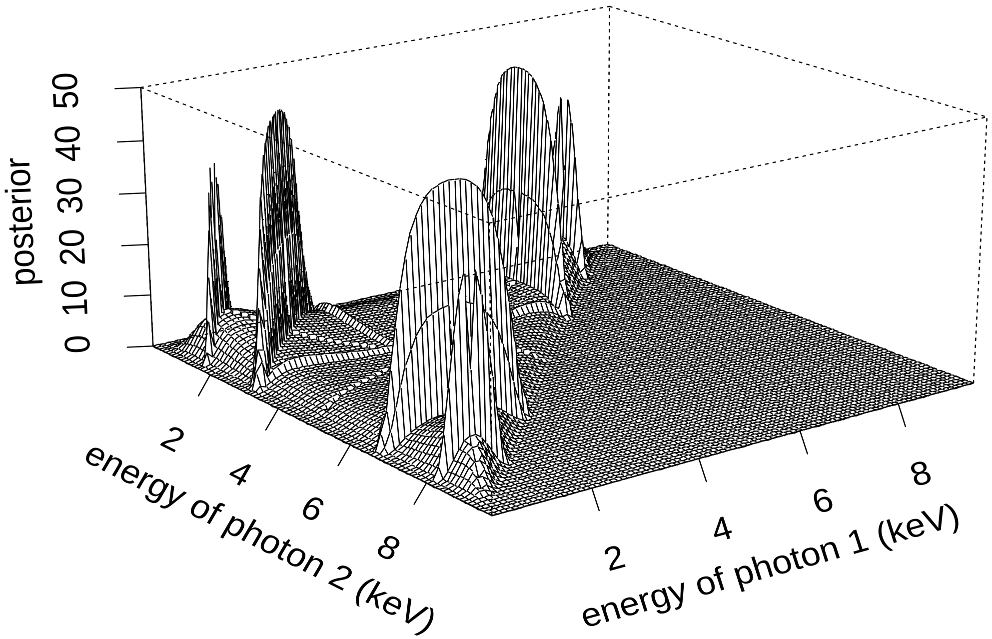


Fig. 3. The joint posterior density of the energy of two of three photons with energies summing to 10 keV with the spectra in Fig. 1.

“one island” Data

- DATA: Chandra ACIS observation of a high redshift quasar PKS 2126-158. Source region covers only the central detection island, hence the name “one island”.
- MODEL: power law (parameters *norm* and Γ) with absorption (N_H).
- TOOLS: the model is fitted with *gibbs*, which implements our model, and *sherpa* (Freeman, Doe and Siemiginowska 2001), which implements the model of Davis 2001.
- Fitted values are the posterior mode and 90% intervals are included in parentheses. *sherpa* uses “error propagation” (or the δ-method assuming the posterior is multivariate normal) to calculate the intervals.
- The pile-up fraction is the fraction of observed events that consist of more than one photon.

	gibbs		*sherpa*	
	pile-up	no pile-up	pile-up	no pile-up
norm	2.5(2.0 2.9)e-3	8.4(8.2 8.6)e-4	1.7(1.6 1.8)e-3	8.6(8.4 8.8)e-4
Γ	1.62(1.58 1.67)	1.03(1.01 1.06)	1.60(1.50 1.70)	1.04(1.02 1.06)
N_H $(10^{22} atoms/cm^2)$	0.11(0.11 0.12)	7.6(7.1 8.1)e-2	0.13(0.12 0.14)	8.6(8.0 9.2)e-2
α	0.50(0.43 0.61)		0.73(0.57 0.95)	
pile-up fraction	0.22		0.22	

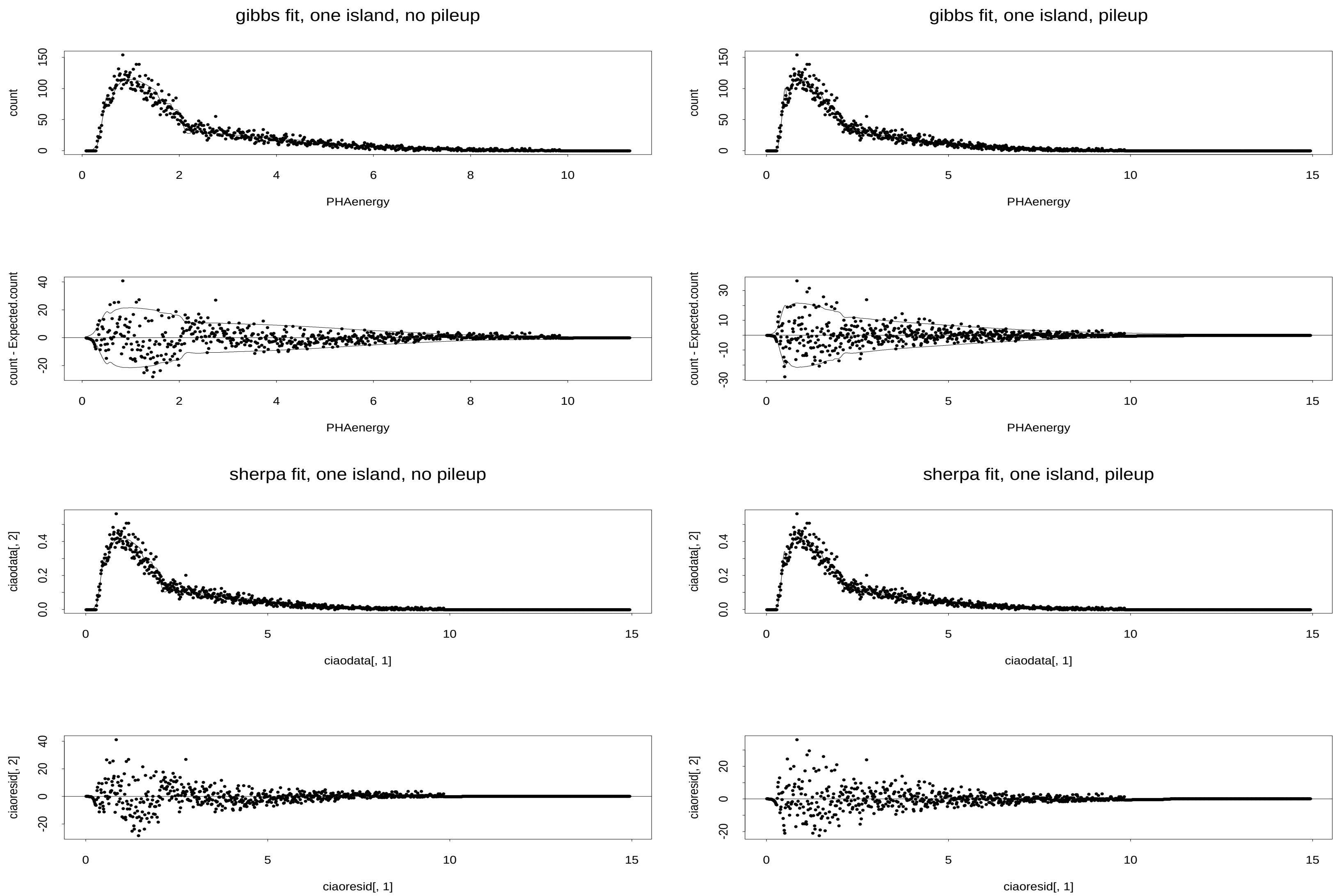


Fig. 4. *gibbs/sherpa* fit and residuals with/without fitting pile-up.

Accounting for Spatial Information

When counts are spread out across several detection islands, the analysis should take into account the fact that (for a point source) the center and the halo have different degrees of pile-up.

- IDEA: Use the combined data of “one island”, and “7.25 islands”, which includes “one island” as the center.
- PROBLEM: Center/Halo ARF ratio varies with energy.
- SOLUTION: Simulate the center ARF fraction using a flat spectrum.

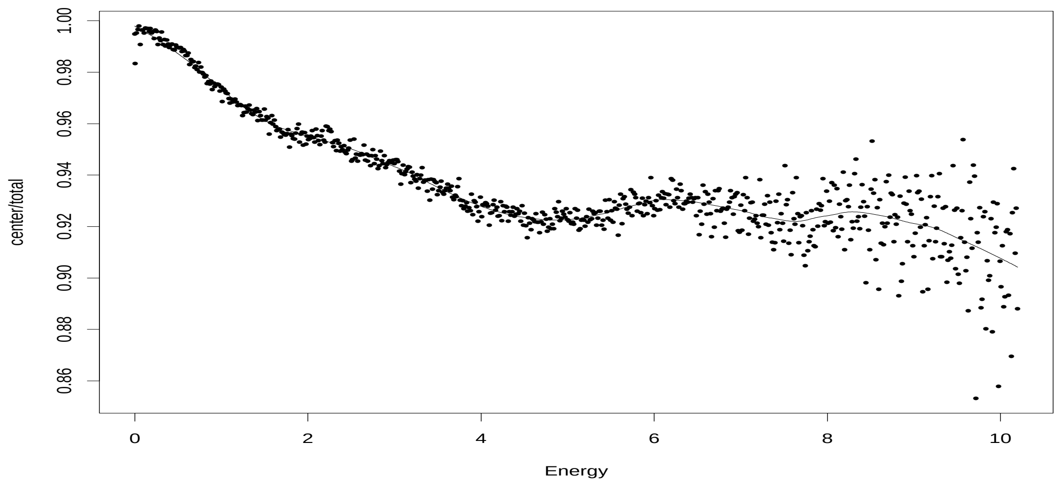


Fig. 5. Center/Total ARF ratio with suitable smoothing. (The ratio is somewhat noisy, especially for the high energy end.)

Combined Analysis Results

$norm$	Γ	N_H
0.00198 (5.79e-05)	1.685 (0.0265)	0.119 (0.00433)

center α	halo α	center pileup frac	halo pileup frac
0.741 (0.0395)	1.7e-5	0.256	3.4e-8

Note: posterior standard deviations in parentheses.

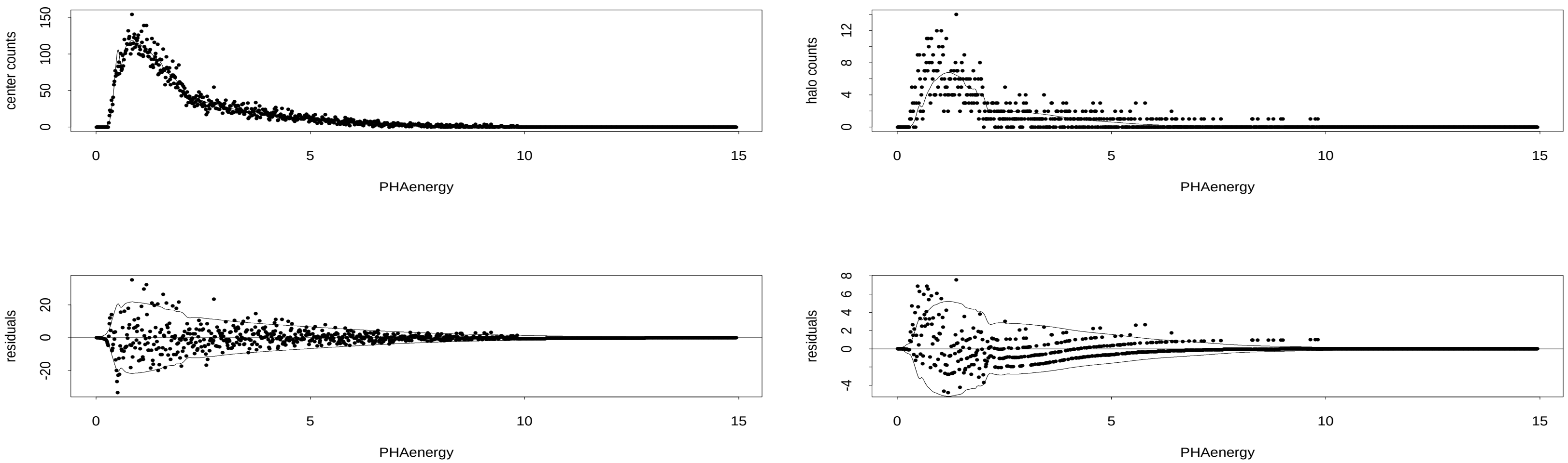


Fig. 6. Model fit and residuals for the center (left) and the halo (right).

The above results are not sensitive to the choice of smoothing strategy for the center ARF ratio.

Conclusions

- Pile-up distorts both the count rate (reflected by parameter *norm*), and the spectrum (reflected by parameters Γ and N_H).
- *gibbs* and *sherpa* give similar pile-up correction except for the difference between two parameters *norm* and α.
- Both our model and the model of Davis 2001 fit well for "one island" data.
- Combined analysis using both "one island" and "7.25 islands" is useful as it gives different pile-up fraction for the center and the halo. The halo is much less piled than the center.