Testing the PN Pileup Correction Method in the Science Analysis Software

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Contents

1 Introduction

The pileup correction is part of the "rmfgen" task in the Science Analysis Software (SAS) and is used to deal with point source observations that are piled-up. The methodology of the pileup correction algorithm is described in detail and has been tested in a pervious work[1], complementing this one. However, in the previous work, it is only tested on simulated data using an IDL version of the code and not the code used in the SAS. As of this writing, the most current build of the pileup correction has been implemented into SAS-build 11 and will be part of the SAS 16.0.0 release. Using this build, the method is again tested to ascertain how well it works in the SAS, and how it behaves for real sources. Costantino[2][1] has already tested an earlier build of the pileup correction on many of the observations used in this work. Those observations are re-tested in order to recognise the affects of the changes to the latest build directly.

In this work, for each observation, the observation data files (ODFs) are downloaded from the XMM-Newton Science Archive (XSA) and reduced in the SAS using the latest calibration files. The spectra are all binned to improve the signal to noise ratio. As such, χ^2 is used to find the maximum likelihood when fitting the model and also as the test statistic to evaluate if the best-fit model parameters belong to the data.

Multiple observations from Markarian 421 (MRK421) and PKS 2155-340 (PKS) are used. Both are active galaxies, categorized as BL Lac objects and are therefore very bright and tend to follow a smooth and featureless spectrum. The sources are also very variable; observed at many different count rates which provides a good range to test the pileup correction on. For each observation, spectra are extracted for a circular source region and multiple annular regions. The corrected response matrix is then generated for each spectrum. All of the spectra are fit

[1]Master Thesis, Universita degli Studi di Bari Aldo Moro, Dipartimento Interateneo di Fisica

with a simple power law model multiplied either by a tbnew[3] (for MRK421) or tbabs (for PKS) absorption between 0.3 and 6.0 keV. The model is fit once after convolution with the original detector response and again after folding with the corrected response instead. For both sources, the elements' abundances from Wilms, Allen and McCray[4] and the photoelectric absorption cross sections from Verner[5] are employed. For MRK421, nH is fixed at $6.3 * 10^{20}$ atoms cm^{-2} and for PKS at $1.24 * 10^{20}$ atoms cm^{-2}. Errors shown have a confidence level of 95%.

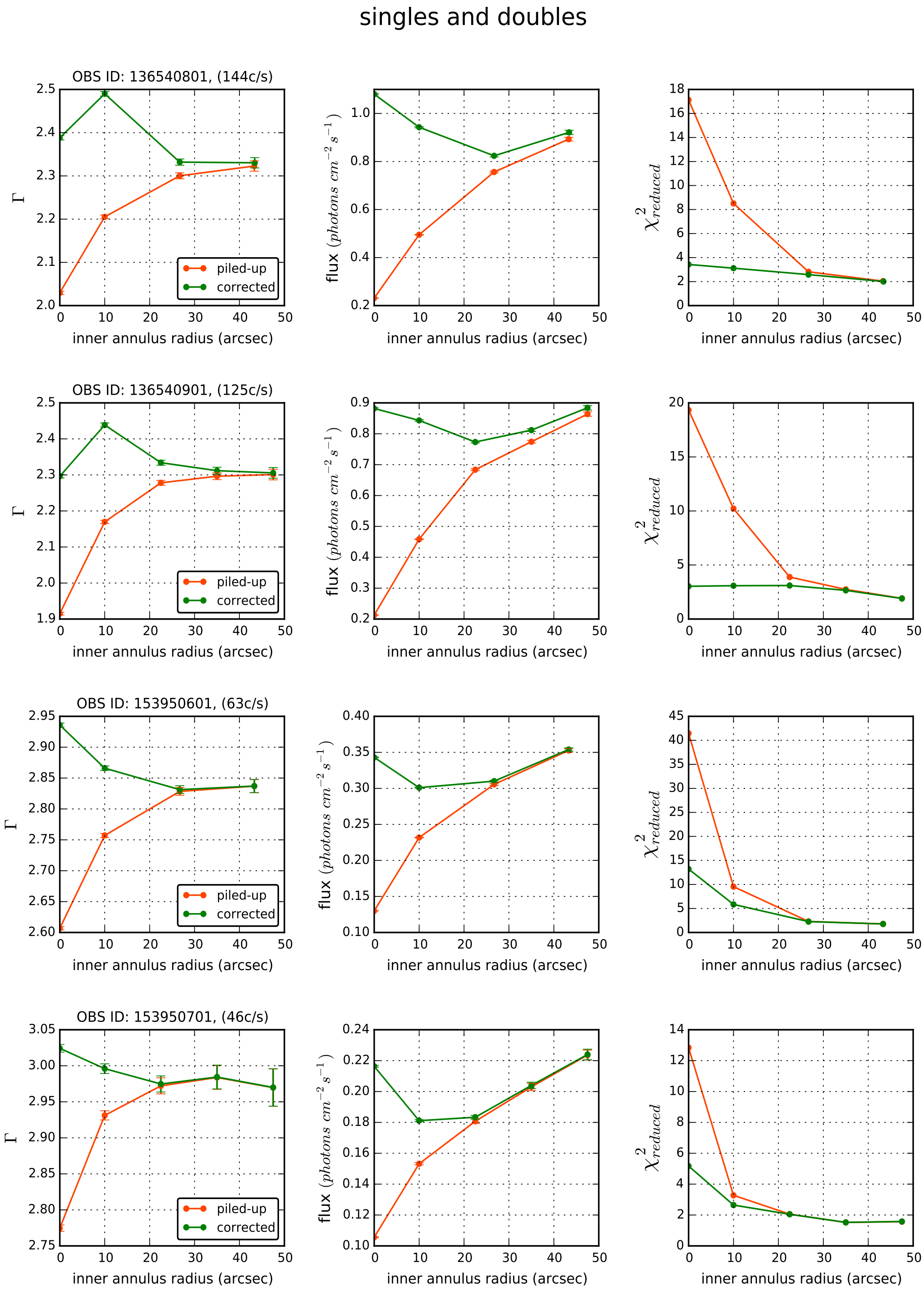
2 Fitting Markarian 421 observations

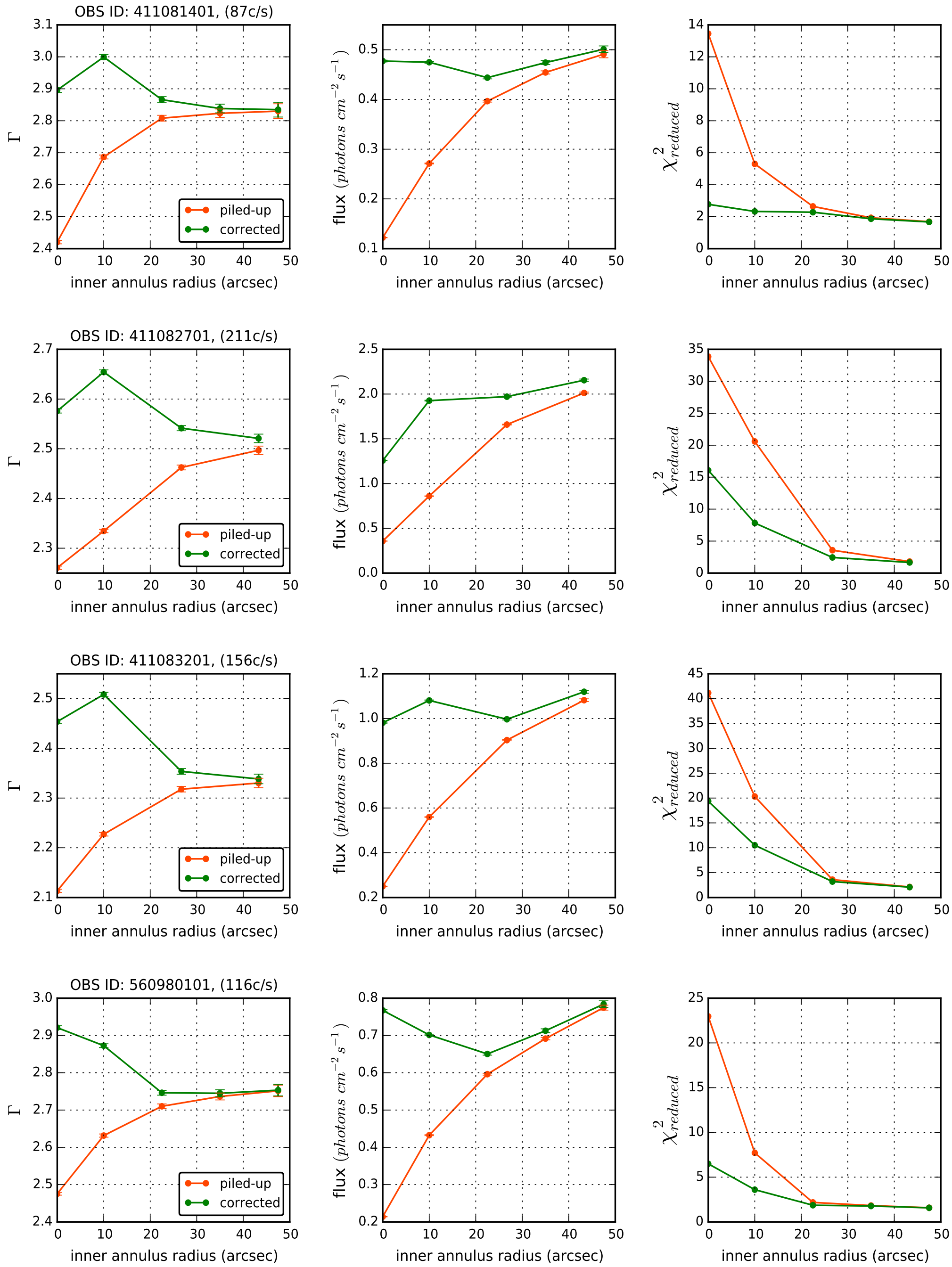
Table 1 lists all of the Markarian 421 observations analysed and their count rates. Figures 1 & 2 give the fit results for the large-window (LW) and full-frame (FF) observations for singles & doubles and singles only spectra respectively. Figure 3 shows the small-window (SW) observation results for singles & doubles spectra.

Observation ID	mode	N of frames	counts s^{-1}	counts $frame^{-1}$
0136540801	LW	0.20	144	6.80
0136540901	LW	0.20	125	5.90
0153950601	LW	0.77	63	2.95
0153950701	LW	0.36	46	2.20
0411082701	LW	0.18	211	9.90
0411083201	LW	0.17	156	7.30
0560980101	LW	0.19	116	5.45
0560983301	LW	0.19	109	5.10
0656380101	LW	0.15	139	6.50
0656380801	LW	0.17	112	5.30
0656381301	LW	0.17	98	4.60
0411081401	FF	0.10	87	4.10
0099280101	SW	5.7	221	1.25
0099280201	SW	6.5	102	0.60
0099280301	SW	8.2	290	1.65
0136540101	SW	6.6	283	1.61
0158970101	SW	7.2	215	1.20
0162960101	SW	5.3	247	1.40
0411080301	SW	12	502	2.90
0658801301	SW	4.8	260	1.50
0658801801	SW	5.3	167	0.95
0658802301	SW	4.9	156	0.90

Table 1: All MRK421 observations analysed in section 2. The number of frames are given as N $*10^6$.

2.1 Large window and full-frame observations

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Γ
flux $(photons\ cm^{-2}\ s^{-1})$
$\chi^2_{reduced}$
inner annulus radius (arcsec)
piled-up
corrected

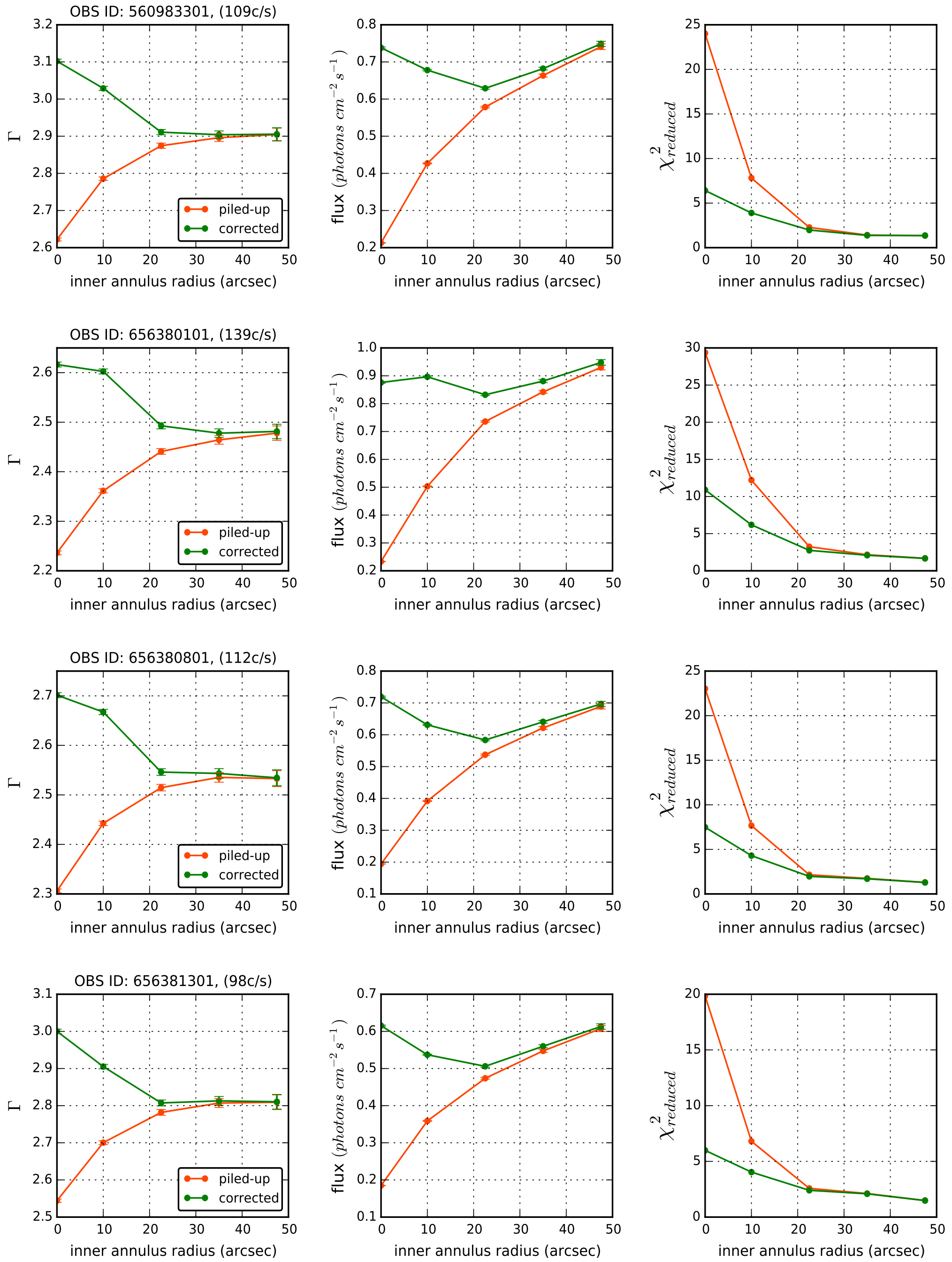
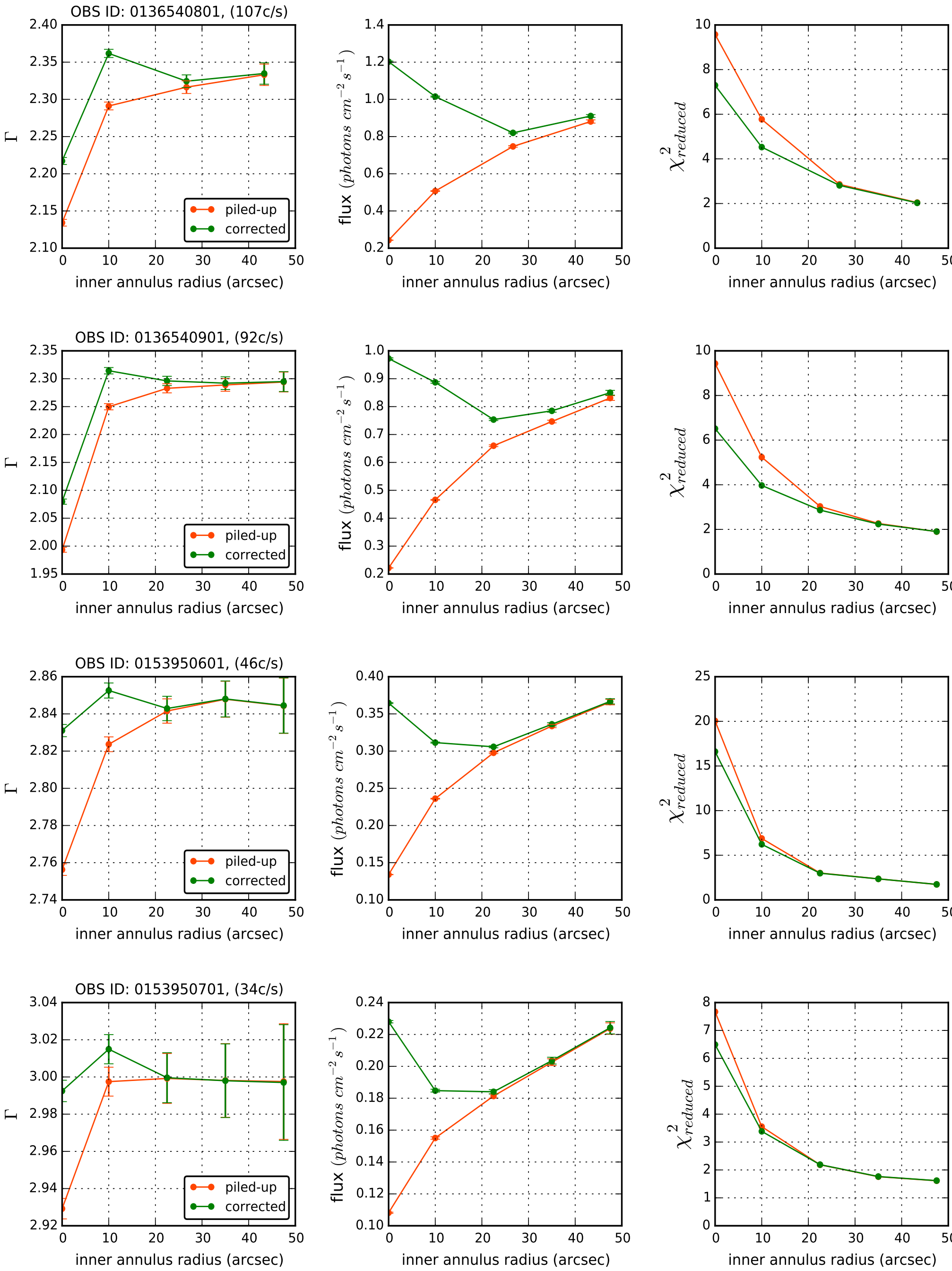
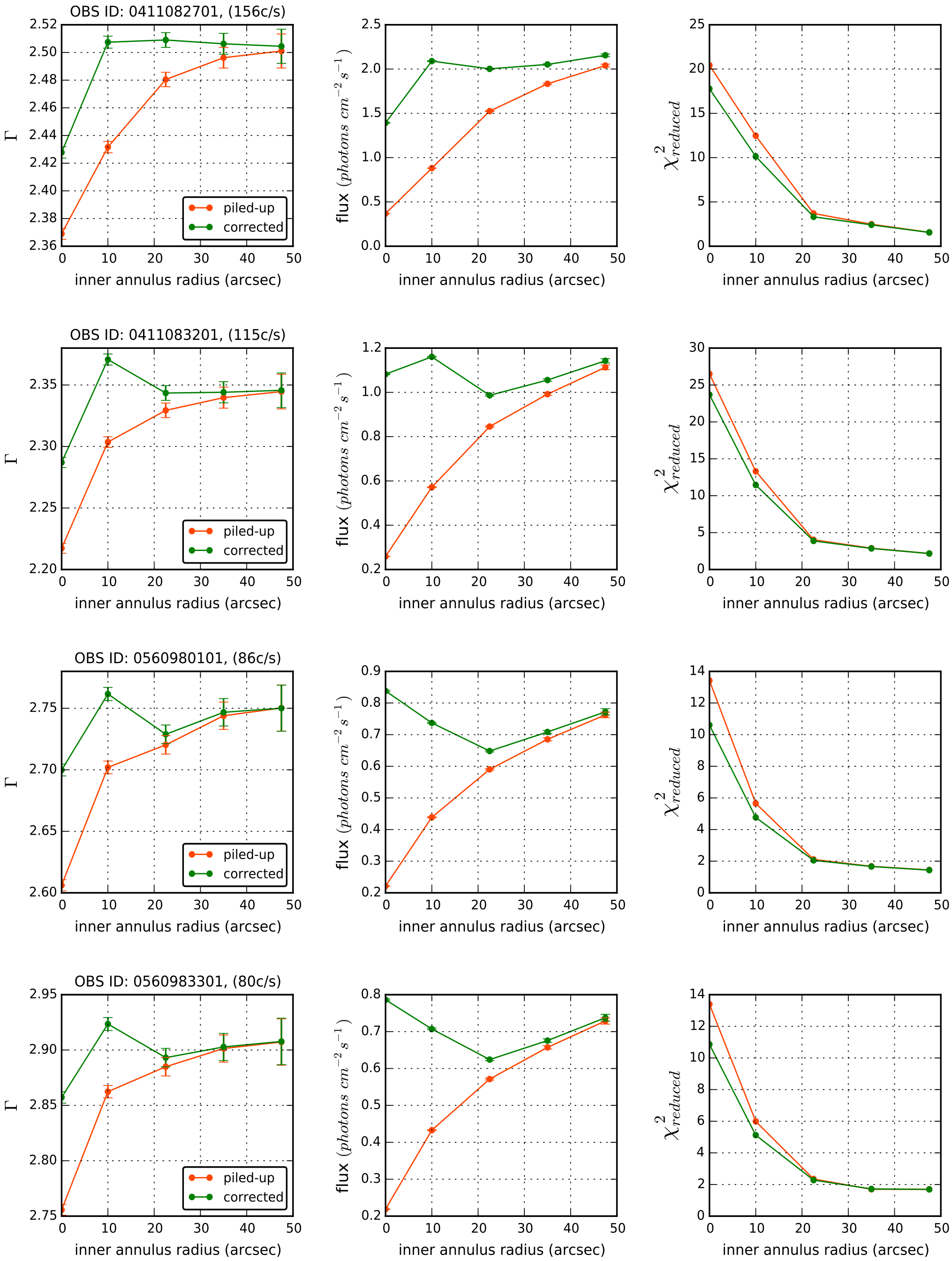


Fig. 1: Fit results for singles and doubles spectra of MRK421. Left: Γ index, centre: flux in the range 0.3-6.0 keV, right: reduced χ^2 for best-fit parameters all as a function of the radius of the removed region from the centre of the observation. A source extraction region of 60 arc-second radius is used.

singles only

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Γ
flux $(photons\ cm^{-2}\ s^{-1})$
$\chi^2_{reduced}$
inner annulus radius (arcsec)
piled-up
corrected

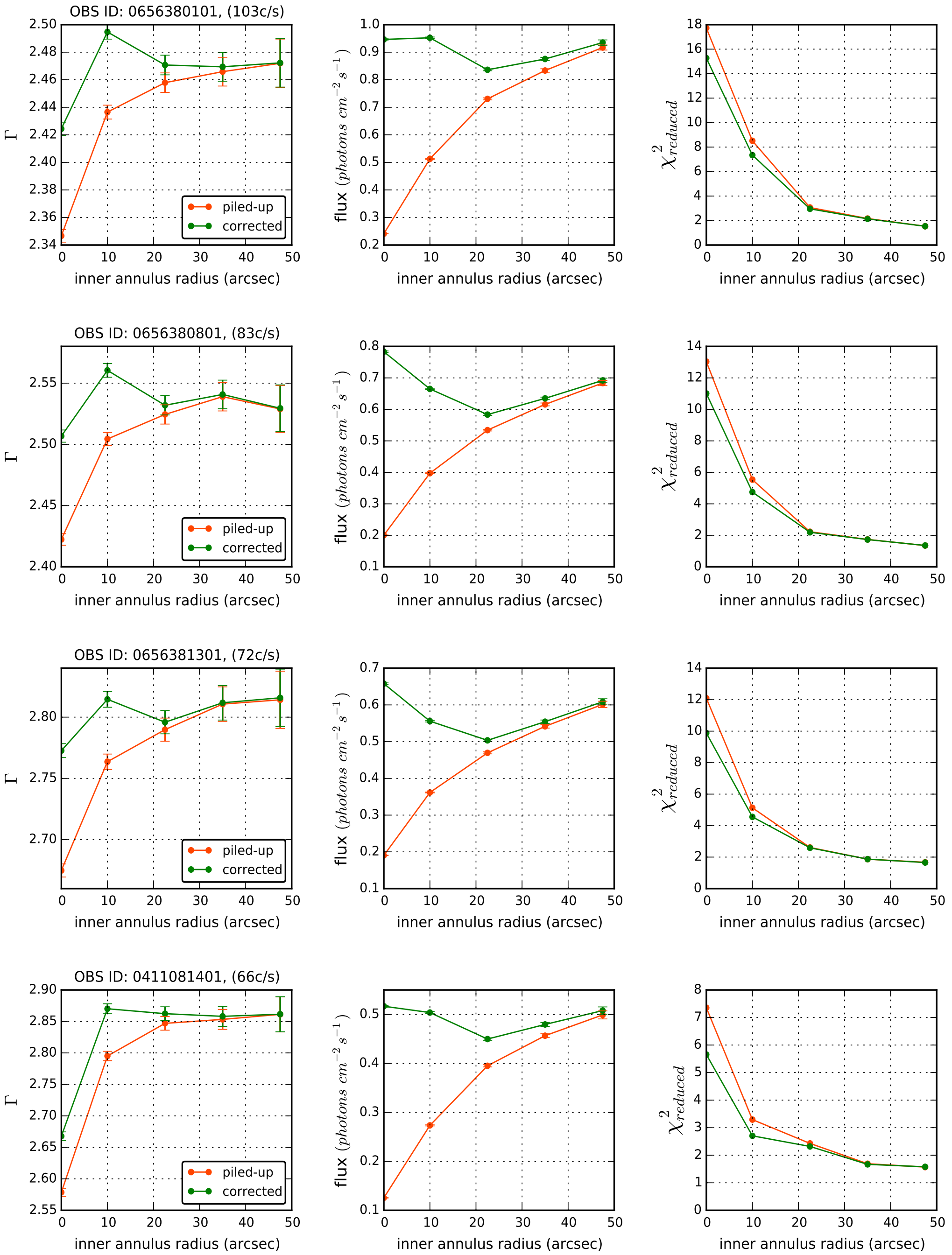
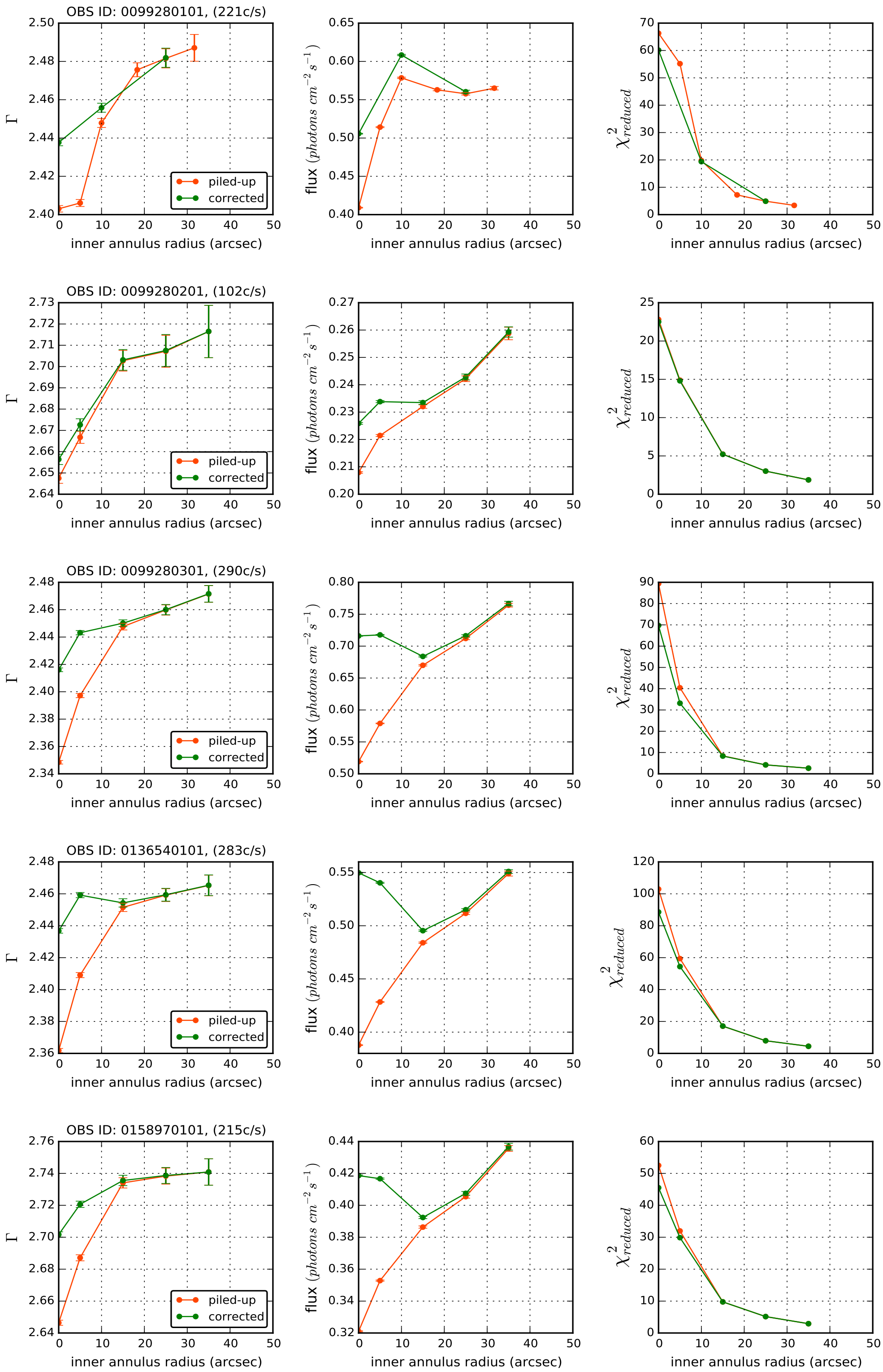


Fig. 2: Fit results for singles only spectra of MRK421. Left: Γ index, centre: flux in the range 0.3-6.0 keV, right: reduced χ^2 for best-fit parameters all as a function of the radius of the removed region from the centre of the observation. A source extraction region of 60 arc-second radius is used. The count rate shown next to the observation ID is the rate for single counts only.

2.2 Small window observations



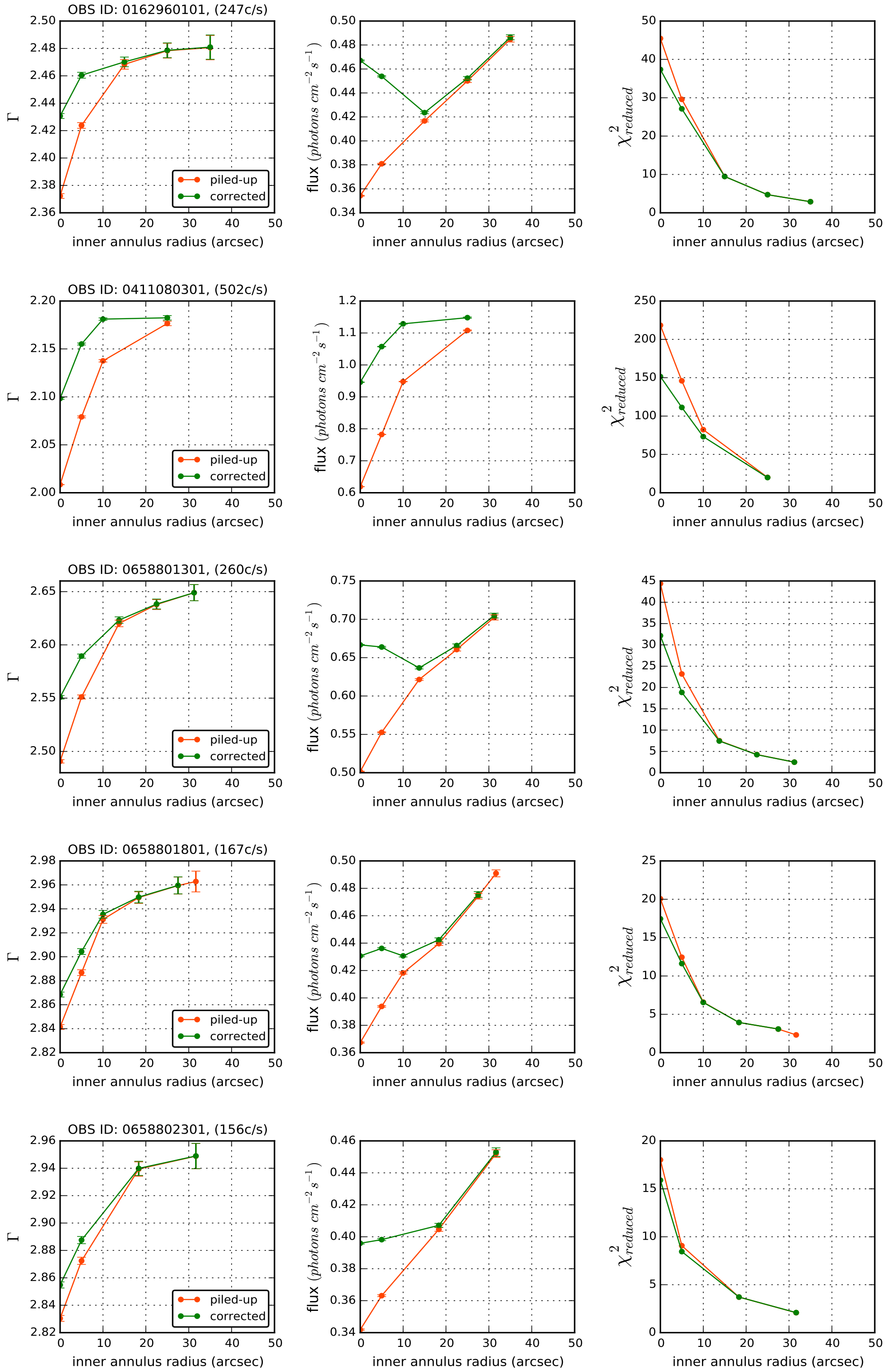


Fig. 3: Fit results for singles and doubles spectra of MRK421 observed in the small-window mode. Left: Γ index, centre: flux in the range 0.3-6.0 keV, right: reduced χ^2 for best-fit parameters all as a function of the radius of the removed region from the centre of the observation. A source extraction region of 45 arc-second radius is used.

2.3 Summary of the MRK421 results

For all observations, when no inner core is removed, the lowest Γ index and flux is observed. As the removed inner radius is increased, these values too increase and approach a constant value. This indicates that the PSF is heavily piled-up in the core. We can see that as more and more of the piled-up core is removed, the fit results when using the original response and the corrected one converge. At this point, the two response files are the same. There is a negligible amount of pileup left in the annular regions with large inner radii. The simulated events added when building the corrected response are therefore unlikely to pileup with the few observed charges left in each frame, instead coming out with the same energy and pattern as originally allocated with. As to be expected, when there is no pileup, the corrected response has no effect on the fit.

In order to evaluate how well the pileup correction is working when there is pileup, we compare the flux and Γ index obtained from the corrected model fit on the circular extraction region spectrum ($0''$ data point), to those values from an annular region[2]. Figure 4 gives this comparison for the flux as a function of counts/frame, from all single & double spectra in the FF, SW and LW modes. The solid lines represent when no attempt is made to deal with pileup. The dotted lines are when pileup is dealt with by either removing the core (orange) or using the corrected response (green). The annular region used is the one where the flux obtained using the original response and the corrected one first converge[3]. In the LW mode the flux recovery appears to work well up to the observation at 7.3 counts/frame. At 9.9 counts/frame, a significant portion of the flux as recovered by the annular region is lost when using the correction method. The LW results, nevertheless, suggest a flux recovery limit much greater than the 1.5 counts/frame limit defined during the tests on the simulated data[1]. For the SW observations the annular region and corrected flux values agree at all observed count rates except at 2.9 counts/frame, where we see a 15% flux underestimation. The same results for the singles spectra, albeit only the LW and FF modes, is shown in figure 7 in appendix 1. It is necessary to mention that although the fit statistics, measured by the reduced χ^2, do improve when using the corrected model, they are still in most cases unacceptable (in particular for the small-window observations). The simple power law model is perhaps not best suited to fit the complex behaviour of Markarian 421 reflected in its spectrum.

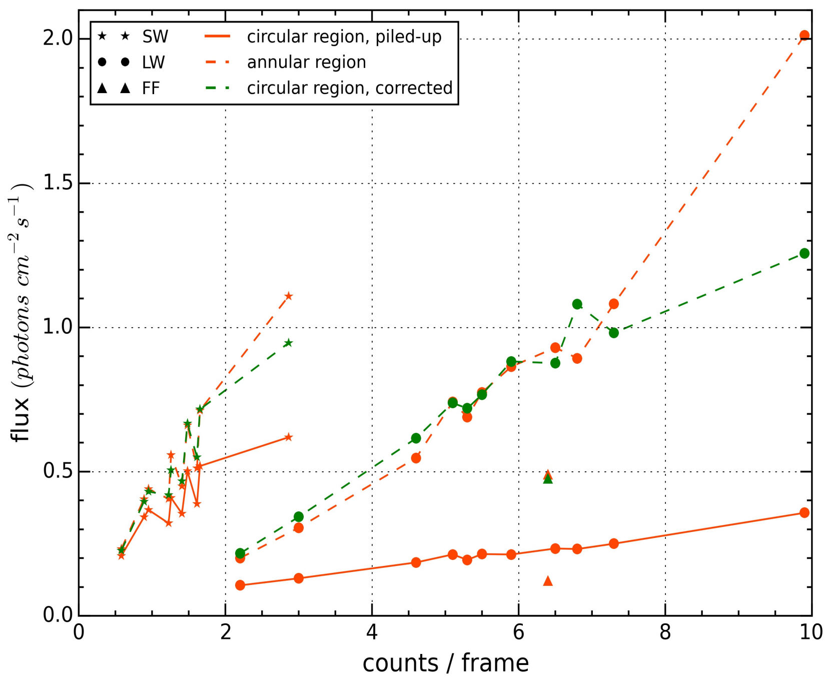


Fig. 4: Flux as a function of counts/frame for the MRK421 single and double spectra in the FF, SW and LW modes.

[2]This does not necessarily mean that the values from the annular region are the true ones, but simply allows a comparison of the pileup correction to the conventional method of removing the core.

[3]This is done because at the annular region where the correction method recovers no more flux, there should be no pileup.

Figure 5 compares the Γ index obtained from the circular spectrum with the value given by the annular region when excising a core of 35 arc-second radius. A ratio of $\Gamma_{circular}/\Gamma_{annulus} = 1.0$ means the model fit to the circular region spectrum and annular region spectrum give the same Γ index. If this is the case when using the corrected detector response, the spectral index is fully recovered. The solid lines represent the best fit Γ index parameter ratio when using the original detector response, and dotted lines when applying the corrected response. The SW results have been omitted from this plot because of the extremely poor fit statistics. For both the single and single & double spectra the corrected detector response brings the spectral index, Γ, closer to the value obtained from annular region spectrum. The general trend is an under-correction for the singles and an over-correction for singles & doubles as the count rate increases. The singles & doubles result is reproduced by the simulations where we also saw an over-correction above the limit set at 2.9 counts/frame[1]. The under-correction for singles was not, however, observed in the simulations. Nevertheless, as in the simulations, the corrected response for the singles & doubles spectra works well up to 3 counts per frame. The Γ index, for the singles spectra, is recovered extremely well up to 5.5 counts/frame based on these results.

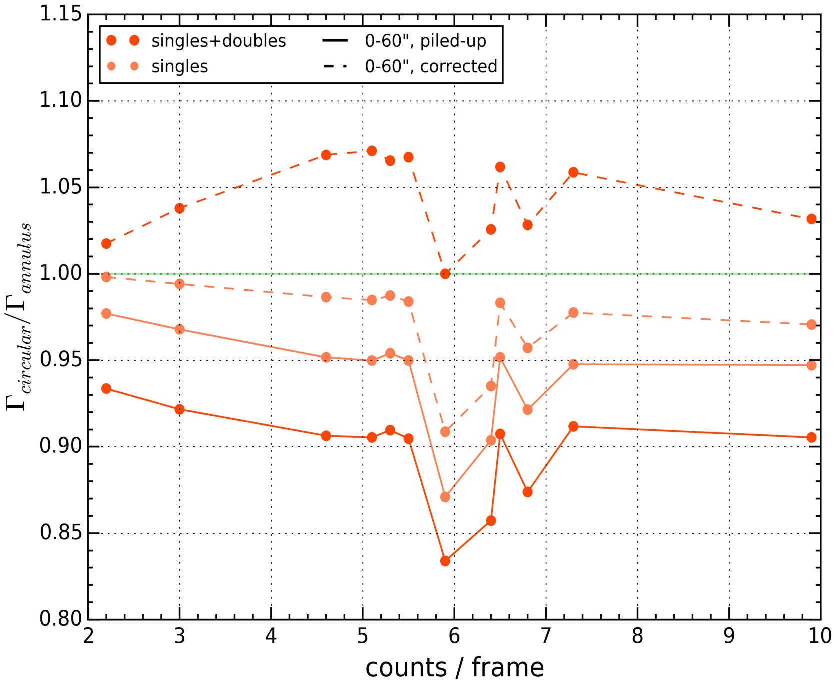


Fig. 5: Γ index using original or corrected response matrix with circular source region over Γ index from the 35-60″ annular region, as a function of counts/frame. All LW and FF observations from singles only and single and doubles spectra.

3 Fitting PKS 2155-304 observations

Observation ID	mode	N of frames	counts s^{-1}	counts $frame^{-1}$
0411782101	SW	13	28	0.16
0727770901	SW	11	30	0.17
0124930301	SW	7.8	120	0.68

Table 2: All PKS observations used in this section. The number of frames are given as N $*10^6$.

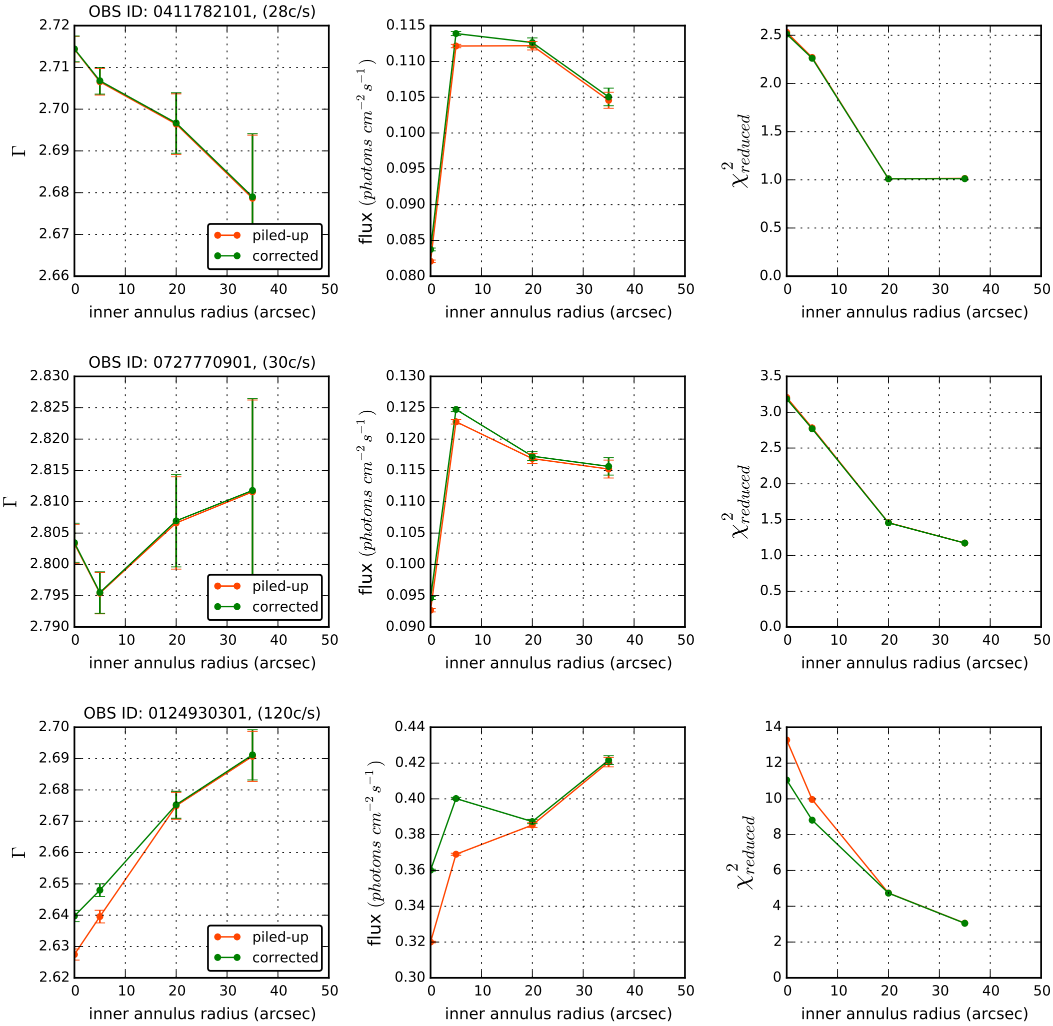


Fig. 6: Fit results for singles and doubles spectra of PKS 2155. Left: Γ index, centre: flux in the range 0.3-6.0 keV, right: reduced χ^2 for best-fit parameters all as a function of the radius of the removed region from the centre of the observation. A source extraction region of 50 arc-second radius is used.

Figure 6 shows the fit results for the three PKS observations. Observations 0411782101 and 0727770901 have count rates below the count rate thresholds defined by Jewtha[6] and are therefore unlikely to be affected by pileup. Therefore, using the pileup corrected model does not have any effect on the spectral parameter and increases the flux by only 2%. Based on the simulated results in the other work[1], a flux loss of ≈2% is to be expected at count rates of 0.16 and 0.17 counts/frame (28 and 30 counts/second). This implies that the flux obtained from the annular regions are incorrect; which suggest a flux loss of ≈26% and ≈21% for the two sources respectively. This is likely due to the uncertainty of the PSF which is included in the effective area for observations where the core is removed. The improvement of the reduced χ^2 to ≈1.0 for the annular regions can be attributed to larger errors.

Observation 0124930301, at 120 counts/s, is above the threshold limit of 50 counts/s for the SW. When fitting the corrected model to the spectrum from the circular extracted region, both some flux and steepness of the power law slope are recovered. This reveals that the core of the observation is piled-up. However, the values from the correction are underestimated when compared to the ones obtained from the annular region with an inner radius of 20 arc-seconds. The flux is recovered to 6.5% of the annular region flux from an initial 17% flux loss. The slope of the corrected fit to the annular one is Γ = 2.64 to Γ = 2.675 respectively. The disagreement between the quantities is possibly due to the inadequacy of the simple power law model for this spectrum. This is reflected by a poor fit statistic of $\chi^2_{reduced} \approx 13$. A broken power law is perhaps the more suitable model and may yield better results when folded with the corrected response. Nevertheless, as we saw from the first two observations of PKS, the flux reconstruction for a removed core has an uncertainty. At 0.68 counts/frame, the simulated data[1] shows a flux loss of ≈10%. This value agrees nicely with the 11% flux recovery when using the corrected response matrix. The 17% flux recovery obtained from the 20 arc-second annular region is therefore likely an over-estimation due to the uncertainty of the PSF.

Appendix 1

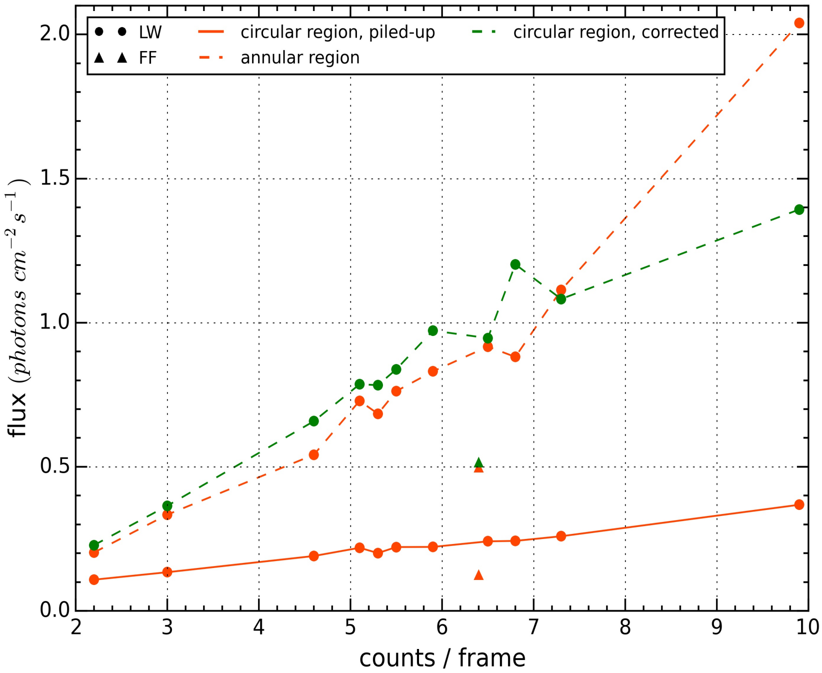


Fig. 7: Flux as a function of counts/frame for the MRK421 singles spectra in the FF and LW modes.

References

[1] Kjell Koch-Mehrin. Correcting for X-ray Pileup in the EPIC pn-CCD camera using simulated Detector Response Matrices. 2016.

[2] Alessandra Costantino. X-ray and gamma-ray study of the TeV blazar Mrk421. 2016.

[3] X-ray absorption in the ISM. `http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/`.

[4] Allen Wilms and McCray. On the Absorption of X-rays in the Interstellar Medium. *ApJ*, 542(2):914–924, 2000.

[5] D.A. Verner. Atomic data for astrophysics. II. New analytic fits for photoionization cross sections of atoms and ions. *ApJ*, 465(487), 1996.

[6] P.Jethwa. Pile-up thresholds for the EPIC cameras. pages 1–4, 2012.