Title: **Pileup in RGS spectra**

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Table 1: Observations performed

source	revolution	observation	mode	flux [1])	pile-up
pks2155	908	0158960901	8 CCD	0.002	no
mkn421	1184	0411080301	8 CCD	0.035	RGS1 - very light
					RGS2 - no
J1655	0956	0112921301	8 CCD	0.006	no
	0964	0112921401	8 CCD	0.6	considerable
	0966	0155762501	1 CCD	1.0	RGS1 - no
			8 CCD	1.0	RGS2 - severe
RS Oph	1159	0410180301	8 CCD	0.4	severe
V4743 Sgr	0608	0127720501	8 CCD	0.2	moderate

[1]) Peak photon flux in the 6 to 38 Åinterval in Photons/cm^2/sec

1 Introduction

Every photon hitting the RGS detector has some chance to hit a spot on which a previous photon has already landed during the same frame integration time, causing pile-up of photons. For most sources this chance is very small, but depending on source intensity, some minor fraction of photons will always be subject to pile-up. Pile-up will cause coinciding first order photons to end up as a single event in second order at a position corresponding to half their wavelength. Most sources have modest intensities in which pile-up is negligible. However, lately it was recognized that some sources, notable very bright TOO sources, do suffer from (severe) pile-up. This report tries to investigate when pile-up plays a role, how to recognize pile-up, what effects pile-up may cause, if any corrective action may be possible and possibilities to prevent pile-up in the first place.

2 Data used

To investigate pile-up, a number of observations were used of piled-up and non-piled-up sources. Table 1 lists the relevant observations and characteristics. The non-piled-up sources are still quite bright compared to the average RGS source. In 'average' RGS sources pile-up does not play a role.

3 Event shapes and pile-up

When a photon hits a pixel next to a pixel where already a photon has hit, the event reconstruction will combine these pixels, resulting in a pile-up event. Since any pixel will have 4 neighbors which can be combined by the event reconstruction, the chance for a more-pixel pile-up event is 4 times higher than for a single pixel pile-up event, provided that a single photon will only activate a single pixel.

However, depending energy of the photon, CCD and location on the CCD, single photons may deposit charge in more than one pixel, resulting in multiple-pixel events. (An event size larger than 1). When on a specific location on a CCD the chance of multiple-pixel events is higher, also the chance of pile-up will be higher, since a multiple pixel event will have more neighboring pixels; hence a larger fraction of the CCD surface will border an event. Thus, the pile-up fraction of a given spectrum not only depends on photon rate, but also on CCD location.

Pile-up may result in 1st order events ending up in 2nd order. However, on locations on the CCD where multiple-pixel events are more likely, pile-up will have a higher chance to result in 'complicated patterns' which will be discarded by the on-board processing.

It was investigated how event patterns are distributed over the detectors in case of pile-up and in the absence of pile-up. Fig's 1 to 8 show the CCD image (top), 'banana' plot (2nd from top), derived event order (3rd from top), and ratio of complicated patterns with respect to the simple single pixel events (bottom). 1^{st} order events are never piled-up, (although there is of course loss of events from 1^{st} order to 2^{nd} order due to pile-up) so the pattern ratio's (bottom) should show the normal situation as far as event pattern distribution is concerned. 2^{nd} order events of very bright sources do have a high likelihood of being piled-up events from 1^{st} order. Fig 1 and 3 show the 1^{st} order of the J1655 observation which suffers from pile-up. This can be compared with fig 5 and 7 of Mkn421, which is not piled-up. Indeed 1^{st} orders have about similar ratio's for the event shapes. These plots also reveal that that are considerable differences in event patterns over the different CCD's. E.g. RGS2 CCD8 (β =0.041 - 0.045) has a significant number of event-pattern=2 while RGS2 CCD7 has excess event-pattern=2 only towards its edges. Also at β = 0.068 - 0.070 (figure 5) there are excess pattern=3 events. (note: pattern=0 are single pixel events, while pattern=1 and pattern>3 have 4 and 3 pixels respectively) Where event counts are low, there is noise of course, but sometimes excess complicated patterns are clearly very spiky even where there is very good statistics. See e.g. fig 1 and 5 at $\beta = 0.056$.

The 2^{nd} order plots show that the frequency of multi-pixel events is increased with respect to 1^{st} order. In particular in the piled-up J1655 observation. E.g. on CCD8 of RGS2 the pattern=2 events increase from 0.6 to about 2. 2^{nd} order events above approximately 2.2 keV in PI space are almost 100% pile-up events since the effective area of RGS above 2.2 keV is very small as can be seen in the 1^{st} order spectra.

Clearly, based on these plots it can be expected that pile-up fractions may vary considerably between CCD locations and can be very sharply peaked at given locations, leading to fake spectral features in e.g. 1^{st} order. Although the effects of pile-up are clearly noticeable, it's hard to inverse the data and correct for pile-up based on event patterns. 2^{nd} order events above 2.2 keV are almost exclusively pile-up events and can in theory be used to correct the 1^{st} order up till about 12 Å. This process can be extended when a source spectrum only has flux above a given wavelength. However, this process is not without problems as said before since, when specific CCD locations promote multiple pixel events, onboard processing may discard pile-up events based on location, leading to fake spectral features.

4 Noticing pile-up

An important diagnostics tool to probe whether pile-up plays a role is the comparison between fluxed spectra of 1^{st} and 2^{nd} order. The RGS calibration of the effective area ensures that the fluxed 1^{st} and 2^{nd} order spectra of normal non-piled-up sources will be identical. Hence, looking at the ratio between the 1^{st} and 2^{nd} order can be a diagnostics tool to determine whether pile-up plays a role. Figures 9 to 22 show comparisons and ratios for a variety of observations.

Figures 9 and 10 show comparisons for a non-piled-up source. The ratio between 1^{st} and 2^{nd} order is around 1.0 indicating that pile-up is not a factor. In fig. 11 and 12 there is clearly pile-up, since the ratio's between 1^{st} and 2^{nd} order deviate from 1.0. In addition it is clear that pile-up in RGS2 is more severe than in RGS1, despite the fact that both RGSs are subject to the same source spectrum and hence the same count rates. This is likely due to the fact that the CCD's in the RGSs behave differently. E.g. CCD's 7 and 8 in RGS2 (see e.g. fig 7) cause significantly more multi-pixel events, leading to higher pile-up fractions.

Easiest remedy against potential pile-up is faster readout of the CCD's. In fig. 13 RGS1 is in single CCD readout mode, effectively decreasing integration time per frame by a factor of 8. Pile-up in this spectrum appears minimal. RGS2 kept the normal 8 CCD readout mode and fig. 14 shows that pile-up in that case is severe.

Figs. 15 to 18 show that in some cases one can to some extent correct for pile-up. Both RS Oph and V4643Sgr have minimal flux below 15 Å and 20 Å respectively. All flux in 2^{nd} order below these wavelengths is 100% pileup from 1^{st} order. Potentially these 2^{nd} order events can be changed into the double amount of 1^{st} order events at double the wavelength. However, such a 'repair' operation is not perfect and will have flaws, due to e.g. loss by onboard removal of 'complicated' events (as explained above) and 2^{nd}-1^{st} order pile-up losses to 3^{rd} order. In addition such an operation can only be attempted in special cases and cannot be performed in general.

For comparison purposes fig. 19 to 22 show sources for which pile-up is not a factor. Still in general terms, Mkn421 and PKS2155 are bright sources. This shows that for the 'average' RGS source, which is (much) weaker than Mkn421 or PKS2155, potential effects of pile-up can be discarded. Looking at event rates in the referenced figures, one can say that one should consider potential pile-up if photon rates approach the range of 0.03 - 0.04 Photons/cm^2/s.

5 models

Given a source spectrum and effective area of an RGS, one can compute the effects of given pile-up fractions in 1^{st} order on the 1^{st} and 2^{nd} order fluxed spectra. Fig. 23 shows the expected ratio for a power law spectrum with index $\gamma = 2.0$ and 10% pile-up. This plot does not include the effects of differences of event patterns between CCD's nor does it take into account factors which may lead to loss of events due to on-board discarding of 'complicated' events or pile-up to 3^{rd} order. The model shows that for pile-up fractions larger then 10% one may expect ratio's between 1^{st} and 2^{nd} order of lower than 0.85 - 0.9.

6 Possible remedies

Clearly the best remedy for pile-up is to prevent it to happen in the first place. Single CCD readout does help a lot (cmp. fig 13 and 14). Of course single CCD readout also means a loss of effective integration time, so the numbers of CCD to readout in a cycle should be carefully tuned to the intensity of the source. Faster CCD clocking sequences, which do not restrict effective integration time, do also help.

The possibilities for 'repair' of the effects of pile-up after the observation has been performed are very limited and cannot be treated in a standard way. If a source spectrum only has flux above a given lower wavelength limit, the corresponding 2^{nd} order events below this limit can be treated as 100% piled-up photons from the source. However, local CCD behavior may lead to potential fake spectral features. Only a careful comparison of the separate different RGS spectra and first and second orders may allow to identify narrow real spectral features. Features present in only one RGS spectrum or order should not be trusted.

In fig 24 an attempt is made to correct the piled-up spectrum of RS Oph for pile-up. This is done by determining which fraction of events in second order has event shapes which lies outside the normal distribution for event shapes (in 1^{st} order). This fraction is subtracted from 2^{nd} order, doubled and added to 1^{st} order. Since the spectrum has no events below 14 Å and all 2^{nd} order events below 14 Å appear to have multiple pixels, this corrections appears to work quite well. However, applying the same procedure to the piled-up spectrum of J1655, gives weird results (fig. 25). Such a procedure should thus only be applied with caution and will not work in general.

In fig 15 it can be seen that a careful separate comparison of individual RGS1 and RGS2 spectra and 1^{st} and 2^{nd} order can reveal interesting narrow unambiguous features in spectra. E.g. the narrow feature at 9.5 Å in 2^{nd} order repeats at 19 Å in 1^{st} order. In addition it is visible in both RGS1 (fig. 15) and RGS2 (fig. 16) data. This 9.5 Å feature is piled-up from 1^{st} order at 19 Å. The broad dip (Oxygen edge of (local) interstellar absorption) around 11 Å (piled-up 2^{nd} order) and 23 Å and the narrow feature at 15.5 Å are also visible in both 1^{st} and 2^{nd} order and in RGS1 and RGS2 spectra. The features at 29-30 Å, are visible in both RGS1 and RGS2. Hence the unambiguous detection of these features shows a rich spectrum, which tells a lot about the source. Since due to the nature of the spectrum, both orders can be corrected for pile-up (fig. 24), a proper analysis of the spectrum can be made, despite its piled-up nature.

7 Conclusions

In this report diagnostics tools have been presented which can indicate whether event pile-up plays a role when interpreting the spectra. In general most RGS sources will not suffer from pile-up. However, when photon rates approach 0.03 - 0.04 Photons/cm^2/s (around the wavelength of maximum effective area (15 Å)), effects of potential pile-up should be considered and suitable diagnostics (ratio of 1^{st} and 2^{nd} order fluxed spectra) be executed. For some bright TOO's in high states, this limit is easily surpassed.

When a source is expected to be as bright that potentially pile-up can be expected to take place, it is better prevented (or minimized) by faster (single) CCD readout. In addition one can consider to have different readout modes for the two RGSs. Having one RGS in single CCD mode and the other in double CCD readout mode, the frame times of both RGSs differ by a factor of two, but are still both faster then in 8-CCD readout. This difference will allow to make an estimate of pile-up. When there is minimal difference between the two RGSs observed, pile-up is not important. Other modes, e.g. going from 4 to 2 to 1-CCD readout mode can be considered depending on count rate going from 0.04 to 1.0 Photons/cm^2/s Another thing to consider though, is the telemetry rate. In the rev. 0966 (obs: 0155762501) of J1655 where RGS1 was in single CCD readout mode, there was considerable loss of frames due to telemetry restrictions. When event rate is high and pile-up is prevented by faster readout, the telemetry should be able to cope with the increased data rate, otherwise the effective integration time and hence spectrum statistics will drop even further.

Pile-up may be different between RGS1 and RGS2 and may abruptly vary between CCD locations due to the nominal event pattern distribution variations over the CCD's.

Repair of 'piled-up' spectra is (very) limited, not standard, and can only be done with great care in some special cases only. Narrow spectral features which are identified can only be trusted if they are consistent between the different RGSs (and piled-up 2^{nd} order at half the wavelength).

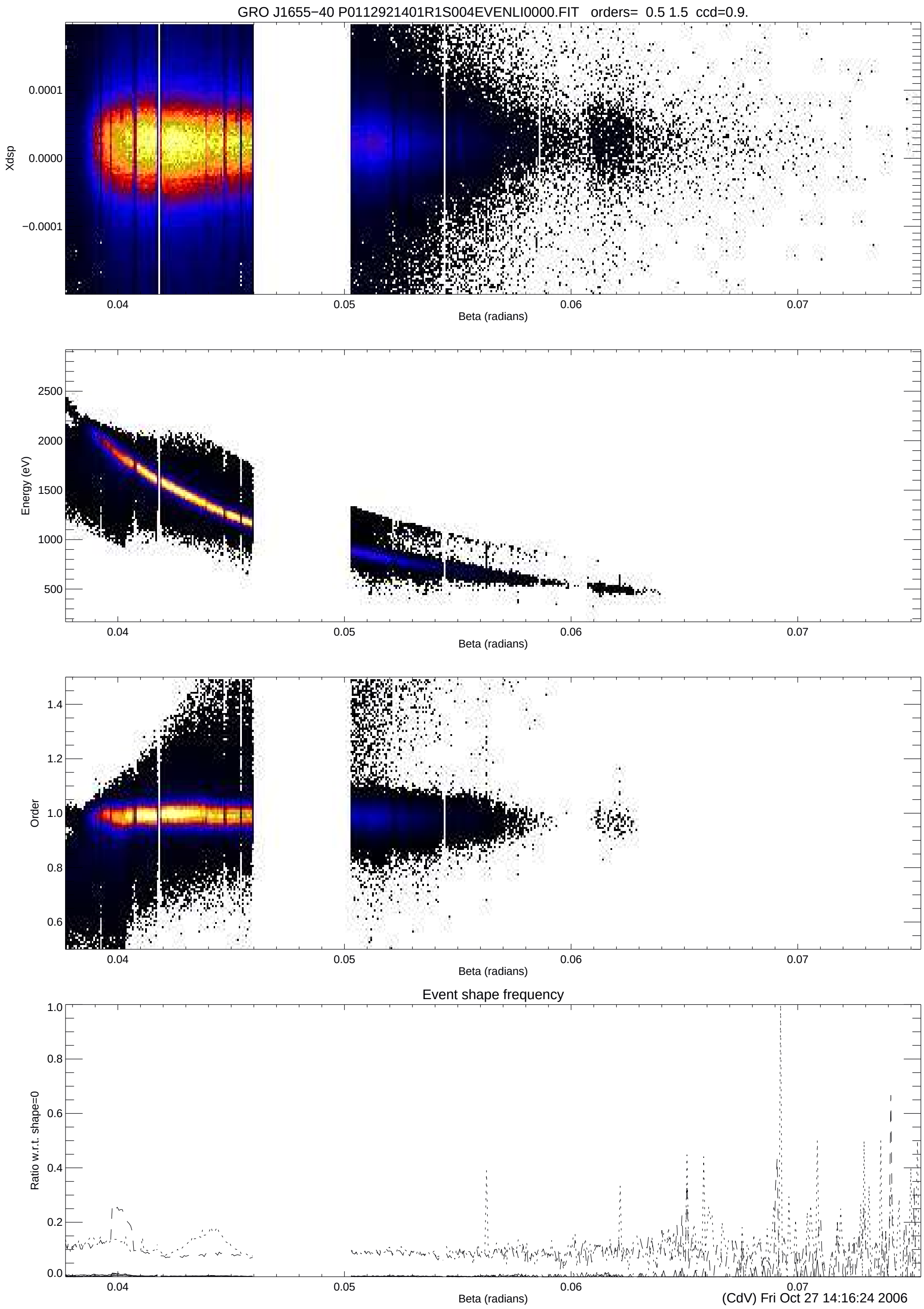

Figure 1: Event patterns of the piled-up observation of J1655. RGS1 1^{st} order events are selected. Top plot shows the CCD image. 2^{nd} from top the 'banana' plot. and 3^{rd} from top the computed order. Bottom plot shows the ratio of multi-pixel event patterns with respect to single pixel events. Each pattern ratio is shown a different line-type. Dotted line are pattern=2 (vertical combination of two pixels) events while the broken line shows pattern=3 (horizontal combination of pixel) events. Other lines show the 3-4 pixel events. (Note: the peak in the pattern=3 events at $\beta = 0.04$ is due to the shallow absorption of photons with energies above the Si edge causing a spread of charge over more pixels.)

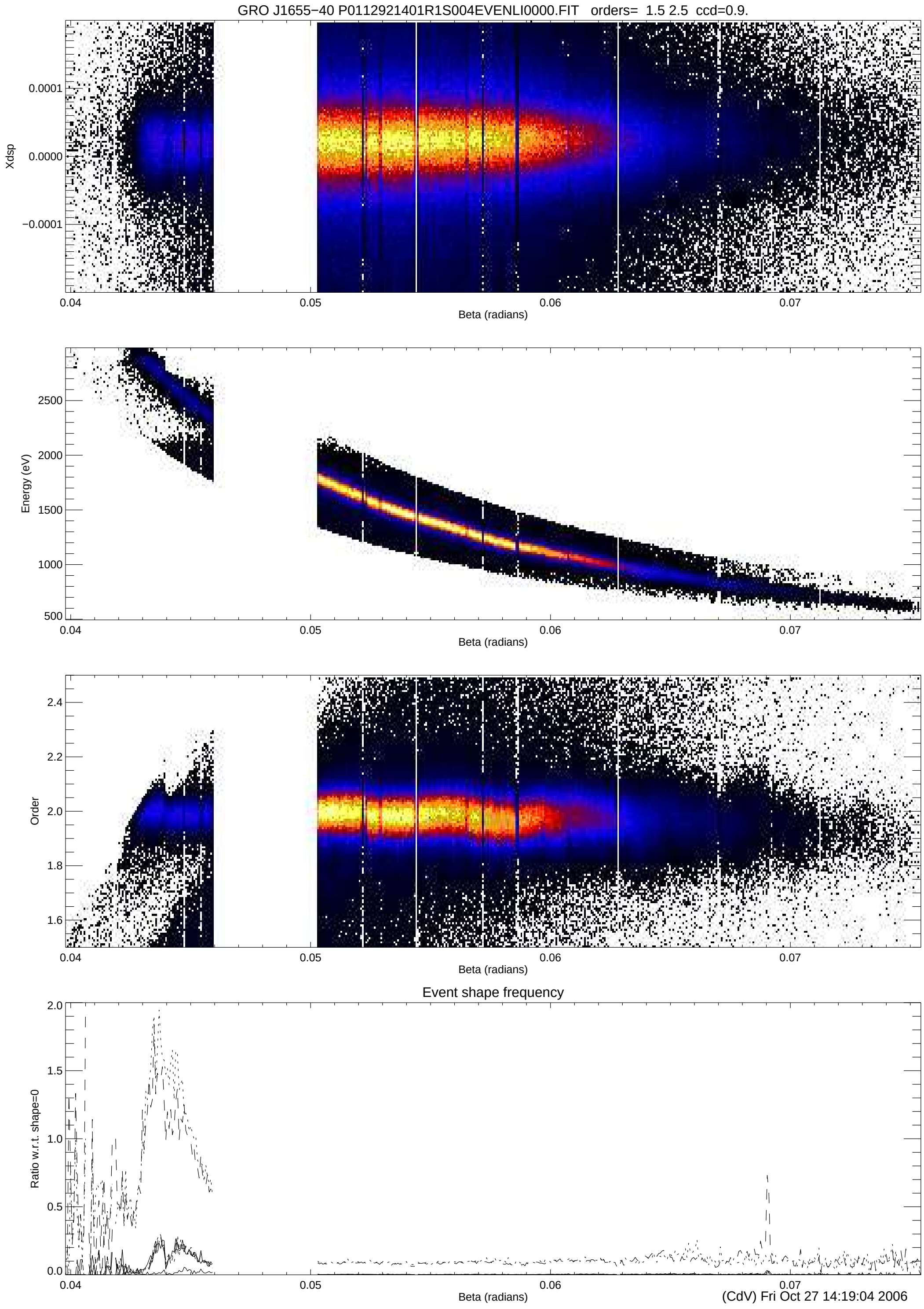

Figure 2: Event patterns of the piled-up observation of J1655. RGS1 2^{nd} order events are selected.

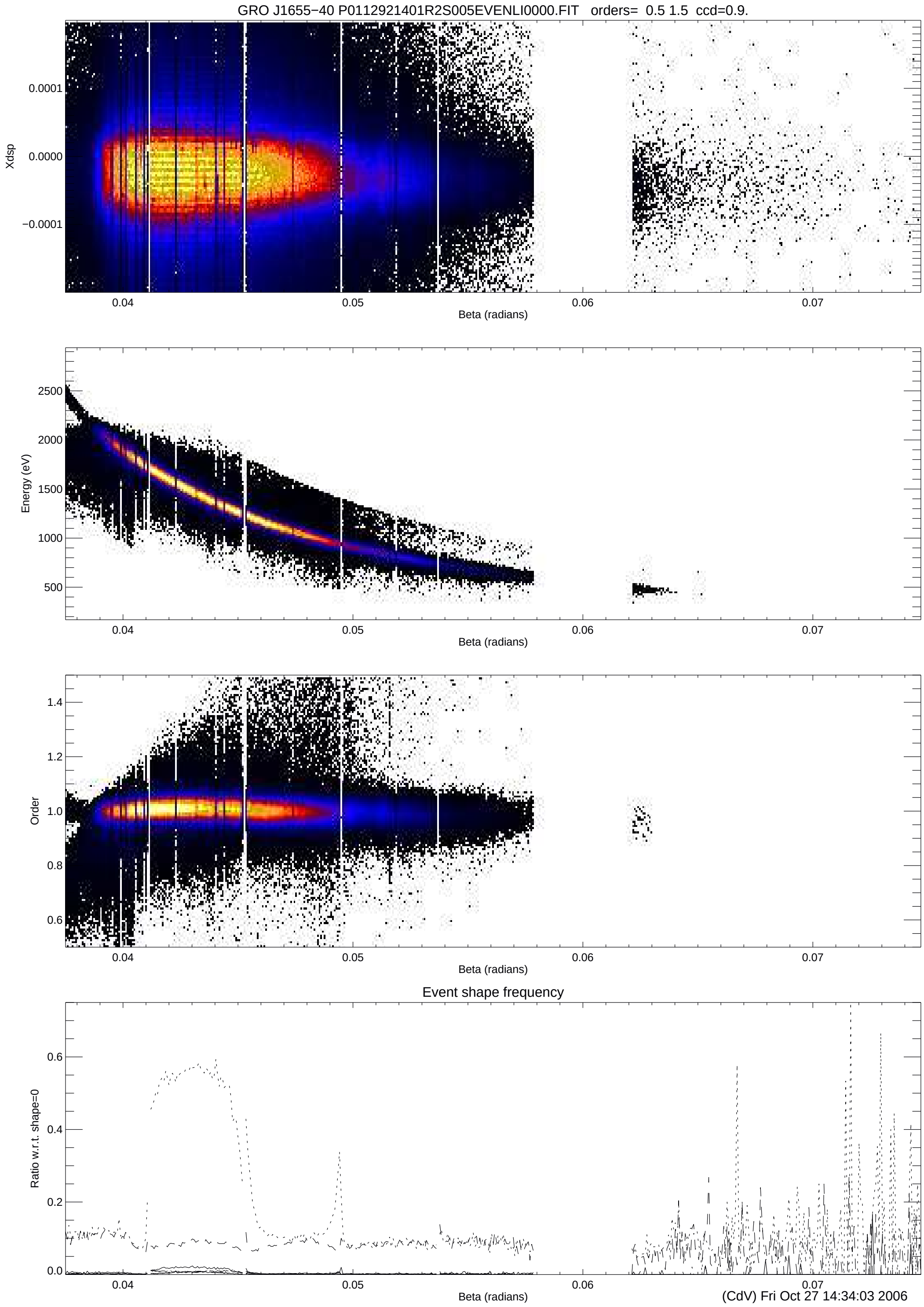

Figure 3: Event patterns of the piled-up observation of J1655. RGS2 1st order events are selected.

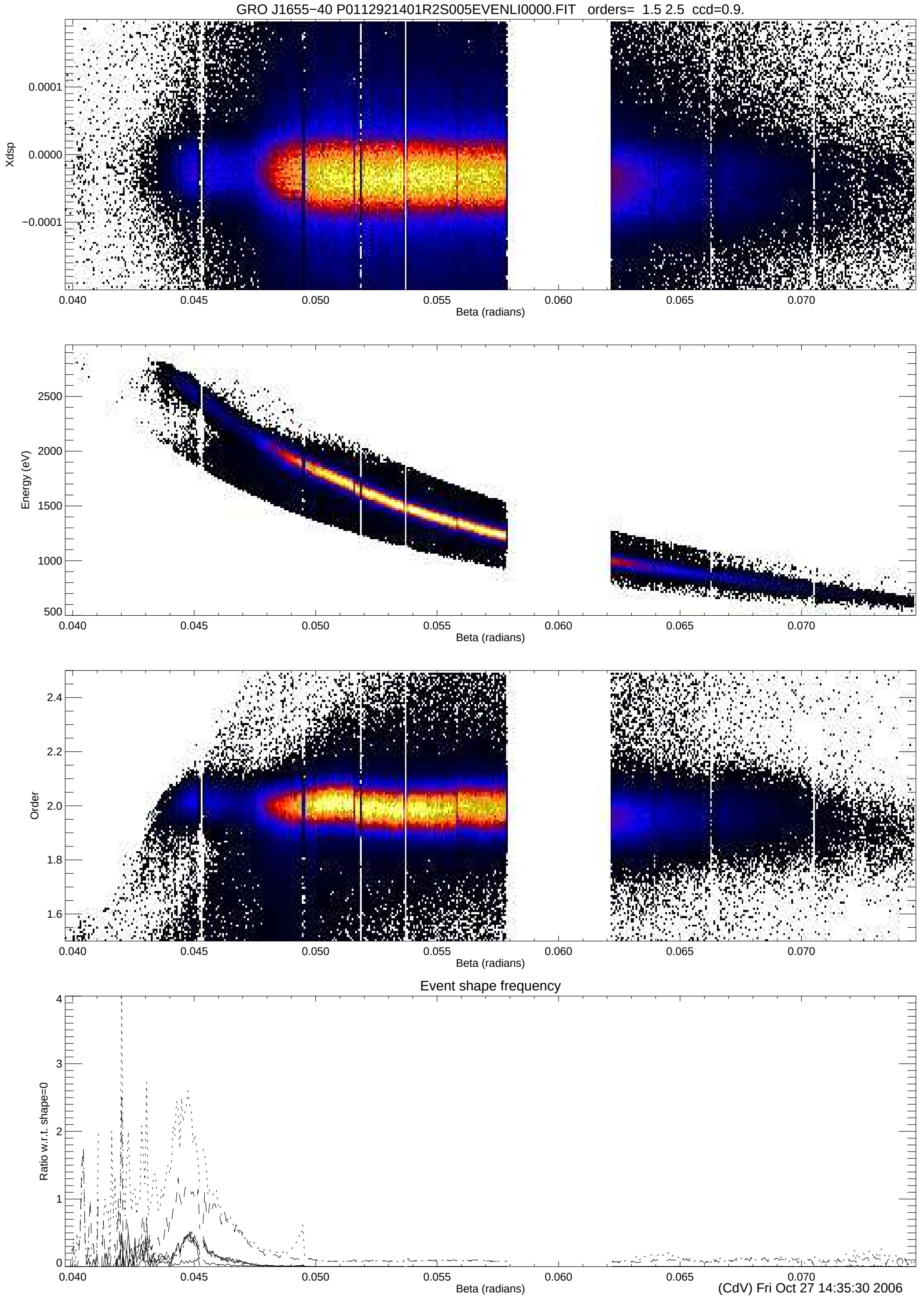

Figure 4: Event patterns of the piled-up observation of J1655. RGS2 2^{nd} order events are selected.

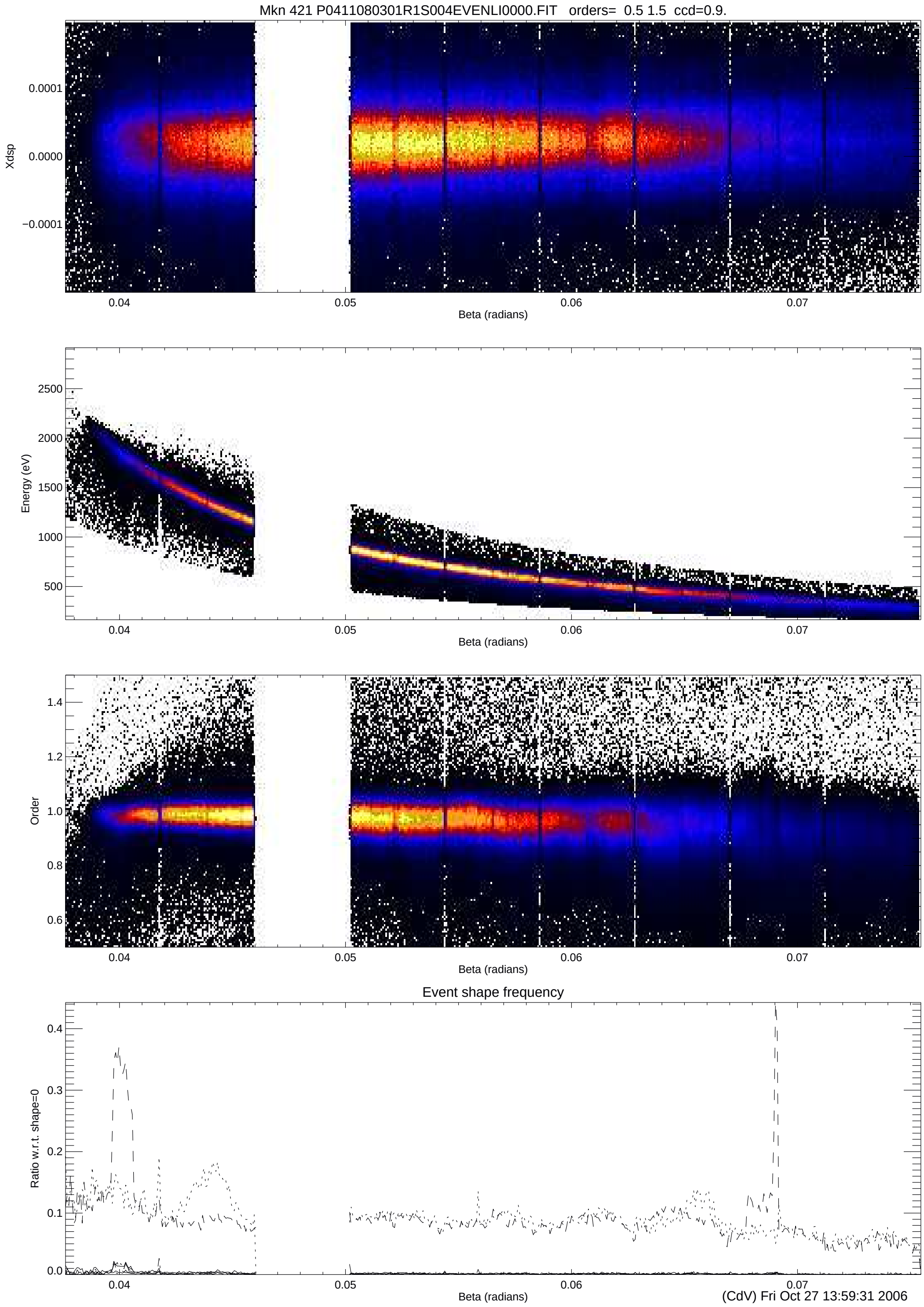

Figure 5: Event patterns of the non-piled-up observation of Mkn421. RGS1 1st order events are selected.

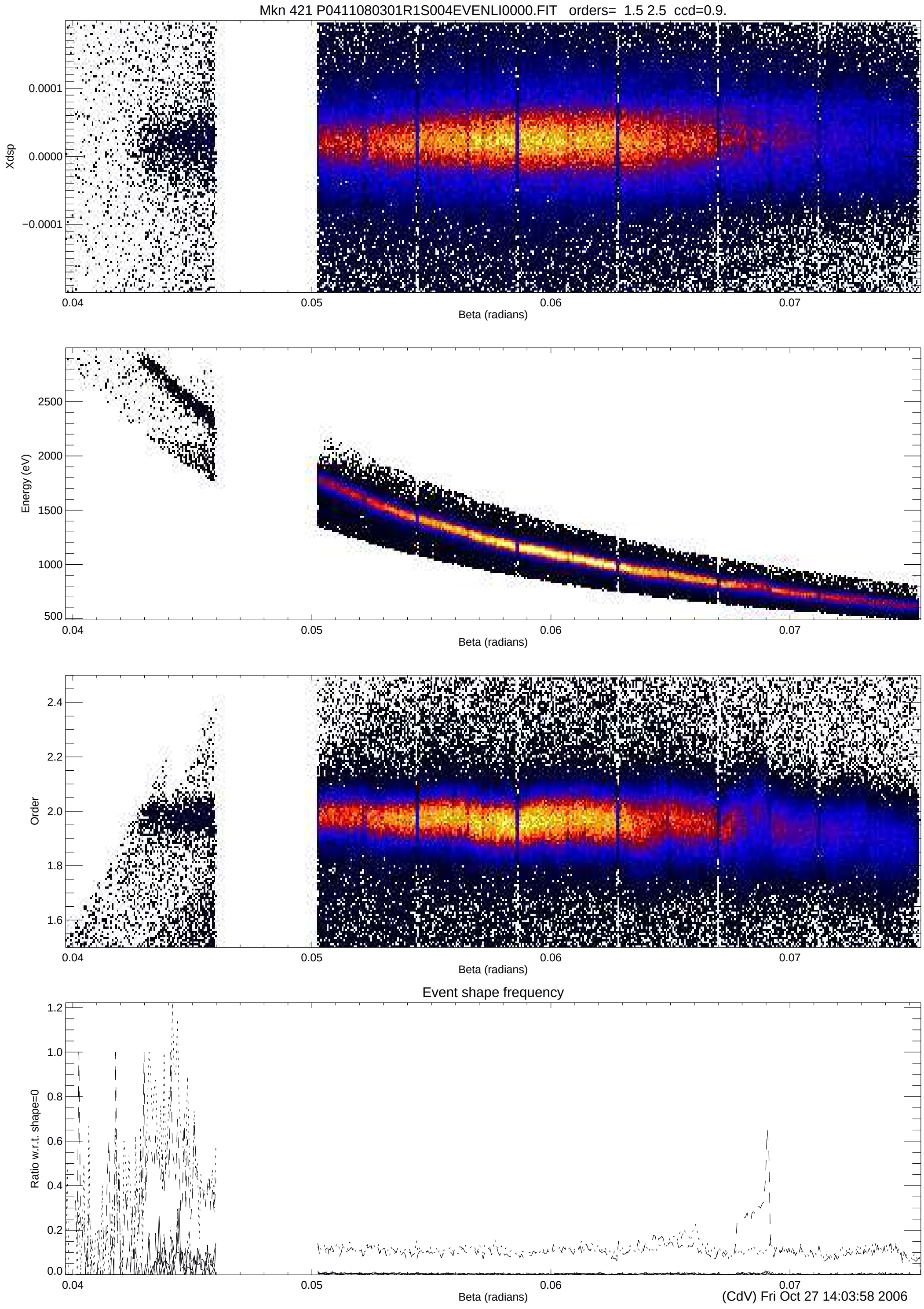

Figure 6: Event patterns of the non-piled-up observation of Mkn421. RGS1 2nd order events are selected.

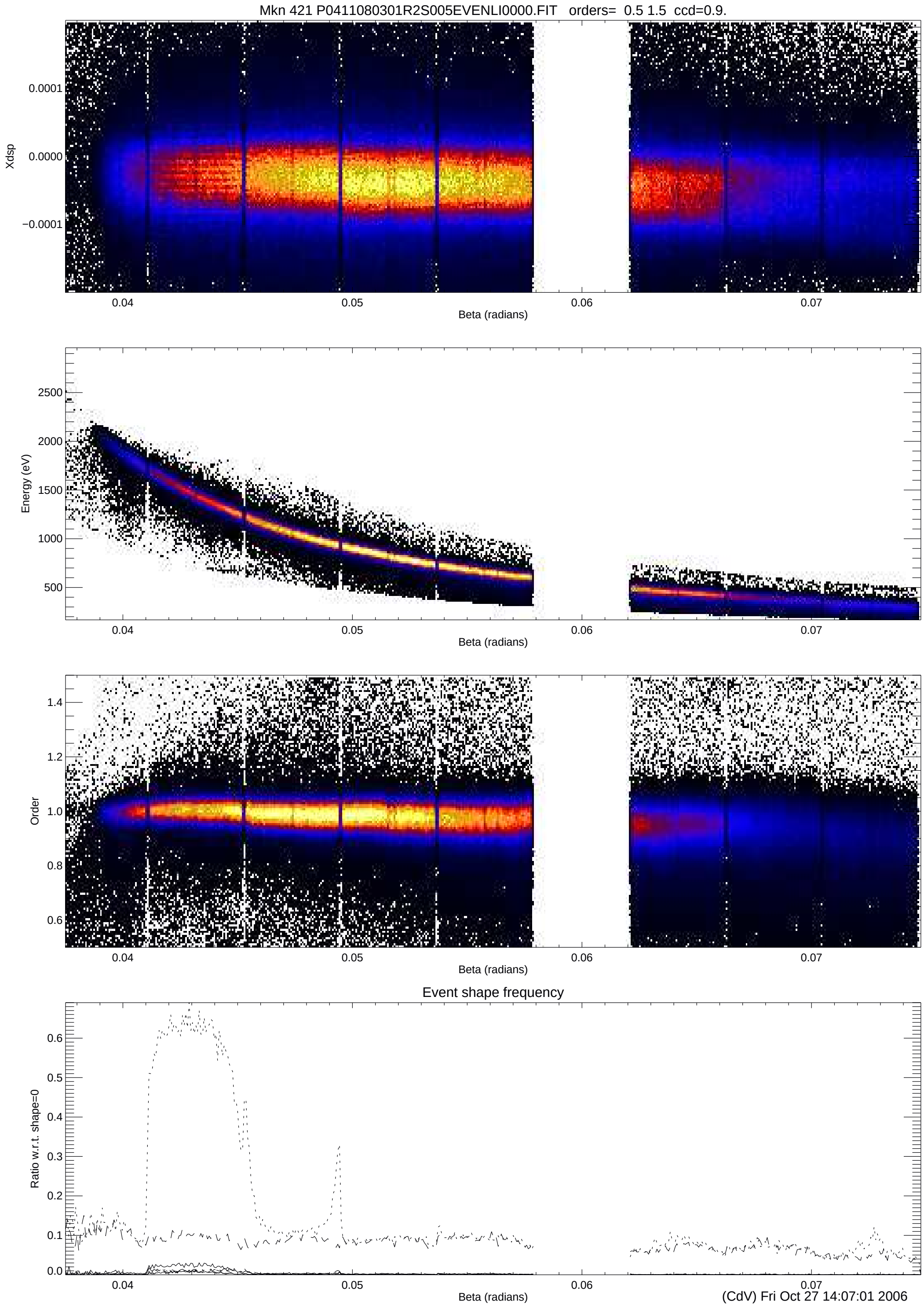

Figure 7: Event patterns of the non-piled-up observation of Mkn421. RGS2 1st order events are selected.

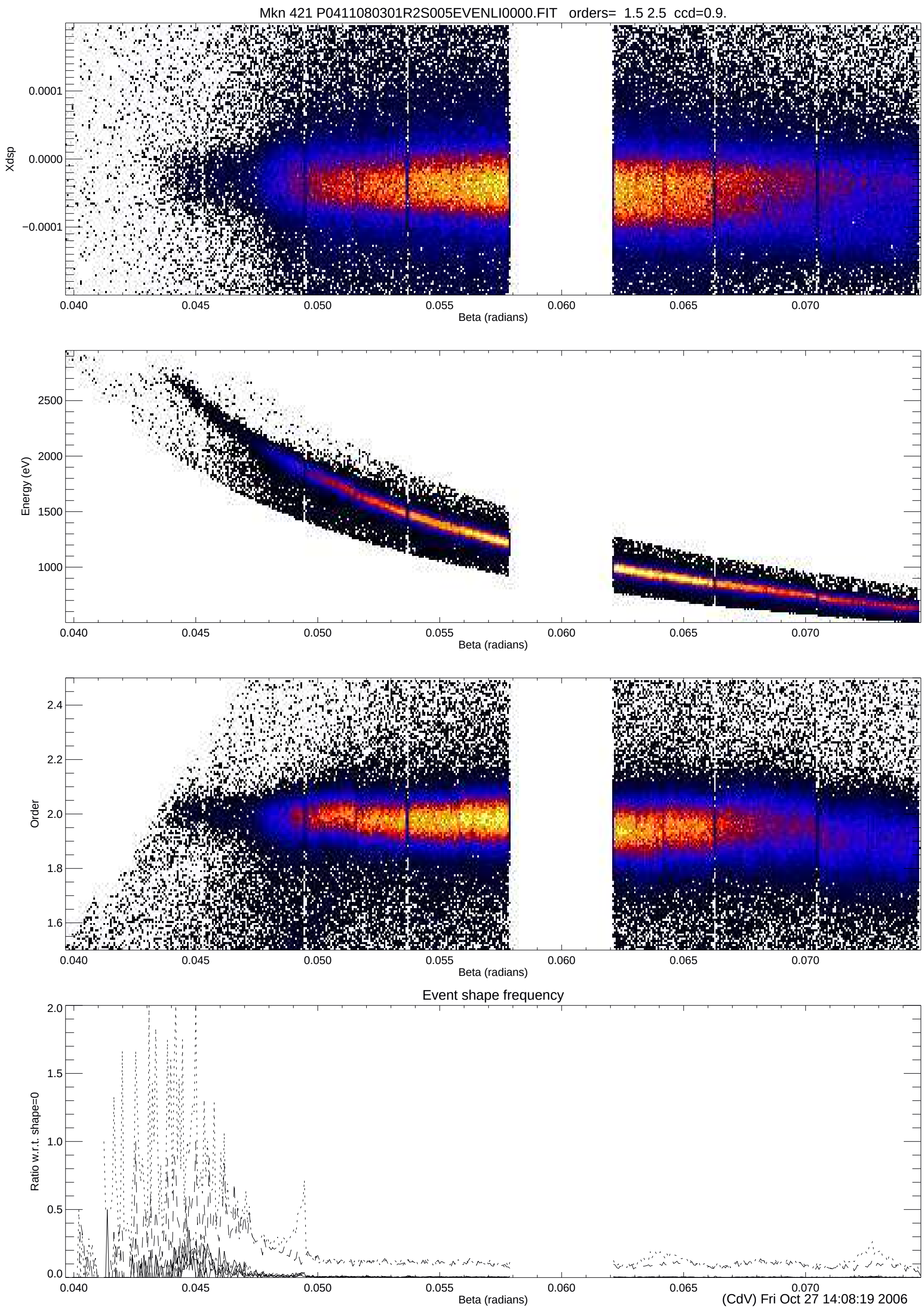

Figure 8: Event patterns of the non-piled-up observation of Mkn421. RGS2 2^{nd} order events are selected.

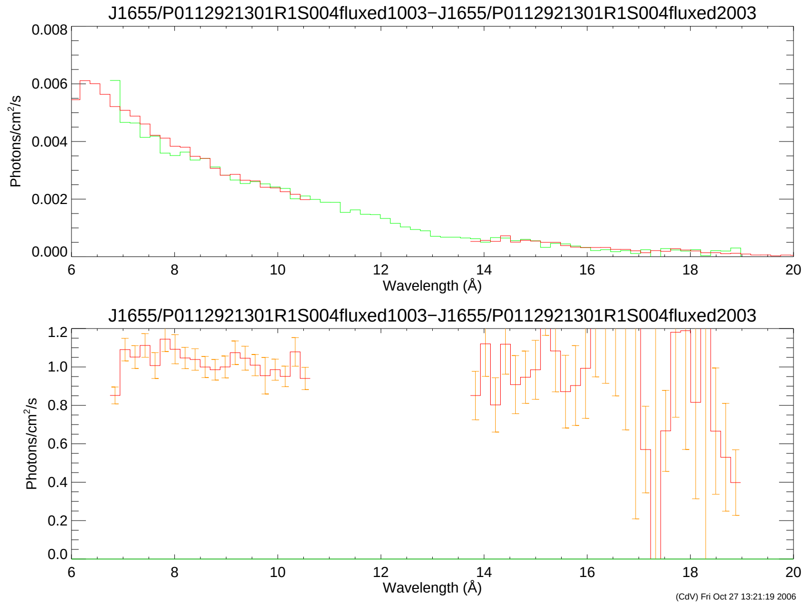

Figure 9: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS1 for J1665 in a low, non-piled-up state. The ratio fluctuates within statistics around 1.0

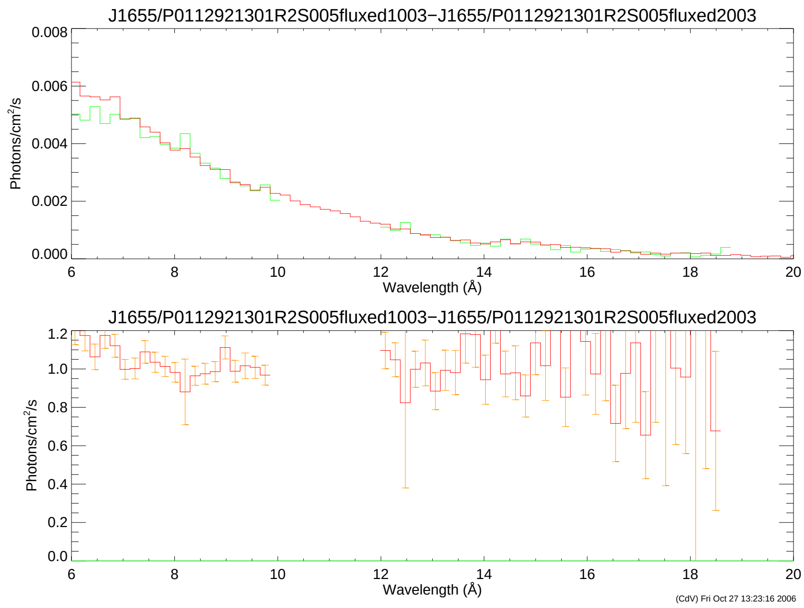

Figure 10: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS2 for J1665 in a low, non-piled-up state. The ratio fluctuates within statistics around 1.0

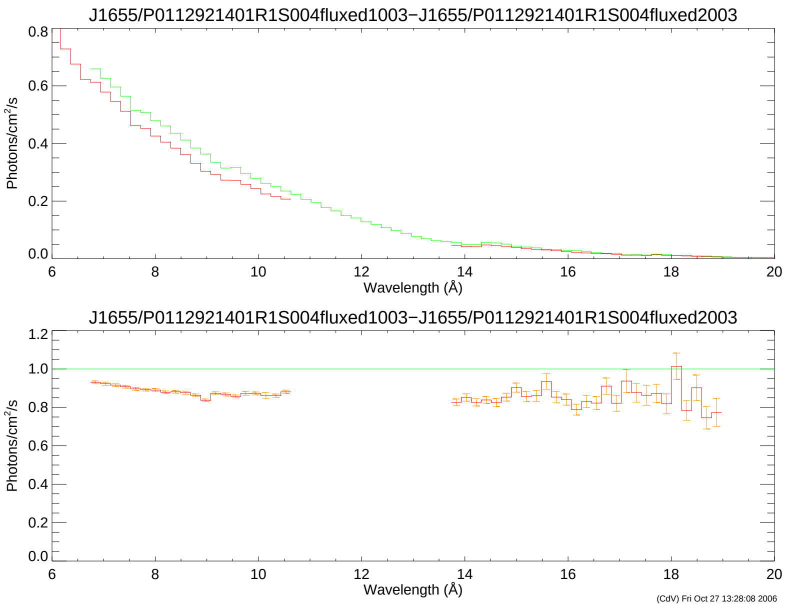

Figure 11: Comparison (top) and ratio (bottom) between 1st (red) and 2nd (green) order of RGS1 for J1665 in a high, piled-up state. The ratio clearly deviates from 1.0

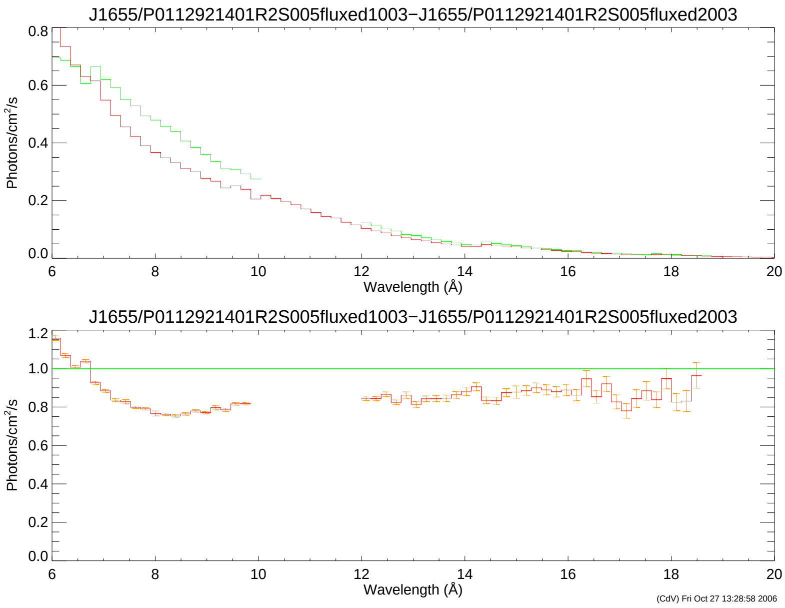

Figure 12: Comparison (top) and ratio (bottom) between 1st (red) and 2nd (green) order of RGS2 for J1665 in a high, piled-up state. The ratio clearly deviates from 1.0. It is also clear (cmp. fig 11) that pile-up between 8 and 10 Å is clearly worse for RGS2 than for RGS1.

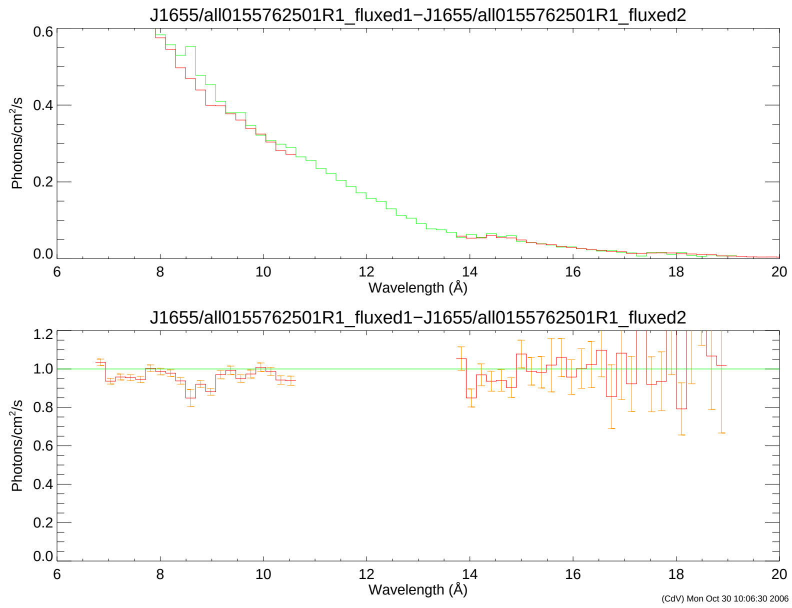

Figure 13: Comparison (top) and ratio (bottom) between 1st (red) and 2nd (green) order of RGS1 for J1665 in a high state, but with single CCD readout. Since the ratio is around 1.0 it shows that pileup is minimal.

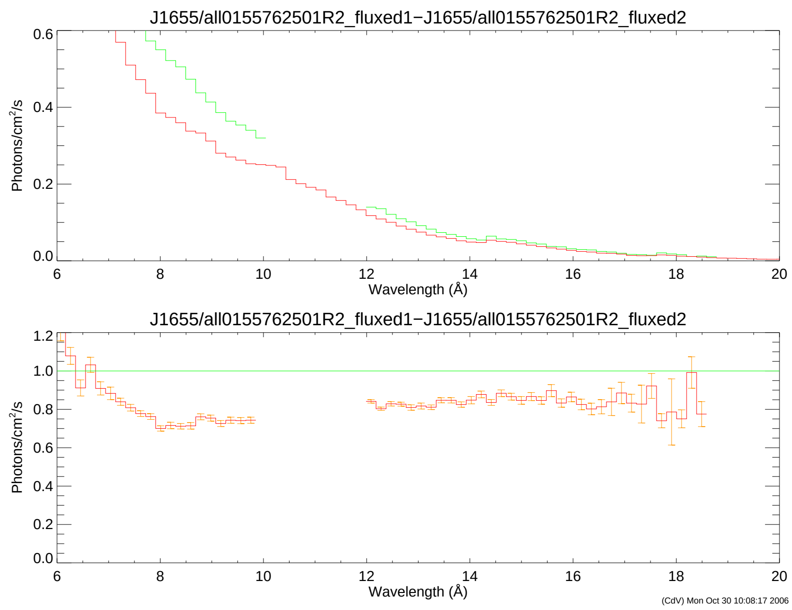

Figure 14: Comparison (top) and ratio (bottom) between 1st (red) and 2nd (green) order of RGS2 for J1665 in the same high state where RGS1 was in single CCD readout mode (fig. 13). For RGS2 the ratio clearly deviates from 1.0, showing that here, contrary to RGS1 pile-up does play a role.

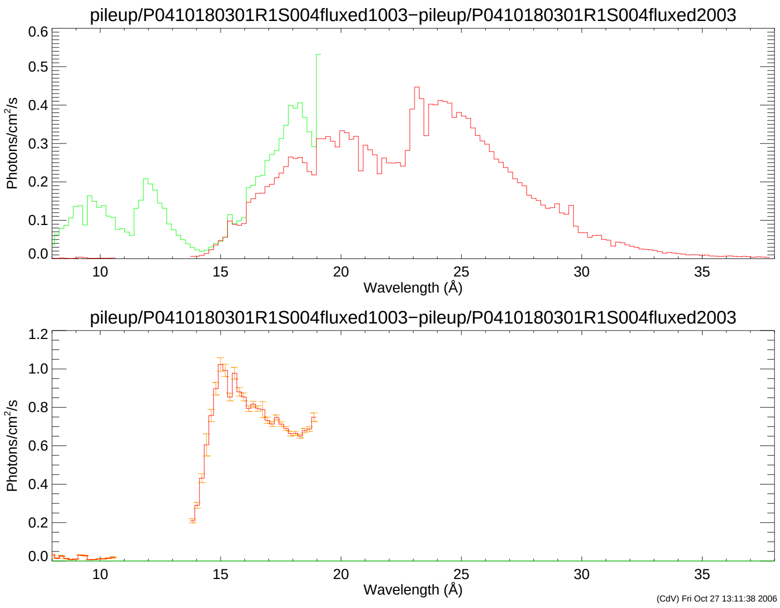

Figure 15: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS1 for RS Oph in a high state. Since the flux below 14 Å is very low, all 2^{nd} order events below 14 Å are pile-up events and show a copy of the first order spectrum above 14 Å.

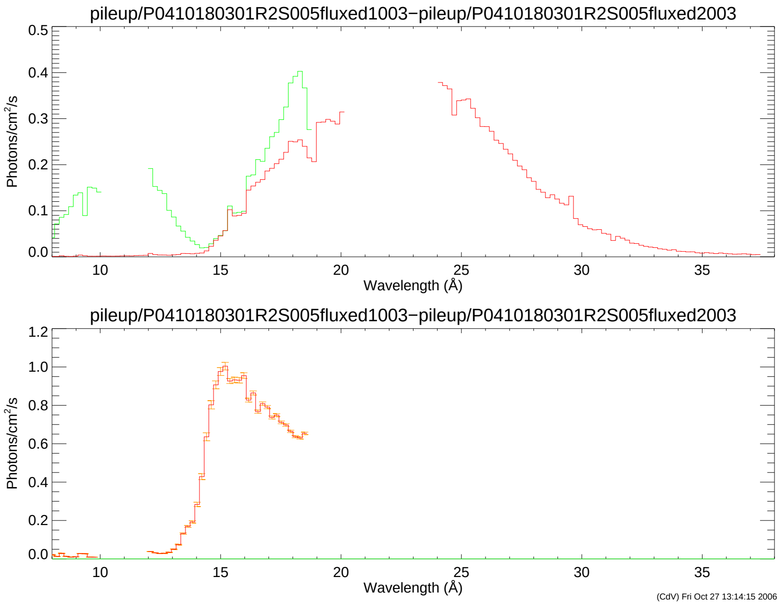

Figure 16: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS2 for RS Oph in a high state similar as fig 15

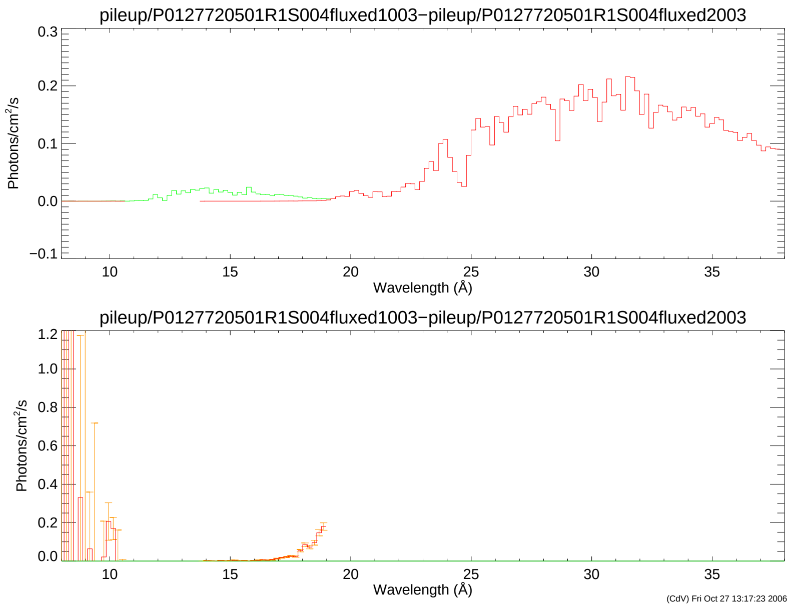

Figure 17: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS1 for V4743Sgr in a high state. Since the flux below 20 Å is very low, all 2^{nd} order events below 20 Å are pile-up events and show a copy of the first order spectrum above 20 Å.

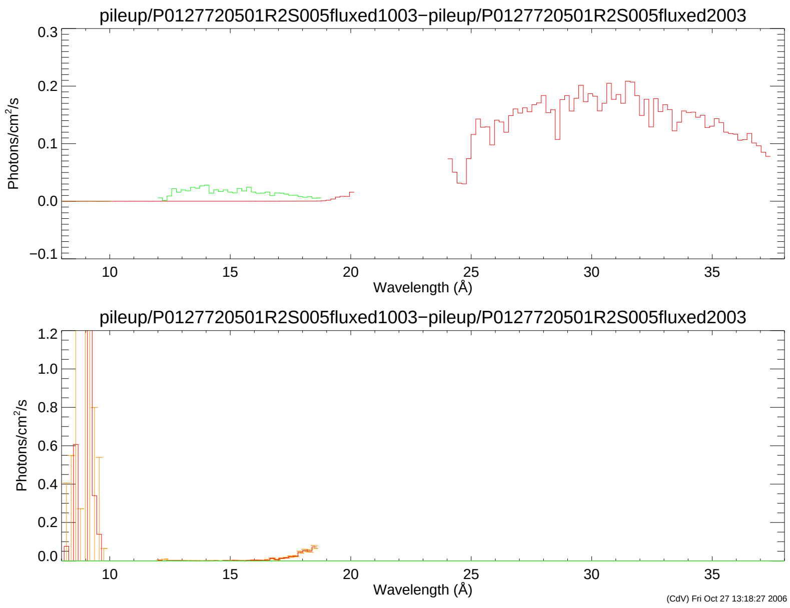

Figure 18: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS2 for V4743Sgr in a high state similar as fig 17

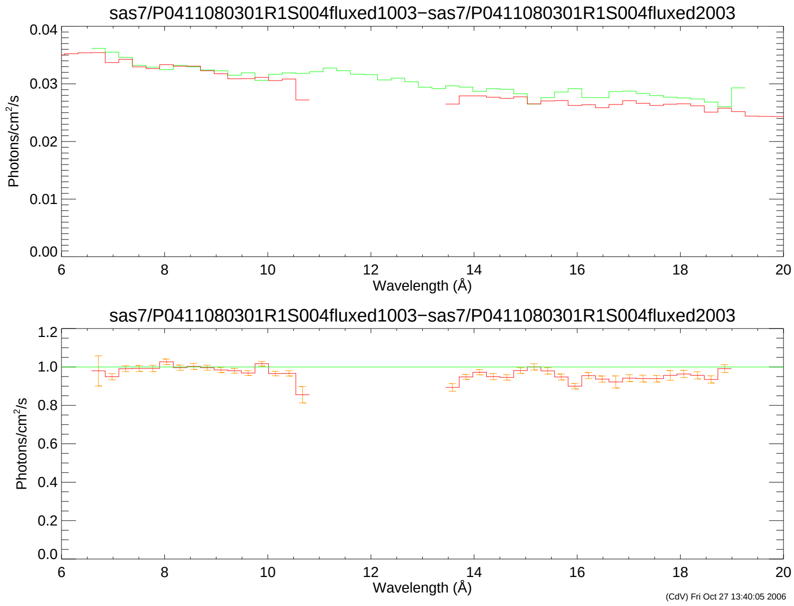

Figure 19: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS1 for Mkn421. The ratio is slightly below 1.0 for wavelengths above 12 Å, indicating some mild pile-up.

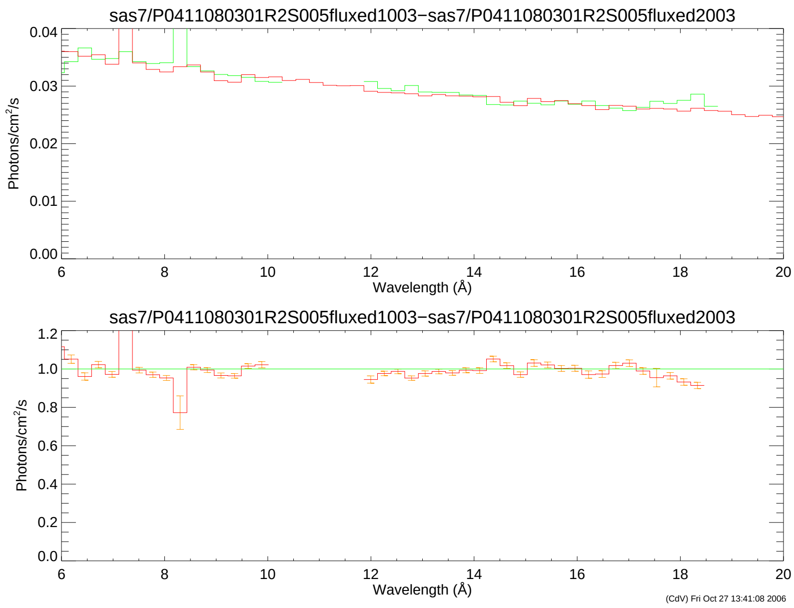

Figure 20: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS2 for Mkn421. Contrary to fig. refc7, the ratio is 1.0, indicating no pile-up for RGS2.

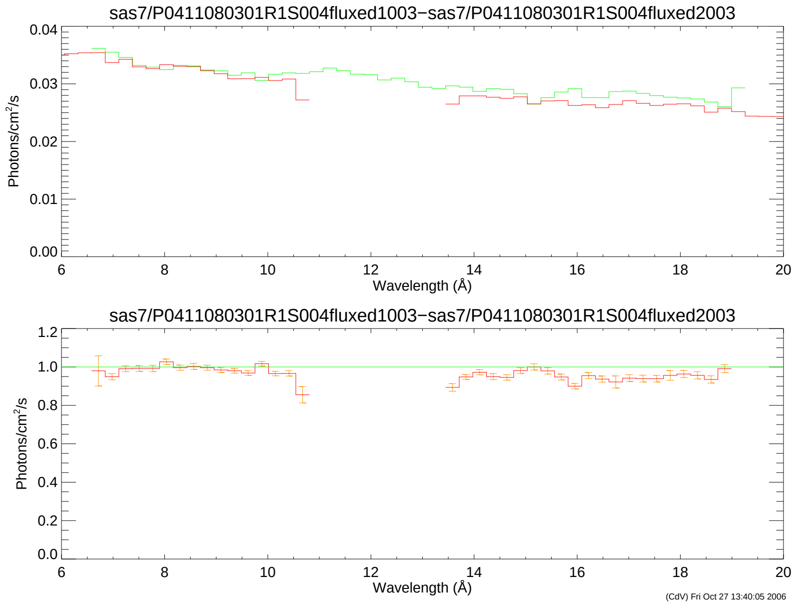

Figure 21: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS1 for PKS2155. The ratio is consistent with 1.0, indicating pile-up is not a factor.

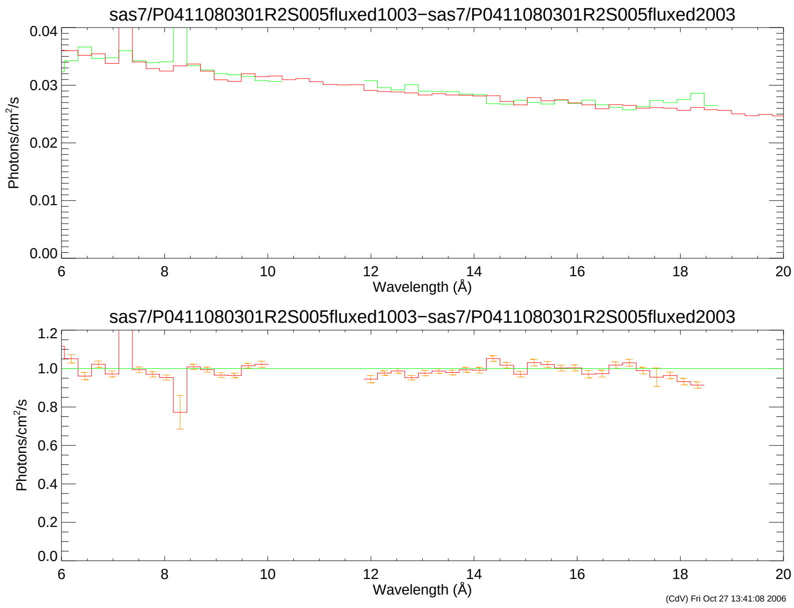

Figure 22: Comparison (top) and ratio (bottom) between 1^{st} (red) and 2^{nd} (green) order of RGS2 for PKS2155. The ratio is consistent with 1.0, indicating pile-up is not a factor.

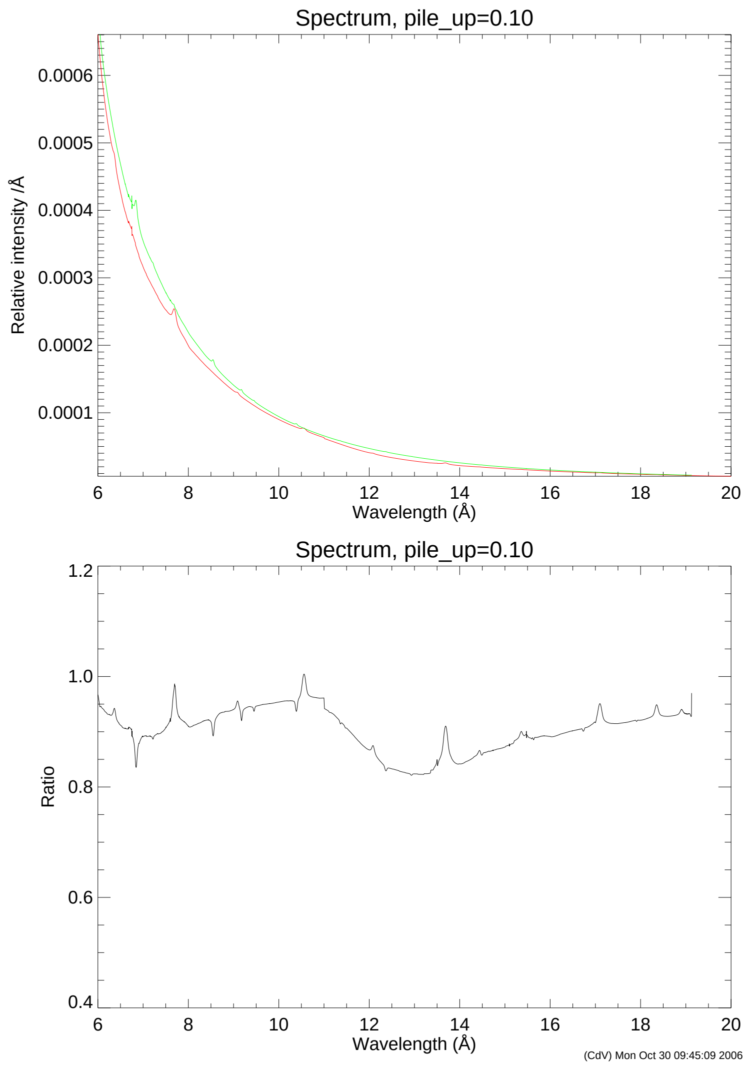

Figure 23: Model calculation of 10% pile-up in RGS1 for a source with a power-law spectrum with index $\gamma = 2.0$. Although the effective area, including the bad pixels/columns has been taken into account, the differences in single photon event patterns between CCD's and locations on CCD's has not been included in the model; all are assumed to be single pixel events. Contrary to the real data, bad columns/pixels in this model spread-out their effect, because for a given wavelength on a bad column there is still some effective area due to the 'line-spread-function' to neighboring columns

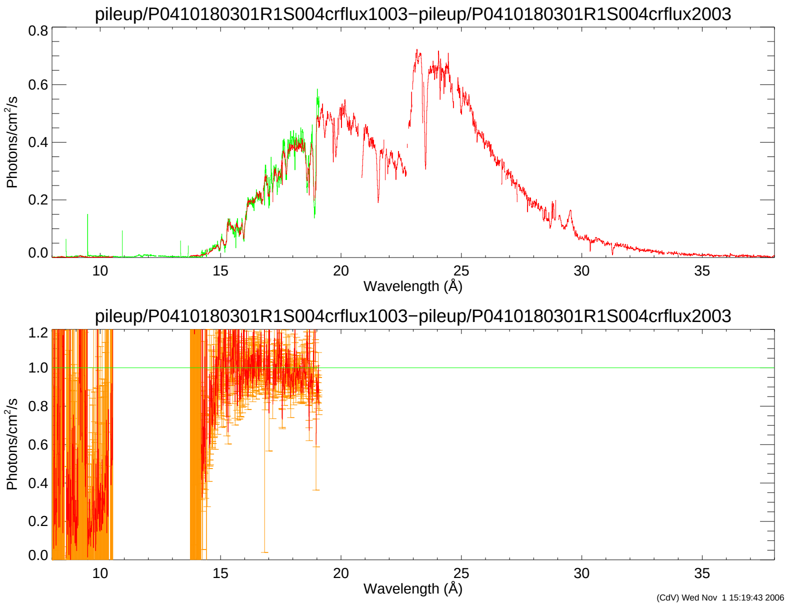

Figure 24: Attempt to correct the piled-up spectrum of RS Oph for pile-up. The corrected 1^{st} order is shown in red and the corrected 2^{nd} order in green in the top plot. Bottom plot shows the ratio between 1^{st} and 2^{nd} order. In fig 15 the uncorrected spectrum is shown. Correction is done by moving (and doubling) the fraction of 2^{nd} order events of which event shapes do not correspond to the 1^{st} order event shape distribution, to 1^{st} order. The procedure seems to perform reasonably.

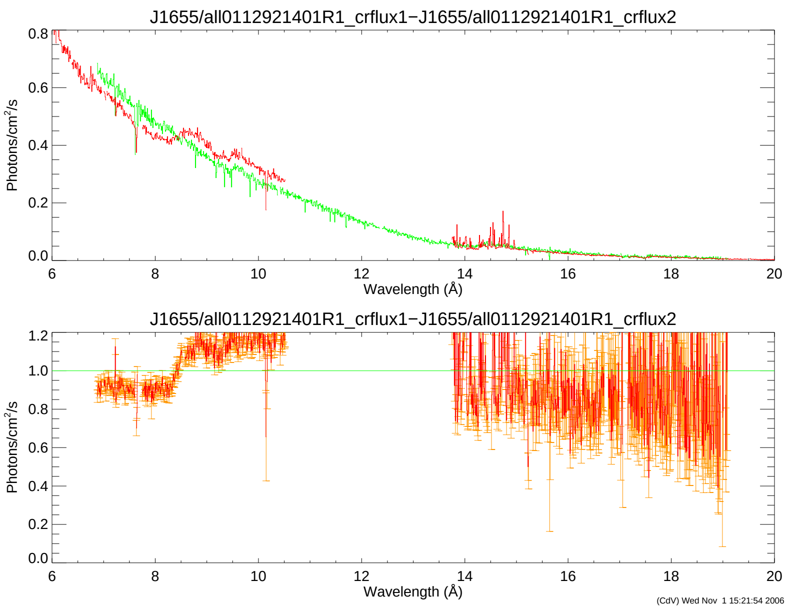

Figure 25: Attempt to correct the piled-up spectrum of J1655 for pile-up. In fig 11 the uncorrected spectrum is shown. Correction is done similar as in fig 24. In this case however, the procedure performs badly.