

XMM-Newton Calibration Technical Note

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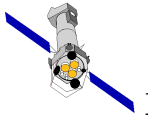
Spectral calibration accuracy in EPIC-pn fast modes

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November 14, 2014

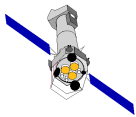
History

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3.0	November 14, 2014	Matteo Guainazzi	Aligned to SASv14
2.1.2	January 16, 2014	Matteo Guainazzi	Editorial revision
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1.6	November 27, 2012	Matteo Guainazzi	Pile-up (§ 6) EPIC-pn versus RXTE/PCA (§ 7)
1.5	April 18, 2012	Matteo Guainazzi	Systematic analysis of Burst Mode data
1.4	January 19, 2012	Matteo Guainazzi	SASv 11.0 & EPIC-pn CTI CCF#45
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1.2	August 18, 2010	Matteo Guainazzi	SASv 10.0 & EPIC-pn CTI #22
1.1	October 6, 2009	Matteo Guainazzi	SASv 9.0 & EPIC-pn CTI #22
1.0	April 6, 2009	Matteo Guainazzi	SASv 8.0 & EPIC-pn CTI CCF#20

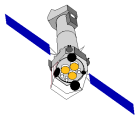


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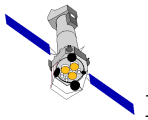


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Configuration summary

Technical Note version	3.0
SAS version	14.0
CCF production date	November 15, 2014
Latest observation date start in the testbed sample	April 30, 2012
Number of sample observations in Timing Mode	252
Number of sample observations in Burst Mode	48
Number of sample observations in Burst Mode pointing to the Crab Nebula	21
EPIC-pn CTI CCF#	CCF#45



1 Scope

This Technical Note (TN) aims at providing a comprehensive summary of the calibration status in EPIC-pn “fast modes” (Burst and Timing Mode). It is based on the analysis of a large source sample. The main goal is to assess the quality of the overall spectral calibration in terms of effective area systematics and accuracy in the energy reconstruction of narrow-band spectral features (primarily emission or absorption lines).

This document is conceived as a “living document”. It will be updated whenever a new SAS version or an update of an EPIC-pn fast mode calibration file affects the results presented in this document. Users interested in this subject are invited to consult regularly the on-line version of this document, available in the XMM-Newton Science Operations Centre (SOC) web page at the following URL:

<http://xmm2.esac.esa.int/docs/documents/CAL-TN-0083.pdf>.

Users’ feedback, comments and suggestions are more than welcome. XMM-Newton users are invited to convey them through the XMM-Newton SOC Help Desk:

http://xmm.esac.esa.int/external/xmm_user_support/helpdesk.shtml.

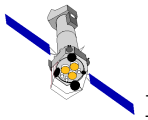
2 Calibration sample and Data Reduction

Unless otherwise specified (see, *e.g.*, Sect. 7), the parent calibration sample discussed in this TN includes - save errors and omissions - all the observations with at least one EPIC-pn exposure in a fast mode, which were available as of April 30, 2012 (April 18, 2009 for Burst Mode). It is planned to expand the sample on a regular basis. The sample includes 252 exposures in Timing and 48 exposures in Burst Mode, respectively. We stress that out of the 48 exposures in Burst Mode discussed in this document, 21 pointed to the sky region where the Crab Nebula is located.

On the Timing Mode parent sample, two further selection criteria have been applied: a) we removed intrinsically variable sources (at a level larger than 3 times the average count rate standard deviation). This leaves 100 out of the original 252 exposures; b) for the calibration of the RDCTI only, we restricted the sample to those sources, whose 1.5–3 keV spectrum is featureless. 49 sources fulfill this criterion. We do not use for calibration purposes any sources affected by pile-up. We exclude also the EPIC-pn exposures of the Crab Nebula, as Timing Mode is not optimised for spectroscopic observations of sources with this level of brightness even if moderately extended (Kirsch et al. 2006, Weisskopf et al. 2010).

Data were reduced using the public SAS (Gabriel et al. 2003) version 14.0. Data reduction was performed with the standard SAS task `epchain`. In the case of the Crab observations in Burst Mode, the optional parameter `withsrccords` was used in conjunction with the SIMBAD coordinates of the Crab pulsar (parameters: `srcra`=83.633208 and `srcdec`=22.014194; Kirsch et al. 2005).

Source spectra for Timing Mode exposures were extracted from 18 pixels-wide intervals in `RAWX`. They were centred on the `RAWX` column having the largest count rate, to ensure centring the spectrum accumulation region around the boresight position. Background spectra were extracted from ranges



centred around `RAWX=4` and with a width of 2 pixels. Similar criteria were followed to extract spectra from exposures in Burst Mode. In this mode, however, spectral extraction needs to be limited to `RAWY<180`, to avoid events severely affected by pile-up as accumulated from the wings of the Point Spread Function during the slow phase of a Burst cycle readout (Kirsch et al. 2006). Spectra were accumulated using single and double events (`PATTERN <= 4`), as the readout pattern in Timing Mode hampers the accurate calibration of single and double event patterns fractions separately. Response files for each individual spectrum were generated with the `arfgen` and `rmfgen` tasks.

Spectra were rebinned to ensure that the instrumental energy resolution is sampled by a factor not larger than three, and that each spectral channel contains at least 50 background-subtracted counts. These criteria ensure that the χ^2 goodness-of-fit test can be used. We use the band 0.6–10 keV for spectral fitting, unless otherwise specified. This choice - which excludes the softest few hundreds electron-Volts with respect to the typically well calibrated energy band-passes in EPIC-pn imaging modes - is justified by the need of avoiding high electronic noise in the double events spectrum peaking at $\simeq 400$ eV. Statistical errors on best-fit parameters in this document are at the 90% confidence level for one interesting parameter.

3 Energy scale

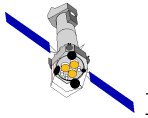
The energy scale in EPIC-pn fast modes is calculated through three corrections, performed by the SAS in the following temporal order:

- the X-Ray Loading (XRL) correction
- the “special gain correction”
- count-rate dependent corrections to the energy scale: the Rate-Dependent PHA correction (RDPHA), and the Rate-Dependent CTI correction (RDCTI) for Timing and Burst Mode, respectively

3.1 X-ray loading

Independent studies carried out during the first half of 2010 led to the unexpected discovery that most of the EPIC-pn exposures in fast modes are affected by **X-ray Loading** (XRL). Before each EPIC-pn exposure, an “offset map” is calculated registering the electron current flowing through the CCD in absence of an astrophysical signal. This current level is subtracted by the on-board processor from the energy scale of each individual event. As “offset maps” were calculated using the same filter as the following science observation¹, the accuracy of this calculation requires that the astrophysical sources in the field-of-view do not contaminate the map. If this does not occur (*i.e.*, if the source *does* contaminate the offset map), the data are affected by XRL. Readers are referred to Smith (2004) for a detailed description of XRL and of its spectral effects.

¹This changed after the public release of SASv12 on the 23rd of May 2012. Offset maps are now being calculated in `CLOSED` filter, thus removing any possible contamination from celestial sources in the field of view.



XRL depends primarily on the overall count rate of the celestial sources in the field of view, and, to a lesser degree, on their hardness. The count rate threshold above which XRL was expected to occur was estimated before launch to be of the same order as the pile-up threshold. However, most EPIC-pn Timing *and* Burst Mode are affected by XRL (Fig. 1, and Fig. 2). XRL exhibits a

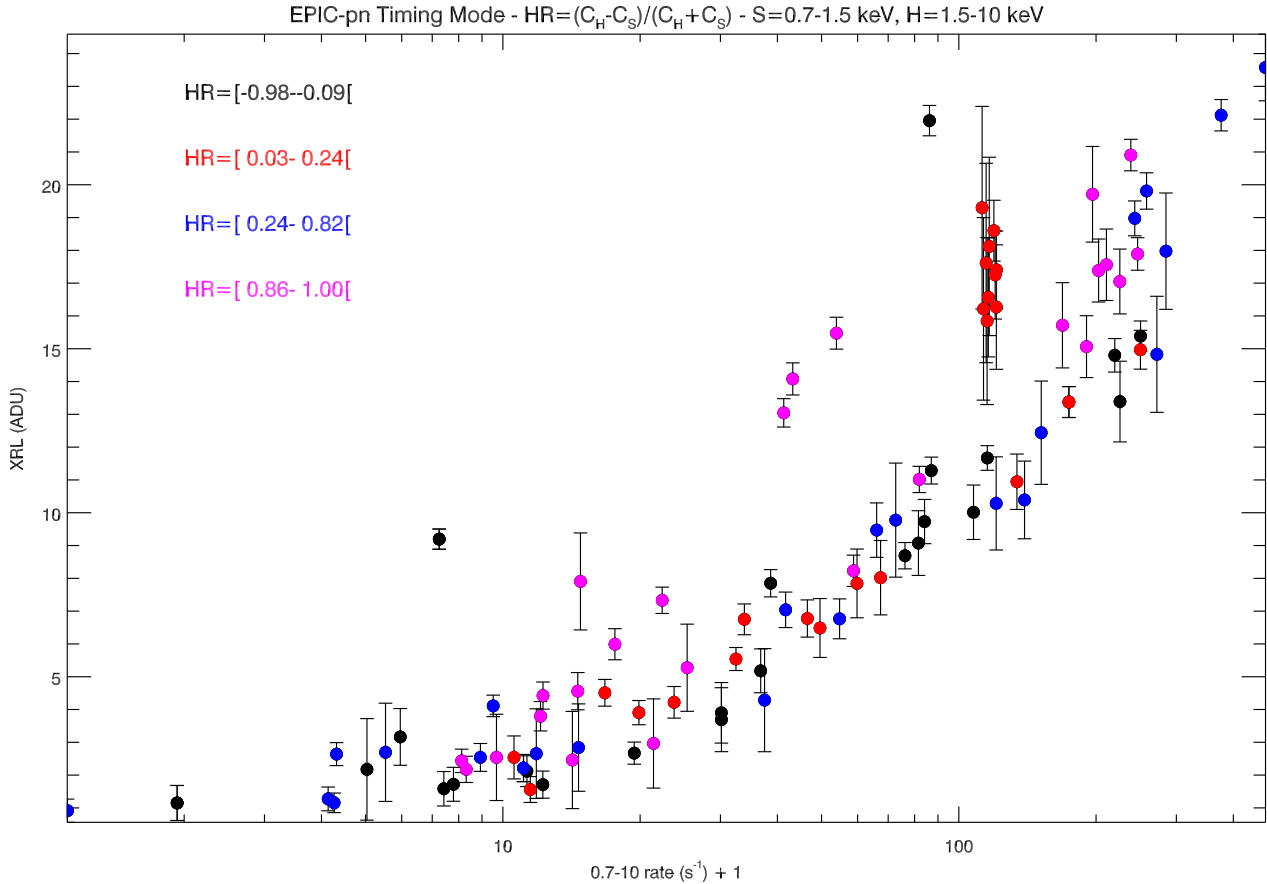


Figure 1: XRL (in ADU units; 1 ADU = 5 eV) as a function of the 0.7–10 keV count rate in the boresight column for a sample of 100 exposures taken in EPIC-pn Timing Mode. Colours identify the quartiles of the hardness ratio distribution: $HR=(C_H-C_S)/(C_H+C_S)$, where C_H and C_S are the counts in the 1.5–10 keV and 0.7–1.5 keV energy ranges, respectively.

strong correlation with count rate, as expected. At equal count rates, harder sources tend to exhibit a higher XRL, although this effect is not statistically significant. The reason for the apparent “turnover” in the XRL versus count rate relation for Burst Mode is currently unknown. It is equally unknown why XRL is so ubiquitous.

As of August 2013, a spectral correction for XRL in EPIC-pn Timing Mode is available (Guainazzi & Smith 2013). The correction is applied by the SAS task `epreject`. It must be invoked in *e.g.* `epchain` through the input parameters `runepreject=Y` and `withxrlcorrection=Y`, or through the `withdefaultcal=Y` parameter in `epproc/epchain`. Its coefficients (corresponding to a simple linear effect: $\Delta PHA \propto XRL$) are embedded in the XRL2PHA extension of the EPIC-pn REJECT CCF.

This XRL correction does not apply to EPIC-pn Burst Mode exposures. It is currently foreseen

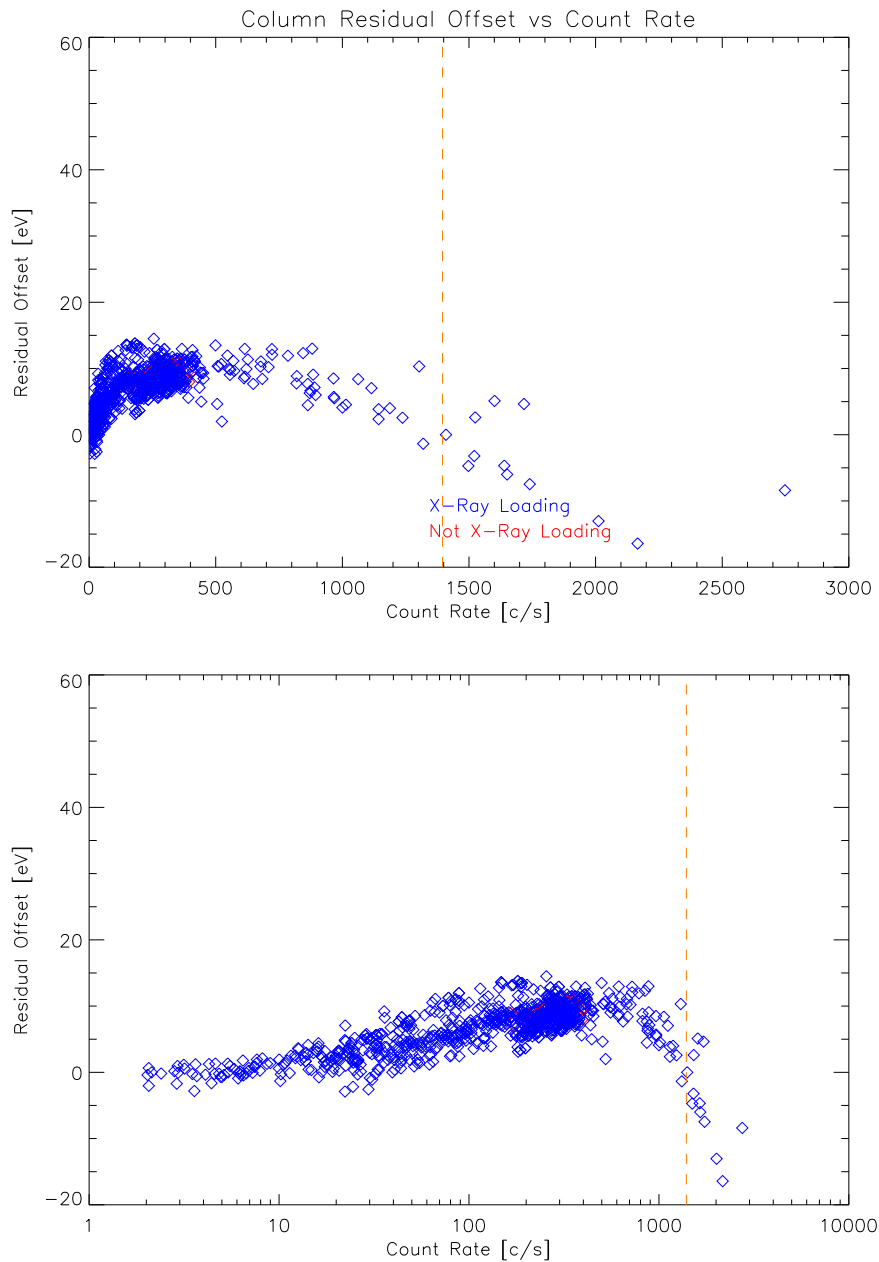
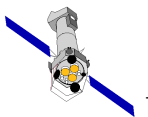
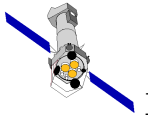


Figure 2: The same as Fig. 1 for EPIC-pn Burst Mode. The *upper* and the *lower* panels contain the same data points, plotted on a linear and logarithmic x-axis scale, respectively. The *dashed line* indicate the nominal pre-launch XRL threshold.

to extend the XRL correction to Burst Mode during 2014, subject to the availability of sufficient resources at the XMM-Newton Science Operations Centre calibration team.



3.2 The special “gain correction”

Early in the mission, a mode-dependent correction to the instrumental gain as determined in Full Frame was calibrated based on on-flight measurements of the Crab Nebula and of N132D (Kirsch 2005; Freyberg et al. 2005). This correction is applied through the parameters `withgaintiming=yes` and `withgainburst=yes` (default in the SAS) for Timing and Burst Mode, respectively.

3.3 The rate-dependent energy scale corrections

3.3.1 RDCTI (Burst Mode)

Sala et al. (2008) presented the first experimental evidence of a dependency of the accuracy of the energy scale on the source count rate in EPIC-pn Burst Mode. This led to the definition of the RDCTI correction.

The correction is formally expressed as a linear “gain” factor, G_{corr} ($\equiv E_{original}/E_{corrected}$):

$$G_{corr} = a_0 * N_e^{a_1} + a_2$$

where N_e is the number of shifted electrons per pixel per second, and the a_i are numerical coefficients.

The a_i coefficients have been calibrated according to the following procedure:

- a sample of 36 exposures in EPIC-pn Burst Mode and 49 exposures in EPIC-pn Timing Mode were selected according to the criteria discussed in § 2.
- for each of the sample sources, four spectra (with single+doubles pixel events) have been extracted from each of the four columns surrounding the boresight column (this one included). For each spectrum a redistribution matrix and an effective area file were generated with SAS. In principle this procedure is not entirely self-consistent, because the instrument response calculated by SAS assumes a pattern distribution calibrated across the whole Point Spread Function (PSF), which may differ from that corresponding to each column. Fig. 3 shows that this effect is unlikely to have an important impact.
- each spectrum was fit in the 1.5–3 keV energy band with a simple continuum model: power-law+black body corrected for photoelectric absorption. A constant gain shift G_{corr} was applied to the spectral model (through the `gain fit` function in XSPEC) and calculated for each spectrum under the condition to minimise the χ^2
- for each spectrum, the number of equivalent shifted electrons N_e was calculated, according to the following formula:

$$N_e = \frac{\sum_{i=1}^{N_p} E_i}{N_{pixels} \times T_{exp} \times 3.6}$$

where E_i is the energy of the i -th photon, N_{pixels} is the number of pixels of the column whence each spectrum was extracted, N_p is the number of detected photons, T_{exp} is the exposure time and the factor 3.6 (in eV) represents the energy required to produce an electron-hole pair.

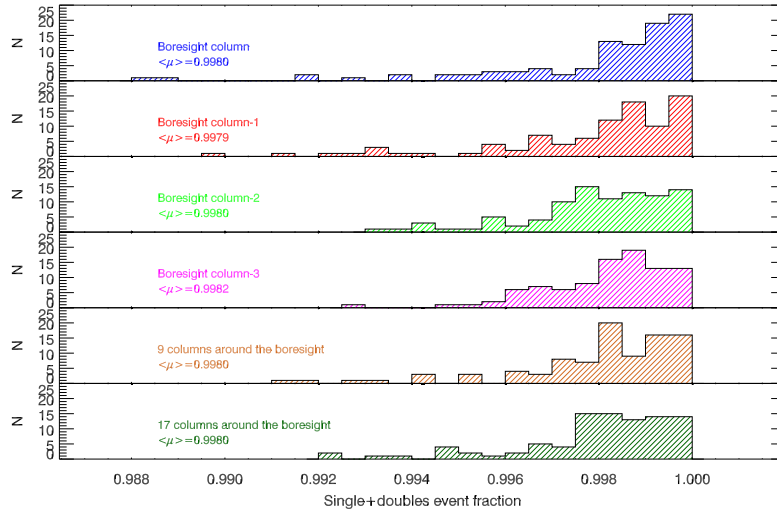
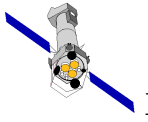


Figure 3: Distribution of single+oubles pixel events fraction in the test sample of Timing Mode observations for spectra extracted from the boresight column, three nearby columns, and the 9 and 17 columns around the boresight. The *labels* indicate the region from which the pattern distribution was extracted, as well as the mean of the distribution.

- The relation between G_{corr} and N_e was fit with the functional form: $a_0 * N_e^{a_1} + a_2$. The extension RATE_DEPENDENT_CTI in the EPIC-pn CTI CCF constituents contains the a_i coefficients

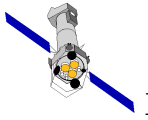
The RDCTI is applied through the parameter `runepfast=yes` in `epproc/epchain` (default as of SASv14.0). It is no longer recommended to run the underlying task SAS `epfast` as a standalone, as it used to be customary with previous SAS versions. The parameter `withdefaultcal` in `epproc/epchain` runs the XRL and associated RDCTI correction with the appropriate calibrations.

3.3.2 To RDCTI or not to RDCTI?

Recently, Walton et al. (2012) suggested that *not applying* the RDCTI correction in Burst Mode yields a more accurate energy reconstruction in the 6–7 keV energy range than applying it. This would be due to the fact that the energy-dependence of the RDCTI assumes that it behaves like a gain correction, as opposed to a true CTI effect.

Admittedly, the underlying cause for the observed rate-dependence of the energy scale is not entirely understood. If due to a true CTI effect, we estimate that the systematic error induced by the implemented energy-dependence when compared to that expected by the CTI in EPIC-pn is lower than 10 eV.

From the observational point of view, the RDCTI is currently the best way available to XMM-Newton users to correct for rate-dependent effects on the energy scale. Users are *warmly rec-*



ommended to use it in their data analysis. As shown in Sect. 3.3.2, failing doing so can yield a substantial underestimate of the energy scale in the iron line regime. Another example is shown in Fig. 4, where the EPIC-pn spectrum of the SNR Cas A is shown as observed in FF, Timing, and

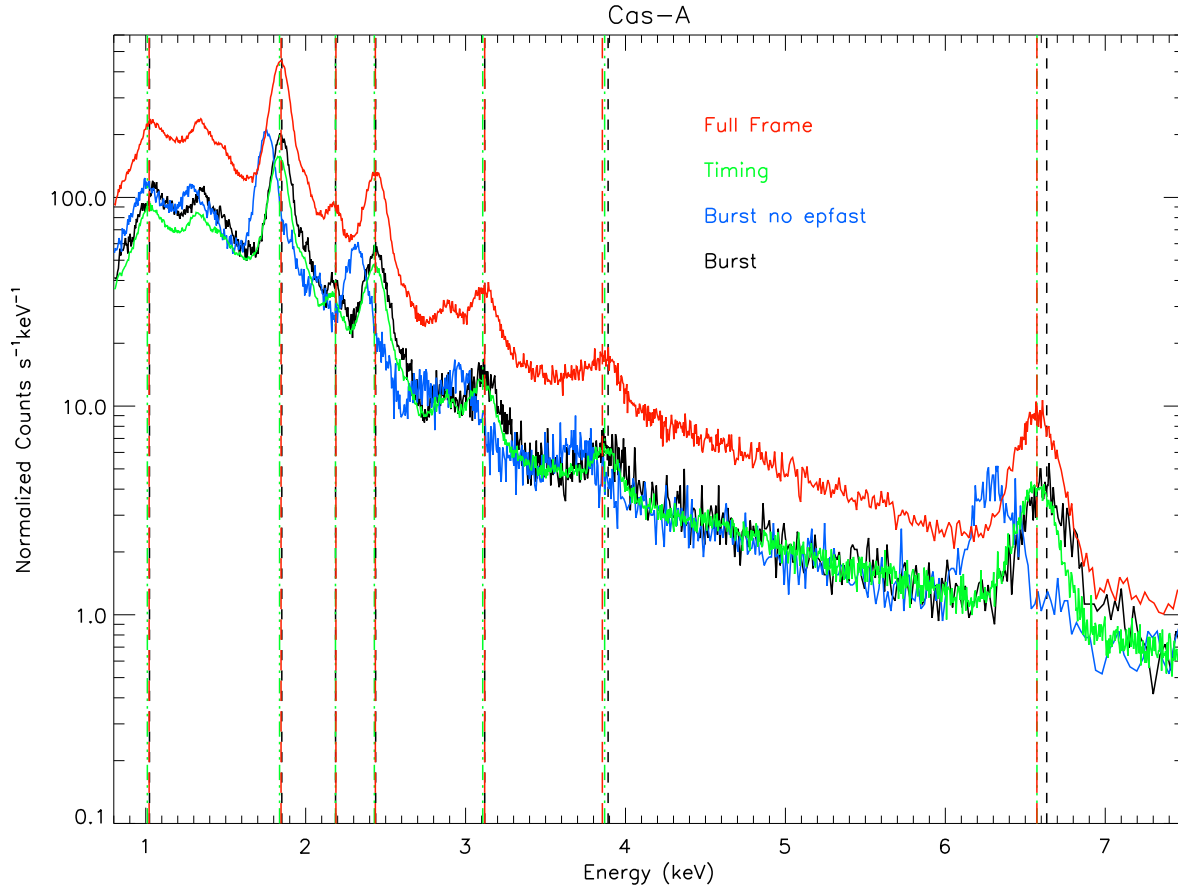


Figure 4: Full Frame, Burst (with and without RDCTI correction) and Timing mode spectra of Cas-A. The spectrum in Full Frame mode has been multiplied by 2 for clarity.

Burst Mode. While an accurate energy reconstruction for this source in Fast Modes is problematic due to its extreme extension ($\simeq 5'$, *i.e.* larger than the aperture), it is apparent that not applying the RDCTI correction on the Burst Mode spectrum yields a shift against the best-fit centroid energy measured in the other modes of $\simeq 300$ eV, much larger than when the RDCTI correction is applied. Comparing spectra with and without applying the RDCTI correction, as well as applying a **gain fit** to the spectrum (with slope fixed to 1 and variable offset) may help users to estimate the systematic uncertainties of the energy scale².

A recalibration of the Burst Mode RDCTI following the calibration of the XRL is ongoing. It is expect to be completed in the first half of 2015.

²While using the **gain fit** function in XSPEC is in principle incorrect, because it modifies the energy scale of the responses, we proved that systematic uncertainties estimated by using it are consistent with those obtained by modifying the PI column in the event list.

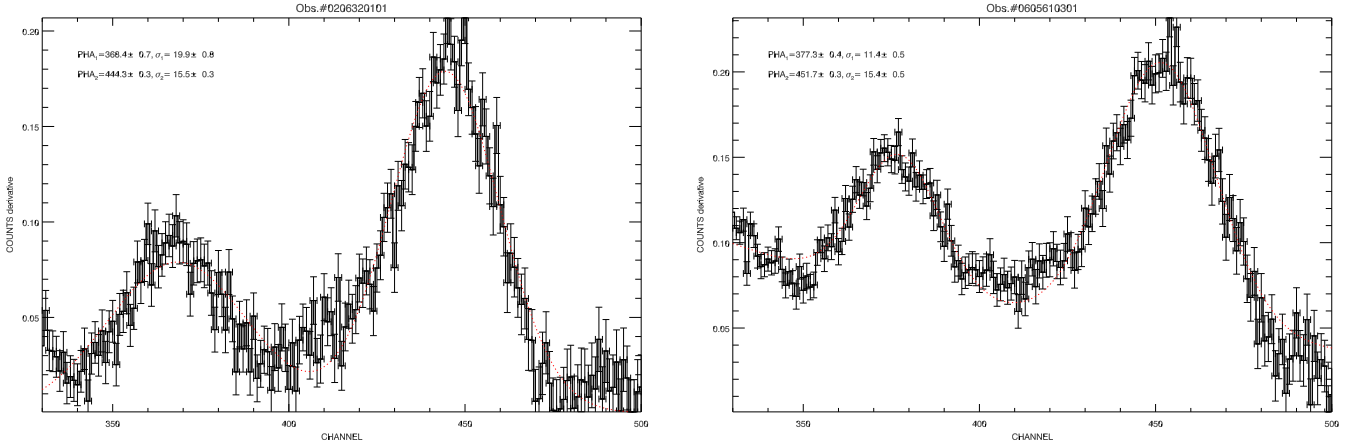
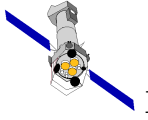


Figure 5: Examples of derivative PHA spectra. The *red dashed* line indicates the best-fit.

3.3.3 RDPHA (Timing Mode)

The rationale of the RDPHA correction relies on the fact that the strongest gradients in an EPIC-pn effective area occur at the location of the Si ($\simeq 1.8$ keV) and Au ($\simeq 2.2$ keV) edges. The exact position of these edges is a sensitive measurement of the energy scale. However, a direct fit of the edges in the PHA spectra is uncertain, and leads to inaccurate measurements due to the resolution of the EPIC-pn cameras. The situation changes radically if one works on the derivative of the spectrum in PHA space, δ , defined as:

$$\delta(PHA, \Delta PHA) \equiv \frac{|C_i(PHA) - C_i(PHA + \Delta PHA)|}{C_i(PHA) + C_i(PHA + \Delta PHA)}$$

Two examples of PHA spectral derivative around the instrumental edges are shown in Fig. 5. The two peaks can be robustly fit with a simple phenomenological model constituted by a power-law and two Gaussian profiles. The public calibration data is based on fitting the best-fit peak PHA values as a function of the rate of shifted electrons N_e :

$$PHA = A_1 \quad \text{for } N_e \leq N_e^{th}$$

$$PHA = A_2 + A_3 \times \log(N_e) \quad \text{for } N_e > N_e^{th}$$

whose fit parameters are A_1 , A_3 and N_e^{th} , and A_2 is determined by the condition of continuity at N_e^{th} . Data points corresponding to the Si and Au edges were fit independently (Fig. 6; Guainazzi 2013a). The CCF contains the values $\Delta PHA \equiv PHA(N_e) - PHA(0)$. The SAS combines the fit results at the Si and Au edges to determine the correction for each observation, weighting them by the statistical errors propagated from the uncertainties on the fit parameters. An energy-dependent calibration based on measurements in the 6 keV regime is discussed in Guainazzi (2013b). This calibration, in tabular form, is embedded in EPN_CTI_0032.CCF and subsequent versions.

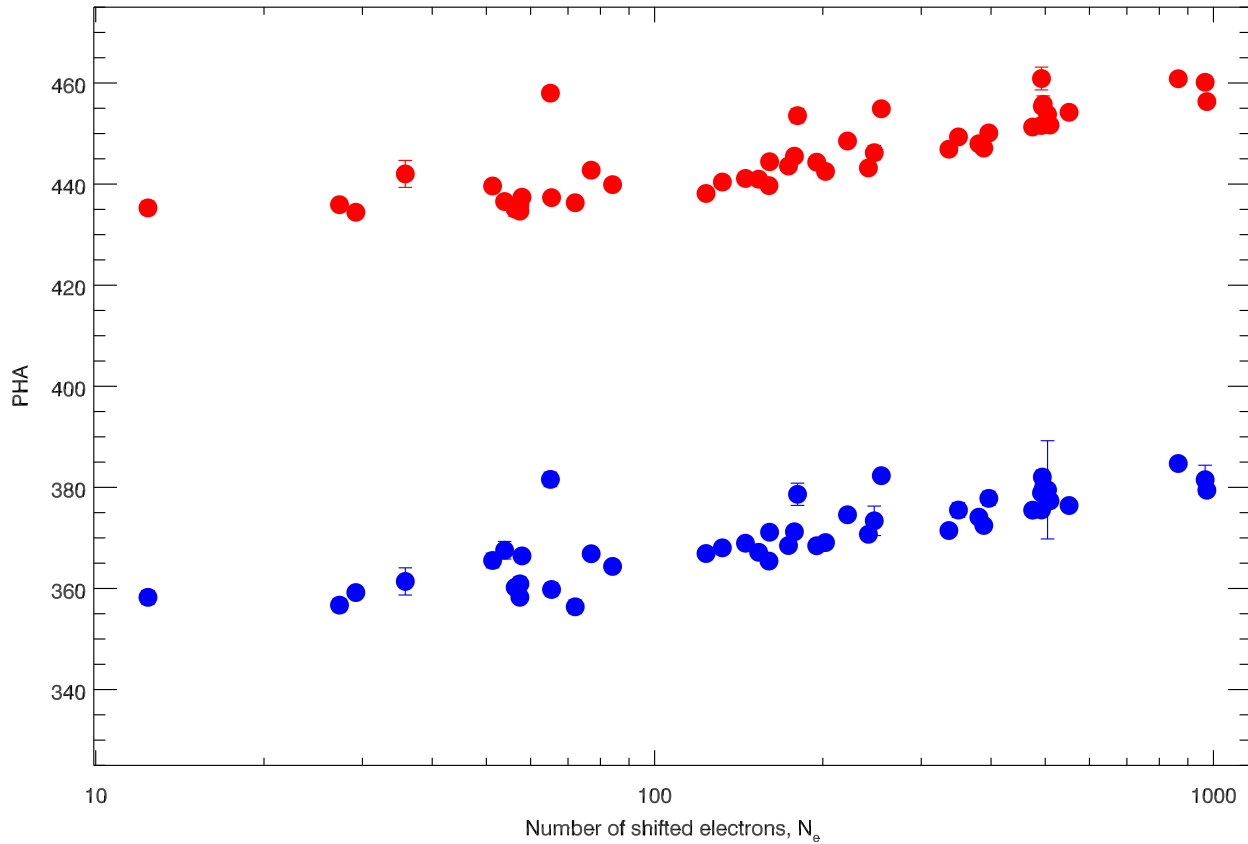
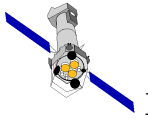


Figure 6: Calibration of the RDPHA correction at the Si (*red*) and Au (*blue*) edges.

3.4 Quality of the energy scale reconstruction

3.4.1 Timing Mode

Fig. 7 shows an histogram of the difference δE between the measured and modelled ΔPHA for the objects used for the calibration of the RDPHA (cf. Fig. 8).³ The standard deviation is $\simeq 20$ eV at both the Si and the Au energies. The slightly larger-than-zero median of the distribution is consistent with the typical systematic uncertainties of the EPIC-pn gain during an observation.

While the calibration at the Si and Au edges made use of a large number of well-exposed spectra, the scientific validation at higher and lower energies is limited by the small number of sources where independent observables of the energy scales are available. This is particularly crucial around 6 keV.

A first assessment of the quality of the energy reconstruction at the energies of Fe fluorescence and recombination transitions was made using four observations of celestial sources, exhibiting

³We use here the standard conversion factor between energy and PHA channel: 1 ADU = 5 eV. However, users shall remember that the RDPHA correction is calibrated in PHA space. The abscissa scale in the histograms in Fig. 8 is therefore only approximate, because it does not take into account gain non-linearity and/or redistribution effects.

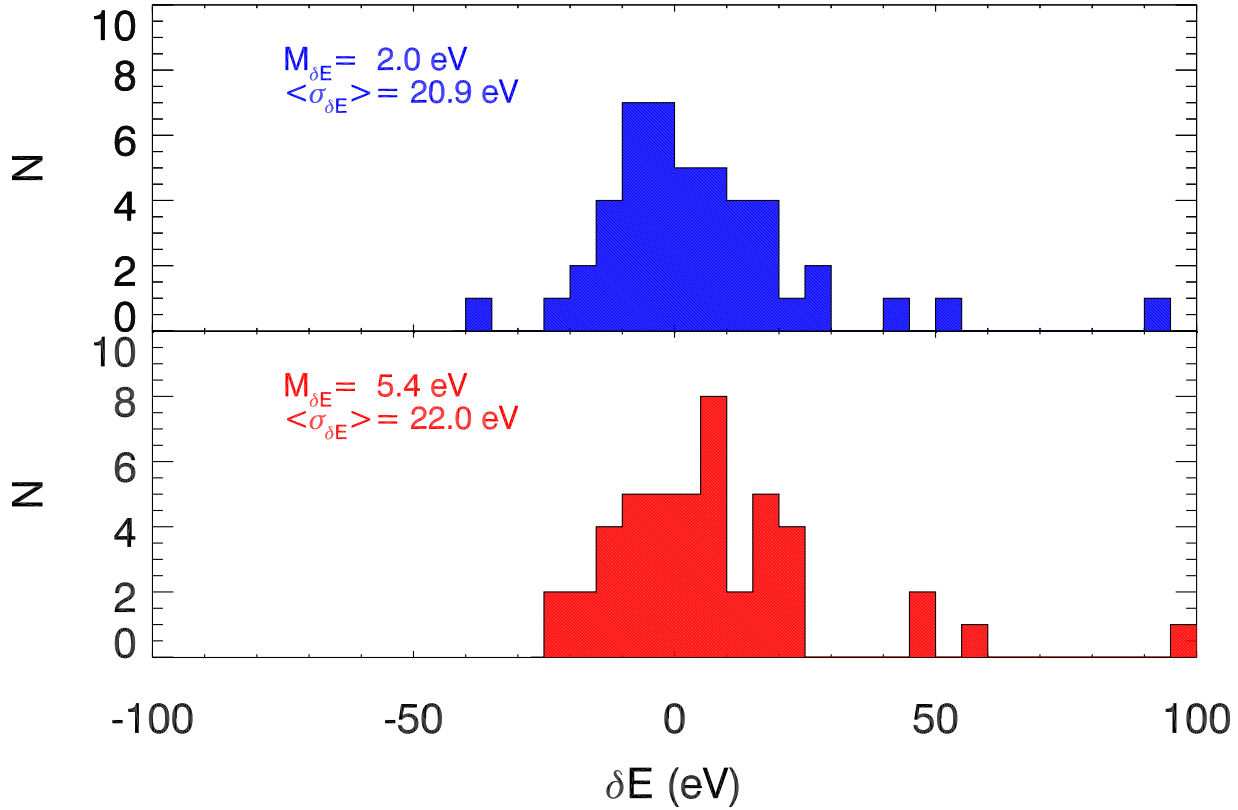
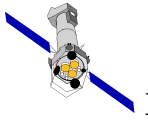
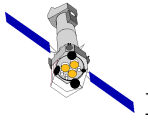


Figure 7: Distribution of the energy scale accuracy (in eV) at the energies of the Si (*upper panel*) and Au (*lower panel*) edges, following the application of the RDPHA correction to the sample used for the correction global calibration.

prominent narrow-band features above 6 keV. The energy scale yielded by the RDPHA is consistent with the atomic physics predictions for observations corresponding to $N_e \leq 100$: XB 1323-619 (Obs.#0036140201), 4U1915-05 (Obs.#0085290301), RS Oph (Obs.#0410180101). The performances were worse for the source with the highest count rate, GX13+1 (Obs.#0122340901). This bright (net count rate in the 0.7–10 keV energy band ≥ 400 s $^{-1}$) source exhibits prominent absorption lines due to resonant transitions of highly ionised iron. I discuss this discrepant case in more details in the next paragraph

Calibrated event lists were reduced applying the XRL correction only, whence the spectra shown in Fig. 24 were extracted. I extracted four spectra corresponding to the boresight column, and to three adjacent columns (“off-axis columns” hereafter). The spectra were fit simultaneously with the same astrophysical model, constituted by a standard X-ray binary continuum (multicolour disk black-body plus power-law), and two absorption lines corresponding to resonant absorption by FeXXV, and FeXXVI, plus three additional absorption lines at higher energies, on whose nature no assumption was made, and whose centroid energies was left free to vary (the best-fit values are



$\simeq 7.8$, 8.2^4 , and 9.5 keV, respectively). The RDPHA calibrated at the Si and Au instrumental edges over-corrects the energy scale at the Fe line energies by $\simeq 20$ eV for the 3 off-axis spectra. The error is larger for the boresight spectrum, suggesting a possible flattening of the RDPHA at high count rates.

3.4.2 Burst Mode

Fig. 8 shows the maximum data/model ratio, when the model used to determine the a_i coefficient

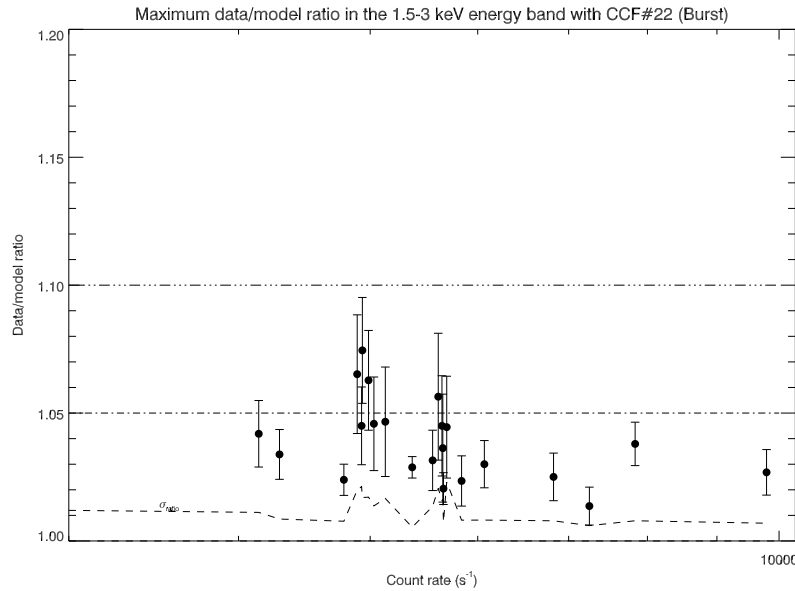


Figure 8: Maximum value of the data/model ratio module (*filled dots*) resulting from the application of the phenomenological model used to calculate the coefficients of the rate-dependent CTI correction (a linear combination of power-law and blackbody modified by photoelectric absorption with all parameters left free to vary) to the test sample of spectra in Burst (*right panel*) Mode as a function of 0.6–10 keV count rate. The *dashed lines* indicate the standard deviation of the data/model ratio distribution. We show only sources with a count rate large enough, that the data/model ratio distribution is not dominated by statistical scatter.

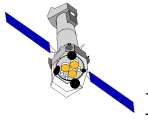
of the rate-dependent CTI correction is employed to fit RDCTI-corrected data in the 1.5–3.0 keV energy range as a function of the source count rate (CR) in the 0.6–10 keV band. Only sources with $CR > 4000 \text{ s}^{-1}$ are shown,⁵ because for lower count rates the data points are dominated by statistical scatter⁶. In all cases with good statistics the maximum data/model ratio (R) is $< 5\%$. This demonstrates that the rate-dependent CTI average correction works well in all individual cases.

Unfortunately only a few sources observed in Burst Mode exhibit strong unresolved atomic transitions, which can significantly constrain the accuracy of the energy scale calibration. Users are referred to Guainazzi (2009) for a discussion on the results of the observation of the Galactic Black

⁴Díaz-Trigo et al. 2012 identify these two lines as FeXXV and FeXXVI K_β

⁵Count rates are corrected for the Burst Mode 97% dead time

⁶We have removed from the analysis off-axis Crab observations: Obs#0312790201, 0312790401, 0160960401, 0160960601



Hole Candidate GROJ1655-40: in a nutshell, after the application of the RDCTI correction, the energy scale around 7 keV is slightly over-corrected ($\Delta E \equiv E_{obs} - E_{ast} \geq 5$ eV, where E_{ast} is the blue-shifted laboratory energy) with respect to the non RDCTI-corrected spectrum ($\Delta E \leq -40$ eV; Fig. 9). Here we focus on another example: 4U 1700-37.

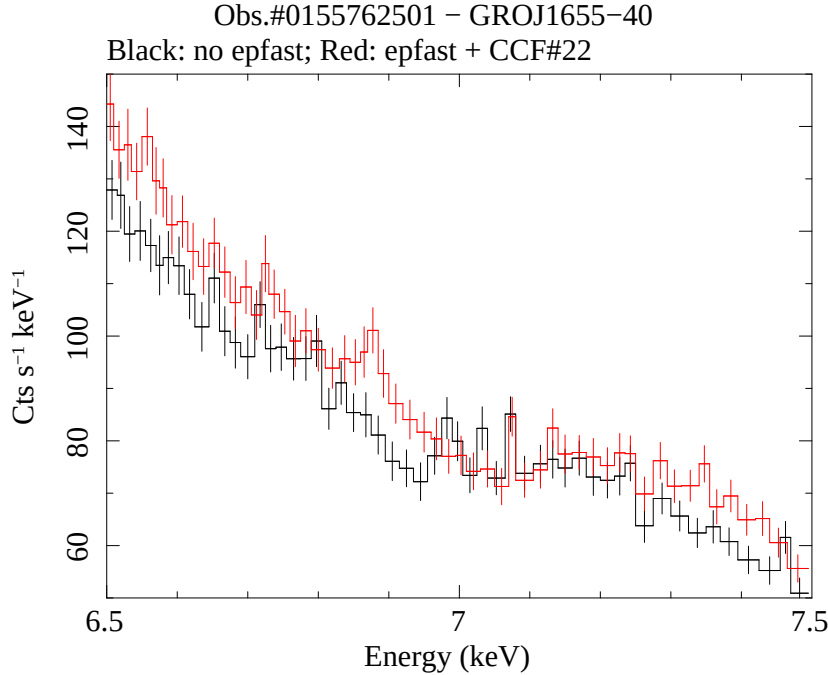


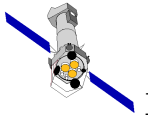
Figure 9: Count spectrum of GROJ1655-40 (Obs.#0155762501) around the Fe xxvi resonant absorption feature. The *red histogram* is the spectrum extracted with EPIC-pn CTI CCF#45, the first one which allows the application of the rate-dependent CTI; the *black histogram* is the spectrum extracted from an event list to which the RDCTI was not applied. Astrophysical considerations suggest that the most likely energy range for this feature is 6.969–6.983 keV.

4U 1700-37 is an eclipsing High Mass X-ray binary in a 3.41-day orbit that has been observed by XMM-Newton in February 2001, covering the full orbital period. The EPIC-pn camera was operating in Burst mode, with the Thick filter. Tab. 1 gives the Obs.#, the Rev.#, the date and the weighted life time of the CCD in the extraction region for the four observations.

Table 1: EPIC-pn Burst Mode spectra of 4U 1700-37.

OBS ID	Rev.	Date	Exp.(s)
0083280101	219	17 February 2001	727
0083280201	219	18 February 2001	952
0083280301	220	19 February 2001	584
0083280401	220	20 February 2001	904

Data were reduced using the SAS version 11.0.0 using the public calibration files and the standard task `epproc`. The event lists were also RDCTI-corrected. Spectra were extracted, with `FLAG=0` and by selecting only single and double events (`PATTERN<=4`). We limited `RAWY<=140` and a background



was extracted in the region `RAWX=[2,8]`. Response files were generated with `arfgen` and `rmfgen`. No proton flares were present in any of the data-set.

Spectra were extracted in the 0.3-10 keV energy band⁷, and rebinned to ensure at least 25 counts per bin. Spectral fitting was performed on spectra extracted over 9 columns centred on the boresight position.

Spectra were analysed using `XSPEC` version 12.7.0. Fig. 10 shows the spectra of the 4 EPIC-pn observations performed at different orbital phases and flaring states. Obs.#0083280401 was taken

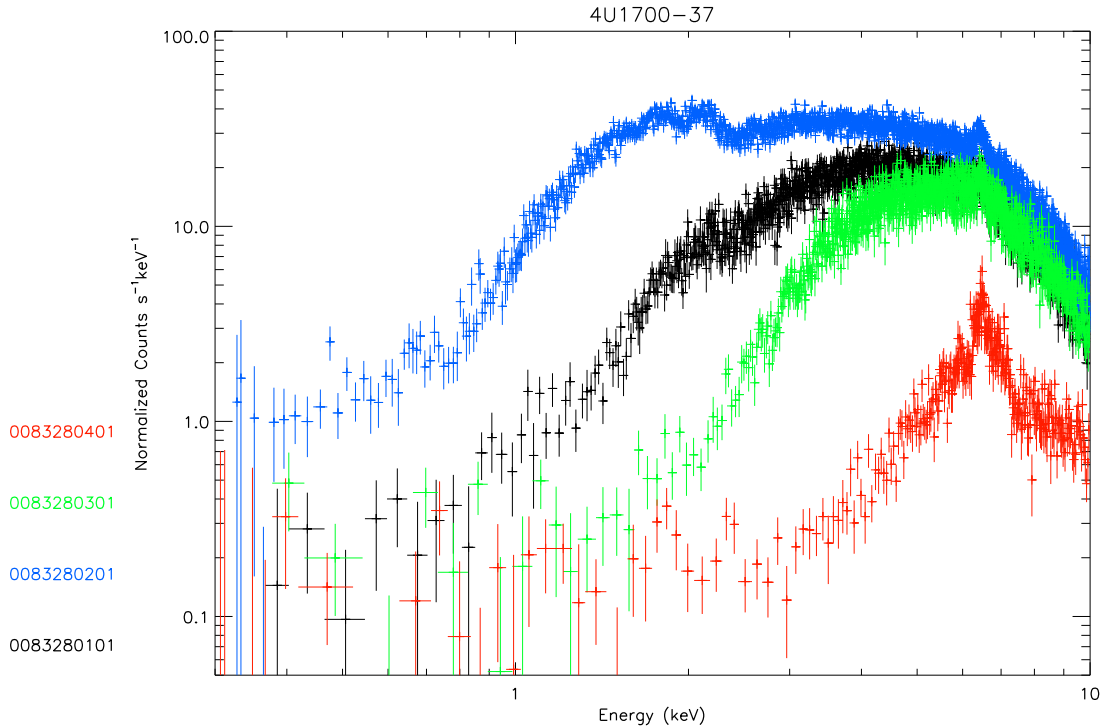


Figure 10: EPIC-pn spectra of the 4 observations.

during the X-ray source eclipse and egress. The continuum over the full spectral range can be modelled with an absorbed power-law or disk blackbody, leaving some soft excess.

Fig. 11 shows the residuals, expressed in units of standard deviations, in the 5.0-8.0 keV energy band for a `phabs*diskbb` fit. A strong Fe K_{α} line is visible in all spectra. The upper plots show the residuals when the RDCTI correction is applied, and the lower plots when the correction is not applied. The lines are clearly shifted to lower values in the latter case.

The iron line was fitted with a Gaussian profile. Fig. 12 shows the energies of the Gaussian lines for the four EPIC-pn observations and the 90% confidence level interval, for events with corrections with the RDCTI (*left*) and without (*right*). In the first case, the energy of the lines varies from 6.43 to 6.45 keV, above the measured 6.40 keV reported by Boroson et al. (2003) for the Chandra observations and the [6.40-6.42] keV reported by van der Meer et al. (2005) for the EPIC MOS-2

⁷The usage of this slightly non-standard energy bandpass is justified by the highly obscured nature of the source.

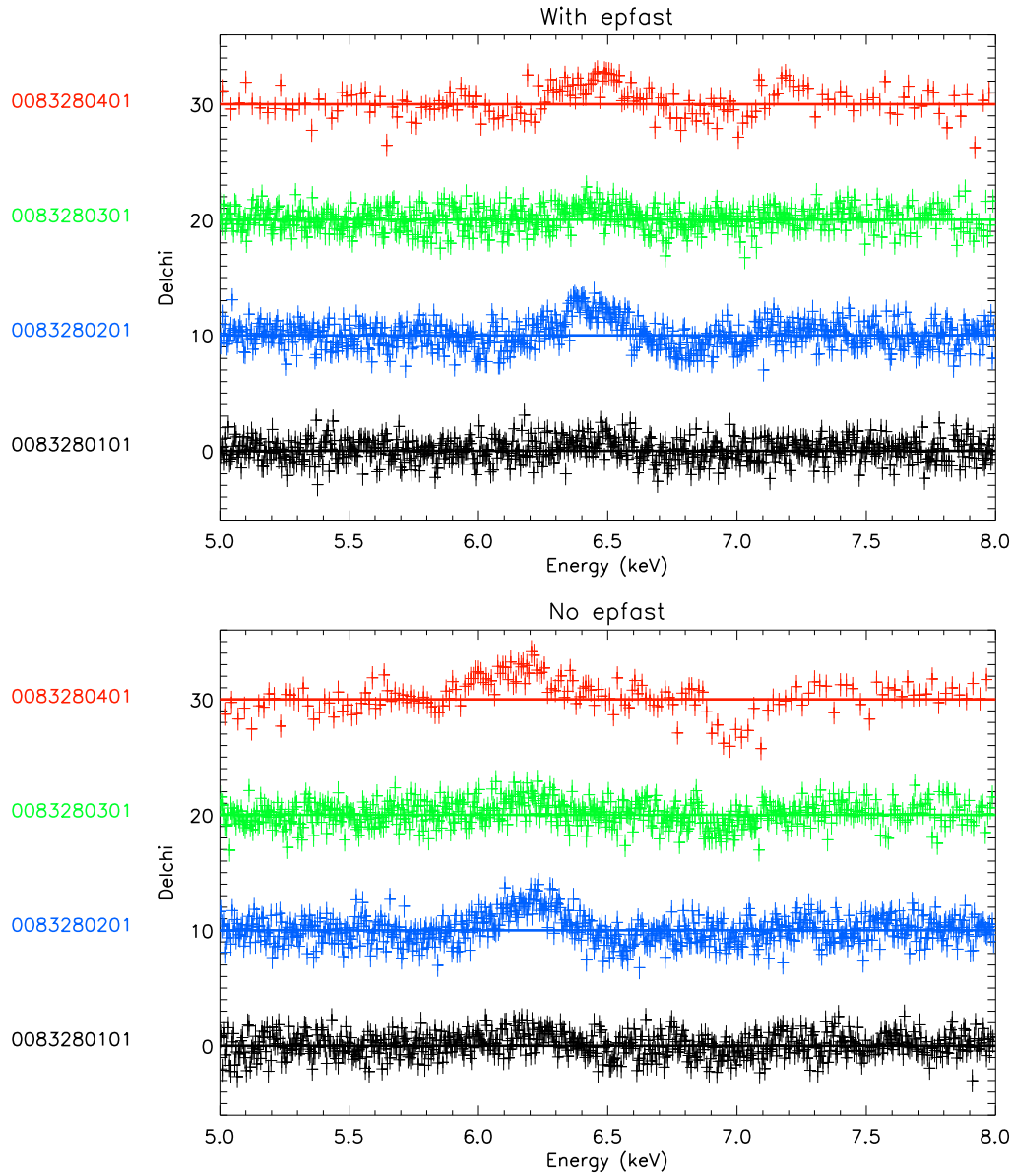
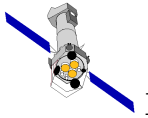


Figure 11: Residuals, expressed in units of standard deviations, when a `phabs*diskbb` model is applied to the 5-8 keV spectrum of the four EPIC-pn observations of 4U 1700-37 in Burst Mode. The curves were shifted by 10 units on the y-axis for clarity. The *upper panel* refers to events corrected by the RDCTI correction, and the *lower panel* without.

observations. Without the RDCTI correction the discrepancy is, however, significantly worse, with energies ranging from 6.16 to 6.20 keV.

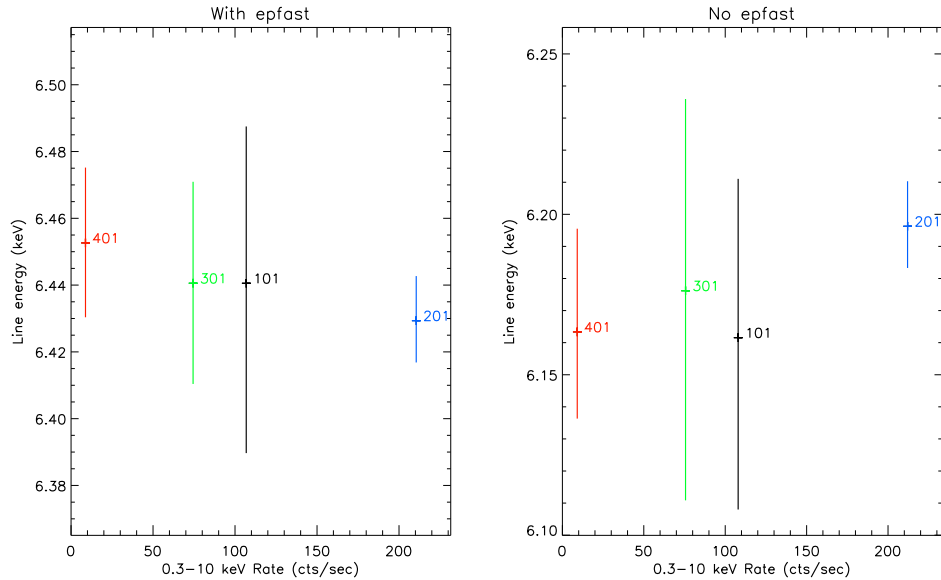
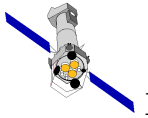


Figure 12: Iron line energy for the four observations as a function of the 0.3-10 keV rate. The vertical bars show the 90% confidence level region. The plot at the left refers to events corrected by the RDCTI correction, and the one at the right without.

3.5 Summary: how to get the most accurate energy scale

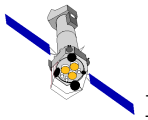
The calibration of the energy scale in EPIC-pn fast modes requires a complex chain of corrections. In order to achieve the nominal accuracy as described in Sect. 3.4.1 and 3.4.2, *all these corrections* must be applied:

- the X-ray Loading (XRL) correction (Timing Mode exposures only), through the parameters `runepreject=yes` and `withxrlcorrection=yes` in `epproc/epchain` (not default in SASv14.0)
- the special gain correction, through the parameters `withgaintiming=yes` and `withgainburst=yes` in `epproc/epchain` for Timing and Burst Mode, respectively (default in SASv14.0)
- the Rate-Dependent CTI (RDCTI) correction, through the parameter `runepfast=yes` in `epproc/epchain` (default in SASv14.0)

These steps are further described in the following SAS threads:

http://xmm.esac.esa.int/sas/current/documentation/threads/EPIC_reprocessing.shtml, and
http://xmm.esac.esa.int/sas/current/documentation/threads/PN_spectrum_timing_thread.shtml.

The default appropriate calibration corrections are automatically applied by `epproc/epchain` if run with the parameter `withdefaultcal=Y` (default as of SASv14).

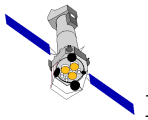


4 The “soft excess” problem in obscured binaries

“Soft excesses” have been reported by several authors (Boirin et al. 2005; Martocchia et al. 2006; Sala et al. 2009; Diaz-Trigo & Done 2009) in spectra of highly obscured X-Ray Binaries (XRBs) observed in EPIC-pn Timing Mode. This feature has been sometimes attributed to residual uncertainties in the redistribution calibration (see, *e.g.*, Hiemstra et al. 2010). In Fig. 13 we show spectra (*upper panels*) and residuals in units of data/model ratio (*lower panels*) for all the observations in our EPIC-pn Timing Mode sample corresponding to highly obscured sources, with column densities in the range $\simeq 6 \times 10^{21}$ to $8 \times 10^{22} \text{ cm}^{-2}$. As almost all these sources are XRBs, we employed a standard spectral model constituted by a photoelectrically absorbed (**tbabs** in XSPEC) combination of disk blackbody and power-law. The shape of the residuals red-wards of the soft photoelectric cut-off does not significantly depend on the continuum parametrisation. Most sources in Fig. 13 exhibit a soft excess, whose strength is broadly correlated with the column density (see also Ng et al. 2010 for a more quantitative analysis of this point on a different sample). Care needs to be exercised in interpreting these results. Astrophysical effects, such as dust scattering halos or coronal emission, may produce the same behaviour. In Fig. 14 two EPIC-pn spectra of 4U1624-49 are compared, taken in different instrumental modes. A strong soft excess below the steep photoelectric cut-off ($N_H \simeq 8.5 \times 10^{22} \text{ cm}^{-2}$) is present. Its shape is, however, similar between the observation in Small Window and that in Timing (Fig. 14). No evidence exists for a mis-calibration of the EPIC-pn redistribution in imaging modes, which may be responsible for such an effect (Guainazzi et al. 2011). The Timing Mode residuals in the 1–2 keV energy range are stronger than in Small Window by $\simeq 10$ –20% only.

4.1 Redistribution in Timing Mode

Only a few EPIC-pn Timing Mode spectra contain strong and well separated enough emission lines, whose individual profile can be used to constrain or test the quality of the redistribution calibration. In Fig. 15 we show spectra and residuals against phenomenological models of the Supernova Remnants (SNRs) N132D and CasA in the soft (0.7–1.4 keV), medium (1.7–3.5 keV) and iron line (5.5–7.5 keV) energy bands. For the medium and iron line band the model is a combination of a thermal bremsstrahlung continuum and unresolved (*i.e.*: intrinsic width, $\sigma=0$) emission lines corresponding to the following transitions: Si XIII (1.85 keV), Si XIV (2.00 keV), S XV (2.45 keV), Ar XVIII (3.10 keV), and Fe XXV (6.7 keV). The residuals below the lines are $\pm 5\%$, and no evidence exists for a systematic deviation between the observed and the calibrated line profile. In the soft band the N132D spectrum is compared with a model of the simultaneous RGS spectrum, constituted by a combination of two thermal bremsstrahlung continua and over 40 unresolved emission lines, and where only a global energy-independent cross-normalisation factor was allowed to vary (a similar comparison with the RGS CasA spectrum is hampered by the larger intervening photoelectric obscuration, as well by the SNR spatial extension, which exceeds the sky area covered by the active CCD in Timing Mode). In this case, residuals are $\pm 10\%$, and systematic deviations are particularly strong at 0.8–0.9 keV (NeIX and NeX) and 1.2–1.4 keV (Mg XI and Mg XVII). Although the complexity of the underlying model in a region where the EPIC-pn has got poorer energy resolution makes difficult to exactly pinpoint the origin of the discrepancy, it is interesting to observe that the residuals around the most prominent emission lines are energy-dependent, again suggesting that a general systematic problem with the calibration of the soft X-ray



resolution in EPIC-pn Timing Mode is unlikely to occur.

Similar conclusions can be drawn from a recent observation of the thermal SNR 1E0102-72 (September 2011; Fig. 16). This slightly extended ($\simeq 1'$ diameter) source has been extensively studied in the framework of a cross-calibration exercise (Plucinsky et al. 2008). An astrophysical model (“IACHEC⁸-model” hereafter) was defined based on the RGS spectrum. It was applied to the EPIC-pn Timing Mode spectrum assuming only the normalisation of the four main emission line complexes: OVII, OVIII, NEIX, NEX, as well as a global normalisation factor as free parameters in the fit. Such a model reproduces the line profiles with an accuracy comparable to that achieved with exposures taken in imaging modes (Plucinsky et al 2008), provided that an overall shift of the energy scale by -11.2 ± 0.5 eV is applied. This is about twice as large as typically measured in Imaging Mode exposures. At energies lower than $\simeq 0.5$ keV (where the astrophysical emission dies out) a $\simeq 10\%$ soft excess appears. Simulations show that this feature, likewise the soft excess observed in binaries, can be formally accounted for by a four-fold (and probably implausible) increase of the redistribution shoulder.

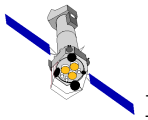
An independent clue on this issue may come by comparing EPIC-pn and RGS spectra in heavily absorbed sources. We tested this on a sample of obscured X-ray binaries. The EPIC-pn spectra were extracted from the largest possible extraction region ($\simeq 2'$ radius) consistent with the CCD aperture in Timing Mode, to match as closely as possible the $2.5'$ radius RGS aperture. The common model is the extrapolation of the best-fit “standard” model (see Sect. 4) applied to the EPIC-pn spectra in the 1.5–5 keV energy band. In Fig. 17 we show only the results for those observations, where the aforementioned fit procedure yields a $\chi_r^2 < 2.0$. In all cases the EPIC-pn residuals agree well with the RGS residuals above 1 keV. Only two spectra of GX13+1 provide some constraints below 1 keV (where the peak of the soft excess is measured). Interestingly, an excellent agreement is found down to 0.9 keV for Obs.#0122340101, while the soft excess is stronger in EPIC-pn in Obs.#0122341001. The background level is the same in these two observations, $< 10\%$ than the 0.7–1.5 keV source count rate during the lowest GX13+1 flux state. The 0.7–10 keV background-subtracted source count rate in the latter is 4.5 times larger than in the former (696.9 ± 0.6 against 153.4 ± 0.2 s⁻¹). This may indicate that a contribution to the soft excess may come from unaccounted for redistribution only for large count rates, close to the nominal pile-up limit of 800 counts per second.

5 Background subtraction

In the EPIC-pn Timing mode there is no source-free background region, since the PSF of the telescope extends further than the central CCD boundaries. The central CCD has a field of view of 13.06×4.04 arc-minutes². In Timing Mode the data are collapsed into a one-dimensional row along the CCD long side. Therefore sources with a count rate ≥ 200 s⁻¹ will dominate the counts across the whole CCD (Fig. 18). In such cases background spectra extracted even from the outermost columns will be substantially “contaminated” by source photons. This effect is, it goes without saying, strongly energy-dependent (Fig. 18).

Readers are referred to Sect 2.2 of Ng et al. (2010) for a detailed discussion on the effects of

⁸Readers are referred to the following web page: <http://web.mit.edu/iachec/> for a definition of the International Astronomical Consortium for High-Energy Calibration (IACHEC)



background subtraction, as well as on why it may be better not to subtract any background at all in these cases. The ultimate choice depends on the nature of the source spectrum.

6 Pile-up

In Fig. 19 we show the double to single event fraction in the 6–10 keV energy band as a function of the total 0.7–10 keV count rate for all 252 EPIC-pn Timing Mode exposures performed until April 2011. The pattern ratio was calculated on spectra extracted from the boresight column. Spectra affected by pile-up at a level larger than 3% according to `epatplot` are labelled with a *large black circle*. This plot confirms the accuracy of the nominal count rate threshold for pile-up reported in the XMM-Newton User's Handbook: 800 counts/s. Most of the spectra affected by pile-up exhibit a larger count rate. There are a few exceptions. However, they are *not* due to pile-up, rather to pending inaccuracies in the calibration of the pattern fraction for boresight position closest to the first macro-pixel border ($RAWY = 190$ and $RAWY = 191$; cf. Guainazzi et al. 2010). This effect may also yield a systematic over-estimate by a few percent of the fraction of single events over the whole sensitive energy bandpass.

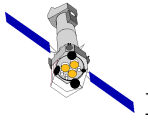
In SASv12.0.1, a novel algorithm was implemented to calculate the encircled energy fraction in EPIC fast modes (Gabriel et al., in preparation). In Fig. 20 and 21 we show the results of a study to evaluate the stability of the fluxes produced by `arfgen` with the new algorithm. Conceptually, we compare here the fluxes measured on a spectrum extracted from a standard extraction box around the boresight column, and spectra extracted from regions where an area around the boresight column was removed (this is the standard procedure to avoid columns affected by pile-up in fast modes). If the encircled energy fraction calculation would be perfect, these measurements should be identical for a point-like source. The sample employed for this tests includes therefore only point-like sources which are not affected by pile-up (total 0.7-10 keV count rate lower than 800 cts/s), while having enough counts for the analysis to make sense (total 0.7-10 keV count rate bigger than 200 cts/s). Only seven sources fulfil these restrictive criteria. The systematic inaccuracy yielded by the encircled energy fraction calculation is of the same order of the systematic error on the effective area calibration. The flux stability reconstruction is at the $\pm 4\%$ level; the spectral dependence thereof at the $\pm 2\%$. Results obtained with the non-default EXTENDED PSF are slightly worse: the flux stability is better than $\pm 10\%$.

Miller et al. (2010) and Ng et al. (2010) present a detailed discussion on pile-up in EPIC-pn Timing Mode exposures and on its impact (or lack thereof) on observed spectra. Users are referred to these papers for further details.

7 Cross-calibration of EPIC-pn Burst Mode against the RXTE/PCA

7.1 Observations

About 21 observations of 10 different X-ray binaries were performed quasi-simultaneously between the EPIC-pn in Burst mode and RXTE/PCA. For 9 of those observations it is possible to adjust the



start and end of the Good Time Intervals (GTIs) of the EPIC-pn to the one of the RXTE instrument. The conversion between the reference day of XMM-Newton and RXTE is: $\text{MJDREF}_{\text{RXTE}} - \text{MJDREF}_{\text{XMM}} = 49353 - 50814 \text{ d} = -1461 \text{ d} = -1.2623 \times 10^8 \text{ s}$. After adjustment of the start and end of observations, the sum of all GTIs of the EPIC-pn is equal to the one of RXTE, or smaller in case extra GTIs are defined for XMM during the observation period. RXTE data were taken from

Obs.	Source	RXTE set	XMM set	Date
(1)	GX 339-4	70130-01-01-00	0093562701	2002-08-24
(2)		70130-01-02-00	0156760101	2002-09-29
(3)		92085-01-03-03	0410581301	2007-03-05
(4)	GRO J1655-40	91702-01-06-01	0155762501	2005-03-18
(5)	Cyg X-1	93120-01-01-00	0500880201	2008-04-18/19
(6)	MAXI J0556-332	96414-01-03-05	0656781001	2011-02-16
(7)	Aql X-1	91028-01-13-00	0303220301	2005-04-11
(8)		91028-01-20-00	0303220401	2005-04-16
(9)	IGR J17091-3624	96420-01-05-00	0677980201	2011-03-28

Table 2: Simultaneous RXTE/PCA and EPIC-pn (burst mode) observations.

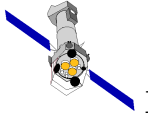
the public archive (<http://heasarc.gsfc.nasa.gov/FTP/xte/data/archive/>). For each observation the PCA standard products of the source and background spectra and the response matrix were used. Table 2 describes the observations analysed in this study. It shows the name of the binary, the RXTE and XMM-Newton ID and the date of the observation.

7.2 XMM-Newton data reduction

XMM-Newton data were reduced with the SAS version 12.0.1 using the public calibration files and the standard task `epproc`. The event lists were corrected for the rate-dependent CTI correction. Spectra were extracted with `FLAG=0`, using GTI files from RXTE, and by selecting only single and double events (`PATTERN<=4`). Source spectra were extracted over the region `RAWY<140` and the background in the region `RAWX=[2,8]`. Response files were generated with `arfgen` and `rmfgen`. Spectral fitting was performed on spectra extracted over 9 columns centred on the boresight position.

7.3 Results of spectral fitting

RXTE/PCA and EPIC-pn data of each simultaneous observation reported in Table 2 were analysed in the 3-10 keV band. A model of the form `const*phabs*(diskbb+power)` was fitted by tying spectral parameters for every simultaneous observation, except the constant factor. Table 3 shows, for the observations of Table 2, the sum of all RXTE and XMM GTIs (`ONTIME` keyword), and the 0.7-10 keV XMM count rate without background subtraction. The last column shows the value of the constant factor (`const`) of RXTE spectra freezing the XMM one to 1.0. Figure 22 shows the ratio of the data to the simultaneous model, for each observation separately. For all sources EPIC-pn data are harder than PCA data at high energy, at least above 6 keV.



Obs	Source	Sum GTIs RXTE (s)	Sum GTIs XMM (s)	XMM RATE 0.7-10 keV (cts/s)	F _{RXTE}
(1)	GX 339-4	3296	2090	4793	1.24
(2)		8432	8376	3436	1.25
(3)		2960	2960	3576	1.23
(4)	GRO J1655-40	4272	4272	6584	1.20
(5)	Cyg X-1	9456	9456	603	1.29
(6)	MAXI J0556-332	3408	3408	308	1.17
(7)	Aql X-1	2912	2912	255	1.29
(8)		3216	3147	293	1.18
(9)	IGR J17091-3624	2720	2719	267	0.73

Table 3: Sum of RXTE and XMM GTIs for the observations described in Table 2, the 0.7-10 keV XMM count rates and the fitted RXTE constant factor.

Furthermore, the spectra of the simultaneous observations were fitted by untying the spectral values. Most of the observations are fitted with a model of the form **diskbb+power** except for GRO J1655-40 and Cyg X-1 which are better fitted by adding photoelectric absorption **phabs*(diskbb+power)**. In Tab. 4 we give the parameter values of the best spectral fit, the reduced chi-square and the number of degrees of freedom. Columns 4 to 8 give when relevant the values

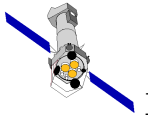
Obs	Source	RXTE/ XMM	N_H 10^{22} cm^{-2}	T_{in} (keV)	N_{diskbb} (cgs) ¹	Γ	N_{power} (cgs) ²	χ^2_{red}	dof
(1)	GX 339	XMM	-	$0.89 \pm^{0.03}_{0.02}$	2200 ± 200	$2.3 \pm^{1.0}_{1.8}$	$0.8 \pm^{6.3}_{0.8}$	1.41	619
		RXTE	-	$0.920 \pm^{0.004}_{0.003}$	1900 ± 60	$3.79 \pm^{0.05}_{0.06}$	21 ± 2		
(2)		XMM	-	$0.91 \pm^{0.04}_{0.03}$	800 ± 200	$3.3 \pm^{0.2}_{0.3}$	$11 \pm^6_4$	1.49	887
		RXTE	-	$1.00 \pm^{0.01}_{0.01}$	440 ± 30	3.91 ± 0.02	$40.7 \pm^{1.9}_{1.9}$		
(3)		XMM	-	$0.82 \pm^{0.09}_{0.06}$	$800 \pm^{500}_{600}$	2.9 ± 0.3	$12 \pm^8_5$	1.45	748
		RXTE	-	$1.92 \pm^{0.03}_{0.05}$	$11.0 \pm^{1.1}_{1.0}$	$3.70 \pm^{0.07}_{0.06}$	47.5 ± 3		
(4)	GRO J1655	XMM	$1.1 \pm^{2.0}_{0.4}$	1.36 ± 0.02	$8.40 \pm^{60}_{50}$	-	< 0.01	1.63	1116
		RXTE	5.0 ± 0.6	1.340 ± 0.004	$940 \pm^{15}_{16}$	4.95 ± 0.13	$420 \pm^{130}_{100}$		
(5)	Cyg X-1	XMM	$11.5 \pm^{3.3}_{1.9}$	$0.51 \pm^{0.06}_{0.04}$	$18000 \pm^{31000}_{13000}$	1.58 ± 0.09	$1.3 \pm^{0.3}_{0.2}$	1.22	1142
		RXTE	15.3 ± 0.7	0.390 ± 0.005	$340000 \pm^{50000}_{40000}$	1.98 ± 0.01	3.6 ± 0.1		
(6)	MAXI J0556	XMM	-	$1.46 \pm^{0.22}_{0.11}$	$10 \pm^5_7$	$7.52^\dagger$	< 600	3.11	156
		RXTE	-	1.45 ± 0.02	9.7 ± 0.7	6.6 ± 0.2	$57 \pm^{15}_{12}$		
(7)	Aql X-1	XMM	-	$1.6 \pm^{3.2}_{0.5}$	$6.6^\dagger$	$1.05^\dagger$	$0.10 \pm^{0.29}_{0.10}$	2.04	278
		RXTE	-	$3.03 \pm^{0.03}_{0.02}$	$1.77 \pm^{0.05}_{0.06}$	$6.7 \pm^{1.3}_{1.2}$	$16 \pm^{50}_{12}$		
(8)		XMM	-	$1.9 \pm^{2.7}_{0.4}$	< 9	$1.05^\dagger$	< 0.8	1.37	323
		RXTE	-	$2.98 \pm^{0.03}_{0.02}$	$2.12 \pm^{0.02}_{0.10}$	$9.34^\dagger$	$3.7\text{E}2 \pm^{110}_{350}$		
(9)	IGR J17091	XMM	-	$1.43 \pm^{0.15}_{0.22}$	$25 \pm^{16}_7$	-	< 0.01	1.14	240
		RXTE	-	$1.85 \pm^{0.10}_{0.18}$	$2.1 \pm^{0.6}_{0.3}$	$3.4 \pm^{0.3}_{0.2}$	$2.3 \pm^{0.8}_{0.4}$		

[†]unconstrained

¹as in **Xspec**: $[R_{in}/D]^2 \times \cos(\theta)$. where R_{in} is the equivalent inner disk radius in kilometres, D is the distance to the source in units of 10 kpc, and θ is the angle between the line-of-sight and the normal to the disk.

²as in **Xspec**: photons $\text{keV}^{-1} \text{s}^{-1} \text{cm}^{-2}$ at 1 keV.

Table 4: Results of the best spectral fitting with untied parameters.



of N_H (equivalent hydrogen column), T_{in} (temperature of the disk), N_{diskbb} (normalisation of the blackbody component), Γ (photon index) and N_{power} (normalisation of the power-law component). We stress that we provide these numbers only to allow readers to reproduce the analysis presented in this document. Given the difference in the effective area calibration (Fig. 22) one should not expect that the spectral deconvolution agrees when the same model is applied to the EPIC-pn and the RXTE/PCA spectra. The fit may readjust itself to a completely different ratio of the two components, making a direct comparison between the parameter models cumbersome. However, Tab. 4 is illustrative of the kind of systematic errors that users have to account for when analysing typical X-ray spectra of binaries taken with instruments with low or moderate energy resolution. Figure 23 shows the same plot as Figure 22 when the spectral fit is performed leaving the parameters free for each spectrum separately. It highlights the systematic uncertainties associated to the effective area of each instrument.

7.4 Reference Crab spectra

Two of the observations of the Crab Nebula in EPIC-pn Burst Mode were performed at a slightly offset position, to ensure that the whole nebula is encompassed by the EPIC-pn field of view (Obs.#0160960401, and 0160960601; September 2004). They represent therefore the reference measurement for the EPIC-pn Crab Nebula spectrum. Given the importance of the Crab Nebula for the cross-calibration of high-energy instruments, we report in Tab. 5 the spectral parameters resulting from a fit with a photoelectrically absorbed power-law (model `varabs` in XSPEC v12.4) on these

Table 5: Spectral best-fit parameters when the Crab spectra of Obs.#0160960401, and 0160960601 are fit with a photoelectrically absorbed power-law model.

Obs.#	Γ	N^a	$N_{H,O}$ (10^{22} cm^{-1})	$N_{H,Ne}$ (10^{22} cm^{-1})	$N_{H,Si}$ (10^{22} cm^{-1})	$N_{H,S}$ (10^{22} cm^{-1})	$N_{H,Fe}$ (10^{22} cm^{-1})	χ^2/ν
0160960401	2.120 ± 0.007	9.39 ± 0.09	0.230 ± 0.014	0.26 ± 0.03	1.00 ± 0.15	3.1 ± 0.5	0.12 ± 0.07	379.3/222
0160960601	2.110 ± 0.013	9.44 ± 0.18	0.20 ± 0.03	0.26 ± 0.07	1.3 ± 0.3	4.1 ± 0.9	0.16 ± 0.13	237.2/222

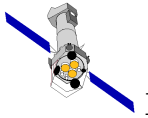
^anormalisation at 1 keV in units of photons $\text{cm}^{-2} \text{ s}^{-1}$

spectra. Abundances have been left free to vary, whenever the corresponding confidence interval was not trivial (*i.e.*, statistically inconsistent with either 0 and 1). We express them as equivalent Hydrogen column densities in Tab. 5. The corresponding spectra are shown in Fig. 24. A comparison between XMM-Newton and other present and past missions can be found in Kirsch et al. (2005), and Weisskopf et al. (2010).

8 Summary of the calibration status

The main conclusions of this TN can be summarised as follows:

- correcting for XRL and RDCTI, and applied the special gain correction embedded in the default EPIC-pn reduction meta-tasks, the energy reconstruction of narrow-band features in EPIC-pn Timing mode is constrained to be better than ± 20 eV between 1 and 8 keV and over the whole range of count rates below the pile-up threshold. A possible degradation of this accuracy in the column-dependent spectroscopy of the XRB GX13+1 suggest a possible



flattening of the RDPHA vs. rate of shifted electron relation at count rates close to the pile-up threshold (Díaz-Trigo et al., 2014). The accuracy is comparable to the nominal accuracy in imaging mode at energies ≥ 2 keV (§ 3.4.1)

- after the rate-dependent CTI correction measurements of the energy of the FeXXVI resonant absorption line in GROJ1655-40 in EPIC-pn Burst Mode are consistent with the astrophysical expectations, while it is overestimated by about 40 eV in 4U 1700-37. (§ 3.4.2)
- as of the public release of SASv12 (expected for the 2nd quarter of 2012), offset maps prior to exposures in EPIC-pn Timing Mode will be taken with the CLOSED optical blocking filter. This will prevent XRL. The SAS reduction meta-task will be able to automatically recognise the filter of the offset map, and apply the calibration appropriate to each instrumental configuration (§ 3.3.2)
- there is currently no convincing evidence for a systematic mis-calibration of the EPIC-pn Timing Mode redistribution below $\simeq 1$ keV, *i.e.* for a systematic difference between the redistribution in imaging and fast modes (the calibration of the EPIC-pn redistribution is not mode-dependent). (§ 4.1)
- due to the intrinsic energy-dependence of the Point Spread Function, background-subtraction can be an issue even for sources observed in EPIC-pn Timing or Burst Mode if they are very steep or heavily obscured. No golden rule applies on how to ideally treat the data in this case, besides using scientific discernment in the data analysis and interpretation (§ 5)
- the pile-up threshold in EPIC-pn Timing Mode is 800 counts per second. For sources exceeding this threshold, at least the boresight column must be excised from the accumulation of any scientific products. Users are referred to a specific section in the SAS Manual to learn how to correctly calculate the corresponding responses (§ 6)
- EPIC-pn Burst Mode spectra yield 20–30% more flux at 10 keV when compared to 2 keV with respect to simultaneous RXTE/PCA spectra. The origin of this discrepancy is unknown (see Tsujimoto et al. 2010 for a systematic cross-calibration study involving, among others, RXTE/PCA and EPIC-pn in an imaging mode) (§ 7.3)

Finally, we present in this TN the best spectral parameters of the Crab Nebula (Burst Mode), for cross-calibration reference.

Acknowledgments

Several comments, encouragements and stimulating discussions with M. Díaz-Trigo greatly enhanced the quality of the calibration work reflected in this document at various stages of its preparation. The authors gratefully acknowledge R. Gonzalez-Riestra for scientific advice on RSOPH. Comments by M. Ehle, E. Ojero, M. Mendez, N. Scharrel, and M. Santos-Lleó significantly improved the presentation of the results. Calibration is a collective undertaking, which takes advantage of the efforts and dedication of many persons active in mission operations. Our gratefulness for the contribution of the whole XMM-Newton SOC and EPIC Instrument Team scientists to this work can hardly be adequately acknowledged.

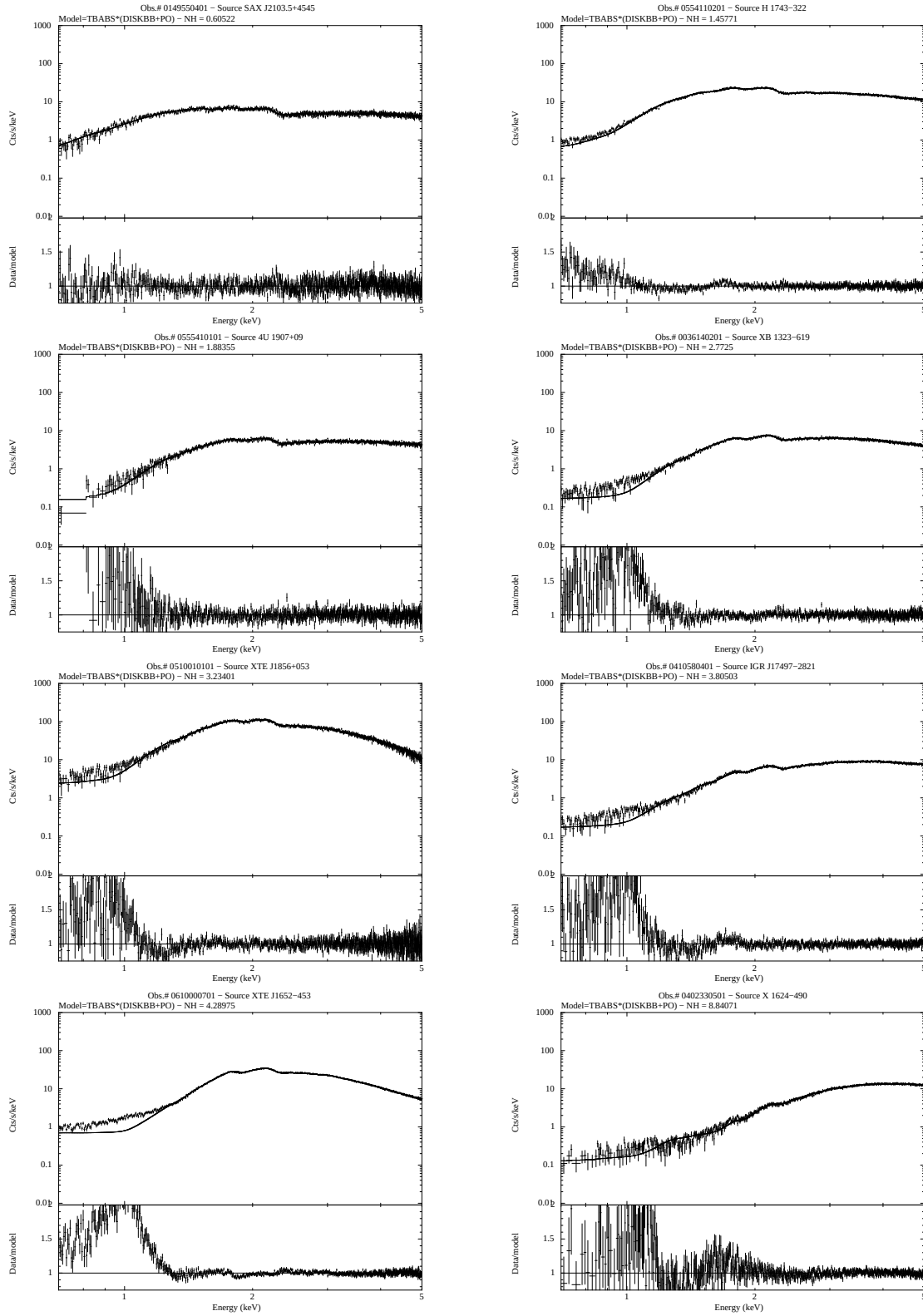
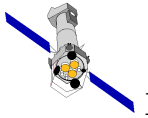


Figure 13: Spectra (*upper panels*) and residuals in units of data/model ratio (*lower panels*) when a power-law + disk blackbody continuum modified by photoelectric obscuration (`tbabs*(diskbb+po)` in XSPEC) is applied in the 0.7–5 keV energy band to a sample of highly-obscured objects observed with EPIC-pn Timing Mode. The objects are listed in increasing order of best-fit column density from *top left* to *bottom right*. Each spectrum is rebinned in order for each spectral channel to have a signal-to-noise ratio >2 for plotting purposes only.

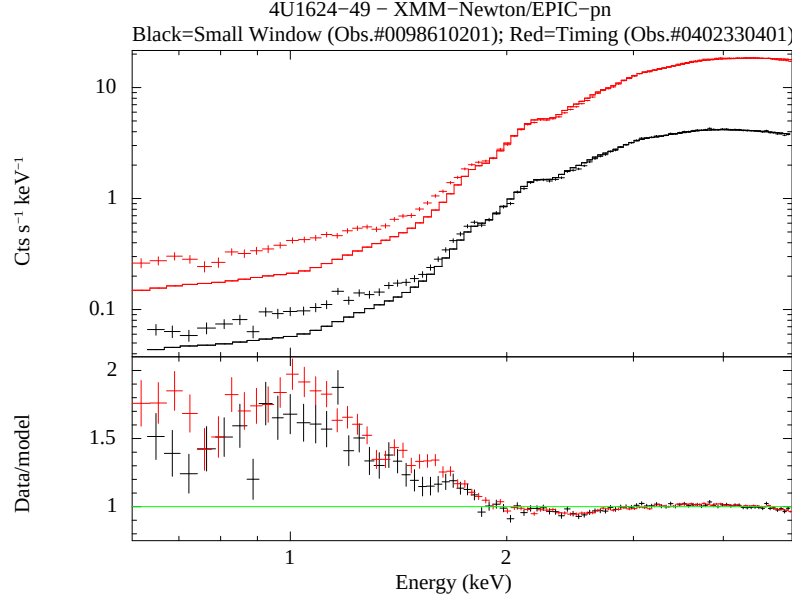
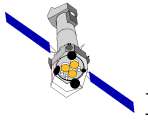


Figure 14: Spectra (*upper panel*) and residuals in units of data/model ratio (*lower panel*) when a photo-electrically absorbed combination of disk blackbody and power-law is applied to the spectra of 4U1624-49 in Small Window (Obs.#0098610201; *black*) and Timing Mode (Obs.#0402330401; *red*). The model parameters are independently fit to each spectrum.

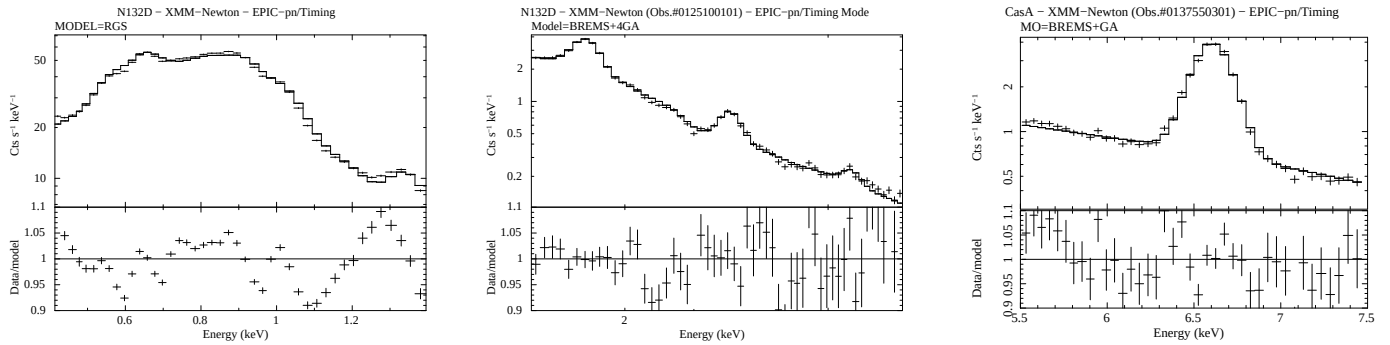


Figure 15: Spectra (*upper panels*) and residuals in units of data/model ratio (*lower panels*) for SNRs observed in EPIC-pn Timing Mode. *Left panel*: N132D in the 0.7–1.4 keV energy band; *centre panel*: N132D in the 1.7–3.5 keV energy band; *right panel*: CasA around the iron line.

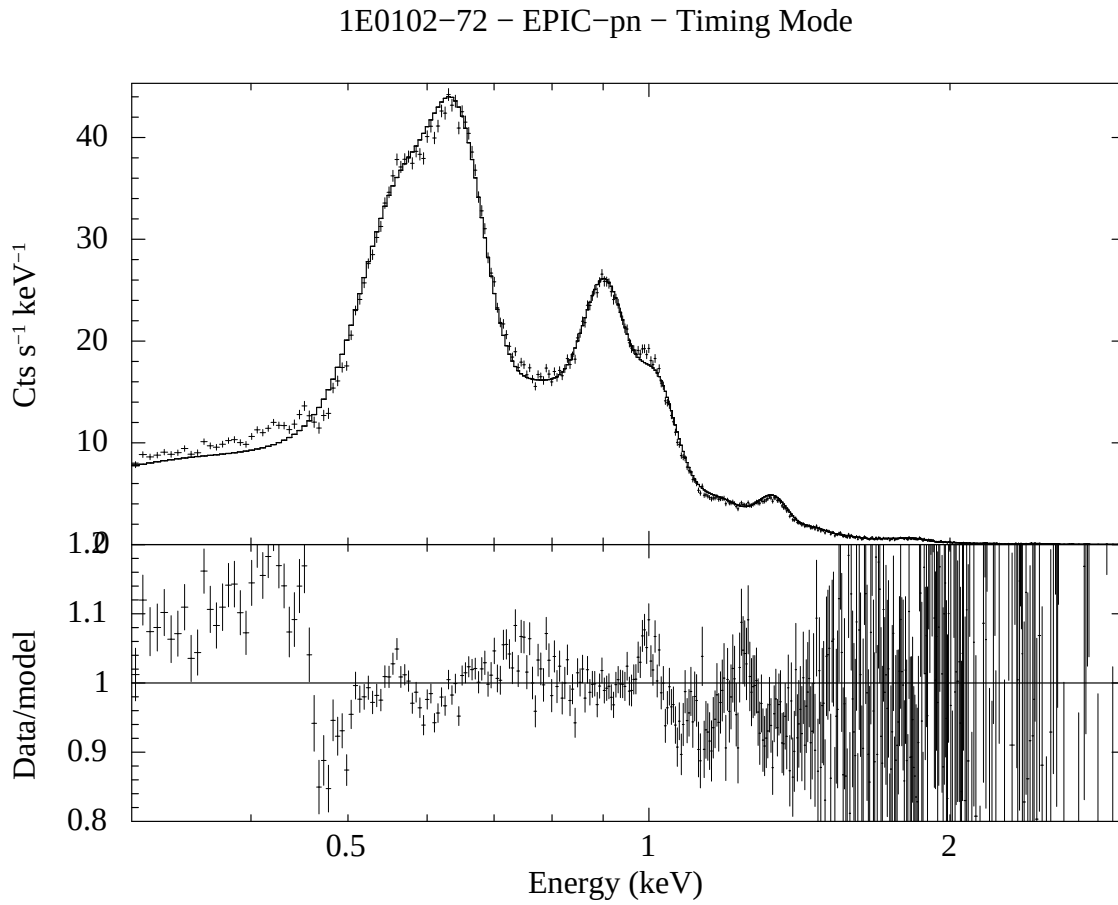
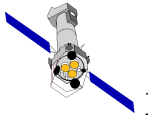


Figure 16: Spectrum (*upper panel*) and residuals in units of data/model ratio (*lower panel*) when the IACHEC-model (Plucinsky et al. 2008) is applied to the September 2011 EPIC-pn Timing Mode observation of 1E0102-72.

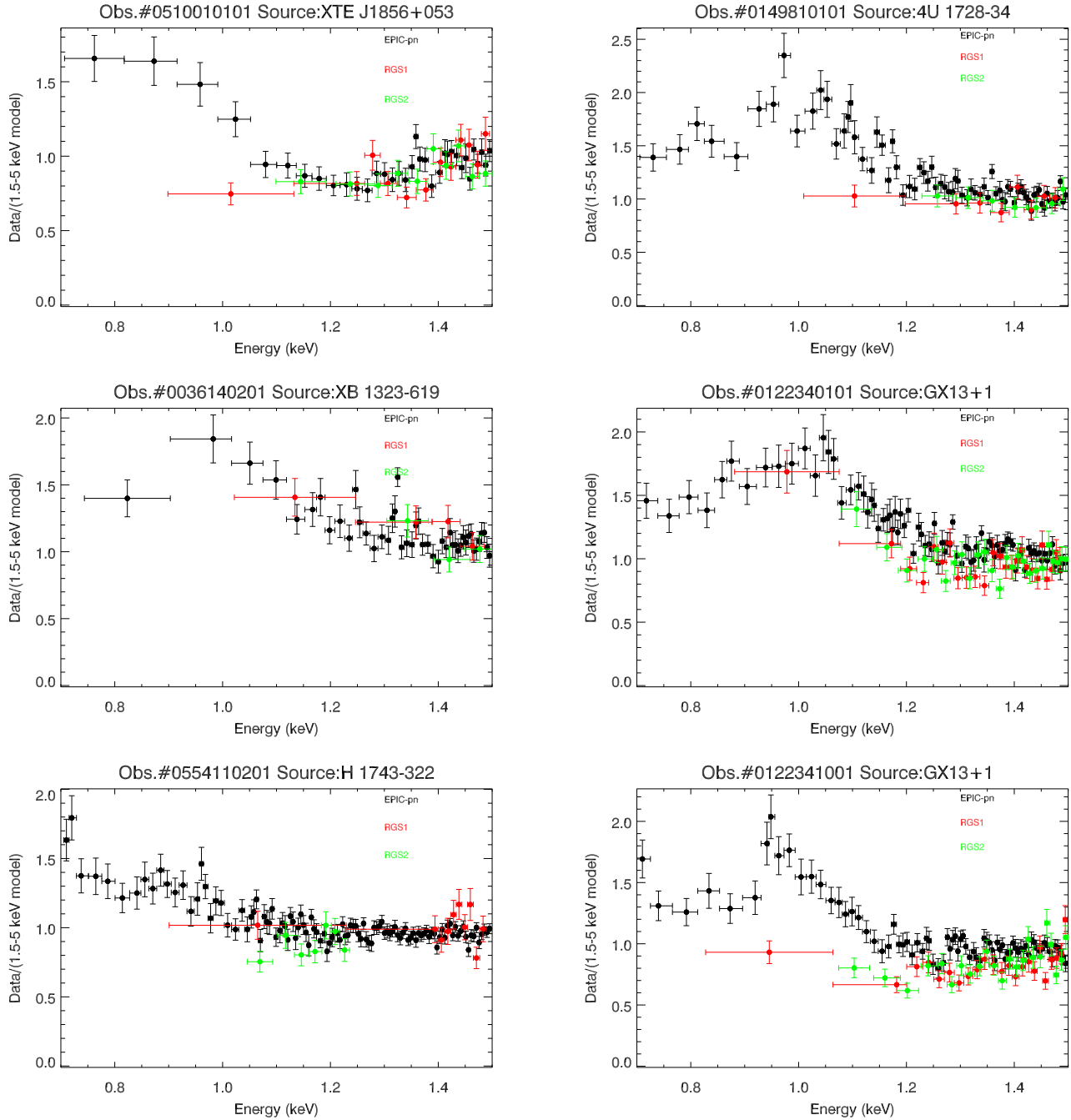
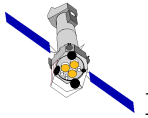


Figure 17: Data/model ratio against the same model for EPIC-pn (*black*), RGS1 (*red*), and RGS2 (*green*) on six obscured binaries (details in Sect. 4.1). Each data point correspond to a statistical error < 10%.

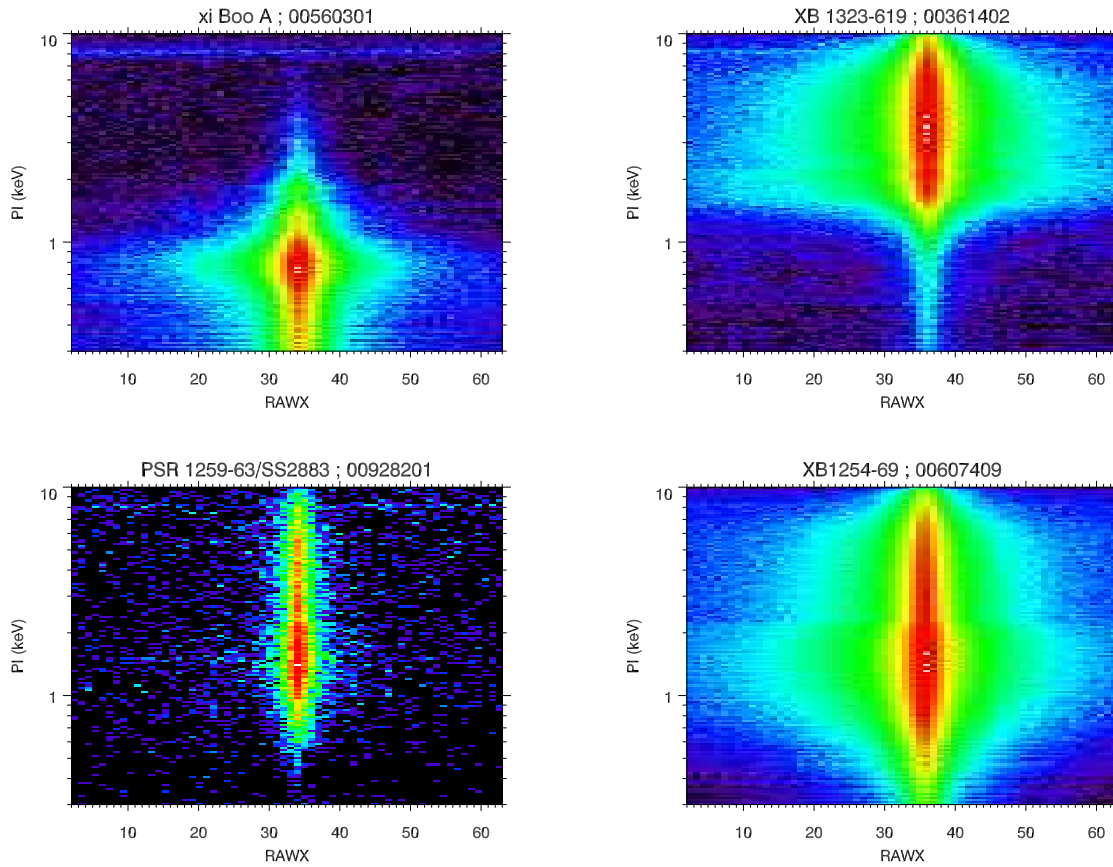
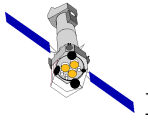


Figure 18: Examples of RAWX versus PI EPIC-pn Timing Mode images. In all of them except PSR1259-63 (a comparatively weak source: the full band count rate is in the range $0.9\text{--}5.6\text{ s}^{-1}$) a background spectrum from the side CCD columns will be substantially “contaminated” by source photons at least in some energy bands.

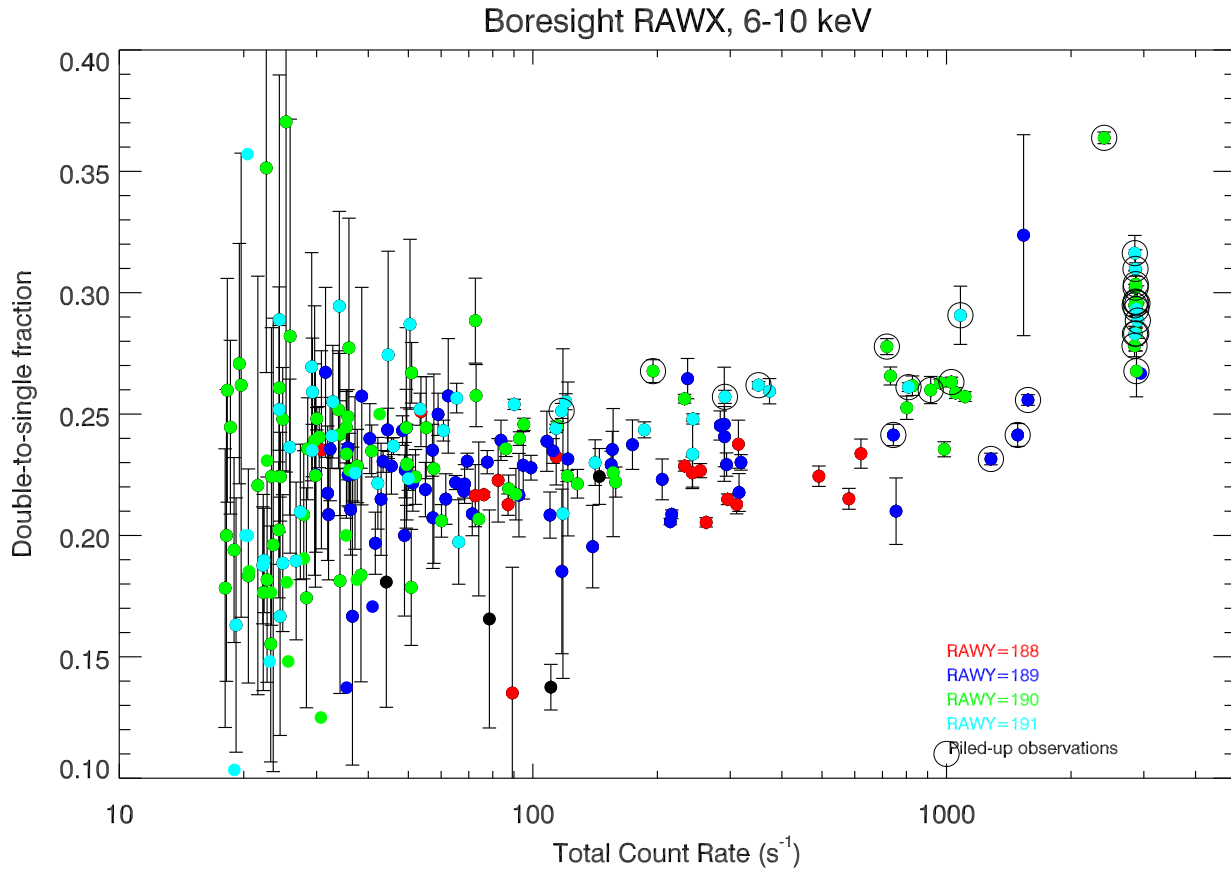
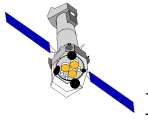


Figure 19: Double-to-single events ratio in the 6–10 keV energy band as a function of the total count rate in the 0.7–10 keV band for all the EPIC-pn Timing Mode exposures in the XMM-Newton Science Archive as of April 2011. Colours code different boresight position (in RAWY). Spectra affected by pile-up are indicated by a large black circle). The nominal pile-up threshold is 800 s^{-1} .

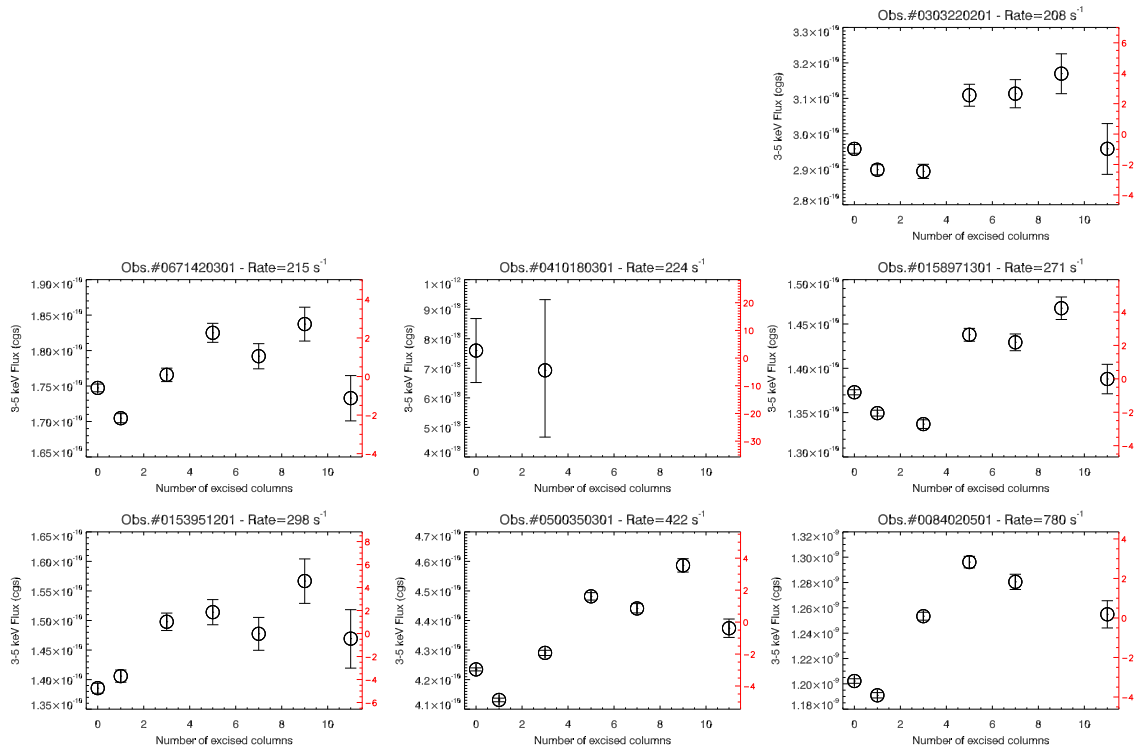
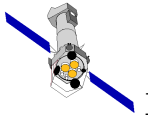


Figure 20: 3–5 keV flux (in units of $\text{erg cm}^{-2} \text{s}^{-1}$) as a function of the number of excised columns. The *right-side* y-axis (*red*) is the same quantity as on the left-side expressed in percentage difference with respect to the mean. Plots are sorted in increasing count rate from *top right* to *bottom right*.

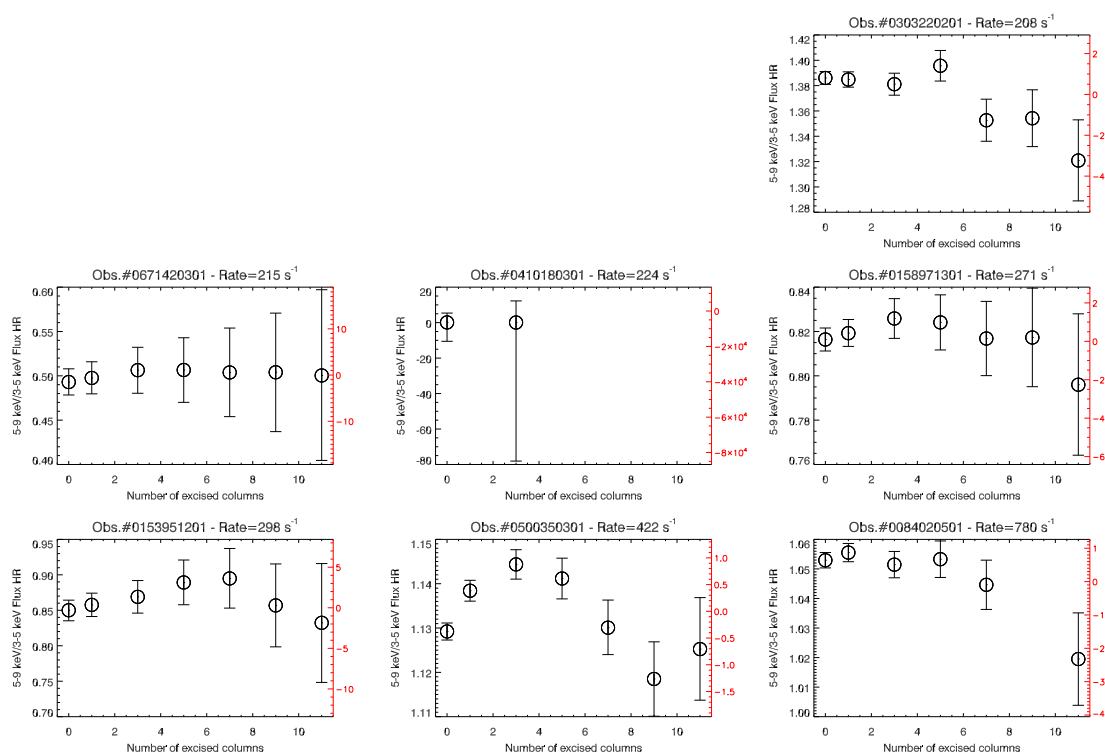
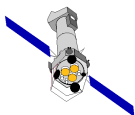


Figure 21: The same as Fig. 20 for the 5–9 keV/3–5 keV hardness ratio.

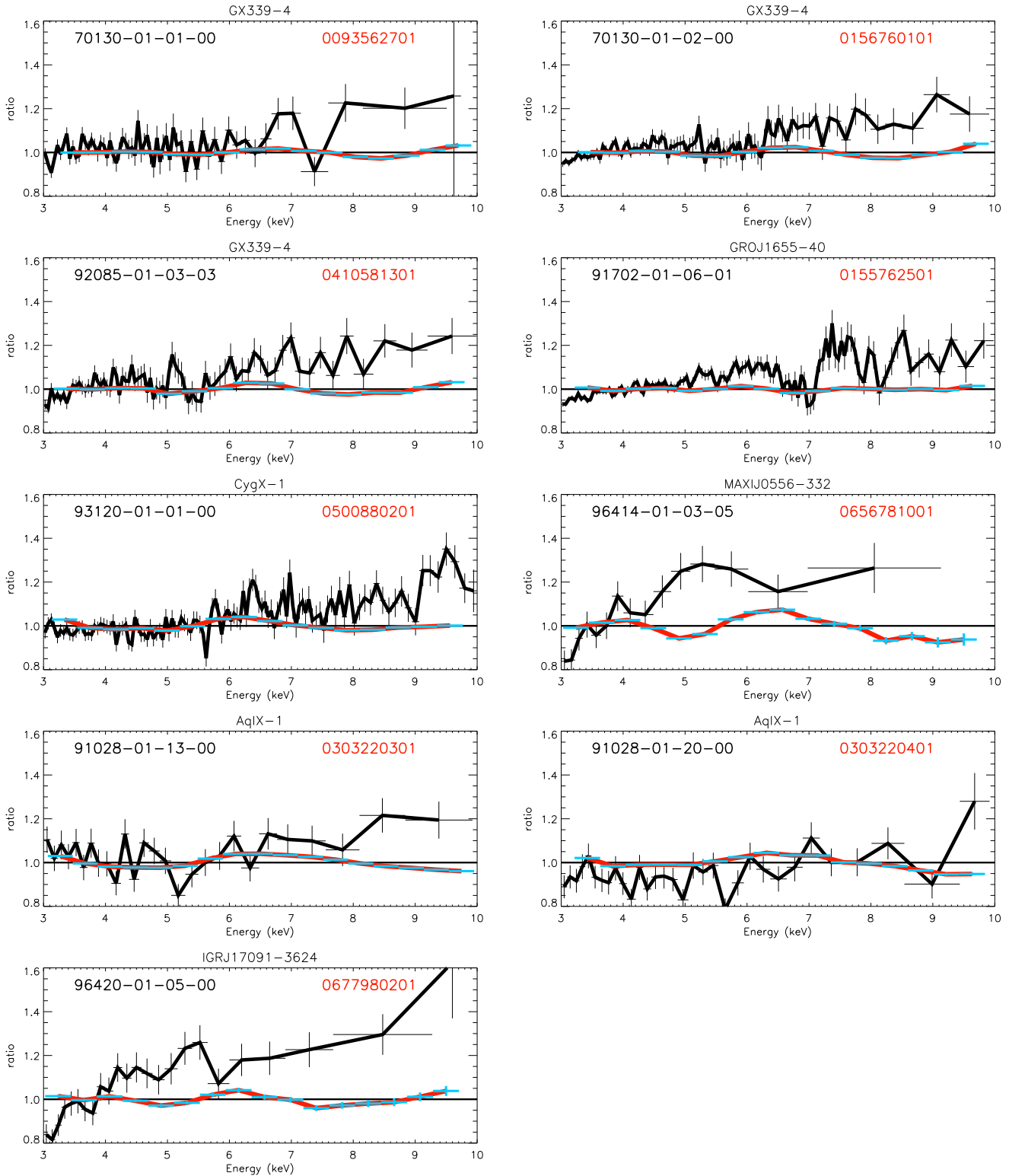
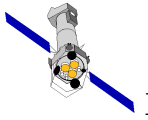


Figure 22: Ratio of the data to model for spectral fitting with tied parameters. *Black*: EPIC-pn; *red line with cyan crosses*: RXTE/PCA. The *inset number* indicate the observation date, and the XMM-Newton observation number.

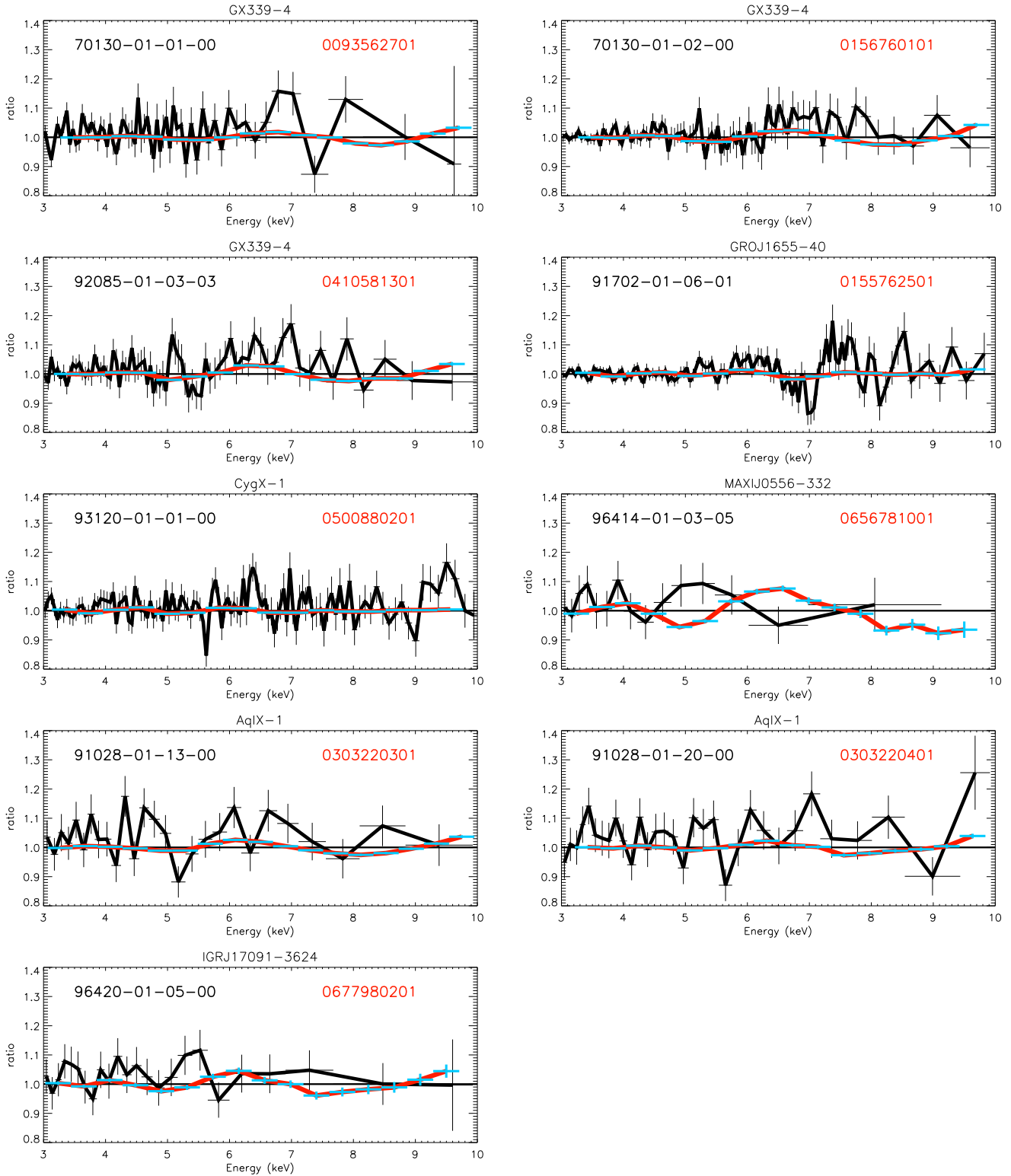
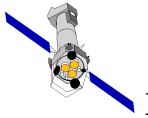


Figure 23: Same as Figure 22 but for spectral fitting with untied parameters.

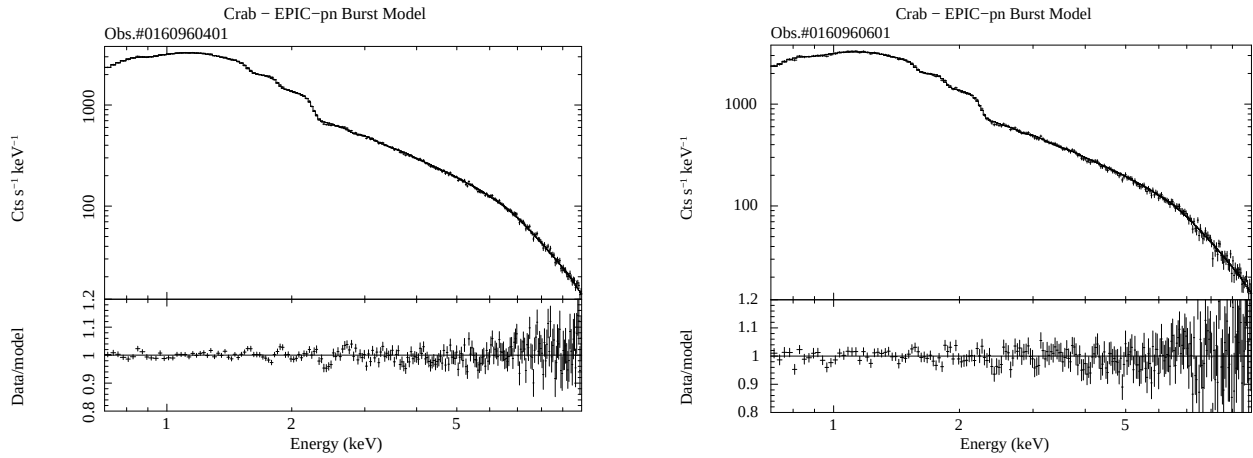
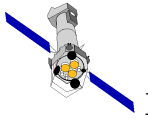
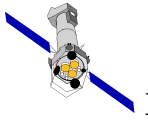


Figure 24: Spectra (*upper panels*) and residuals in units of data/model ratio (*lower panels*) when the Crab spectra of Obs.#0160960401 (*left panel*) and 0160960601 (*right panel*) are fit with a photoelectrically absorbed power-law (cf. Tab. 5). For plotting purposes only, spectra are rebinned in such a way that each spectral channel has got a signal-to-noise >10 .



References

- Boirin L., et al., 2005, *A&A*, 436, 195
- Boroson, B., et al., 2003, *ApJ*, 592, 516
- Díaz-Trigo M., et al., 2007, *A&A*, 462, 657
- Díaz-Trigo M., et al., 2014, *A&A*, 571, 76
- Done C. & Díaz-Trigo M. 2010, *MNRAS*, 407, 2287
- Freyberg M., et al., 2005, MPE Report, 288. 159
- Guainazzi M., 2009, XMM-CCF-REL-256 (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-SRN-0256-1-0.ps.gz>)
- Guainazzi M., 2010, XMM-CCF-REL-265 (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-SRN-0265-1-0.ps.gz>)
- Guainazzi M., 2011, XMM-SOC-CAL-TN-0018 (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018-1-0.pdf>)
- Guainazzi M., 2013a, XMM-SOC-CCF-REL-306 (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-SRN-0306-1-1.ps.gz>)
- Guainazzi M., 2013b, XMM-SOC-CCF-REL-312 (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-SRN-0312-1-4.pdf>)
- Guainazzi M. & Smith M., 2013, XMM-SOC-CAL-SRN-304 (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-SRN-0304-1-1.pdf>)
- Hiemstra B., et al., 2011, *MNRAS*, 411, 137
- Kirsch M.G/F., 2005, Ph.D. Thesis (available at:
<http://astro.uni-tuebingen.de/publications/kirsch-diss.shtml>)
- Kirsch M.G.F., et al., 2005, *SPIE*, 5598, 22
- Kirsch M.G.F., et al., 2006, *A&A*, 453, 173
- Martocchia A., et al., 2006, *A&A*, 448, 677
- Miller J., et al., 2010, *ApJ*, 724, 1441
- Ng C., et al., 2010, *A&A*, 522, 96
- Plucinsky P., et al., 2008, *SPIE*, 7011, 68
- Sala G., et al., 2008, *A&A*, 489, 1239
- Smith M., 2004, XMM-SOC-CAL-TN-0050, (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-TN-0050-1-0.ps.gz>)
- Smith M., et al., 2010, XMM-CCF-REL-271, (available at:
<http://xmm2.esac.esa.int/docs/documents/CAL-SRN-0271-1-0.ps.gz>)
- Tsujimoto M., et al., 2010, *A&A*, 525, 25
- van der Meer, A., et al., 2005, *A&A*, 432, 999
- Walton D.J., et al., 2012, *MNRAS*, 422, 2510
- Weisskopf M., et al., 2010, *ApJ*, 713, 912