eROSITA Energy Conversion Factor

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ABSTRACT

In this tutorial, we introduce concepts relevant for eROSITA flux measurement in X-ray imaging and spectral analyses. Based on them, we introduce the definition and calculation of energy conversion factors (ECF) between the physical flux of an astronomical X-ray source and its count rate measured by eROSITA.

1. INTRODUCTION

X-ray imaging analysis is done in the space of photon counts or count rates, and an energy conversion factor (ECF) is needed for conversion between source count rates and physical fluxes. The calculation of ECF for eROSITA is identical to that of previous X-ray telescopes. Experienced readers could go directly to the end of this tutorial in § 4.3, where example code of calculating eROSITA ECF is provided.

Before introducing the energy conversion factor (ECF) in § 4 Energy conversion factor, we clarify a few basic concepts in X-ray imaging and spectral analysis in § 2 X-ray imaging concepts and § 3 X-ray spectral concepts. In eROSITA pointing mode observations, the X-ray flux measurement is done in an identical way as that for XMM-Newton and Chandra. In scanning mode, a different situation has to be accounted for, that is, target object moving across the telescope field of view (FOV) instead of staying at a fixed position in the FOV. As a result, count rate is defined differently in imaging and spectral analyses. Some caveats to users of eROSITA spectra are introduced in § 3 X-ray spectral concepts.

2. X-RAY IMAGING CONCEPTS

2.1. Source flux and EEF

In this tutorial, we consider X-ray flux measurements in two cases for point (unresolved) sources and diffuse emissions respectively. For a point source, we measure its flux in a given energy range in units of erg cm^{-2} s^{-1} by extracting the X-ray signal inside a small aperture. Since the point spread function (PSF) extends to a scale larger than the aperture, the enclosed energy fraction (EEF) of the aperture is needed to correct for the fraction of signal outside. Note that PSF is energy dependent, thus if the energy band is broad, more uncertainties will be introduced because

of the varying PSF. For diffuse emission, we ignore its brightness gradient and measure its surface brightness (in unit of erg cm^{-2} s^{-1} deg^{-2}) by dividing the flux by the extraction area. The flux measurement is identical to the first case except that we assume no correction for out-of-aperture loss is required. Please note that typical galaxy clusters have significant brightness gradients. Some of them could even be compact and thus needs PSF correction. In such cases, please refer to the eROSITA galaxy cluster catalog paper (Bulbul et al. in prep.) for a better treatment.

2.2. *Exposure time and vignetting*

By "exposure time", we do not literally refer to the length of an observation. In X-ray imaging analysis, exposure time is defined as corresponding to a specific region (e.g., source extraction aperture) on the sky (not the detector), and is generally presented in terms of exposure maps, which are created for eROSITA using the eSASS task `expmap`. The corresponding exposure map of an image must be created using the same event flag filter, event pattern filter, and good time intervals as that used to create the image. Two types of exposure maps are provided. Raw exposure maps store the time (Exp_0) that a sky position is exposed (inside the FOV), and in vignetted exposure maps, the exposure time is multiplied by the vignetting factor (Vig). In scanning mode, the vignetting factor at a sky position varies when the position moves across the FOV, the varying vignetting factor is averaged during the exposure time when creating vignetted exposure maps with `expmap`. Vig is also energy dependent. When averaging it in an energy band, a spectral shape is assumed. By default, `expmap` assumes a power law with $\Gamma = 1.7$. `expmap` also takes bad pixels into account.

eROSITA has seven telescope modules, TM1–7, which are more or less identical. TM0 indicates a combination of TM1–7. TM8 indicates a combination of TM1, 2, 3, 4, and 6, excluding TM5 and 7, which are affected by light leak. TM9 indicates a combination of TM5 and 7. Please note that not all the seven TMs are necessarily active simultaneously, but by default, `expmap` average the exposure map among all the seven TMs. In other words, the exposure map stores the effective exposure time of TM0, which could be shorter than the observation time because some TMs are inactive.

2.3. *Count rate and ECF*

In a given energy band, the photon counts from a source with a given flux captured in the source extraction aperture depend on a few factors, including the local exposure time Exp_0, the local vignetting Vig, and the on-axis effective area $Area_0$:

$$Counts = F_p \times Exp_0 \times Area_0 \times Vig \times EEF, \qquad (1)$$

where F_p is photon flux in units of counts cm^{-2} s^{-1} in the given energy band, and can be converted to physical flux (erg cm^{-2} s^{-1}) by a factor of mean energy of photons in this band.

Although vignetting is irrelevant to exposure time, in X-ray imaging analysis, Vig is generally combined with Exp_0 into a vignetted exposure map, such that $Area_0$, which is determined by the mirror collecting area and the detector quantum efficiency, can be kept separately as a source-independent factor.

Considering energy-dependent factors, an accurate form of the counts should be

$$\sum_I Counts(I) = \sum_I \int f_p(E)\ RMF(I, E)\ Exp_0\ Area_0(E)\ Vig(E)\ EEF(E)\ dE,$$

(2)

where $f_p(E)$ is the spectral model in units of counts $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$, I indicates an energy channel, and RMF is the energy redistribution matrix. In X-ray imaging analysis, we adopt equation 1 as a simplification of equation 2, in the sense that all the energy-dependent factors have a typical value in the given energy range. For each source, $Counts$ within an aperture of a given EEF is measured from the X-ray image with background subtracted in some way, and $Exp_0 \times Vig$ can be read from the vignetted exposure map. The only missing piece of information to calculate source flux is $Area_0$, the on-axis effective area, which is intrinsic to the instrument and stored in the on-axis ARF curve (as displayed in Fig. 1). Therefore, a convenient strategy is to calculate a source count rate that is corrected for vignetting and PSF incompleteness, and use a source-independent $Area_0$ for conversion between source count rate and source flux. For better accuracy, the averaging of the energy-dependent factors in the given band should be done assuming an appropriate source spectral shape, as will be introduced in § 4.
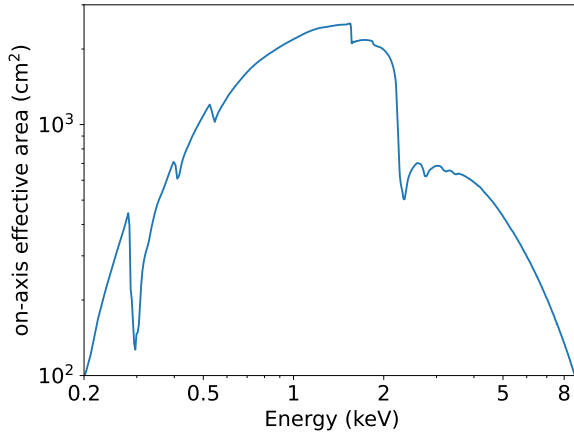
Figure 1. On-axis effective area of the seven TMs of eROSITA.

By doing aperture photometry at source positions, eROSITA catalogs present the total counts inside small apertures measured from the X-ray image and the background image using the task `apetool`, that is, the total aperture counts APE_CTS and the background aperture counts APE_BKG. Dividing the net aperture source counts (APE_CTS-APE_BKG) by the vignetted exposure time (APE_EXP) and the

EEF (APE_EEF), the net source count rate can be calculated and corrected for vignetting and PSF incompleteness.

By fitting the X-ray image and background map with the PSF model, eROSITA catalogs also present the net source counts ML_CTS and source count rate ML_RATE. ML_RATE is corrected for both vignetting and PSF incompleteness. ML_CTS, calculated by multiplying ML_RATE by the vignetted exposure map, is only corrected for PSF-incompleteness.

For Diffuse emission without any brightness gradient, we can drop the item of EEF in equation 1 and rewrite it as

$$\frac{Counts}{PixelArea} = \frac{F_p}{PixelArea} \times Exp_0 \times Area_0 \times Vig, \tag{3}$$

where $PixelArea$ is the area of a pixel in degree^2. So that the ECF between the vignetting-corrected surface count rate (per degree^2) and the surface brightness is identical to that for point sources.

Skipping PSF-incompleteness, the count rate of diffuse emissions can be calculated by subtracting background from the image and dividing the net counts by the vignetted exposure map.

3. X-RAY SPECTRAL CONCEPTS

3.1. *Flux and X-ray photon counts*

Under the framework of Xspec, the flux of a spectral model in a given energy band can be considered differently in the two cases introduced at the beginning of § 2. By default, since the standard keyword AREASCAL is set to 1, flux is in units of erg cm^{-2} s^{-1} , which is appropriate for point sources. In the case of diffuse emission, by setting AREASCAL to the geometric area of the extraction region in units of deg^2, the measured flux becomes surface brightness in units of erg cm^{-2} s^{-1} deg^{-2}.

We use the eSASS task `srctool` to extract eROSITA spectra and corresponding response files. The spectrum file stores the aperture photon counts in each energy channel. Both the instrument's intrinsic characteristics and source-dependent factors that affect the photon counts are stored in the response files (ARF and RMF). Spectral fitting software like Xspec could convolve the spectral model with the response files to predict the detected photon counts, which can then be compared with the real data in the spectrum file.

3.2. *Exposure time and ARF*

In X-ray imaging analysis, the exposure time in the exposure map is defined corresponding to a given sky position. In the spectrum extracted by `srctool`, the "EXPOSURE" keyword stores the total exposure time during which at least one pixel of the extraction aperture is in the FOV. It is defined corresponding to a region rather than a position. In scanning mode, since extraction region is sometimes partially in the FOV, the spectral exposure time is larger than Exp_0, the exposure depth at the source

position. So, the definition of EXPOSURE causes a region-covering incompleteness in scanning mode observations. For point sources, since the extraction apertures are small, the region-covering incompleteness is negligible, and EXPOSURE $\gtrapprox Exp_0$.

The ARF file created by the task `srctool` stores the effective area in the SPECRESP column, which is corrected for all the three factors that impact the captured photon counts, that is, vignetting, PSF incompleteness correction, and region-covering incompleteness correction. Vignetting factors are stored in the CORRVIGN column. PSF incompleteness and region-covering incompleteness are combined into one correction factor CORRPSF [1]. . In the case of small extraction apertures for point sources (`srctool` must be run with psftype=2D_PSF), region-covering incompleteness is minor and the CORRPSF is dominated by PSF incompleteness (EEF). In the case of large extraction regions for diffuse emission (`srctool` must be run with psftype=NONE), PSF correction is skipped and the CORRPSF stores the region-covering incompleteness correction factor.

The EXPOSURE keyword and the ARF are a symbiotic combination. The EXPOSURE is only meaningful when the region-covering incompleteness in the ARF is considered, and the ARF is only valid during the EXPOSURE time. It is common that X-ray astronomers plot X-ray spectra in units of counts s^{-s} keV^{-1} and compare the spectra of the same source obtained at different epochs. Such count rate values calculated using only the EXPOSURE time but not the ARF could be wrong in the case of eROSITA scanning observation, especially when the extraction region is large and thus EXPOSURE$> Exp_0$. Even for point sources with small extraction apertures, the comparison above is not accurate either, because the source vignetting and EEF are variable and depend on the trace of the source moving across the FOV.

3.3. *Area and ARF*

X-ray spectrum file has a standard keyword "BACKSCAL" in the header. Generally it stores the geometric area of the extraction region. In the case of eROSITA, `srctool` calculates BACKSCAL as the exposure-weighted average area (in degree^2) of intersection of the extraction region with the FOV, and saves the geometric area of the extraction region in a nonstandard keyword "REGAREA" (in degree^2). Because of the region-covering incompleteness, in the scanning mode, BACKSCAL is smaller than REGAREA. In the case of point sources with small extraction aperture, BACKSCAL $\lesssim$ REGAREA. The ratio between BACKSCAL and REGAREA is the region-covering incompleteness factor, which is applied to the effective area in the ARF. For diffuse emission spectra extracted without any PSF correction (psftype=None for `srctool`), the CORRPSF column of the ARF stores the region-covering incompleteness factor.

In the standard Xspec spectra fitting mode with the `srctool`-created ARF, the standard spectrum keyword "AREASCAL" should be set to 1 (default) for point sources, so that the flux of the spectral model is in units of erg cm^{-2} s^{-1} . For

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[1] Bad pixels are also taken into account by `srctool`

diffuse emission, AREASCAL should be set to REGAREA, so that the flux of the spectral model is averaged in this region and turned to surface brightness in units of erg cm^{-2} s^{-1} deg^{-2}. ARF is for sky X-ray signals that transmit through the mirror. It does not apply to the component of particle background, which is not from the sky but generated inside the telescope. The particle background component can be modeled without loading response files in Xspec. In this case, AREASCAL should be set to BACKSCAL, so that the region-incompleteness is corrected in the surface brightness of the model.

The effective area (SPECRESP) in the on-axis ARF reflects intrinsic characteristics of the telescope. The ARF of TM0 is a sum of the ARF of the seven TMs (see more details about how `srctool` combines multiple TMs in the `srctool` document and Liu et al. (2022)). In an ARF extracted at a fixed position (very small region), the CORRVIGN stores the averaged vignetting curve, which is determined by the instrument characteristics and the trace of the position in the FOV. However, if extracted from a large region in survey mode, the ARF does not directly reflect instrument characteristics any more, because of the region-covering incompleteness. Extracted from a larger region, the ARF effective area becomes smaller because it is averaged in a longer EXPOSURE, and the CORRVIGN becomes smaller too.

4. ENERGY CONVERSION FACTOR

4.1. *ECF, for convenience*

The directly measured quantity of source brightness, count rate, depends on both the spectra of the emissions and the instrument throughputs (responses). Spectral fitting mimics the process of emissions transmitted through the instrument throughputs and provides an accurate evaluation of source fluxes based on the measured photon counts. Since the instrument characteristics are broadly constant (but see Liu et al. 2017, for the example of Chandra), for a particular type of astronomical object with a typical spectral shape, an energy conversion factor (ECF) can be used for conversion between count rates (count/s) and physical fluxes (erg cm^{-2} s^{-1}). Here we define

$$ECF = \frac{Count\ rate}{Flux},$$

thus it is in units of counts cm^2 erg^{-1}. Note that some authors might prefer to define it as

$$ECF = \frac{Flux}{Count\ rate}.$$

ECF is an estimate of how efficiently the full hardware + software system converts incoming X-ray flux (with an assumed spectral shape) into count rate reported by imaging analysis.

We use the spectral fitting software Xspec, but only make use of its forward folding function, which mimics the process of X-ray emissions transmitted through the X-ray mirrors and captured by the detector. The forward folding function predicts the

detected count rate for a given spectral model and a set of response files. An ECF can be calculated as the ratio between the input model flux and the predicted count rate. It provides a convenient way of connecting X-ray data and physical models, either calculating source fluxes from X-ray data or predicting X-ray data based on theoretical models, bypassing the time consuming spectral analysis.

It is essential that the Xspec predicted count rate must be defined identically to that in the imaging analysis, but it is not true with the standard `srctool`-extracted ARF. As discussed in § 2.3, it is the most convenient to define ECF on the "full" count rate that is corrected for the source-dependent vignetting and PSF incompleteness, such that the ECF is determined by instrument characteristics and independent of source position. Loading in Xspec the on-axis ARF, which stores the uncorrected telescope effective area, the predicted count rate is equivalent to this "full" count rate.

4.2. *Various ECF*

ECF is the conversion factor between count rate and flux. In the simplest case, it can be between the observed "full" count rate and the observed flux in the same energy band. However, ECF can be defined in various ways in six aspects. To calculate an ECF for a particular goal, one needs to answer the following six questions.

1. **Which instruments?**

The ARF file "onaxis_tm0_arf_filter.fits" corresponds a combination of seven TMs of eROSITA. The seven TMs of eROSITA are broadly identical, except in the very soft band below 0.5 keV. If using only one TM, the effective area and thus the predicted count rate of a source will be seven times smaller. So is the ECF.

Please check eROSITA website for any possible update of the ARF and RMF.

2. **Which event filters?**

The ARF and RMF [2] were extracted with the event flag filter 0xE000F000 and event pattern filter PATTERN$\leqslant$15. If using a different filter, for example, selecting only single-pattern events (PATTERN==1), the predicted count rate of a source will be smaller. So is the ECF.

3. **Which spectral model?**

ECF is model dependent. Specifically, it only depends on the spectral shape and not the normalization. Usually, a powerlaw model is adopted for AGN. When an unique ECF is used to convert the count rates in an X-ray catalog to fluxes, one must keep in mind that the intrinsic scatters of spectral shapes are ignored. The uncertainty caused by spectral shape variability is larger in broader energy bands and smaller in narrower bands. However, this fact does not leads to a simple solution of using multiple narrow bands instead of one broad band, because the

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[2] In the current version of eSASS (eSASSusers_211214), the selection of PATTERN threshold through the PAT_SEL option is reflected in the normalization of RMF but not ARF. It might change in future eSASS versions.

photon-starving nature of X-ray emissions might cause large uncertainties in other aspects of imaging analysis in narrow bands.

4. Which energy bands?

The count rate and the flux do not have to share the same energy bands. In the simplest case, ECF is based on a spectral model with redshift= 0. But one could introduce redshift into the model and perform k correction based on the model asumption.

5. Which flux?

The models adopted for the measurements of count rate and flux do not have to be identical either. For example, by measuring the flux of an unabsorbed emission model and the predicted count rate of this model under a uncertain level of absorption, one can include absorption correction in the ECF and use it to calculate absorption corrected flux from observed count rate.

6. Which count rate?

Generally, the count rate should be corrected for the source-dependent vignetting and PSF incompleteness, like ML_RATE in eROSITA catalogs. To see if a theoretically predicted source signal is detectable in the eROSITA survey, one would like to know the photon counts that are actually captured by eROSITA, i.e., vignetted. However, vignetting is nonuniform in eROSITA surveys. One has to assume a typical case of scanning observation to make this prediction. It might be done in two ways, depending on the resources that are available. If both vignetted exposure maps and raw exposure maps of the survey are available, the vignetting factor can be estimated as the ratio between them. One could first use the standard ECF to convert flux to vignetting-corrected count rate, and then multiply it by the typical vignetting factor. Alternatively, if the spectra responses of a typical source in the survey are available, one could adopt a vignetted ARF instead of the on-axis ARF to calculate the ECF, which converts flux to vignetted count rate. Such an ARF can be created from a `srctool`-extracted ARF, in which SPECRESP has been corrected for vignetting (CORRVIGN) and PSF (or region-covering) incompleteness (CORRPSF). One could uncorrect SPECRESP as follows, so that the resultant ARF can be used in Xspec to mimic the effect of vignetting but not others.

```
ftcopy An_ARF.fits"[1][col ENERG_LO,ENERG_HI,SPECRESP=
    SPECRESP/CORRPSF]" ARF_with_vignetting.fits
fparkey SPECRESP ARF_with_vignetting.fits[1] EXTNAME add
    =yes #guarantee that it has a standard extension name
```

4.3. *Examples of eROSITA ECF*

The Python3 code below gives an example of calculating eROSITA ECF using pyXspec[3]. Please download the eROSITA RMF (onaxis_tm0_rmf.fits) and the on-axis ARF of the seven TMs (onaxis_tm0_arf_filter.fits). Based on them, the code mimics an eROSITA exposure without vignetting or PSF incompleteness, and then calculates the ratio between the vignetting-corrected count rate and the model flux.

```python
from xspec import *

ARF='onaxis_tm0_arf_filter.fits'
RMF='onaxis_tm0_rmf.fits'

Model('TBabs*powerlaw') #Absorbed powerlaw model
AllData.fakeit(1,FakeitSettings(response=RMF,arf=ARF,
    exposure=100),noWrite=True) #Just to set up the
    framework

Gamma=1.7
AllData.ignore('0-.5 2.0-**') #The energy band to measure
    observed count rate
Xset.chatter=0
Xset.abund='wilm'

ms=AllModels(1)
d1=AllData(1)
ms.powerlaw.PhoIndex.values=Gamma
ms.TBabs.nH.values=0 #Unabsorbed
AllModels.calcFlux('0.5 2.')
Flux0=d1.flux[0] #Save the flux of the unabsorbed model
print(f'''Assuming an unabsorbed powerlaw with Gamma={
    Gamma},
0.5-2 keV count rate: {d1.rate[3]:f} (counts/s),
Model flux 0.5-2 keV: {Flux0:g} (erg/cm^2/s),
0.5-2 -> 0.5-2  ECF = {d1.rate[3]:f}/{Flux0:9g} = {d1.rate
    [3]/Flux0:9g} (cm^2/erg),
which is used for conversion between the 0.5-2 keV flux
    and the 0.5-2 keV count rate that is corrected for both
     vignetting and EEF.''')

logNH=21
ms.TBabs.nH.values=10**logNH*1e-22
```

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[3] https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/python/html/index.html

```
AllModels.calcFlux('0.2 2.3')
print(f'''\nAssuming logNH={logNH},
0.5-2 keV count rate: {d1.rate[3]:f} (counts/s),
Model flux 0.2-2.3 keV: {d1.flux[0]:g} (erg/cm^2/s),
0.5-2 -> 0.2-2.3  ECF = {d1.rate[3]:f}/{d1.flux[0]:9g} = {
    d1.rate[3]/d1.flux[0]:9g} (cm^2/erg),
which is used for conversion between the 0.5-2 keV count
    rate and the 0.2-2.3 keV observed flux of the obscured
    powerlaw model.
0.5-2 -> 0.5-2  absorption corrected ECF = {d1.rate[3]:f
    }/{Flux0:9g} = {d1.rate[3]/Flux0:9g} (cm^2/erg),
which is used for conversion between the 0.5-2 keV count
    rate and the 0.5-2 keV absorption corrected flux of the
     powerlaw model.''')
```

If you want to use the standard Xspec instead of the Python version, the calculation above can be implemented interactively with the following commands

```
XSPEC12> abund wilm #choose this abundance table for the
    absorption model
XSPEC12> model TBabs*powerlaw
        #and initialize the parameters, nH=0, PhoIndex
            =1.7
XSPEC12> fakeit nowrite none
        #and input the response file onaxis_tm0_rmf.fits,
            the ancillary file onaxis_tm0_arf_filter.fits
XSPEC12> ignore 0-.5 2.-**
        #select energy range for data
XSPEC12> flux 0.5 2.
        #get a flux of 2.2372e-09 ergs/cm^2/s
XSPEC12> show all
        #get Model predicted rate: 2618.09
XSPEC12> newp 1 0.1 #change NH from 0 to 1e21
XSPEC12> show all
        #get Model predicted rate: 2098.10
XSPEC12> flux 0.2 2.3
        #get a flux of 2.2897e-09 ergs/cm^2/s
```

4.4. eROSITA ECF assuming a power law

In order to show how spectra shape affects eROSITA ECF, we assume an obscured powerlaw model ("TBabs*powerlaw" in Xspec), adopt a series of absorption column density N_H between $10^{19.5}$ and $10^{22.5}$ and powerlaw slope Γ between 1.4 and 2.6, and
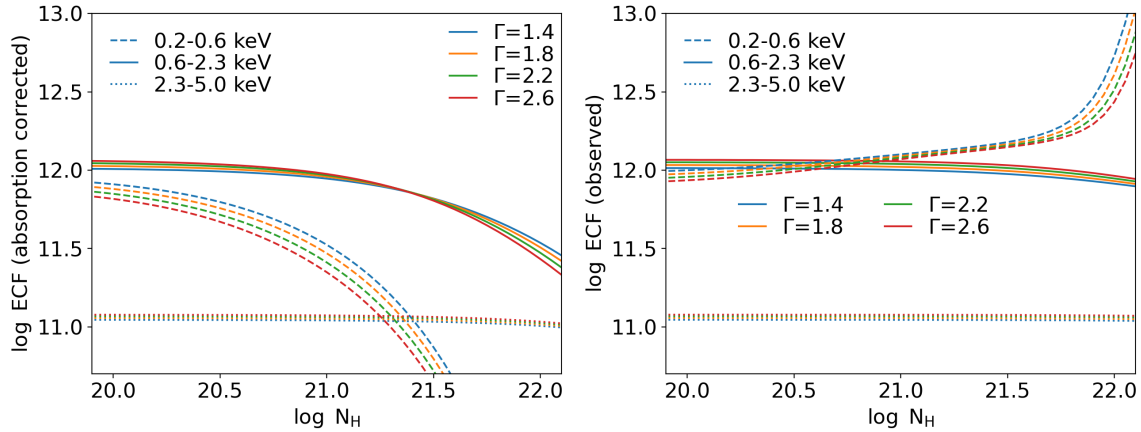
Figure 2. Assuming an obscured powerlaw model, the left and right panels display the ECF that are corrected and uncorrected for absorption, respectively, in three energy bands (in dashed, solid, and dotted lines) and assuming four powerlaw slopes (blue, orange, green, and red colors).

calculate two versions of ECF from count rate (corrected for vignetting and PSF incompleteness) to flux corrected and uncorrected for absorption respectively, in a few energy bands (0.2–0.6, 0.6–2.3, and 2.3–5 keV). The results are provided in the attached table "eRO_ECF_powerlaw.dat" and displayed in Fig. 2.

REFERENCES

Liu, T., Tozzi, P., Wang, J.-X., et al. 2017, ApJS, 232, 8, doi: 10.3847/1538-4365/aa7847

Liu, T., Buchner, J., Nandra, K., et al. 2022, A&A, 661, A5, doi: 10.1051/0004-6361/202141643