NuSTAR Spectral Analysis beyond 79 keV with Stray Light

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Abstract

Due to the structure of the NuSTAR telescope, photons at a large off axis (>1°) can reach the detectors directly (stray light), without passing through the instrument optics. At these off-axis angles NuSTAR essentially turns into a collimated instrument and the spectrum can extend to energies above the Pt K edge (79 keV) of the multilayers, which limits the effective area bandpass of the optics. We present the first scientific spectral analysis beyond 79 keV using a Cygnus X-1 observation in StrayCats: the catalog of stray light observations. This serendipitous stray light observation occurred simultaneously with an INTEGRAL observation. When the spectra are modeled together in the 30–120 keV energy band, we find that the NuSTAR stray light flux is well calibrated and constrained to be consistent with the INTEGRAL flux at the 90% confidence level. Furthermore, we explain how to treat the background of the stray light spectral analysis, which is especially important at high energies.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); Calibration (2179); Black hole physics (159)

1. Introduction

The X-ray detectors on board the Nuclear Spectroscopic Telescope Array (NuSTAR; Harrison et al. 2013) are able to detect photons in the energy range between 2 and 160 keV. Due to the separation between the optics and the detectors and the Pt/C multilayers deposited on the mirrors, NuSTAR is able to focus hard X-ray photons in the 3–79 keV bandpass. However, because of the open geometry of the mast that connects the optics and the focal plane modules (FPMs), photons can also reach the detectors without passing through the optics.

Sources within 1°–5° of the primary target cause stray light (SL), also referred to as “aperture flux”, and when bright enough it will leave a distinct circular pattern (Madsen et al. 2017a). This pattern is easy to predict and identify on the detectors, especially when produced by a single source. Although the position angle of the observatory is typically optimized to minimize the stray light pattern for a given observation (since it may cause additional background for the focused target), in some cases it is unavoidable (Grefenstette et al. 2021). These serendipitous observations of sources that are not the focused target can be of great use to perform additional science for several reasons: (1) they can be used to monitor a source even though a focused observation was not scheduled; and (2) they can be used to expand the NuSTAR energy range above 79 keV since the stray light does not go through the optics where the Pt K edge of the multilayer coatings drastically decreases the response of the instrument.

Madsen et al. (2017b) considered stray light observations of the Crab during two different epochs and they showed that it is possible to reconstruct the response for stray light sources, and to perform spectral analysis of X-ray sources. Grefenstette et al. (2021) presented the first stray light catalog (StrayCats) wherein they examined 1400 NuSTAR observations up to mid-2020 and identified nearly 80 stray light sources. The StrayCats has recently been updated (StrayCats v2; Ludlam et al. 2022) to include additional NuSTAR observations up to the beginning of 2022. Moreover, StrayCats v2 contains new information to characterize the behavior of the sources such as long-term MAXI and Swift’s Burst Alert Telescope (Swift/BAT) light curves of the stray light sources, region files to extract products, mean intensity for each stray light detection, and a proxy for the background level based on the “empty” detector region (excluding the stray light region and the primary source). Brumback et al. (2022) reported the first scientific timing analysis of a stray light source. They took advantage of the serendipitous stray light observations of SMCX-1 (a high-mass X-ray binary) to confirm the orbital ephemeris and study the shape of the pulse profile over time. They show that stray light observations are suitable to perform timing analyses of X-ray binaries.

In this work, we consider Cygnus X-1, a well-studied high-mass X-ray binary hosting a stellar mass black hole. This source is a great candidate to extend the high-energy limit of the NuSTAR spectrum since it is one of the brightest persistent X-ray binaries in the sky that exhibits a hard X-ray spectrum in the sky (e.g., Del Santo et al. 2013; Grinberg et al. 2013; Walter & Xu 2017; Cangemi et al. 2021). We perform the first spectral analysis of a stray light observation and demonstrate that it is possible to extend spectral analysis above 79 keV. We
Table 1
Some Characteristics of the NuSTAR Stray Light Observation Analyzed in This Work

| ObsID          | Date     | SL Source | Primary | Exposure (s) | Area SL (cm²) |
|---------------|----------|-----------|---------|--------------|---------------|
| 90501328002   | 2019 June 4 | Cygnus X-1 | 4U 1954+31 | 40,791       | 0.82          |

compare the stray light energy spectrum with the INTEGRAL-IBIS spectrum (Lebrun et al. 2003; Ubertini et al. 2003). The NuSTAR flux at high energies (above 30 keV) of the stray light is equivalent to the INTEGRAL-IBIS flux within a 90% confidence level, thus demonstrating that the nominal NuSTAR energy band can be extended to higher energies when properly accounting for the background.

2. NuSTAR Stray Light Data

Cygnus X-1 was observed three times in stray light prior to 2021. We consider observation 90501328002, since this is the only observation with simultaneous INTEGRAL exposure. Table 1 provides information about the observation. Stray light is visible on Det #2 and marginally on Det/#1 of FPMA as shown in Figure 1. The FPMB detectors do not show evidence of stray light contamination, thus no analysis of FPMB is needed. The primary source (4U 1954+31) is positioned in Det #0 and affects a portion of the field of view separate from the stray light region, thus it is easy to exclude during the analysis. We use SAOImage DS9 to define the circular segment region where the stray light is present (see thick red line in Figure 1). We define the stray light region using a circular region with a radius of 500′ and centered outside the field of view since that area does not contribute to the event file.

The background extraction is problematic for this observation. The aperture stops in front of the detectors are designed to block the low energy stray light photons producing the characteristic stray light pattern in Figure 1. However, the materials of aperture stops become transparent to the high-energy photons above 50 keV (Madsen et al. 2017a). Figure 2 shows the NuSTAR field of view filtered for energies above 50 keV that have been smoothed with a Gaussian function (radius = 5 and σ = 2). The Cygnus X-1 stray light contaminates all four detectors, which makes it impossible to select a background region valid for the high energies. Wik et al. (2014) showed that above 30 keV the dominant background component is the internal background of the instrument, which consists of the internal continuum and emission lines (see nuskybgd9 and Figure 10 in Wik et al. 2014). For the purpose of this work we can neglect the contribution of the internal lines and focus on correctly estimating the internal continuum background that dominates over the internal lines above 120 keV. Therefore, when we fit the energy spectrum we consider up to 160 keV, and we use a constant background model with free normalization that is mainly constrained by the counts in the 120–160 keV range.

We produce stray light science products (including the flux-energy spectrum) using the StraylightWrapperExample notebook in the nustar-gen-utils.10 In particular, we use the

functions “make_det1_image” to create the image, “extract_det1_events” to extract the event file, and “make_det1_spectra” together with “make_exposure_map,” “make_straylight_arf,” and “straylight_area” to create the energy spectrum and the auxiliary response file response accounting for the correct area of the stray light. The response generation tools for stray light are consistent in flux normalization with the nominal configuration of the CALBD.
Figure 3. Top panel: Swift/BAT (black) and MAXI (blue) long-term daily light curves of Cygnus X-1. Bottom panel: hardness ratio as a function of time of Cygnus X-1 computed using MAXI energy bands. In both panels the red dashed lines indicate when the stray light observation was performed and the orange lines indicate NuSTAR pointed observations of Cygnus X-1.

3. INTEGRAL Data

INTEGRAL observed Cygnus X-1 in 2019 from May 24 until June 5. We select the portion of this observation simultaneous with NuSTAR to obtain the same exposure (∼40 ks). For data reduction we use the off-line scientific analysis (OSA) tools version 11.1. For this work we only make use of data from the ISGRI, the upper detector layer of the IBIS instruments. We generate a spectrum on a logarithmic energy grid from 25 to 400 keV with 30 bins, but only consider energies above 30 keV during the spectral analysis due to the low energy threshold of ISGRI.

4. Spectral Analysis

We generate light curves and calculate hardness ratios from the stray light observations of Cygnus X-1 to characterize the state of the source. We analyze energy spectra of simultaneous NuSTAR and INTEGRAL observations to check the stray light cross calibration at high energies. Figure 3, the top panel, shows MAXI and Swift/BAT light curves of Cygnus X-1 around the time the stray light observation was performed (red dashed line). The bottom panel shows the hardness ratio calculated using two MAXI bands (see y-axis label in the figure). Looking at the hardness ratio versus time, we infer that the source is caught during the transition from the soft to the hard state when it was observed by NuSTAR in stray light. The MAXI and Swift/BAT light curves show that the thermal component is still present in the flux-energy spectrum. Since the stray light observation allows us to extend the energy range above the optics bandpass, we consider the NuSTAR spectrum up to 160 keV, fitting for the background with a constant model. The value of the background is mainly determined by the 120–160 keV energy range. Again, we consider the INTEGRAL-IBIS spectrum strictly simultaneous with the NuSTAR stray light observation in order to match the exposure of the two instruments. Figure 4 shows how the relative short timescale variability of the source is seen consistently by the two instruments. We performed several fits to the energy spectrum with different combinations of models. All the parameter values of our best-fit results are listed in Table 2 and Table 3.

We start by comparing the two instruments above 30 keV. In this case, we choose to perform the fit using both the Cash (Cash 1979) and \( \chi^2 \) statistic in xspec (Arnaud 1996). By definition, the Cash statistic accounts for the errors based on the counts in each energy bin. The spectrum of INTEGRAL-IBIS has more than 8.5 million counts whereas the NuSTAR stray light spectrum has 5300 counts with the same exposure of 40 ks. Therefore, the INTEGRAL-IBIS spectrum dominates the fit when we use the Cash statistics. With the \( \chi^2 \) statistic, we can add a systematic error to the INTEGRAL-IBIS data; with 1% systematics, as suggested in the IBIS analysis user manual, the results change only slightly. Figure 5 shows the spectra fitted with a phenomenological cutoff power law (model 1) using the \( \chi^2 \) statistic. The two spectra do not show any significant deviation from the cutoff power-law model with \( \Gamma = 1.57 \pm 0.06 \) and high-energy cutoff at 99\(^{+9}_{-8}\) keV. We note that the cross calibration constant between the two instruments is 1.02 ± 0.03. This is a remarkably good agreement between the NuSTAR and INTEGRAL-IBIS fluxes that are constrained to be consistent within the 90% confidence level. We obtain the same result when the Cash statistic (cstat in xspec) is applied. In Table 2 we report the model flux for each of the instruments in the overlapping energy range (30–120 keV). In the case of NuSTAR, the value of the flux refers to the source model without considering the background.

When we consider the NuSTAR spectrum at lower energies, down to 3 keV (the lower limit of the nominal NuSTAR band), the absorbed cutoff power-law model cannot reproduce the shape of the spectrum. The top panel of Figure 6 shows the residuals of model 1 when we include channels below 30 keV for NuSTAR. The upturn at low energies cannot be accounted for by just adding a thermal component (e.g., diskbb) since the disk temperature reaches values above 1 keV, which is hotter than has been observed in the soft state of Cygnus X-1 (e.g., Tomsick et al. 2014). Moreover, accounting for the low energy excess with a thermal component reveals clear residuals.
around the iron line (6.4 keV) region suggesting that the reflection emission contributes to the spectrum.

Since the stray light spectrum is well calibrated at low energies (Madsen et al. 2017b), we proceed focusing on the NuSTAR stray light data. It is possible to fit the energy spectrum with a typical hard state model—model 2: TBabs*(cutoffpl + relxill). We fix the neutral column index at $N_H = 6 \times 10^{21}$ cm$^{-2}$ as is typical for the source (e.g., Gilfanov et al. 2000; Tomsick et al. 2014). Due to the relatively high lower limit of the NuSTAR energy band (3 keV), it is not relevant to let the hydrogen column density to be free in the fit. Figure 7 shows that model 2 leads to a good fit of the NuSTAR energy spectrum. There are no broad structures in the residuals and the narrow residuals around 30–40 keV are internal background lines (see nuskybgq Wik et al. 2014). The parameters are sensible for the soft-to-hard state transition of Cygnus X-1 (see Table 2).

Once we obtained an acceptable fit of the stray light spectrum with model 2, we reconsidered the INTEGRAL–IBIS spectrum. The bottom panel of Figure 6 shows the residuals of model 2 when we only account for the different cross calibration of the INTEGRAL–IBIS spectrum, but without refitting the model. It is clear that the curvature of model 2 is incompatible with the INTEGRAL–IBIS spectral shape. Thus we discard model 2.

We fit model 2 simultaneously to both the spectra with the continuum (cutoff power law) and reflection parameters free to vary (we refer to this fit as model 2b). The parameter values are listed in last column of Table 2. Even though the fluxes of the two instruments are still compatible, the fit is not statistically good, $\chi^2$/dof=1138/779. The high-energy cutoff and the disk inclination are unconstrained, and the index of the emissivity profile (Index1) is extremely low. Moreover, Figure 8 shows that model 2b presents some broad residuals in the NuSTAR spectrum around the Fe Kα emission line (6.4 keV) and the Compton hump ($\sim$20 keV). Model 2b cannot reproduce the shape of the two spectra simultaneously and we argue the best fit is driven by the higher signal to noise of the INTEGRAL–IBIS spectrum even with the addition of 1% systematic errors. Despite the fit result, model 2b strengthens our confidence in the flux calibration of the stray light spectrum above 30 keV. The flux difference between the two instruments, in the overlapping band, is within 6% at a 90% confidence level even for model 2b. We also note that there is some level of degeneracy between the presumed source model and the background level when the source and the background spectral shapes are similar, which is likely affecting the result for model 2b.

The poor fit of model 2b might be caused by the wrong shape of the continuum model (power law). It has been shown that the exponential cutoff of the cutoffpl model is not a good representation of the sharp drop of the data at high energies. However, when we considered a more physical model such as nthComp + relxillCp, the fit leads to the same conclusions, showing residuals very similar to the ones shown in Figure 8.

### 5. Discussion

We considered a stray light observation of Cygnus X-1 simultaneously with INTEGRAL in order to test the calibration of NuSTAR at energies above 79 keV. In this Section we discuss the flux calibration of the stray light energy spectrum.
and the background at high energies. We also attempt to fit the broadband energy spectra with slightly more complicated models.

5.1. NuSTAR above 79 keV and Background

The stray light observations present a great opportunity to study X-ray sources above 79 keV with NuSTAR. It is important to demonstrate that the stray light energy spectrum can be trusted above the nominal NuSTAR bandpass. We found that the NuSTAR flux is well calibrated and consistent with the INTEGRAL flux at the 90% confidence level. This allows us to utilize the energy range when stray light observations are performed.

Intentional stray light observations are performed by the NuSTAR team when a target is particularly bright in order to reduce the telemetry load. For example, the Crab was intentionally observed in stray light to calibrate the low energies (Madsen et al. 2017b), and also bright black hole binaries such as MAXI J1820+070 and MAXI J1535-571. In those cases, if the signal-to-noise ratio is high enough, it is possible to analyze simultaneously the stray light spectrum together with the focused light spectrum to study the source emission above 79 keV. This type of analysis is possible even for serendipitous stray light observations, although the pointed observations will always have a better signal-to-noise ratio below 79 keV.

### Table 3

| Parameters | Model X (χ²; Disk + Gaussian) | Model Y (χ²; High-energy Tail) |
|------------|-------------------------------|---------------------------------|
| Cross Calibration | 1.01±0.02 | 1.00±0.02 |
| Γ | 1.5±0.04 | 2.1±0.01 |
| E_cut [keV] | 99±3 | 500±50 |
| Norm | 1.8±0.2 | 6.0±0.1 |
| T_disk [keV] | 1.0±0.1 | --- |
| Norm_disk | 466±24 | --- |
| rexlill | Index1 | --- | 9±1 |
| Incl [deg] | --- | 76±2 |
| log(τ/erg cm s⁻¹) | --- | 1.7±0.1 |
| A_Fe [C] | --- | 10⁻⁴±⁻⁸ |
| Normoff | --- | 0.04±0.002 |
| Gaussian | LineE [keV] | 6.4 (fixed) | --- |
| Sigma [keV] | 1.5±0.1 | --- |
| Normgau | 0.07±0.02 | --- |
| High en pl | low E_cut [keV] | 100 (fixed) | --- |
| Γ | --- | 2.5±0.03 |
| Norm | --- | 2.2±2 |
| Flux and bkg | Normdeg | 1.8±0.2×10⁻⁴ | 1.8±0.2×10⁻⁴ |
| Flux30-120 keV Nu [erg cm⁻² s⁻¹] | 1.2±0.01×10⁻⁸ | 1.2±0.01×10⁻⁸ |
| Flux30-120 keV INT [erg cm⁻² s⁻¹] | 1.2±0.01×10⁻⁸ | 1.2±0.01×10⁻⁸ |
| χ²/dof | 850/780 | 944/777 |

**Notes.** The column density is always fixed to 6×10²¹ cm⁻². Statistical errors are quoted at a 90% confidence level.

a The high-energy cutoff is pegged to its upper limit (500 keV).
b The iron abundance is pegged to its upper limit (10).
c The slope of the high-energy slope tail is pegged to the upper limit (2.5).
The background is less trivial to evaluate. At high energies above 120 keV, as we explained in Section 2. The astrophysical contaminants all the detectors (Figure 2). Therefore, it is not possible to extract the background spectrum from a region. We caution the user about the background estimation, especially at high energies. We can reliably estimate the constant internal background by inspection of the flux level above 120 keV, as we explained in Section 2. The astrophysical background is less trivial to evaluate. At high energies (above 20 keV), the stray light can penetrate the aperture stops and contaminate all the detectors (Figure 2). Therefore, it is not possible to extract the background spectrum from a region.

5.2. NuSTAR and INTEGRAL

We found almost perfect agreement between the NuSTAR stray light and the INTEGRAL-IBIS flux in the overlapping band 30–120 keV. We also argue that the spectral shape in this band is the same, since we can jointly fit both spectra with a high-energy cutoff power law. However, when we simultaneously fit the two spectra in the extended 3–400 keV energy range, model 2b cannot reproduce the shape of the two spectra. We argue that since the source was caught during the state transition, the spectral analysis might require a more complicated model than the continuum + reflection addressed in our model 2b. Here we propose two phenomenological test models that consider extra components contributing only to the low or to the high-energy band, but not to the shared energy range of the two instruments.

Thermal emission + simple reflection (model X). In this first case we consider the model TBabs*(diskbb + cutoffpl + Gauss). The model accounts for the soft excess in the NuSTAR spectrum with a strong thermal component, which is not required when we fit only NuSTAR. The reflection is simply a broad Gaussian line at 6.4 keV without a Compton hump, thus there is no contribution to the INTEGRAL-IBIS energy band. Figure 9 shows the best-fit model and the residuals. The residuals do not show particular structures and the fit has an acceptable reduced $\chi^2$ of 850/755. The second column in Table 3 shows the parameter values of model X. All the parameters are tied between the two instruments, apart from the cross calibration constant. We note that this model reproduces the shape of the broadband spectrum by accounting for the soft-energy excess in the stray light using two additional components (thermal disk blackbody and iron line emission), neither of which contribute significantly at higher energies (above 20 keV). However, we are inclined to reject this model.

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**Figure 7.** Best fit of the NuSTAR energy spectrum with model 2 (TBabs*(cutoffpl + relxill)). The hydrogen column density is fixed to $6 \times 10^{20}$ cm$^{-2}$. Top panel: flux-energy spectrum in units of counts per seconds per keV, both data and model. The solid line is the total model. The nonsolid lines are the additive components of the model: the dotted line is the background model, the dashed line is the continuum, and the dashed–dotted line is the reflection. Bottom panel: residuals of the best fit.

**Figure 8.** Best fit of the NuSTAR (black) and INTEGRAL-IBIS (red) spectra with model 2b. Top panel: flux-energy spectrum in units of counts per seconds per keV, both data and model. The solid lines are the additive components of the models: the dotted line is the background model, the dashed lines are the continuum, and the dashed–dotted lines are the reflection. Bottom panel: residuals of the best fit.

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https://www.physics.nist.gov/PhysRefData/Xcom/html/xcom1.html
because the temperature of the disk is too high to reasonably represent the Cygnus X-1 hard state, and the lack of an iron edge and Compton hump does not match our physical understanding of the reflection process.

High-energy tail (model Y). In this second case we consider a model component contributing at high energies in addition to model 2b. This high-energy component has been detected and studied in Cygnus X-1 since the source was observed at high energies (>100 keV; e.g., Ling et al. 1987; Phillips et al. 1996; McConnell et al. 2002; Bouchet et al. 2003; Pottschmidt et al. 2003; Zdziarski et al. 2012, 2014; Cangemi et al. 2021). Our attempt is to understand if neglecting this component in our model could artificially lead to a harder power-law spectrum, biasing our results at low energies when INTEGRAL and NuSTAR spectral slopes are tied together. We use the model TBabs*(cutoffpl + relxill + expabs*powerlaw).

The last component is our simplistic attempt to account for the high-energy tail (see Connors et al. 2019). A more physical model is beyond the scope of this work. For a complete analysis of this subject, we refer to Cangemi et al. (2021), which is one of the most recent attempts to fit the Cygnus X-1 spectrum with Comptonization emitted by a hybrid population of thermal and nonthermal electrons (but see also the references previously mentioned in this paragraph). Figure 10 shows the best-fit model and the residuals performed with model Y. The high-energy tail component contributes to both the instruments and it considerably softens the power-law index ($\Gamma = 2.15^{+0.05}_{-0.03}$). We fixed the upper limit of the high-energy power-law index to 2.5 and the lower limit of the exponential low energy cutoff to 100 keV, since without these constraints the additional component tends to compensate for the curvature introduced by the Compton hump in the INTEGRAL-IBIS spectrum at relatively low energies. This would lead the high-energy component contributing to the 30–40 keV energy range, and below it, which is not its physical purpose. The fit prefers a much lower ionization of the disk $\xi = 1.7 \pm 0.1$ compared to the previous models. Despite the fact that model Y should be considered a more physical model than model 2b, the fit is statistically unacceptable with a reduced $\chi^2$ value of 944/777. Moreover, the INTEGRAL-IBIS residuals show that the new component overestimates the high-energy flux. For all these reasons we tend to discard model Y.

We also tried to fit the high-energy tail with the model expabs*cutoffpl with $\Gamma$ fixed at 2.5 and the high-energy cutoff tied to the continuum component. This model significantly improves the chi squared, 913 for 777 dof, but it remains too high to accept this fit. Moreover, this fit does not require the continuum component that has a normalization compatible with zero. This is clearly nonphysical. If we remove the reflection component the fit shows significant residuals around the iron line.

Unfortunately, these tests seem to be inconclusive to establish the model that can fit the broadband spectrum of the two instruments. We think there is more complexity in the spectral shape of Cygnus X-1, especially when such a broadband energy range is considered, and we postpone a more extensive analysis when pointed and stray light observations are performed simultaneously with INTEGRAL observations.

As a final remark we cannot completely rule out the possibility that there is cross calibration slope difference between the two instruments since we did not find an acceptable model to fit the broadband NuSTAR+INTEGRAL spectrum. We note that the best measurement of the Crab spectrum using NuSTAR stray light (Madsen et al. 2017a) produces a power-law slope from the Crab of $\Gamma = 2.106 \pm 0.006$. This is consistent with the spectral shape as reported by the calibration measurement using INTEGRAL-IBIS, which reports a slope of $2.13 \pm 0.03$ (Jourdain et al. 2008), though there is some evidence for a spectral break above 100 keV measured by INTEGRAL-IBIS. The NuSTAR stray light

Figure 9. Best fit of the NuSTAR (black) and INTEGRAL-IBIS (red) spectra with model X. Top panel: flux-energy spectrum in units of counts per seconds per keV, both data and model. The solid lines are the total models. The nonsolid lines are the additive components: the dotted line is the background model, the dashed line is the continuum, the dashed–dotted line is the Gaussian, and the dashed–dotted–dotted line is the thermal disk. Bottom panel: residuals of the best fit.

Figure 10. Best fit of the NuSTAR (black) and INTEGRAL-IBIS (red) spectra with model Y. Top panel: flux-energy spectrum in units of counts per seconds per keV, both data and model. The solid lines are the total models. The nonsolid lines are the additive components: the dotted line is the background model, the dashed line is the continuum, the dashed–dotted lines are the reflection, and the dashed–dotted–dotted lines are the high-energy tail. Bottom panel: residuals of the best fit.
observations of the Crab are background-dominated at these energies. However, the fact that the two instruments provide similar power-law indices indicates that a relative slope offset between the two is unlikely.

The spectral index for model 2b $(1.85^{+0.04}_{-0.05})$, which considers only the NuSTAR spectrum, is significantly softer than for model 1 $(1.57 \pm 0.06)$. This is due to the lack of high-energy curvature in model 2b ($E_{\text{cut}} \sim 500$ keV). This arises from a mismatch in the statistical power of the INTEGRAL-IBIS data (even with added systematic error) and the NuSTAR data at low energies and is an example of the complexity of fitting data across such a wide bandpass. We argue that the curvature of the model introduced by the reflection at high energies might be either incorrect for this source or might require additional complexity due to the state of the source. We stress the importance of further investigations on comparing the NuSTAR and INTEGRAL energy spectra especially at high energies in other sources. This analysis will be the subject of future work.

6. Conclusions

We analyzed the stray light flux-energy spectrum of Cygnus X-1, extending the NuSTAR energy range to 3–120 keV. We compare the stray light flux at high energies with the flux of the INTEGRAL-IBIS spectrum extracted during a simultaneous observation. We described how to account for the internal background that is the only source of background at high energies (above 30 keV). We demonstrated that the astrophysical background can be neglected at low energies since it is only a few percent of the source flux. Based on the fact that the instrument produces the same spectral shape in the overlapping energy bands and produces compatible fluxes in the overlapping energy bands, we conclude that the NuSTAR stray light data can be used for scientific purposes up to 120 keV.

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