

DUST BUSTERS:
THE EFFECTS OF DUST SCATTERING ON OBSERVATIONS OF X-RAY BINARIES

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ABSTRACT

Black hole X-ray binaries contain a black hole that accretes gas from a companion star, producing bright X-rays. By fitting their X-ray spectra with astrophysical models, we can estimate key parameters such as the black hole's mass and spin. However, the observed spectrum is modified on its way to the telescope by interstellar dust, which scatters photons and can bias spectral fits if not modeled properly.

The standard spectral analysis software, XSPEC, contains the xscat model, which accounts for dust scattering but assumes an extraction-region geometry that does not match the way SWIFT/XRT data are actually extracted. Secondly, bright sources are observed in the Windowed Timing (WT) mode to reduce pileup, yet residual pileup remains and is removed during data cleaning by excising the central region. xscat ignores this excision, biasing the model calibration and leading to underestimates of the black hole spin. The goal of this project is to resolve this mismatch by developing an improved model, xscatxy, that uses a consistent extraction geometry and accounts for the removed section of the data.

With these two corrections, I make SWIFT data more suitable for black hole spin estimation. The new model, xscatxy is planned to be incorporated into XSPEC, which is maintained by NASA.

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I. Introduction

1.1 Black Holes and X-ray Binaries

Black holes are major architects of the cosmos. They shape spacetime through their intense gravity and play crucial roles in the dynamics of galaxies, stars, and planetary systems. Studying black holes helps us understand general relativity, whose effects are already incorporated into technologies such as satellite timing and navigation. In particular, particles ejected in relativistic jets can be a source for star formation. Black hole spins are an important property in astrophysics because spin strongly affects how jets are launched and how powerful they can be, interacting with magnetic fields. Spin also serves as a record of a black hole's history, preserving clues about how it has formed and evolved through accretion and mergers.

An X-ray binary consists of two orbiting stars. One, called the 'donor' star, gives off mass to its partner, which can be a neutron star or, usually, a black hole. The accreting matter's gravitational energy is transformed into thermal energy as it falls into the black hole. This superheats the accretion disk to millions of Kelvin and thereby releases X-rays.

The spectrum of light that the accretion disk emits is dynamic. When a lot of mass is rapidly falling in, the disk has high luminosity and is mainly composed of low energy (soft) X-rays. When the accretion rate is slow, it is less luminous and is dominated by high energy (hard) X-rays from the corona.

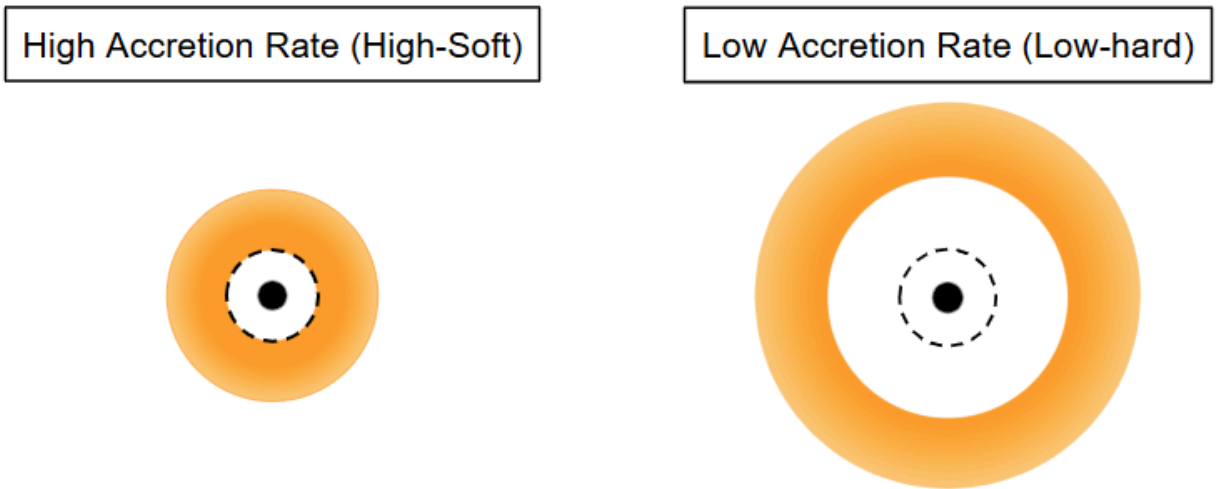


Fig. 1 When the accretion rate is high, the accretion disk extends close to the black hole, reaching all the way to the Innermost Stable Circular Orbit (ISCO), which is shown with the dashed lines.

1.2 Disk Continuum Fitting

The radius of the Innermost Stable Circular Orbit (ISCO) is dependent only on the spin of the black hole. We cannot actually see the ISCO since it is a theoretical construct of the Kerr model of black holes but we expect the accretion disk extends to the ISCO when the X-ray binary is in the high-soft stage. Therefore, we can find out the spin of the black hole from the inner radius of the accretion disk, which is manifested in the spectrum. This is the basis of *disk continuum fitting*, (Zhang et al. 1997) a method that determines how fast the black hole is spinning by modeling the spectrum of the light we observe.

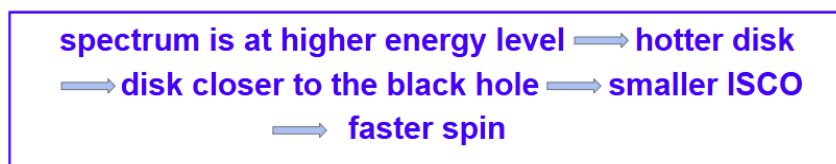


Fig. 2 How the spectrum of X-rays emitted by the disk gives us information about the spin: the basis of disk continuum fitting.

For analysis of astrophysical spectral data, XSPEC is the standard software package for X-ray spectral fitting. It is developed and maintained as part of NASA’s HEASoft/HEASARC software suite, and it provides a broad library of additive and multiplicative models for common physical processes—such as thermal emission, Comptonization, photoelectric absorption, dust scattering, and relativistic accretion-disk spectra—as well as tools for forward-folding models through instrument responses and estimating best-fit parameters and uncertainties.

Kerrbb is an XSPEC spectral emission model of a geometrically thin, optically thick accretion disk around a Kerr (spinning) black hole. It computes the disk spectrum with general-relativistic effects (Doppler boosting, gravitational redshift, light bending), and uses parameters, such as the black hole mass, spin, mass accretion rate, inclination, and distance as well as a spectral hardening factor. It is used to fit the disk-dominated (“high/soft”) state and infer spin via continuum fitting.

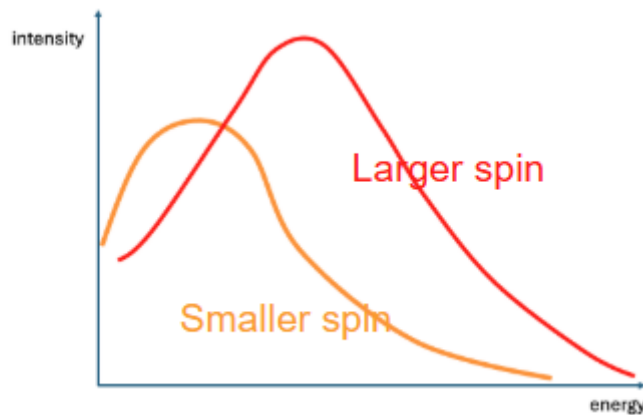


Fig. 3 The model spectra of kerrbb have a peak intensity dependent on the spin of the black hole, as seen from this diagram.

1.3 Extinction Models: Absorption and Scattering

In order to apply the disk continuum model, however, we need to consider the alteration of X-rays by the interstellar medium (ISM) as they travel to the telescopes. Precise knowledge of this modification is essential (Wilm et al. 2000, Smith et al. 2016); the observed X-ray spectra from cosmic sources have to be corrected before the data can be interpreted.

The key limitation of using `kerrbb` to model the accretion disk alone is that it does not account for extinction, energy-dependent attenuation caused by absorption and scattering. This extinction is due to solid interstellar dust along the line of sight to the X-ray binary. Disk continuum fitting therefore requires two additional components: `tbabs` for dust absorption and `xscat` for dust scattering, both of which are multiplicative models.

`tbabs` is an XSPEC photoelectric absorption model for dust along the line of sight. It attenuates an intrinsic spectrum using energy-dependent X-ray absorption cross sections and elemental abundances, with the main parameter being the dust column density, N_H . It's the standard absorption model used in X-ray spectral fits.

`xscat` is an XSPEC multiplicative model that accounts for X-ray dust scattering from outside of the direct line of sight (i.e., photons scattered into a halo around the source). It computes the energy-dependent scattering given the dust location along the line of sight.

$$\text{Model spectrum} = \text{xscat} * \text{tbabs} * \text{kerrbb}$$

Fig. 4 The current standard model spectrum is made using `xscat`, `tbabs`, and `kerrbb`. Since `xscat` and `tbabs` are multiplicative models, the values outputted by each model are multiplied.

Modeling extinction requires knowledge of both the dust composition and the grain size distribution. In this work, we adopt the generally accepted composition and size distributions from Wilms et al. We additionally assume that the majority of the dust lies in a thin region along the line of sight, commonly referred to as a dust screen [Smith, Valencic, Corrales 2021]. Since the precise location and total amount of dust are poorly constrained, these quantities are treated as free parameters. Which means that the extinction models, `tbabs` and `xscat`, infer the dust column density and screen position from the data, while the composition and size distribution are fixed.

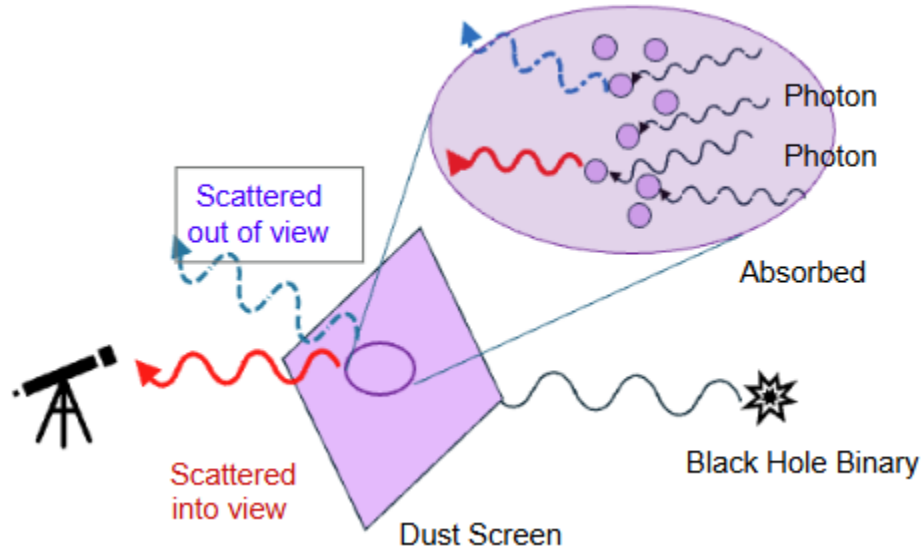


Fig. 5 The X-ray binary releases X-rays that encounter a dust screen before reaching the telescope. Light can be scattered into our line of sight, out of our line of sight, or absorbed.

Dust scattering also produces an effect called a dust-halo around the source. Dust-halos occur since some photons that were not initially bound for the telescope get scattered into view by the dust. Based on how much light is being scattered into view, xscat finds where the dust screen is and how much dust there is.

model	function	parameters
Kerrbb	Relativistic emission model	η , the magnetic field strength; a , the spin; i , the inclination of the accretion disk; M_{bh} , the mass of the black hole; M_{dd} , the accretion rate; D_{bh} , the distance to the black hole; h_d , the hardening factor.
tbabs	Extinction model, calculating interstellar medium absorption cross section	N_H , the amount of dust in between us and the source.

xscat	Extinction model, calculating interstellar medium scattering cross section	NH; X _{pos} , the position of the dust screen; R _{ext} , the radius of the extraction region.
xscatxy (NEW, this paper)	Extinction model, calculating interstellar medium scattering cross section for a rectangular extraction geometry with pileup removed	NH; X _{pos} ; X _{ext} , the width of the extraction region; X _{in} , the width of the removed, piled-up region.

Table 1. Models in the spectral data fitting software, XSPEC, and their parameters

II. Data and Observation

2.1 SWIFT/XRT: Windowed Timing Mode

The Neil Gehrels Swift X-Ray Telescope (SWIFT/XRT) can be operated in multiple readout modes, most commonly Photon Counting (PC) mode and Windowed Timing (WT) mode. PC mode provides two-dimensional imaging over the full 600x600 pixel grid, but refreshes slowly. This occasionally leads to two photons hitting the same pixel within one refresh and being incorrectly registered as only one photon with the combined energy of the two. This phenomenon is called ‘pileup’ and is a concern for bright sources, like X-ray binaries. This effect can bias both the flux and the spectral shape, and is therefore a significant concern for bright X-ray binaries. WT mode was designed to reduce pile-up by increasing the effective time resolution. It does so by compressing one spatial dimension, producing essentially one-dimensional imaging (position retained along one axis, collapsed along the other), enabling faster readout, which mitigates pile-up. The trade-off is reduced spatial information and affects how the extraction region, the region of data that you fit to, should be defined.

While observatories such as XMM-Newton and Chandra provide higher spectral resolution and/or broader energy coverage in many configurations, SWIFTXRT offers two practical advantages for disk-dominated X-ray binary studies: 1) an energy range well-suited to

disk-dominated spectra in the high–soft state for many stellar-mass black holes, 2) dense temporal coverage through frequent monitoring, which enables studies of disk continuum evolution across multiple high–soft state observations and can help reduce the uncertainty in spin estimation. In comparison, Chandra and Newton-XMM capture spectra in higher resolution but they are not necessarily in high/soft state. Moreover, the pileup problems in these other telescopes are even more challenging since the refresh rates are relatively longer.

2.2 Issues with the Data

The main problem of using xscat for Swift data is that xscat assumes a circular extraction region. This is fundamentally incompatible with the SWIFT/XRT Windowed Timing mode since, with 1D data, you can only take extraction regions that are rectangular. This leads to systematic bias that underestimates the spin of the black hole.

This paper aims to develop and implement an improved dust-scattering model that mitigates pileup and properly accounts for the extraction region. By reducing these systematic biases, we provide an enhanced framework for analyzing SWIFT/XRT data that more accurately captures instrumental and dust-related effects that can otherwise skew black hole spin measurements.

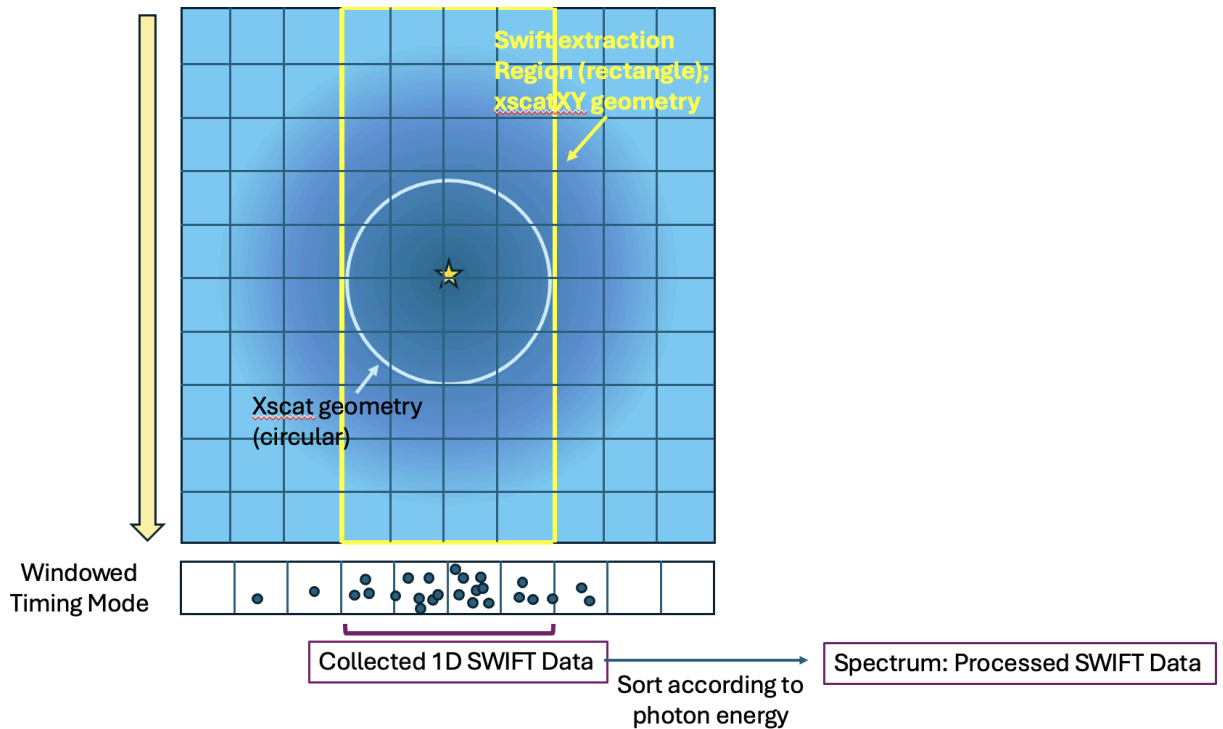


Fig. 6 This figure shows a diagram of an X-ray binary (star in the center) with scattered light around it (blue) as we would see it in PC mode, and the data collapsed into 1D, as we would see it in the WT mode. If you extract the middle four pixels of the 1D data, you are taking data from the middle four columns of the 2D data. This means that the data is of all the photons in the middle four columns but xscat assumes we are using the data from only the circle. The new model, xscatxy, fixes this inconsistency by assuming the rectangular extraction region in yellow.

Another issue is pile up. Even with the Windowed Timing (WT) mode mitigating the pileup, some residual pileup effects may still exist. So, a standard part of cleaning up the raw data is to remove the section of data that is likely to be piled-up. However, xscat does not account for this and fits to the data as if we didn't remove anything. In order to get a more accurate fit, a replacement of xscat that removes the piled-up region in its model form is necessary.

2.3 GRO J1655-40

GRO J1655-40 is a bright X-ray binary in our galaxy, well-suited for the black hole spin study since some of the system’s parameters such as mass, inclination, and distance have been well-constrained in previous works (Miller) and is the only X-ray binary that does not have a high-energy powerlaw component which would be due to the plasma corona, allowing for better fits. Despite that, large uncertainty remains due to different methods, modeling assumptions, incorrect disk state (not high/soft) of data, inadequate extinction models, etc. (Salvesen 2021, Stachlik 2018). The spin parameter a for a black hole is defined as

$$a = \frac{cJ}{GM^2}$$

where c is speed of light, J is angular momentum, G is gravitational constant, and M is mass. When $a = 0$, the black hole is non-rotating while $1 \geq a > 0$, it is rotating.

Shafee et al. 2006	McClintock et al. 2006	Motta et al. 2014	Yilmaz et al. 2023
0.65 - 0.75	> 0.9	0.29	0.75-0.77

Table 2 Various estimates of the spin of GRO J1655-40 using different methods, models, and data.

Fixed Parameters for GRO J1655-40

	Mass	Inclination	Distance	Hardening factor	Magnetic field
value	$6.3 M_{\odot}$	85°	2.9 kpc	1.7	0

Table 3 Parameters for the GRO J1655-40 system using various methods (Salvesen, G., Plohr, T., and Turoňová, Z.)

III. Methods

This paper aims to develop an improved dust scattering model for SWIFT/XRT data by making two corrections: 1) removing the region containing pileup in the xscat model and 2) by making the model consistent with the WT rectangular extraction geometry.

3.1 XscatXY

We fix the extraction geometry by first transforming xscat from spherical to Cartesian coordinates and integrating the flux density function in the rectangular extraction region. We name the new model xscatxy. In essence, xscatxy is a dust-scattering model that computes the energy-dependent scattered X-ray flux for Swift/XRT Windowed Timing data by integrating the dust halo over a rectangular extraction region (with optional core excision to account for pile-up filtering). xscatxy is modeled as

$$F = \underbrace{F_0 \exp(-\sigma_0 N_H)}_{\text{direct flux}} + \underbrace{F_0 \int dx dy (\text{correction factor}) * \exp(-\sigma_s(x, y) N_H)}_{\text{halo flux}}$$

(1)

where F_0 is the intrinsic flux from a point source, σ_s is the scattering cross section, σ_0 is the scattering cross section specifically at the center of the extraction region, and N_H is dust abundance.

Eq. (1) is how the xscatxy model calculates the flux the telescope observes. The first term represents the amount of light the telescope observes in the direct line of sight of the X-ray binary and the second term represents the amount of light observed in the dust halo using a rectangular extraction region (integral over x and y rather than r). For details, see Salvesen, G., Plohr, T. 2026.

3.2 Pile-up mitigation

In scattering models (xscat or xscatxy), accumulative fluxes are calculated, meaning for a specified extraction region (by radius r_{ext} in xscat and (x_{ext}, y_{ext}) in xscatxy), the total flux inside is calculated. In order to remove the pile-up region in the xscatxy, we simply subtract the flux of the pile-up region. More concretely, for xscatxy, given (x_{ext}, y_{ext}) for extraction region and (x_{in}, y_{in}) for pileup region,

$$\text{Flux with pileup removed} = F(x_{ext}, y_{ext}) - F(x_{in}, y_{in})$$

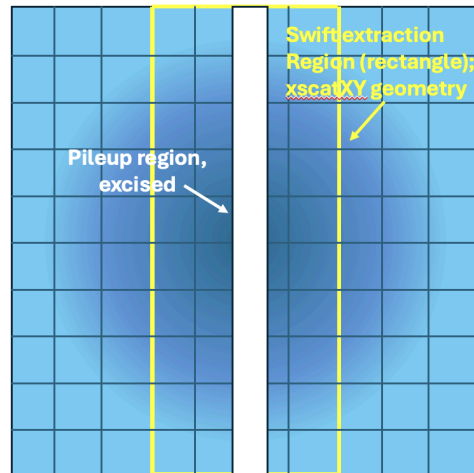


Fig. 7 The flux in the pile up region is subtracted from the total flux.

With these two corrections, the spectral model calibration will be done as following:

$$\text{Model spectrum} = \underbrace{(\text{xscatXY; pileup})}_{\text{Our New Model}} * \text{tbabs} * \text{kerrbb}$$

Fig. 8 Newly proposed spectral model calibration

VI. Workflow

4.1 Implementation

Xscatxy is implemented in C++, xscat's native language, and also in Python, using a C++ Python wrapper. To use Python packages that are not default in XSPEC, we have to use a pipe to run a separate Python process and communicate between the two using json files. Then, we integrate xscatxy into the NASA-managed spectral data analysis package, XSPEC. As a proof of concept, we will apply the standard model (xscat) and our new model (xscatxy) to datasets of a bright X-ray binary (GRO J1655-40) and compare the estimates of the black hole spin when other parameters are fixed.

4.2 XSPEC framework

Xscat, tbabs, and kerrbb are models implemented in XSPEC (Arnaud 1996, HEASoft). We are using the latest version of XSPEC, version 12.15.1. The procedure is to load in each dataset, remove the low quality sections of the data, define the model in terms of xscat/xscatxy, tbabs, and kerrbb, and to fit the model to the data. XSPEC then gives us the best-fit parameters, most importantly, the spin of the black hole. We infer the black hole spin of GRO J1655-40 using three SWIFT/XRT datasets.

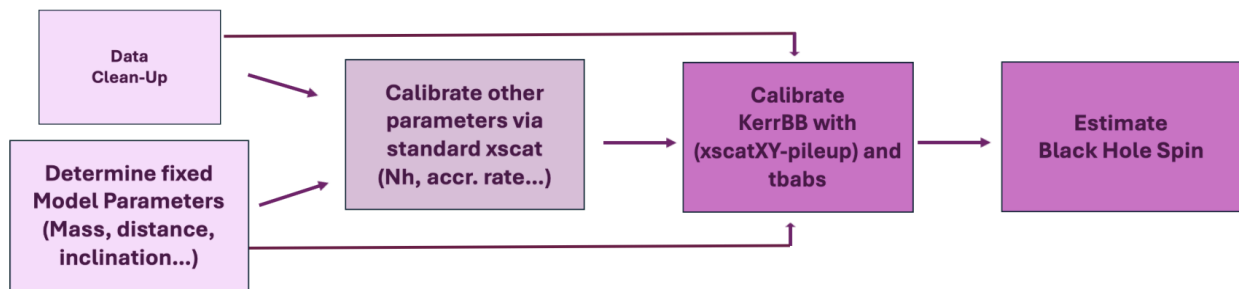


Fig. 9 Diagram of the steps taken to estimate the black hole spins. The darker the color of a box is, the harder the task is. The core parameter calibration is done in the darkest pink box, where

data, fixed parameters, and other standard parameters are fed in. This step is detailed in Fig. 8 as well.

The calibration process of the spectrum model by xscatxy is illustrated in Fig. 8. The main routines of xscatxy (TateXY.py) is written in python and needs to be incorporated into the XSPEC process. Since XSPEC does not allow non-standard python libraries, I made another layer, pyxscatxy that runs TateXY.py and uses json files to communicate with it.

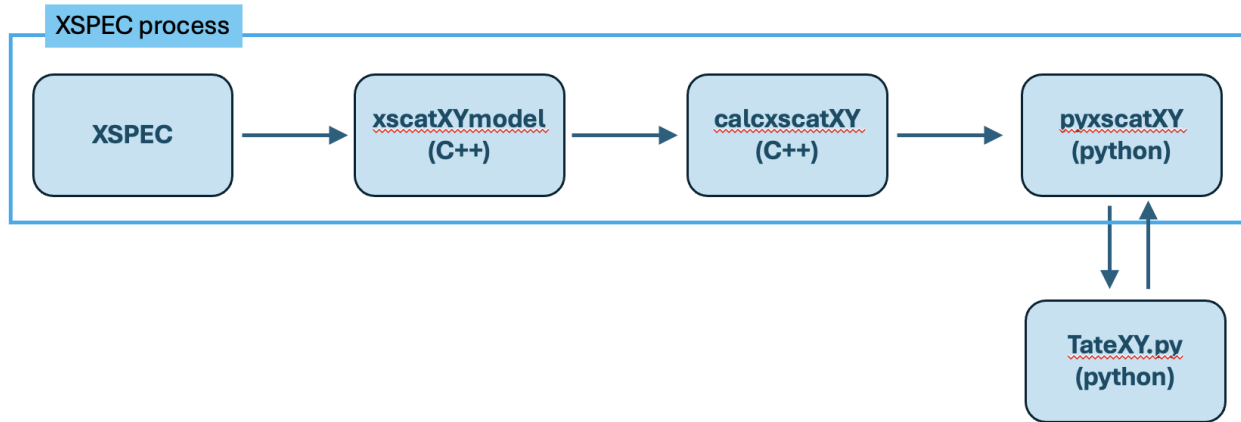


Fig. 10 XscatXY Programming Pipeline: XSPEC calls the xscatxymodel C++ program to find the best fit. The xscatxymodel program iteratively calls calcxscatxy to get the model spectrum for a given set of parameters. calcxscatxy is a Python wrapper that calls pyxscatxy, which is a Python program. Since XSPEC doesn't allow any non-standard python libraries, pyxscatxy creates a new process that runs TateXY.py, which does the actual calculations of the model spectrum, using necessary Python libraries. The result gets sent back through the chain, allowing XSPEC to fit the model. Since pyxscatxy and TateXY are in different processes, they use json files to communicate.

V. Results

We have performed two tests that demonstrate the effects of using `xscatxy` for Swift data.

5.1 Impact of absorption and scattering; comparison between `xscat` and `xscatxy`

First, we illustrate how the model spectrum changes as the successive components (`kerrbb`, `tbabs`, `xscat`, and `xscatxy`) are added. In Fig. 11, the blue curve is a model spectrum from `kerrbb` where the emission is pretty uniform across the energy levels. The orange curve corresponds to the spectrum when the `tbabs-kerrbb` model is applied and the green corresponds to when the `xscat-tbabs-kerrbb` model is applied. The red curve is obtained by applying `xscatxy` in place of `xscat`. This shows that adding successive extinction models decreases the model flux, mainly at low energies, which is expected since the effect of scattering and absorption decrease with energy.

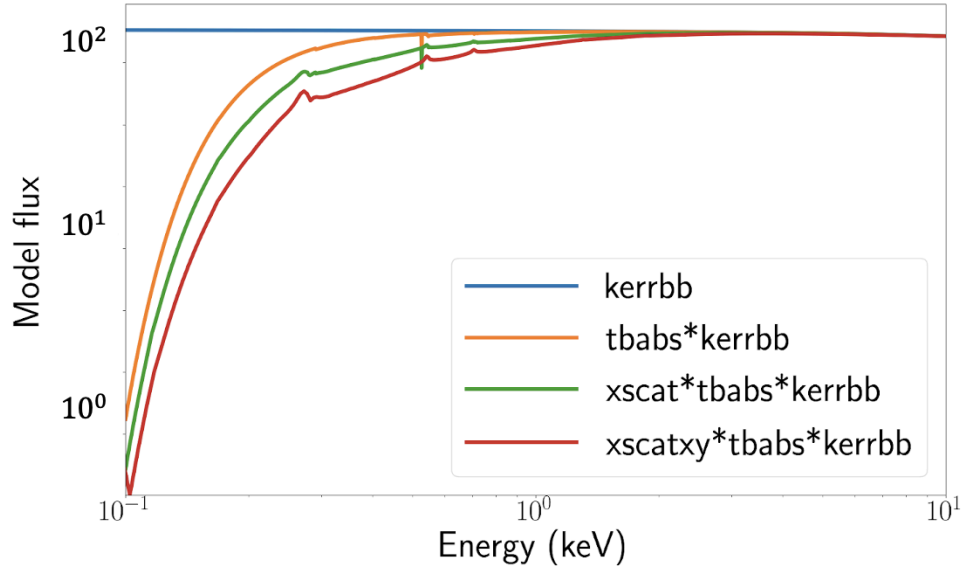


Fig. 11 This plot shows the flux as a function of the energy of the X-rays. The extinction models predict lower flux, especially in the low energy region.

5.2 Black Hole Spin Fitting

Next, we compared the best-fit black hole spins obtained with `xscat` and `xscatxy`, using three datasets from GRO J1655-40 as in Fig. 12. In order to isolate the effects of `xscatxy`, we froze all other parameters except for a , the spin.

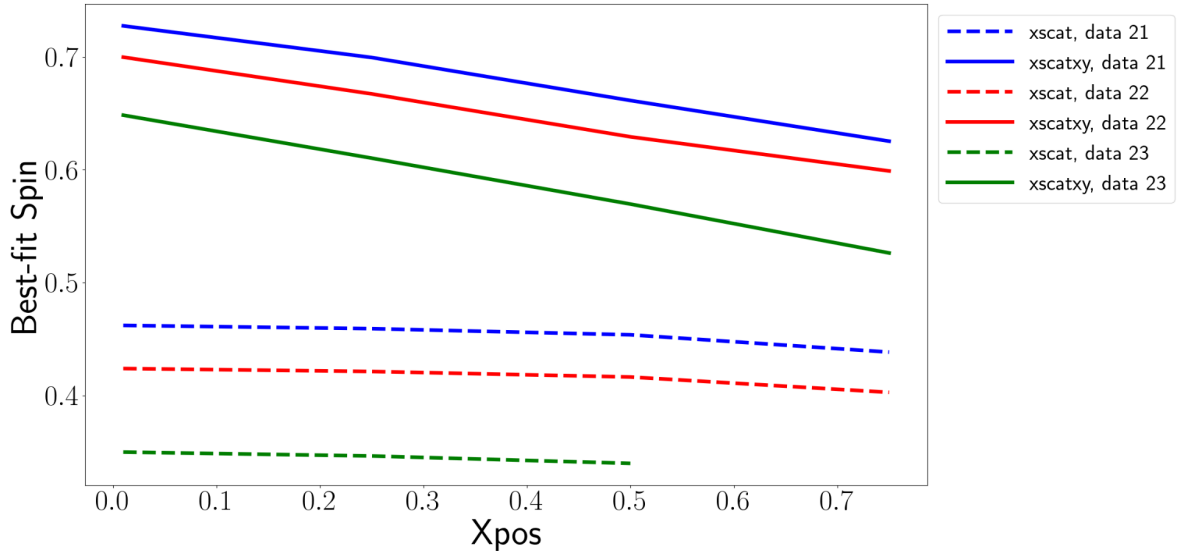


Fig. 12 This plot shows the spin parameter, a , as a function of the dust screen position, X_{pos} , which varies from 0 (at the telescope) to 1 (at the X-ray binary). All other parameters are frozen to see the effects of `xscatxy` on the spin specifically. The fits using `xscat` are shown in the dashed lines and `xscatxy` in the solid lines. The numbers 21, 22, and 23 correspond to the dataset numbers.

These plots function as verification since, as expected, `xscatxy` has a lower intensity model spectra and therefore predicts higher spin across the data sets. Next, we calibrate spin, NH , X_{pos} , and accretion rate using `xscat` and `xscatxy` for J1655-40.

Calibrated Parameters for GRO J1655-40

	spin	NH	Xpos	Accretion rate
xscat	0.486447	0.737978	0.669595	4.59796
xscatxy	0.496473	0.980033	0.813585	4.70848

Table 4 Best-fit parameters using xscat and xscatxy for GRO J1655-40.

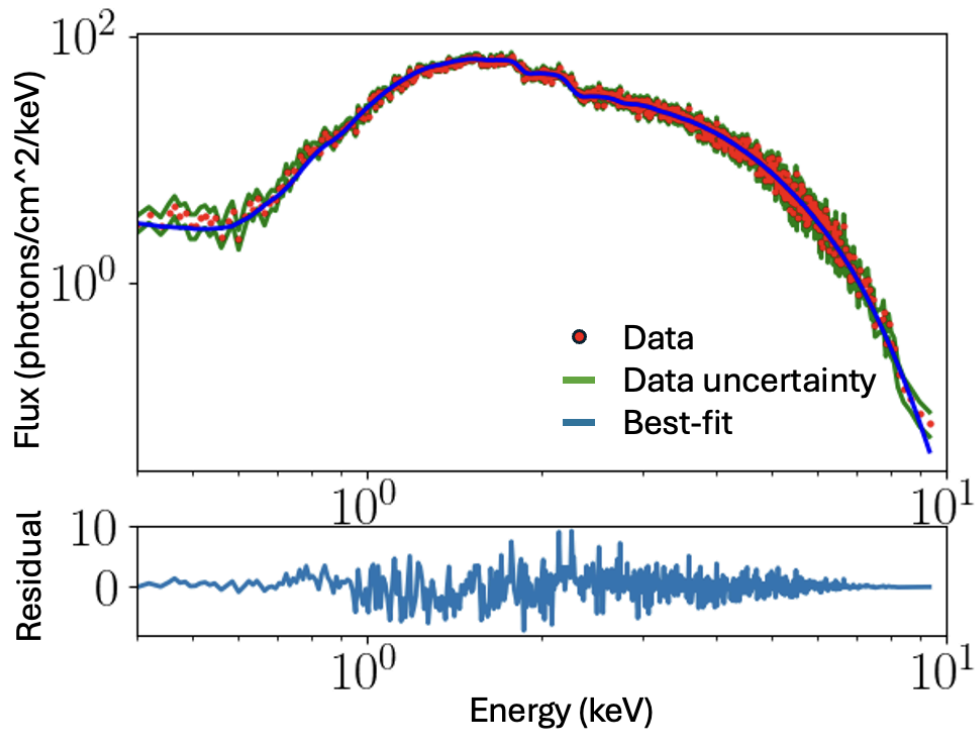


Fig. 13 This plot shows the xscatxy-tbabs-kerrbb model being fit to dataset 21. The y-axis is the amount of light and the x-axis is the energy of the light. The blue line in the top subplot is the model spectrum, the red dots are the datapoints, and the green lines are the error of the data. The bottom figure shows the difference between the model and the data (the residuals).

Comparing the fitted parameters from xscat and xscatxy, we find that the spin, Xpos, accretion rate, and NH increase. Xpos and NH increase by a significant amount while spin and accretion rate are pretty similar between the two models. These parameters are degenerate in the

sense that their effects can negate each other, leading to many combinations of parameters with similar fits.

Conclusion

This paper addresses a key systematic bias in black hole spin estimation by improving dust-scattering and pileup modeling for SWIFT/XRT Windowed Timing data. The `xscatxy` model is a customized version of `xscat` that uses a rectangular extraction region and accounts for pile-up. We verified that the successive application of the extinction models reduces the expected X-ray spectrum. This would lead to `xscatxy` inferring systematically higher spins than `xscat` when other parameters are fixed, which was shown to be true in Fig. .

In conclusion, we have developed an improved model for analyzing SWIFT/XRT data that more accurately accounts for instrumental and dust-related effects that can bias black hole spin calibration. `XscatXY` will be incorporated into the NASA-developed/maintained spectral analysis package, `XSPEC`, with implications for both previous studies and future X-ray analyses.

More broadly, this work demonstrates how instrument-specific modeling can allow for precise measurements from data previously considered unsuitable.

Acknowledgements

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