Presenter: Kaushik Chatterjee

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Insight-HXMT, NICER, and NuSTAR Views to the Newly Discovered Black Hole X-Ray Binary Swift J151857.0–572147

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Short Talk
Milky Way Group Meeting
16 December 2024

SWIFAR

Contents

- Newly discovered source Swift J151857.0-572147
- Spectral Analysis with physical reflection models
- Results
- Estimating the spin, mass, and distance of the BHC
- Conclusions
- Open Questions in the field

Main Motivation of the Paper

To estimate the two most important intrinsic properties:

- Mass
- Spin

Along with Mass and Spin, **Charge** is also an intrinsic property of a black hole (BH). However, the overall charge can be neutralized due to hot plasma in the surroundings.

Why Mass and Spin are important?

- **Mass:** The mass of a black hole provides a physical scale. The mass distribution of such black holes can provide important clues to the end stages of the evolution of massive stars.

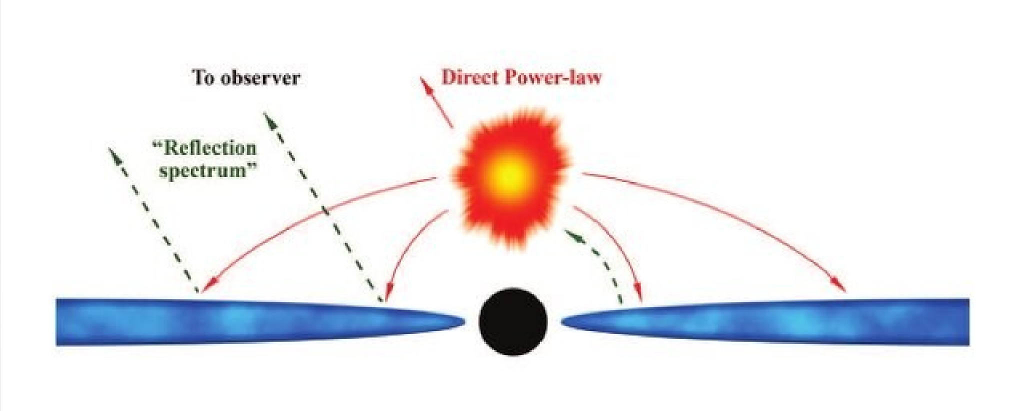
- **Spin:** The spin of a black hole fundamentally changes the geometry of spacetime. The gravitational well of an extreme Kerr black hole of the same mass is significantly deeper compared to a spinless black hole, resulting in a much harder X-ray spectrum and significantly enhancing its efficiency in converting the accreted rest mass into radiant energy. And the spin of black holes plays an important role in the mechanism of jets, core collapse of gamma-ray bursts, gravitational-wave astronomy in predicting the waveforms of merging black holes.

How the Spin Can be measured?

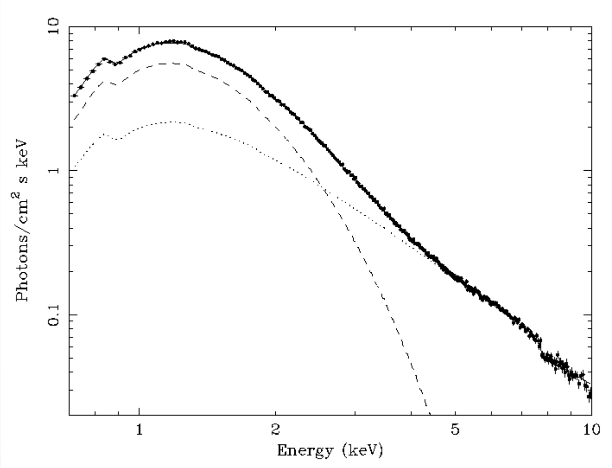
Spectral Modeling with physical models in XSPEC.

Modeling a spectrum requires combinations of two kinds of models:

- Continuum (comes from the accretion + corona)
- Reflection (comes from the radiation that reflects back to the disk due to the gravitational effect of the BH)



Uttley et al. (2014)



Continuum Spectrum

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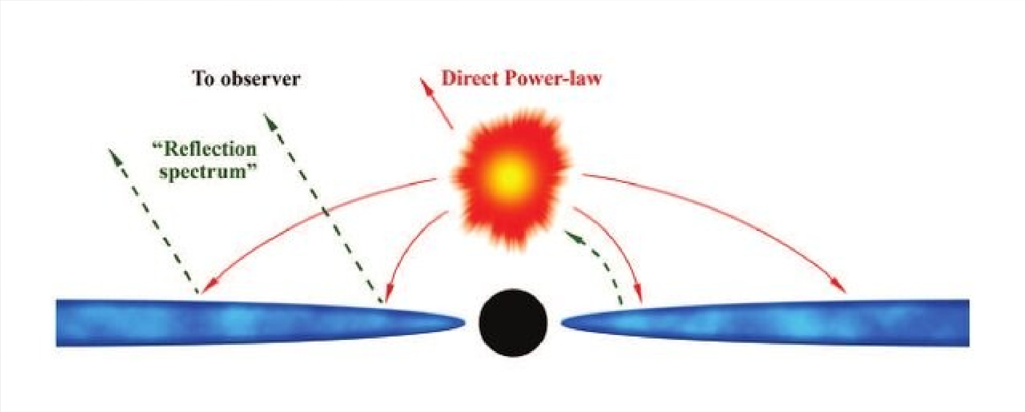

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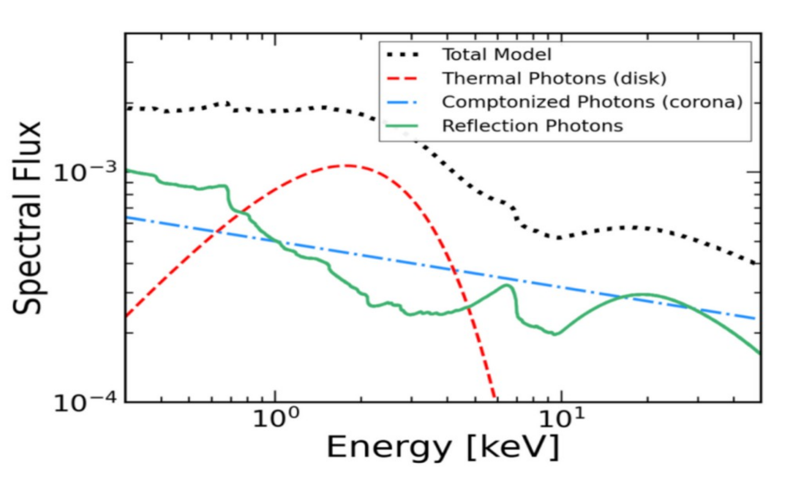

Continuum with Reflection Spectrum

How the Spin Can be measured?

Spectral Modeling with physical models in XSPEC.

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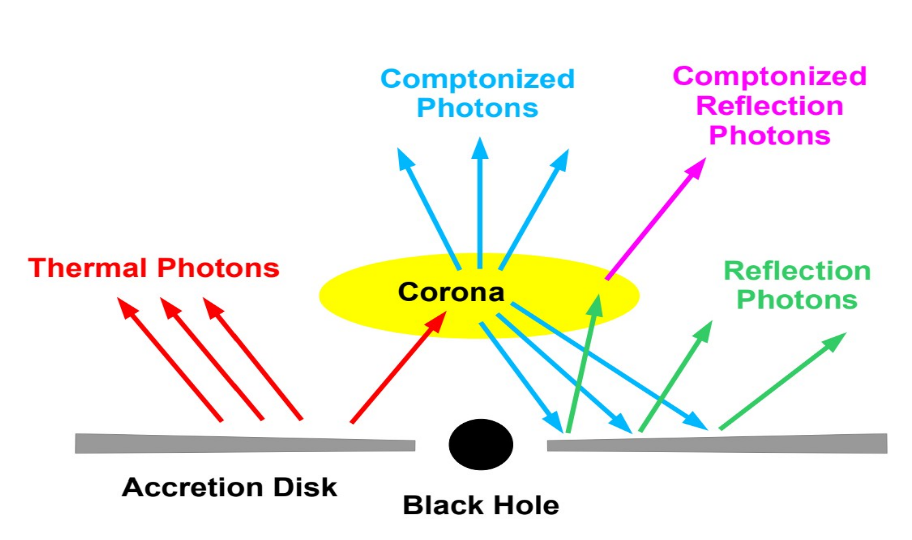
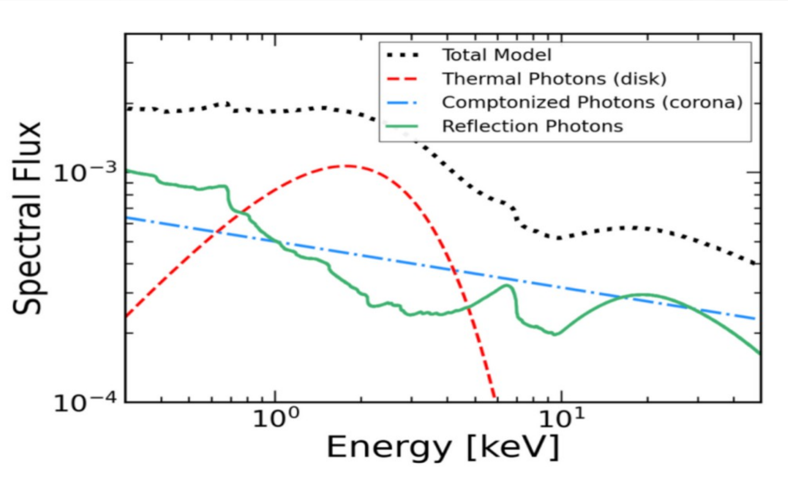


Li et al. (2024)



Continuum with Reflection Spectrum

Models for Accretion Disk, Coronal, and Reflection Emissions

Accretion Disk

- Disk
- Diskir
- Diskpn
- Diskpbb
- **Diskbb**
- Kerbb
- Kerrd
- Kerrdisk
- Bboby
- Bbodyrad

Etc.

Coronal Emission

- **Power-law**
- Broken power-law
- Cutoff power-law
- CompST, CompTT, CompPS
- Thcomp, Nthcomp
- BMC

Etc.

Reflection Emission

A. For Iron Line:

- **Gaussian**
- Laor / Laor 2

B. For Compton Hump:

- **Relxill**
- Pexrav
- Pexriv

Etc.

Here is the link to XSPEC Models

Estimation of Mass

Not as straightforward as spin!

Few methods to estimate the Mass:

- The most reliable way is obtaining the mass function from the orbital modulation of the line emission of the companion (Tetarenko et al. 2016).
- Mass can also be estimate from the binary black hole merger event using Laser Interferometry from Gravitaional-Wave Obervatory (Bodensteiner et al. 2022).
- Another way of estimating mass is buy using the luminosity. According to the authors, the luminosity reaches to 30% Eddinton luminosity (L_Edd) at the High Soft State. Using this relation, one can estimate the mass of the BH. The authors used this method to estimate the mass of this source. **Let's come to that later**.

Source Introduction

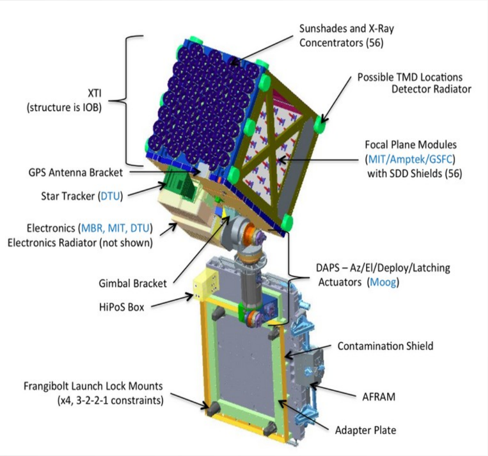
- Discovered in March 2024
- An extremely bright radio flare was discovered on March 9 2024 by ATCA
- Flux density was found as f(E) ~ E^-x, where x ~ 1.8, which is consistent with a BH hard state (HS)
- The HI spectroscopic measurement gave a distance of ~ 4.5-16 *kpc* (large range!)
- The source entered in the soft state (SS) on March 10 2024

Authors Motivation to take this Work

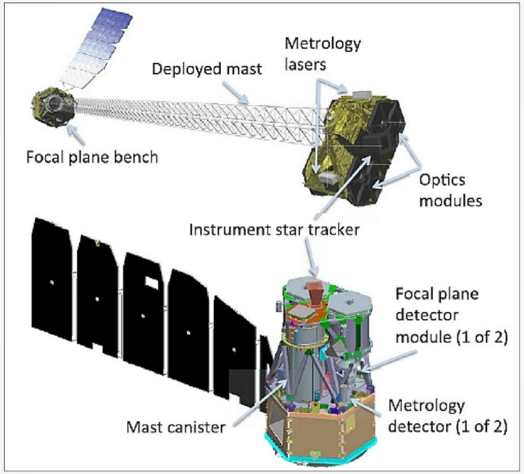
- The range of distance was too high ~ 4-16 kpc
- The inclination and spin was not properly measured (at the time)
- They wanted to estimate the mass (also not measured at the time)

Satellites Used

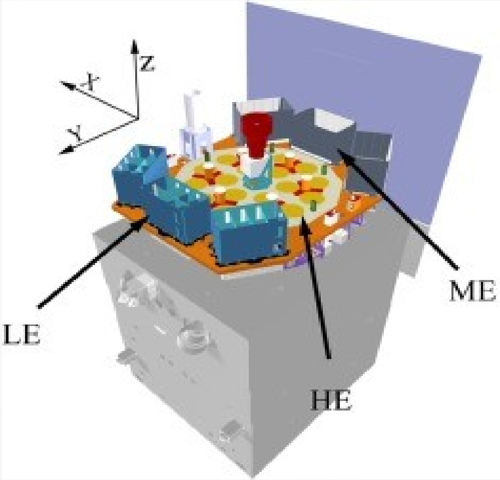
NICER



NuSTAR

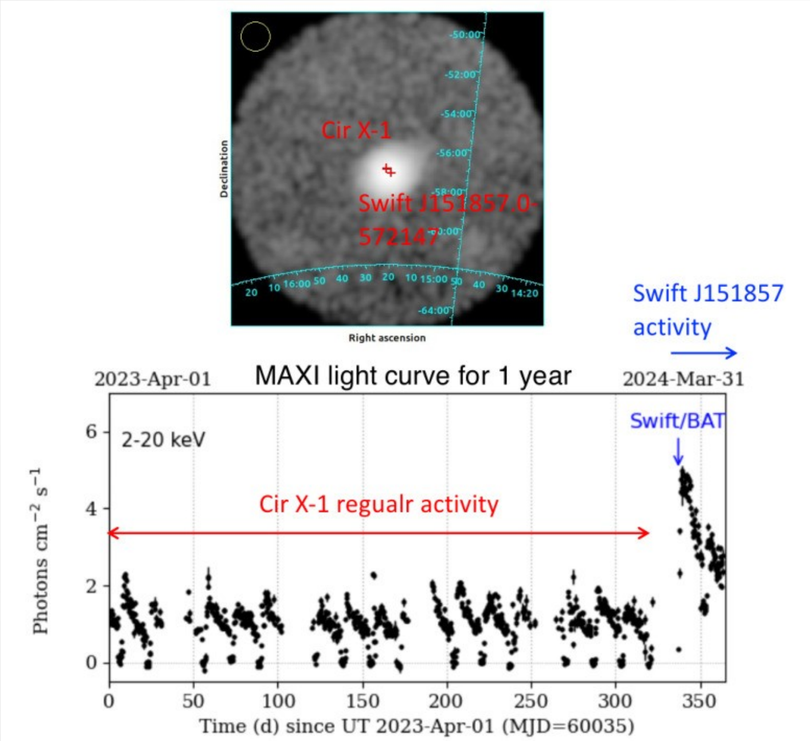


Insight-HXMT



Instrument	Energy Range (keV)	Effective Area (cm^2)	Resolution	Purpose
NICER	0.2-12	>2000 @ 1.5keV ; 600 @ 6keV	85 eV @ 1keV, 137 eV @ 6 keV	Blackbody
NuSTAR	3-79	800 @ 10keV, 100 @ 59 keV	400 eV at 10 keV, 900 eV at 68 keV	Reflection
HXMT	LE (1-15), ME (5-30), HE (20-250)	LE (384), ME (952), HE (5100)	LE (2.5%@6), ME (15%@20), HE (17%@60)	Reflection

Close Proximity to Cir X-1!



Credit: MAXI Team

This source is interesting, as there was the close proximity of another source called Cir X-1. The profile of the Cir X-1 was moreover stable over the duration of this outburst and it was in the SS. Thus, it was only contributing to the lower energies. So they performed spectral analysis with ME and HE with the combo of NICER data.

Results

Variation of light curve:

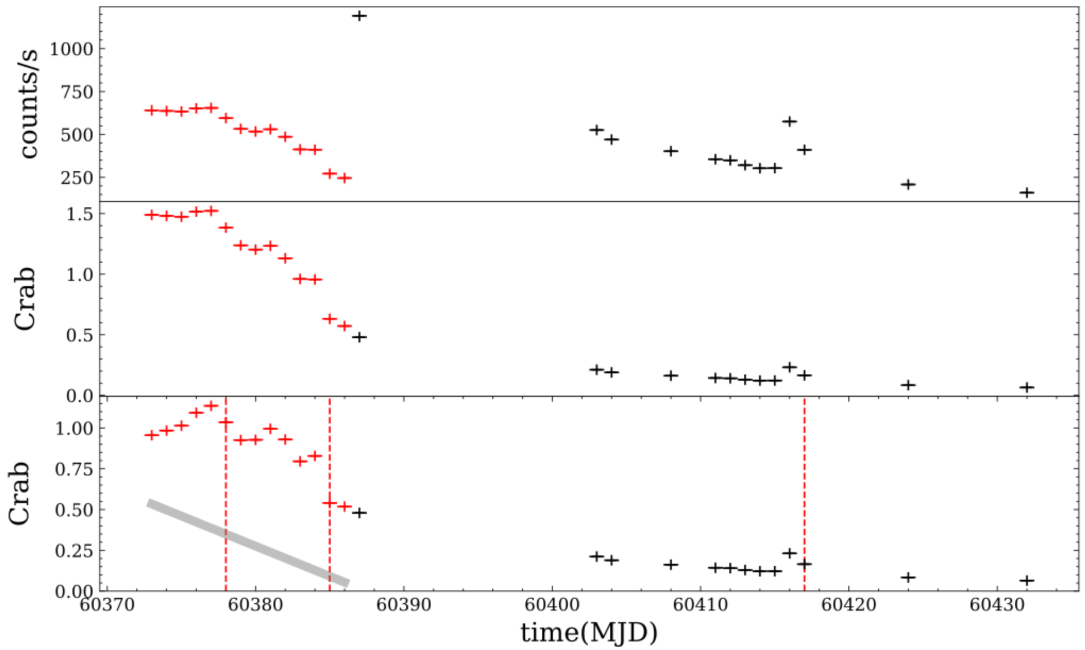


Figure 1. The light curves of Swift J151857.0–572147 observed by Insight-HXMT and NICER during the 2024 outburst. The red dots represent Insight-HXMT observations and the black dots represent NICER observations. Top panel: the light curve of Insight-HXMT LE and NICER in 2–12 keV. Middle panel: the light curves are normalized to the Crab. Bottom panel: the light curve of Insight- HXMT after subtracting off the Cir X–1 (a gray area) and the light curve of NICER. The red dotted lines correspond to about 90%, 50%, and 10% of the peak flux, respectively.

Results

Hardness Intensity Diagram (HID):

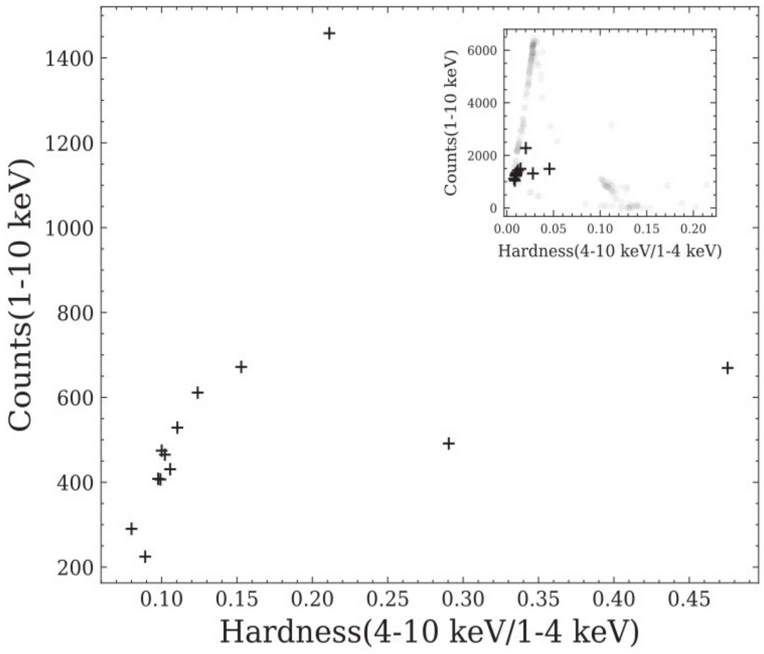
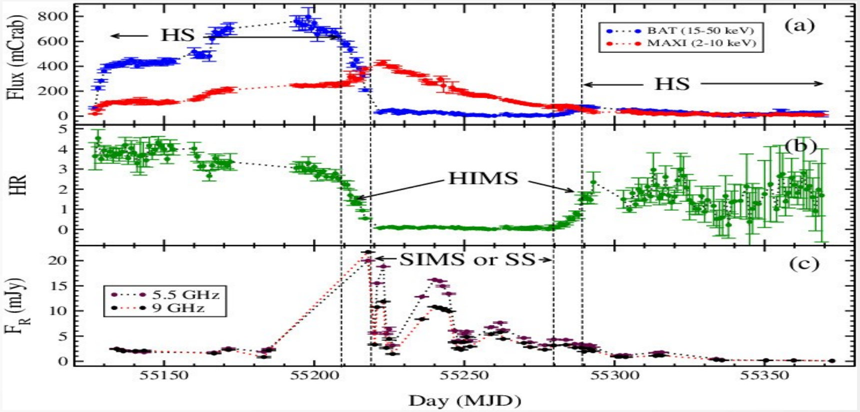
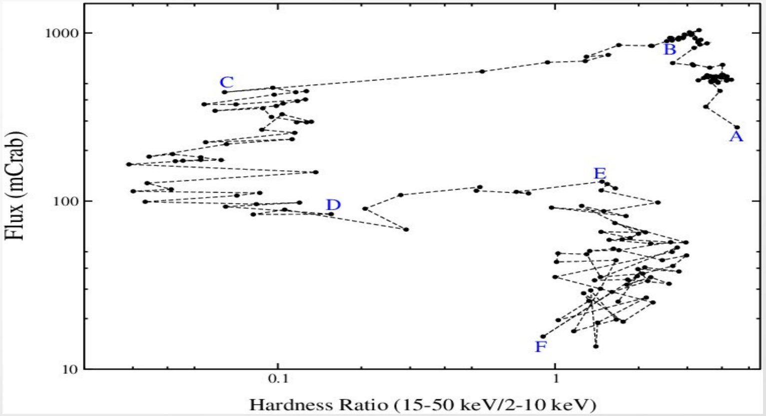


Figure 2. The NICER HID of Swift J151857.0–572147, where the hardness is defined as the ratio of 4–10 to 1–4 keV count rate. The subplot shows the distribution of the outburst trajectory of Swift J151857.0–572147 after scaling the count rate relative to the trajectory of the 2021 outburst of GX 339–4.





Chatterjee et al. (2020)

Spectral Analysis

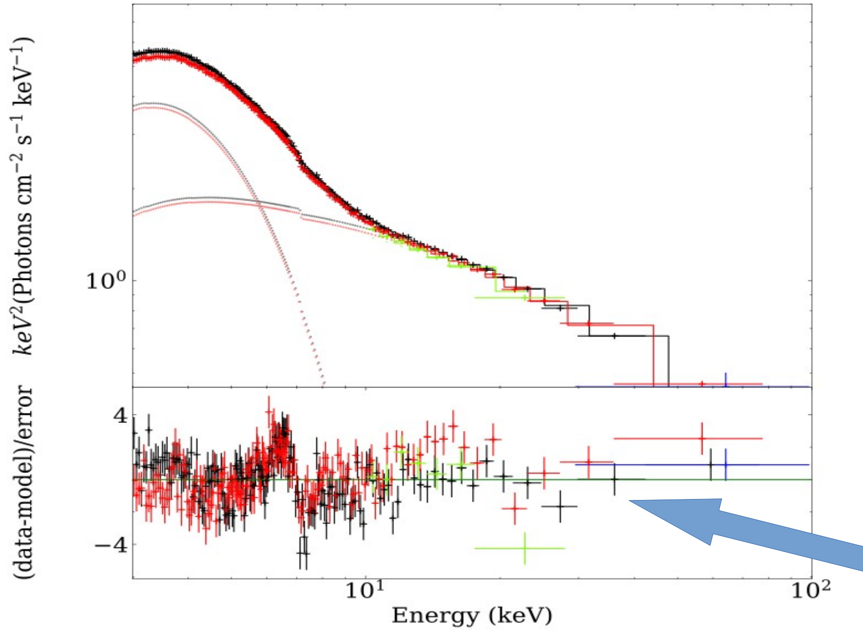


Figure 3. The simultaneous broadband spectrum with the model (constant*tbabs*(diskbb+cutoffpl)) of Swift J151857.0–572147 is observed from NuSTAR/FPMA (black), NuSTAR/FPMB (red), Insight-HXMT ME (green), and Insight-HXMT HE (blue).

- **tbabs**: for interstellar absorption
- **diskbb**: for accretion continuum
- **cutoffpl**: for non-thermal emission

Fitting is not good as $\mathrm{chi}^2_{\mathrm{reduced}} \sim 1.34$

There is presence of significant reflection nature at the high energy part of the spectrum

Spectral Analysis

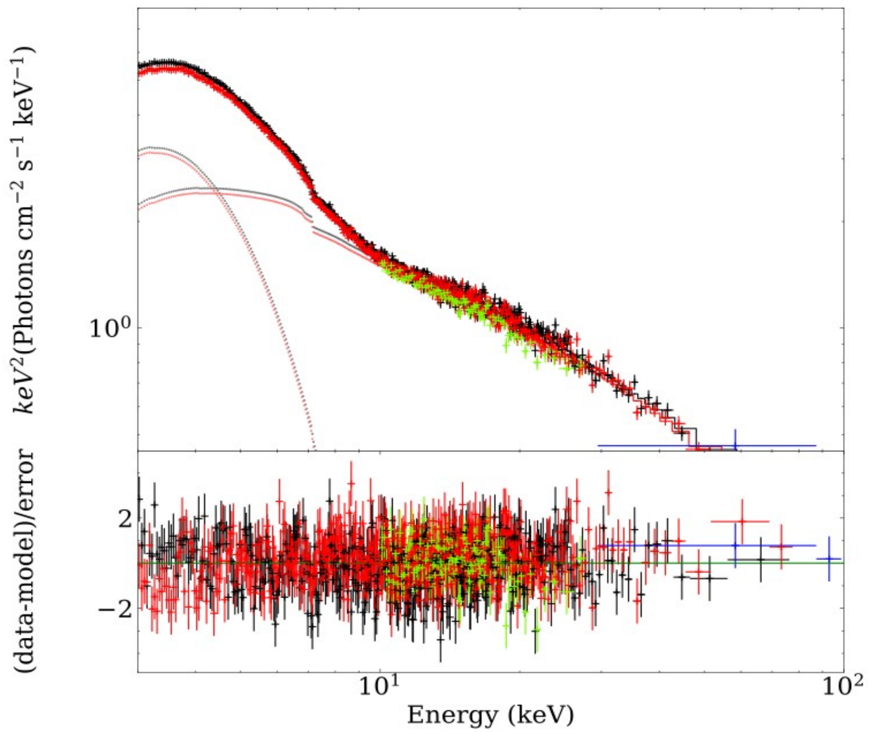


Figure 4. The simultaneous broadband spectrum with the model M1 of Swift J151857.0–572147 is observed from NuSTAR/FPMA (black), NuSTAR/FPMB (red), Insight-HXMT ME (green), and Insight-HXMT HE (blue).

- **tbabs**: for interstellar absorption
- **diskbb**: for accretion continuum
- **relxill**: for reflection emission

Fitting is good as chi$^2_{reduced}$ ~ 1.06

The reflection nature is now not present in the residual at the high energy part of the spectrum

Spectral Result

Table 3
The Results of Spectral Fitting the Insight-HXMT+NuSTAR and NICER +NuSTAR Data for Model M1

Model	Parameter	91001311002 +HXMT	NICER +91001311004
tbabs	$N_{\mathrm{H}}[10^{22}\ \mathrm{cm}^{-2}]$	$3.32^{+0.02}_{-0.01}$	$3.37^{+0.13}_{-0.10}$
diskbb	T_{in}	$0.90^{+0.01}_{-0.01}$	$0.90^{+0.01}_{-0.01}$
	norm	$1320.5^{+17.1}_{-36.2}$	$1615.5^{+64.4}_{-113.3}$
relxill	a	$0.86^{+0.12}_{-0.14}$	$0.82^{+0.13}_{-0.22}$
	i [°]	$20.2^{+0.5}_{-0.8}$	$21.9^{+4.5}_{-3.5}$
	Γ	$2.56^{+0.01}_{-0.01}$	$2.63^{+0.01}_{-0.01}$
	R_{in}	-1[a]	-1[a]
	R_{out}	400[a]	400[a]
	R_{br}	15[a]	15[a]
	index1	3[a]	3[a]
	index2	3[a]	3[a]
	logxi	$4.38^{+0.10}_{-0.06}$	$4.02^{+0.11}_{-0.21}$
	A_{fe}	$5.02^{+0.13}_{-0.23}$	$3.87^{+0.87}_{-1.53}$
	E_{cut}	$111.1^{+7.3}_{-3.3}$	$122.2^{+21.7}_{-12.8}$
	fefl_frac	$0.16^{+0.02}_{-0.01}$	$0.21^{+0.04}_{-0.03}$
	norm$[10^{-2}]$	$7.67^{+0.12}_{-0.11}$	$6.39^{+0.17}_{-0.14}$
constant	con[NICER]	...	1[a]
	con[NFPMA]	1[a]	$1.61^{+0.06}_{-0.06}$
	con[NFPMB]	$0.97^{+0.01}_{-0.01}$	$1.57^{+0.06}_{-0.06}$
	con[ME]	$0.94^{+0.01}_{-0.01}$	
	con[HE]	$0.82^{+0.11}_{-0.04}$	
	χ^2/(dof)	1.06	1.01

Note.
[a] These parameters are fixed during the fitting.

- Spin ~ $0.84^{+0.17}_{-0.26}$
- Inclination ~ $21.1^{+4.5}_{-3.6}$

Ionization is high > 4

This is due to the low electron density in the disk that is considered in the relxill model (~10^{15} cm^{-3})

Spectral Result

Table 4
The Results of Spectral Fitting the Insight-HXMT+NuSTAR and NICER +NuSTAR Data for Model M1*

Model	Parameter	91001311002 +HXMT	NICER +91001311004
tbabs	$N_{\rm H}[10^{22}\ {\rm cm}^{-2}]$	$2.98^{+0.12}_{-0.09}$	$4.44^{+0.03}_{-0.01}$
diskbb	$T_{\rm in}$	$0.95^{+0.02}_{-0.01}$	$0.84^{+0.01}_{-0.01}$
	norm	$1000.2^{+53.5}_{-82.3}$	$2242.6^{+39.7}_{-100.9}$
relxill	a	$0.87^{+0.11}_{-0.33}$	$0.86^{+0.06}_{-0.23}$
	i [°]	$20.4^{+3.1}_{-2.7}$	$22.3^{+3.0}_{-2.7}$
	Γ	$2.54^{+0.02}_{-0.02}$	$2.59^{+0.02}_{-0.01}$
	$R_{\rm in}$	-1[a]	-1[a]
	$R_{\rm out}$	400[a]	400[a]
	$R_{\rm br}$	15[a]	15[a]
	index1	3[a]	3[a]
	index2	3[a]	3[a]
	logxi	$2.30^{+0.03}_{-0.27}$	$3.30^{+0.16}_{-0.02}$
	$\log N[{\rm cm}^{-3}]$	$19.00^{+0.03}_{-0.01}$	$19.00^{+0.03}_{-0.14}$
	$A_{\rm fe}$	$4.02^{+0.13}_{-0.23}$	$3.94^{+0.24}_{-0.153}$
	$kT_{\rm e}$[keV]	$61.5^{+15.1}_{-13.2}$	$67.2^{+21.7}_{-12.8}$
	fefl_frac	$0.19^{+0.06}_{-0.05}$	$0.10^{+0.01}_{-0.02}$
	norm$[10^{-2}]$	$6.02^{+0.29}_{-0.28}$	$3.49^{+0.04}_{-0.03}$
constant	con[NICER]	...	1[a]
	con[NFPMA]	1[a]	$1.25^{+0.01}_{-0.05}$
	con[NFPMB]	$0.97^{+0.01}_{-0.01}$	$1.22^{+0.01}_{-0.05}$
	con[ME]	$0.94^{+0.01}_{-0.01}$	
	con[HE]	$0.82^{+0.11}_{-0.04}$	
	χ^2/(dof)	1.06	1.01

Note.
[a] These parameters are fixed during the fitting.

Changed the **relxill** model with **relxillCp** in which disk density has a density from 10^{15} to 10^{20} cm^{-3}.

- Spin ~ 0.865
- Inclination ~ 21.35

Ionization ~ 2.3-3.3

Only NICER Data

Table 1
NICER Observations of Swift J151857.0–572147 during the 2024 Outburst

NICER ObsID	Observed Date (MJD)	Exposure Time (s)
7204220111	60387.55	4193
7661010101	60404.18	3907
7204220112	60405.22	569
7204220113	60408.90	228
7204220114	60409.16	404
7661010103	60412.06	2682
7204220115	60412.77	262
7204220116	60413.67	799
7204220117	60414.06	1411
7204220118	60415.41	1065
7204220119	60416.25	1265
7204220120	60417.29	565
7661010104	60417.41	3218
7661010105	60425.09	2474
7661010107	60433.02	2021

Due to the absence of any reflection feature in the NICER data (since NICER only has energy range upto 12 keV, reflection is not noticed in that energy. Plus the data is in HSS. Reflection is generally not noticed in SS or HSS), relxill model was removed. However, there was the presence of non-thermal Comptonized emission. To account for that, the author added a model called **thcomp**.

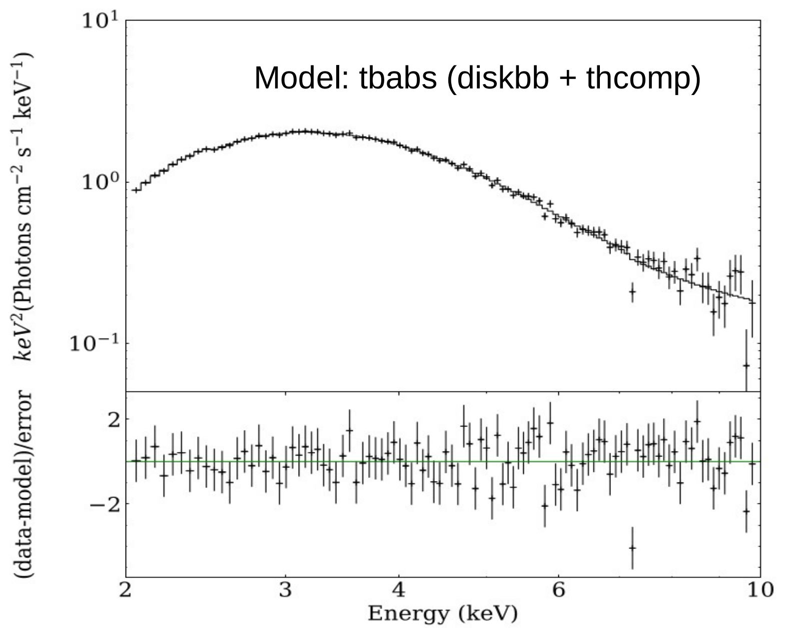


Figure 5. The spectral fittings for the data born out of NICER observations of Swift J151857.0–572147.

Result

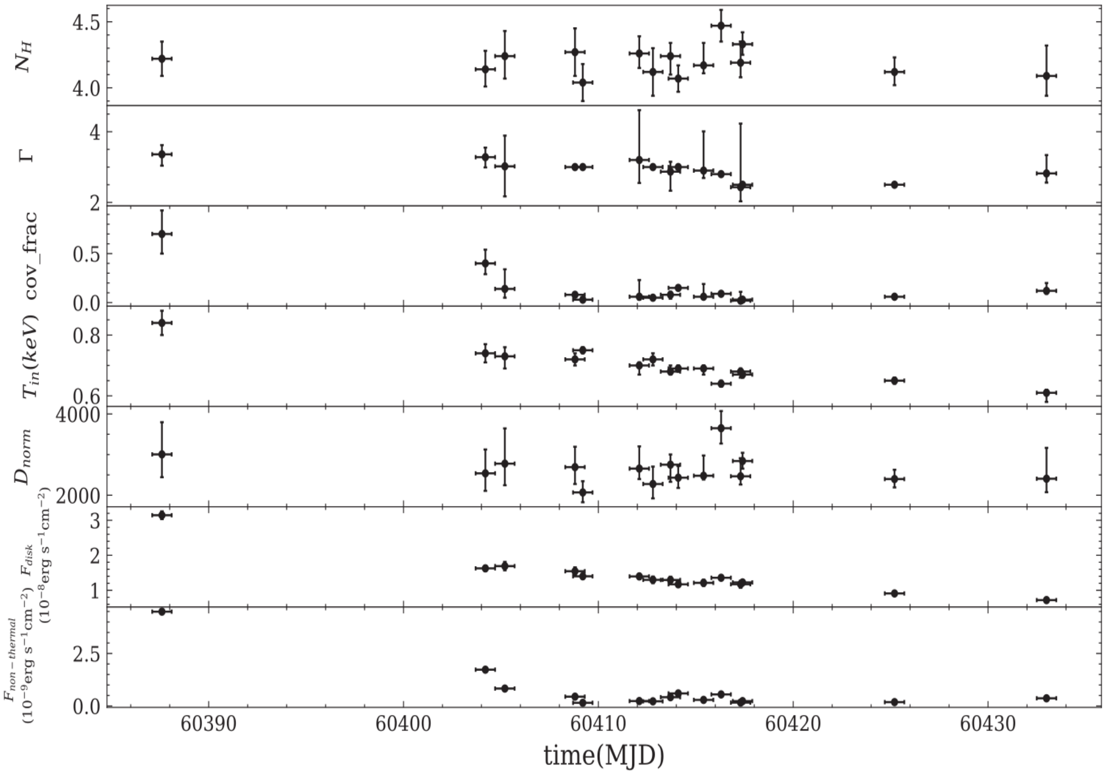


Figure 6. Evolution of the spectral parameters of Swift J151857.0–572147 in 2024 from model M2: N_H is the column density, Γ the low-energy power-law photon index, T_{in} the temperature of the inner disk, Cov_frac the coverage factor, and r_{in} the inner radius of the disk. F_{disk} and $F_{non-thermal}$ are disk flux and nonthermal flux, respectively.

The photon index and inner-disk temp collectively makes the spectral nature as soft. As also one can see from the last 2 panels, the flux from the soft disk component is more than 10 times higher than the non-thermal flux. This also supports the spectral nature as soft. The only thing which is high here is the hydrogen column density. Generally, for Galactic BHs, the N_H < 1 * 10^{22} cm^{-2}. For this, the value is ~ 4-5 * 10^{22} cm^{-2}. This could mean that there could be some local absorption to the source. This could be sue to some wind feature which is blocking the photons (maybe). The authors do not mention this.

Correlation between disk flux and disk temperature

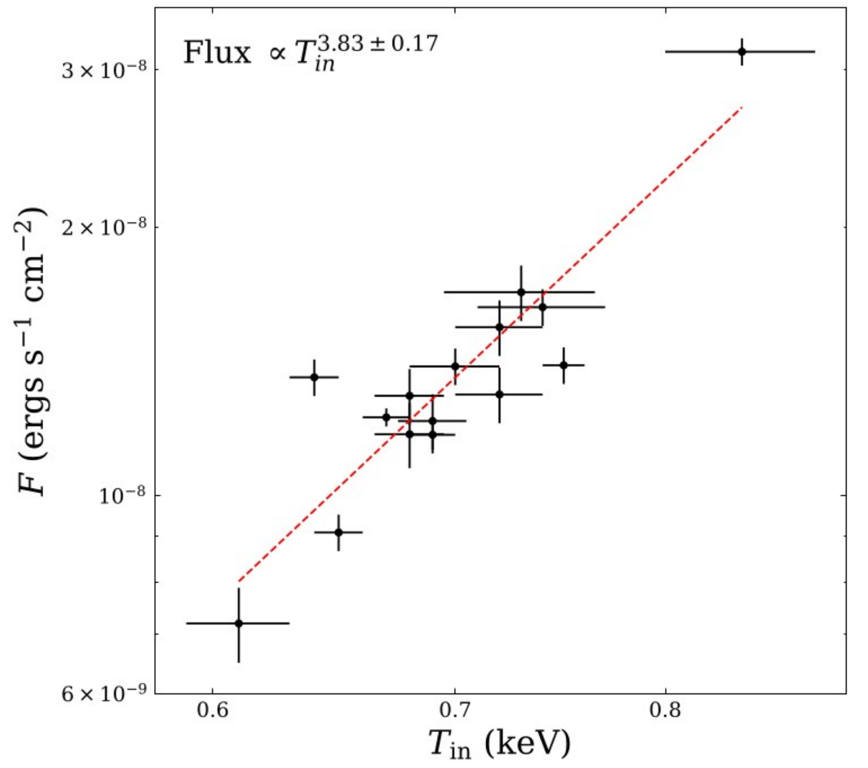


Figure 7. The disk unabsorbed flux (0.01–100 keV) versus the disk inner temperature ($T_{\rm in}$). Flux is found to vary with temperature in form $T_{\rm in}^{3.83\pm0.17}$.

They have fitted the flux and the disk temp with an empirical relation as,

$$F_{disk} \sim Norm*(T_{in})^x.$$

They found x = 3.83 +- 0.17. This is quite in agrrement with the actual relation of

$$L_{disk} \sim 4*pi*(R_{in})^2*sigma*(T_{in})^4$$

Measurement of Mass

The authors used the normalization of the diskbb model which is given as,

$$\boldsymbol{Norm_{diskbb} = (R_{in}/D_{10})^2 \cos(i)}$$

If you know the inclination of and distance to the source D_{10} (in units of 10 *kpc*), you can measure R_{in}.

For a BH, with a spin of ~0.85, R_{in} is given as,

$$\boldsymbol{R_{in} \sim 2.6\ R_g} \ (R_g \text{ is the gravitaional radius} = GM_{BH}/c^2)$$

So, if you know R_{in}, you get the mass. But, you need distance. The distance of this source was in a very long range of almost 4-16 *kpc*.

Thus the authors approached to a different way to constrain distance.

Distance Measurement

Yan & Yu (2015) took **36 low mass X-ray binary sources**. They analyzed a total of **110 outbursts** from these 36 sources with **RXTE data** from 1**996 to 2011**. They derived a number of very fruitful characteristics. This includes the relation between various properties like peak luminosity, e-folding timescales, outburst duration, total radiated energy. According to them,

For total radiated energy and peak luminosity,

$$log\ E = (-13.26 +- 6.53) + (1.52 +- 0.17)*L_{peak}$$

For total radiated energy and e-folding rise and decay timescales,

$$log\ E = (43.46 +- 0.10) + (0.68 +- 0.11)*log(tau_{rise,10\%-90\%})$$

$$log\ E = (43.72 +- 0.10) + (0.49 +- 0.13)*log(tau_{rise,10\%-50\%})$$

$$log\ E = (43.48 +- 0.12) + (0.60 +- 0.12)*log(tau_{rise,50\%-90\%})$$

$$log\ E = (42.65 +- 0.12) + (1.14 +- 0.10)*log(tau_{decay,10\%-90\%})$$

$$log\ E = (42.65 +- 0.12) + (1.00 +- 0.11)*log(tau_{decay,10\%-50\%})$$

$$log\ E = (43.09 +- 0.13) + (0.75 +- 0.10)*log(tau_{decay,50\%-90\%})$$

Distance and Mass Measurement

The authors first estimated the timescales from the light curve in which the flux is **10, 50,** and **90%** respectively. Then using the above relations, they estimated the total radiated energy. They also estimated the peak flux from the light curve (~ $\mathbf{2.6 * 10^{-8}}$ ***erg*** $\boldsymbol{cm^{-2}\ s^{-1}}$). From that they also estimated the total radiated energy. With the formula of total radiated energy at a distance D, they estimated the values of D and got an average of **5.8 +- 2.5** ***kpc***, which is in a comparatively very narrow range with respect to the previous measurement.

Thus, they estimated the value of R_{in} to be very precisely as $\mathbf{30.8^{+13.3}_{-13.3}}$ ***km***. From this using the previous mentioned relation, they got the mass as $\mathbf{8.07^{+3.70}_{-0.04}}$ ***Solar Mass***.

Discussion

A. Reason for the positive correlation between the total radiated energy and peak luminosity:

From Lasota (2001), it is seen that the X-ray luminosity is a function of the disk mass, i.e., the luminosity will depend on the matter accretion. If one assumes that other properties (e.g., radiation efficiency) remain constant, disk mass will be very important to determine outburst properties. The total radiated energy will also correspond to the total accretion mass of the disk. Thus, they have a positive correlation.

B. Shortcomings of the used model to constrain the Mass:

- The model does not consider a zero-torque condition (Zimmerman et al. 2005), which makes the estimation of radii 2.2 times smaller. This actually makes the mass of the BH 2.2 times smaller from 8 Solar mass to 3.7 Solar mass.

- There is a color correction factor in this model which aims to account for the scattering in the disk atmosphere. This factor f_{col} an have an error or uncertainty of 10% which can make an error of 20% in the estimation of the innerdisk radius.

Open Question

It has been observed that most of the XRBs have very high spin from the reflection modeling, whereas the events from the gravitational wave suggests that BHs have low spin. This is a causality effect in the field.

There is still work going on to resolve this problem.

Thank you!