AstroSat Investigations of Black hole candidate MAXI J1820+070

(**Mudambi** et al., 2020, *ApJL*, 889, L17;
Maqbool, **Mudambi** et al., 2019, *MNRAS*, 486, 2964)

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Growing Black Holes: Accretion & Mergers
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Outline

- ✓ Introduction
- ✓ Objectives of the study
- ✓ Data and Methodology
- ✓ Spectral and Temporal analysis
- ✓ Stochastic propagation model and Comparison with Cygnus X-1
- ✓ Results and Discussion
- ✓ References

Introduction

- First discovered - 6th March 2018 in optical by ASSESN survey (*Tucker et al., 2018*) and in X-rays on 11th March 2018 by MAXI *(Kawamuro et al., 2018)*
- Subsequent multi-wavelength observations revealed MAXI J1820+070 to be a black hole X-ray binary (BHXB) (*Baglio et al., 2018)*
- Located at a distance of $3.26^{+2.18}_{-1.03}$ kpc (*Gandhi et al., 2018*), one of the brightest X-ray novae discovered till date (*Corral-Santana et al., 2016*)
- Outburst period lasted for almost a year
- Showed rapid, frequent, alternating hard-soft spectral transitions *(Russell et al., 2019)*

- Showed high frequency reverberation lags between the bands 0.1-1.0 keV and 1.0-10.0 keV, seen for the first time in BHXBs (*Kara et al., 2019*)

- *Bharali et al., (2019)*, using *NuSTAR* and *SWIFT* data constrained the inclination to be ~ 30˚ and inner disk radius to be 4.2 r_g
  - Spectral analysis revealed a reflection component along with dominant thermal comptonization component

- Proximity, high flux rate and low absorption column – ideal candidate – stochastic propagation model – *Maqbool et al., (2019)*

Objectives of the study

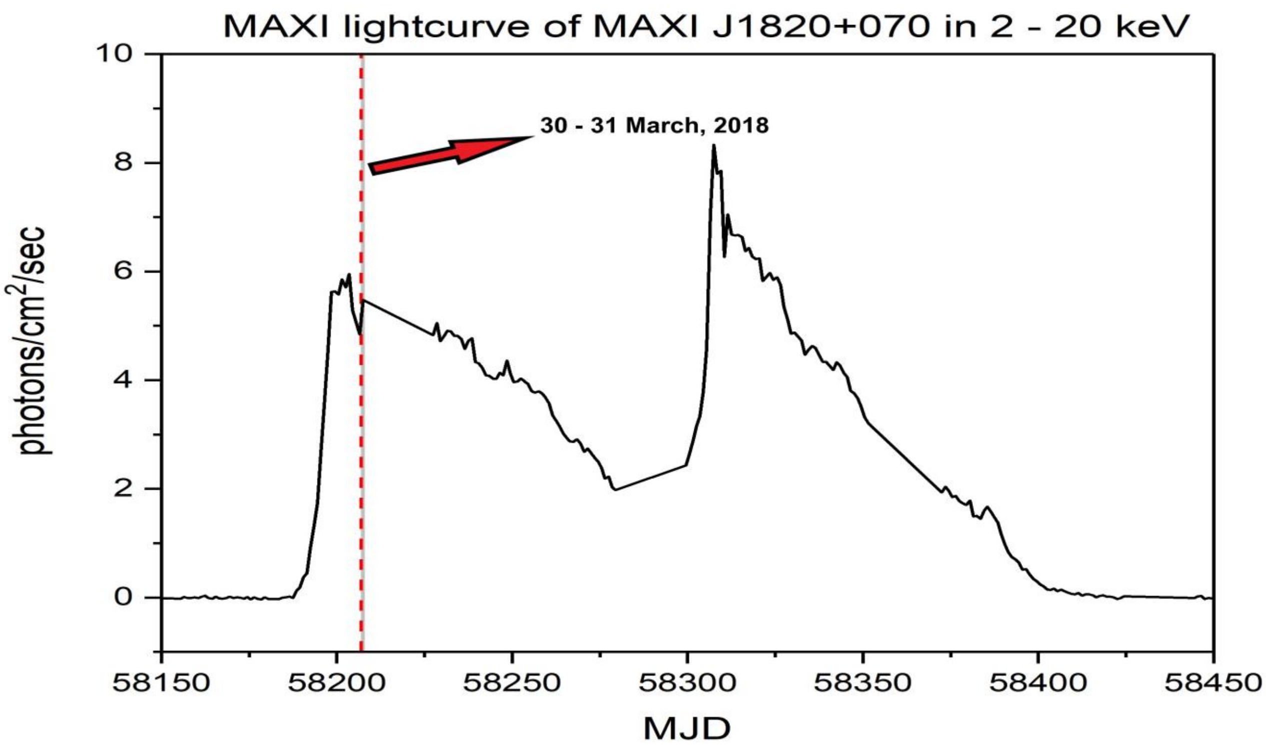
1. To perform comprehensive broad band spectral and temporal analysis to constrain the physical parameters of the accretion disk.

2. To look for the presence of quasi periodic oscillations (QPOs) through temporal studies.

3. To study the energy dependent fractional rms and time-lags above 30 keV.

4. To validate the stochastic propagation model proposed by Maqbool et al., (2019)

Data and Methodology



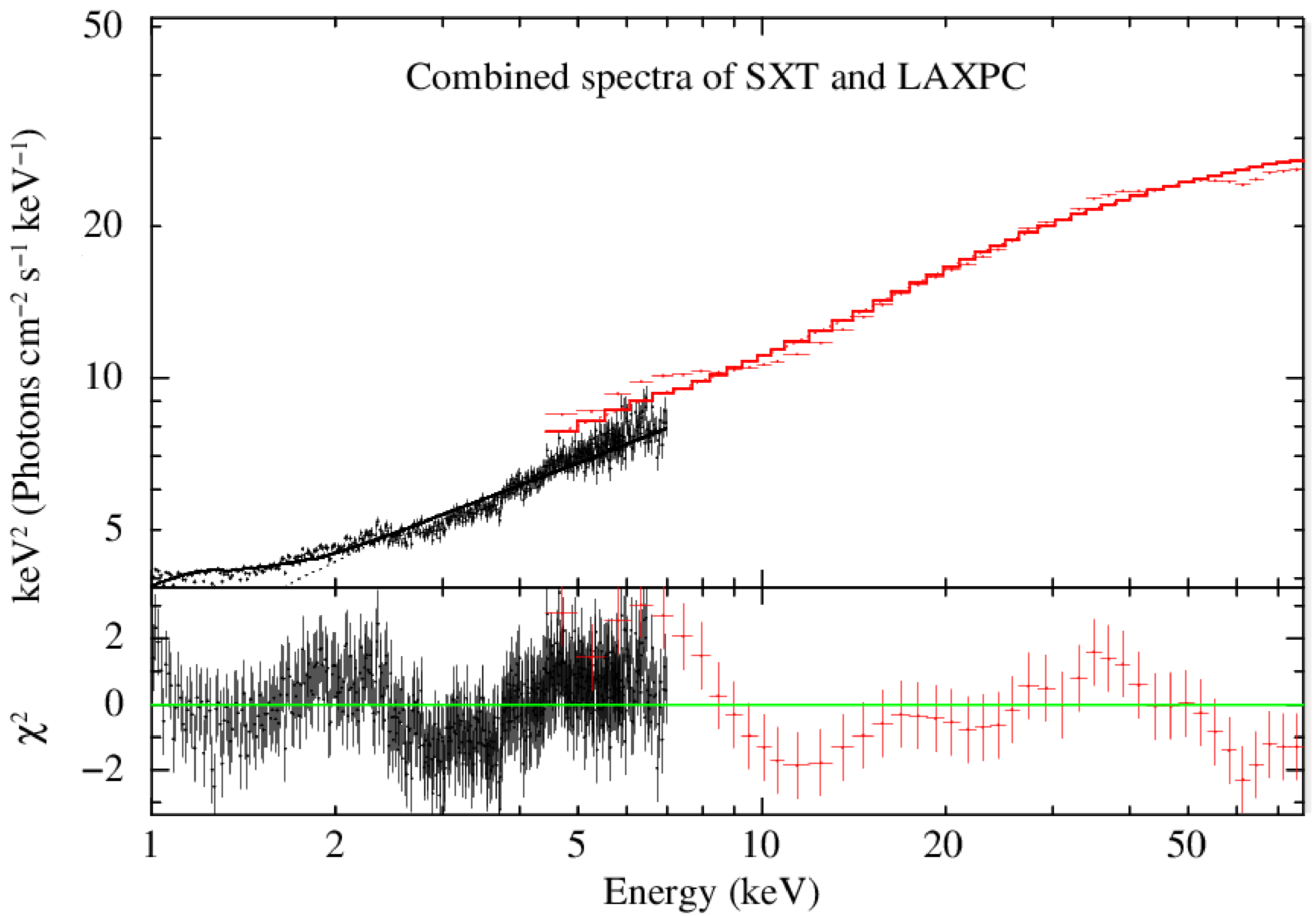
https://gads.issdc.gov.in/astro-gads/webapp/search.xhtml

- SXT - standard response and background files, SXT ARF generation tool
- LAXPC subroutines – background and response

Spectral and Timing analysis

- Combined spectra modelled – 0.7-80.0 keV
- Spectra was modelled using *nthComp, ireflect and diskbb* models
- N_H was fixed at 1.5 x 10^{21} cm^{-2} *(Uttley et al., 2018)*
- Disk emission – seed photons for Comptonization
- Disk inclination fixed at 30° (Barali et al., 2019)

Spectral Parameters						
Model parameters (Description)	rel_refl (Relativistic reflection)	Γ (Asymptotic power law)	N_{comp} (Normalization factor)	kT_{in} (Temperature at inner disk radius) keV	N_{disk} (Normalization factor) $\times 10^5$	χ^2/degree of freedom (dof)
Best-fit value	$0.17^{+0.04}_{-0.05}$	$1.61^{+0.01}_{-0.01}$	$3.42^{+0.05}_{-0.06}$	$0.22^{+0.01}_{-0.01}$	$2.4^{+0.6}_{-0.6}$	696/578



Mudambi et al., 2020, *ApJL*, 889, L17

- LAXPC20 event mode data – 3.0-50.0 keV
- PDS showed a QPO, weak oscillation and 3 broadband humps
- PDS was fitted with Lorentzians

PDS parameters

Feature	QPO	Weak oscillation	Noise hump 1	Noise hump 2	Noise hump 3	χ^2/dof
Centroid frequency (Hz)	$47.7^{+1.6}_{-2.0} \times 10^{-3}$	$109.4^{+2.8}_{-1.2} \times 10^{-3}$	0[a]	0[a]	$1.04^{+0.13}_{-0.20}$	
Width (Hz)	$11.9^{+5.0}_{-3.6} \times 10^{-3}$	$<1.7 \times 10^{-3}$	$10.7^{+2.3}_{-1.3}$	$0.24^{+0.02}_{-0.02}$	$1.6^{+0.7}_{-0.6}$	123/114
Norm $\times 10^{-3}$	$2.5^{+0.6}_{-0.6}$	$0.3^{+0.2}_{-0.1}$	$10.3^{+0.8}_{-1.1}$	$11.1^{+0.6}_{-0.6}$	$2.1^{+1.9}_{-0.9}$	

Note.
[a] Parameter frozen during fitting.

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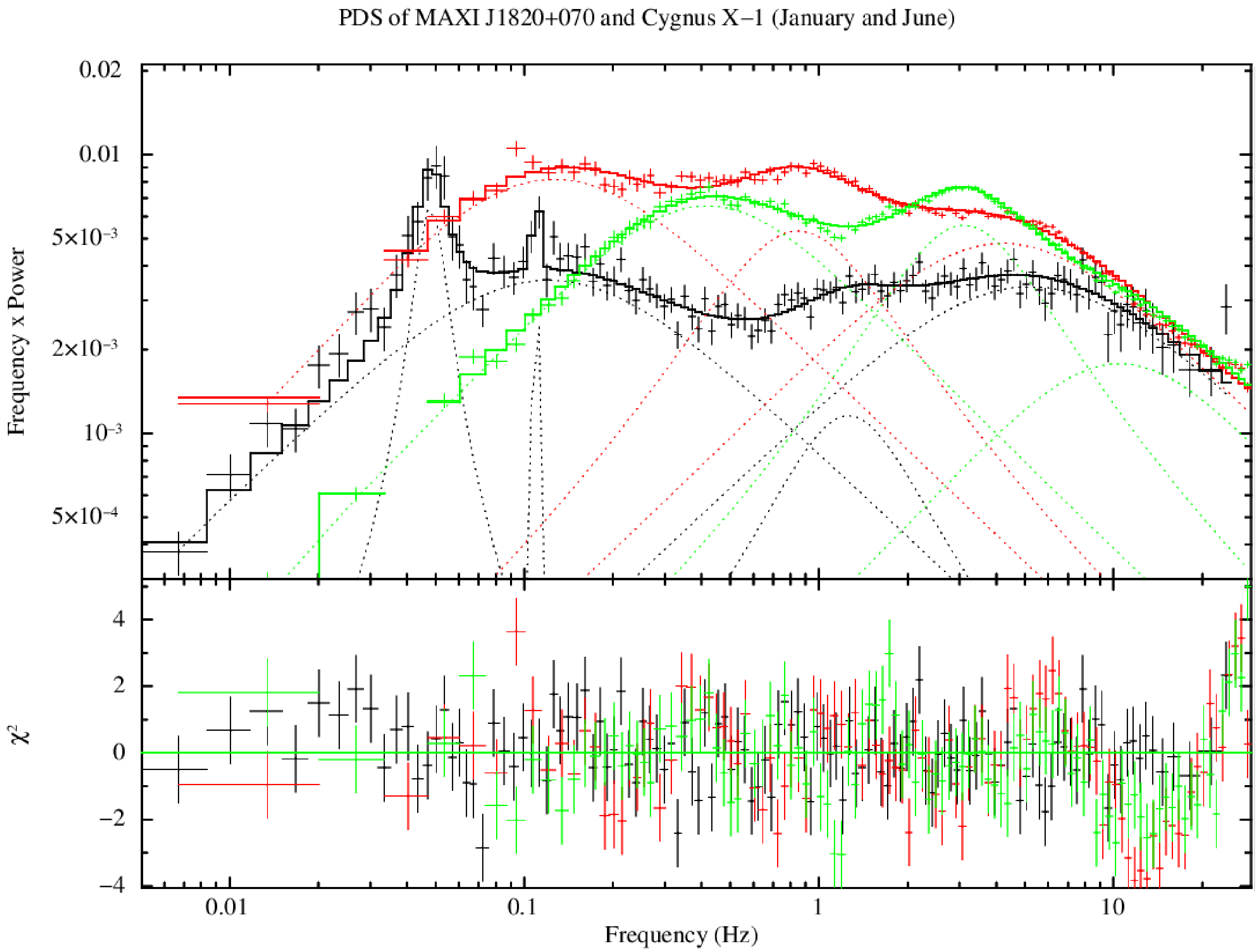

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Modelling rms and time-lags – Empirically

- Time lags computed - reference energy band 4.15 - 4.65 keV
- The fractional rms and time-lags were fitted empirically using the following relations:

1. Fractional rms - $F(E,f) = A(f) * E^{p(f)}$
2. Time-lag - $\delta t(E,f) = T_d(f) * \log(\frac{E}{E_{ref}})$, where $E_{ref} =$ 4.39 keV

- Reduced chi-square below 2

- The empirical relation describes the complete temporal behavior of the source in frequency and energy space
- Fails to provide a physical interpretation of the behaviour of the system.
- Fails to draw parallels between the behaviour of the source and the time-averaged energy spectra.
- There is a need to develop a physical model and compare the observed energy dependent rms and time-lag with its prediction.

- A new model called "A Single-zone Stochastic Propagation Model" is developed – *Maqbool et al., (2019)*
- Primary goal is to use fewer parameters to explain the energy dependent rms variability and time-lags.

Modelling rms and time-lags – Stochastic propagation model

- Assumptions made while developing the model:
  - ✓ Geometry of the hard state - standard accretion disk truncated at a large distance with a hot inner accretion disk
  - ✓ Hot inner accretion disk is homogenous and has uniform temperature (T_e)
  - ✓ Hot inner accretion disk comptonizes the photons arising from the cold outer accretion disk and thus producing the comptonized spectra (S_c)
  - ✓ A perturbation/oscillation arises at the outer regions and travel inwards

- A perturbation/oscillation results in the:
    1. temperature variation in truncation radius
    2. changes input flux of the photons entering the hot inner region
- The change in the flux photons correspondingly changes the temperature of the hot inner region to maintain the same power output
- After a propagation time delay, the perturbation will reach the inner regions causing a variation of its temperature

- The first order variation of the comptonized spectrum due to these effects can be written as :

$$\delta S_c\left(E, T_{e,} T_s\right) = \frac{\partial Sc}{\partial Ts}(E, Te, Ts)\delta T_s(t\ ) + \frac{\partial Sc}{\partial Te}(E, Te, Ts)\delta T_e(t - \tau_D)$$

where τ_D is the time taken for the propagation to travel from the outer truncated disk to inner regions

- To compute the behaviour of the system in a particular frequency we define:

$\delta T_s\ (t\ ) = |\delta T_s\ (t\ )|\ e^{-i2\pi f t}$ and

$\delta T_e\ (t\ ) = |\delta T_e\ (t\ )|\ e^{-i2\pi f (t-\tau_D)}$

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- Computing the partial derivative at a constant heating rate we get the final form of the equation to be:

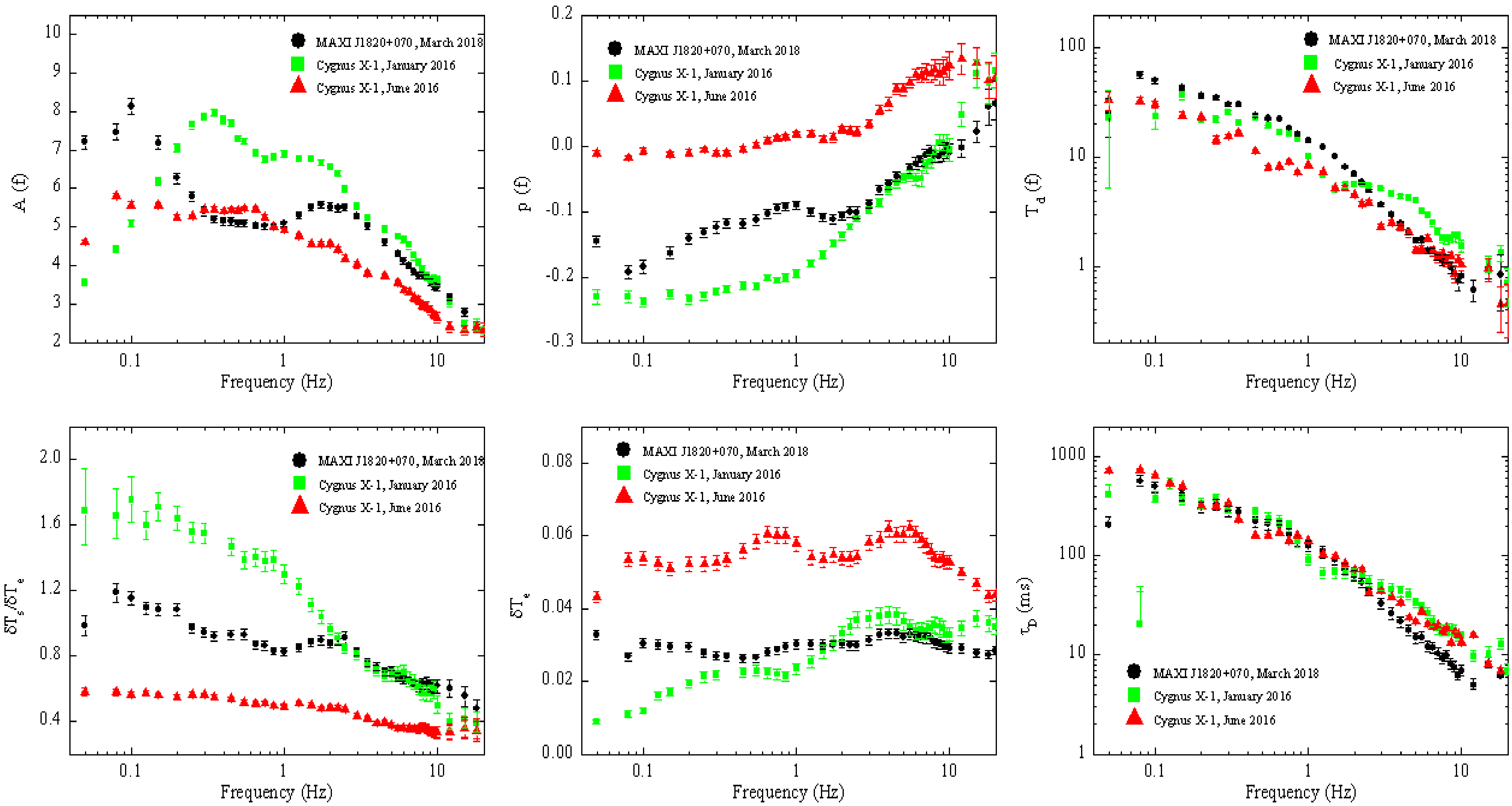
$$\frac{\partial S_c(E,T_e,T_s)}{\partial T_s} \sim \frac{S_c(E,T_e,T_s) - S_{ca}(E,T_{ea},T_{sa})}{\delta T_s}$$

for small δT_s i.e. $\delta T_s << T_s$ and $S_{ca}(E,T_{ea},T_{sa})$ is the time averaged comptonized spectrum at a slightly higher temperature T_e. The other parameters are kept constant.

- Three parameters characterizes the model - the normalized amplitudes of temperature of the truncation, inner radii and the time-lag between them.

- These parameters are obtained via simultaneous spectral fitting of the SXT and LAXPC data.

Model fitting and Comparison with Cygnus X-1



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Results

- Source was found in its hard state with photon index (Γ) = 1.61
- Joint SXT and LAXPC spectra well represented by dominant Comptonized component along with reflection and disk black body component
- Spectral analysis revealed a cool disk (0.22 keV) truncated at a large distance (~ 512 km)
- First confirmed detection of QPO at 47.7 mHz in MAXI J1820+070 using AstroSat *(Honman et al., 2018; Mereminskiy et al. 2018)*
- Able to fit energy dependent fractional rms and time-lag for a range of frequencies quantitatively

- Able to find the time-lags between the hard photons and soft photons
- Lags of the order of 100 milliseconds and is frequency dependent
- Able to successfully model the observed time-lags and rms variability using the stochastic model proposed by *Maqbool et al. (2019)*
- Our results show a very good agreement with the results of Cygnus X-1

Future work

- Extend this work to other types of X-ray binaries

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Thank You

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