Accretion flow Geometry and Variations of Spectra-Temporal Parameters of a black hole candidate; MAXIJ1535-571

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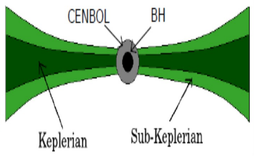
Outline;

- Introduction.
- Aim & Objectives.
- Data reduction and Analysis.
- Results/Discussion.
- Summary/Conclusion.

Introduction: MAXI J1535-571 outburst evolution & Accretion flow



- 02 September 2017.
- R.A. & Dec.; $15^h\ 35^m\ 19.73^s$, -57° 13′48″.
- Constellation Norma @ 4.1 – 6.5kpc.

Accretion Flow characteristics

1) Spectral properties/parameters

- Hard state (HS). 1.3 ≤ Γ≤ 1.8 — $\dot{M}$, Γ, T, L, F_x, etc. $\dot{M}_d$ ↑
- Hard-intermediate state (HIMS). Γ~ 1.8–2.3 — $\dot{M}_h$ & ARR ↓
- Soft-intermediate state(SIMS). Γ= 2.3–3.0
- Soft state(SS). ?

2) Temporal (Timing) properties

QPO A, B, & C; Indicator of changes in spectral states.

(e.g. Belloni, 2006,2010; Nandi+ 2012; Shidatsu+ 2014; Mereminskiy +2018; Tao+ 2018) vQPOs:1 mHz -1 kHz

Physical Mechanisms ?

- Hard/soft X-ray flux variability and flickering behavior.
- Outburst/spectral evolution.
- Oscillatory waves in the post-shock regions that produces QPO.
- Fluctuation & saturation effect.
- Origin of Γ–vQPO relation.
- Accretion flow dynamics/geometry.

$\dot{M}$ → $\dot{M}_h$ & $\dot{M}_d$

(Nakahira+ 2018; Tao+ 2018; Stiele & Kong, 2018; Shang+ 2019; Sreehari+ 2019; Bhargava+ 2019)

Mass accretion rate ($\dot{M}$) variations/fluctuations during outburst evolution

- Magnetic activity/viscosity → $\dot{M}_d$ ↑, $\dot{M}_h$ ↓
- Rising phases ($\dot{M}$) → Declining phases → X-ray flux variability

(Narayan, McClintock, & Yi, 1996; Hameury+ 1997; Esin+ 1997;Homan+, 2001) Accretion flow Dynamics/Geometry ⟷ Spectral Evolution

Aim & Specific objectives:

- Spectral analysis of MAXI J1535-571 data observed on the same and/or close-in epochs.
- Constrain physical parameters of the accretion flow, and obtain their correlations.
- Determine the variations of mass accretion rates and other accretion flow parameters and examine them.
- Determine the physical processes responsible for fluctuations and saturation effect in the accretion flow parameters, and the flickering behavior of MAXI J1535 -571.
- examine the dynamic/geometry of the accretion flow, and compare the results with that of other similar sources.

Data Reduction/Analysis & Fitting/modelling

- Source of Data: *MAXI/GSC*, *Swift/BAT*, & *NuSTAR*; 14th Sept. 2017.

HEASARC(https://heasarc.gsfc.nasa.gov/docs/archive.htm) — HEASoft v6.28, *mxproduct*, *batsurvey product*, *nupipeline v1.6*, *XSPEC v12.10.1f*, etc.

MAXI/GSC: UT 03:36:00 to 06:00:00, 17:35:59 to 19:59:59, &04:36:00 to 21:00:00..

Swift/BAT: 05:02:51 to 14:23:29, 05:21:58 to 14:41:58, & 05:43:54 to 20:52:58.

NuSTAR: 05:11:09 to 13:16:09, 09:51:09 to 20:16:09,& 03:16:09 to 21:38:18

- Data reduction /Analysis

Merge → Spectral fitting/modeling

- *const*tbabs*(bmc*highecut+bbody+diskbb+grad+gaus)- M 1*
- *const*tbabs*(nthcomp+diskbb+grad+gaus)- M2*
- *const*(PL+diskbb+grad+gaus)-M 3*
- *cosnt*tbabs*(TCAF+Xillver+gaus)- M4*
- *const*tbabs*(TCAF+nthcomp+diskbb+grad+gaus)-M5*

TD model: optically thick - & thin-plasma

TCAF model: Keplerian and sub-Keplerian flow

(Chakrabarti & Titarchuk, 1995; Kubota and Makishima, 2004; Done + 2007; Debnath + 2014; Banerjee +2020)

Estimation of Accretion flow Characteristics – MATLAB

$$r_i=\left(\frac{K}{\cos\theta}\right)^{1/2}\times D_{10} \quad (1)$$

$$R_i=\xi.K^2.r_i \quad (2)$$

$$T_i=\left[\frac{3GM_{bh}\dot{M}_{bh}}{8\pi\sigma_R r_i^3}\left(1-\beta\sqrt{\frac{R_i}{r_i}}\right)\right]^{1/4} \quad (3)$$

$$F_{bbb}=2\cos\theta.r_i^2\sigma_R T_i^4.D^{-2}=\frac{3GM_{bh}\dot{M}_{bh}\cos\theta}{4\pi r_i D^2}\left(1-\sqrt{\xi.K^2}\right) \quad (4)$$

$$L_{bbb}=4\pi r_i^2\sigma_R T_i^4=\frac{3GM_{bh}\dot{M}_{bh}}{2r_i}\times\left(1-\sqrt{\xi.K^2}\right) \quad (5)$$

$$F_{bbb}=\frac{\left[F_x-F_{disk}\right]}{2\cos\theta} \quad (6)$$

$$F_x=0.0165\left[\frac{r_i^2\cos\theta}{D^2}\right]\left[\frac{T_i}{1\text{keV}}\right]^3\times\text{photonss}^{-1}\text{cm}^{-2}$$

$$L_{bbb}=2\pi D^2\times\frac{\left[F_x-F_{disk}\right]}{\cos\theta} \quad (7)$$

$$\dot{M}_{bbb}=\frac{L_{bbb}}{\eta c^2} \quad (8)$$

$$\dot{m}=\frac{\dot{M}_{thin}}{\dot{M}_{Edd}}$$

$$\dot{M}_E=\frac{L_E}{\eta c^2}=\frac{4\pi GMm_p}{\eta\sigma_T c} \quad (9)$$

(Narayan, McClintock & Yi, 1996; Shidatsu et al., 2014; Makishima et al., 1986; Kubota & Makishima, 2004)

Estimation of Accretion flow Characteristics – MATLAB

$$F_{ss}=7.6\times10^{26}r^{-3}I\left(\frac{M}{M_\odot}\right)^2\left(\frac{\dot{M}_d}{1.4\times10^{17}}\right)ergcm^{-2}S^{-1} \quad (10)$$

$I=1-(3/r^{1/2})$, $M_d=\dot{m}_{disk}\times\dot{M}_{Edd}$

$$T_s=\frac{m_p\left[R-1\right]c^2}{2R^2k_B\left[X_s-1\right]} \quad (13)$$

$$v_{spo}=\frac{c}{2\pi Rr_g r_s\left[r_s-1\right]^{1/2}}=\frac{v_{so}}{2\pi Rr_s\left[r_s-1\right]^{1/2}} \quad (11)$$

$r_g=2GM_{bh}/c^2$ $v_{so}=c/r_g=c^3/2GM_{bh}$

$$\tau_r=\frac{t_c}{t_i}=3.5\times10^{-4}\left(\frac{1+A_r}{f_o\Gamma}\right)\left(1-\frac{1}{R^2}\right)=0.5<\tau_r<1.5 \quad (14)$$

$A_r=M_s+M_d/M_d$ $M_s=m_{disk}\times M_{Edd}$

$$H_s=\left[\frac{\gamma\left[R-1\right]X_s^2}{R^2}\right]^{1/2} \quad (12)$$

$t_i=X_s/V_{s-}RX_s(X_s-1)^{1/2}$ $V_{s-}=1/(X_s-1)^{1/2}$

(Chakrabarti & Titarchuk, 1995; Molteni et al., 1995, 1996; Debnath, Mondal & Chakrabarti, 2014; Chakrabarti, 2015)

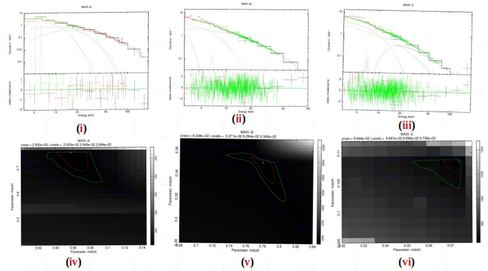
Resonance Condition

RESULTS & DISCUSSION

T1_M4

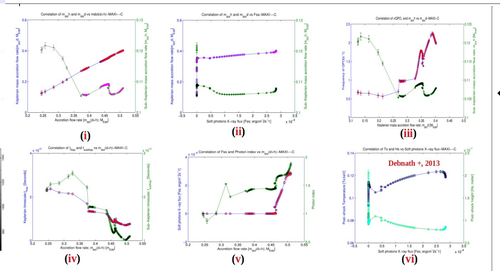
Spectral Parameter/Units	MAXI-A	MAXI-B	MAXI-C
const	0.98	0.92	1.02
N_H/cm^{-2}	$(2.634\pm1.64)\times10^{22}$	$(2.807\pm0.37)\times10^{22}$	$(2.52\pm0.13)\times10^{22}$
$m_{dot}d_{\_TCAF}/M_{Edd}$	0.548 ± 0.032	0.628 ± 0.001	0.721 ± 0.012
$m_{dot}h_{\_TCAF}/M_{Edd}$	$0.791^{+0.01}_{-0.03}$	0.737 ± 0.014	0.682 ± 0.201
$m_{bh\_TCAF}/M_\odot$	9.674 ± 0.131	$8.901^{+0.32}_{-0.24}$	10.05 ± 0.191
$Xs_{\_TCAF}/r_g$	$56.214^{+0.301}_{-0.807}$	$48.284^{+1.432}_{-0.242}$	$46.475^{+4.20}_{-1.342}$
$R_{\_TCAF}$	4.002 ± 1.023	$3.949^{+0.540}_{-0.141}$	3.84 ± 0.002
$norm_{\_TCAF}$	33.641 ± 1.045	$25.062^{+0.04}_{-0.21}$	59.012 ± 0.104
$\Gamma_{\_xillver}$	2.13 ± 0.08	2.02 ± 0.01	2.21 ± 0.11
$\theta_{\_xillver}$ (°)	$48.68^{+0.17}_{-0.12}$	$60.24^{+0.05}_{-0.08}$	$59.72^{+0.09}_{-0.13}$
$norm_{\_xillver}$	7.58 ± 0.021	5.82 ± 0.124	6.214 ± 0.117
$E_{6.5\_gaus}$ /keV	$6.486^{+0.103}_{-0.188}$	6.500 ± 0.002	$6.521^{+0.021}_{-0.011}$
E_{sigma}/keV	0.142 ± 0.015	0.102 ± 0.004	0.317 ± 0.158
$norm_{gaus}$	1.049 ± 0.001	0.540 ± 0.011	0.181 ± 0.022
χ^2	31.81	493.01	530.87
d.o.f	27	483	454
rd-χ^2	1.17	1.02	1.16
N_{hp}	2.391×10^{-01}	3.664×10^{-01}	7.311×10^{-01}

const = constant energy independent model, N_H = hydrogen absorption column density of *tbabs* model,$m_{dot}d_{\_TCAF}$ = Keplerian flow mass accretion rate of *TCAF* model, $m_{dot}h_{\_TCAF}$ = sub-Keplerian flow mass accretion rate of *TCAF* model, m_{bh_TCAF} = mass of the black hole of *TCAF* model, $Xs_{\_TCAF}$ = shock location of *TCAF* model, r_g = gravitational radius, $R_{\_TCAF}$ = compression ratio of *TCAF* model, $norm_{\_TCAF}$ = normalization parameter of TCAF model,E-6.5 $_{gaus}$ = iron emission line at 6.5 keV of *gaus* model, E_{sigma} = emission line width of *gaus* model, $norm_{gaus}$ = normalization parameter of the *gaus* model, $\Gamma_{\_xillver}$ = photon index of the *xillver* model, $\theta_{\_xillver}$ = angle of inclination of the *xillver* model, $norm_{\_xillver}$ = normalization parameter of *xillver* model, χ^2 (Chi-squared) = Fit/Test statistics, d.o.f = degree of freedom, rd-χ^2 = reduced Chi-squared, N_{hp} = Null hypothesis probability.



(i) (ii) (iii) (iv) (v) (vi)

Fig. 1: Upper: X-ray spectra of MAXI J1535-571. Lower: Contour plot of $m_{dot}h$ vs $m_{dot}d$.



(i) (ii) (iii) (iv) (v) (vi)

Fig. 2: Accretion flow parameters.

Correlation of accretion flow characteristics

T2_M5

MAXI-C						
Figure	Parameter	Correlation coefficient (R)	P-value	Lower bound	Upper bound	Direction & strength of correlation
Fig.2 (i)	$m_{dot}d$ vs m_{dot} (d+h)$_{M5}$	0.999	0.0000	0.998	1.000	Very strong positive
	$m_{dot}h$ vs m_{dot}(d+h)$_{M5}$	– 0.606	0.0000	– 0.721	– 0.458	strong negative
Fig.2 (ii)	$m_{dot}d$ vs Fss$_{M5}$	0.587	0.0000	0.435	0.707	Strong positive
	$m_{dot}h$ vs Fss$_{M5}$	– 0.257	0.0133	– 0.439	– 0.055	Weak negative
Fig.2 (iii)	vQPO vs $m_{dot}d_{M5}$	0.889	0.0000	0.836	0.925	Very strong positive
	$m_{dot}h$ vs $m_{dot}d_{M6}$	– 0.641	0.0000	– 0.747	– 0.501	Strong negative
Fig.2 (iv)	t_{hyp} vs m_{dot}(d+h)$_{M5}$	– 0.973	0.0000	– 0.982	– 0.959	Very strong negative
	$t_{sub\text{-}hyp}$ vs m_{dot} (d +h)$_{M5}$	– 0.938	0.0000	– 0.959	– 0.908	Very strong negative
Fig.2 (v)	Fss vs m_{dot} (d+h)$_{M5}$	0.594	0.0000	0.443	0.712	Moderate positive
	Γ vs m_{dot}(h+d)$_{M5}$	0.847	0.0000	0.777	0.896	Very strong positive
Fig.2(vi)	Ts vs Fss$_{M5}$	0.658	0.0000	0.523	0.760	Strong positive
	Hs vs Fss$_{M5}$	– 0.536	0.0000	– 0.667	– 0.372	Strong negative

m_{dot}d = Keplerian mass accretion rate, m_{dot}h = sub-Keplerian mass accretion rate, m_{dot} (d+h) = Accretion flow rate, Γ = photon index, vQPO = quasi-periodic oscillation frequency. Fss = intercepted soft X-ray flux, Ts = shock temperature, Hs = shock height, t_{hyp} = Keplerian timescale, t_{subhyp} = sub-Keplerian timescale. A p-value = 0 in Pearson product-moment correlation signifies that the correlated accretion flow parameters are statistically significant and there is a strong linear relationship between them. The p-value < 0.0001 means that the correlated parameters are statistically significant. .

Summary

- AF: optically thin (sub-Keplerian) & optically thick (Keplerian) flow/plasma (Chakrabarti & Titarchuk, 1995; Kubota & Makishima, 2004).
- AF Geometry: a mix of geometrically thick and geometrically thin; ➡ dynamic (Done + 2007; Debnath +2015).
- ARR ($m_{dot}h/m_{dot}d$) decrease from1.4 to 0.9. ➡ spectral evolution/transition tied to the variation of m_{dot}d and m_{dot}h (Nandi + 2012; Debnath +2015).
- The saturation effect occurs when the variations in m_{dot}h and m_{dot}d are not significant; an indication of converging flow observed in other galactic BHCs (Titarchuk +1997; Titarchuk & Seifina, 2016).
- Hs and Ts are anti-correlated (Fig. 2(iv)) instead decreasing with an increase in the interception of soft photons, and suppression of coronal activities (Debnath +2013).
- This suggests flickering behavior of MAXI J1535-571 in that variations of m_{dot}h and m_{dot}d change the shape of the post-shock region periodically (Esin +2012; Debnath + 2014).
- The variations/fluctuations of m_{dot}h and m_{dot}d created QPO (Chakrabarti & Manickam, 2000; Ingram & Done, 2011) in the accretion flow (post-shock region) when their timescales are roughly matched (Fig. iv; Molteni + 1995) as earlier noted in H 1743-322, and MAXI J1543–564 (Mondal + 2014; Chatterjee + 2016).
- The resonance condition of (0.62–0.79) ± 0.04 (Fig. 14; Chakrabarti, 2015) and best-fit photon index of 2.02–2.21 (Tao +2018; Nakahira + 2018) affirms the presence of QPO in the accretion flow of MAXI J1535-571 during the HIMS.
- The value of vQPO obtained is consistent with the type-C QPO frequency; 0.1–10 Hz observed in hard states of BHCs (Motta + 2012; Mereminskiy + 2018).
- The variations/fluctuations of m_{dot}d and m_{dot}h in the post-shock region causes distribution of power-law energy spectral indices, and create corresponding variations/fluctuations in Γ (see Fig. 3c–e; Sunyaev & Truemper, 1979; Sunyaev & Titarchuk, 1980; Chakrabarti & Titarchuk, 1995; Yaqoob, 1997; Esin + 1998).

Conclusion

- The spectral results and correlation of accretion flow parameters suggests that m_{dot}d and m_{dot}h are intrinsic properties of the accretion flow that interact at varying distances, causing a decrease in the ARR as the outburst progresses. This could be responsible for the delay in transition period of MAXI J1535-571).

Acknowledgment

MAXI/GSC, NuSTAR, and Swift/BAT observation team for providing data and softwares, Prof. Dipak Debnath; Institute of Astronomy, Space and Earth Science, India.

Recommendation

Broadband spectral analysis of the source using additional data of *AsTROSAT*, *HXMT*, and *NICER* alongside *MAXI/GSC*, *NuSTAR*, and *Swift/BAT* to elucidate this study. Also, investigation of the role of magnetic viscosity/field in driving the components of the accretion flow and transition period during the outburst evolution are paramount.

Thanks for Listening