Peculiar X-ray properties of MAXI J1631-479 and their understanding

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MAXI J1631-479 is a bright black hole X-ray transient discovered in 2018. MAXI-GSC and Swift-XRT data do not show a typical q-shape track but an inverse Y-shape one in the hardness and intensity diagram (HID) during the course of the outburst. Using MAXI and Swift data, we demonstrate such an inverse Y-shape track and observed various states (low/hard, hard and soft intermediate, and high/soft states) are naturally explained by current accretion disk models.

MAXI J1631-479, and MAXI and Swift observations

MAXI, Monitor of All-sky X-ray Image [1], discovered MAXI J1631-479 (hereafter J1631) on 2018 December 21 [2] through the MAXI-GSC Nova Alert system [3]. The outburst peaked at about 2.5 Crab, and lasted about 300 days, which is one of the brightest X-ray novae MAXI observed [4]. MAXI-GSC observed almost the whole outburst, and the Swift-XRT started observations from January 16 due to the sun-angle constraint.

The source was in the low/hard state (LHS) at the beginning, and underwent state transitions to the hard intermediate state (HIMS), the soft intermediate state (SIMS), the HIMS, the SIMS, and the high/soft state (HSS), and returned to the LHS.

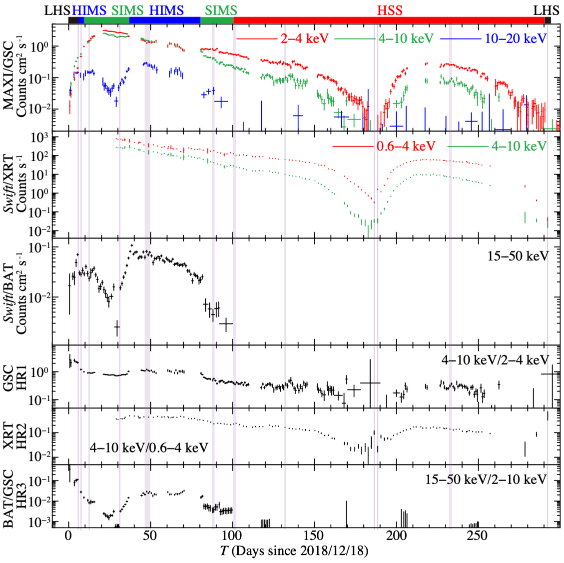

Fig. 1 MAXI-GSC, Swift-XRT, Swift-BAT light curves and hardness ratios of J1631 from Kobayashi et al. [4].

Hardness and Intensity Diagram, HID

A hardness and intensity diagram was often used to investigate spectral changes during the outburst. Many X-ray black hole novae are known to draw a 'q'-shape in the HID [5]. Gierliński and Newton pointed out that some bright novae did not so, but showed a more complex behavior especially near the peak of the outburst, characterizing an inverse 'Y'-shape in the HID [6].

MAXI and Swift long-term observations revealed that J1631 had the latter characteristics, and did not enter the LHS until the X-ray flux decreased by more than three orders of magnitudes from the peak flux [4]. These are very similar to MAXI J1535-571 [7].

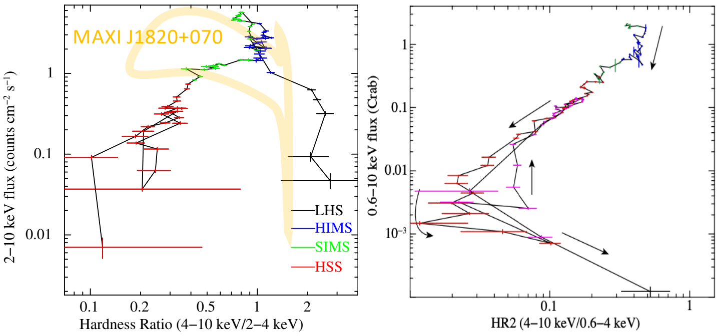

Fig. 2 Hardness-intensity diagrams obtained from the MAXI-GSC (right) and Swift-XRT (right) from Kobayashi et al. [4]. Each color represents the corresponding state shown in the right panel. In the right panel, MAXI data of MAXI J1820+070 is illustrated as a reference of a q-shape source.

Spectral Fits

We also intensively investigated spectral evolution by fitting GSC and XRT energy spectra with the absorbed power-law model in the LHS and the absorbed Comptonized disk blackbody model, `simpl*diskbb`, in the other states, taking account of the dust scattering effect as best as possible [4].

Discussion

Another method to characterize the spectral evolution especially focusing on the optically thick component is an inner disk temperature $T_{\rm in}$ versus its bolometric luminosity $L_{\rm DBB}$ ($\propto N_{\rm DBB} T_{\rm in}^4$) diagram using the disk blackbody model [8].

Figure 3 displays a $N_{\rm DBB} T_{\rm in}^4$ versus $T_{\rm in}$ diagram obtained with the GSC and the XRT data [4,9]. The solid line shows a $L_{\rm DBB} \propto T_{\rm in}^4$ relation for a constant $N_{\rm DBB}$ (e.g., a constant inner disk radius, $R_{\rm in}$). In the SIMS in the rising phase (filled green circles), the data points are much below the solid line due to small $R_{\rm in}$. Near the peak flux, the data points is roughly proportional to $T_{\rm in}^2$ rather than $T_{\rm in}^4$ (shown by the dotted line in the inset), suggestive of the slim disk state [10] as discussed by Kubota & Makishima [8].

HIMS data in the decline phase (blue circles) are slightly higher than the solid line, implying the disk truncation. In the following SIMS (open green circles and crosses) and HSS (red circles and magenta), data in $T_{\rm in} > 0.5$ keV are basically on the solid line, whereas HSS data in $T_{\rm in} < 0.5$ keV show higher disk fluxes than those expected from $L_{\rm DBB} \propto T_{\rm in}^4$ relation, showing roughly $L_{\rm DBB} \propto T_{\rm in}^3$ (the dashed line).

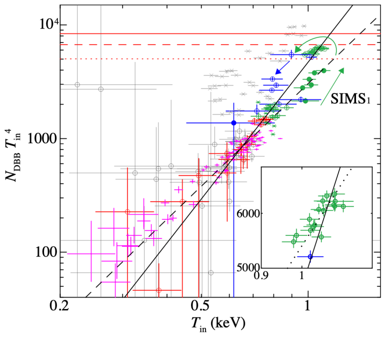

Fig. 3 $T_{\rm in}$ versus $N_{\rm DBB} T_{\rm in}^4$ diagram obtained with the GIS (closed and open circles) and the XRT (others) [4, 9]. Gray XRT data suffer from the pile-up (after the correction) and dust scattering.

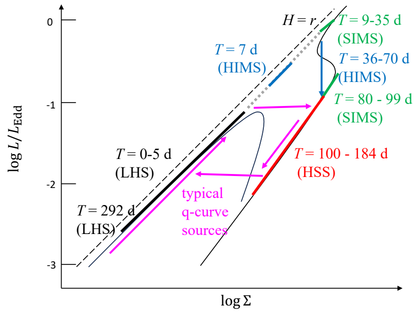

Fig. 4 Observed states on the the mass accretion rate ($\propto L_{\rm DBB}$) versus surface density Σ diagram.

These properties and other observed ones, e.g., iron line widths, are well understood in the mass accretion rate versus surface density diagram (Fig.4). In short, the smaller $R_{\rm in}$ in the rise phase results from the advection flow from the LHS to the SIMS. The (unstable) HIMSs in the rise and decay phases are consequences of crossing the optically thin-to-thick brunches (rise phase) and the Lightman-Eardley instability [11]. More quantitative and comprehensive discussion and remaining problems will be reported elsewhere [9].

References

[1] Matsuoka, M., et al. 2009, PASJ, **61**, 999 [2] Kobayashi, K., et al. 2008, ATel #12320 [3] Negoro, H., et al. 2016, PASJ, **68**, S1 [4] Kobayashi, K., et al. in prep. [5] Fender, R. P., Homan, J., & Belloni, T. M. 2009, MNRAS, **396**, 1370 [6] Gierliński, M., & Newton, J. 2006, MNRAS, **370**, 837 [7] Cúneo, V. A., et al. 2020, MNRAS, **496**, 1001 [8] Kubota, A., & Makishima, K. 2005, ApJ, **601**, 428 [9] Negoro, H., & Kobayashi, K. in prep. [10] Watarai, K., & Mineshige, S. 2001, PASJ, **53**, 915 [11] Lightman, A. .P., & Eardley, D. M. 1974, ApJL, **187**, L1