produce the observed LFQPO (Ingram et al. 2009). Because there is a misalignment between the hot accretion flow and the accretion disk, the reflection fraction changes with the hot accretion flow precession. The variation of the reflection fraction with LFQPO phases strongly depends on the inclination angle and the truncated disk radius (You et al. 2020).

In an alternative accretion geometry, the so-called lamppost geometry, a point corona lies above the black hole which illuminates the accretion disk. If the precession of the disk is the proposed mechanism to produce the LFQPO under this accretion geometry (Schnittman et al. 2006), the modulation in the Compton component at high energy band (say, e.g., above 100 keV) is not expected unless the corona is partially obscured by the precessing disk.

Besides, oscillation of the corona has also been proposed to explain the observed LFQPOs (Cabanac et al. 2010). However, the variations of the corona properties such as the electron temperature predicted by this model was not observed. In addition, an increasing trend of the RMS variability with energy relation predicted by this model is not seen either. Our results rule out the oscillation of the corona as the cause of the LFQPOs.

We have also noticed that the Two-Comptonent Advection Flow (TCAF) is used to explain the X-ray spectral and timing properties of black hole binaries in the hard state. The post-shock region in this model acts as a Compton cloud, and the oscillation of the Compton cloud causes the LFQPO(Chakrabarti et al. 2008). The Keplerian disk is situated outside the shock location and should be very far away from the central black hole (hundreds of r_g) in order to match the observed LFQPO frequency(Debnath et al. 2014). It would be very difficult to produce a strong disk reflection component and the potential oscillation of the Compton cloud further out in such a scenario.

Jet can also act like a corona which produces Compton photons (Markoff et al. 2005). MHD simulations have shown that a precessing jet can be formed and precession of the jet might be responsible for the LFQPO (Liska et al. 2018). Our results are rather consistent with such an idea that the Compton emission from the jet or jet base illuminates the accretion disk and produces the reflection component (e.g. Dauser et al. 2013; Kara et al. 2016). Other proposals which attribute the broadband X-ray LFQPOs as due to processing jet alone (Ma et al. 2020; Ferreira et al. 2022) is not supported by our spectral analysis, as a reflection component with strong effect of reflection fraction is required.

4 CONCLUSION

By performing LFQPO phase-dependent spectral analysis, we found the most varied parameter between the energy spectra corresponding to the peak phase and the trough phase of the black hole LFQPOs is the normalization *norm* in the Comptonization model we applied, and the second most varied parameter is the reflection fraction $\mathcal{R}$. Both the Compton and reflection spectral components contribute to the LFQPOs observed in broadband X-rays. In the spectral model applied in our spectral analysis, the difference in the normalization *norm* represents the variation in the Compton emission component, and the parameter reflection fraction $\mathcal{R}$ serves as an apparent amplification of the incident Compton component into the resulted reflection component, adding additional modulation in the reflection component with the LFQPO phase. Our investigation implies that the original timing signals or beats that are responsible for the LFQPOs lie in the Compton emission component, and the energy-dependent behavior of the LFQPOs at softer energies ($\lesssim$ 30 keV) is the result of the reflection component with a rather large reflection fraction. If the LFQPOs are due to Lense-Thirring precession, the phase information of precession then lies in the Compton component rather than in the reflection component.

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DATA AVAILABILITY

The public data used in this work can be downloaded in the *Insight*-HXMT official website (`http://hxmten.ihep.ac.cn/`)

REFERENCES

Atri P., et al., 2020, Monthly Notices of the Royal Astronomical Society, 493, L81
Belloni T. M., Motta S. E., 2016, arXiv, 440, 61
Buisson D. J. K., et al., 2019, Monthly Notices of the Royal Astronomical Society, 490, 1350
Cabanac C., Henri G., Petrucci P.-O., Malzac J., Ferreira J., Belloni T. M., 2010, Monthly Notices of the Royal Astronomical Society, 404, 738
Casella P., Belloni T., Homan J., Stella L., 2004, Astronomy & Astrophysics, 426, 587
Chakrabarti S. K., Debnath D., Nandi A., Pal P. S., 2008, Astronomy & Astrophysics, 489, L41
Dauser T., Garcia J., Wilms J., Böck M., Brenneman L. W., Falanga M., Fukumura K., Reynolds C. S., 2013, Monthly Notices of the Royal Astronomical Society, 430, 1694
Debnath D., Chakrabarti S. K., Mondal S., 2014, Monthly Notices of the Royal Astronomical Society: Letters, 440, L121
Done C., Gierlinski M., Kubota A., 2007, The Astronomy and Astrophysics Review, 15, 1
Dziełak M. A., Zdziarski A. A., Szanecki M., De Marco B., Niedźwiecki A., Markowitz A., 2019, Monthly Notices of the Royal Astronomical Society, 485, 3845
Esin A. A., McClintock J. E., Narayan R., 1997, The Astrophysical Journal, 489, 865
Fabian A. C., Ross R. R., 2010, Space science reviews, 157, 167
Ferreira J., et al., 2022, Astronomy & Astrophysics, 660, A66
Foreman-Mackey D., Hogg D. W., Lang D., Goodman J., 2013, Publications of the Astronomical Society of the Pacific, 125, 306
Garcia J., Kallman T. R., 2010, The Astrophysical Journal, 718, 695
Huang Y., et al., 2018, The Astrophysical Journal, 866, 122
Ingram A. R., Motta S. E., 2019, New Astronomy Reviews, 85, 101524
Ingram A., van der Klis M., 2015, Monthly Notices of the Royal Astronomical Society, 446, 3516
Ingram A., Done C., Fragile P. C., 2009, Monthly Notices of the Royal Astronomical Society: Letters, 397, L101
Ingram A., van der Klis M., Middleton M., Done C., Altamirano D., Heil L., Uttley P., Axelsson M., 2016, Monthly Notices of the Royal Astronomical Society, 461, 1967
Ingram A., van der Klis M., Middleton M., Altamirano D., Uttley P., 2017, Monthly Notices of the Royal Astronomical Society, 464, 2979
Kara E., Miller J. M., Reynolds C., Dai L., 2016, Nature, 535, 388
Kara E., et al., 2019, Nature, 565, 198