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Exploring the X-ray universe via timing: mass of the active galactic nucleus black hole XMMUJ134736.6+173403

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Abstract. A strong quasi-periodic modulation has recently been revealed in the X-ray flux of the X-ray source XMMUJ134736.6+173403. The two observed twin-peak quasiperiodic oscillations (QPOs) exhibit a 3:1 frequency ratio and strongly support the evidence for the presence of an active galactic nucleus black hole (AGN BH). It has been suggested that detections of twin-peak QPOs with commensurable frequency ratios and scaling of their periods with BH mass could provide the basis for a method intended to determine the mass of BH sources, such as AGNs. Assuming the orbital origin of QPOs, we calculate the upper and lower limit on the AGN BH mass M, reaching $M \approx 10^7 - 10^9 M_\odot$. Compared to mass estimates of other sources, XMMUJ134736.6+173403 appears to be the most massive source with commensurable QPO frequencies, and its mass represents the current observational upper limit on the AGN BH mass obtained from the QPO observations.

Keywords. black hole physics; accretion; accretion disks

1. Introduction

The X–ray power density spectra (PDS) of several Galactic BH systems show high-frequency (HF) QPOs. Their frequencies lie within the range of $40 - 450$Hz, which corresponds to timescales of orbital motion in the vicinity of a BH, suggesting thus that the observed signal likely originates in the innermost parts of an accretion disk (McClintock & Remillard, 2006). In Galactic microquasars, the commonly found detections of HF QPO peaks display more or less constant frequencies that are specific for a given source. The observed frequencies often come in ratios of small natural numbers, the most common one being 3:2 (Abramowicz & Kluźniak, 2001; Remillard *et al.*, 2002; McClintock & Remillard, 2006).

The 3:2 frequencies observed in the Galactic microquasars can be matched by the following relation (McClintock & Remillard, 2006),

$$\nu_{\mathrm{U}} = \frac{2.8\mathrm{kHz}}{M^*}. \tag{1.1}$$

Here, ν_{U} is the higher of the two frequencies that form the 3:2 ratio, $R = \nu_{\mathrm{U}}/\nu_{\mathrm{L}} = 3/2$, and $M^* = M/M_\odot$, where M is the BH gravitational mass and $M_\odot$ is the solar mass. The microquasar's 3:2 QPO frequencies and their scaling are illustrated in Figure 1. It has been proposed by Abramowicz *et al.* (2004) that detections of 3:2 QPOs and scaling (1.1) could provide the basis for a method intended to determine the mass of BH sources,

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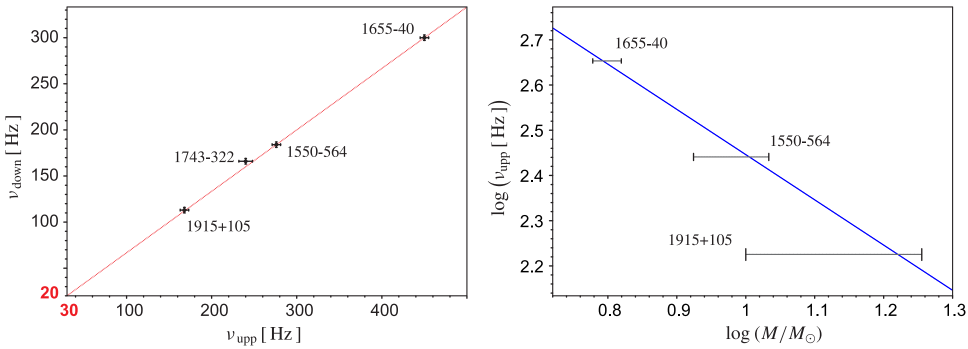

Figure 1. Left: The 3:2 HF QPO frequencies observed in Galactic microquasars. Right: The $1/M$ scaling of these frequencies, which supports the QPO orbital origin hypothesis.

such as AGNs. Here we briefly report on a recent progress in this field. A more detailed discussion along with a number of references can be found in Goluchová *et al.* (2019).

2. Estimation of the upper limit on the AGN mass

The two QPOs that occur on a daily timescale and exhibit a 3:1 frequency ratio have recently been observed in the X-ray source XMMUJ134736.6+173403 by Carpano & Jin (2018). This observation allows us to obtain the upper limit on the AGN BH mass in this source.

The Keplerian frequency of matter orbiting a BH monotonically increases as the orbital radius r decreases down to the inner edge of the accretion disk. Location of the inner edge depends on the disk's radiative efficiency, ranging from the innermost stable circular orbit (r_{ISCO}) to the marginally bound orbit (r_{RISCO}). At these orbits, Keplerian frequency for a Schwarzschild BH ($a \equiv cJ/(GM^2) = 0$) scales with BH mass as (e.g., Bardeen *et al.*, 1972)

$$\nu_{ISCO} = \frac{2.20\mathrm{kHz}}{M^*}, \quad \nu_{RISCO} = \frac{4.04\mathrm{kHz}}{M^*}, \tag{2.1}$$

while for an extremely rotating Kerr BH ($a = 1$), one may write:

$$\nu_{ISCO} = \nu_{RISCO} = \frac{16.2\mathrm{kHz}}{M^*}. \tag{2.2}$$

Figure 2 shows the above relations, which determine the highest allowed orbital frequencies. Assuming that the higher QPO frequency observed in XMMUJ134736.6+173403 corresponds to Keplerian frequency of matter anywhere inside the disk, we estimate the mass of the source to be no higher than $M \doteq 1.1 \times 10^9 M_\odot$.

3. Discussion

Provided that the observed BH HF QPOs can be described by a QPO model that deals with orbital motion, XMMUJ134736.6+173403 likely represents the most massive BH source with commensurable QPO frequencies. Using the ISCO frequency relation that gives the highest possible orbital frequency inside the disk, the estimation of M is found to be no higher than $M \approx 10^9 M_\odot$. This result can be viewed as the current observational upper limit on the AGN BH mass inferred from the QPOs. It is, however, valid only as long as the oscillation frequencies characteristic for a given QPO model are not much higher than the Keplerian frequency. This condition is, nevertheless, likely to be satisfied (Straub & Šrámková, 2009).

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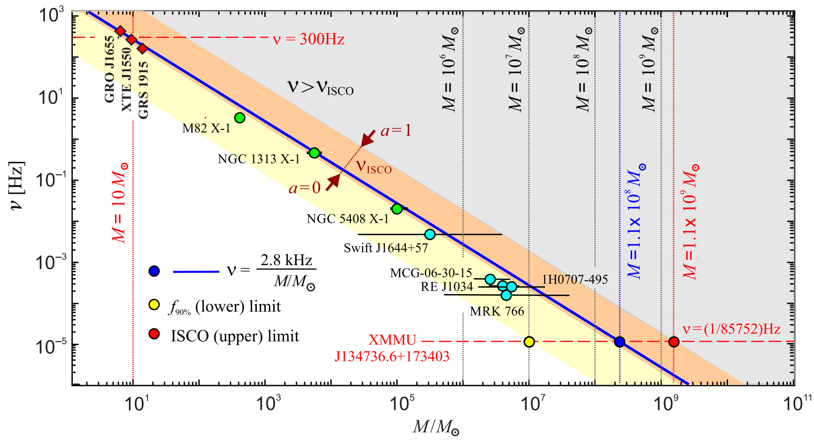

Figure 2. Large scaling of BH HF QPO frequencies vs. Keplerian frequencies in the accretion disk. The upper left corner of the plot corresponds to Galactic microquasar BHs, while the lower right corner corresponds to supermassive BHs. The light orange region denotes the ISCO frequencies in the range of $a \in [0, 1]$. The grey area indicates frequencies that are higher than the ISCO frequency. The light yellow area denotes Keplerian frequencies in the inner part of the (thin) disk that radiates more than 90% of the whole disk luminosity ($a \geq 0$). The green circles denote intermediate-mass BH sources, whose mass estimate is based either fully or in large part on the observations of HF QPOs.

For a large range of M, various orbital QPO models provide similar mass-spin relations. Following a quadratic approximation, we may write:

$$M \approx (5^{+11}_{-3} a^2 + 8^{+17}_{-4} a + 8^{+12}_{-4}) \times 10^7 M_\odot, \qquad (3.1)$$

where the upper limit corresponds to models that imply a high BH mass (low QPO excitation radius) and the lower limit to models giving a low BH mass (high QPO excitation radius, Goluchová *et al.*, 2019).

Finally, we also note that, very recently, Gupta *et al.* (2019) discussed a gamma ray QPO in the high-redshift blazar B2 1520+31. Using the ISCO frequency relation, they found the upper limit on the BH mass to be $M \approx 10^{10} M_\odot$.

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