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Detection of a Possible X-ray Quasi-periodic Oscillation in the Active Galactic Nucleus 1H 0707-495 (Postprint)

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Abstract

Quasi-periodic oscillation (QPO) detected in the X-ray radiation of black hole X-ray binaries (BHXBs) is thought to originate from dynamical processes in the close vicinity of the black holes (BHs), and thus carries important physical information therein. Such a feature is extremely rare in active galactic nuclei (AGNs) with supermassive BHs. Here we report on the detection of a possible X-ray QPO signal with a period of 3800,s at a confidence level >99.99% in the narrow-line Seyfert 1 galaxy (NLS1) 1H~0707-495 in one data set in 0.2-10,keV taken with {*XMM-Newton*}*. The statistical significance is higher than that of most previously reported QPOs in AGNs. The QPO is highly coherent (quality factor Q= /Δ 15) with a high rms fractional variability (15%). A comprehensive analysis of the optical spectra of this AGN is also performed, yielding a central BH mass 5.2×106M from the broad emission lines based on the scaling relation. The QPO follows closely the known frequency-BH mass relation, which spans from stellar-mass to supermassive BHs. The absence of the QPO in other observations of the object suggests it a transient phenomenon. We suggest that the (high-frequency) QPOs tend to occur in highly accreting BH systems, from BHXBs to supermassive BHs. Future precise estimation of the BH mass may be used to infer the BH spin from the QPO frequency.*

Full Text

Preamble

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ABSTRACT

Quasi-periodic oscillation (QPO) detected in the X-ray radiation of black hole X-ray binaries (BHXBs) is thought to originate from dynamical processes in the close vicinity of black holes (BHs), and thus carries important physical information therein. Such a feature is extremely rare in active galactic nuclei (AGNs) with supermassive BHs. Here we report on the detection of a possible X-ray QPO signal with a period of 3800 s at a confidence level > 99.99% in the narrow-line Seyfert 1 galaxy (NLS1) 1H 0707-495 in one data set in 0.2–10 keV taken with XMM-Newton. The statistical significance is higher than that of most previously reported QPOs in AGNs. The QPO is highly coherent (quality factor Q = / > 15) with a high rms fractional variability (15%). A comprehensive analysis of the optical spectra of this AGN is also performed, yielding a central BH mass of 5.2 × 10 M from the broad emission lines based on the scaling relation. The QPO follows closely the known frequency–BH mass relation, which spans from stellar-mass to supermassive BHs. The absence of the QPO in other observations of the object suggests it is a transient phenomenon. We suggest that (high-frequency) QPOs tend to occur in highly accreting BH systems, from BHXBs to supermassive BHs. Future precise estimation of the BH mass may be used to infer the BH spin from the QPO frequency.

Subject headings: *galaxies: active —galaxies: nuclei —X-rays: galaxies — galaxies: individual (1H 0707-495)*

INTRODUCTION

Active galactic nuclei (AGNs), powered by black hole (BH) accretion with BHs of 10 -10 M at the center of galaxies, are thought to be scaled-up versions of black hole X-ray binaries (BHXBs) (McHardy 2010; González-Martín & Vaughan 2012; Markoff et al. 2015; Scaringi et al. 2015). A compelling line of evidence for this postulation is the striking similarity in the variability of the X-ray radiation between AGNs and BHXBs (e.g., Uttley et al. 2002; Markowitz et al. 2003; McHardy et al. 2006; McHardy 2010; Vaughan et al. 2003a, 2011).

One characteristic and enigmatic feature of the variable X-rays is Quasi-Periodic Oscillation (QPO), which has been observed in the X-ray light curves of dozens of BHXBs (e.g., Strohmayer 2001; Remillard et al. 2002). X-ray QPOs were found to have two types: low-frequency QPOs (LFQPOs) and high-frequency QPOs (HFQPOs) (Remillard & McClintock 2006, hereafter RM06). HFQPOs sometimes occur in pairs with a constant frequency ratio of 3:2, and unlike LFQPOs, their frequencies (f_QPO) are stable despite significant variations in fluxes (Remillard et al. 2002). This indicates that HFQPO is likely a fundamental property that might be linked to the mass (and spin) of the BH. Based on only three BHXBs with measured BH masses, RM06 suggested an inverse linear relation between f_QPO and BH mass, which was later extended to intermediate-mass BH (IMBH) in ultraluminous X-ray sources (ULXs) by Abramowicz et al. (2004). A number of HFQPO models have been proposed in the literature (see Lai & Tsang 2009 and Belloni & Stella 2014 for reviews and references therein).

In AGNs with supermassive BHs (SMBHs), however, QPOs are rarely detected. So far, there is only one widely accepted case in which a significant QPO was unambiguously detected in the Narrow-Line Seyfert 1 (NLS1) galaxy RE J1034+396 with f_QPO 2.7 × 10 Hz (Gierliński et al. 2008; Alston et al. 2014; Hu et al. 2014). Recently, a 200 s X-ray QPO was detected in the transient X-ray source Swift J164449.3+573451, thought to be from tidal disruption of a star by a dormant SMBH (Reis et al. 2012). By extending BH masses to the SMBH range, Zhou et al. (2015) suggested that the f_QPO–M_BH scaling relation is universal, spanning 6 orders of magnitude from stellar-mass BHs to SMBHs.

Besides RE J1034+396, possible detections of X-ray QPOs were also reported in a few other AGNs, however, at relatively low levels of significance. A 3.8 hr QPO in 2XMM J123103.2+110648 was reported and suggested to be a LFQPO (Lin et al. 2013), and a 2 hr HFQPO was also reported in MS 2254.9-3712 (Alston et al. 2015).

In this letter, we report on the discovery of a significant QPO signal in one XMM-Newton observation of 1H 0707-495, a nearby (redshift 0.04), typical NLS1 (Véron-Cetty & Véron 2010). We also re-examine the BH mass of 1H 0707-495 by analyzing its available optical spectroscopic data, and compare the QPO with the f_QPO–M_BH relation. A cosmology with H = 70 km s ¹ Mpc ¹, Ω_m = 0.3 and Ω_Λ = 0.7 is adopted.

2. X-RAY QUASI-PERIODIC OSCILLATION

1H 0707-495 was observed with XMM-Newton with an exposure of 100 ks on February 6, 2008 in the full frame imaging mode (Obs ID: 0511580401). We follow the standard procedure to reduce the data and extract science products from the observation data files (ODFs) using the XMM-Newton Science Analysis System (SAS, version 13.0.0). Only good events (single and double pixel events, i.e., PATTERN 4 for PN or 12 for MOS) are used. Source events are extracted *from a 40-arcsec circular region, and background events from a source-free circle with the same radius on the same CCD chip. X-ray light curves are constructed for all three EPIC detectors in the 0.2–10 keV energy band with a binsize of 100 s, and are corrected for instrumental factors using EPICLCCORR.*

The combined PN+MOS1+MOS2 light curve is shown in Figure 1 [Figure 1: see original paper]. Even by eye, a periodicity can be clearly seen. We search for periodicity by calculating the root-mean-square (rms) amplitudes of the light curve folded with various periods as a function of period. A strong peak appears at around 3800 s. It is also found that this peak is the strongest if the latter half of the light curve is used only, with a quasi-period of 3800 ± 170 s (full-width at half-maximum). We thus take an operational cut as indicated in Figure 1 (solid vertical line) and consider only the last 55 ks segment hereafter, in order to achieve the highest confidence level for the periodic signal. This segment has a mean count rate of 6.1 counts s^{1} and fractional rms variability of 41%, while the whole light curve gives 6.7 counts s^{1} and 37%, respectively. The folded light curve with a period of 3800 s is also shown in Figure 1 (inset), with the best-fit sinusoid model.

The power spectrum density (PSD) of the light curve is computed as the modulus-squared of the discrete Fourier transform (DFT), and the (rms/mean)^2 normalization is chosen (Vaughan et al. 2003b). The PSD for the last 55 ks segment is plotted in Figure 2 [Figure 2: see original paper], and a strong peak at 2.6 × 10 Hz is evident. The continuum (red noise) is well fitted with a power-law of slope −1.90 (^{2} = 301/282 dof, in log-log space). This signal is even more prominent in the residuals plot (data/model). To test its statistical significance, a Monte Carlo technique is applied following Reis et al. (2012) and Lin et al. (2013). We simulate one million light curves using the method of Timmer & Koenig (1995) from a PSD, which is assumed to be the above best-fit power-law. Thus the distribution of the variability power at each Fourier frequency can be obtained from the PSDs of the simulated light curves. The dashed line in Figure 2 represents the 99.99% significance level, indicating a significant QPO. Using the data from the PN camera and the combined MOS cameras individually leads to the same result with QPO significance levels > 99.99% in both cases.

To test the QPO in RE J1034+396, Gierliński et al. (2008) used a method developed by Vaughan (2005). This method was later improved significantly by Vaughan (2010) to be an even more stringent test based on Bayesian statistics, in combination with PSD fitting. We also adopt this improved method here. Instead of a simple power-law (H model), a bending power-law (H model) is used to fit the PSD continuum. The low-frequency slope is fixed at −1, while the high-frequency slope is fitted to be −2.4 ± 0.22, with a bending frequency of 1.4 × 10 Hz. Then Markov Chain Monte Carlo simulations are performed, resulting in a small posterior predictive p-value of 2.5(±0.5) × 10^{3} for the significant outlier at frequency 2.6 × 10 Hz [p = 3.9(±0.62) × 10^{3} for the PN light curve and p = 4.0(±0.63) × 10^{3} for the combined MOS light curve, respectively]. This strongly indicates the presence of the QPO. This periodicity *of 2.6 × 10 Hz is highly coherent and confined to only one frequency bin in our analysis. Considering the frequency resolution for the observation (1/T = 1.75 × 10 Hz), the quality factor (Q = / > 15) is high. The rms fractional variability in the QPO is 15%.*

Compared to the rare previously reported QPOs in AGNs in the literature, the QPO in 1H 0707-495 has a significance level at least similar to or even higher than most of the others but only somewhat lower than that in RE J1034+396[1]*. The significance of this QPO would be reduced to < 90% if the whole observation duration is considered. We also analyzed data from 14 other XMM-Newton observations of 1H 0707-495 with exposure times longer than 40 ks, but no significant QPO was found. Thus the QPO appears to be a transient feature, similar to that found in RE J1034+396 (Gierliński et al. 2008; Middleton et al. 2011).*

[1]*The p-value for RE J1034+396 is 5 × 10 , if only the second segment of its light curve is used, following Gierliński et al. (2008).*

Fig. 1.*—XMM-Newton light curve of 1H 0707-495, extracted and combined from the PN, MOS1 and MOS2 detectors in 0.2-10 keV with a binsize of 100 s. The light curve is divided into two segments by the solid line, and only the second segment is used in this letter. The dotted vertical lines show the expected periodicity of 3800 s, which can be seen from the light curve even by eye. Upper Right Inset: The folded light curve with a period of 3800 s. Errors are propagated from the unfolded curve. The best-fit sinusoid is shown as the solid line and the mean count rate as the dotted line. Two cycles are plotted for clarity.*

Fig. 2.*—Power spectrum density of the X-ray light curve of 1H 0707-495. The solid line represents the best-fit power-law, and the dashed line represents the 99.99% confidence level. The dotted horizontal line shows the expected level of Poissonian noise. The data/model residuals are shown in the lower panel. A statistically significant peak is clearly present at 2.6 × 10 Hz.*

3. BLACK HOLE MASS ESTIMATION AND THE f_QPO-M_BH RELATION

Using the empirical virial method based on optical spectroscopic data, the BH mass of 1H 0707-495 has been estimated in previous studies as 1 × 10 M from a 6dF spectrum (Bian & Zhao 2003) and 4 × 10 M (Done & Jin 2015) from a CTIO spectrum taken by Leighly & Moore (2004). We re-analyze both spectra, following the procedure described in Yao et al. (2015) to fit the optical spectra. Only the CTIO spectrum is shown in Figure 3 [Figure 3: see original paper] for demonstration. The flux of the 6dF spectrum is calibrated using the CTIO spectrum. The continuum is modeled with a power law and the Fe II emission is modeled using the Véron-Cetty et al. (2004) templates. The Balmer lines are deblended into a broad and a narrow component, with the former modeled with a Lorentzian profile. The narrow component is modeled by a Gaussian with FWHM fixed at the CTIO spectral resolution (330 km s ¹, Leighly & Moore 2004). The *flux ratio of the [O III] 4959, 5007 doublet is fixed at the theoretical value of 1:3 while each of them is fitted with two Gaussians, one for the line core with FWHM fixed to the narrow Balmer line widths, the other for the blueshifted wing. The widths of the broad H line are fitted to be 1002 km s ¹ (CTIO) and 1054 km s ¹ (6dF), which agree with each other within mutual errors. The narrowness of the broad H line, as well as the strong Fe II emission, are characteristic of NLS1 AGN. The BH mass is estimated using the broad H line width and the monochromatic luminosity at 5100 Å (L = 4.0 × 10 ³ erg s ¹) (Vestergaard & Peterson 2006), giving M_BH = 5.2 × 10 M (CTIO) and 5.7 × 10 M (6dF), respectively.*

Given the large uncertainty of 0.5 dex for this method (Vestergaard & Peterson 2006), the estimated BH mass is consistent with previous results. We consider our spectral analysis to be more comprehensive and rigorous compared to those in previous work, and thus adopt M_BH = 5.2(±0.5 dex) × 10 M as the best estimate of the BH mass in 1H 0707-495. Adopting a bolometric luminosity of 3.6 × 10 erg s ¹ estimated from 9 × L (Kaspi et al. 2000), the Eddington ratio is 0.5, which is typical of NLS1.

By extending the f_QPO–M_BH relation from stellar-/intermediate-mass BH to the SMBH regime, Zhou et al. (2015) suggested it to be a universal relationship for astrophysical BHs at all mass scales. In Figure 4 [Figure 4: see original paper], we reproduce the f_QPO–M_BH relation derived by RM06 based on three BHXBs (solid line) and overplot 1H 0707-495, as well as those BH systems with known QPOs (see Table 1 in Zhou et al. 2015). Clearly, the QPO in 1H 0707-495 conforms with the f_QPO–M_BH relation within the BH mass uncertainty range.

***Fig. 3.**—CTIO spectrum of 1H 0707-495. The continuum modeled with a power-law is plotted in green. The best-fit Fe II emission is represented by the lower black curve. The residual emission line spectra (black line) after subtracting the power-law continuum and the Fe II model is shown in the insets for the H +[O III] and H regions, respectively (red: broad lines; blue: narrow lines). See text for details.*

4. DISCUSSION

4.1. Reliability of the QPO and Comparison with RE J1034+396

A significant QPO signal is detected at >99.99% confidence level in one of the X-ray light curves of the NLS1 AGN 1H 0707-495 taken with XMM-Newton. The QPO frequency (2.6 × 10 Hz) and the estimated mass of the central BH (M_BH = 5.2 × 10 M) conform with the previous f_QPO–M_BH relation. We note that the same data set was also analyzed by González-Martín & Vaughan (2012) in a study of the X-ray timing properties of a large sample of AGN, but no significant QPO was reported. This might be ascribed to the fact that the data of the whole observation duration was used in their work, which led to reduced significance of the signal (<90%, most likely due to a shift of the QPO phase).

The same situation also occurred in the case of RE J1034+396, in which the QPO was significant in only part of the light curve, and the significance became much lower when the whole light curve was used (Gierliński et al. 2008; Middleton et al. 2011). For 1H 0707-495 there are 15 XMM-Newton observations with good quality light curves, totaling 1200 ks exposure time. This may be equivalent to the QPO being detected in only one out of effectively 1200 ks/55 ks 22 searches. Considering all the non-detections would lower the overall significance of the detection in the statistical sense, giving only a null probability p 22 × (2.5 × 10 ³) 0.05. However, this is the most conservative case and should only be considered as a limit, since it is known that a QPO does not always repeat in every observation. QPOs in AGNs may well be a transient phenomenon (e.g., the data suggest a duty cycle 5% in the case of 1H 0707-495). Furthermore, the fact that the QPO in 1H 0707-495 follows closely the f_QPO–M_BH relation supports its genuineness.

The QPO frequency in 1H 0707-495 is very close to that in RE J1034+396 (2.7 × 10 Hz), which was argued to be a HFQPO (Zhou et al. 2010, 2015). This is not surprising given their similar BH masses (M_BH = 4 ³ × 10 M for RE J1034+396 and 5.2 × 10 M for 1H 0707-495). Moreover, the two AGNs are similar in several ways, e.g., the NLS1 classification (Véron-Cetty & Véron 2010), the high Eddington ratios (L_Bol/L_Edd = 1.25 for RE J1034+396 and 0.5 for 1H 0707-495), the X-ray spectra with a strong soft excess below 1 keV, as well as the PSD shapes (González-Martín & Vaughan 2012). This suggests that HFQPOs tend to occur in this type of AGN.

4.2. Do HFQPOs Tend to Occur at the Highest Accretion State?

HFQPOs in BHXBs are observed only when the systems are at the very high state with high accretion rates (Remillard & McClintock 2006; Lai & Tsang 2009). Interestingly, the two AGNs having significant QPO detections, RE J1034+396 and 1H 0707-495, are both NLS1s, which are thought to be an AGN analogue of BHXBs at the very high state. Figure 5 [Figure 5: see original paper] shows the distribution of the Eddington ratios for all BH accretion systems with reliable QPO detections (as shown in Figure 4) from BHXBs to AGNs. For the three BHXBs, the Eddington ratios are calculated from the average bolometric luminosities at which the QPO occurred (Remillard et al. 2002; Belloni et al. 2006). For the tidal disruption event (TDE) Swift J164449.3+573451 in which a QPO was found, the Eddington ratio is believed to be around unity or even higher since its observed luminosity is highly super-Eddington (Reis et al. 2012). The Eddington ratio of M82 X-1 was suggested to be 0.8 (Pasham et al. 2014). As a comparison, we overplot the Eddington ratio distribution for the AGN sample of González-Martín & Vaughan (2012), in which QPOs were searched for but not found. Clearly the two distributions differ significantly; a two-sided Kolmogorov-Smirnov test yields a small p-value of 0.2%. This result suggests that HFQPOs tend to occur at the highest accretion state of BH accretion systems.

Fig. 4.—*Relation between QPO frequency and BH mass. This is an updated*

version of Figure 1 from Zhou et al. (2015), where objects with significant QPO detections are plotted (dots), together with the newly detected QPO in 1H 0707-495 (star). The solid line represents the extrapolation of the relation derived in RM06, based on the three BHXBs. The dotted line and dashed line represent the relations derived from the model of 3:2 resonance (Kluzniak & Abramowicz 2002) with the spin parameter a=0.998 (dotted) and a=0 (dashed), respectively. Upper right inset: A zoom-in comparison of 1H 0707-495 with the model predictions, with various available BH mass estimates. a and b denote the mass from Bian & Zhao (2003) and Done & Jin (2015) respectively, while c denotes our best-estimated mass derived in this paper. Lower left inset: The inferred BH spin for a range of BH mass values for 1H 0707-495 from the 3:2 resonance model, assuming that the QPO represents the 2 × f peak.

Fig. 5.—*Distribution of the Eddington ratios of the BH accretion systems with HFQPO detected (blue), including BHXBs, ULX (M82 X-1), TDE (Swift J164449.3+573451) and AGNs (1H 0707-495 and RE J1034+396). As a comparison, also plotted is the distribution of the Eddington ratios of AGNs from the González-Martín & Vaughan (2012) sample in which QPO was searched for but not detected. The Kolmogorov-Smirnov test gives a probability p = 0.2% that the two distributions are drawn from the same population.*

4.3. Origins of HFQPO and Possible Link with BH Spin

The origin of HFQPO is unclear, though a number of models have been proposed in the literature, e.g., the relativistic precession model (RPM, Stella et al. 1999), resonance model (RM, Abramowicz & Kluźniak 2001), acoustic oscillation modes in pressure-supported accretion tori (AOM, Rezzolla et al. 2003), instability at disk-magnetosphere interface (IDI, Li & Narayan 2004), accretion-ejection instability in magnetized disks (AEI, Tagger & Pellat 1999), and global corotational instability of non-axisymmetric g-mode or p-mode trapped in the innermost region of the accretion disk (g-/p-mode models; Li et al. 2003). All these models can explain the 3:2 frequency ratio of the twin-peak QPOs. The f_QPO-M_BH relation is also predicted in all except the g-mode model (Silbergleit & Wagoner 2008). Only the AEI and p-mode models can explain why HFQPOs occur exclusively at the very high accretion state. A common issue for the RPM, RM and AOM models is a lack of underlying physical mechanisms at work, e.g., how orbiting hot spots survive in a differentially rotating disk, how the resonances are produced, etc. (see Lai & Tsang 2009; Belloni & Stella 2014 for brief reviews and references therein). Discussion concerning these models is beyond the scope of this paper. Nevertheless, here we briefly address the explanation and implication of our results in the framework of the resonance model.

In the resonance model, HFQPOs are suggested to be associated with the frequencies of three fundamental oscillation modes of disk fluid elements around a BH: the Kepler orbital motion, and the radial and vertical (to the orbital plane) epicyclic oscillation modes (Abramowicz & Kluźniak 2001). These frequencies naturally scale inversely and linearly with the BH mass, with a dependence on the BH spin (Nowak & Lehr 1998). Assuming that the observed 3:2 twin-peak QPO frequencies correspond to the vertical and radial epicyclic frequencies as in Kluzniak & Abramowicz (2002), the predicted f_QPO-M_BH relation is well consistent with the fitted relation from RM06 (solid line in Figure 4), which corresponds to a high BH spin close to the maximum value (Zhou et al. 2015). To illustrate the effect of BH spin, the f_QPO-M_BH relations assuming two extreme spin values a=0 (no spin; dashed) and a=0.998 (maximum spin; dotted) are overplotted in Figure 4 for the 2×f frequency (the lower frequency of the 3:2 twin-peak QPO). A zoom-in comparison with the results for 1H 0707-495 is shown in the upper-right inset of Figure 4, where the BH mass estimates from this and previous work are overplotted. As can be seen, the model can well reproduce the observed QPO frequency for a wide range of BH spin, given the relatively large uncertainty range of M_BH. The inferred spin values from a range of BH masses are shown in the lower-left inset of Figure 4. As one immediate inference, the allowed BH mass in 1H 0707-495 is in the range (2-8) × 10 M (corresponding to from a=0 to a=0.998). Our best-estimate M_BH = 5.2 × 10 M indicates a moderately high BH spin 0.8. It should be noted that Fabian et al. (2009) suggested a high BH spin for 1H 0707-495 based on its relativistic Fe line and reflection spectra, while Done & Jin (2015) argued for a low spin. In general, NLS1 AGNs are suggested to have average low or moderate BH spins as a population, as found by Liu et al. (2015) from the relativistic Fe line profile of stacked spectra. Clearly, a precise BH mass measurement, e.g., via the reverberation mapping method with which an accuracy of 30% could be reached (Peterson et al. 2004), is needed for constraining the BH spin in such AGNs with detected QPOs.

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