Pan, Yuan, Yao, Zhou, Liu, Zhou & Zhang, 2016, ApJL, 819, L19

Detection of a possible X-ray Quasi-periodic Oscillation in the Active Galactic Nucleus 1H 0707-495

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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≥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 $5.2 \times 10^6 M_\odot$ 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.

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.

Introduction

AGNs, powered by black hole (BH) accretion with BHs of $10^5 - 10^9 M_\odot$ at the center of galaxies, are thought to be scaled-up versions of BHXBs. A compelling line of evidence for this postulation is the striking similarity in the variability of the X-ray radiation between AGNs and BHXBs. 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. Also an inverse linear relation has been suggested between BH mass and the frequency of high-frequency QPO (HFQPOs).

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 NLS1 galaxy RE J1034+396 with $f_{\rm QPO} \simeq 2.7 \times 10^{-4}$ Hz (Gierliński et al. 2008; see figure 1). By extending BH masses to the SMBH range, Zhou et al. (2015) suggested that the $f_{\rm QPO}$- $M_{\rm BH}$ scaling relation is universal spanning ~6 orders of magnitude from stellar-mass BHs to SMBHs.

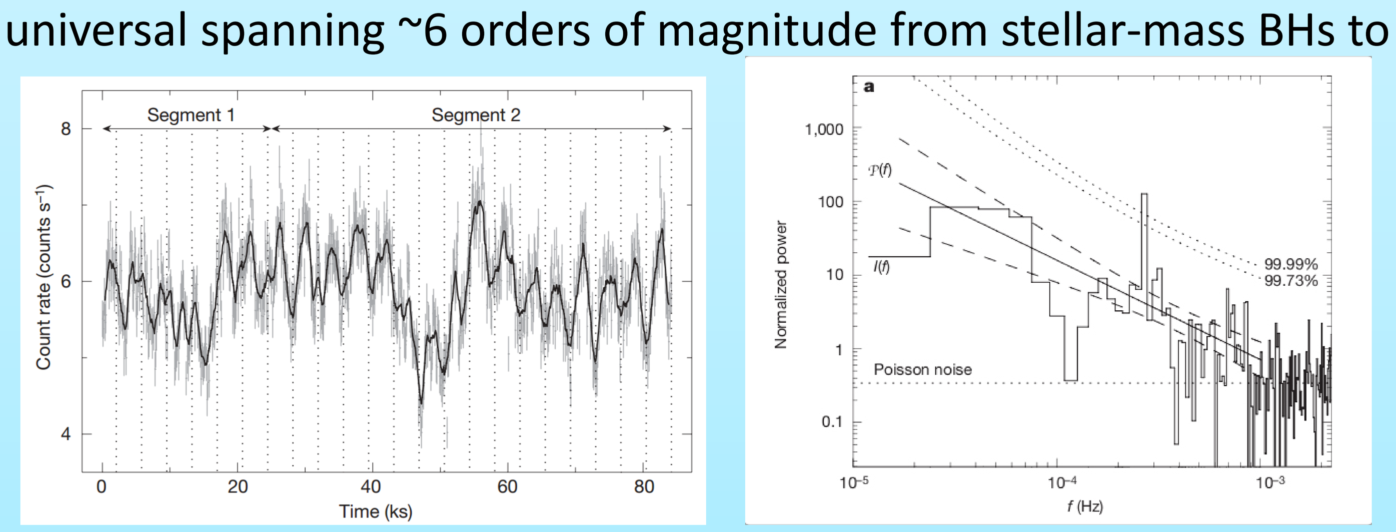


Fig. 1.— The light curve and power spectrum density of RE J1034+396. The strong peak in the power spectrum density indicated a QPO signal with $f_{\rm QPO} \simeq 2.7 \times 10^{-4}$ Hz at significance level higher than 99.99% (Gierliński et al. 2008).

In this work, 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. We also re-examine the BH mass of 1H 0707-495 by analysing its available optical spectroscopic data, and compare the QPO with the $f_{\rm QPO}$- $M_{\rm BH}$ relation.

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).

The combined PN+MOS1+MOS2 light curve is shown in Figure 2, and its power spectrum density (PSD) is shown in Figure 3. A strong peak at 2.6×10^{-4} Hz indicates a significant QPO signal.

The quality factor ($Q = \nu/\Delta\nu \geq 15$) is high, and The rms fractional variability in the QPO is ~15%.

A Monte Carlo technique is applied and suggests that the QPO significance level is higher than 99.99%, while an even more stringent test based on Bayesian statistics is also tried and indicates a small posterior predictive *p*-value of 2.5×10^{-3}.

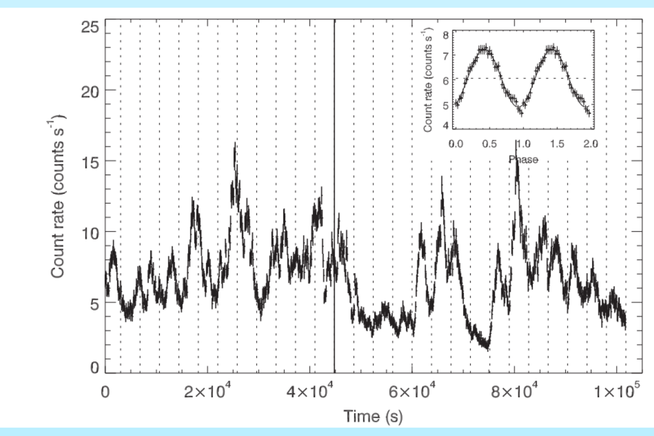
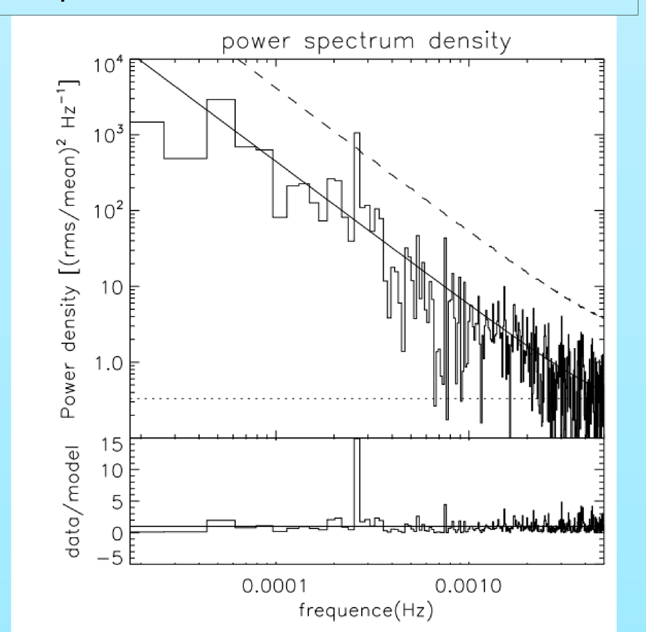


Fig. 2.—XMM-Newton light curve of 1H 0707-495, which is extracted and combined from the PN, MOS1 and MOS2 detectors in 0.2-10 keV with a binsize of 100 s. The light curve is divided into two segments by the solid line, and only the second segment is used in this letter. The dotted vertical lines show the expected periodicity of 3800 s. ***Upper Right Inset***: the folded light curve with a period 3800 s

Fig. 3.— Power spectrum density of 1H 0707-495. The solid line represents the best-fit power-law, and the dashed line represents the 99.99% confidence level. The data/model residuals are shown in the lower panel. A statistically significant peak is clearly present at 2.6×10^{-4} Hz .



Black hole mass estimation and the $f_{\rm QPO}$- $M_{\rm BH}$ 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 $2 \times 10^6 M_\odot$ from a 6dF spectrum (Bian et al. 2003) and $4 \times 10^6 M_\odot$ (Done & Jin 2016) from CTIO spectrum.

We re-analyze both the spectra, as shown in Figure 4. The widths of the broad Hβ line are fitted to be 1002 km/s (CTIO) and 1054km/s (6dF), which agree with each other within mutual errors. The BH mass is estimated using the broad Hβ line width and the luminosity at 5100Å ($\lambda L_\lambda = 4.0 \times 10^{43}$ erg/s) (Vestergaard & Peterson 2006), giving $M_{\rm BH} = 5.2 \times 10^6 M_\odot$ (CTIO) and $M_{\rm BH} = 5.7 \times 10^6 M_\odot$ (6dF), respectively.

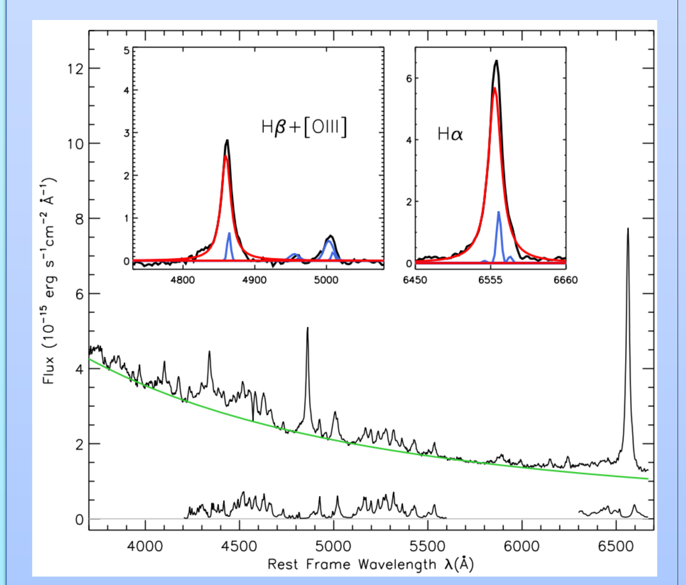


Fig. 4.— CTIO spectrum of 1H 0707-495. The continuum modeled with a power-law is plotted in green. The best-fit Fe II emission is represented by the lower black curve. The residual emission line spectra (black line) after subtracting the power-law continuum and the Fe II model is shown in the insets for the Hβ+[OIII] and Hα regions, respectively (red: broad lines; blue: narrow lines).

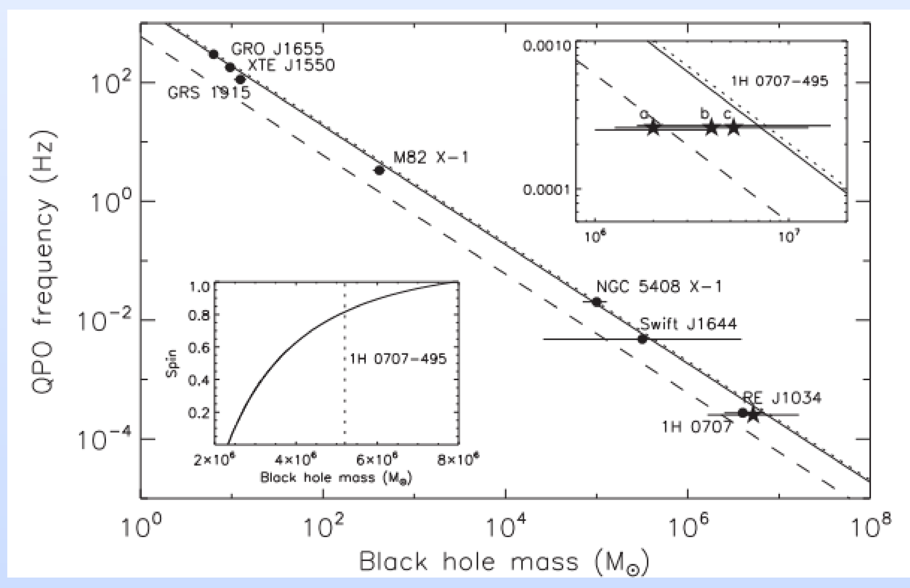
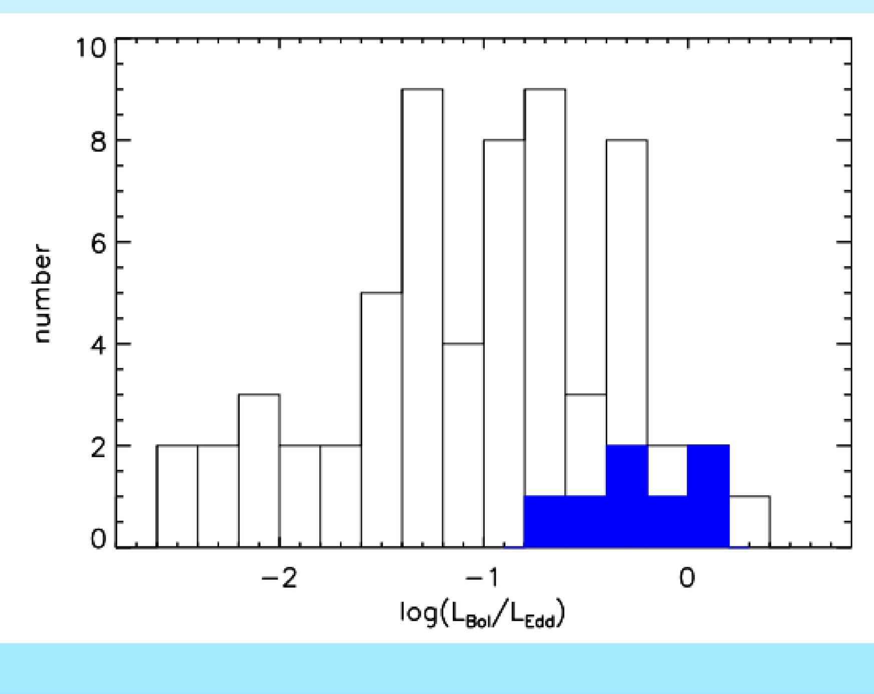


Fig. 5.— Relation between QPO frequency and BH mass. This is an updated version of Figure 1 from Zhou et al. (2015), where objects with significant QPO detections are plotted (dots), together with the newly detected QPO in 1H 0707-495 (star). The solid line represents the extrapolation of the relation from the three BHXBs. The dotted line and dashed line represent the relations derived from the model of 3:2 resonance 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 et al. (2003) and $M_\odot$ Done & Jin (2016) 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 $2f_0$ peak.

Do HFQPOs tend to occur at the highest accretion state?

Figure 5 shows the distribution of the Eddington ratios for all the BH accretion systems with reliable QPO detections (blue). As a comparison, we overplot the Eddington ratio distribution for the AGN sample of González-Martín, & Vaughan, et al. 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 the HFQPOs tend to occur at the highest accretion state of BH accretion systems.



Conclusion

1. A significant QPO signal with frequency 2.6×10^{-4} Hz is detected at a >99.99% confidence level in one XMM-Newton observation of the NLS1 AGN 1H 0707-495.
2. We re-analyze all the available optical spectroscopic data and find $M_{\rm BH} = 5.2 \times 10^6 M_\odot$. The QPO follows the universal scaling relation between the (3:2 twin-peak) QPO frequency and BH mass spanning ~6 orders of magnitude in $M_{\rm BH}$.
3. It is demonstrated that HFQPOs tend to occur in highly accreting systems, from BHXBs to AGNs.

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