An X-Ray Periodicity of $\sim 1.8$ hr in Narrow-line Seyfert 1 Galaxy Mrk 766

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Abstract

In the narrow-line Seyfert 1 galaxy Mrk 766, a quasi-periodic oscillation (QPO) signal with a period of $\sim 6450$ s is detected in the XMM-Newton data collected on 2005 May 31. This QPO signal is highly statistically significant at the $\sim 5\sigma$ confidence level, with a quality factor of $Q = f / \Delta f > 13.6$. The X-ray intensity changed by a factor of 3, with a root mean square fractional variability of 14.3%. Furthermore, this QPO signal is present in the data of all three EPIC detectors and two RGS cameras and its frequency follows the $f_{\text{QPO}} - M_{\text{BH}}$ relation spanning from star- mass to supermassive black holes. Interestingly, a possible QPO signal with a period of $\sim 4200$ s had been reported in the literature. The frequency ratio of these two QPO signals is $\sim 3:2$. Our result is also in support of the hypothesis that the QPO signals can just be transient. The spectral analysis reveals that the contribution of the soft excess component below $\sim 1$ keV is different between epochs with and without QPO. This property, as well as the former frequency ratio, are well-detected in X-ray BH binaries, which may shed some light on the physical origins of our event.

Key words: galaxies: active – galaxies: individual (Mrk 766) – galaxies: nuclei – X-rays: galaxies

1. Introduction

Narrow-line Seyfert 1 galaxies (NLS1s) are a subclass of active galactic nuclei (AGNs) that are powered by supermassive black hole (SMBHs) accretion at the center of galaxies. NLS1s are characterized by a narrow width of the broad Balmer emission line, with FWHMs ($H\beta < 2000$ km s$^{-1}$, along with strong optical Fe$\text{II}$ lines and weak forbidden lines. Their X-ray emissions have rather rapid variability with respect to other sources. Such variabilities are usually attributed to the dynamical processes in close vicinity to black holes (BHs) and thus play an important role in revealing the radiation mechanisms and structure of AGNs.

Quasi-periodic emissions are an interesting phenomena of some X-ray and gamma-ray emission sources. The quasi-periodic oscillation (QPO) signal has attracted wide attention. It is widely believed to be related to the accretion in the innermost stable circular orbit (ISCO) around BHs (Remillard & McClintock 2006) and thus carries important physical information about the ISCO. However, the QPO signal is rarely detected in AGNs, especially in NLS1s. The first significant transient QPO has been detected in NLS1 galaxy RE J1034+368 (Gierlinski et al. 2008). Recently, two transient QPO signals with a frequency ratio of $\sim 2:1$ were detected by Pan et al. (2016) and Zhang et al. (2017) in NLS1 galaxy 1H 0707-495. Other possible detections of X-ray QPOs in AGNs have been reported in the literature as well, including, for example, a $\sim 3.8$ hr QPO in 2XM J123103.2+110648 (Lin et al. 2013), a $\sim 2$ hr QPO in MS 2254.9−3712 (Alston et al. 2015), and a QPO signal at $\sim 2.4 \times 10^{-4}$ Hz in a nearby NLS1 of Mrk 766 ($z = 0.0127$; Boller et al. 2001).

In this work we report the detection of a significant QPO signal at $\sim 1.55 \times 10^{-4}$ Hz with a confidence level of $\sim 5\sigma$, in XMM-Newton observation on 2005 May 31 with an exposure time of $\sim 90$ ks. This signal has a frequency about 2/3 times that of the one suggested in Boller et al. (2001). We also find some differences between the spectral components with QPOs and those without QPO signals, similar to the behavior detected in black hole binaries (BHBs). The QPO signal frequency and the mass of the SMBH of Mrk 766 are found to be consistent with the relation suggested in previous literature (Kluzniak & Abramowicz 2002; Remillard & McClintock 2006; Zhou et al. 2010, 2015; Pan et al. 2016). This work is organized as follows. In Section 2 we describe the data analysis and show the main results, and in Section 3 we provide a summary and a discussion.

2. Observations and Analysis

2.1. Observations and Data Reduction

The European Space Agency’s X-ray Multi Mirror mission (XMM-Newton) was launched on 1999 December 10th. It carries two sets of X-ray detectors including three European Photon Imaging Cameras (EPIC; PN, MOS1, and MOS2; Strüder et al. 2001; Turner et al. 2001) and two Reflection Grating Spectrometers (2RGS; den Herder et al. 2001). NLS1 Mrk 766 was monitored 9 times for long observation ($\geq 30$ ks) by XMM-Newton from 2000 May to 2015 July in the full-frame imaging mode. We reduce the data and extract the science products using the tool eveselect following the standard procedure in the Science Analysis Software (SAS) package, using version 16.0.0 provided by the XMM-Newton science operations center. In our data analysis, we select the events from a 40 arcsec circle region of interest (ROI) centered at the position R.A. = 12:18:26.48 and decl. = +29:48:46.15, over energy band 0.2−10 keV. The events are selected for periods with high background flaring rates using the tool tabgtigen by making a secondary good time interval (GTI) file. The light
curves are generated with high-quality science data using the PATTERN \( \leq 12 \) for the two MOS detectors and \( \leq 4 \) for the PN detector in the tool `evselect`. The background light curves are extracted with the events from source-free circle ROI (without any X-ray source) with the same diameters, and in the same chips as the source regions. For these nine observations, the pile-up effect is negligible. The light curves are evenly sampled with a time bin of 100 s. Background subtraction, together with corrections for various sorts of detector inefficiencies, were performed with the SAS task `epiccorr`. We combine light curves with data from the three cameras (PN+MOS1+MOS2). We then also obtain the combined light curves from the two RGS detectors. The following time series analysis is based on these combined light curves. For spectra analysis, the energy spectra from Mrk 766 and the background are extracted with the same regions that were applied to derive the light curves with the parameter of `spectralbinsize = 15` in the tool `evselect` for the EPIC Cameras, and the corresponding response matrices are extracted simultaneously. Detailed information for this step is provided in the SAS data analysis Threads.7

2.2. The Combined Light Curve Analysis

To search for the quasi-periodic signal, we employ two of the most widely used methods, the generalized Lomb–Scargle Periodogram (LSP; Lomb 1976; Scarle 1982; Zechezmeier & Kürster 2009) and the Weighted Wavelet Z-transform (WWZ; Foster 1996), to obtain the power spectra of the (combined EPIC and 2RGS) light curves. In this work, the power spectra of the LSP method is checked with the independent results of the WWZ approach. Particularly for the light curves on 2005 May 31 (Obs ID: 0304030601), following the previous works (Gierlinski et al. 2008; Pan et al. 2016; Zhang et al. 2017), we divide the EPIC light curve into two segments (Segment I and Segment II), as shown in the upper panel of Figure 1. We focus on the power spectra of Segment I and show the results in the left image of Figure 2. In the left image, the 2D plane contour plotting for the WWZ power spectrum is shown in the lower left panel. In the lower right panel, the red solid and black solid lines represent the LSP (with average an Nyquist frequency \( \sim 0.005 \text{ Hz} \)) and time-averaged WWZ power spectra. A strong peak at \( \sim (1.55 \pm 0.11) \times 10^{-4} \text{ Hz} \) (with a period cycle of 6451.6 s) is detected in both the WWZ and LSP powers (while in Segment II, the signal disappears at all spectra, as shown in the middle panel of Figure 1 and in Figure 3). The uncertainty of the signal is evaluated with the FWHM of the Gaussian-function fitting at the position of the peak. The probability \( p_{\text{prob}} \) of obtaining a power equal to or larger than the threshold from the chance fluctuation (the noise) is \( \ll 1 \times 10^{-13} \) (Horne & Baliunas 1986). Then, the probability is corrected based on the number of independent frequencies sampled (the number of trials). The frequency resolution \( \Delta f \) is \( \sim 1/T_{\text{exposure}} \), the frequency range \( \Delta f \) is \( f_{\text{max}} - f_{\text{min}} \) (Zechmeister & Kürster 2009), and the \( N \) is approximately \( \sqrt{\frac{N}{\Delta f}} = 312 \). The false-alarm probability \( \text{FAP} = 1 - [1 - p_{\text{prob}}]^{N} \) is \( \ll 3.2 \times 10^{-13} \). To estimate the confidence level more robustly, we generate \( 10^{6} \) artificial light curves based on the power spectral density (PSD) and the probability density function of the variation of the EPIC light curve. The simulated light curves have the full properties of statistics and variability of the EPIC light curve. To determine the best-fitting PSD, we use a bending power law plus a constant function to model the PSD of the EPIC light curve using the \( \chi^2 \) minimization technique of Minuit, and get a \( \chi^2/\text{dof} = 0.3 \) (where \( \text{dof} \) represents the degree of freedom). And the function is \( P(f) = Af^{-1}[1 + (f/f_{\text{bend}})^{\alpha - 1}]^{-1} + C \) (González-Martín & Vaughan 2012), where the \( A, \alpha, f_{\text{bend}}, \) and \( C \) represent the normalization, spectral index above the bend, bending

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1. https://www.cosmos.esa.int/web/xmm-newton/sas-thread-pn-spectrum

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Figure 1. Upper panel: XMM-Newton EPIC light curve of Mrk 766 in 0.2–10 keV, with 100 s per bin. The light curve is separated into two segments by a red dashed line. Middle panel: 2D plane contour plot of the WWZ power of the whole light curve. Lower panel: the pulse shape of the light curve is folded with Segment I using the period cycle of 6451.6 s (two cycles are shown).
frequency, and Poisson noise level, respectively. The values of $\alpha$ and $\log(f_{\text{end}})$ are $3.1 \pm 0.9$ and $-3.5 \pm 0.3$, respectively. To check the parameters, we also employ a maximum likelihood method (proposed by Stella et al. 1994; Israel & Stella 1996; Vaughan 2010; Barret & Vaughan 2012; Guidorzi et al. 2016) to derive the values of power spectral. And the parameters of $\alpha$ and $\log(f_{\text{end}})$ are $3.3 \pm 0.5$ and $-3.3 \pm 0.2$, respectively. The parameters are well in agreement with those found using the $\chi^2$ minimum technique in our work. Then, we employ the method provided in Emmanoulopoulos et al. (2013) to obtain the artificial light curves, and evaluate the confidence curves shown in the lower right panel of the left image of Figure 2. The green dashed–dotted and blue dashed lines represent the $5\sigma$ and $4\sigma$ confidence levels, respectively. The confidence level is estimated at $\sim5.5\sigma$. Mrk 766 has been monitored 9 times for over $\sim30$ ks with $XMM$-$Newton$ (in fact, the total exposure is $\sim0.7$ Ms, or $\sim10$ segments of similar length with QPO). The power peak is independent of the frequency bins within its FWHM. Accounting for the number of trials, the confidence level of the QPO is $5.1\sigma$ (99.999965%). We also searched for the QPO signal in other observations but found nothing. This result may indicate that the QPO in NLS1s is a transient phenomenon, consistent with Gierliński et al. (2008) and Pan et al. (2016). Furthermore, the periodic signal in the EPIC light curve is confirmed by the results of the 2RGS light curve at $1.55 \times 10^{-4}$ Hz, which is plotted in the right image of Figure 2.

With the tool efold provided in HEASOFT,\(^8\) we fold Segment I of the EPIC light curve with the period cycle of 6451.6 s, and show it in the lower panel of Figure 1. The errors are calculated from the standard deviation ($68.3\%$) of the

\(^8\) https://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/examples/efold.html
mean values of each phase bin. For clarity, two cycles are plotted. We fit the folded light curve with a constant rate, and derive the reduced $\chi^2_{\text{red}} = 165.6/49$. The mean count rate is $\sim 25.66$ counts s$^{-1}$, and is shown as a red dashed–dotted line in the lower panel of Figure 1. From it, we can see that the amplitude of the X-ray flux clearly varies with phase.

2.3. Time-averaged Spectral Analysis

The spectral analysis is performed using XSPEC (v. 12.9.0n, Arnaud 1996). We fit the spectra derived from the three EPIC Cameras simultaneously with several models of $TBabs \times zxipcf \times (zbbody + zpowerlw)$ (Boller et al. 2001) in an energy band of 0.2–10 keV. In the model, $zpowerlw$ is a variant of a simple power law corrected by the redshift of the target, which represents the continuum spectrum. $TBabs$ is the Tübingen-Boulder ISM absorption model representing the Galactic absorption for Mrk 766. The EPIC spectra clearly indicate the presence of the emission of a strong soft excess component below 1 keV. Then, we employ $zbbody$ (a blackbody spectrum with an additional redshift parameter) to fit the strong soft excess, and the blackbody temperature ($kT_{\text{BB}}$) is estimated at $\sim 107$ eV (listed in Table 1), which is consistent with the observed temperature of the soft excess emission of NLS1s (Czerny et al. 2003; Gierliński & Done 2004). Furthermore, its emission contains a majority of the flux between 0.2–1.0 keV. A strong warm absorber is detected at $\sim 1$ keV, and we then use an ionized absorber model ($zxipcf$, a model of absorption by partially ionized material) to fit the absorption feature. All the fitting results for the analysis are acceptable, and the best-fit parameters are listed in Table 1. In fitting the model to data, we employ a $\chi^2$ statistic with the errors quoted at the 90% confidence limit. The four EPIC spectra for all periods are 0–98650 s, Sub I; 0–62650 s (with QPO; the very high state); Segment II: 62650–98650 s (without QPO); and Sub3: 78050–97950 s (the lowest flux state); and are selected in this analysis. The best-fitting model and the residuals are shown in Figure 5.

3. Summary and Discussion

In this work, we carry out a systematic analysis of XMM-Newton observations of NLS1 Mrk 766 and detect a QPO signal with a period cycle of $\sim 6450$ s ($1.55 \times 10^{-4}$ Hz) at a significance of $> 5.1 \sigma$ in only part of Segment I (0–62650 s) of the observation on 2005 May 31. The periodic signal is subsequently confirmed in the data of 2RGS. In the second part of the X-ray light curve, no signal is detected at all. If we analyze the whole light curve, the significance becomes much lower, similar to that previously found in other events (e.g., Remillard & McClintock 2006; González-Martín & Vaughan 2012; Pan et al. 2016). Together with the lack of detection of QPO signals for Mrk 766 in other observations, we suggest that the QPO in NLS1 is likely a transient phenomenon. In previous works, Boller et al. (2001) reported a possible QPO signal on 2000 May 20 with $2.4 \times 10^{-4}$ Hz. The frequency ratio of

Table 1: Spectral Parameters of Our Best-fitting to the Data

| Model Component | Parameters | Segment I 0–26250 s | Segment II 62650–98650 s | Sub3 78050–97950 s | Average Spectrum 0–98650 s |
|-----------------|------------|---------------------|--------------------------|-------------------|-----------------------------|
| $TBabs$         | $N_{\text{H}} (10^{20} \text{ cm}^{-2})$ | 1.97 ± 0.06          | 0.88 ± 0.09               | 0.41 ± 0.13       | 1.65 ± 0.05                 |
| $zxipcf$        | $N_{\text{H}} (10^{20} \text{ cm}^{-2})$ | 32.78 ± 4.88         | 13.92 ± 3.39              | 13.83 ± 7.35      | 22.95 ± 2.37                |
| $zpowerlw$      | log $\xi$ (erg cm s$^{-1}$) | 0.83 ± 0.03          | 0.81 ± 0.06               | 0.86 ± 0.07       | 0.82 ± 0.03                 |
| $zbbody$        | $kT_{\text{BB}}$ (eV) | 107.01 ± 1.38        | 106.23 ± 1.37             | 108.17 ± 1.71     | 106.57 ± 1.0                |
|                 | $\Gamma$   | 2.06 ± 0.01          | 1.76 ± 0.01               | 1.63 ± 0.02       | 1.98 ± 0.01                 |
|                 | $\text{Norm}_{\text{pl}} (\times 10^{-5})$ | 7.06 ± 0.06          | 2.83 ± 0.04               | 2.11 ± 0.04       | 5.44 ± 0.04                 |
| Reduced $\chi^2/\nu$ | … | 1.7/2532             | 1.2/2241                  | 1.2/1871          | 1.9/2750                    |

Note. Spectral parameters obtained from the fitting of the time-averaged spectrum and the three time-resolved spectra. $\text{Norm}_{\text{pl}}$ is in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV. The redshift in fitting is fixed to be 0.0127.

Figure 4. Correlation between BH masses and QPO frequencies. The events reported in previous works are shown with green points and the new QPO signal detected in Mrk 766 is plotted with a red square. The three lines represent the relations suggested in Remillard & McClintock (2006) and Kluzniak & Abramowicz (2002). See Zhou et al. (2010, 2015) and Pan et al. (2016) for additional information.
these two QPO signals, if both valid, is \( \sim 3:2 \), which would mark the first time such a ratio in the X-ray emission of NLS1s has been found. We also analyze the energy spectra derived from EPIC data and the best-fitting results are listed in Table 1. The ratio of the two periodic signals and the properties of energy spectra are similar to the behaviors of X-ray BHBs. The QPO and \( M_{\text{BH}} \) of Mrk 766 are consistent with the correlation reported in Remillard & McClintock (2006), Kluzniak & Abramowicz (2002), Zhou et al. (2015), and Pan et al. (2016).

It is widely believed that QPO signals can be produced by instabilities in the inner accretion disk, or pulsating accretion when it is close to the Eddington limit, or X-ray hot spots orbiting the BH or disk precession according to the Bardeen–Petterson effect (Sunyaev 1973; Bardeen & Petterson 1975; Guilbert et al. 1983; Mukhopadhyay et al. 2003; Li & Narayan 2004; Remillard & McClintock 2006; Gangopadhyay et al. 2012). Specifically, in BHB systems, pairs of QPOs have also been detected with frequency ratios of nearly 3:2 (Abramowicz & Kluzniak 2001; Strohmayer 2001a, 2001b; McClintock & Remillard 2006).

The QPO frequencies in RE J1034+396 (Gierliński et al. 2008) and 1H 0707−495 (Pan et al. 2016; Zhang et al. 2017) have been argued to be high-frequency QPOs (HFQPOs; Zhou et al. 2010, 2015). The one we found in Mrk 766 is at a similar frequency. Moreover, all three of these sources are NLS1s with similar power spectral shapes, strong soft excesses between 0.1 and 1 keV in their X-ray energy spectra, and high Eddington ratios. Hence, the signal reported in this work may be an HFQPO. The correlation of \( f_{\text{QPO}} - M_{\text{BH}} \) (Kluzniak & Abramowicz 2002; Remillard & McClintock 2006; Zhou et al. 2010, 2015; Pan et al. 2016) is shown in Figure 4 and the QPO in Mrk 766 is consistent with it; the mass is adopted from Turner et al. (2006). Generally, the HFQPOs are only detected in very high states with high accretion rates for X-ray BHBs (Remillard & McClintock 2006; Lai & Tsang 2009). Interestingly, the QPOs of NLS1s are also detected at their high state. The origin of HFQPOs is unclear in X-ray BHBs and NLS1s. Our results may provide us with more information for understanding this phenomenon.

The energy spectral fit results indicate that the blackbody temperatures remain constant at \( \sim 10^7 \) eV, within a few percent (listed in Table 1), during the four time intervals of the X-ray light curve shown in Figure 1. Comparing the best-fit results of Segment I and Segment II (especially Sub3), the blackbody components contributing to flux between 0.2–1.0 keV are remarkably different. In view of the middle panel of Figure 1 and Figure 3 (i.e., the signal disappeared in Segment II), we suggest that the presence or absence of the signal is related to the change of the physical process taking place at Mrk 766, rather than the signal-to-noise ratio. A similar scenario was also detected in galactic X-ray BHBs (e.g., GRO J1655−40; McClintock & Remillard 2006; Remillard & McClintock 2006).
This may provide evidence that AGNs are scaled-up versions of Galactic BHBs.

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