The host galaxy of a narrow-line Seyfert 1 galaxy, RE J1034+396, with X-ray quasi-periodic oscillations

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ABSTRACT
Using simple stellar population synthesis, we model the bulge stellar contribution in the optical spectrum of a narrow-line Seyfert 1 galaxy, RE J1034+396. We find that its bulge stellar velocity dispersion is $67.7 \pm 8 \text{ km s}^{-1}$. The supermassive black hole (SMBH) mass is about $(1–4) \times 10^6 \text{ M}_\odot$ if it follows the well-known $M_{\text{BH}}-\sigma_*$ relation found in quiescent galaxies. We also derive the SMBH mass from the H$\beta$ second moment, which is consistent with that from its bulge stellar velocity dispersion. The SMBH mass of $(1–4) \times 10^6 \text{ M}_\odot$ implies that the X-ray quasi-periodic oscillation (QPO) of RE J1034+396 can be scaled to a high-frequency QPO at 27–108 Hz found in Galactic black hole binaries with a 10-M$_\odot$ black hole. With the mass distribution in different age stellar populations, we find that the mean specific star formation rate (SSFR) over the past 0.1 Gyr is 0.0163 $\pm$ 0.0011 Gyr$^{-1}$, the stellar mass in the logarithm is 10.155 $\pm$ 0.06 units in solar mass and the current star formation rate is 0.23 $\pm$ 0.016 M$_\odot$ yr$^{-1}$. For RE J1034+396, there is no relation between the Eddington ratio and the SSFR as suggested by Chen et al., despite a larger scatter in their relation. We also suggest that about 7.0 per cent of the total H$\alpha$ luminosity and 50 per cent of the total [O $\pi$] luminosity come from the star formation process.

Key words: black hole physics – galaxies: bulges – galaxies: individual: RE J1034+396 – galaxies: nuclei – galaxies: stellar content.

1 INTRODUCTION
It is thought that active galactic nuclei (AGN) are scaled-up versions of Galactic black hole binaries (BHBs; Gierlinski et al. 2008 and references therein). The power spectrum of the X-ray variability in BHBs shows quasi-periodic oscillations (QPOs) of 0.01–450 Hz (Remillard & McClintock 2006). It is believed that we can also find QPOs in AGN, with the similar behaviour of accretion flow around the black hole (BH). Compared to a BH of 10 M$_\odot$ in BHBs, typical high-frequency QPOs of 100 Hz would be smaller by $10^6$ (i.e. $\sim 10^{-3}$ Hz) for a supermassive black hole (SMBH; $M_{\text{BH}}$) of $10^7$ M$_\odot$ if QPO frequencies scale inversely with the BH mass (Remillard & McClintock 2006).

With a long XMM–Newton observation (91 ks), Gierlinski et al. (2008) detected a significant QPO signal ($v = 2.7 \times 10^{-4}$ Hz, corresponding to a period of about 1 h) for a nearby ($z = 0.043$) spiral active galaxy, RE J1034+396 (J2000, RA = 158.66082, Dec. = 39.64119). This is optically classified as a narrow-line Seyfert 1 galaxy (NLS1), with similar small linewidth for the high-ionization and low-ionization emission lines (Puchnarewicz et al. 2001), the slim disc fitting of SED (Puchnarewicz et al. 2001), the slim disc fitting of SED (Wang et al. 1999; Wang & Netzer 2003), the full width at half-maximum (FWHM) of the H$\beta$ line, [O $\pi$] FWHM and soft X-ray luminosity, the SMBH mass in RE J1034+396 cannot be determined very well, from $6.3 \times 10^6$ to $3.6 \times 10^7$ M$_\odot$ (Wang & Lu 2001; Bian & Zhao 2004). Its QPO type (high-frequency or low-frequency QPOs) cannot be uniquely identified (Gierlinski et al. 2008).

Over the past two decades, there has been considerable progress in finding more reliable methods to calculate SMBH masses in AGN, using the linewidth, $\Delta V$, of H$\beta$ (or H$\alpha$, M$g$, C IV) from the broad-line region (BLR) and the BLR size, $R_{\text{BLR}}$ (e.g. Kaspi et al. 2000; Bian & Zhao 2004; McLure & Jarvis 2002; Peterson et al. 2004; Greene & Ho 2005; Bian et al. 2008). There are two main ways to parametrize the linewdths of broad emission lines: the FWHM and the second moment ($\sigma_{\text{line}}$) (e.g. Bian et al. 2008). The second moment of the broad components of the H$\beta$ line provides a more precise measurement of the SMBH mass because the H$\beta$ profile is non-Gaussian in NLS1s. It is suggested that the mean...
value of the SMBH masses in NLS1s from the Hβ second moment is larger by about 0.50 dex than that calculated using the FWHM (Bian et al. 2008). The well-known \( M_{\text{BH}}-\sigma \) relation of inactive galaxies (Tremaine et al. 2002) can also be used to estimate the SMBH mass when the stellar velocity dispersion, \( \sigma \), is available (Kaufrmann et al. 2003; Onken et al. 2004; Greene & Ho 2006; Graham & Li 2009).

The X-ray QPO frequency may depend on the mass and the spin of a BH (Remillard & McClintock 2006). SMBH masses are important in the study of QPOs in AGN. Here we use the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009) data of this object to determine its SMBH mass using its \( \sigma \), and the Hβ second moment instead of the \( H\beta \) FWHM as in Bian et al. (2004). We also use the star formation history of its host bulge using simple stellar population (SSP) synthesis. All the cosmological calculations in this paper assume \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3 \) and \( \Omega_\Lambda = 0.7 \).

2 DATA AND ANALYSIS

The SDSS used a dedicated 2.5-m wide-field telescope at Apache Point Observatory near Sacramento Peak in Southern New Mexico to conduct an imaging and spectroscopic survey for about a quarter of the sky area. The SDSS data have been made public in a series of yearly data releases, and the present is the Seventh Data Release (DR7), including data up to the end of SDSS-II in 2008 July.

The optical spectrum of RE J1034+396 was downloaded from SDSS DR7. Its spectrum covers the wavelength range of 3800–9200 Å with a spectral resolution of 1800 < \( R < 2100 \). At its redshift of 0.043, the projected fibre aperture diameter of 3 arcsec is about 2.4 kpc, containing most light from its bulge. With nuclear spectrum superimposed on it, the stellar absorption features in its SDSS spectrum provide us with the possibility of investigating the property of its host bulge, including the bulge stellar velocity dispersion, the stellar mass and the star formation history. We did not apply aperture correction to the stellar velocity dispersion because this effect can be omitted for \( z < 0.3 \) (Bernardi et al. 2003).

We outline the steps we take to perform the SDSS spectral analysis.

(i) We use SSP synthesis (STARLIGHT; Cid Fernandes et al. 2005) to model the stellar contribution in the Galactic extinction-corrected spectrum in the rest frame (Cid Fernandes et al. 2005; Bian et al. 2006, 2008; Bian, Chen & Gu 2007). The Galactic extinction law of Cardelli, Clayton & Mathis (1989) with \( R_V = 3.1 \) is adopted, which is also used for the host extinction with V-band extinction (from 0 mag to 5.0 mag). We use 45 default templates in Cid Fernandes et al. (2005), which are calculated from the model of Bruzual & Charlot (2003). The linear combination of 45 templates is used to represent the host bulge spectrum. These 45 templates comprise 15 ages, \( t = 0.001, 0.00316, 0.00501, 0.01, 0.02512, 0.04, 0.10152, 0.28612, 0.64054, 0.90479, 1.434, 2.5, 5, 11 \) and 13 Gyr, and three metallicities, \( Z = 0.2, 1 \) and 2.5 \( Z_\odot \) (Cid Fernandes et al. 2005). At the same time as the SSP fit, we add a power-law component in the code to represent the AGN continuum emission, and an optical Fe II template from the prototype NLS1 I Zw1 (Boroson & Green 1992) to model the Fe II emission. We exclude the AGN emission lines, such as H Balmer lines, \([\text{O} II]\lambda \lambda 3727, 3869, [\text{O} III]\lambda \lambda 4959, 5007, [\text{N} II]\lambda \lambda 6548, 6583, [\text{S} II]\lambda \lambda 6717, 6731\).

The synthetic spectrum is built using the following equation:

\[
M^*_s = M^*_1 \sum_{j=1}^{N} x_j b_{j,\lambda} r_{\lambda} \otimes G(v_0, v_d) + x_{fe} \otimes G(v_{fe}, \sigma_{fe})
\]

(1)

Here, \( b_{j,\lambda} \) is the \( j \)-th template normalized at \( \lambda_0 = 4020 \AA \), \( x_j \) is the flux fraction at 4020 Å, \( M^*_s \) is the synthetic flux 4020 Å and \( r_\lambda \equiv 10^{0.04\lambda A_\lambda - A_\lambda} \) is the reddening term by V-band extinction \( A_V \). \( G(v_0, v_d) \) is the line-of-sight stellar velocity distribution, modelled as a Gaussian centred at velocity \( v_0 \) and broadened by the velocity dispersion \( v_d \). Because of different velocity dispersions in the stellar lines and Fe II lines, we use another line-of-sight Fe II velocity distribution \( G(v_{fe}, \sigma_{fe}) \) for the Fe II emission. \( x_{fe} \) is the Fe II flux fraction at 4020 Å. The line-of-sight Fe II velocity distribution \( G(v_{fe}, \sigma_{fe}) \) is also modelled as a Gaussian centred at velocity \( v_{fe} \) and broadened by the velocity dispersion \( \sigma_{fe} \). We first fit the Fe II lines and the continuum in the fitting windows, and we find that \( \sigma_{fe} = 411 \pm 46 \text{ km s}^{-1} \). \( \sigma_{fe} \) is fixed by 411 km s\(^{-1}\) in the fitting of SSP and Fe II. When we change \( \sigma_{fe} \), the SSP and Fe II fitting results do not change, considering the errors. We also exclude the Fe II emissions and carry out the SSP fit; considering the errors, the SSP results do not change. The best fit is reached by minimizing reduced \( \chi^2 \):

\[
\chi^2(x, M^*_s, A_V, v_0, v_d) = \sum_{\lambda=1}^{N_\lambda} \left( \frac{1 - \chi_{\lambda} w^2 \lambda}{N} \right)
\]

(2)

Here, the weighted spectrum \( w_\lambda \) is defined as the noise associated with each spectral bin as reported by the SDSS pipeline output, and \( N \) is the total unmasked pixels. \( \chi^2 \) is calculated by the difference between the observed spectrum and the model spectrum in the fitting of SSP and Fe II. For RE J1034+396, the best fit of SSP and Fe II gives \( \chi^2 = 1.4 \) (Fig. 1). We find that \( A_V = 0 \), and the host extinction can be neglected (Fig. 1). Using the above spectral synthesis, we can obtain some parameters, such as the bulge velocity dispersion \( v_d \), the flux fraction \( x_j \), the mass fraction \( \mu_i \) and the stellar mass \( M_s \). The mass–flux ratio can be found in the STARLIGHT manual on the webpage, http://www.starlight.ufsc.br/. The results are shown in Fig. 1 and Table 1.

With the simulation, it is suggested that the uncertainty in the SSP results can be given by the effective starlight signal-to-noise (S/N) at 4020 Å (Cid Fernandes et al. 2005; Bian et al. 2007). The S/N at 4020 Å is 37 and the starlight fraction at 4020 Å is about 43 per cent (Table 1). Therefore, the effective starlight S/N at 4020 Å is about 16, corresponding to an uncertainty of 8 km s\(^{-1}\) for the velocity dispersion, 7 per cent for the mass fraction, 8 per cent for the flux fraction and 0.06 dex for the stellar mass \( \log M_s \) (Cid Fernandes et al. 2005; Bian et al. 2007). We adopt 10 per cent as the uncertainty of the host bulge flux fraction.

(ii) Considering the broad wing in the Hβ line profile, two broad components are used to model the broad Hβ profile from BLRs. The Hβ line from the narrow-line regions (NLRs) has the same profile as the [O III] line from NLRs. Two components are used to model the asymmetric [O III] line profile, and two components are used to model the Hβ line profile from BLRs (Bian et al. 2008). Therefore, a total of four Gaussians are used to model the Hβ line profile, and two sets of two Gaussians are used to model the [O III]\( \lambda \lambda 4959, 5007 \) lines. Similar to the Hβ profile, four Gaussians are used to model the Hα profile (two broad components from BLRs and two narrow components from NLRs), and two sets of two Gaussians are used to model the [N II]\( \lambda \lambda 6548, 6583 \) lines. We take the same linewidth for each corresponding component of [O III]\( \lambda \lambda 4959, 5007 \) and Hβ from NLRs, we fix the flux ratio of [O III]\( \lambda 4959 \) to [O III]\( \lambda 5007 \) to be 1:3, and we set the wavelength separation to the laboratory value. We take the same linewidth for each corresponding component of [N II]\( \lambda \lambda 6548, 6583 \) and Hα from BLRs, we fix the flux ratio of [N II]\( \lambda 6548 \) to [N II]\( \lambda 6583 \) to be 1:3,
Host galaxy of RE J1034+396

3 RESULTS AND DISCUSSION

3.1 Mass

First, we derive the mass from the bulge stellar velocity dispersion, \( \sigma_\star \). Using the SSP method, the measured bulge stellar velocity dispersion, \( \sigma_\star = 28 \) km/s.


Table 1. The host bulge properties of RE J1034+396. Column 1 is the host bulge stellar velocity dispersion, column 2 is the stellar mass, column 3 is the host bulge specific star formation rate and column 4 is the host bulge flux fraction at 4020 Å with 10 per cent uncertainty.

| \( \sigma_v \) (km s\(^{-1}\)) | \( \log M_\star (M_\odot) \) | SSFR (Gyr\(^{-1}\)) | \( f_{\text{host}} \) |
|-----------------|-----------------|-----------------|-----------------|
| 67.7 ± 8        | 10.155 ± 0.06   | 0.0163 ± 0.0011 | 43 ± 4 per cent |

Figure 2. An example of the line fit for RE J1034+396. Top panel. The line fit for H\( \beta \) and the [O\( \text{III} \)] line. The black line is the original spectrum after Galactic-extinction correction, the starlight subtraction, the power-law continuum and the Fe\( \text{II} \) subtraction in the rest frame. The residual is shown at the bottom. The multiple Gaussian components are in blue and the sum of these is in red. The fitting window is in green. Bottom panel. The line fit for H\( \alpha \) and the [N\( \text{II} \)] line. The line colours are the same as in the top panel.

dispersion \( v_d \) is 28 ± 8 km s\(^{-1}\). Considering the resolutions of the SDSS spectra and the template spectra, we have to perform these corrections using the following formula:

\[
\sigma_\star = \sqrt{v_d^2 + \sigma_{\text{temp}}^2 - \sigma_{\text{inst}}^2}.
\] (3)

Here, the SDSS spectral resolution \( \sigma_{\text{inst}} \) is taken to be 60 km s\(^{-1}\) (Greene & Ho 2005a). The template spectral resolution \( \sigma_{\text{temp}} \) is taken to be 86 km s\(^{-1}\) (Cid Fernandes et al. 2005). Assuming that the errors on \( \sigma_{\text{inst}} \) and \( \sigma_{\text{temp}} \) are negligible, the error on \( \sigma_\star \) will be the same as that on \( v_d \), \( \sigma_\star = 28 ± 8 \text{ km s}^{-1} \) leads to \( \sigma_\star = 67.7 ± 8 \text{ km s}^{-1} \).

Using the \( M_{\text{BH}} - \sigma_\star \) relation for quiescent galaxies, \( M_{\text{BH}}(\sigma_\star) = 10^{8.15}[\sigma_\star/(200 \text{ km s}^{-1})]^{1.42} M_\odot \) (Tremaine et al. 2002), we derive the SMBH mass to be \( 1.7 ± 0.7 \times 10^{7} M_\odot \) for \( \sigma_\star = 67.7 ± 8 \text{ km s}^{-1} \). The uncertainty of 8 km s\(^{-1}\) for \( \sigma_\star \) would lead to an error of 0.1 dex for \( \log M_{\text{BH}} \). The total uncertainty is about 0.32 dex, considering the error of 0.3 dex from the \( M_{\text{BH}} - \sigma_\star \) relation (Tremaine et al. 2002). Therefore, the SMBH mass of RE J1034+396 derived from \( \sigma_\star \) is about \( (1-4) \times 10^{7} M_\odot \).

Secondly, we derive the mass from the broad H\( \beta \) second moment \( \sigma_{\text{HB}} \) and the empirical \( R_{\text{BLR}} - \lambda L_\lambda(5100 \text{ Å}) \) relation (Kaspi et al. 2000, 2005; Bentz et al. 2006; Bian et al. 2008). With the power-law component, we can derive the nuclear flux at 5100 Å to be \( 45 ± 8 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \), and \( \lambda L_\lambda(5100 \text{ Å}) \) to be \( 5.6 × 10^{42} \text{ erg s}^{-1} \). The first moment of the line profile \( P(\lambda) \) is

\[
\lambda_0 = \frac{\int \lambda P(\lambda) d\lambda}{\int P(\lambda) d\lambda}.
\] (4)

The second moment of the line profile \( P(\lambda) \) is

\[
\sigma_{\text{line}}^2 = \frac{\int \lambda^2 P(\lambda) d\lambda}{\int P(\lambda) d\lambda} - \lambda_0^2.
\] (5)

For a Gaussian line profile, the ratio of the FWHM to the second momentum is \( \text{FWHM}/\sigma_{\text{line}} = \sqrt{8 \ln 2} ≈ 2.35 \); while for a Lorentzian profile, \( \sigma_{\text{line}} \rightarrow \infty \). For RE J1034+396, the H\( \beta \) second moment \( \sigma_{\text{HB}} \) is calculated from the reconstructed H\( \beta \) profile of two broad H\( \beta \) components from BLRs in step 2 of the spectral analysis, and \( \sigma_{\text{HB}} = 577 ± 144 \text{ km s}^{-1} \). From the reconstructed H\( \beta \) profile from BLRs, the FWHM is \( 802 ± 200 \text{ km s}^{-1} \). The SMBH mass can be calculated from the H\( \beta \) second moment using the following equation (Bian et al. 2008):

\[
M_{\text{BH}} = \frac{f R_{\text{BLR}} V^2}{G} = f \times 7.629 \times 10^8 \times \left[ \frac{\lambda L_\lambda(5100 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right]^{0.518} \left[ \frac{\sigma_{\text{HB}}}{1000 \text{ km s}^{-1}} \right]^2 M_\odot.
\] (6)

\( ^{a}\text{The FWHM of a Gaussian profile in units of km s}^{-1}. \)
\( ^{b}\text{In units of} 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}. \)
\( ^{c}\text{Fe} \text{II} \text{ flux between 4434 and 4684 Å.} \)
\( ^{d}\text{The components from NLRs. The second weaker broad component of H}\alpha \text{ is probably due to the contribution from the continuum subtraction.} \)
Here, $R_{\text{BLR}} = 39.08 \times (|\lambda L_\lambda(5100 \, \text{Å})/(10^{44} \, \text{erg s}^{-1})|)^{0.515}$ light-days (Bentz et al. 2006), and $f = 3.85$ (Collin et al. 2006). With $\sigma_{\text{Hβ}} = 577 \pm 144 \, \text{km s}^{-1}$ and $f = 3.85$, the estimated SMBH mass is $(0.7-3.4) \times 10^6 \, M_\odot$. The uncertainty of the mass calculation from the Hβ line is mainly from the systematic uncertainties, up to about 0.5 dex, which is a result of the unknown kinematics and geometry in BLRs (e.g. Krolik 2001; Peterson et al. 2004). Grupe et al. (2004) gave $\lambda L_\lambda(5100 \, \text{Å})$ as $1.5 \times 10^{45} \, \text{erg} \, \text{s}^{-1}$. Considering the half-light contribution from the host bulge, the nuclear $\lambda L_\lambda(5100 \, \text{Å})$ is consistent with ours. They also gave the HβFWHM as $700 \pm 110 \, \text{km s}^{-1}$. When using this FWHM value to calculate the mass, the mass would be smaller by 0.5 dex than that from $\sigma_{\text{Hβ}}$ (Bian et al. 2004, 2008). The new mass from the Hβ FWHM is consistent with that from the $M_{\text{BH}}-\sigma_*$ relation. Hereafter, we adopt $(1-4) \times 10^6 \, M_\odot$ as its SMBH mass. This SMBH mass value of RE J1034+396 is consistent with that derived from the accretion disc fitting of its SED (Puchnarewicz et al. 2001; Wang & Netzer 2003).

It is suggested that the gaseous kinematics of NLRs are primarily governed by the bulge gravitational potential. Using the linewidth of [O iii] or [N ii] to trace $\sigma_\star$, we find that, from the narrow [O iii] component, $\sigma_{[\text{O} \, \text{iii}]} = 124 \, \text{km s}^{-1}$ (see Table 2). This would lead to a mass of $2 \times 10^7 \, M_\odot$, which is larger than the mass from $\sigma_\star$ and $\sigma_{\text{Hβ}}$ by an order of magnitude. For RE J1034+396, $\sigma_{[\text{O} \, \text{iii}]}$ cannot be used to trace $\sigma_\star$.

### 3.2 High-frequency quasi-periodic oscillations and black hole spin

QPOs can be classified as low-frequency QPOs (roughly 0.1–30 Hz) and high-frequency QPOs (roughly 40–450 Hz; Remillard & McClintock 2006). Assuming that the QPO frequency ($\nu_{\text{BHB}}$) scales inversely with the BH mass ($M_{\text{BH}}$) in BHBs, $M_{\text{BH}}/M_{\text{BH}} = v_{\text{BHB}}/v_{\text{BHB}}$, where $v_{\text{BHB}}$ is the QPO frequency for SMBHs in AGN. Using $v_{\text{BHB}} = v_{\text{BHB}} = (M_{\text{BH}}/M_{\text{BH}})$, the QPO frequency of $2.7 \times 10^{-4}$ Hz in RE J1034+396 (its SMBH mass is $2 \times 10^7 \, M_\odot$), with an uncertainty of a factor of 2) corresponds to a frequency of $27-108 \, \text{Hz}$ in Galactic BHBs with a 10-M$\odot$ BH. Our result of $27-108 \, \text{Hz}$ suggests that the QPO found in RE J1034+396 belongs to a high-frequency QPO. Larger estimated SMBH mass and smaller adopted BHB mass would make this frequency value larger.

It is believed that high-frequency QPOs may depend only on the mass and the spin of the BH. This dependence can be expected for coordinate frequencies (see Merloni et al. 1999) or for disc oscillation modes in the inner accretion disc (see Kato 2001). For a Schwarzschild BH, the innermost stable circular orbit (ISCO) corresponds a maximum orbit frequency as $v_{\text{ISCO}} = 2200 \times (M_{\text{BH}}/M_\odot)^{-1} \, \text{Hz}$. For an extreme Kerr BH, $v_{\text{ISCO}} = 16150 \times (M_{\text{BH}}/M_\odot)^{-1} \, \text{Hz}$ (Remillard & McClintock 2006). For three BHBs with high-frequency QPOs and well-constrained BH masses, Remillard & McClintock (2006) suggested an empirical frequency–mass relation for high-frequency QPOs, $\nu_0 = 931(M_{\text{BH}}/M_\odot)^{-1} \, \text{Hz}$. With an SMBH mass of $2 \times 10^7 \, M_\odot$ in RE J1034+396, the corresponding frequencies derived from the ISCO of a Schwarzschild BH, the ISCO of an extreme Kerr BH and the empirical frequency–mass relation are $11.0 \times 10^{-4}$, $8.0 \times 10^{-4}$ and $4.7 \times 10^{-4} \, \text{Hz}$, respectively. Considering an uncertainty of a factor of 2 in the SMBH mass and another uncertainty in the empirical frequency–mass relation for the high-frequency QPOs (e.g. the BH spin), the double or triple value of the fundamental frequency $4.7 \times 10^{-4} \, \text{Hz}$ does not deviate much from the observed frequency of $2.7 \times 10^{-4} \, \text{Hz}$ in RE J1034+396. This implies that the QPO phenomenon has the same origin in BHBs and AGN (e.g. Gierliński et al. 2008).

### 3.3 Star formation

The method widely employed to measure the current star formation rate (SFR) is the use of the ultraviolet continuum, the emission lines of H$\alpha$ and [O ii] (Kennicutt 1998). For a sample of 82 302 star-formation galaxies from the SDSS, Asari et al. (2007) investigated the current SFR derived from the SSP synthesis and found that it is consistent with that from the H$\alpha$ SFR indicator (see their fig. 6). The current specific SFR (SSFR) is defined by the mean SFR over the past 0.1 Gyr, that is, the first 21 of the 45 templates described in Section 2 with an age less than 0.1 Gyr (Asari et al. 2007; Chen et al. 2009):

$$\text{SSFR}(t < 0.1 \, \text{Gyr}) = \frac{\text{SFR}}{M_\star} = \frac{\sum_{j=1}^{21} M_j}{0.1 \, \text{Gyr}}. \quad (7)$$

For RE J1034+396, the current SFR ($t < 0.1 \, \text{Gyr}$) is $0.0163 \pm 0.0011 \, \text{Gyr}^{-1}$, $M_\star$ is $10.244$ and SSFR ($t < 0.1 \, \text{Gyr}$) is $0.02786 \, \text{Gyr}^{-1}$. Using 150 templates, $\sigma_\gamma$ and $M_\star$ are consistent with those using 45 templates, the stellar flux fraction is 47 per cent, and the SSFR would be larger by 70 per cent.

Using a type II AGN sample from the Max-Planck-Institut für Astrophysik/Johns Hopkins University (MPA/JHU) catalogue (Kauffmann et al. 2003), Chen et al. (2009) found a correlation between the Eddington ratio $\lambda$ (the ratio of the bolometric luminosity, $L_{\text{bol}}$, to the Eddington luminosity, $L_{\text{Edd}}$) and the mean SSFR, $\log \lambda = (-0.73 \pm 0.01) + (1.5 \pm 0.01) \log (\text{SSFR}/\text{Gyr}^{-1})$, suggesting that supernova explosions play a role in the transportation of gas to galactic centres. Considering that the difference between type II AGN and type I AGN is due to the orientation of the line of sight, type I AGN would also follow this log $\lambda$–log SSFR relation. Here we calculate the Eddington ratio for RE J1034+396. Using $L_{\text{bol}} = 9 \times \lambda L_\lambda(5100 \, \text{Å})$ (Kaspi et al. 2000), $L_{\text{Edd}} = 1.26 \times 10^{38} (M_{\text{BH}}/M_\odot) \, \text{erg} \, \text{s}^{-1}$, and $M_{\text{BH}} = 2 \times 10^6 \, M_\odot$, we find that the Eddington ratio is 0.2. Considering the uncertainty of a factor of 2 in $M_{\text{BH}}$, the uncertainty of the Eddington ratio is a factor of 2 (i.e. log $\lambda = -1 \sim -0.4$). Using equation (3) of Chen et al. (2009), the SSFR of $0.0163 \pm 0.001 \, \text{Gyr}^{-1}$ leads to a log $\lambda$ of $-3.45 \sim -3.37$, which deviates greatly from the value of $-1 \sim -0.4$. The deviation of log $\lambda$ is $2.37 \sim 3.05$ in the log $\lambda$–log SSFR diagram of Chen et al. (2009). Considering that most of the bolometric luminosity is emitted in the ultraviolet and soft X-ray band, Grupe et al. (2004) estimated the bolometric luminosity from a combined power-law model fit with an exponential cut-off to the optical–ultraviolet data and a power law to the soft X-ray data. They found $L_{\text{bol}} = 22 \times \lambda L_\lambda(5100 \, \text{Å})$, which is consistent with its hot big blue bump. If this is the case, log $\lambda$ would be larger by 0.39. Therefore,
4 CONCLUSIONS

The host bulge of a NLS1, RE J1034+396, with X-ray QPOs is investigated through its optical spectrum from the SDSS DR7. The main conclusions can be summarized as follows.

(i) The host bulge flux contribution at 4020 Å is about (43 ± 4) per cent in the SDSS spectrum and the bulge stellar velocity dispersion $\sigma_*$ is 67.7 ± 8 km s$^{-1}$. Considering the scatter in the $M_{BH}$-$\sigma_*$ relation, the SMBH mass from the $M_{BH}$-$\sigma_*$ relation is $(1 - 4) \times 10^6 M_\odot$.

(ii) Using multi-Gaussians to model the H$\beta$, [O III], H$\alpha$ and [N II] emission lines, we find that the mass from $\sigma_{H\alpha}$ and $\lambda L_\alpha(5100 \text{ Å})$ is $(0.7 \pm 3.4) \times 10^6 M_\odot$, consistent with that from $\sigma_*$. However, the [O III] velocity dispersion is 124 ± 2 km s$^{-1}$, about double that of $\sigma_*$. 

(iii) The SMBH mass of about $(1 - 4) \times 10^6 M_\odot$ implies that the QPO of $2.7 \times 10^4$ Hz found in RE J1034+396 can be scaled to a high-frequency QPO at about 27–108 Hz found in Galactic BHBs with a 10-M_\odot BH.

(iv) From the SSP synthesis, we find that current SSFR ($t < 0.1$ Gyr) is 0.0163 ± 0.0011 Gyr$^{-1}$, log ($M_\star/M_\odot$) is 10.155 ± 0.06, and the current SFR is $0.23 \pm 0.016 M_\odot$ yr$^{-1}$. RE J1034+396 does not follow the relation between the Eddington ratio and SSFR. About 6.1–7.0 per cent of the total H$\alpha$ luminosity and 44–50 per cent of the total [O II] luminosity come from the star formation process.

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