Modeling the flare in NGC 1097 from 1991 to 2004 as a tidal disruption event

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ABSTRACT

In the Letter, interesting evidence is reported to support a central tidal disruption event (TDE) in the known AGN NGC 1097. Considering the motivations of TDE as one probable origination of emission materials of double-peaked broad emission lines and also as one probable explanation to changing-look AGN, it is interesting to check whether there are clues to support a TDE in NGC 1097, not only a changing-look AGN but also an AGN with double-peaked broad emission lines. Under the assumption that the onset of broad Hα emission was due to a TDE, the 13-years-long (1991-2004) variability of double-peaked broad Hα line flux in NGC 1097 can be well predicted by theoretical TDE model, with a $(1−1.5)M_\odot$ main-sequence star tidally disrupted by the central BH with TDE model determined mass about $(5−8) \times 10^7 M_\odot$. The results provide interesting evidence to not only support TDE-related origin of double-peaked broad line emission materials but also support TDE as an accepted physical explanation to properties of changing-look AGN.

Key words: galaxies:active - galaxies:nuclei - quasars:emission lines - galaxies:Seyfert - transients: tidal disruption events - quasars: individual (NGC 1097)

1 INTRODUCTION

TDEs (Tidal Disruption Events) have been well studied in detail for more than four decades (Rees 1988; Loeb & Ulmer 1997; Cenko et al. 2012; Gezari et al. 2012; Guillochon & Ramirez-Ruiz 2013; Guillochon et al. 2014; Komossa 2015; Wang et al. 2018; Thorp et al. 2019), with accreting fallback debris from stars tidally disrupted by central black holes (BHs) leading to apparent time-dependent variability. Based on TDE expected variability properties, there are more than 100 TDE candidates detected and reported in the literature (see the collected TDE candidates listed in https://tde.space/), strongly supporting the idea that TDEs can be used to locate massive BHs and accreting BH systems. More recent reviews on theoretical simulations on TDEs can be found in Stone et al. (2018) and on detected TDE candidates can be found in Gezari (2021). More recent large samples of dozens of TDE candidates can be found in the van Velzen et al. (2021) from the First Half of ZTF (Zwicky Transient Facility) Survey observations and in Sazonov et al. (2021) from the SGR all-sky survey observations.

Along with studying on TDEs, some special spectroscopic features have been considered to be tightly related to TDEs, such as double-peaked broad emission lines, see the discussions in Eracleous et al. (1995) for AGN with double-peaked broad emission lines (hereafter, double-peaked AGN). More detailed discussions on variability properties of double-peaked broad emission lines in TDE candidates can be found in SDSS J0159 in Merloni et al. (2015); Zhang (2021), in ASASSN-14li in Holoien et al. (2016), in PTF09dji in Liu et al. (2017), in PS18kh in Holoien et al. (2019), in AT2018hyy in Short et al. (2020); Hung et al. (2020), etc.. Therefore, it is interesting to check whether are there double-peaked AGN as host galaxies of TDE candidates. Moreover, TDEs could be probably related to or probably detected in changing-look AGN (AGN with type transitioned between Type 1 and Type 2), such as the detailed results in the changing-look AGN SDSS J0159 in Merloni et al. (2015); LaMassa et al. (2015) and more detailed discussions on a sample of changing-look AGN in Yang et al. (2018) and in the bluest changing-look quasar in Zhang (2021b). Therefore, TDE candidates could be more preferred in changing-look double-peaked AGN.

Fortunately, there is an AGN, the low luminosity AGN NGC 1097, which has been classified as a double-peaked AGN and also as a changing-look AGN. Changing-look properties of NGC 1097 can be confirmed by the following spectroscopic features: no broad emission lines before 1990 as reported in Walsh et al. (1986) but apparently double-peaked broad emission lines in the 1990s and in early 2000s as discussed in Storchi-Bergmann et al. (1993, 2003). Moreover, Kondo et al. (2012) have studied properties of central regions of NGC 1097 through near-infrared spectrum and reported that there are no any evidence for nuclear activity in NGC 1097 in Jul. 18th, 2008, which can be well applied to discuss physical models of flare in NGC 1097. And, the apparently detected double-peaked broad Hα lead NGC 1097 to be clearly classified as a double-peaked AGN, although NGC 1097 has central continuum luminosity at 5100Å around $10^{40}$ erg/s (see Fig. 3 in Storchi-Bergmann et al. (2005) much lower than common values around $10^{44}$ erg/s of broad line AGN (Shen et al. 2011).

In the Letter, variability properties of NGC 1097 are well studied to check whether is there strong evidence to support a central TDE in NGC 1097. Section 2 presents our main results on variability of broad Hα line flux from 1991 to 2004, and necessary discussions.

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Section 3 gives our final conclusions. And in the Letter, we have adopted the cosmological parameters of $H_0 = 70 \text{km} \cdot \text{s}^{-1} \text{Mpc}^{-1}$, $\Omega_L = 0.7$ and $\Omega_m = 0.3$.

2 LONG-TERM VARIABILITY OF DOUBLE-PEAKED BROAD H\alpha LINE FLUX FROM 1991 TO 2004

Besides spectroscopic results in Storchi-Bergmann et al. (2003) from 1991 to 2001, another spectroscopic results can be collected from the HST (Hubble Space Telescope) mission (ID:8684, PI: Dr. E. Eracleous) in 2004 with broad H\alpha line flux about $F_{\text{b,obs}} \sim (85.6 \pm 7.1) \times 10^{-15} \text{erg/s/cm}^2$. Here, three broad Gaussian components are applied to describe the broad H\alpha and the other seven narrow Gaussian components are applied to describe the narrow H\alpha, [O \iota],6300, 6363\AA, [N \ii],6548, 6583\AA and [S \ii],6716, 6731\AA doublets. Through the Levenberg-Marquardt least-squares minimization technique, the emission components can be well determined and shown in Fig. 1.

As discussed in Storchi-Bergmann et al. (2003), in order to correct effects of aperture sizes on optical spectra with different instruments, total line intensity of narrow H\alpha is determined to-
uous time after considering the viscous delay effects as discussed in Guillouchon & Ramirez-Ruiz (2013; Mockler et al. 2019). Here, a grid of 31 log(T, temp(years)) range from -3 to 0 are applied to create templates of M dot for each impact parameter. Finally, templates of M dot include 736 (640) time-dependent viscous-delayed accretion rates for 31 different T v, of each 23 (20) impact parameters for the main-sequence star with polytropic index γ of 4/3 (5/3).

Second, simple linear interpolations are applied to determine accretion rates M dot(T v, β) for TDEs with input model parameters of β and T v different from the list values in β temp and in T v temp. Assuming that β 1, β 2 in the β temp are the two values nearer to the input β and T v 1, T v 2 in the T v temp are the two values nearer to the input T v, the expected M dot(T v, β) can be estimated by

\[ M_{\text{dot}}(T_v, \beta_1) = M_{\text{dot}}(T_v, \beta_1) + \frac{T_v - T_v^1}{T_v^2 - T_v^1} (M_{\text{dot}}(T_v, \beta_1) - M_{\text{dot}}(T_v, \beta_1)) \]

\[ M_{\text{dot}}(T_v, \beta_2) = M_{\text{dot}}(T_v, \beta_2), \beta_2 = M_{\text{dot}}(T_v, \beta_2) - M_{\text{dot}}(T_v, \beta_1)) \]

\[ M_{\text{dot}}(T_v, \beta) = M_{\text{dot}}(T_v, \beta_1) + \frac{\beta - \beta_1}{\beta - \beta_1} (M_{\text{dot}}(T_v, \beta_2) - M_{\text{dot}}(T_v, \beta_1)) \]

(2)

Third, for TDEs with input M BH and M*, different from 10^6M⊙ and 1M⊙, as discussed in Guillouchon & Ramirez-Ruiz (2013; Mockler et al. 2019), actual viscous-delayed accretion rates M and the corresponding time information are created by the following scaling ratios applied with input BH mass, mass and radius of the disrupted main-sequence star,

\[ M = M_{\text{BH,6}}^{0.5} \times M_\star^{1.5} \times M_{\text{BH}}(T_v) \]

\[ t = (1 + z) \times M_{\text{BH,6}}^{0.5} \times M_{\text{BH}}^{-1} \times R_{\text{BH}}^{1/5} \times t_{\text{BH}}(T_v, \beta) \]

, where M BH,6, M*, R*/BH represent central BH mass in unit of 10^6M⊙, stellar mass in unit of M⊙, stellar radius in unit of R⊙, and redshift of host galaxy of a TDE, respectively. And the mass-radius relation discussed in Tout (1996) has been accepted in the Letter for main-sequence stars.

Fourth, the time-dependent output emission spectrum in rest frame based on the TDE model expected accretion rate M(t) can be determined by the simple black-body photosphere model as discussed in Guillouchon et al. (2014; Mockler et al. 2019),

\[ F_i(t) = \frac{2\pi G c^2}{\lambda^5} \frac{1}{\exp(\hbar c/kT_p(t)) - 1} \frac{R_p(t)}{D}^2 \]

\[ R_p(t) = R_0 \times a_p \times \eta \left( \frac{M(t)}{1.3 \times 10^{38} M_{\text{BH}} M_\odot} \right)^{1/3} \]

\[ T_p(t) = \frac{\eta M(t)}{4 \pi \sigma_{SB} a_p}^{1/4} \]

, where D means the distance to the earth calculated by redshift z = 0.00424 (the redshift of NGC 1097), k is the Boltzmann constant, T p(t) and R p(t) represent the time-dependent effective temperature and radius of the photosphere, respectively, and η is the energy transfer efficiency smaller than 0.4, σSB is the Stefan-Boltzmann constant, and t p is the time information of the peak accretion. Then, based on the F_5100Å(t) in rest frame, time-dependent broad Hα line fluxes f Hα(t) can be determined by

\[ f_{H\alpha}(t) = F_{5100\AA}(t) \times K_{cl} \]

with K cl as the intensity ratio of broad Hα line flux to continuum emission intensity at 5100Å in rest frame, through the strong correlation between continuum luminosity and broad Hα line luminosity (Greene & Ho 2005; Zhang et al. 2008).

When the procedure above is applied to describe the observed variability of broad Hα line flux, there is only one limitation that the determined tidal disruption radius R TDE = (M*)^{-1/3} (M BH)^{-2/3} R* to be larger than event horizon of central BH R G = 2GM BH/c^2.

Finally, the theoretical TDE model expected time dependent light curves f Hα(t) can be described by eight model parameters, central BH mass log(M BH), stellar mass log(M*) (corresponding stellar radius R*, calculated by the mass-radius relation), energy transfer efficiency log(η), impact parameter log(β), viscous timescale log(T v), parameters l p and R 0 related to the black-body photosphere model, and ratio K cl. Then, through the well-known maximum likelihood method combining with the Markov Chain Monte Carlo (MCMC) technique (Foreman-Mackey et al. 2013), the variability of broad Hα line fluxes in NGC 1097 can be well predicted and shown in Fig. 2 from 1991 to 2004, accepted prior uniform distributions of the model parameters and the corresponding starting values listed in Table 1. Two-dimensional posterior distributions of the model parameters are shown in Fig. 3. And the final accepted model parameters and corresponding uncertainties are also listed in Table 1. Here, the uncertainty of each parameter is determined by the half width at half maximum of distribution of each parameter. Based on the determined model parameters, the expected TDE is starting from JD=2447275 ± 140 (around Apr. 24th, 1988) and from JD=2446997 ± 180 (around Jul. 20th, 1988) for the model with γ = 4/3 and γ = 5/3, respectively. Considering the mass limitation of central disrupted stellar in Guillouchon & Ramirez-Ruiz (2013; Mockler et al. 2019): M* < 0.3M⊙ or M* > 22M⊙ for γ = 5/3, the TDE model with γ = 4/3 is preferred in NGC 1097. The determined model parameters have reasonable values, compared with the values for the other optical TDEs candidates in the literature, providing direct and interesting clues to support a central TDE in NGC 1097 from 1991 to 2004.

Then, it is interesting to check whether the TDE model predicted Hα line flux is lower enough to be consistent with the reported none apparent AGN activity in 2008 in Kondo et al. (2012). As shown in Fig. 2, the expected broad Hα line flux in 2008 is about 25 × 10^{-13} erg/s/cm², about 3.5 times weaker than that observed in 2004. Now, it is interesting to check whether so weak broad Hα component

### Table 1. Parameters of TDE models for NGC 1097

| parameter | prior | p0 | valuea | valueb |
|-----------|-------|----|--------|--------|
| log(M BH, 6) | [-3, 3] | 1.86 ± 0.22 | 1.73 ± 0.34 |
| log(M*/M BH) | [-2, 1.7] | 0.16 ± 0.17 | 0.12 ± 0.13 |
| log(β) (4/3) | [-0.22, 0.6] | 0.12 ± 0.09 | ... |
| log(β) (5/3) | [-0.3, 0.4] | 0. . . . ± 0.06 |
| log(T vis) | [-3, 0] | -0.14 ± 0.12 | -0.17 ± 0.14 |
| log(t p) | [-3, -0.4] | -2.28 ± 0.75 | -2.69 ± 0.76 |
| log(R 0) | [-3, -3] | 0.13 ± 0.55 | -0.10 ± 0.55 |
| log(l p) | [-3, 0.6] | 0.006 ± 0.12 | 0.19 ± 0.12 |
| log(K cl) | [-3, 6] | 1.55 ± 0.59 | 1.65 ± 0.64 |

Notes: The first column shows the applied model parameters. The second column shows limitations of the prior uniform distribution of each model parameter. The third column with title "p0" lists starting value of each parameter. The fourth column with column title marked with * means the values of model parameters for the TDE model with γ = 4/3. The fifth column with column title marked with b means the values of model parameters for the TDE model with γ = 5/3.
can be well detected in spectrum. As an oversimplified example, based on the observed spectrum in 2004 with the broad component weakened by a factor of 3.5 (similar values for the TDE model with different \( \gamma \)), the expected spectrum in 2008 is shown in Fig. 2: no apparent broad H\( \alpha \) to be consistent with the reported none-activity in NGC 1097 in 2008 in Kondo et al. (2012). In other words, the none apparent activity in 2008 reported in Kondo et al. (2012) could be simply expected, under the assumption of a central TDE in NGC 1097. Therefore, the determined TDE model is reasonable.

Based on the best descriptions shown in Fig. 2, the variability from 1991 to 2004 in NGC 1097 can be well predicted by theoretical TDE model, under the assumption of double-peaked broad H\( \alpha \) emissions related to a TDE. However, there is an interesting question whether there is further evidence to support the emission materials of the double-peaked broad emission lines related to the central TDE. As discussed in Storchi-Bergmann et al. (2003), the double-peaked features provide the corresponding emission regions with inner radius about 225\( R_\odot \) and outer radius about 800\( R_\odot \) (here, \( R_\odot \) is twice of the unit used in Storchi-Bergmann et al. (2003)). If the double-peaked broad H\( \alpha \) were related to the central TDE, we could expect the regions of accreting debris in the TDE could cover the emission regions for the double-peaked broad H\( \alpha \). Based on the model parameters, the distance of accreting debris as discussed in (Guillochon et al. 2014) can be roughly estimated by \( R_\odot \sim 2 \times (\frac{G M_{\text{BH}} x^2}{\pi})^{1/3} \), leading to \( R_\odot \sim 3200R_\odot \) in 2000 (where \( x \) is about 3400days), indicating the accreting debris totally cover the expected emission regions of the double-peaked broad H\( \alpha \) in NGC 1097. Therefore, it is plausible to accept that the double-peaked broad H\( \alpha \) are from accreting debris in the central TDE in NGC 1097. Furthermore, through the well measured stellar velocity dispersion about 190km/s in NGC 1097 in Lewis & Eracleous (2006) and discussed in Storchi-Bergmann et al. (2003); Onishi et al. (2015), the central BH mass of NGC 1097 has been reported to be around 10\(^8\)M\(_\odot\) through the well-known \( M_{\text{BH}} = \sigma \sqrt{\frac{3}{2G}} \) (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy & Ho 2013; Batiste et al. 2017; Bennert et al. 2021), simply consistent with the TDE model determined BH mass after considering the uncertainties, providing further evidence to support the central TDE in NGC 1097.

Before end of the section, three further points are noted. First, besides the long-term variability of double-peaked broad H\( \alpha \) over ten years from 1991 to 2004, there are apparent variability of double-peaked broad H\( \alpha \) from 2010 to 2013, as discussed in Schimoia et al. (2012, 2015), which are shown as small circles in Fig. 2. Considering the long-term variability from 1991 to 2013 in NGC 1097 shown in Fig. 2, the variability pattern is quite like the case discussed in Campana et al. (2015); Grupe et al. (2015) in the known changing-look AGN IC 3599. Different models have been proposed to explain the multiple flares. Campana et al. (2015) have shown that a tidal stripping in partial TDE can lead to repeated tidal disruption flares. However, Grupe et al. (2015) have shown that the second flare in IC 3599 should be related to accretion disk variability. Mandel & Levin (2015) have shown that binary stars disrupted by central massive BH (double TDE) can lead to repeated flares. There are so far no confirmed physical origin of repeated flares in IC 3599, neither in NGC 1097. However, based on special properties of NGC 1097, further discussions can be given on the proposed models. Mandel & Levin (2015) have shown that the majority of double-star disruptions produce two flares close enough in time that they overlap. As NGC 1097 was apparently inactive in 2008 (Kondo et al. 2012), between the two peaks of H\( \alpha \) flux, then this scenario in Mandel & Levin (2015) should be disfavoured. Probably, the second flare in NGC 1097 should be related to an independent TDE, because the TDE expected \( t^{-5/3} \) (shown as solid red line in Fig. 2) can be roughly applied to describe the variability from 2011 to 2013.

Second, as the discussed variability around 2010 in Schimoia et al. (2012) (time duration less than 400days), there is an interesting plateau phase (shown in Fig. 5 in Schimoia et al. (2012)), which can not expected by standard TDE model. The interesting variability properties could including effects of accretion disk variability. Therefore, long-term variabilities with scale about ten years could be simply expected by standard TDE model, however, short-term variability with time scale about hundreds of days should be related to central accretion disk variability. Therefore, the long-term variability from 1991 to 2004 is mainly considered in the Letter, due to well predicted by the standard TDE model.

Third, as the shown best fitting results in Fig. 2 from 1991 to 2004, a decay in flux of a factor 5 in 10 years is slow for standard TDEs. However, after considering viscous delay effects, the decaying trend should be quite flatter than \( t^{-5/3} \). Similar flat decay can be found in some other reported TDEs, such as the PS1-11af, TDE2, etc.
shown in Fig. 1 in Mockler et al. (2019) with magnitude decay about 1.5-2 mags (flux decay factor about 4-6) from the time with peak intensity to late times. Therefore, the slower decay trend in NGC 1097 can be well accepted. Certainly, as reported and discussed in Gezari et al. (2008, 2009) and simple descriptions in Gezari (2021), quite flatter decaying trend could be also found in TDE expected light curves at late stages, such as in the TDE candidate D3-13 with index $r^{-0.82}$ at late stages. Therefore, it is interesting to consider whether the flatter decaying trend in NGC 1097 is due to catching the event in the late stages. If accepted the variability from 1991 to 2004 from TDE expected variability at late stages, expected starting time of the TDE should be earlier than 1986, under simply considering the flatter decaying trend at late stages having similar (or even two times) time duration as the steeper decaying trend at early stages around the peak. However, there are no broad Hα emissions in 1986, indicating the consideration of catching the event in the late stages should be not favoured to explain the flatter decaying trend in NGC 1097. Moreover, based on the TDE model determined parameters, the peak accretion rate is estimated to be $\dot{M} \sim 0.02 M_\odot$/year, and the total accreted mass during the 13-years-long flare is estimated to be $0.2M_\odot$. Considering the determined energy efficiency about log($\eta$) $\sim -2.28$, the corresponded observed peak bolometric luminosities is about $\eta \times M c^2 \sim 6 \times 10^{42}$ erg/s. However, after considering the probable intrinsic reddening effects with $A_V = 3$ mag as discussed in Storchi-Bergmann et al. (2005), the intrinsic peak bolometric luminosity is about $9 \times 10^{43}$ erg/s well consistent with the peak bolometric luminosities around $9 \times 10^{42}$ erg/s of the other TDE candidates as discussed in Mockler et al. (2019), to support the central TDE in NGC 1097.

3 CONCLUSIONS

Finally, we give our main conclusions as follows. Under the assumption of double-peaked broad emission lines coming from TDE related debris, theoretical TDE model with a $1 - 1.5M_\odot$ main-sequence star disrupted by the central BH with TDE model determined mass about $(5 - 8) \times 10^7 M_\odot$ can be well applied to predict the 13-years-long (1991-2004) variability of double-peaked broad H$\alpha$ line fluxes in the well-known low luminosity AGN NGC 1097, providing interesting evidence to support a central TDE in NGC 1097 which has been classified as both a changing-look AGN and a double-peaked AGN. Therefore, NGC 1097 is so-far the best candidate to support the TDE related origin of double-peaked broad Balmer emission materials and to support TDE as the physical explanation to properties of changing-look AGN.

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DATA AVAILABILITY

The data underlying this article will be shared on request to the corresponding author (aexueguang@qq.com).

REFERENCES

Batiste, M.; Bentz, M. C.; Raimundo, S. I.; Vestergaard, M.; Onken, C. A., 2017, ApJL, 838, 10
Bennert, V. N.; Treu, T.; Ding, X.; et al., 2021, ApJ, 921, 36
Campana, S.; Mainetti, D.; Colpi, M.; Lodato, G.; D’Avanzo, P.; Evans, P. A.; Moretti, A., 2015, A&A, 581, 17
Cenko, S. B.; Krimm, H. A.; Horesh, A.; et al., 2012, ApJ, 753, 77
Eracleous, M.; Livio, M.; Halpern, J. P.; Storchi-Bergmann, T., 1995, ApJ, 458, 610
Ferrarese, F.; Merritt, D., 2000, ApJL, 539, 9
Foreman-Mackey, D.; Hogg, D. W.; Lang, D.; Goodman, J., 2013, PASP, 125, 306
Geibhardt, K.; et al., 2000, ApJL, 539, 13
Gezari, S.; Basa, S.; Martin, D. C.; et al., 2008, ApJ, 676, 944
Gezari, S.; Heckman, T.; Cenko, S. B.; et al., 2009, ApJ, 698, 1367
Gezari, S.; Chornock, R.; Rest, A.; et al., 2012, Nature, 485, 217
Gezari, S., 2021, ARA&A, 59, 21
Greene, J. E.; & Ho, L. C., 2005, ApJ, 630, 122
Grupe, D.; Komossa, S.; Saxton, R., 2015, ApJ, 803, 28
Guillochon, J.; & Ramirez-Ruiz, E., 2013, ApJ, 767, 25
Guillochon, J.; Manukian, H.; Ramirez-Ruiz, E., 2014, ApJ, 783, 23
Holoien, T. W. S.; Kochanek, C. S.; Prieto, J. L.; et al., 2016, MNRAS, 455, 2918
Holoien, T. W. S.; Huber, M. E.; Shappee, B. J.; et al., 2019, ApJ, 880, 120
Hung, T.; Foley, R. J.; Ramirez-Ruiz, E.; et al., 2020, ApJ, 903, 31
Komossa, S., 2015, HEEp, 7, 148
Kondo, T.; Kaneda, H.; Oyabu, S.; et al., 2012, ApJL, 751, 18
Kormendy, J.; Ho, L. C., 2013, ARA&A, 51, 51
LaMassa, S. M.; Cales, C.; Moran, E. C.; et al., 2015, ApJ, 800, 144
Lewis, K. T.; & Eracleous, M., 2006, ApJ, 642, 711
Liu, F. K.; Zhou, Z. Q.; Cao, R.; Ho, L. C.; Komossa, S., 2017, MNRAS Letter, 472, 99
Loeb, A.; Ulmer, A., 1997, ApJ, 489, 573
Mandel, I.; Levin, Y., 2015, ApJL, 505, 4
Merloni, A.; Dwelly, T.; Salvador, A. G.; et al., 2015, MNRAS, 452, 69
Mockler, B.; Guillochon, J.; Ramirez-Ruiz, E., 2019, ApJ, 872, 151
Onishi, K.; Iguchi, S.; Sheth, K.; Kohn, K., 2015, ApJ, 806, 39
Rees, M. J., 1988, Nature, 333, 523
Sazonov, S.; Gilfanov, M.; Medvedev, P.; et al., 2021, MNRAS, 508, 3820
Schimoia, J. S.; Storchi-Bergmann, T.; Nemmen, R. S.; Winge, C.; Eracleous, M., 2012, ApJ, 748, 1498
Schimoia, J. S.; Storchi-Bergmann, T.; Grupe, D.; et al., 2015, ApJ, 800, 63
Shen, Y.; Richards, G. T.; Strauss, M. A.; et al., 2011, ApJS, 194, 45
Short, P.; Nicholl, M.; Lawrence, A.; Gomez, S.; et al., 2020, MNRAS, 498, 4119
Stone N. C.; Kesden M.; Chang R. M.; van Velzen S.; General Relativity and Gravitation, 2018, arXiv:1801.10180
Storchi-Bergmann, T.; Baldwin, J. A.; Wilson, A. S., 1993, ApJ, 410, 11
Storchi-Bergmann, T.; Nemmen, R. S.; Eracleous, M.; et al., 2003, ApJ, 489, 8
Storchi-Bergmann, T.; Nemmen, R. S.; Spinelli, P. F.; Eracleous, M.; Wilson, A. S.; Filippenko, A. V.; Livio, M., 2005, ApJL, 624, 13
Thorup, S.; Chadwick, E.; Sesana, A., 2019, MNRAS, 488, 4042
Tout, C. A.; Pols, O.; Eggleton, P.; Han, Z., 1996, MNRAS, 281, 257
van Velzen, S.; Gezari, S.; Hammerstein, E.; et al., 2021, ApJ, 908, 4
Walsh, J. R.; Nandy, K.; Thompson, G. I.; Meaburn, J., 1986, MNRAS, 220, 453
Wang, T.; Yan, L.; Dou, L.; et al., 2018, MNRAS, 477, 2943
Yang, Q.; Wu, X. B.; Fan, X.; et al., 2018, ApJ, 862, 109
Zhang, X. G., 2008, MNRAS, 385, 1087
Zhang, X. G., 2021, MNRAS Letter, 500, 57
Zhang, X. G., 2021b, ApJ, 919, 13
Zhang, X. G., 2022, ApJ accepted, Arxiv:2202.11265