Reverberation Mapping of the Narrow-line Seyfert 1 Galaxy I Zwicky 1: Black Hole Mass

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Abstract

We report results of the first reverberation mapping campaign of I Zwicky 1 during 2014–2016, which showed unambiguous reverberations of the broad Hβ line emission in the varying optical continuum. From analysis using several methods, we obtain a reverberation lag of τHβ = 37.2±1.5 days. Taking a virial factor of fBLR = 1, we find a black hole mass of Mbh = 9.30±1.26 × 10⁹Msun from the mean spectra. The accretion rate is estimated to be 203.9±64.0 L_{Edd}, suggesting a super-Eddington accretor, where L_{Edd} is the Eddington luminosity and c is the speed of light. By decomposing Hubble Space Telescope images, we find that the stellar mass of the bulge of its host galaxy is log(M_{bulge}/M_*) = 10.92 ± 0.07. This leads to a black hole to bulge mass ratio of ~10^{-4}, which is significantly smaller than that of classical bulges and elliptical galaxies. After subtracting the host contamination from the observed luminosity, we find that I Zw 1 follows the empirical R_{BLR} ≈ L_{5100}^{1/2} relation.

Key words: galaxies: active – galaxies: individual (I Zw 1) – galaxies: nuclei

Supporting material: machine-readable table

1 Introduction

Narrow-line Seyfert 1 galaxies (NLS1s) are thought to be a special subclass of active galactic nuclei (AGNs). Compared to the broad-line Seyfert 1 galaxies, NLS1s have (1) narrower Balmer lines (FWHM_{Hβ} ≲ 2000 km s⁻¹ by definition, where FWHM_{Hβ} is the FWHM of the broad Hβ emission line), (2) a smaller intensity ratio of the [O III] λ5007 to Hβ line (OIII)/Hβ < 3, (3) stronger optical FeII multiplet emissions, and (4) usually steeper soft X-ray spectra and more rapid X-ray variability (Osterbrock & Petke 1985; Goodrich 1989; Boroson & Green 1992; Boller et al. 1996; Sulentic et al. 2000; Wang et al. 2004). These distinctive properties of NLS1s can be explained by less massive black holes accreting with higher mass accretion rates (Boroson & Green 1992; Boller et al. 1996; Wang & Netzer 2003; Grube 2004; Peterson et al. 2004; Mathur & Grube 2005). Black holes in NLS1s are therefore undergoing fast growth through super-Eddington accretion (e.g., Kawaguchi et al. 2004; Zhang & Wang 2006; Wang & Zhang 2007). In the high-z universe, such fast growth was suggested to be a possible way of forming supermassive black holes (Volonteri & Rees 2005; Wang et al. 2006; Mordlock et al. 2011; Banados et al. 2018). Moreover, these super-Eddington accreting massive black holes (SEAMBHs) have saturated luminosities predicted by the slim accretion disk model (Abramowicz et al. 1988; Wang & Zhou 1999) and could be used as a new kind of standard candle to study the expansion history of the high-z universe (Wang et al. 2013, 2014; Marziani & Sulentic 2014; Cai et al. 2018; Marziani et al. 2019) because they are quite common from the low-z to high-z universe (Du et al. 2016a; Martínez-Aldama et al. 2018; Negret et al. 2018). Reliably measuring the black hole mass of local super-Eddington AGNs greatly helps elucidate these issues.

The reverberation mapping (RM) technique is a powerful tool for measuring the mass of the black hole in the center of AGNs (Peterson 1993; Peterson et al. 2004; Peterson 2014). The widely accepted scenario is that gas around the central black hole is photoionized by the continuum emissions from the accretion disk and emits the observed broad emission lines. This is known as the broad-line region (BLR). Because of the light-travel time from the central black hole to the BLR, the variation in the flux of emission lines will delay that of the continuum. RM campaigns monitor the flux variations in the continuum and broad emission lines to measure the lags between them. Thus, the observed lags are regarded as a measurement of the radius of the BLR. Assuming that the motion of BLR gas is governed by the gravity of the black hole, the profiles of these lines would provide the kinematic information of the BLR, and the virial mass of the black hole can be estimated by

\[ M_b = \frac{f_{BLR} R_{BLR} V_{FWHM}^2}{G}, \]

where \( f_{BLR} \) is the virial factor, \( G \) is the gravitational constant, and \( R_{BLR} = c \times \tau_H \) is the emissivity-weighted size of the BLR emitting the broad Hβ line, with \( c \) the light speed and \( V_{FWHM} \) the...
velocity of the BLR clouds inferred from the width of the broad H$\beta$ line. Recently, the mass of the black hole in 3C 273 has been determined by another novel technique using GRAVITY on VLTI (Very Large Telescope Interferometer; Strum et al. 2018), and the result is in good agreement with that given by a 10 yr RM campaign (Zhang et al. 2018).

As one of the most famous NLS1s, I Zwicky 1 (PG 0050 +124 or Mrk 1502; $z = 0.061$; hereafter I Zw 1) is selected to be one of the candidates in our large RM campaign focusing on AGNs with SEAMBHs (Du et al. 2014). I Zw 1 is a nearby and bright ($m_v = 14.06 \pm 0.05$ from Slavcheva-Mihova & Mihov 2011b) prototypical NLS1 (Schmidt & Green 1983; Osterbrock & Pogge 1985; Halpern & Oke 1987) with FWHM$_{H_{\beta}} \approx 1200$ km s$^{-1}$, a large relative strength of optical Fe II emission lines ($R_{Fe} = 1.47$ from Boroson & Green 1992), weak intensity of the [O III] line, and a steep X-ray ($2-10$ keV) photon index ($\Gamma = 2.15 \pm 0.02$ from Gallo et al. 2007). Its Fe II spectrum is commonly used as a template to fit the optical and ultraviolet spectra of AGNs and quasars (Boroson & Green 1992; Vestergaard & Wilkes 2001; Vérón-Cetty et al. 2004). Similar to other NLS1s, Hubble Space Telescope (HST) images clearly show that the host galaxy of I Zw 1 is a spiral galaxy with asymmetric knotty spiral arms (Slavcheva-Mihova & Mihov 2011a) consisting of young stellar populations and ongoing nuclear star formation activity (Hutchings & Crampton 1990; Scharwächter et al. 2007). It would be highly instructive to measure the black hole mass and accretion rate of I Zw 1 in order to understand the relation of its central engine to its host galaxy. As far as we know, only Giannuzzo et al. (1998) have obtained seven epochs with a mean cadence of about 170 days to monitor the optical variability of I Zw 1. This is not enough for RM measurements.

In this paper, we report the results of the first RM campaign for I Zw 1. In Section 2, we describe the observations and data reduction. In Section 3, we analyze the light curves to measure the H$\beta$ time lags for the black hole mass and fit the HST images to separate the host component to test the empirical $R_{BLR} \sim L_{5000}$ relation. Brief discussions are provided in Section 4. A summary is given in the last section. Throughout this work, we adopt a cosmology with $H_0 = 67$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\Lambda} = 0.68$, and $\Omega_m = 0.32$ (Ade et al. 2014).

2. Observations and Data Reduction

2.1. Observations

Our observations were performed from 2014 November to 2016 February using the Lijiang 2.4 m telescope of Yunnan Observatories, Chinese Academy of Sciences. A versatile instrument called the Yunnan Faint Object Spectrograph and Camera (YFOSC) was used because it can switch from spectroscopy to photometry within one second (Du et al. 2014). During the spectroscopic observations, we used grism 14, which covers the wavelength range of 3800–7200 Å, and a long slit with a fixed width of 2$^\prime$5 to minimize flux loss caused by the different seeing conditions. The final spectral resolution was roughly 500 km s$^{-1}$. The spectral resolution was estimated by comparing the width of the [O III] line of the Lijiang spectrum with the one obtained from the Sloan Digital Sky Survey (Hu et al. 2015; Du et al. 2016b). For accurate flux calibration, we adopted the method described by Maoz et al. (1990) and Kaspi et al. (2000), putting I Zw 1 and a nearby comparison star simultaneously in the long slit during the exposure. The comparison star (RA$_{J2000} = 00:53:46.92$, decl$_{J2000} = +12:39:56.8$) is a stable G star without intrinsic changes, as confirmed from the photometric light curve shown in Appendix A. The position angle between the comparison star and I Zw 1 is $120^\circ$, and the angular distance is 3$^\prime$4. Flux changes caused by unstable weather can be corrected by the comparison star. To mitigate the influence of cosmic rays, we used two consecutive exposures with a typical exposure time of 600 s each. Between the two exposures, we took an image to inspect whether I Zw 1 and the comparison star still sit in the middle of the slit. If not, we adjust the slit for realignment. Every night, we also took two consecutive exposures of a spectrophotometric standard star. In order to minimize the impact of atmospheric differential refraction, we took spectra only when the air mass was $\leq 1.5$ (median air mass $\leq 1.3$ for our data). In addition, we also made $V$-band photometric observations to verify the accuracy of the spectral calibration. Three consecutive 90 s exposures were taken to reduce the impact of cosmic rays. We obtained 66 epochs of spectroscopic observations and 74 epochs of photometric observations for I Zw 1 during our campaign. The median cadence is $\approx 4$ days.

2.2. Data Reduction

All of the spectroscopic and photometric data were reduced following standard methods using IRAF v2.16. For spectroscopic data, the extraction aperture was 8$^\prime$$'$5. Standard neon and helium lamps were used for wavelength calibration, and the comparison star was used for flux calibration, as described by Du et al. (2014).

Here, we briefly describe the method of flux calibration. (1) We used spectrophotometric standard stars to calibrate the spectra of the comparison star. (2) A fiducial spectrum of the comparison star was made from its flux-calibrated spectra taken over several nights under good weather conditions. The uncertainty of the absolute flux calibration was $\sim 10\%$ (Du et al. 2016c). (3) By comparing the observed spectrum of the comparison star to the calibrated fiducial spectrum, we obtained a sensitivity function for each exposure. (4) This sensitivity function was then used to calibrate the spectrum of I Zw 1. (5) We combined the separate exposures taken each night into a single epoch spectrum for that night. This method can achieve an accuracy of $\sim 3\%$ in the calibrated spectra (Du et al. 2018), which is especially necessary for targets such as I Zw 1 and other SEAMBHs, whose [O III] $\lambda 5007$ line tends to be too weak to be used for relative flux calibration, as conventionally practiced for RM (Foltz et al. 1981; Peterson et al. 1982). To generate the photometric light curves of I Zw 1, six stars in the same fields were used to perform differential photometry. The radius of the aperture for I Zw 1 was 5$^\prime$$'$1, and that for the background was 8$^\prime$$'$5–17$^\prime$$'$. Specifically, for each exposure, we obtained the instrumental magnitudes of I Zw 1 and the six stars by IRAF. We calculated the differential magnitude between I Zw 1 and the mean of the six stars, and the uncertainties in all of the instrumental magnitudes were propagated to the uncertainty in this differential magnitude. Then, we averaged the differential magnitudes of the three exposures in the same night as the value of that individual night, and calculated a statistical uncertainty from the uncertainty of each exposure by error propagation. In addition, we calculated the scatters between the differential magnitudes of the three exposures as the systematic uncertainty. The two uncertainties are added in quadrature as the final uncertainty of the differential magnitude in each night.
3. Data Analysis and Results

3.1. Light Curves

We use the following method to determine the 5100 Å flux density and the H\(\beta\) flux. The 5100 Å flux is the median flux between 5075 and 5125 Å in the rest frame. The H\(\beta\) flux is obtained by integrating the flux between 4810 and 4910 Å from the continuum-subtracted spectrum, while the continuum underlying the H\(\beta\) line is determined by a linear interpolation between two continuum bands (4740–4790 Å and 5075–5125 Å). The continuum windows are selected to minimize the contamination from other emission lines, such as [O III], Fe II, and He II. In Figure 1, we mark the window for the H\(\beta\) line by the red band and the windows for the continuum by the gray bands. The measurement errors of the light curves come from both Poisson noise and systematic uncertainty. The systematic uncertainty arises from poor weather conditions, slit positioning, telescope tracking, and choice of continuum window. It can be estimated from the standard deviation of the residuals after subtracting a median-filtered, smoothed light curve. Table 1 lists the continuum flux density at 5100 Å and the H\(\beta\) flux. Only 27 epochs are included from the 2014–2015 season, while 39 epochs are available for the 2015–2016 season. The seasonal gap between 2015 March and 2015 June is 120 days. We show the 5100 Å and H\(\beta\) light curves during 2014–2016 in Figures 6(i) and (j), respectively. The large errors of some points from 2015 June 20 to 2015 July 6 are caused by the bad weather during the rainy season at the Lijiang Station.

To improve the sampling of the continuum light curves, we used the V-band photometry data from ASAS-SN (All-Sky Automated Survey for SuperNovae).\(^9\) ASAS-SN is a long-term project aiming to monitor the entire visible sky to a depth of \(V < 17\) mag with a cadence of 2–3 days (Shappee et al. 2014; Kochanek et al. 2017). Between 2014 May and 2016 March, ASAS-SN monitored I Zw 1 with two telescopes: “Brutus,” deployed at the Hawaii station of the Las Cumbres Observatory, and “Cassius,” deployed in Chile. Seventy-three epochs for the 2014–2015 season and 72 epochs for the 2015–2016 season, with enough signal-to-noise ratio (S/N), were adopted here.

We merge the V-band photometry data from Lijiang and ASAS-SN into the 5100 Å light curves by applying a multiplicative scale factor and an additive flux adjustment, which are determined by a Markov Chain Monte Carlo (MCMC) implementation (Li et al. 2014; Du et al. 2015). The combined continuum light curves are shown in Figure 7(i), which contain 136 epochs from the 2014–2015 season and 149 epochs from the 2015–2016 season. By combining ASAS-SN data, the continuum light curve shows an obvious structure for the 2014–2015 season (shown in Figure 7(i)), which corresponds to that in the light curve of H\(\beta\), and the seasonal gap is shortened to 94 days. However, as shown in Figure 7(i), the 5100 Å light curves increase the scatter of the continuum light curve, so we merge only the V-band photometry data from ASAS-SN into the photometry data from Lijiang to obtain the final photometry continuum light curve shown in Figure 2(i). The final photometric continuum light curve contains 109 and 110 epochs from the 2014–2015 and 2015–2016 seasons, respectively. We adopt the photometric continuum light curve to obtain the H\(\beta\) lags in this paper. However, for comparison, we also show the results for the 5100 Å and the combined continuum light curves in Appendix B.

3.2. Variability Characteristics

We use the methods described by Rodríguez-Pascual et al. (1997) to calculate the light-curve characteristics of the continuum and H\(\beta\) emission line. The variability characteristics are given by

\[
F_{\text{var}} = \frac{(\sigma^2 - \langle \Delta F \rangle^2)^{1/2}}{\langle F \rangle},
\]  

Note. \(F_{5100}\) is the flux at \((1+z)\) 5100 Å in the observed frame. (This table is available in its entirety in machine-readable form.)

Table 1: Continuum and H\(\beta\) Fluxes

| JD-2456700+ | \(F_{5100}\) (10\(^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\)) | \(F_{\text{H}\beta}\) (10\(^{-13}\) erg s\(^{-1}\) cm\(^{-2}\)) |
|------------|-----------------|------------------|
| 271.28     | 6.11 ± 0.06     | 2.58 ± 0.02      |
| 274.08     | 6.44 ± 0.07     | 2.75 ± 0.02      |
| 277.27     | 6.40 ± 0.08     | 2.62 ± 0.02      |
| 284.12     | 6.44 ± 0.06     | 2.58 ± 0.02      |
| 286.19     | 6.44 ± 0.06     | 2.64 ± 0.02      |

\(^9\) http://www.astronomy.ohio-state.edu/~assassin/index.shtml

Figure 1. The mean and rms spectra for I Zw 1 from the 2014–2015 season. The gray bands are the continuum windows, and the red band is the integration window for H\(\beta\). The blue line is the narrow-line-subtracted profile, and the red line is the mean of the errors of the individual spectra.
Figure 2. Light curves and results of the correlation analysis using the photometric continuum light curves for I Zw 1. The left panels are the light curves for different seasons. The red lines are the continuum light curves fitted by JAVELIN, while the gray bands are those fitted by MICA. The right panels show the correlation analysis. Panels (c), (g), and (k) show the ICCF results, and panels (d), (h), and (l) show the results for MICA and JAVELIN for seasons 2014–2015, 2015–2016, and 2014–2016, respectively. The blue lines are the cross-correlation functions and the blue histograms are the cross-correlation centroid distributions. The red histograms show the posterior probability of the time lags for JAVELIN, and the gray histograms show the corresponding one for MICA. JAVELIN, MICA, and ICCF produce consistent lags for the same data.
The error of the individual spectra of I Zw 1 is quite good. We also plot the mean of the variation in the light curves of the 5100 Å continuum, the combined continuum, the photometry continuum, and the broad H β line, respectively. Table 2 lists the time lags and the associated uncertainties. The time lags obtained by JAVELIN (red line) and MICA (gray band) are consistent with each other, within uncertainties.

In order to avoid potential biases introduced by seasonal gaps, we analyze the observations from the 2014–2015 and 2015–2016 seasons, as well as that for the whole campaign, separately (Figure 2). Figures 2(a) and (b) show the light curves for the photometric continuum and H β emission line for season 2014–2015. The light curves reconstructed by JAVELIN (red line) and MICA (gray band) are superposed. Figure 2(c) shows the CCF and the cross-correlation centroid distribution (CCCD) for season 2014–2015, and Figure 2(d) shows the posterior distributions of the time lags obtained by JAVELIN (red) and MICA (gray). Figures 2(e)–(h) are the same as Figures 2(a)–(d), but for season 2015–2016, and the results for the entire 2014–2016 season are shown in Figures 2(i)–(l). Table 3 summarizes the time lags determined using the above three methods. They are consistent with each other, within uncertainties.

We detect significant time lags with small uncertainties using the photometric light curves. The H β time lags for the 2015–2016 data have large uncertainties (Figures 2(g) and (h)) because of the small variability amplitude and large flux dispersion of the light curves (see Figures 2(e) and (f)). In principle, JAVELIN and MICA can reconstruct the light curves during the large seasonal gaps, such that, for data for the whole campaign, the lags obtained by JAVELIN and MICA should be more robust than that derived by ICCF. We also find that the lags obtained using JAVELIN and MICA (Figure 2(i)) are more consistent with that obtained by ICCF for the 2014–2015 data (Figure 2(c)). From inspection of the CCF peak value \( r_{\text{max}} \), we adopt \( r_{\text{max}} = 37.2\text{,}4_{\pm}^{+5.5} \) days from the ICCF analysis of the photometric continuum and H β light curves from 2014–2015, and we use this value to calculate the black hole mass below.

### 3.4. Host Galaxy

We use images obtained with the HST to study the host galaxy, in particular its overall morphology, bulge-to-total ratio, and bulge stellar mass. We also need to determine the degree to which the spectroscopically measured optical continuum is contaminated by host galaxy emission. The highest quality HST observations currently available are those obtained with the WFC3 camera on 2013 November 2 (GO-12903, PI: Luis C. Ho). I Zw 1 was observed for 300 s with the F438W filter (395–468 nm) in the UVIS channel and for 147 s
with the F105W filter (901–1204 nm) in the IR channel. An additional short (40 s) F438W exposure was taken to warrant against the saturation of the nucleus in the long exposure. These two filters were purposefully chosen to mimic B and I in the rest frame of I Zw 1, at the same time avoiding contamination from strong emission lines. The large wavelength separation between the two filters also offers the most leverage for constraining the stellar population (Section 5.2).

To better sample the point-spread function (PSF), the long UVIS observation was taken with a three-point linear dither pattern, while the IR observation was taken with the four-point boxy dither pattern. To avoid overheads due to buffer dump, we employed the UVIS2-M1K1C-SUB 1k × 1k subarray for the UVIS channel and the IRSUB512 subarray for the IR channel, which results in a restricted field of view of 40″ × 40″ and 67″ × 67″, respectively.

Because of the sparseness of field stars in the vicinity of I Zw 1, the observations were conducted in GYRO mode, which, unfortunately, led to considerable degradation of the PSF of the dither-combined image generated from the standard data reduction pipeline. Instead, we use the DrizzlePac task AstroDrizzle (v1.1.16) to correct the geometric distortion, align the sub-exposures, perform sky subtraction, remove cosmic rays, and, finally, combine the different exposures. The core of the AGN was severely saturated in the long F438W exposure, and it was replaced with an appropriately scaled version of the 40 s short exposure. Because the PSF of HST is undersampled, we broaden both our science and PSF images by convolving them with a Gaussian kernel so that the PSF can be parametrized with the F105W filter. To extract quantitative measurements of the bulge, we use the program GALFIT (v3.0.5; Peng et al. 2002, 2010) to fit.
two-dimensional surface brightness distributions to the HST images. A crucial ingredient is the PSF, which will have a strong effect on the bright and active nucleus. Unfortunately, no suitably bright star is available to be used as the PSF within the limited field of view of the subarray WFC3 images. Instead, we generated a high-S/N stacked empirical PSF by combining a large number (24 for F105W and 57 for F438W) of bright, isolated, and unsaturated stars observed during the course of other WFC3 programs. Extensive tests, consisting of fits to isolated bright stars, indicate that our stacked empirical PSF is far superior to synthetic PSFs generated from the TinyTim program (Krist & Hook 1999), and it has higher S/Ns than the PSFs of individual stars. The reduced \( \chi^2 \) of the fits are ~3 times larger for the TinyTim synthetic PSF. Comparison of empirical PSFs observed from different programs indicates that the WFC3 PSF does not vary significantly with time (<10%).

We concentrate first on obtaining the best global fit to the deeper F105W image, whose red wavelength is also more sensitive to the host. After much experimentation, we adopt a model with three components: a point source (represented by the PSF) for the nucleus, a bulge parameterized as a Sérsic (1968) function with index \( n \), and an exponential disk (equivalent to a Sérsic function with \( n = 1 \)), with coordinate rotation turned on to fit the spiral arms. We could not obtain a robust solution that considers the faint, bar-like feature, and in the end we did not consider it. We use the \( m = 1 \) Fourier mode of the disk, which is sensitive to lopsidedness, to gauge the degree of global asymmetry of the galaxy (see, e.g., Kim et al. 2008, 2017). The best model (Figure 3(a)) reveals a bulge with \( n = 1.73 \pm 0.06 \), formally but barely below the conventional threshold for pseudo-bulges \( (n < 2) \); Fisher & Drory 2008) and an overall \( B/T = 0.52 \pm 0.04 \). The disk is moderately asymmetric, with Fourier amplitude \( a_1 = 0.11 \pm 0.01 \). As the host is considerably weaker in the F438W image, we fit it by keeping the structural parameters fixed to the values obtained from the F105W model, solving only for the magnitude.

The uncertainties of the decomposition are dominated by PSF mismatch in the nucleus. We estimate the effect of the PSF by generating variants of the empirical PSF by combining different subsets of stars, and then repeating the fit. The final error budget is the quadrature sum of these two contributions.

### 3.5. The R – L Relation

A proper evaluation of the \( R – L \) relation must consider the influence of host galaxy contamination on the luminosity (Kaspi et al. 2000; Bentz et al. 2013). We use the decomposition of the HST images of I Zw 1 to estimate the contribution of the host galaxy within the spectral extraction aperture. The host flux at 5100 Å is transformed from the F438W magnitude with the IRAF task `sphot`, assuming a stellar population template with an age of 5.0 Gyr (Section 4.2), after correcting for redshift \( \Delta z = 0.061 \) and Galactic reddening \( E(B-V) = 0.057 \) mag; Schlafly & Finkbeiner 2011) using the extinction curve of Cardelli et al. (1989).

Table 4 lists the observed total, host galaxy, and AGN fluxes at 5100 Å. With an AGN luminosity of \( L_{5100} = 3.19 \times 10^{44} \) erg s\(^{-1}\), I Zw 1 follows the empirical \( R_{BLR} - L_{5100} \) relation (Figure 4(a)).

| Parameter | Value |
|-----------|-------|
| \( F_{ obs}(5100 \text{ Å}) \) | \( 6.62^{+0.38}_{-0.28} \times 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) |
| \( F_{ gal}(5100 \text{ Å}) \) | \( 1.50^{+0.10}_{-0.09} \times 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) |
| \( F_{ AGN}(5100 \text{ Å}) \) | \( 5.12^{+0.44}_{-0.40} \times 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) |
| \( L_{5100}(AGN) \) | \( 3.19^{+0.27}_{-0.27} \times 10^{44} \) erg s\(^{-1}\) |
| FWHM(mean) | \( 1131^{+30}_{-28} \) km s\(^{-1}\) |
| FWHM(rms) | \( 606^{+28}_{-28} \) km s\(^{-1}\) |
| \( M_\ast \) | \( 9.30^{+0.36}_{-0.35} \times 10^8 \) M\(_\odot\) from the mean spectrum |
| \( \dot{M} \) | \( 2.99^{+0.46}_{-0.44} \times 10^4 \) M\(_\odot\) yr\(^{-1}\) from the rms spectrum |
| \( \dot{\lambda} \) | \( 8.18^{+0.74}_{-0.75} \times 10^2 \) M\(_\odot\) yr\(^{-1}\) from the polarized spectrum |

Note. \( F_{ obs} \) and \( F_{ gal} \) are the observed and host galaxy flux densities at (1 + z) 5100 Å in the observed frame. \( L_{5100} \) is the mean AGN luminosity \( \lambda L_\lambda \) at rest-frame 5100 Å after subtracting the host galaxy and correcting for Galactic extinction.

### 4. Black Hole Mass and Accretion Rate

#### 4.1. Mass

To measure the black hole mass, the velocity of the BLR clouds is measured through the FWHM of the broad emission line (Equation (1)). The narrow H\(_\beta\) component \( (F_{ H\beta}) \) of I Zw 1 is too weak to be decomposed directly by spectral fitting even for the mean spectrum. Thus, we subtract the \( F_N \) from the mean spectrum of the 2014–2015 season assuming \( F_N/F_{ [O \text{ III}] } \approx 0.1 \) (Hu et al. 2012), where \( F_{ [O \text{ III}] } \) is the flux of \([O \text{ III}] \lambda 5007 \) Å. Then, we measure the FWHM directly from the narrow-line-subtracted profile (blue line in Figure 1). The uncertainty is bracketed by assuming that \( F_N/F_{ [O \text{ III}] } \) = 0 and 0.2. Correcting for an instrumental broadening of 500 km s\(^{-1}\) (Hu et al. 2015; Du et al. 2016b), \( V_{\text{FWHM}} \) = \( 1131^{+30}_{-28} \) km s\(^{-1}\) (Table 4). Adopting \( \lambda L_\lambda = 37.2 \) days and \( f_{BLR} = 1 \), Equation (1) yields \( M_\ast = 9.30^{+0.36}_{-0.35} \times 10^8 \) M\(_\odot\). It is known that the observed kinematics of the BLR are generally influenced by inclination effects, which will lead to uncertainties of the virial factor (Krolik 2001; Collin et al. 2006). In principle, \( f_{BLR} \) can be calibrated using the \( M_\ast - \sigma \) relation of inactive galaxies, and the current best estimates of \( f_{BLR} \) are 1.3 ± 0.4 for classical bulges and 0.5 ± 0.2 for pseudo-bulges, when \( f_{BLR} \) is calibrated using FWHM based on mean spectra (Ho & Kim 2014). The host galaxy of I Zw 1 likely contains a pseudo-bulge (Section 5.2). However, the large scatter of the \( M_\ast - \sigma \) relation of pseudo-bulges (Kormendy & Ho 2013) introduces significant uncertainty into the estimate of \( f_{BLR} \). For consistency with our previous work on SEAMBHs (Du et al. 2014, 2015, 2016b), we adopt \( f_{BLR} = 1.0 \) (Netzer & Marziani 2010; Woo et al. 2013). We also estimate the black hole mass from the FWHM of the rms spectrum \( (V_{\text{rms}} = \text{FWHM}) \) = \( 606^{+28}_{-28} \) km s\(^{-1}\) using \( f_{rms} = 1.12 \) (Woo et al. 2015) and obtain \( M_\ast = 2.99^{+0.46}_{-0.48} \times 10^4 \) M\(_\odot\).

Meanwhile, polarized spectra of type 1 AGNs can provide invaluable information for estimating black hole masses. Considering electron scattering in the equatorial plane (Smith et al. 2005), a polarized spectrum is equivalent to a spectrum seen by an observer on the midplane. Thus, polarized spectra can yield more reliable estimates of the black hole mass (Afanasev & Popović 2015; Baldi et al. 2016; Songsheng & Wang 2018). For
equatorial scattering of a BLR with a flattened geometry,

\[ M'_b / M_\odot = f'_b R_{BLR} V_{FWHM}^2 / G \]

\[ = 8.18 \times 10^6 \left( \frac{\tau_{H3}}{37.2 \text{ days}} \right) \left( \frac{V_{FWHM}}{2165 \text{ km s}^{-1}} \right)^2, \tag{6} \]

where the virial factor \( f'_b \approx 0.24 \) (with small uncertainty) and \( V_{FWHM} \) is the FWHM of the broad-line profile in the polarized spectrum (Figure 3 in Songsheng & Wang 2018). Fortunately, a polarized spectrum of I Zw 1 for the H\(_\alpha\) emission line has been taken using the 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Science (L. Popović 2018, private communications).\(^{11}\) We find FWHM\(_{H\alpha}\) = 1983 km s\(^{-1}\) from the polarized spectrum. The relation between the widths of H\(_3\) and H\(_\alpha\) in the polarized spectrum is unclear, but a reasonable assumption is that the same relation is followed as in the total spectrum if (1) both lines are scattered by the same population of electrons, and (2) the regions emitting H\(_3\) and H\(_\alpha\) lines are much smaller than theelectron-scattering region. So, we use the relation FWHM\(_{H\alpha}\) = 1.07 \times 10\(^3\)(FWHM\(_{H\alpha}\)/10\(^3\) km s\(^{-1}\))\(^{0.03}\) from Grenne & Ho (2005), and obtained \( V'_{FWHM} = \text{FWHM}_{H\alpha} = 2165\text{ km s}^{-1} \). This value needs to be tested observationally in the future.

Equation (6) then yields \( M'_b = 8.18 \times 10^6 M_\odot \), which agrees remarkably well with the mass estimates based on the mean spectrum.

### 4.2. Accretion Rates

Photon trapping causes the radiated luminosity of slim disks to saturate (Abramowicz et al. 1988; Wang & Zhou 1999; Mineshige et al. 2000). Under these conditions, the normal Eddington ratio \( L_{bol} / L_{Edd} \) is very insensitive to the accretion rate and mainly depends on the black hole mass, where \( L_{Edd} \) is the Eddington luminosity and \( L_{bol} \) is the bolometric luminosity. This renders \( L_{bol} / L_{Edd} \) unsuitable to indicate the accretion rate of SEAMBHs. As derived from the self-similar solution of the slim disk, the photon-trapping radius is \( R_{trap} \approx 72(\dot{M}/80)R_g \),

where \( R_g = GM_c / c^2 \), and the radius emitting optical (5100 Å) photons is \( R_{bol} \approx 4.3 \times 10^3 m_v^{-1/3} R_g \) (Wang & Zhou 1999), which is much larger than \( R_{trap} \). So, optical photons can escape freely, and hence accretion rates can be reliably estimated from the formalism of the standard accretion disk model (Shakura & Sunyaev 1973). The dimensionless accretion rate is defined as \( \dot{M} / L_{bol} \), with \( M_c \) the mass accretion rate. Given the 5100 Å luminosity and the black hole mass, \( \dot{M} = 20.1(\ell_{dd} / \cos i)^{3/2} m_v^{-2} \), where \( \ell_{dd} = L_{bol} / 10^{45} \text{ erg s}^{-1} \), \( m_v = M_c / 10^6 M_\odot \), and \( i \) is the inclination angle between the line of sight and the accretion disk (Du et al. 2015). For I Zw 1, we have

\[ \dot{M} / L_{bol} \approx 203.9 \left( \frac{\ell_{dd}}{3.19} \right)^{3/2} \left( \frac{m_v}{0.93} \right)^{-2}, \tag{7} \]

yielding \( \dot{M} / L_{bol} \approx 203.9 \times 10^{3.9} \), for \( \cos i = 0.75 \). As discussed in Du et al. (2016b), \( \cos i = 0.75 \) is a reasonable mean value for Type 1 AGNs. If we take \( \Delta \log \cos i \lesssim 0.1 \), then the uncertainty on \( \dot{M} / L_{bol} \) due to \( i \) will be \( \Delta \log \dot{M} / L_{bol} = 1.5 \Delta \log \cos i \lesssim 0.15 \). The inclination also has an insignificant effect on the observed width of the broad emission lines \( V'_{FWHM} \). If we know the Keplerian velocity \( V_c \) and the height \( H_{BLR} \) of the flattened BLR, by the zeroth-order approximation, \( V'_{FWHM} \approx (H_{BLR}/R)^2 \times \sin^2 i / V_c \). Through detailed modeling of RM data, Li et al. (2013) and PacoMaco et al. (2014) suggested \( H_{BLR} / R \approx 1 \), thus \( \sin i \approx H_{BLR} / R \), which implies that the inclination has an insignificant influence on \( V'_{FWHM} \), hence \( M_c \) and then \( \dot{M} \). The high dimensionless accretion rate indicates that I Zw 1 is a SEAMBH. Note that the accretion rate could be even higher by a factor of \( \sim 10 \) than the present, if the FWHM obtained from the rms spectrum is used in the calculation.

### 5. Discussion

#### 5.1. The R–L Relation

There is growing evidence that the empirical \( R_{BLR} - L_{bol} \) relation does not apply to SEAMBHs. For a given luminosity, SEAMBHs tend to have a shorter H\(_3\) lag, suggesting that the size of the BLR is related not only to luminosity but also to the accretion rate (Du et al. 2015, 2016b, 2018). According to the unified scaling relation for sub- and super-Eddington AGNs.

\[ \text{Figure 4. The (a) } R_{BLR} - L_{bol} \text{ and (b) } \Delta R_{BLR} - \dot{M} \text{ plots, in which the open and solid points are from Bentz et al. (2013) and Du et al. (2018), respectively. The black dashed line is the classical } R - L \text{ relation (Bentz et al. 2013). The red star is I Zw 1, and the blue triangle is Mrk 493 from Hu et al. (2015); both are outliers in panel (b). In panel (b), the red dashed line is } \Delta R_{BLR} = 0. I Zw 1 \text{ and Mrk 493 have (} \Delta R_{BLR} - \log \dot{M} \text{) } = (-0.22, 2.31), (-0.02, 1.88), \text{ respectively.} \]
suggested by Du et al. (2016b),

\[ R_{\text{BLR}} = 29.6 \, \ell_{5100}^{0.56} \text{minutes} \left[ \frac{M}{11.2} \right]^{-0.52} \, \text{lt-day}, \]  

I Zw 1 is predicted to have an Hβ delay of 12.5 days, which is much shorter than our measured value of 37.2 days. Unlike other SEAMBHs, I Zw 1 actually follows the standard \( R_{\text{BLR}} - L_{5100} \) relation and does not show an obvious shortened Hβ lag (Figure 4(a)). Defining the deviation \( \Delta R_{\text{BLR}} = \log \left( R_{\text{BLR}} / R_{\text{L}} \right) \), where \( R_{\text{L}} \) is given by the empirical \( R_{\text{BLR}} - L_{5100} \) relation, Figure 4(b) plots \( \Delta R_{\text{BLR}} \) versus \( \ell \). I Zw 1 deviates from the trend defined by most SEAMBHs. So does Mrk 493. The reasons for these outliers are unclear. One possibility is that some lags are too short to detect, given the current observation cadence. Within the SEAMBH framework described by Wang et al. (2014) and Du et al. (2018), there are two BLRs: a normal one that is unshadowed, and another shadowed by the inner part of the disk and much closer to the central black hole. The emissivity-weighted gas distribution yields two peaks in the transfer function, corresponding to the unshadowed and shadowed BLRs, respectively. Such a two-region BLR scenario is supported by the recent modeling of the observed RM data in Mrk 142 by Li et al. (2018), who constructed flexible one-region and two-region models that included the spatial distribution and anisotropic emissivity of BLR clouds. They found that the two-region model is preferable to the one-region model. However, the observed Hβ lag depends on the data quality, especially the cadence. For example, low cadence will smooth the light curves and yield a single broad peak in the CCF, although there are two peaks in the transfer function. To measure the potential shorter lag, campaigns with higher cadence than the present are being planned for getting detailed BLRs of I Zw 1 and Mrk 493, as done with Mrk 142.

5.2. Black Hole and Bulge Stellar Masses

The GALFIT decomposition of the HST images of I Zw 1 yields a bulge magnitude of 17.23 ± 0.04 mag in F438W and 14.07 ± 0.07 mag in F105W. We apply K-correction to convert the HST-based magnitudes to rest-frame magnitudes in \( B \) and \( I \). We generate a series of template spectra with ages spanning 1 to 12 Gyr, adopting Bruzual & Charlot (2003) models with solar metallicity, a Chabrier (2003) stellar initial mass function, and an exponentially decreasing star formation history with a star formation timescale of 0.6 Gyr. After accounting for Galactic extinction and redshift, we convolve the spectra with the response functions of the HST filters and generate synthetic F438W and F105W magnitudes. The observed bulge color of F438W − F105W = 3.16 ± 0.08 mag is best matched with a stellar population of age 5.0±0.5 Gyr, resulting in rest-frame \( M_B = -22.70 ± 0.07 \) mag and \( B - I = 1.96 ± 0.09 \) mag. From Table 4 of Bell & de Jong (2001), we derived \( M_{\text{bulge}} = 10^{10.18±0.09} M_\odot \), assuming solar metallicity and a Salpeter (1955) initial mass function. A Chabrier initial mass function gives 45% less mass (Longhetti & Saracco 2009), and therefore, \( M_{\text{bulge}} = 10^{10.92±0.07} M_\odot \).

For \( M = 10^{9.97} M_\odot \), \( M/M_{\text{bulge}} \approx 10^{-4} \), which is lower by a factor of ~50 than the value inferred from the \( M - M_{\text{bulge}} \) relation for classical bulges and elliptical galaxies, but lies within the large scatter and lower ratios found for pseudo-bulges (Kormendy & Ho 2013). I Zw 1 very likely hosts a pseudo-bulge, in view of its relatively low Sérsic index of \( n = 1.73 ± 0.06 \) (Fisher & Drory 2008) and evidence for recent (see discussion above) and ongoing (Scharwächter et al. 2007) nuclear star formation.

6. Summary

The first campaign for I Zw 1 had been performed by the SEAMBH project during 2014–2016. The main conclusions are as follows.

1. Applying the ICCF centroid method for the 2014–2015 data, the Hβ time lag is \( \tau_{\text{Hβ}} = 37.2^{+4.5}_{-4.3} \) days, and it follows the empirical \( R_{\text{BLR}} - L_{5100} \) relationship.

2. Using the total mean spectra, we calculate a black hole mass of \( M_\bullet = 9.30^{+0.26}_{-0.18} \times 10^6 \, M_\odot \) and an accretion rate of \( 203.9^{+61.0}_{-65.8} L_{\text{Edd}} c^{-2} \). From the rms spectrum, we estimate \( M_\bullet = 2.99^{+0.46}_{-0.43} \times 10^6 \, M_\odot \), whereas the polarized spectrum yields \( M_\bullet = 8.18^{+1.74}_{-1.55} \times 10^5 \, M_\odot \).

3. We derive the stellar mass for the bulge of the host galaxy from detailed decomposition of HST images. We find a mass ratio of \( M_\ast/M_{\text{bulge}} \approx 10^{-4} \), much lower than that for nearby inactive classical bulges and elliptical galaxies.

I Zw 1 is famous for its strong and narrow Fe II lines; however, the current data do not allow us to successfully measure a lag for Fe II. We are in the process of scheduling a new monitoring campaign with improved cadence and homogeneity in observations more favorable for detecting Fe II lags.

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Appendix A

Light Curve of the Comparison Star

In order to check the stability of the comparison star during the campaign, we obtain its photometric light curve using five stars in the same field to perform differential photometry. The light curve of the comparison star is shown in Figure 5. The standard deviation is 1.9%, demonstrating that the comparison star does not vary significantly.
Appendix B
Light Curves and Hβ Lags

Figures 6 and 7 show the results of the correlation analysis using the 5100 Å and combined continuum light curves. For the 2014–2015 data, the Hβ time lag cannot be constrained well solely using the 5100 Å light curves. As shown in Figures 6(c) and (d), the CCF is very spiky and the posterior distributions of the time lags obtained by JAVELIN and MICA are not well defined. This may be caused by the short duration and the large scatter of the continuum light curves. As shown in Tables 3 and 5, the uncertainty of the time lags derived using only the photometry continuum light curves is smaller than that using the combined continuum light curves.

In Figure 8, we show the ASAS-SN light curve of I Zw 1 from 2012 to the end of 2018. Generally, the source was less variable in those 7 yr except for the period from 2014-07 to 2016-01. During the whole period, the variability of the continuum flux is $F_{\text{var}}(\%) = 0.63 \pm 0.02$, which is much smaller than that of the 2014–2016 period. We were lucky in this SEAMBH campaign and captured the largest variations in this period. Figure 8 shows that it is less variable again after the present campaign, which implies that we may need a longer waiting for sharp variations. Cadence higher than 2–3 days is also necessary for more details of the BLR structure. On the other hand, the long-term stability of I Zw 1 supports SEAMBHs as cosmic candles for cosmology (Wang et al. 2013, 2014; Cai et al. 2018).

Figure 5. The photometry light curves for the comparison star of I Zw 1. The solid line marks the average value, and the dashed lines mark the $\pm 1\sigma$ standard deviation.
Figure 6. Light curves and results of the correlation analysis using the 5100 Å continuum light curves for I Zw 1 (same as Figure 2).
Figure 7. Light curves and results of the correlation analysis using the combined continuum light curves for I Zw 1 (same as Figure 2).
Figure 8. The 7 yr V-band light curves of I Zw 1 monitored by ASAS-SN. It shows that I Zw 1 is quite stable over the long term. This makes it difficult to capture the reverberation of the Hβ line.

Table 5
Results of Correlation Analysis

| Parameter  | 2014–2015 | 2015–2016 | 2014–2016 |
|------------|-----------|-----------|-----------|
|             | Observed  | Rest-frame | Observed  | Rest-frame | Observed  | Rest-frame |
| Hβ versus F_{5100} |           |           |           |           |           |           |
| \(r_{\text{max}}\) | ...       | ...       | 0.72      | 0.72      | 0.74      | 0.74      |
| \(\tau_{\text{cent}}\) (days) | 73.3^{+11.7}_{-14.8} | 69.1^{+11.0}_{-13.9} | 61.9^{+18.2}_{-16.7} | 58.3^{+18.2}_{-17.2} | 65.2^{+18.9}_{-20.0} | 61.4^{+16.5}_{-16.6} |
| \(\tau_{\text{peak}}\) (days) | 87.7^{+8.9}_{-20.4} | 82.7^{+8.4}_{-19.2} | 57.9^{+35.1}_{-24.0} | 54.6^{+22.6}_{-22.6} | 64.0^{+23.1}_{-20.0} | 60.3^{+18.8}_{-17.4} |
| \(\tau_{\text{JAVELIN}}\) (days) | 78.0^{+7.4}_{-12.6} | 73.5^{+7.6}_{-10.4} | 59.1^{+7.9}_{-10.4} | 55.7^{+8.6}_{-10.4} | 64.0^{+7.4}_{-10.4} | 60.3^{+5.1}_{-12.1} |
| \(\tau_{\text{MICA}}\) (days) | 66.2^{+34.9}_{-34.9} | 62.4^{+32.9}_{-32.9} | 59.9^{+12.5}_{-12.5} | 56.5^{+11.8}_{-11.8} | 72.1^{+28.9}_{-28.9} | 67.9^{+22.2}_{-22.2} |
| Hβ versus F_{\text{combine}} |           |           |           |           |           |           |
| \(r_{\text{max}}\) | 0.86      | 0.86      | 0.75      | 0.75      | 0.87      | 0.87      |
| \(\tau_{\text{cent}}\) (days) | 44.1^{+5.1}_{-3.5} | 41.6^{+4.8}_{-5.2} | 48.9^{+5.0}_{-10.4} | 46.1^{+4.4}_{-9.4} | 54.2^{+5.0}_{-9.4} | 51.4^{+4.6}_{-3.9} |
| \(\tau_{\text{peak}}\) (days) | 39.3^{+2.7}_{-1.0} | 37.6^{+2.4}_{-1.3} | 49.2^{+2.8}_{-14.4} | 46.4^{+5.6}_{-13.6} | 57.4^{+7.0}_{-13.1} | 54.1^{+6.6}_{-12.4} |
| \(\tau_{\text{JAVELIN}}\) (days) | 33.1^{+6.5}_{-1.5} | 31.2^{+6.4}_{-1.4} | 54.0^{+5.4}_{-3.0} | 50.9^{+5.8}_{-2.8} | 57.9^{+5.9}_{-4.5} | 54.6^{+6.0}_{-6.1} |
| \(\tau_{\text{MICA}}\) (days) | 45.5^{+22.8}_{-22.8} | 42.9^{+21.5}_{-21.5} | 53.6^{+10.5}_{-10.5} | 50.5^{+7.9}_{-9.9} | 42.2^{+2.7}_{-2.7} | 39.8^{+2.5}_{-2.5} |

Note. \(\tau_{\text{cent}}\) and \(\tau_{\text{peak}}\) are lags from ICCF analysis with the corresponding correlation coefficient \((r_{\text{max}})\), while \(\tau_{\text{JAVELIN}}\) is the lag for JAVELIN and \(\tau_{\text{MICA}}\) is the lag for MICA.

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