High-resolution ALMA observations of SDP.81. I. The innermost mass profile of the lensing elliptical galaxy probed by 30 milli-arcsecond images

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Abstract

We report a detailed modeling of a mass profile of a $z = 0.2999$ massive elliptical galaxy using 30 milli-arcsecond resolution 1-mm Atacama Large Millimeter/submillimeter Array (ALMA) images of the galaxy–galaxy lensing system SDP.81. The detailed morphology of the lensed multiple images of the $z = 3.042$ infrared-luminous galaxy, which is found to consist of tens of $< 100$-pc-sized star-forming clumps embedded in a $\sim 2$ kpc disk, are well reproduced by a lensing galaxy modeled by an isothermal ellipsoid with a 400 pc core. The core radius is consistent with that of the visible stellar light, and the mass-to-light ratio of $\sim 2 L_\odot^{-1}$ is comparable to the locally measured value, suggesting that the inner 1 kpc region is dominated by luminous matter. The position of the predicted mass centroid is consistent to within $\sim 30$ mas with a non-thermal source detected with ALMA, which likely traces an active galactic nucleus of the foreground elliptical galaxy. While the black hole mass and the core radius of the elliptical galaxy are degenerate, a point source mass of $> 3 \times 10^8 M_\odot$ mimicking a supermassive black hole is required to explain the non-detection of a central image of the background galaxy. The required mass is consistent with the prediction from the well-known correlation between black hole mass and host velocity dispersion. Our analysis demonstrates the power of high resolution imaging of strong gravitational lensing for studying the innermost mass profile and the central supermassive black hole of distant elliptical galaxies.

Key words: black hole physics — gravitational lensing: strong — galaxies: individual (H-ATLAS J090311.6+003906) — galaxies: structure — submillimeter: galaxies

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1 Introduction

Galaxy–galaxy lensing occurs ubiquitously in the observable universe. Magnified images from gravitational lensing allow us to understand the detailed mass structure of the intervening galaxy as well as the background source structure (e.g., Koopmans 2005; Inoue & Chiba 2005; Vegetti et al. 2012; Hezaveh 2013a; Hezaveh et al. 2013b; Hezaveh 2014). Furthermore, a detection or absence of a central lensed image offers a unique opportunity to map the innermost mass distribution of the lensing galaxy and to directly measure the mass of the central supermassive black hole (SMBH, Mao et al. 2001; Winn et al. 2004; Inada et al. 2008). Precise mass modeling requires sensitive, extinction-free, and extremely high resolution imaging toward the very center of a lensing galaxy (Hezaveh et al. 2015). This is now possible with long baseline capabilities offered by the Atacama Large Millimeter/submillimeter Array (ALMA). Here we present a detailed modeling of a mass resolution 1-mm images obtained at ALMA.

SDP.81 is a gravitationally lensed $z = 3.042$ galaxy discovered in the Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS). The characteristic features (“Einstein ring”) are evident in the 2″ resolution interferometric maps (Negrello et al. 2010; Omont et al. 2013; Bussmann et al. 2013) and the Hubble Space Telescope (HST) image (Negrello et al. 2014; Dye et al. 2014), indicating strong magnification. Carbon Monoxide (CO) and water (H$_2$O) emission were successfully detected from the background galaxy (Omont et al. 2013). The foreground elliptical galaxy is identified in the Sloan Digital Sky Survey (SDSS) as SDSS J090311.57+003906.5 (hereafter SDSS J0903) with a spectroscopic redshift of $z = 0.2999 \pm 0.0002$ (Negrello et al. 2014). We hereafter refer to the foreground and background galaxies as SDSS J0903 and SDP.81, respectively. Detailed discussion on the spatial/kinematic structure and the star-formation activity in SDP.81 will be presented in a subsequent paper (Paper II; Hatsukade et al. 2015).

Throughout this paper, we assume a flat universe with $\Omega_m = 0.26$, $\Omega_k = 0.74$, and $H_0 = 72 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$. The angular scale of 1″ corresponds to 4.36 kpc at the lens redshift $z_l = 0.2999$ and 7.78 kpc at source redshift $z_s = 3.042$.

2 Data

2.1 ALMA observations and images

The ALMA data at wavelengths of 1.0, 1.3 and 2.0 mm were obtained during the long baseline campaign of Science Verification (ALMA Partnership 2015b). The resulting spatial resolution achieved at 1.0, 1.3 and 2.0 mm are $23 \times 31 \, \text{mas}$ (PA = 15°), $30 \times 39 \, \text{mas}$ (PA = 20°) and $54 \times 60 \, \text{mas}$ (PA = 18°), with r.m.s. noise level of 10, 10, and 9 \mu\text{Jy beam}^{-1}, respectively. The CO (5–4), (8–7) and (10–9) images were also taken simultaneously in the 2.0, 1.3 and 1.0 mm bands, respectively. The CO images are $uv$-tapered to $\simeq 170 \, \text{mas}$ in order to increase the sensitivity to extended structure. Details of the observations are given in ALMA Partnership (2015a) and ALMA Partnership (2015b).

A three-color image composed from the 1.0 and 1.3 mm data are shown in figure 1a. The quadruple images of SDP.81 are clearly resolved, three of which are bridged by a 3″-long arc. The arcs consist of four bright knots connected by thin smooth filaments. The grainy clumps seen around the arcs are not coherent among the different frequency bands (figure 1a), and thus they are likely to be artifacts due to phase calibration residuals. On the other hand, we find fainter, but significant knots embedded in the arcs that are consistent in all different waveband images. These are real features that are likely tracing the internal substructures of SDP.81. A central point source bracketed by the long and short arcs is not resolved with the Band 7 beam and has a 1.0–2.0 mm power-law spectral index of $\alpha = -0.3 \pm 0.7$ (ALMA Partnership 2015a). The extrapolated flux at 20 cm is consistent with that of the cataloged radio source FIRST J090311.5+003906 ($S_{20\text{cm}} = 1.21 \pm 0.16 \, \text{mJy beam}^{-1}$, Becker et al. 1995). The power-law spectral index from 1.0 mm to 20 cm is $\alpha = -0.64 \pm 0.01$ (see inset of figure 1b), which is consistent with the spectral index measured for 1.0–2.0 mm. If the non-thermal emission arises from SDP.81, it should also dominate the emission from the arcs. However, the observed spectral index of the arc is positive (typically $\alpha \gtrsim 2$), meaning that dust emission is the better model to explain the emission characteristics of the arc ALMA Partnership (2015a). Furthermore, no molecular lines of CO and H$_2$O at $z = 3.042$ are found at the position. It is therefore likely that the non-thermal emission arises from an Active Galactic Nucleus (AGN) of SDSS J0903.

2.2 Hubble images

We retrieve the archival HST image (proposal ID: 12194, Negrello et al. 2014) taken with the Wide Field Camera 3 (WFC3) at 1.6 \mu\text{m} (F160W, H band). The point spread function (PSF) is 151 mas in FWHM. We calibrate the coordinates of the WFC3 image using the catalog data from the SDSS Data Release 12. We use 46 SDSS objects located in the WFC3 image to derive the astrometric fit using IRAF. The r.m.s. errors of the fit are 85 mas in right ascension and 100 mas in declination. The nominal center of SDSS J0903 matches the position of the central non-thermal source in the ALMA images within 15 mas.

We use the GALFIT software (Version 3.0.5, Peng et al. 2002).
Table 1. Lens model parameters.

| Parameter | Value |
|-----------|-------|
| $x_a$ | $6.22_{-0.32}^{+0.22}$ |
| $y_a$ | $5.4_{-0.22}^{+0.22}$ |
| $\sigma_v^e$ | $265_{-10}^{+10}$ |
| $c$ | $0.14_{-0.07}^{+0.07}$ |
| $\theta_e$ | $11 \pm 13$ |
| $\gamma$ | $48_{-28}^{+28}$ |
| $r_{core}$ | $4.0_{-1.2}^{+1.2}$ |
| $\theta_0^*$ | $3.2_{-2.3}^{+2.3}$ |
| $\delta$ | $3.0_{-1.2}^{+1.2}$ |
| $e$ | $41 \pm 22$ |
| $\epsilon$ | $2.4_{-1.7}^{+1.7}$ |
| $\theta_0^\delta$ | $35_{-13}^{+13}$ |

The errors represent 68% confidence intervals estimated from a Markov-chain Monte Carlo simulation. (a) The central position of an isothermal ellipsoid in units of mas, relative to the position of the non-thermal source at $9^{h}3^{m}11^{s}.573$, $+0^{\circ}39^{\prime}6^{\prime\prime}.54$, respectively. (b) Velocity dispersion of the isothermal ellipsoid (km s$^{-1}$). (c) Ellipticity and its position angle (deg). (d) core radius of the isothermal ellipsoid (mas). (e) external shear and its position angle (deg). (f) third-order external perturbation and its position angle (deg). (g) multipole perturbation with $(m, n) = (4, 2)$ and its position angle (deg). See Oguri (2010) for the definitions of the parameters.

Fig. 1. (a) ALMA 1.0–1.3 mm with HST/F160W where the stellar light of SDSS J0903 is subtracted (contours). Two sets of counter-images of stellar peaks are indicated by filled and open stars, respectively. The synthesized beam size is indicated at the bottom-left corner. The origin of the image is taken at the position of a central compact non-thermal source. (b) The ALMA 1.0 mm image. Upper inset shows CO (5–4) spectra at the positions of the source A (upper) and E (lower). Bottom inset shows the spectral energy distribution of the central compact source, which is well fitted by a power-law function with a spectral index of $-0.64$ (solid line), suggesting the synchrotron emission. (c) The modeled brightness distribution on the image plane. The image is smoothed by a Gaussian with FWHM = 23 mas. The inner and outer ellipses represent radial and tangential critical curves, respectively. (d) The modeled brightness distribution on the source plane, which is 0.5" on a side. The star represents the source position of the stellar peaks denoted as filled stars in (a). The position of this panel is indicated as a dotted square in (c). The solid curves represent the caustics. The scale bar at the bottom-left corner shows a physical scale of 200 pc at $z = 3.042$. 
Fig. 2. Correlation matrix of the lens parameters computed by a Markov-chain Monte Carlo simulation. The probability distribution of two parameters are indicated by a greyscale map with contours of $1\sigma$, $2\sigma$ and $3\sigma$. The diagonal panels show the probability distribution of each parameter in which the rest parameters are marginalized over. The asterisk in the $x$–$y$ correlation plot marks the position of the AGN at the center of SDSS J0903.

Following the procedure adopted by Negrello et al. (2014), two Sérsic profiles are simultaneously fitted to the HST image. As a result, the radial profile of SDSS J0903 is decomposed into a brighter ($H$-band absolute AB magnitude of $M_H = 17.56$) elliptical with a Sérsic index of $n_s = 4.42$ and a fainter ($M_H = 18.69$) exponential disk with $n_s = 1.03$. Although our total flux is $1.2 \times$ higher, this is consistent with the model presented by Negrello et al. (2014). The residual image shown in figure 1 clearly exhibits the stellar arcs which are significantly ($> 100$ mas) offset from the 1-mm ALMA arcs (see Paper II for the interpretation).

3 Gravitational lens model

3.1 Methods and results

We use the GLAFIC software (Oguri 2010)\(^2\) to reproduce the lensed image using an isothermal ellipsoid with a flat core. The choice of an isothermal ellipsoid is supported by the fact that the radial density profile of SDSS J0903 is consistent with $\rho(r) \propto r^{-2}$ (Dye et al. 2014; Rybak et al. 2015), which is the profile expected for an isothermal ellipsoid. The structure of SDP.81 is, however, too complex to be accounted for by a single isothermal ellipsoid alone. We examine the SDSS cluster catalog of Oguri (2014) and find a cluster of galaxies at $z = 0.306$ with the richness of $\sim 21$ and located $\sim 2'$ away

\^2\url{http://www.slac.stanford.edu/~Eoguri/glafic/}
The knots A are quadruple lensed images of a single source, whereas those reported by Omont et al. (2013) and ALMA Partnership (2015a), respectively. This method allows us to predict that the enclosed mass predicted by this model, and we find that the model is consistent with the brightness peak of the stellar distribution within the 1σ astrometric uncertainty of HST (≈100 mas), but also with the location of the candidate AGN, i.e., (x, y) = (0, 0), to within ≃ 20 mas, while the uncertainties of the 10 knots which are close to the critical curve and/or possibly suffering from blending are set to 100–200 mas. The uncertainties of the four HST images are set to 130–200 mas.

The best-fit parameters of the mass model are listed in table 1, where the 1σ confidence intervals are computed by Marcov-chain Monte Carlo simulations as shown in figure 2. Note that the core radius (r_c,σ) and velocity dispersion (σ_v) of the isothermal ellipsoid are highly degenerate. The central position of the isothermal ellipsoid is not only consistent with the brightness peak of the stellar distribution but also with the position of the candidate AGN, i.e., (x, y) = (0, 0), to within ≃ 30 mas (1σ). This suggests that the AGN is indeed located at the bottom (innermost <100-pc) of the potential well of SDSS J0903. The best-fit parameters of the isothermal ellipsoid and external shear are in good agreement with those independently obtained using the same ALMA images (Rybak et al. 2015; Dye et al. 2015) and the HST images (Dye et al. 2014) at 1σ level.

The crosses in figure 1b mark the positions of the counter-images predicted by this model, and we find that the model is qualitatively consistent with the peak positions of the 1.0-mm brightness distribution (χ^2 = 3.45). Figures 1c and 1d show the predicted brightness distributions on the image and source planes, respectively. The observed images are reproduced by 35 ∼100-pc-sized knots embedded in an extended disk. While the uncertainty is relatively large, the total magnification factor is expected to be µ_k ≃ 22. This is consistent with the value obtained by Rybak et al. (2015) (µ_k = 17.6 ± 0.4 for total, µ_k = 25.2 ± 2.6 for a central star-forming disk), while it is ≃ 2× higher than the value previously obtained with the SMA (µ_k ≃ 11, Busmann et al. 2013). This is likely because, as suggested by Rybak et al. (2015), the ALMA image allows us to identify more compact structures close to the caustics, resulting in higher magnifications than those obtained previously.

### 3.2 Mass profile of SDSS J0903

In figure 3, we show the surface mass profile of the gravitational lens model normalized by a cosmological critical density for a source redshift z_s = 3.042 (i.e., convergence κ(r)) and a radial

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1 We use GLAFIC mass models claus5 and claus2 with (n, n) = (4, 2) for the quadrupole perturbation (equation 13 of Oguri 2010). The central positions of the perturbation components are fixed to that of the isothermal ellipsoid.

4 The GLAFIC model of SDP81 is available at http://www.ioa.s.u-tokyo.ac.jp/~Eytamura/SDP81/.

5 Note that the ellipticity ϵ used in Rybak et al. (2015) is related by ϵ = 1 − q.
profile of the 1.6-μm stellar light obtained by the HST/WFC3 F160W imaging observations. The critical density is $\Sigma_{\text{crit}} = 4.3 \times 10^3 M_\odot \text{kpc}^{-2}$, and the stellar surface mass is scaled using a fiducial mass-to-light ratio of $2 M_\odot L_\odot^{-1}$ at $\lambda_{\text{rest}} \simeq 1 \mu$m (e.g., Bell et al. 2003), which is a typical value for local massive ellipticals. Because the stellar profile is lowpass-filtered by the PSF of HST (151 mas, see the dotted curve), the profile is only reliable at $r \gtrsim 0.1''$. It is evident that there is a knee in the stellar profile at a characteristic radius of $\simeq 0.15''$.

In figure 3, we also show the lensing mass profile smoothed by the HST PSF. The knee position and the amplitude of the profile are in agreement with the lens model. Although the derived core ($r_{\text{core}} = 48^{+169}_{-28}$ mas, which corresponds to a core diameter of $\sim 400$ pc) is slightly smaller than the stellar core ($r \simeq 150$ mas), the two core radii are consistent to within the 1σ uncertainty. Furthermore, the position angle of the isothermal ellipse ($\theta_c = 11 \pm 13^\circ$) is consistent with that of the stellar profile ($10 \pm 1^\circ$, Dye et al. 2014), suggesting that the baryonic matter, traced by the stellar light, dominates the mass in the inner 1-kpc region of the galaxy. At larger radii ($\gtrsim 3$ kpc), however, the stellar light falls below the model surface density ($\kappa(r) \propto r^{-1}$), which can be interpreted as the presence of dark matter in the outer parts of SDSS J0903.

4 Discussions and conclusions

The non-detection of the central ‘odd’ image of SDP.81 in the deep ALMA images rules out a top-flat plateau in the gravitational potential, but instead requires the presence of a steep (or cuspy) radial profile in the innermost potential distribution. A SMBH can make the central potential more cuspy even if the stellar mass distribution is top-flat as suggested from the WFC3 radial profile. As a consequence, this can erase the central image if the black hole is massive enough to fully perturb the core potential. Since there is a clear sign of the presence of an AGN at the center of SDSS J0903, we add a point source mimicking the SMBH to the lens model in order to investigate how the SMBH affects the flux of the central image. A point mass with $M_{\text{BH}} = 10^7$ to $10^9 M_\odot$ is placed at the position of the AGN and $r_{\text{core}}$ is fixed to the stellar core radius of 150 mas, while the rest are treated as free parameters ($N_{\text{DOF}} = 89$).

Figure 4 shows $S_{\text{central}}/S_{\text{tot}}$ (i.e. the ratio between the flux from the central image to all of the counter-images) as a function of $M_{\text{BH}}$. The fit to the model is generally good ($\chi^2 \simeq 3.7$) in the range of $10^7 < M_{\text{BH}}/M_\odot < 10^9$. The ratio is insensitive to the black hole mass if it is less than $1 \times 10^8 M_\odot$, but the central image rapidly dims as the black hole mass is higher than $2 \times 10^9 M_\odot$. The horizontal dotted line shows the 3σ upper limit of the 1.0-mm image on the flux ratio. The dashed line is the upper limit of the ALMA 1.0-mm image on the flux ratio. The solid line is the upper limit of the ALMA 1.0-mm image on the flux ratio. The solid line with circles is $S_{\text{central}}/S_{\text{tot}}$ from the ALMA Partnership 2015a, suggesting that the ALMA non-detection places a constraint to the black hole mass of $M_{\text{BH}} > 3 \times 10^8 M_\odot$. Note that if we adopt $r_{\text{core}} = 48$ mas, the limit is slightly relaxed to $M_{\text{BH}} > 1 \times 10^8 M_\odot$.

A black hole mass can independently be estimated from the well-known correlation between black hole mass and the velocity dispersion of the bulge (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000). The black hole estimated from the velocity dispersion of the lens ($\sigma_v = 265^{+12}_{-4}$ km s$^{-1}$, Table 1) and using the local correlation (Kormendy & Ho 2013) is $M_{\text{BH}} = (1 \pm 0.1) \times 10^9 M_\odot$, which is consistent with the lower limit derived above. It will difficult to detect the central image of SDP.81 even in future ALMA observations if $M_{\text{BH}} \sim 1 \times 10^9 M_\odot$. We demonstrate in this work that the detailed gravitational lens modeling using sensitive, high-resolution imaging with ALMA is capable of constraining the central $\lesssim 1$ kpc mass profile and the black hole mass, which will help us understand the co-evolution of the SMBHs and the host galaxies through, for example, SMBH scouring (Hezaveh et al. 2015).

Finally, we note that a similar conclusion on the mass of the SMBH ($\log M_{\text{BH}}/M_\odot > 8.4$) was made by a recent analysis by Wong et al. (2015), where they used an independent code GLEE (Suyu & Halkola 2010) and different sets of multiple images from the ALMA images tapered to $\sim 170$ mas to construct a lens model. Nevertheless, we prefer to use the full resolution ALMA images (up to 23 mas), which allows us to (1) accurately model higher-order perturbations, and to (2) robustly identify multiple features in the images and construct a reliable lens model.

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References

ALMA Partnership, Vlahakis, C., Hunter, T. R., et al. 2015, ApJL, in press (arXiv:1503.02652)
ALMA Partnership, Fomalont, E. et al. 2015, ApJL, submitted
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Bussmann, R. S., Pérez-Fournon, I., Amber, S., et al. 2013, ApJ, 779, 25
Dye, S., Negrello, M., Hopwood, R., et al. 2014, MNRAS, 440, 2013
Dye, S., Furlanetto, C., Swinbank, A. M., et al. 2015, MNRAS, submitted (arXiv:1503.08720)
Eales, S., Dunne, L., Clements, D., et al. 2010, PASP, 122, 499
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L9
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13
Hatsukade, B., Tamura, Y., Iono, D., et al. 2015, PASJ, submitted (arXiv:1503.07997)
Hezaveh, Y. D., Dalal, N., Holder, G., et al. 2013, ApJ, 767, 9
Hezaveh, Y. D., Marrone, D. P., Fassnacht, C. D., et al. 2013, ApJ, 767, 132
Hezaveh, Y. D. 2014, ApJL, 791, L41
Hezaveh, Y. D., Marshall, P. J., & Blandford, R. D. 2015, ApJL, 799, L22
Inada, N., Oguri, M., Falco, E. E., Broadhurst, T. J., Ofek, E. O., Kochanek, C. S., Sharon, E., & Smith, G. P. 2008, PASJ, 60, L27
Inoue, K. T., & Chiba, M. 2005, ApJ, 633, 23
Koopmans, L. V. E. 2005, MNRAS, 363, 1136
Kormendy, J., & Ho, L. C. 2013, ARA&A, 51, 511
Mao, S., Witt, H. J., & Koopmans, L. V. E. 2001, MNRAS, 323, 301
Negrello, M., Hopwood, R., De Zotti, G., et al. 2010, Science, 330, 800
Negrello, M., Hopwood, R., Dye, S., et al. 2014, MNRAS, 440, 1999
Oguri, M. 2010, PASJ, 62, 1017
Oguri, M. 2014, MNRAS, 444, 147
Omont, A., Yang, C., Cox, P., et al. 2013, A&A, 551, AA115
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2010, AJ, 139, 2097
Rybak, M., McKean, J. P., Vegetti, S., Andreani, P., & White, S. D. M. 2015, MNRAS, submitted (arXiv:1503.02025)
Suyu, S. H., & Halkola, A. 2010, A&A, 524, AA94
Vegetti, S., Lagattuta, D. J., McKean, J. P., et al. 2012, Nature, 481, 341
Winn, J. N., Rusin, D., & Kochanek, C. S. 2004, Nature, 427, 613
Wong, K. C., Suyu, S. H., & Matsushita, S. 2015, MNRAS, submitted (arXiv:1503.05558)