



The Central Kinematics and Black Hole Mass of 4C+37.11

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Abstract

We report on integral field unit (IFU) measurements of the host of the radio source 4C+37.11. This massive elliptical contains the only resolved double compact nucleus at parsec-scale separation, likely a bound supermassive black hole binary (SMBHB). *i*-band photometry and GMOS-N IFU spectroscopy show that the galaxy has a large $r_b = 1''.5$ core and that the stellar velocity dispersion increases inside of a radius of influence $r_{\text{SOI}} \approx 1''.3$. Jeans Anisotropic Modeling analysis of the core infers a total SMBHB mass of $2.8_{-0.8}^{+0.8} \times 10^{10} M_{\odot}$, making this one of the most massive black hole systems known. Our data indicate that there has been significant scouring of the central kiloparsec of the host galaxy.

Unified Astronomy Thesaurus concepts: Supermassive black holes (1663); Giant elliptical galaxies (651); Brightest cluster galaxies (181)

Supporting material: data behind figure

1. Introduction

Maness et al. (2004) found that the radio galaxy 4C+37.11 (0402+379) contains two central, compact, flat-spectrum, variable components (designated C1 and C2) with a Very Long Baseline Array (VLBA)-measured separation 7.3 pc at $z = 0.055$ and argued that this is a gravitationally bound supermassive black hole binary (SMBHB). Subsequent VLBA observations by Rodriguez et al. (2006) have bolstered that claim and even detected a possible relative proper motion of the binary components (Bansal et al. 2017). The binary's host is remarkable, being an extremely massive elliptical embedded in a bright X-ray halo (Romani et al. 2014; Andrade-Santos et al. 2016), which represents a cluster's worth of stars and mass in a relatively isolated galaxy. Such “fossil clusters” are believed to be the product of multiple major mergers. We report here on a kinematic study of the central region of this galaxy, which supports a scenario where the source contains a supermassive black hole pair whose present (and former) interactions have scoured the galaxy core. The estimated SMBHB mass is very large, the second largest kinematically measured value in the local Universe.

We assume a $H_0 = 69.6$, $\Omega_M = 0.286$, and $\Omega_{\Lambda} = 0.714$ cosmology (Bennett et al. 2014), so at the redshift of $z = 0.055$, 4C+37.11 has a luminosity distance $D_L = 246.9$ Mpc, angular diameter distance $D_A = 221.9$ Mpc, and a projected scale of 1.076 kpc^{-1} .

2. Observations, Data Reduction, and Measurement

Our kinematic study uses two observations. A 2008 December 12 WIYN 3.6 m 2200 s OPTIC *i* band image presented in Romani et al. (2014) has image quality FWHM $< 0''.6$ and measures the galaxy surface brightness profile. For

spectroscopy, we use a 2015 December 1 Gemini 8.1 m 6×1200 s GMOS-N integral field unit (IFU) observation of the galaxy center, downloaded from the Gemini Science archive. These observations used the B600 grating, covering 6300–9195 Å at dispersion $0.47 \text{ Å pixel}^{-1}$. Conditions were good, with low airmass throughout. The IFU feeds a fiber array with a $0''.22$ pitch, and with the observations dithered on the sky, IRAF GMOS pipeline processing calibrated and cleaned the spectra, assembling a data cube covering $4''.5 \times 6''.2$ at $0''.1$ scale, centered on the active galactic nucleus (AGN), with reduced net exposure at the edges. Measurements of images of the point-spread function (PSF)-distributed line wings of the AGN core find an angular resolution of $0''.64$ (FWHM) and sky lines give a median effective spectral resolution of 2.0 Å FWHM .

For our kinematic study, we fit the emission line-free range 7810–9190 Å, masking a small range near 8230 Å affected by a chip gap. We log rebin the spectra over this range to a velocity scale of 15.3 km s^{-1} . Reliable measurements of the line-of-sight velocity distribution (LOSVD) require a signal-to-noise ratio (S/N) of ~ 20 per resolution element. Our data cube provides only $S/N \sim 7$ per spaxel in the galaxy center, falling to $S/N \sim 1$ in the more poorly exposed outskirts of the data cube. Thus, we use Voronoi binning (Cappellari & Copin 2003) to combine the spaxels. With a target $S/N \sim 20$ at the rebinned velocity scale, we get 31 bins (Figure 1); edge bins generally do not reach the S/N target. Imperfectly excised cosmic-ray events and poor sky subtraction affect many of the edge pixels with few IFU exposures. We therefore used iterative sigma clipping to excise outlier pixels from each wavelength in the Voronoi tiles. The means of the clipped tile wavelength measurements form the final spectra, with their dispersion as the associated error vector. Velocity structure is measured with the Penalized PiXel Fitting method (pPXF) of Cappellari (2023), which convolves template stellar spectra with a Gauss–Hermite decomposition of the LOSVD. With the limited S/N , we fit only V and σ , skipping the higher order h_3 and h_4 moments.



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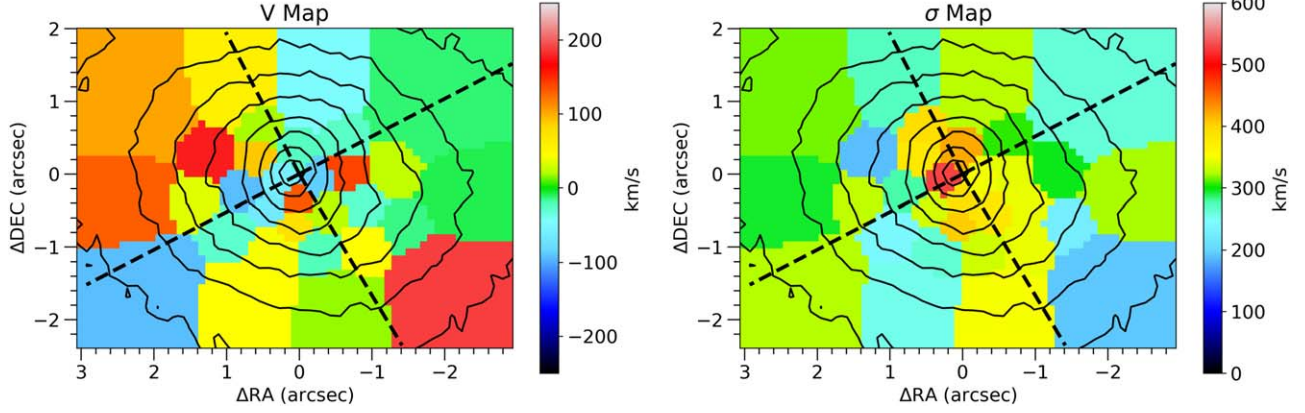


Figure 1. Radial velocity (V) and velocity dispersion (σ) maps of pPXF measurements in the Voronoi bins. The origin is the AGN location, determined from the wings of the [N II] emission lines. Solid contours mark $0.9\times, 0.8\times, \dots, 0.2\times$ the peak surface brightness and dashed lines separate quadrants along the major and minor axes.

For the stellar templates, we used a combination of G0–M2 giants from the Indo-US Stellar Library (Valdes et al. 2004). These templates have a slightly finer scale of $0.44 \text{ \AA pixel}^{-1}$, with a median spectral resolution of $\sim 1 \text{ \AA}$. To match the templates to the host galaxy spectra, we convolve the templates using the difference in the spectral resolutions, following Section 2.2 in Cappellari (2017). pPXF uses additive and multiplicative polynomials in the fitting model for both the target and template spectra to reduce sensitivity to imperfect continuum fluxing and veiling components. We varied the order of these polynomials, finding that both additive and multiplicative terms required order ≥ 4 to achieve stable fits. Here we use fourth-order additive and sixth-order multiplicative Legendre polynomials (4A+6M) as fiducial. Sample spectral fits at three different radii are shown in Figure 2.

Radial velocity and velocity dispersion maps from the Voronoi tiles are shown in Figure 1. We detect little if any coherent rotation, typical for massive ellipticals. However, given the large size of the Voronoi bins, we cannot exclude a kinematically distinct core, sometimes seen among nonregular rotators (Cappellari 2016). We do see a substantial Keplerian-like peak in $\sigma(r)$, which flattens out at $\sim 300 \text{ km s}^{-1}$ beyond $\sim 2''$. Although we lack kinematic data at the half-light radius ($R_e \sim 12''$; see below in the discussion of the Multi-Gaussian Expansion), we can follow Saglia et al. (2016, their Appendix A) and estimate the effective velocity dispersion by integrating the surface-brightness-weighted V_{rms} to our outermost bin, finding $\sigma_e = 332 \pm 11 \text{ km s}^{-1}$. This likely overestimates σ_e , as over a third of our bins are affected by the central velocity cusp.

For dynamical modeling, we also require the host surface brightness profile. This was measured from the WIYN i' image using the Multi-Gaussian Expansion (MGE) method of Cappellari (2002). We first masked stars and galaxies near $4C+37.11$. We then obtained the image PSF from 15 unsaturated stars near the host, using the *photutils* effective PSF (ePSF) routine (Bradley et al. 2023). In host fitting we assume axisymmetry, with the surface brightness modeled as a sum of elliptical Gaussian components aligned along the direction of the photometric major axis (x'):

$$\Sigma(x', y') = \sum_{j=1}^N S_j \exp \left[-\frac{1}{2\sigma_i} \left(x'^2 + \frac{y'^2}{q_i^2} \right) \right]. \quad (1)$$

Here we have N Gaussian components with surface brightness S_j and axial ratio q_j . The position angles of the Gaussians were fixed

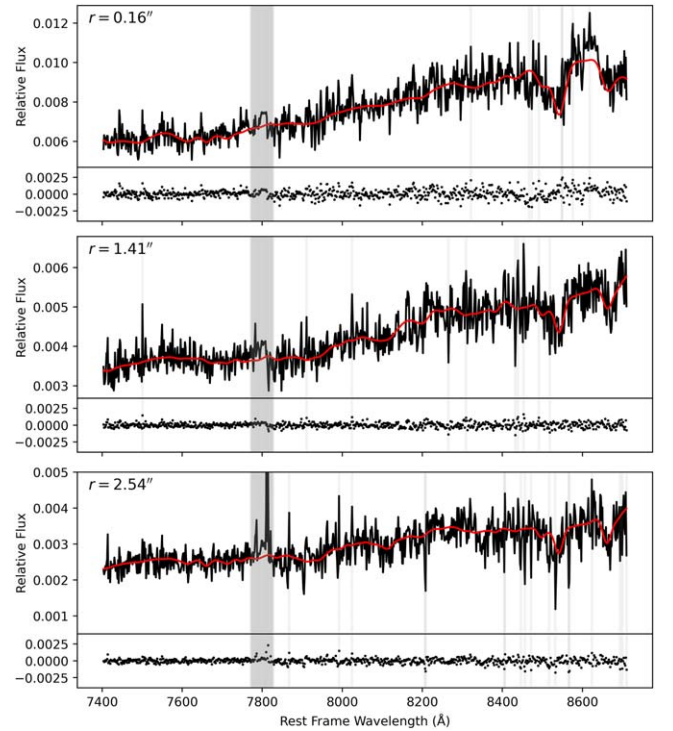


Figure 2. Sample spectral fits (red) and residuals for $S/N \sim 20$ Voronoi bins at three different radii. For plotting purposes, the spectra were rebinned to 61.2 km s^{-1} , $4\times$ the width used for the kinematic extraction. Grey bars show masked pixels from chip gaps and from 2σ iterative clipping.

at $PA_{\text{MGE}} = 72.4^\circ$ and q_j had a flat prior $0.75-1$. Before fitting we convolve Equation (1) with an MGE expansion of the WIYN PSF. The MGE fits for the PSF and the i' band image are summarized in Tables 1 and 2, respectively. Figure 3 shows the MGE fits for the IFU region and the entire region used in mass modeling. While somewhat triaxial at large radii, the axisymmetric assumption is adequate over the IFU kinematics region. Using the MGE, with the routine `mge_half_light_isophote` of the package *JamPy* of Cappellari (2008) we find a half-light radius for $4C+37.11$ to be $R_e = 12''$.

It was noted in Romani et al. (2014) that the host-surface-brightness profile flattened within $\sim 1.5 \text{ kpc}$ from an outer $n = 4$ Sérsic profile, indicating that $4C+37.11$ is a cored elliptical.

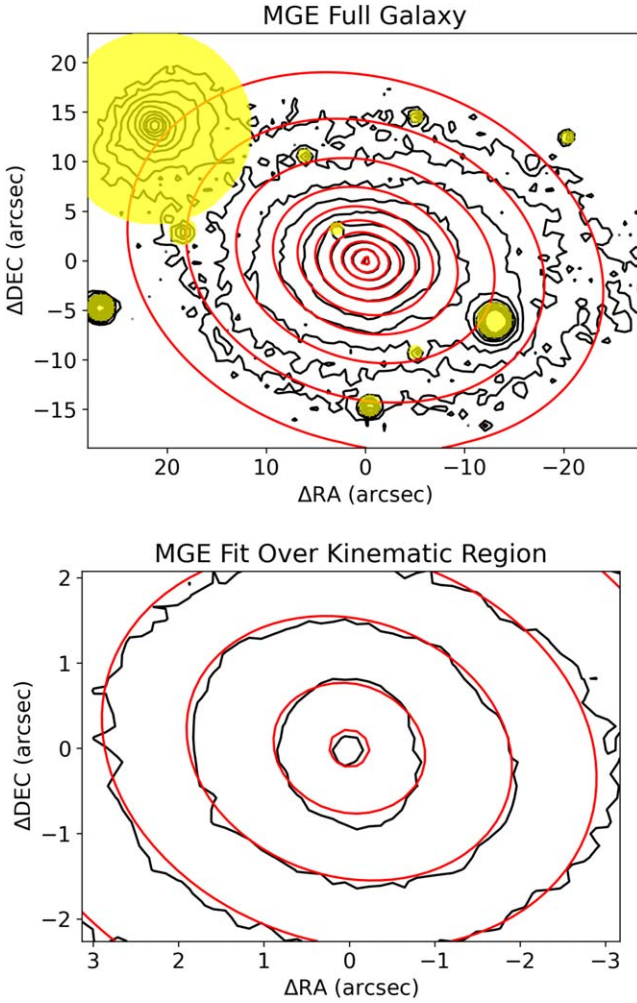


Figure 3. i' image isophote contours (black) and MGE fit ellipses (red). Top: the full region. Bottom: the IFU region with kinematic measurements. The yellow regions correspond to masked pixels in the MGE fits.

Table 1
WIYN PSF MGE

j	S_j	σ_j (arcsec)	q_j
1	0.23	0.15	0.71
2	1.38	0.27	0.93
3	0.362	0.36	1.00
4	0.10	0.56	0.96
5	0.02	0.94	1.00
6	0.002	2.1	1.00

We measure the core radius r_b by fitting a core-Sérsic model, with a point-source excess for the AGN light, to the i' band image, using the reconstructed PSF for model convolution and minimizing with the 2D fitting software `imfit` (Erwin 2015). The core-Sérsic profile is described as

$$I(r) = I' \left[1 + \left(\frac{r_b}{r} \right)^\alpha \right]^{\frac{\gamma}{\alpha}} \exp \left[-b_n \left(\frac{r^\alpha + r_b^\alpha}{r_e^\alpha} \right)^{\frac{1}{\alpha n}} \right], \quad (2)$$

where

$$I' = I_b 2^{-\gamma/\alpha} \exp [b_n (2^{1/\alpha} r_b / r_e)^{1/n}], \quad (3)$$

Table 2
PSF-convolved 4C+37.11 MGE

j	$\log(S_j) (L_\odot \text{ pc}^{-2})$	σ_j (arcsec)	q_j
1	4.18	0.11	0.75
2	3.18	1.25	0.75
3	2.83	3.02	0.76
4	2.29	6.38	0.75
5	2.01	17.8	0.75

Table 3
2D Core-Sérsic + Point-source Model-fit Parameters

Core Sérsic Parameters	Value
PA (deg)	81.9 ± 0.3
ϵ	0.293 ± 0.003
$S_{b,i'}$ (mag arcsec $^{-2}$)	18.26 ± 0.03
n	3.92 ± 0.08
r_e (arcsec)	19.0 ± 0.5
r_b (arcsec)	1.49 ± 0.05
γ	0.40 ± 0.03
Point-source Parameters	Value
i'_{tot} (mag)	20.2 ± 0.3

Note.

Magnitudes $S_{b,i'}$ and i' are corrected for an estimated $A_{i'} = 2.2$ mag extinction.

as per Graham et al. (2003). For our fit, we fix the sharpness parameter at $\alpha = 100$ (Graham et al. 2003; Trujillo et al. 2004) and derive the fit parameters in Table 3, where we have converted intensity at the break radius to a surface brightness $S_{b,i'}$. We do indeed see that the outer galaxy has $n \approx 4$ and find a core radius $r_b = 1.60 \pm 0.05$ kpc. For $\alpha > 10$, we find that r_b varies by $< 2\sigma$ from this value.

3. Dynamical Modeling

Given the low S/N kinematics data extending only to $\sim 3''$, we do not attempt full Schwarzschild orbit-superposition modeling. Instead, we conducted axisymmetric Jeans Anisotropic Modeling (JAM) using the software `JamPy` (Cappellari 2008), which does not require large-radius kinematics to achieve good constraints (Simon et al. 2024) and produces black hole masses consistent with Schwarzschild analyses (Cappellari et al. 2010).

Unlike the Schwarzschild method, axisymmetric JAM makes a number of assumptions about the distribution of stellar velocities. In particular, the velocity ellipsoid is either assumed to be aligned with spherical (r, ϕ, θ) or cylindrical (R, ϕ, z) coordinates, neither of which can fully represent a real galaxy. Spherically aligned velocity ellipsoids are typically good approximations to slow rotator ellipticals, which are weakly triaxial and have spherical isophotes in the inner half-light radius (Simon et al. 2024). Cylindrically aligned velocity ellipsoids are typically applied to fast rotator massive ellipticals (Cappellari 2008) but have also been assumed for slow and nonregular rotators, as in the ATLAS3d survey (Cappellari et al. 2013). Here, we compare JAM models using both a cylindrically aligned and spherically aligned velocity ellipsoid. In the cylindrical case, we assume radial anisotropy $\beta_z = 1 - \sigma_z^2 / \sigma_R^2$ is constant with $\sigma_R^2 = b \sigma_z^2$. In the spherical

Table 4
The Self-consistent Model Posterior Medians and 1σ Ranges for the Different Kinematic Models/Data Sets

S/N	Velocity Ellipsoid	Central Kin. Bin	i (deg)	σ_θ/σ_r	σ_z/σ_R	M_* ($M_\odot$)	$\Upsilon_{i'}$ ($M_\odot/L_{\odot,i'}$)
20	Spherical	Kept	73^{+12}_{-14}	$1.0^{+0.3}_{-0.2}$	...	$(2.8^{+0.8}_{-0.8}) \times 10^{10}$	$4.9^{+0.9}_{-0.7}$
20	Spherical	Removed	71^{+13}_{-15}	$0.83^{+0.23}_{-0.18}$	...	$(2.0^{+0.9}_{-0.9}) \times 10^{10}$	$4.7^{+0.8}_{-0.7}$
20	Cylindrical	Kept	66^{+15}_{-13}	...	$0.92^{+0.09}_{-0.10}$	$(2.7^{+0.5}_{-0.4}) \times 10^{10}$	$4.8^{+0.5}_{-0.5}$
20	Cylindrical	Removed	66^{+17}_{-15}	...	$0.91^{+0.08}_{-0.10}$	$(2.4^{+0.5}_{-0.5}) \times 10^{10}$	$4.9^{+0.5}_{-0.5}$
18	Spherical	Kept	72^{+12}_{-14}	$0.85^{+0.20}_{-0.16}$	...	$(2.0^{+0.6}_{-0.6}) \times 10^{10}$	$4.1^{+0.7}_{-0.5}$
18	Spherical	Removed	72^{+12}_{-15}	$0.83^{+0.18}_{-0.16}$	...	$(1.9^{+0.6}_{-0.3}) \times 10^{10}$	$4.1^{+0.6}_{-0.5}$
18	Cylindrical	Kept	66^{+15}_{-15}	...	$0.89^{+0.08}_{-0.10}$	$(2.3^{+0.3}_{-0.3}) \times 10^{10}$	$4.2^{+0.4}_{-0.4}$
18	Cylindrical	Removed	68^{+15}_{-16}	...	$0.89^{+0.07}_{-0.09}$	$(2.2^{+0.4}_{-0.4}) \times 10^{10}$	$4.2^{+0.4}_{-0.4}$

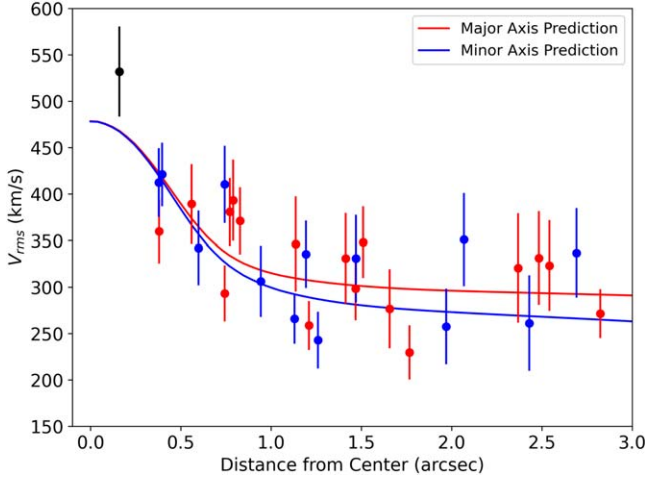


Figure 4. $V_{\text{rms}} = \sqrt{V^2 + \sigma^2}$ vs. radius compared with the best-fit spherical JAM model. While the fit was to all data, the points are color-coded by major axis/minor axis sector (Figure 1), and the curves show the expected model runs along the major and minor axes. The V and σ values are available.

(The data used to create this figure are available.)

case, radial anisotropy $\beta = 1 - \sigma_\theta^2/\sigma_r^2$ is constant. The JAM models include no tangential anisotropy $\gamma = 1 - \sigma_\phi^2/\sigma_R^2 = 0$, since the velocity second-moment predictions are independent of γ ; nonzero tangential anisotropy is not usually needed to model the overall kinematics of real galaxies (Cappellari 2016).

3.1. JAM Models

For both the spherically and cylindrically aligned cases, we incorporate a self-consistent model, assuming that the total mass density follows the surface brightness profile. In particular, the projected mass density can be obtained by multiplying each Gaussian component in Equation (1) by a constant mass-to-light ratio $\Upsilon_{i'}$. The parameters for this model are then $\Upsilon_{i'}$, the radial anisotropy parameter (σ_z/σ_R for cylindrical or σ_θ/σ_r for spherical), inclination i , and the black hole mass M_* . Here inclination i is the angle between the galaxy's symmetry axis and the line-of-sight direction and M_* represents the total mass of the binary, which is modeled by a Keplerian point mass potential. We represent the PSF of the kinematic observations with a single circular Gaussian of dispersion $0''.27$ (as described in Section 2). We do not incorporate a model for the contribution of the dark halo's potential due to the limited S/N and radial range of the kinematic data; tests with a Navarro–Frenk–White halo give no

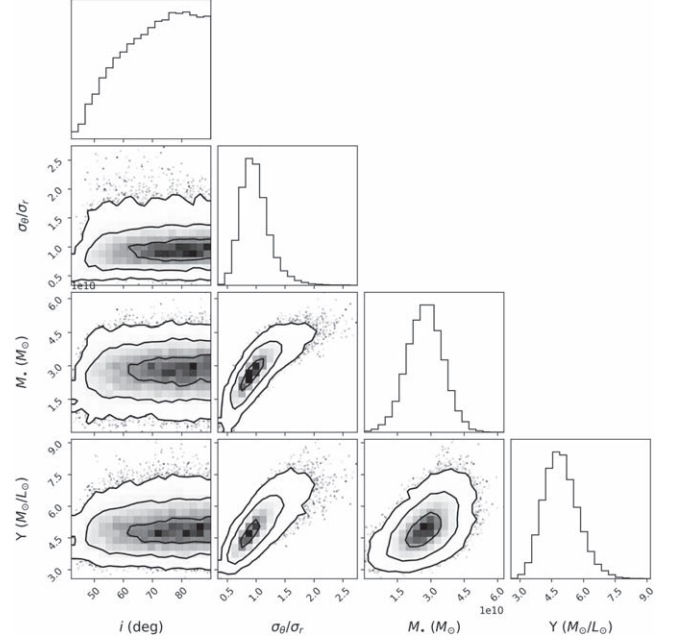


Figure 5. Corner plot for the spherical S/N = 20 JAM fit.

halo constraints and negligible changes to the other fit parameters.

At S/N ~ 20 the central bin has a large $V_{\text{rms}} = \sqrt{V^2 + \sigma^2} \approx 532 \text{ km s}^{-1}$ (Figure 4). Since this has a strong effect on the black hole mass fit, we tested for sensitivity and systematic bias by optionally dropping the innermost bin. We also fit using a lower Voronoi target S/N = 18, for additional bins across the central $0''.5$. In all cases, the V_{rms} rise from the SMBHB is still apparent.

3.2. Results

We perform Markov Chain Monte Carlo fitting of the JAM models, with a $\sin(i)$ prior on the inclination and wide uniform priors on the other parameters. The marginal posterior values and 68% confidence regions are summarized in Table 4 for two S/N binnings, both velocity ellipsoid models, and retention or exclusion of the central kinematic point. We note that while error bars are larger on the spherical model parameters and while low S/N binning tends to slightly reduce the best-fit black hole masses, all results are consistent at the $\sim 1\sigma$ level.

Some additional systematic sensitivity comes from the choice of the spectrum/template polynomials. We explored this by refitting the cylindrical S/N = 20 model (with its

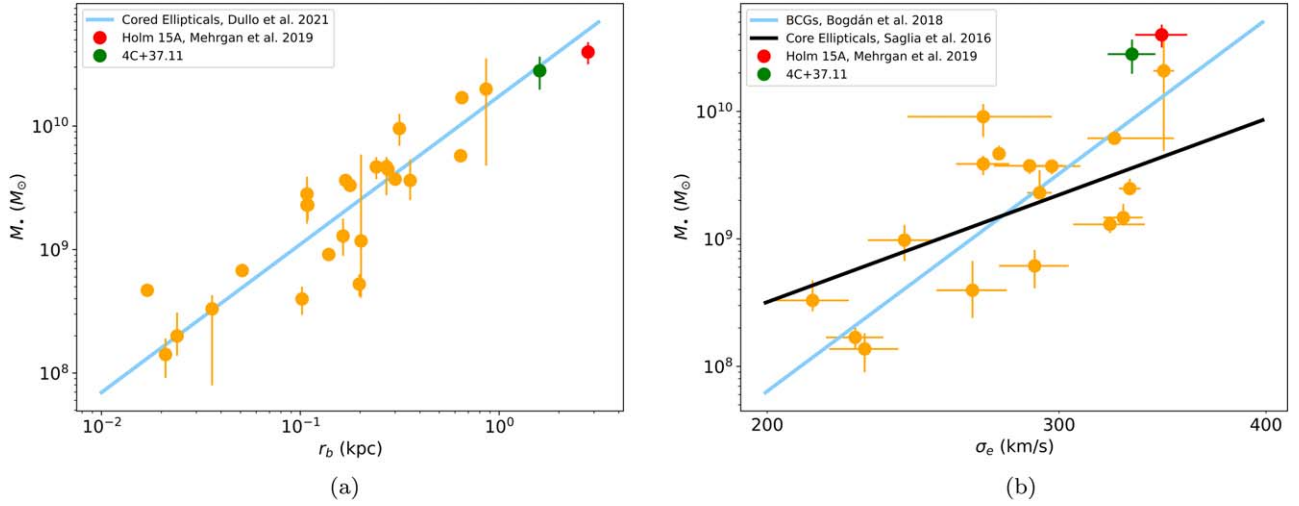


Figure 6. (a) Correlation between core radius and black hole mass from Dullo et al. (2021), including measurement of depleted core Holm 15A from Mehrgan et al. (2019). (b) Correlation with effective velocity dispersion for BCGs from Bogdán et al. (2018), represented by the orange data points and blue fit line. The black line is the trend for all core ellipticals from Saglia et al. (2016). Note that 4C+37.11/Holm 15 lie well above the relation for all ellipticals, but are consistent with the BCG trend.

smaller statistical errors), varying the degree of multiplicative and additive polynomials from 4 through 7 (16 combinations). Since the SMBHB mass M_* is our prime measured parameter, we focus on its sensitivity. While over half of the values fell within $0.5 \times 10^{10} M_\odot$ of the 4A+6M fit result, values ranged from $2.25 - 3.75 \times 10^{10} M_\odot$. Evidently, significant systematic uncertainties remain in the velocity extractions; these can be controlled with higher S/N data.

Since 4C+37.11 appears to be a slow rotator, we take the spherical S/N=20 fits as our standard, giving $M_* = (2.8 \pm 0.8) \times 10^{10} M_\odot$, statistical errors only. While the mass is large, so are the error bars, encompassing nearly all of the other fits and polynomial choices. However, a slightly more conservative interpretation might adopt $M_* \approx 2.4 \times 10^{10} M_\odot$, about $\sigma/2$ lower, since the central S/N=20 bin does tend to increase the mass. The radial V_{rms} run and corner plots for the spherical fit are shown in Figures 4 and 5. In the latter, we note that i is only weakly constrained within the prior and that M_* is correlated with the velocity anisotropy, with larger hole masses demanded for $\beta < 0$. Higher S/N is clearly needed to pin down β (and its possible radial dependence due to core scouring, see below).

Using the black hole mass, constant stellar mass-to-light ratio, and inclination for the spherical model, we estimate the radius of the sphere of influence r_{SOI} of the binary. Following Mehrgan et al. (2019) and Simon et al. (2024), we define r_{SOI} by $M_*(\leq r_{\text{SOI}}) = M_*$, where M_* is the enclosed stellar mass. Using the routine `mge_radial_mass` of `JamPy` (Cappellari 2008) to compute the enclosed stellar mass within a radius r using the MGE of the surface brightness, we find $r_{\text{SOI}} \approx 1''.29$ (1.38 kpc), quite consistent with the observed V_{rms} flattening.

4. Discussion and Conclusions

It is interesting to compare our dynamical $M_* \approx 2.8 \times 10^{10} M_\odot$ estimate for 4C+37.11's binary with values found for other massive ellipticals. These M_* values correlate with host properties, especially those of the host core, giving insight into black holes/host coevolution (Kormendy & Ho 2013; Saglia et al. 2016; Bogdán et al. 2018).

The core radius r_b has been found to tightly correlate to the central black hole mass among massive ellipticals (Mehrgan et al. 2019; Dullo et al. 2021). We compare our 4C+37.11 values with dynamically measured M_* and r_b for other elliptical galaxies (Dullo et al. 2021), including Holm 15A, which has the largest dynamically measured black hole mass in the local Universe, from Mehrgan et al. (2019). We find our value is quite consistent with these authors' best-fit trends for cored ellipticals (Figure 6(a)).

Another well-known correlation is the M_* - σ relation, which has been found to depend on the host type. While our $\sigma_e = 332 \pm 11 \text{ km s}^{-1}$ is somewhat suspect since we can only integrate to $\approx 0.25 R_e$, we can compare with the trends seen by various authors. We first consider the cored ellipticals with dynamical mass measurements in Saglia et al. (2016). Our estimate exceeds their best-fit correlation's prediction by $\sim 7.2 \times$. However, if we compare with the cored ellipticals that are also brightest cluster galaxies (BCGs) from Bogdán et al. (2018), we find that 4C+37.11 (and Holm 15A) follow their best-fit trend more closely (Figure 6(b)).

The $M_* \approx 2.8 \times 10^{10} M_\odot$ dynamical mass for 4C+37.11's SMBHB is one of the largest measured in the local Universe. While exceeding the value predicted for a typical elliptical, it is in line with expectations for cored ellipticals and, especially, those that are also BCGs. This fits well with the picture that the host is a fossil cluster, the product of several major mergers. If these mergers were largely dry, dissipation-less events, they would grow the central black hole mass faster than the stellar velocity dispersion (Mehrgan et al. 2019). In addition, the back-action from the current binary (and likely from earlier binary phases) has "scoured" the core, removing stars capable of exerting dynamical friction via three-body gravitational slingshots (Begelman et al. 1980). In that, 4C+37.11 resembles other extreme cored ellipticals, including Holm 15A. This picture can be tested and extended by additional kinematic studies, which can measure $\beta(r)$, tighten the M_* estimate, and constrain the orbit anisotropy of the stars in the host core, probing the system's merger history. While such measurements will be challenging or impossible from the ground, the JWST

NIRSpec IFU field is well-matched to the host r_b and can provide important information on the core kinematics.

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