Investigating the Candidate Displaced Active Galactic Nucleus in NGC 3115

Megan L. Jones1,2, Sarah Burke-Spolaor1,2, Kristina Nyland3, and Joan M. Wrobel4

1 Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26506, USA
2 Center for Gravitational Waves and Cosmology, West Virginia University, Chestnut Ridge Research Building, Morgantown, WV 26505, USA
3 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
4 National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA

Received 2018 November 2; revised 2019 February 13; accepted 2019 February 23; published 2019 March 28

Abstract

The nearby galaxy NGC 3115 contains a known radio-emitting, low-luminosity active galactic nucleus (AGN), and was recently claimed to host a candidate AGN displaced 14.3 pc from the galaxy’s optical photocenter. Our goal is to understand whether this represents a single offset AGN, an AGN in orbit around a central black hole, or something else. We present a new, sensitive (rms = 4.4 μJy beam⁻¹) 10 GHz image, which finds evidence for only one AGN. We place a stringent limit on the radio luminosity of any secondary supermassive black hole of L₁₀GHz < 5.8 × 10^{33} erg s⁻¹. An analysis of the relative positioning of the radio core, X-ray nucleus, and stellar bulge in this galaxy indicates that the radio source is centrally located, and not offset from the galactic bulge. This provides an argument against a single offset AGN in NGC 3115; however, it does not provide conclusive evidence against the purported offset AGN as an inspiralling secondary black hole.

Key words: galaxies: active – galaxies: individual (NGC 3115) – galaxies: nuclei – radio continuum: galaxies

1. Introduction

Supermassive black hole (SMBH) binaries should form during major galaxy mergers. Through the loss of orbital energy, the SMBH pair will eventually coalesce, releasing an enormous amount of energy in the form of gravitational waves. Gravitational waves produced by SMBH mergers would be detectable by pulsar timing arrays. Gravitational waves produced by SMBH mergers would be an enormous amount of energy in the form of gravitational waves. If this energy, the SMBH pair will eventually coalesce, releasing an enormous amount of energy in the form of gravitational waves. From this process, a black hole recoils with kick velocities up to 400 km s⁻¹, causing the SMBH to be ejected from the galaxy; Blecha et al. 2016. The SMBH should eventually settle into the host galaxy’s center due to drag and other dynamical interactions with the stellar and gas environment (e.g., Begelman et al. 1980; Campanelli et al. 2007). While recoiling SMBHs may return to the center after several gigayears, SMBH recoils in gas-poor galaxy mergers can remain noncentrally located for much longer periods of time (Blecha et al. 2016).

SMBH recoils induced by these kicks have astrophysical implications for the host galaxy, such as SMBH and galaxy evolution, galactic core structures, galaxy-SMBH scaling relations, and the dependence of gravitational wave signals on redshift, among others (Komossa 2012). The identification of potential recoiling SMBHs is therefore important in exploring past galaxy mergers, information on kick properties, as well as investigating predictions made via numerical relativity.

There are not many small-orbit binary SMBH systems known, with only a few examples below separations of 1 kpc (e.g., Rodriguez et al. 2006). There have likewise been scant discoveries of post-merger systems where the SMBH is seen in a state of offset/recoil, with only a few unconfirmed candidate systems (Komossa et al. 2008; Postman et al. 2012; Blecha et al. 2013; Lena et al. 2014; Chiaberge et al. 2017). To achieve sufficient active galactic nucleus (AGN) offsets such that the object is identifiable as an offset system, a large kick velocity is necessary. High kick velocities, while possible, are likely to cause stripping of much of the emissive material (e.g., much of the narrow line region) from the SMBH after its departure from the galactic center; therefore, bright AGN with large offsets are likely to be rare.

At a distance of 10.2 Mpc, NGC 3115 is the nearest host of a billion-solar-mass black hole, and represents one of the first SMBHs with an accurate mass measurement based on stellar or gas dynamics (M_{BH} = 9.6 × 10⁸ M_☉) (Kormendy & Richstone 1992; Gültekin et al. 2009). At the object’s distance 1″ = 49.5 pc, making the task of spatially resolving any offset more feasible than for more distant sources. Compact radio emission with a luminosity of 3.1 × 10^{33} erg s⁻¹ that is coincident with the optical center in the nucleus of NGC 3115 was first detected by Wrobel & Nyland (2012) by analyzing archival Very Large Array (VLA) data, with an Eddington luminosity of L_{Edd} = 1.2 × 10^{47} erg s⁻¹. This detection is also coincident with an X-ray candidate nucleus identified by Wong et al. (2011), who conservatively estimate the luminosity as L_X < 4.3 × 10^{38} erg s⁻¹. These data suggest the existence of a low-luminosity AGN residing in the center of this galaxy.

Using the Gemini-South telescope, Menezes et al. (2014) reported the detection of a broad-line Hα emission with a luminosity of L_{Hα} = (4.2 ± 0.4) × 10^{37} erg s⁻¹ that was displaced from the photometric center of NGC 3115’s stellar bulge by 290 ± 50 mas (14.3 ± 2.5 pc). Upon inspecting several possibilities including a rotating relativistic disk around the central black hole and imprecise starlight subtraction, they concluded that the emission is most likely associated with an offset AGN. If this detection genuinely represents an offset AGN, there are two potential interpretations. First, it is possible the black hole fueling the offset AGN is actually in a parsec-scale binary with a second black hole situated at the photocenter. Alternately, the AGN displacement could be the result of a black hole that has been kicked from the galaxy photocenter via recoil.
In this paper we present a radio search for evidence of a binary or offset AGN in NGC 3115. Section 2 reports new 10 GHz data collected with National Science Foundation’s Karl G. Jansky VLA. Section 3 discusses the new radio measurements in the context of our detection of only one radio core, and reports a closer examination of the relative positions and astrometric errors of several different measurements of the AGN and galaxy center. We discuss the implication of these results in Section 4.

2. Very Large Array Data

We observed NGC 3115 with the VLA at X-band in the A-configuration on 2015 June 12, with 84 minutes on-target. The observational setup had 64 frequency channels in each of 32 unique spectral windows, across the range 7.976–12.024 GHz with a center frequency of \( \sim 10 \) GHz. The target pointing position was 10:05:13.927, –07:43:06.96. We performed primary flux density and bandpass calibration using standard VLA calibrator 3C286, and used J1007−0207 as a phase calibrator.

We calibrated the data using the VLA calibration pipeline, and interactively deconvolved the images using the CLEAN algorithm in the CASA software package (McMullin et al. 2007). The rms of our final image is 4.4 \( \mu \)Jy beam\(^{-1}\). The synthesized beam had major and minor axes of 360 mas and 160 mas, respectively, with a position angle of 40°. Multi-frequency synthesis was performed to account for the large fractional bandwidth with \( \Delta f / f = 2 \) due to the size of the imaged field. We used Briggs weighting with a robust value of 0.0 and a minpb of 0.2. The cell size was set to 36 mas.

3. Analysis of Available Data

3.1. 10 GHz Measurement Results

Our new radio image improved on the rms sensitivity of our previous image by a factor of \( \sim 5 \). Figure 1 shows a compact source located in the center of NGC 3115 down to our detection limit of three times the rms. The IMFIT procedure in CASA was used to fit a two-dimensional elliptical-Gaussian to this sole source, yielding the integrated flux density, position, and one-dimensional position error appearing in Table 1. The tabulated position errors are reported as the radius of the error circle at the 95% confidence level. The flux density error is the quadratic sum of the 3% scale error (Perley & Butler 2013) and the fit residual. The position error is the quadratic sum of terms due to the phase-calibrator position error (less than 2 mas), the phase-referencing strategies (estimated to be 100 mas), and the signal-to-noise ratio of the component (4 mas). The source was found to be point-like, with upper limits of 190 mas (9.4 pc) on its major axis and 22 mas (1.1 pc) on its minor axis, for a position angle of 40.5° ± 0.5°.

We detected two additional 10 GHz sources, each offset by more than 1/5 from the nuclear 10 GHz source and thus unlikely to be associated with it. As an independent cross-check of the VLA position error for the nuclear 10 GHz source (Table 1), we searched the literature for counterparts to the two offset sources. Only one had any counterparts. Figure 2 shows that offset 10 GHz source plus the positions of its Chandra X-ray and \( \gamma \)l counterparts (Cantiello et al. 2015, 2018; Lin et al. 2015), and serves to validate the VLA astrometry.

Using previous radio data as listed in Table 1 along with the data presented here, for the NGC 3115 nuclear source we measure a spectral index of \( \alpha = -0.37 \pm 0.13 \). This is consistent with the index measured by Wrobel & Nyland (2012) of \( \alpha = -0.23 \pm 0.20 \) (Figure 3). The relatively flat spectral index of the emission indicates that this emission is likely related to a radio core component, i.e., marks the location of an SMBH rather than marking a distant jet outflow. The flat spectrum and persistence of the source show that it is likely in a low-hard or quiescent state, consistent with the SMBH accreting slowly from the hot gas traced by the X-rays. The integrated flux measured in our new broadband VLA data from 8 to 12 GHz is consistent with that from archival VLA observations at 8.5 GHz (Table 1). The variability here cannot conclusively be determined; thus, in the absence of strong variability, there is no evidence for significant deviation from a single power law in this radio component (i.e., we are not clearly observing a self-absorption turn-over, nor do we seem to be seeing two distinct regions with vastly different properties within our beam).

It is clear that we have not detected any radio source related to NGC 3115 except for the one previously reported by Wrobel & Nyland (2012). We initially set out to test the report of Menezes et al. that there was an active nucleus offset from the kinematic and photometric center of NGC 3115. As hypothesized in their paper, this could mean they either detected a single offset black hole, or an inspiralling black hole offset from another at the galaxy center, or that there is simply a single black hole at the galaxy center and the offset emission detected by Menezes et al. is caused by, for instance, an outflow. However, several questions remain in the investigation of our initial hypotheses: First, should we have detected a secondary black hole, given the detection of the first one? Second, can we determine whether this object corresponds to the galaxy photocenter or to the purported offset AGN of...
Negative contours are dashed and positive ones are solid.

References. (1) NED/2MASS; (2) this work; (3) Wrobel & Nyland (2012); (4) White et al. (1997); (5) Evans et al. (2010); (6) Menezes et al. (2014).

![Figure 2. VLA image of Stokes I emission near 10 GHz centered on a background source with a X-ray counterpart (Lin et al. 2015) and an ugi counterpart (Cantiello et al. 2015, 2018). The symbols encode the counterpart positions and their errors at the 95% confidence level. The slightly larger circle to the left represents the Chandra X-ray counterpart, which is offset 147 mas from the 10 GHz background source. The slightly smaller circle to the right represents the ugi counterpart, with an offset of 249 mas from the background source. For the 10 GHz image, the local rms noise is 11.4 μJy beam⁻¹ (1σ). The beam is displayed in the bottom left corner, with major and minor axes of 360 mas and 160 mas, respectively, and a position angle of 40°. The allowed contours are at 1σ times −6, −4, −2, 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20. Negative contours are dashed and positive ones are solid.]

Menezes et al. (2014)? Third, might the central radio source actually encompass two SMBHs? The first question we address here, and the latter two require a discussion of the relative astrometry of measurements in other wavebands; this is discussed in Section 3.3.

3.2. Would we have Detected a Distinct SMBH Companion?

The radio nucleus in this system has a low luminosity of \( L_{40\text{ GHz}} = 8 \times 10^{34} \text{ erg s}^{-1} \). In considering the hypothesis that this target could contain a binary SMBH, we want to assess the probability that we should have detected a secondary SMBH in our observation given our limiting flux of three times the rms of the off-source image, \( S_{\text{lim}} = 13.8 \mu\text{Jy beam}^{-1} \). At the distance of NGC 3115 this corresponds to a limiting luminosity of \( L_{\text{lim}} = 5.8 \times 10^{33} \text{ erg s}^{-1} \). Due to the excellent VLA sensitivity and the small distance of this source, our limit on the luminosity of any secondary AGN is exceptionally low; in fact it lies several orders of magnitude below the span of published radio-quiet quasar distributions. If there is a companion, we would classify any secondary SMBH in this system as “radio-silent” (Padovani et al. 2015; Padovani 2016).

Past work has assessed the probability of finding a secondary AGN by integrating over radio luminosity functions down the limiting luminosity in an observation (e.g., Burke-Spolaor 2011). If this target had a radio-loud or even radio-quiet secondary SMBH by the standard definitions, we should have detected it. It is possible that a secondary SMBH is not in an active state at all, in which case no waveband would have detected its emission. Lützgendorf et al. (2016) discuss gas patchiness as a result of stellar winds; the presence of a second SMBH accreting rapidly from a gas patch is also possible,

---

**Table 1**

| Measurement | Position, J2000 | Positional Uncertainty (mas) | Peak Flux Density (μJy beam⁻¹) | Int. Flux Density (μJy) | Reference |
|-------------|----------------|------------------------------|--------------------------------|------------------------|-----------|
| 2MASS       | 10:05:13.93    | −07:43:07.1                  | 120                            | ...                    | 1         |
| 10 GHz      | 10:05:13.928   | −07:43:07.00                 | 200                            | 189 ± 5                | 2         |
| 8.5 GHz     | 10:05:13.927   | −07:43:06.96                 | 200                            | ...                    | 3         |
| 1.4 GHz     | 10:05:14.03    | −07:43:07.6                  | 1000                           | 400 ± 200              | 4         |
| X-ray       | 10:05:13.93    | −07:43:07.0                  | 460                            | ...                    | 5         |
| M14 AGN     | 10:05:13.817   | −07:43:07.87                 | ...                            | ...                    | 6         |
| M14 Bulge   | 10:05:13.800   | −07:43:08.00                 | ...                            | ...                    | 6         |

Note. The 2MASS reference tie corresponds to the ICRS (Cutri et al. 2003). We adopted the minor axis of the beam size for the error on our position measurement. The Chandra X-ray and Menezes et al. (2014) reference ties were obtained from comparing Chandra and Gemini data to data from SDSS (Margutti et al. 2012). As the AGN found in Menezes et al. (2014) is measured to a position relative to the stellar kinematic center, we adopt the uncertainty on that measurement as the uncertainty in the position.
which would show up as a broad-line AGN and only rarely exhibit radio emission.

3.3. Multi-wavelength Astrometry

Understanding the relative positions of the radio and X-ray emission, the purported offset AGN of Menezes et al. (2014), and the galaxy kinematic center and/or photocenter is key to our interpretation of this object. The study of Menezes et al. (2014) benefited from precise position comparisons due to analysis of relative positioning within a single observation, while our study is by nature limited by astrometric and measurement errors. We will both examine astrometric errors, and re-examine the results of Menezes et al.

While NGC 3115 is a well-studied object, there are relatively few works reporting on the actual position of the galaxy’s kinematic center. Here we assess the optical photocenter, the X-ray component, and the radio component to understand what confidence we can have in their relative positioning. Unfortunately, there were insufficient numbers of objects detected both in our image and the X-ray/2MASS data to do a direct astrometric comparison. Instead, the reference tie and measurement errors reported by source publications for each observation are identified in Table 1.

The 8.5 GHz observations were also performed with the VLA with the same frame tie accuracy (Wrobel & Nyland 2012), while the 1.4 GHz measurement comes from the FIRST survey, which reports a mean astrometric precision of 50 mas (White et al. 1997). The 2 μm photocenter position for NGC 3115 was taken from 2MASS. The 2MASS survey is tied to the Tycho 2 catalog, which is accurate to ~70 mas (Cutri et al. 2003). The position and error listed is that for the NGC 3151 photocenter from the 2MASS point source catalog (Skrutskie et al. 2006). The 0.5–7 keV Chandra X-ray nuclear component was obtained from the Chandra Source Catalog (Evans et al. 2010). The localization of any potential AGN-related nucleus is limited by the fact that there is no nuclear point source, only a plateau of X-ray emission in the core of this galaxy (Wong et al. 2011). The X-ray reference tie is as quoted by Evans et al. (2010) for the 1σ external astrometric error. While the absolute astrometry of Gemini (used by Menezes et al. 2014) is about as accurate as that of Chandra, the astrometrically corrected position information was not reported by Menezes et al. (2014). The AGN and bulge reported by Menezes et al. (2014) are relative positions in the frame of their observation, thus we do not show these errors in Figure 4.

Menezes et al. (2014) fit the 2D kinematic profiles of the data in order to obtain a position measurement for the offset broad Hα emission line that indicates the presence of an AGN. They compare this position to the kinematic center of the galaxy (as determined by the velocity dispersions in that region) as well as the stellar bulge center (they equate the image of their collapsed data cube as representing the center of the stellar bulge) and determine that the AGN is coincident with neither the kinematic nor stellar bulge centers of NGC 3115.

In their analysis, Menezes et al. identified an offset of ∼290 ± 50 mas (∼14.3 ± 2.5 pc), with the uncertainties determined using a Monte Carlo simulation. They determine that the kinematic center is coincident with the stellar bulge center; however, they do not report an absolute position of either the kinematic center, bulge center, or offset AGN. Based on observation headers that are not likely astrometrically corrected, the Gemini pointing center (directed at the stellar bulge center) was at a position of J2000 R.A., decl. 10:05:13.80, −07:43:08.00 (R. Menezes 2019, private communication). The position of the off-centered AGN is reported as ∼260 mas east and 130 mas north from the stellar bulge center, giving an uncorrected AGN position of J2000 R.A., decl. 10:05:13.82, −07:43:07.87.

The relative positions and net position errors are displayed atop 2MASS contours in Figure 4. The AGN detected by Menezes et al. (2014) is offset 1′′84 from our detected radio source, and their position measurement of the stellar kinematic center is 2″89 from the 2MASS photocenter; thus, there are clear residual absolute astrometry offsets in the observations of Menezes et al. (2014).

4. Discussion and Conclusions

4.1. Where is the Radio AGN in NGC 3115?

As shown in Figure 4, the position of our radio AGN agrees with the stellar bulge center as indicated by 2MASS, to significantly less than the separation between the offset between the bulge and AGN measured by Menezes et al. As such, it appears that the black hole related to this radio AGN is likely resident in, and not offset from, the galaxy center. As seen in Figure 4, the position listed in the Menezes et al. FITS data file header do not appear to have any absolute astrometric correction applied. Regardless, if the bulge center were shifted to the 2MASS position, it is clear that the radio AGN is not colocated with the purported offset AGN.

4.2. Does NGC 3115 Contain a Binary, Offset, or Singular Central AGN?

Based on the relatively flat spectrum of the radio AGN and its colocation with the stellar bulge, it is clear that NGC 3115 does not contain a singular offset (recoiling or wandering) AGN.

It is possible that the position-offset Hα line does represent a separate SMBH, in which case the offset system may still be undergoing inspiral after a previous merger. Assuming this SMBH has a mass $\gtrsim 10^8 M_\odot$, the dynamical friction timescale of such an object at this separation is on the order of 100 kyr, thus relatively short but not so infeasible to have detected it at
this state of inspiral (Lacey & Cole 1993). The 2D kinematic measurements of Menezes et al. demonstrated some support for this argument, indicating that the iscontours of velocity dispersion demonstrated an elongated, elliptical shape, rather than showing a singular peak at the photometric center. However, the elongation was not along the axis of the AGN offset, suggesting some ongoing mobility of this secondary SMBH in the system under this hypothesis. There are no other large-scale indications that NGC 3115 underwent a merger in the last few gigayears.

Finally, it is possible that NGC 3115 simply contains a single, centrally located low-luminosity AGN that is giving rise to the radio source and some component of the central X-ray emission. If the offset source is indeed its own AGN, it appears to have no associated radio emission.

M.L.J. and S.B.S. are members of the NANOGrav Physics Frontiers Center which is supported by NSF award 1430284. S.B.S. is supported by NSF EPSCoR award number 1458952. We thank R. B. Menezes for providing helpful clarifications about the Gemini observations we discuss in this report. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Software: CASA (McMullin et al. 2007).

ORCID iDs
Megan L. Jones @ https://orcid.org/0000-0001-6607-3710
Sarah Burke-Spolaor @ https://orcid.org/0000-0003-4052-7838
Kristina Nyland @ https://orcid.org/0000-0003-1991-370X
Joan M. Wrobel @ https://orcid.org/0000-0001-9720-7398

References
Arzoumanian, Z., Baker, P. T., Brazier, A., et al. 2018, ApJ, 859, 47
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Natur, 287, 307
Blecha, L., Civano, F., Elvis, M., & Loeb, A. 2013, MNRAS, 428, 1341
Blecha, L., Sijacki, D., Kelley, L. Z., et al. 2016, MNRAS, 456, 961
Burke-Spolaor, S. 2011, MNRAS, 410, 2113
Campanelli, M., Lousto, C. O., Zlochower, Y., & Merritt, D. 2007, PhRvL, 98, 231102
Cantiello, M., Capaccioli, M., Napolitano, N., et al. 2015, A&A, 576, A14
Cantiello, M., D’Abrusco, R., Spavone, M., et al. 2018, A&A, 611, A93
Chiaberge, M., Ely, J. C., Meyer, E. T., et al. 2017, A&A, 600, A57
Cutri, R. M., Skrutskie, M. F., Van Dyk, S., et al. 2003, Explanatory Supplement to the 2MASS All Sky Data Release and Extended Mission Products, nasa/IPAC Infrared Science Archive, http://www.ipac.caltech.edu/2mass/releases/allsky/doc/
Evans, I. N., Primini, F. A., Glotfelty, K. J., et al. 2010, ApJS, 189, 37
Gületekin, K., Richstone, D. O., Gebhardt, K., et al. 2009, ApJ, 698, 198
Komossa, S. 2012, AdAst, 2012, 364973
Komossa, S., Zhou, H., & Lu, H. 2008, ApJL, 678, L81
Kormendy, J., & Richstone, D. 1992, ApJ, 393, 559
Lacey, C., & Cole, S. 1993, MNRAS, 262, 627
Lena, D., Robinson, A., Marconi, A., et al. 2014, ApJ, 795, 146
Lin, D., Irwin, J. A., Wong, K.-W., et al. 2015, ApJ, 808, 19
Lützgendorf, N., Helm, E. v. d., Pelupessy, F. I., & Portegies Zwart, S. 2016, MNRAS, 456, 3645
Margutti, R., Berger, E., Fong, W., et al. 2012, ApJ, 756, 63
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
Menezes, R. B., Steiner, J. E., & Ricci, T. V. 2014, ApJL, 796, L13
Padovani, P. 2016, A&ARv, 24, 13
Padovani, P., Bonzini, M., Kellermann, K. I., et al. 2015, MNRAS, 452, 1263
Perley, R. A., & Butler, B. J. 2013, ApJS, 204, 19
Postman, M., Lauer, T. R., Donahue, M., et al. 2012, ApJ, 756, 159
Rodriguez, C., Taylor, G. B., Zavala, R. T., et al. 2006, ApJ, 646, 49
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1161
White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479
Wong, K.-W., Irwin, J. A., Yukita, M., et al. 2011, ApJL, 736, L23
Wrobel, J. M., & Nyland, K. 2012, AJ, 144, 160