Observing the Time Evolution of the Multicomponent Nucleus of 3C 84

Brian Punsly1,2,* 1 1415 Granvia Altaimira, Palos Verdes Estates, CA 90274, USA; brian.punsly@cox.net
2 ICRANet, Piazza della Repubblica 10 Pescara I-65100, Italy

Abstract

The advent of global millimeter-band very long baseline interferometry (VLBI) in recent years has finally revealed the morphology of the base of the two most prominent nearby, bright, extragalactic radio jets in M87 and 3C 84. The images are quite surprising considering the predictions of jet theory and current numerical modeling. The jet bases are extremely wide compared to expectations, and the nucleus of 3C 84 is very complicated. It appears as a large, low-frequency radio halo (not anticipated in seminal works on simple jet theory (Giovannini et al. 2018; Kim et al. 2018; Punsly 2019)) that was subsided in the 1990s, but a triple is distributed primarily along the east–west direction with a triple nucleus with 30 μas–4 mas scales. We explore the emergence of an (east–west) double nucleus in the lower-resolution 43 GHz Very Long Baseline Array (VLBA) imaging from 2018 August to 2020 April. The double nucleus is marginally resolved. We exploit the east–west resolution associated with the longest baselines, ~0.08 mas, to track a predominantly east–west separation speed of ∼0.086 ± 0.008c. We estimate that the observed mildly relativistic speed persists over a deprojected distance of ~1900–9800 times the central, supermassive black hole gravitational radius (~0.3–1.5 lt-yr) from the point of origin.

Unified Astronomy Thesaurus concepts: Radio loud quasars (1349); Radio jets (1347); Relativistic jets (1390)

1. Introduction

The galaxy NGC 1275 harbors the radio source 3C 84 with both a parsec-scale jet and a kiloparsec-scale jet, as well as a large, low-frequency radio halo (Pedlar et al. 1990; Walker et al. 2000). It has been the brightest extragalactic radio source at high frequency with flux densities of 45–65 Jy in 1980 at 270 GHz and ~40–50 Jy at 90 GHz from 1965 to 1985 (Nesterov et al. 1995). The flare subsided in the 1990s, but a new strong flare began in 2005 (Nagai et al. 2010; Trippe et al. 2011). Due to its proximity (z = 0.0176) and its brightness, 3C 84, along with M87, is the best candidate for resolving the jet near the launching region with high-frequency very long baseline interferometry (VLBI). High-resolution observations of M87 and 3C 84 have displayed extremely wide jet opening angles within 0.1 mas of the core, ~127° and 138°, respectively, and both jets are extremely edge brightened near the base (Giovannini et al. 2018; Kim et al. 2018; Punsly 2019). The large degree of edge brightening and the enormous (the maximum possible geometrically is 180°) opening angles were not anticipated in seminal works on simple jet theory (Blandford & Kónigl 1979). Numerical models of jet formation have been designed to explain these extreme properties in M87. It was hoped that choosing lines of sight (LOSs) that are nearly aligned with the jet axis and plasma emissivity/plasma enthalpy profiles (injected by numerical researchers) that were specifically designed to produce the high-resolution radio images would resolve the conflict (Mościbrodzka et al. 2016; Chael et al. 2019). However, current numerical simulations still produce synthetic jet images that are far too narrow and not nearly edge brightened enough near their bases when compared directly to the highest-resolution interferometric images of the jet base (Punsly 2019). This wide base seems to abruptly transition to a highly collimated inner jet. The power-law fit to the jet width, W(z), as a function of axial displacement along the jet, z, is W(z) ∝ z^k, k = 0.230 ± 0.049 for 0.06 mas < z < 0.3 mas in M87, even though the jet might be parabolic (k = 0.5) at larger z (Punsly 2019). A similar abrupt transition also seems to occur in the jet of 3C 84 juxtaposed to its wide base; see Giovannini et al. (2018) or Figures 9 and 10 of this paper. Furthermore, 3C 84 was shown to have a triple nucleus in the highest-resolution radio observation, 30 μas, performed with RadioAstron at 22 GHz10 (Giovannini et al. 2018). The triple is distributed primarily along the east–west direction roughly orthogonal to the jet that is directed toward the south and is defined by two bright ridges, beginning 150 μas to the south (see the schematic diagram in Figure 1). These circumstances suggest that there is jet launching physics to be discovered with the high resolution of VLBI, and not just the verification of existing theory.

Thus motivated, this study explores the nature of the multicomponent nucleus that has been seen with the highest-resolution VLBI, ~30 μas in the east–west direction with RadioAstron on 2013 September 21–22 (Giovannini et al. 2018). Our method is to use the lower-resolution 7 mm Very Long Baseline Array (VLBA) data that are created for the

**10** We define the multiplicity of the nucleus, i.e., double or triple, as the apparent number of components that can be discerned from visual inspection of the image. This designation is a function of the resolution of the telescope. If the resolution were much higher, then there could be many small components that could not be seen at lower resolution.
The purpose of approximately monthly monitoring by a Boston University–based research effort, the VLBA-BU Blazar Monitoring Program (Jorstad et al. 2017). Thus, we can, in principle, detect time evolution of the nuclear region. A partially resolved double nucleus has appeared in the CLEAN images from 2018 August 26 to 2020 April 7. We rely on the publicly available files from the BU website to extract the highest-resolution data, corresponding to the longest baselines associated with the 43 GHz VLBA.

We begin with a description of the very complex nuclear inner light year of the jet that has been revealed in recent high-resolution VLBI campaigns. Figure 1 is a schematic diagram of the numerous nuclear features that have been detected in this nearby very bright radio source. A schematic is much clearer than overlaying numerous images made at various frequencies. An approximate scale is indicated at the bottom, in both angular size and physical dimension (projected on the sky plane). The primary feature is the triple nucleus (enclosed by the ellipse) from the 22 GHz RadioAstron observations (Giovannini et al. 2018). This region is the focus of this study. This nuclear feature is apparently not time stationary. A more recent 86 GHz global VLBI observation on 2015 May 16 revealed this region to be a double nucleus along the east–west direction (Kim et al. 2019). With 43 GHz VLBA, a double nucleus has never been identified previously. Based on the aforementioned higher-resolution VLBI, the east–west separation is \( \sim 0.1–0.15 \) mas, similar to the nominal east–west restoring beam of the uniformly weighted 10-station VLBA of 0.15 mas. Thus, we expect to see partially resolved structure in epochs of wide separation.

Figure 1 shows other complicating features as well and helps to illustrate the ultimate goal of finding a unifying picture that incorporates all of these important elements. First, there is the faint counterjet that has been seen at numerous frequencies (Walker et al. 2000; Lister 2001; Fujita & Nagai 2017). Then, there are the very prominent east and west ridges that frame the jet headed to the south. They are of varied prominence from epoch to epoch and observation to observation. In the high-resolution 22 GHz RadioAstron observation they are significantly brighter than the almost hollow interior of the jet. This “double rail” configuration has also been seen with 43 GHz VLBA (Nagai et al. 2014). A similar double rail configuration has been detected in high-resolution VLBI images of M87 adjacent to the nucleus as well (Hada et al. 2014; Kim et al. 2018). The most curious aspect of these ridges in the 43 GHz BU VLBA monitoring data is that most of the time one ridge is much brighter than the other for periods of time that last years. The fundamental question that we wish to gain some insight into is, what is the relationship between the multiple east–west nucleus and these vacillating bright ridges of emission that emerge almost orthogonal to the axis of nuclear emission, in the southern direction?

Some of these features are evident in the magnified views of the nuclear region from the total intensity images taken from the BU website in Figure 2. We note one other aspect of the nuclear region. A modest feature has emerged to the west of the nuclear region from the total intensity images taken from the BU website in Figure 2. We note one other aspect of the nuclear region. A modest feature has emerged to the west of the 2018, about 0.25 mas away. It appears to be real because it is persistent and is seen a few contours above the noise level. It also seems to be stationary. With all the components emerging in almost every direction, the situation is not well explained by a simple pencil-beam jet. We are actually getting close to the jet-launching region, so we are starting to uncover some of the messy details of the physical mechanism. We do not attempt to resolve these complexities in the present paper. We take a more modest approach and merely try to establish and quantify the rate of nuclear expansion within the central ellipse of Figure 1.

Section 2 describes our methods of extracting the nuclear separation from the data. In Section 3, we describe how we use the CLEAN component (CC) models from the BU program to extract the east–west resolution associated with the longest baselines. Section 4 presents our estimate of the apparent speed of separation of the double nucleus. In Section 5, we explore the nontrivial methods of fitting the nuclear components in the \((u, v)\)-plane using Gaussian models. In Section 6, we compare the nuclear configuration observed by the 43 GHz VLBA in 2018–2020 with the nuclear triple observed by RadioAstron in 2013. Throughout this paper, we adopt cosmological parameters \( H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_L = 0.714, \) and \( \Omega_m = 0.286 \) and use Ned Wright’s Javascript Cosmology Calculator website (Wright 2006). In our adopted cosmology we use a conversion of 0.360 pc to 1 mas.
The nucleus in the 43 GHz image starts elongating in the east–west direction in 2018 August. The nucleus appears almost fully resolved by 2019 November. The eastern component seems to veer toward the large-scale southerly directed jet in the 2020 images. The details of the degree of degradation of many compromised observations in 2019 can be found in Table 1. The 2019 June and July images reflect the significant degradation indicated in Table 1. The contours start from 10 mJy beam$^{-1}$ and increase in steps of 2× in all the plots. The restoring beam is indicated by the cross in the lower left corner.

**Figure 2.** The nucleus in the 43 GHz image starts elongating in the east–west direction in 2018 August. The nucleus appears almost fully resolved by 2019 November. The eastern component seems to veer toward the large-scale southerly directed jet in the 2020 images. The details of the degree of degradation of many compromised observations in 2019 can be found in Table 1. The 2019 June and July images reflect the significant degradation indicated in Table 1. The contours start from 10 mJy beam$^{-1}$ and increase in steps of 2× in all the plots. The restoring beam is indicated by the cross in the lower left corner.
### 2. Method of Estimating Nuclear Expansion

It is fortuitous that the nucleus expands primarily in the east–west direction; this is also the direction of maximum resolution of the VLBA at 43 GHz (the major axis of the restoring beam has a position angle of −10°). The FWHM of the beam is approximately 0.28 mas × 0.15 mas for uniformly weighted (u, v) data. However, when the data have sufficiently high signal-to-noise ratio (S/N), the interferometer can resolve structures significantly smaller than the nominal beam size. In our case the longest baselines provide a typical resolution of approximately 0.08 mas in the east–west direction. The resolution of the interferometer is defined here as the FWHM of a circular Gaussian brightness distribution that gives a visibility amplitude of 50% times the zero-baseline value. Mathematically, this is expressed as resolution = (91 \( \text{M} \lambda / \text{baseline length} \)) mas (Marscher 1985). It is known that higher resolution can be achieved by analyzing the visibility domain, and these resolution limits depend on the noise in the (u, v)-plane (Martí-Vidal et al. 2012). However, working in the image plane has the advantage of less ambiguity as to whether the model chosen for the source is appropriate (Fomalont 1999). Since we are measuring small changes to a small separation on a complex background, the ambiguities in the models can cause a significant degradation of accuracy. In Appendix A, we provide simulations in the visibility domain to motivate the Marscher (1985) resolution limit as appropriate to this study. These simulations incorporate all the details of the observations that degrade the very high resolution limits achievable with the model fitting of the visibility data with near-perfect circumstances. We incorporate the (u, v) coverage, S/N, and the complexity of the source structure. Even though this analysis is in the (u, v)-plane, “analysis of a properly made CLEAN image via good analysis techniques should produce values and errors which are equal to those of model fitting visibility data” (Fomalont 1999). The CC-based method utilized in this paper will be shown to be an example of a “good analysis technique” in the image plane. We are able to find Gaussian fitting methods in Section 5 that yield similar resolution limits to our CC-based methods. This forms a bridge between the simulations in Appendix A and the CC-based method presented here.

So, in theory, there is information within the observations that can resolve east–west features larger than 0.1 mas, provided that their S/N is high. The 0.28 mas × 0.15 mas uniformly weighted restoring beam is too large to do this cleanly; the resultant blurring prevents a clear east–west determination. The images in Figure 2 show this to be the case, as there appear to be two heavily blurred components that are separating over time. We need to extract these partially resolved structures from the observations in order to quantify the east–west separation over time. There are three possible methods: super-resolved images based on a restoring beam smaller than the central peak of the conventional interferometer beam, direct analysis of the CC model, and fitting the visibilities with simple models of the core structure. The super-resolved images highlight the multiple nuclei but create large artifacts at angles more than 45° from the east–west direction. The net result is a suggestive image, but Gaussian fits to the multiple components fail to converge to a unique decomposition. The same circumstances exist with efforts to fit the visibilities with simple Gaussian models (see Section 5). The other alternative is to use the CC models. Even though the models cannot be considered robust in a single epoch, they should be suitable for identifying a trend that persists over time, especially with regard to very bright features as is the case here. This is the primary guiding principle of the following analysis.

Before describing our models, we first note that most observations in 2019 are degraded to varying degrees by bad weather, down observing stations, and inaccurate antennae pointing. The issues are summarized in Table 1. Modest degradation of observations in 2019 adversely affected the CC models, and one of the main tasks of this analysis is to quantify this degradation in terms of an uncertainty in our results.

| Date       | Missing Stations | Severely Compromised Stations | Comments | Quality |
|------------|------------------|-------------------------------|----------|---------|
| 2019 Feb 3 | MK and BR        | ...                           | East–west resolution severely degraded | unusable |
| 2019 Feb 8 | NL               | BR and HN much data deleted due to bad weather | Only ~7 stations disperses the distribution of CCs in image plane | unusable |
| 2019 Mar 31| HN               | LA missing half of the data | Good east–west resolution from SC and MK, low S/N | usable |
| 2019 May 12| SC               | ...                           | MK and HN still provided | usable |
| 2019 Jun 18| SC               | ...                           | Inaccurate pointing of the antennae, low S/N | usable |
| 2019 Jul 1 | SC               | ...                           | Inaccurate pointing of the antennae, low S/N | usable |
| 2019 Oct 19| BR               | ...                           | low S/N | usable |

Note. Details of the observations generously provide by A. Marscher, 2019. Station acronyms: MK (Maunakea), BR (Brewster, Washington), NL (North Liberty, Iowa), HN (Hancock, New Hampshire), LA (Los Alamos, New Mexico), SC (St. Croix).
October 15 and 2018 December 9, which appears as increasing elongation of the nucleus toward the east in Figure 2. The spacing between the peaks keeps increasing, and on 2019 March 31 and 2019 May 12 there are clearly two distinct components in the image plane. Notice that 2019 January 10 has a different cross section with just a single peak. This is out of family with the other epochs, including the epoch just before and the epoch just after in December and March, respectively. Consequently, we analyze this observation separately in Appendix B in order to assess the reason that the uniform cross-sectional procedure failed to pick up the second peak and nature of the root cause.

3. The CLEAN Component Models

CC models are provided for each observation epoch on the BU website. During the first year of monitoring in Figure 2, the western component of the double nucleus (WN hereafter) is brighter and fortunately is predominantly a tight east–west distribution of the bright CCs that always includes the brightest CC. We face two primary technical issues that we illustrate in Figure 4 with four examples. The issues are as follows:

1. How should the cluster of components be defined for both the eastern component of the nucleus (EN hereafter) and the WN?
2. How do we define the coordinates of the cluster of components and the uncertainty in this location?

We explore these issues below.

3.1. Defining the Clustering of the CLEAN Components

This is a slightly subjective exercise at times in which we use the visual evidence from Figures 2 and 3 and the structure of the components in the previous epoch and the subsequent epoch. The peak surface brightness is about 1.5–3.0 Jy beam$^{-1}$ in each image. We consider any CC with a flux density larger than $\sim$20–35 mJy as significant. This varies depending on the quality of the observation. This choice typically scales with the magnitude of the strongest negative contour in the FITS image file (see Table 2). In practice, components less than 40 mJy never contribute significantly to our flux-density-related results (component centroids and uncertainties). Figure 4 plots all the components larger than 20 mJy in the vicinity of the nucleus in

Figure 3. East–west intensity cross sections created from the CLEAN images. They are fixed in the north–south direction by locating them to pass through the peak intensity. Notice the emergence of a local maximum to the east of the peak on 2018 August 26. A double peak is clearly seen on 2018 October 15. A third local maximum emerges in 2019 October. Notice that 2019 January 10 has a different cross section with just a single peak. This epoch requires special attention (see Appendix B).
four epochs. The red ellipse defines all the components that we associate with the WN, and the blue ellipse encapsulates all the components associated with the EN. We crudely estimate that the east–west spread of the CCs in the WN and EN will be distributed within a length <0.1 mas. This follows from deconvolving the 0.1 mas FWHM restoring beam from the FWHM of the intensity cross-section peaks in Figure 3. We get 20 estimates of the FWHM of peaks that range from 0.023 to 0.112 mas with a mean of 0.076 mas. Truncating the east–west width of the CC distribution <0.1 mas is the fundamental constraint for estimating which components should be included in the WN and EN. This approximate limit guarantees that the sizes of the distributions of CCs in the EN and WN are small enough that the nuclear components can be clearly differentiated in our efforts to estimate separations as small as 0.1 mas. If this condition is not obeyed by the data, then the CC clustering method cannot be used to measure the smallest separations, ∼0.1 mas. A priori we do not know whether this assumption is consistent with the data. Ultimately, this assumption is verified empirically. For example, we present seven CC scatter plots of the nuclear region in Figures 4 and 7–9. There is a strong tendency for the adjacent background to be almost devoid of any CCs above 20 mJy in the surrounding regions, as well as regions that exist between clusters of strong CCs ≤0.1 mas across in the east–west direction. The north–south resolution is worse, making the constraint on the north–south distribution of CCs comprising the WN and EN more subjective in nature. The north–south distributions of CCs in Figures 4 and 7–9 also seem to naturally cut off at a size <0.15 mas, similar to the resolution of the longest north–south baselines (∼0.13–0.14 mas).

The details of our CC models of the WN and EN can be found in Table 2. The first two columns are the date of the observation and the number of days since the nuclear separation was first detected. This is not the same as the time from the epoch of physical separation due to the finite resolution of the array. The next two columns are the flux densities of the WN and EN and the total of these numbers, respectively. The absolute flux calibration accuracy of the BU data is about 5% (Jorstad et al. 2017). Column (5) provides the properties of the uniformly

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**Figure 4.** Location of the nuclear CCs in four epochs. The two examples in the top row are used to illustrate our methods of defining which CCs determine the WN and EN. The WN and EN are defined by the CCs enclosed within red and blue ellipses, respectively. The red and blue triangles are the corresponding centroids of the flux density for each physical component. The details of these constructions are provided in the text. Note that the CCs outside the solid ellipses are weak (20–35 mJy) and do not affect the centroid estimates, but we cut the CC distribution off once it approaches 0.1 mas in east–west width as motivated in the text. The two examples in the bottom row show the emergence of a weaker (green) component in the fall of 2019. We consider EN as the first ejection, ejection A, and the green cluster of CCs as a second ejection, ejection B.

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12 Normally, the VLBA-BU-BLAZAR fluxes are accurate to within ∼5%, but from early 2019 to 2019 September it is quite a bit more uncertain, at least 30%, because of pointing errors. Given the diffuse nature of 3C 84, we can only roughly estimate corrections through use of the Metsähovi monitoring program fluxes at 37 GHz (for a description of the Metsähovi monitoring, see Teräsranta et al. 2004). The VLBA resolves out too much of the structure to do that accurately, as we can for more compact sources.
Table 2
Details of the CLEAN Component Models of the Double Nucleus

| Date      | Day | $F_{\nu, WN}$ | $F_{\nu, EN}$ | Uniformly Weighted Beam (Naturally Weighted Beam) | $I_{\text{peak}}$ | Min. Neg. | Smallest | $\Delta$R.A. | $\Delta$Decl. | Separation |
|-----------|-----|---------------|---------------|--------------------------------------------------|-------------------|----------|----------|-------------|--------------|------------|
|           |     |               |               | Size/PA (mas/deg$^{-1}$)                          | (Jy beam$^{-1}$)  | (mas)    | (mas)    | (mas)      | (mas)        | (mas)      |
|           |     |               |               |                                                  | (mas)             | (mas)    | (mas)    | (mas)      | (mas)        | (mas)      |
| 2018 Aug 26 | 0   | 1.448         | 0.479         | $0.303 \times 0.179/\pm 11.0$ ($0.370 \times 0.231/\pm 13.3$) | 1.572            | -15      | 20       | 0.116 ± 0.013 | 0.010 ± 0.021 | 0.116 ± 0.013 |
| 2018 Oct 15 | 50  | 1.856         | 0.838         | $0.314 \times 0.154/\pm 3.6$ ($0.352 \times 0.175/\pm 1.1$) | 2.462            | -14      | 25       | 0.133 ± 0.011 | 0.001 ± 0.022 | 0.133 ± 0.011 |
| 2018 Dec 9  | 105 | 2.707         | 1.441         | $0.345 \times 0.166/\pm 14.9$ ($0.381 \times 0.190/\pm 10.3$) | 2.875            | -10      | 20       | 0.144 ± 0.013 | -0.030 ± 0.024 | 0.147 ± 0.014 |
| 2019 Jan 10 | 137 | 3.349         | 1.079         | $0.361 \times 0.160/\pm 21.4$ ($0.405 \times 0.187/\pm 21.0$) | 2.974            | -15      | 20       | 0.147 ± 0.014 | -0.075 ± 0.024 | 0.178 ± 0.012 |
| 2019 Mar 31 | 217 | 1.325         | 0.901         | $0.306 \times 0.153/\pm 8.9$ ($0.344 \times 0.185/\pm 7.4$) | 2.204            | -24      | 25       | 0.175 ± 0.011 | -0.031 ± 0.021 | 0.183 ± 0.015 |
| 2019 May 12 | 259 | 1.356         | 0.894         | $0.407 \times 0.176/\pm 13.2$ ($0.435 \times 0.197/\pm 10.8$) | 2.064            | -17      | 20       | 0.178 ± 0.014 | -0.045 ± 0.028 | 0.183 ± 0.015 |
| 2019 Jun 18 | 296 | 2.337         | 0.799         | $0.397 \times 0.183/\pm 16.4$ ($0.432 \times 0.211/\pm 14.5$) | 2.462            | -29      | 35       | 0.173 ± 0.015 | 0.003 ± 0.027 | 0.173 ± 0.015 |
| 2019 Jul 1  | 309 | 3.448         | 2.116         | $0.425 \times 0.175/\pm 14.3$ ($0.434 \times 0.210/\pm 12.9$) | 4.030            | -36      | 35       | 0.149 ± 0.014 | 0.019 ± 0.029 | 0.150 ± 0.014 |
| 2019 Oct 19 | 419 | 0.793         | 0.823         | $0.329 \times 0.142/\pm 5.2$ ($0.386 \times 0.159/\pm 8.3$) | 1.840            | -29      | 35       | 0.193 ± 0.010 | -0.043 ± 0.023 | 0.198 ± 0.011 |
| 2019 Nov 3  | 434 | 0.973         | 0.988         | $0.318 \times 0.153/\pm 3.6$ ($0.387 \times 0.183/\pm 0.6$) | 1.490            | -13      | 20       | 0.206 ± 0.011 | -0.030 ± 0.022 | 0.208 ± 0.011 |
| 2020 Jan 4  | 496 | 1.311         | 1.268         | $0.330 \times 0.165/\pm 2.1$ ($0.399 \times 0.205/\pm 0.1$) | 1.633            | -13      | 20       | 0.220 ± 0.012 | -0.067 ± 0.023 | 0.230 ± 0.013 |
| 2020 Apr 7  | 590 | 1.634         | 1.613         | $0.316 \times 0.144/\pm 4.5$ ($0.342 \times 0.160/\pm 6.4$) | 2.127            | -10      | 20       | 0.238 ± 0.010 | -0.068 ± 0.022 | 0.248 ± 0.012 |
weighted beam on top and the naturally weighted beam below in parentheses. Column (6) is the peak intensity from the CLEAN images (Figure 2) for comparison with the numbers in the previous columns. Columns (7) and (8) are the largest-magnitude negative contour values from the CLEAN image and the CC cutoff used in our models, respectively. Columns (9)–(11) are the uncertainties in the nuclear separation that are computed per the methods of Section 3.2.

First, let us consider the epoch of 2018 August 26. Since the absolute astrometry is lost in the phase self-calibration step of the VLBI data reduction, we are only interested in the relative positions of the EN and WN, and we place the brighter WN at the origin. We include all the CCs within a region $\leq$0.1 mas in the east--west direction. The blue (red) ellipse encircles all the CCs that are associated with the EN (WN). The EN involves considerably weaker CCs than the WN, and the distribution tends to be more elongated in the north–south direction. This is typical during the first year of our monitoring of the time evolution of the nuclear region. The 2019 May 12 observation in the top right panel of Figure 4 shows a larger separation between the EN and WN.

The bottom two panels of Figure 4 show the emergence of a third component in the fall of 2019. It was clearly seen in the 2019 October observation, but the S/N was poor, so we show the high-S/N epochs of 2019 November and 2020 January. The bottom right panel shows that the centroids of the three clusters of CCs (see the next subsection) are nearly colinear. Thus, it makes sense to consider them all part of the same flow. As such, we tentatively relabel the three components as follows. Based on the early epochs, the WN is associated with the point of origin. It is the brightest feature in 2018, and the much weaker EN seems to flow out of the partially resolved cluster in the time frame of August to December. We therefore consider the EN as the first ejection, or ejection A. In the fall of 2019, the new feature shown inside the green ellipse is about half the brightness of the EN and WN; we call it ejection B. We actually never see it separate from the WN, so this scenario is not verified, but suggested by the pattern evolution. We cannot rule out that the red ellipse represents a new ejection in the western direction and the green component is the point of origin. This is disfavored because it would require the EN to be contracting toward the point of origin and the point of origin would change from being a much brighter component than the EN to much fainter than the EN.

3.2. The Position of the Features

We calculate the position of the features by taking the flux-density-weighted mean (centroid) of the CC positions in the feature. In Figure 4, the red triangle inside the red ellipse and the blue triangle inside the blue ellipse are the locations of the centroids of the flux density of the CCs encapsulated within each ellipse. We assign an uncertainty to the centroid location. The origin of the coordinates will be the centroid of the WN, and all displacements are measured relative to this. The uncertainty in the positional locations is $\sim$10% of the synthesized beam FWHM for these bright components (Lister et al. 2009). In Table 2, the uncertainties in coordinate separation, $\sigma_{\Delta X}$ and $\sigma_{\Delta Y}$ ($X$ is R.A. and $Y$ is decl.), are the uncertainties on the individual centroid coordinates added in quadrature. Similarly, the uncertainty of the total displacement between the EN and WN, $\sigma_{\Delta d}$, is calculated as the error propagation of the centroid uncertainties. The random noise contribution to the separation uncertainty can be estimated by $\sigma_{\Delta d} (\text{noise}) \approx 0.5 d \sqrt{\sigma_{\text{rms}}/S_{\text{peak}}}$, where $\sigma_{\text{rms}}$ is the post-fit rms noise of the image and $S_{\text{peak}}$ is the flux density of a putative unresolved component of size $d$ (Fomalont 1999; Lee et al. 2008). $\sigma_{\text{rms}} < 1$ mJy for all epochs except 2019 June and July, where it is closer to 2 mJy. We determine in Table 2 that $S_{\text{peak}} > 479$ mJy, so all the S/N are $>500$ except 2019 June, which is $>400$. It is therefore clear that positional uncertainty is not dominated by the random noise component. The error estimate adopted in Table 2 is much more conservative than stochastic noise errors and incorporates systematic uncertainty.

4. The Separation Rate of the Double Nucleus

The motivation for defining the locations of the EN and WN and the corresponding uncertainty is to track the time evolution of the separation of the components. This is performed in Figure 5. The top left panel is the plot of the displacement versus time. However, we note that the displacement is primarily east--west and the highest resolution is in this direction. We plot east--west (x direction) displacement in the top right panel for direct comparison to the intensity cross sections in Figure 3.

The data were fit by a least-squares fit with uncertainty in the vertical variable (Reed 1989). The solid line is the fit, and the dashed lines represent the standard error to the fit. Based on the fit and standard error, the time-averaged nuclear separation speed is $0.086 \pm 0.008c$. The fit to the total displacement yields a separation rate of $73 \pm 7 \mu\text{as yr}^{-1}$ compared to $70 \pm 6 \mu\text{as yr}^{-1}$ for pure east--west displacement. Note that we also plot (in green) the separation of the second ejection, ejection B, in the lower right corner of the two panels. We also provide very crude, four point, fits to the ejection velocity.

It is apparent that the EN–WN separations in the spring and summer of 2019 (days 217–309) deviate from the least-squares fits in Figure 5. This is not unexpected from Tables 1 and 2. These are the most compromised observations. However, the 2019 July estimated separation lies particularly far from the fit. It is possible to explain this behavior as being due to the ejection “B” that is shown in the bottom panels of Figure 4. This central component is resolved from EN and WN in our CC cluster models first in 2019 October, but it is most likely present already in earlier epochs. If this is indeed the case, then we may just not resolve it in 2019 July, but it is there and it blends with WN, moving its measured position slightly toward EN. This can cause the small inward motion seen at that epoch. The results of this paper do not rely on this interpretation.

By considering the east--west displacement, we are able to directly compare the results of the intensity profile description in Figure 3 with the CC models of the EN and WN in Section 3. The distribution of intensity cross-section separations is generally consistent with both the standard error of the least-squares fit and the uncertainty of the CC model fits to the EN–WN separation (the measurement uncertainty given in Table 2) except for two regions, in 2019 June and July, for which the S/N was poor, and the last two points, 2020 January and April. Figure 2 and the bottom panel of Figure 5 seem to indicate that, beginning in 2020 January, the EN no longer appears to follow a predominantly east--west trajectory, but begins to veer southward toward the southerly directed large-scale jet. The EN appears to propagate in a southeasterly direction rather than an easterly direction. Thus, a pure
The east–west cross section is unable to properly capture the intensity peaks of both components. The situation is more extreme in April, and this could cause the measurement using the intensity cross section to be less than the true east–west displacement. This circumstance illustrates the limitation of the simple east–west cross-section method of measuring separation if the trajectory curves.

For the sake of completeness, we plot the southern displacement of the EN as it separates from the WN in the bottom panel of Figure 5. The putative trend is far less pronounced than the east–west separation, and the uncertainty is much larger (the synthesized beam is elongated in this direction). Consequently, there is no robust quantitative assessment that can be made owing to the limitations of the CC-based method of this paper.

One can also perform a long extrapolation back in time (assuming that the separation velocity was approximately constant in time) of the linear fits in order to find the epoch of zero separation from the nucleus. From Figure 5, we have that ejection A, the WN, emerged on 2017 January 1, with a large uncertainty that places it anywhere between 2016 September 21 and 2017 March 22. We can crudely estimate the zero separation epoch for ejection B as 2017 November 6. The two ejections originated at least 7 months apart and represent two distinct nuclear events. Our estimate of the 2017 January 1 ejection is not tightly constrained, but we would be remiss not to mention that there was a major gamma-ray flare reaching TeV energies that was detected by the Large Area Telescope on board the Fermi satellite and MAGIC telescopes that peaked around 2016 December 31 to 2017 January 1 (Baghmanyan et al. 2017; Ansoldi1 et al. 2018).

5. The Double Nucleus in the (u, v)-plane

It is customary for astronomers to fit the visibility data with a small number of Gaussians in order to track component
separations. Thus, we explore the possibility of evidence of the double nucleus in the \((u, v)\)-plane by making Gaussian fits to the nuclear region. However, there are two concerns for this method in the context of the separating nuclear features in Figure 2. First, the radio source 3C 84 is extremely complex compared to a typical blazar nucleus, and it is extended. So, one needs to use a CC model to represent it, but that creates a problem regarding how large of an area around the core should be cleared from CCs before model fitting. This is always a bit subjective and can influence the results significantly. The second issue is that the initial stages of the expansion in Figure 2 are at the limits of the resolution of the VLBA. There is no unique solution to the fitting method. Each ambiguity and assumption adds a possible error to the fitting process. After some initial attempts to make Gaussian fits to the nuclear region, we found two methods that give reasonable results.

5.1. Gaussian Fitting Method 1

The first method addresses the issue of the complex background emission by a simple excision method that can be uniformly applied to each epoch. We took the CLEAN model and automatically removed CCs from the area three times the uniformly weighted beam size (from Table 2) around the core. The excised region is then modeled with circular Gaussians. We added new components in the model if a clear peak was seen in the residual image after fitting. The background subtraction is not perfect, so it introduces additional Gaussian components in addition to those associated with the EN, WN, and ejection B. This method typically needs many components to represent the core, which can make the fit unstable.

5.2. Gaussian Fitting Method 2

We took the CLEAN model but removed only those CCs that roughly correspond to the double (triple) nucleus in a super-resolved image (created with a 0.1 mas circular beam). This CC excision was done “by eye,” so there is some subjectivity here. We modeled this region with two or three circular Gaussian components. The method is less subjective than the first as a result of incorporating additional information from the super-resolved image. However, the method relies significantly on the CLEAN model, and it is therefore not independent.

5.3. Comparison of Methods

In Figure 6 we reproduce Figure 5 with the addition of the Gaussian components for both models given in Table 3. The image is overlaid on the plots from Figure 5. Method 1 and 2 are the distances from the Gaussian representing the EN and WN, and ejection B. Method 1 and 2 are the distances from the Gaussian representing the ejection B and from the Gaussian representing the WN. Similarly, method 1B and 2B are the distances from the Gaussian representing the ejection B and from the Gaussian representing the WN. Do not present error bars on the Gaussian fit data since it would clutter the graph, making it unintelligible.

Figure 6. The Gaussian components produced by the Difmap fit in the visibility domain are indicated by blue and orange symbols, for method 1 (described in Section 5.1) and method 2 (described in Section 5.2). These are overlaid on the plots from Figure 5. Method 1A and 2A are the distances from the Gaussian representing the EN and WN. Similarly, method 1B and 2B are the distances from the Gaussian representing the ejection B and from the Gaussian representing the WN. We do not present error bars on the Gaussian fit data since it would clutter the graph, making it unintelligible.

In Figure 7, the Gaussian components for both models given in Table 3 are overlaid on the position solution for two adjacent epochs. We define EN and WN as in Figure 4. The image is qualitative, but it gives the reader a feel for the difference between the two model results and the difference between the models and the CC-based methods. Method 2, which utilizes information from the super-resolved images, seems very consistent with the EN and WN identifications in 2019 May. Figure 6 and Tables 2 and 3 indicate some significant discrepancies between the results of the CC method of Sections 3 and 4 and the Gaussian models during the epoch 2020 April 7. This is most pronounced for ejection B. In Figure 8, we overlay the Gaussian fits on the CC scatter plot from Figure 4. There is clearly disagreement between the two fits. Furthermore, model 1 seems to blend the EN and ejection
### Table 3
Gaussian Fits to the Double Nucleus

| Date       | Model | $F_{\nu,WN}$ (Jy) | $F_{\nu,EN}$ (Jy) | $\Delta$R.A. (mas) | $\Delta$Decl. (mas) | Separation of Components (mas) | Gaussian FWHM WN (mas) | Gaussian FWHM EN (mas) |
|------------|-------|-------------------|-------------------|-------------------|-------------------|-----------------------------|----------------------|----------------------|
| 2018 Aug 26 | 1     | 1.337             | 1.437             | 0.093             | 0.046             | 0.104                       | 0.073                | 0.156                |
| 2018 Aug 26 | 2     | 1.146             | 0.840             | 0.135             | 0.001             | 0.135                       | 0.068                | 0.102                |
| 2018 Oct 15 | 1     | 2.525             | 1.138             | 0.157             | -0.053            | 0.166                       | 0.104                | 0.127                |
| 2018 Oct 15 | 2     | 2.219             | 1.459             | 0.146             | -0.008            | 0.146                       | 0.088                | 0.134                |
| 2018 Dec 9  | 1     | 3.211             | 1.435             | 0.166             | -0.027            | 0.168                       | 0.113                | 0.052                |
| 2018 Dec 9  | 2     | 2.819             | 1.856             | 0.151             | -0.034            | 0.155                       | 0.085                | 0.082                |
| 2019 Jan 10 | 1     | 1.179             | 4.634             | 0.139             | 0.019             | 0.140                       | 0.085                | 0.190                |
| 2019 Jan 10 | 2     | 2.030             | 2.321             | 0.127             | 0.018             | 0.128                       | 0.076                | 0.072                |
| 2019 Mar 31 | 1     | 1.193             | 1.576             | 0.169             | -0.009            | 0.169                       | 0.068                | 0.132                |
| 2019 Mar 31 | 2     | 1.819             | 0.932             | 0.166             | 0.022             | 0.167                       | 0.066                | 0.071                |
| 2019 Apr 12 | 1     | 2.735             | 0.593             | 0.200             | -0.007            | 0.200                       | 0.143                | 0.018                |
| 2019 Apr 12 | 2     | 2.601             | 0.786             | 0.199             | -0.043            | 0.204                       | 0.119 point source   |                      |
| 2019 Jun 18 | 1     | 2.794             | 0.970             | 0.170             | -0.010            | 0.170                       | 0.091                | 0.011                |
| 2019 Jun 18 | 2     | 2.470             | 0.795             | 0.151             | 0.018             | 0.152                       | 0.074                | 0.107                |
| 2019 Jul 1  | 1     | 2.716             | 1.961             | 0.162             | 0.007             | 0.162                       | 0.019                | 0.055                |
| 2019 Jul 1  | 2     | 3.876             | 2.032             | 0.151             | 0.028             | 0.153                       | 0.071                | 0.029                |
| 2019 Oct 19 | 1     | 2.505             | 1.629             | 0.183             | -0.066            | 0.195                       | 0.100                |                      |
| 2019 Oct 19 | 2     | 1.284             | 1.454             | 0.221             | -0.026            | 0.223                       | 0.091                | 0.092                |
| 2019 Nov 3  | 1     | 0.688             | 1.041             | 0.234             | -0.040            | 0.237                       | 0.063                | 0.053                |
| 2019 Nov 3  | 2     | 1.193             | 1.120             | 0.222             | -0.031            | 0.224                       | 0.104                | 0.059                |
| 2020 Jan 4  | 1     | 1.370             | 1.109             | 0.232             | -0.066            | 0.242                       | 0.104                | 0.042                |
| 2020 Jan 4  | 2     | 1.222             | 1.523             | 0.240             | -0.064            | 0.249                       | 0.075                | 0.081                |
| 2020 Apr 7  | 1     | 2.517             | 0.706             | 0.264             | -0.111            | 0.286                       | 0.144                | point source         |
| 2020 Apr 7  | 2     | 1.878             | 1.286             | 0.262             | -0.080            | 0.274                       | 0.109                | 0.046                |

B, and model 2 seems to ignore all the CCs at the north end of the EN. This suggests that the Gaussian fit methods have difficulty resolving three components within a total extent of 0.24 mas. The figure clearly shows the origin of the larger displacements for ejection B in the 2020 April epoch of Figure 6 given by the Gaussian models compared to the CC-based analysis.

The main objective of this study is to track the time evolution of the double separation as close to its inception as possible in order to estimate the trajectory and separation speed as accurately as possible. There is arbitrariness in the Gaussian fitting procedure that is accentuated in the early epochs (in 2018) when the component separation was smaller. The intensity cross sections were introduced in Figure 3 to provide a clear diagnostic of the model-fitting schemes. Based on Figure 6, both Gaussian decomposition schemes give worse fits to the east–west separation derived from the intensity cross sections in the early epochs than the CC-based methods of Section 3 and 4. We do not advocate extrapolating the Gaussian fitting method to the first three epochs of small component separation. Similarly, Figure 8 seems to indicate that the second ejection crowds the narrow 0.24 mas field, making it difficult for the Gaussian fits to segregate components uniquely or with high accuracy. For this reason, we consider the CC method of this paper preferable to conventional Gaussian fitting for exploring the partially resolved compact nuclear region of 3C 84. The Gaussian fitting does provide qualitative agreement with CC model fitting. As such, along with the intensity cross sections, this corroborates the results of the CC-based analysis. We have also demonstrated that with proper care in the definition of the Gaussian models, one can achieve a similar estimate (within 15%) to the nuclear separation.

### 6. The Nuclear Separation in the Context of RadioAstron

In order to create more context for these results in 2018–2020, we compare the nuclear structure to the triple nucleus observed on 2013 September 21–22 by RadioAstron (Kardashev et al. 2013, 2017). First of all, the RadioAstron observations were accompanied by a 43 GHz observation with an array of the VLBA combined with the phased VLA (Giovannini et al. 2018, T. Savolainen et al. 2020, in preparation). We use the CC model from imaging of these data, together with the methods of this paper to detect evidence of a triple nucleus using the east–west resolution of the VLBA. There were no September or October observations by the BU monitoring program. The top panel of Figure 9 is a nuclear clustering model similar to Figure 4. It shows all the CCs >20 mJy in a nuclear region that is a square, 0.4 mas on a side. Without the RadioAstron results, this compact configuration would have been more ambiguous to decompose into three components. Based on the RadioAstron images, we cluster the CC components into three regions of concentration, RA East (blue), RA Central (red), and RA West (green). The nuclear region is very clean, there are relatively few CCs compared to the other epochs considered, and the background CC field is sparse near the triple nucleus in the innermost 0.2 mas. This fortuitous circumstance facilitates the identification of the components of the triple nucleus. The distance from RA East to RA Central is ∼0.08 mas, and that from RA Central to RA West is ∼0.09 mas.

We overlay the locations of RA East, RA Central, and RA West as blue, red, and green triangles, respectively, from the top panel on the RadioAstron image. The locations appear to be close to what is expected from the 22 GHz image. The flux densities of RA East, RA Central, and RA West are 456, 2106, and 845 mJy, respectively, in the 43 GHz CC decomposition of the EN.
Figure 7. The foreground Gaussian components from Table 3 are indicated by the dashed black circles with the inscribed black crosses. Both model 1 (described in Section 5.1) and model 2 (described in Section 5.2) are plotted, but separately for clarity. The diameter of the circle represents the FWHM of the Gaussian component. These are superimposed on the CC component models as defined in Figure 4. The flux densities are in black near or inside each Gaussian component. The eastern component of Gaussian model 2, in May, is a point source, and it is represented by a black cross.

Figure 8. Comparison of the Gaussian models with the CC-derived components during the epoch 2020 April 7. The figure is formatted the same as Figures 4 and 7. The three bright components in close proximity to each other seem to provide a challenge for the Gaussian models as evidenced by the significant differences between the models from methods 1 and 2. The eastern component of Gaussian model 1 is a point source, and it is represented by a black cross. We have not included the 0.1 mas rulers in this figure in order to avoid distracting clutter.
We cluster the CCs as three physical components RA East simultaneous with the 22 GHz RadioAstron observation in the bottom panel. Based on this identification, we also show the positions of the EN in 2018 August 26 and 2019 May 12 relative to the RadioAstron image in the bottom panel of Figure 9. In this cross-identification scenario, the nuclear structure has widened by ~40 μas and the whole pattern is shifted to the east.

The first cross-identification scenario is straightforward, but just one of many possible choices. Thus, in Figure 10 we show a different plausible cross-identification based on the high-S/N 2020 January 4 observation of the nuclear triple. The color-coding of the dots corresponds to the color-coding of the triangles in the CC model in the bottom right panel of Figure 4. Note that the dots have a different identification than in Figure 9. In this scenario the nuclear structure has widened by ~60 μas and the point of origin of the ejections is the red dot at the far west edge of the jet. The triple axis is tilted relative to the base and the point of origin of the ejections is the red dot at the far west edge of the jet.

We try to assess the degree to which the nuclear region has changed in terms of morphology and size in 2018–2020 compared to 2013. The cross-identification of components is rather uncertain owing to 5 yr between the observations. We cannot make any robust cross-identifications of the components from epoch to epoch owing to the known variability of the morphology and the effects of blending with low resolution. We simply give two plausible cross-identifications in the bottom panel of Figures 9 and 10 to help elucidate the large qualitative changes that might be occurring over time. First, we identify the brightest component of VLBA with the brightest component of RadioAstron. With this chosen scenario, we tentatively identify RA Central as the same physical feature as the WN in Figure 4. We also overlay the locations of the EN in 2018 August 26 and 2019 May 12 on the RadioAstron image in the bottom panel of Figure 9. In this cross-identification scenario, the nuclear structure has widened by ~40 μas and the whole pattern is shifted to the east.

7. Conclusion

In this paper, we consider three methods for resolving the nuclear structure in 43 GHz VLBA observations of 3C 84: intensity cross section, Gaussian fitting in the (u, v)-plane, and CC models. The time-averaged separation speed from 2018 August to 2020 April is estimated as 0.086 ± 0.008 c. A second ejected component was identified in 2019 October to 2020 April with a similar speed. The multiple nucleus has been detected before with RadioAstron and 86 GHz global VLBI, but the dynamical evolution has never been seen previously. This separation speed estimate accomplishes the primary goal of this paper.

The most relevant comparisons are the component measurements at the base (inner ~0.2 mas) of the 43 GHz VLBA component.
southerly directed jet (Dhawan et al. 1998). They found apparent velocities in the range of 0.035c–0.1c. However, there was uncertainty in the identification of the location of the nucleus. Independent of any of the nuclear identification scenarios, the apparent velocity was slow by relativistic standards, \( \lesssim 0.1c \), very similar to what was found in this study of the multiple east–west nucleus. The apparent jet speed accelerates as the jet propagates southward with \( \sim 0.25c \) at \( \sim 1 \) mas, and the highest estimates approach \( 0.47c \sim 2 \) mas away (Suzuki et al. 2012).

It is tempting to try to understand the observed motion in the context of the complicated circumnuclear structure depicted in Figure 1. However, we choose not to speculate and use our result as one piece of the puzzle that must be incorporated into future efforts to explain the base of the jet in 3C 84. It is certainly odd to see an inner flow or expansion that appears to be orthogonal to the large-scale jet that is clearly delineated only \( 150 \mu \)as downstream (Giovannini et al. 2018; Kim et al. 2019). One thing that we can say is that the double separation is \( \sim 0.3 \) lt-yr on the sky plane in 2020 April. This corresponds to an intrinsic distance of \( \sim 0.3/\sin \theta \) lt-yr, where \( \theta \) is the LOS angle to the component motion. This equates to \( \sim (1900/\sin \theta) M \), where \( M \sim 10^8 M_\odot \sim 1.5 \times 10^{10} \) cm is the black hole mass in geometrized units (Scharwachter et al. 2013; Punsly et al. 2018; Nagai et al. 2019). Thus, this slow apparent separation speed persists very far from the source. The LOS angle has been estimated at \( 11^\circ – 65^\circ \) based on jet/counterjet asymmetry (Walker et al. 1994; Asada et al. 2006; Lister et al. 2009; Fujita & Nagai 2017). However, these viewing angle estimates are for the north–south jet. The direction of the east–west core motion may differ significantly from this. It is perhaps more relevant that historical data indicate that 3C 84 sometimes appears moderately blazar-like based on broadband variability and optical polarization as high as 6% (Veron 1978; Angel & Stockman 1980; Chuvanov 1985; Nesterov et al. 1995). In current nomenclature, it is a slightly “off angle blazar” at times (Punsly et al. 2018). For the sake of comparison, estimates for blazars are typically \( \theta \sim 1^\circ – 3^\circ \) (Hovatta et al. 2009; Jorstad et al. 2017). However, the blazar-like properties have been far more benign for the past 35 yr (Punsly et al. 2018). As an example, in the past 12 yr the optical polarization has been consistently between 1% and 3%, with the very rare jumps to 4% (see footnote 11). So we cannot rule out \( \theta \sim 10^\circ \), but this behavior does not favor an extreme blazar-like LOS. Based on the published ranges of \( \theta \), the physical distance between the EN and WN is \( \sim 0.3–1.5 \) lt-yr, or \( \sim 190 M \sim 9800 M \). What is extremely odd is that at this large distance the VLBA images seem to indicate a dramatic change in the jet direction. The most straightforward interpretation is that we are detecting the internal dynamics of a jet that is \( \sim 2000 M \) wide. The lateral expansion near the central engine proceeds subrelativistically at \( \sim 0.086c \). The jet is collimated on scales \( \sim 2000 M \). The RadioAstron image and the 2020 April image in Figure 2 seem to indicate a continuous flow between the central, wide core component and bright components moving along the edges of the jet going south.

Based on RadioAstron and this analysis, the bifurcating nuclei are bright ejections of plasma that can go primarily to the east or west. In the epochs considered here there is an ejection to the east. In 2020, the images in Figure 2 appear to show that the EN trajectory starts to bend toward the south. It might be joining the highly collimated portion of the jet that is directed almost due south. However, this is not so simple based on Figure 2 because the western ridge is much brighter at this time. The ejection might traverse (twist around) the front face of the southerly directed jet and join the western ridge.

The discussion above shows how confusing the dynamics of the inner jet are likely to be. Considering the variations in the ridge brightness distribution over time suggests that the jet dynamics are not even consistent from epoch to epoch. A year-long series of target-of-opportunity, 43 GHz relative astrometry VLBA observations of \( > 8 \) hr with two calibrators triggered by a \( > 0.15 \) mas separation of the nuclear double could be a feasible method of tracking the time evolution of the ejections accurately. The observations could be triggered by a separation determined by the methods of this paper from the BU data. Perhaps 86 GHz observations with global VLBI (including the Atacama Large Millimeter Array) spread out over 6 months that are triggered simultaneous with the VLBA observations might shed light on what kind of dynamics are occurring. These are challenging observations, but this might be one of our best laboratories for studying the base of a powerful extragalactic jet.

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### Appendix A

## The Resolution Limits of the VLBA Observations

The ability to resolve structures in interferometic data depends on several factors, e.g., the length of the longest baselines, gaps in the (\( u, v \)) coverage, S/N of the data, and the complexity of the source structure itself. Giving an accurate number for any given experiment requires simulations of that exact experimental setup and the source. Therefore, one usually resorts to simple rules of thumb like the fringe spacing, the uniformly weighted beam size, or the criterion we have adopted for the current paper. Since all the observations we consider have similarly high S/N and similar complexity of the source structure, it is reasonable to assume that any variation in the resolution limit from epoch to epoch is mainly due to the longest baselines available. Since we use only epochs that have either MK–SC baseline or MK–HN baseline present, the variation in the maximum baseline length in the E–W direction is only \( \sim 15\% \). The important question is whether our adopted resolution limit of 0.08–0.10 mas is on average correct for the VLBA in the high-S/N case. We explore this by means of simulations in the visibility domain.

Using AIPS task UVMOD, we simulated visibility data with exactly the same (\( u, v \)) coverage and noise properties as in the 2018 August observation, the epoch of minimum detectable separation with our CC-based method presented in this paper. As an input model, we used the 2018 August CC model. From this CC model, we excised an area of three uniform beam sizes (FWHM) around the core. To the resulting model, we added two 1 Jy point sources separated from the origin symmetrically...
in relative RA by ±0.02 mas. The independent variable in this experiment is the separation in relative RA, the horizontal axis in Figure 11, measured in mas. We created eight simulated data sets increasing the separation between the point sources from 0.04 to 0.18 mas in steps of 0.02 mas. Then, we used the MODELFIT task in Difmap to fit the visibility data with a model consisting of two point sources in the core region. After making the fit, we plotted the two dependent variables of the experiment, the flux ratio and the fitted separation of the components, in Figure 11, as the vertical axis in the top and second panels, respectively. At separations of 0.04 and 0.06 mas, the fitted data do not accurately represent the real separation or the real brightness ratios. At 0.08 mas, this abruptly changes to precise fits to both quantities. It clearly shows that two equally bright point sources can be resolved, if their separation is 0.08 mas or larger.

We also made a second set of simulations with the same input model. However, instead of point sources we used two 1 Jy Gaussian distributions with an FWHM of 0.1 mas each. Recall from Section 3.1 that there were 20 estimates of the FWHM of the components that range from 0.023 to 0.112 mas with a mean of 0.076 mas. The fitting in Difmap was made with point sources as in the previous experiment. The results are presented in the third and bottom panels of Figure 11. It seems that separations of 0.10–0.12 mas (∼10% accuracy in the separation) or larger are needed in this case to accurately estimate the relative positions. We note that the smallest measurable distance with our CC method in Table 2 is

![Figure 11](image-url)
0.116 ± 0.013 mas in 2018 August. Not coincidentally, this is the value obtained by the simulation. We also note that the analysis of the simulations used an inexact model of the flux distributions. This analysis seems consistent with the model fitting in the (u, v)-plane in Figure 6. When compared to the CC model method, the model fits seem less accurate with higher model dependence for separations less than ~0.13 mas.

Appendix B
The CC Model from 2019 January 10

The 2019 January 10 intensity profile looks different from the adjacent epochs in Figure 3. It has one peak instead of two. Thus, this epoch needs to be studied in detail. From Section 2, we repeat the fundamental philosophy of implementing CC models: “Even though the models cannot be considered robust in a single epoch, they should be suitable for identifying a trend that persists over time, especially with regard to very bright features as is the case here.” We use this as our guide for assessing what has occurred during this epoch.

Figure 12 is an analog of Figure 4 that displays the distribution of CCs. The figure considers two plausible decompositions into a WN and EN. The single-peak structure of the intensity profile is explained by the figure; the EN lies to the south of the WN by ≤0.1 mas. Thus, it is not captured by the intensity cross section that is centered on the peak intensity (near the centroid of the WN). The other odd feature is that the core now appears to have a bright feature emitted to the west. This is slightly to the south of the intensity peak and appears as an inflection point in the western skirt of the intensity profile in Figure 3. Such a feature would be consistent with the nuclear triple detected by RadioAstron (Giovannini et al. 2018). Our main task in this appendix is to investigate whether these two features, the southern displacement of the EN and the western new component, are accurate reconstructions of the source or affected by artifacts of the observation and/or the CC model.

The first thing to consider is the quality of the observations. 2019 January 10 appears to be a good epoch with all 10 antennas operating normally, only with MK and Pie Town (PT) taken out for the last two scans of 3C 84 for use by the Navy. Thus, we look for other indicators of the root cause of the morphological change, bearing in mind the fundamental qualifying assumption of using the CC models that was restated at the beginning of this appendix.

Do the other epochs tell us anything? None of the other epochs, including the one just before in December or the one after in March, have an EN this far south relative to the WN, nor do they have an ejection to the west. The putative ejection to the west is very bright (1.095 Jy), brighter than the EN, so why does it not appear in March and May? Such rapid changes could occur with blazar-like phenomena. However, we are seeing a steady, mildly relativistic separation of the nucleus in Figure 5. If we treat the changes in the CC model in January as real, then it would imply an abrupt change from this slow (by relativistic standards), steady nuclear separation to one in which the EN veers south and a bright component is ejected west. Then, in March it appears to be an extrapolation of the slow, steady separation that was occurring from August to December. The EN pops back up to the north, similar to previous epochs, and the bright west ejection disappears, and this basic structure persists in May. This is not impossible (and would be very interesting), but it is not supported by any other evidence that we have. This would correspond to the bottom identification of CC clustering for the EN and WN in Figure 12. We will refer to the bottom panel of Figure 12 as model 2, since it is not our preferred model.

The CC clustering model (model 1) in the top panel of Figure 12 assumes that the western bright spot is not a new ejection or background feature but is separated from the peak intensity possibly as an artifact of the (u, v) coverage. Thus, the two features are combined into one feature that is stretched out in the east–west direction in this interpretation. Similarly, the southward veer of the EN would be a result of imperfect (u, v) coverage and calibration. The disturbing aspect for our method is that instead of the east–west separation of the CCs composing the WN being ~0.1 mas, it is 0.16 mas. We were motivated to prefer this interpretation by the smooth transition to and from the epochs adjacent to it in time. Model 1 is used in Figure 5. This model has a displacement that is fairly close to the least-squares fit in both panels of Figure 5.

Now, we can compare this with model 2. We show the fits in Figure 13 that are the analogs of those from Figure 5, but we have substituted model 2 for model 1 in Figure 5. The fits are similar to Figure 5, but model 2 lies very far from the least-squares fit of the east–west displacement. Thus, Figures 5 and 13 favor model 1 over model 2 based on the trends of the other epochs.
The anomalous intensity cross section in Figure 3 and the ambiguity in the component decomposition (two or three components) of the nucleus are disturbing considering that this observation had all 10 stations. In order to investigate this further, we tried reimaging the \((u, v)\) data with CLEAN + self-cal since the end result of the image reconstruction depends on the “route” that is taken during the imaging process for imperfect data (i.e., sampling is poor and/or data have significant gain errors). The resultant images are sensitive to the initial phase self-cal steps, and we were able to redistribute the CCs in the image plane. However, none of the images had an intensity cross section that was “in-family” with the cross section expected from Figure 3 (i.e., two well-defined, distinct peaks). Furthermore, none of the images resolved the ambiguity between a two-component decomposition of the nucleus and a three-component decomposition of the nucleus. Similar to Figure 12, the EN–WN separation was always in the range of 0.13–0.17 mas, regardless of the self-calibration or the particular choice of the identifications of the CCs with the EN and the WN. It is therefore concluded that the “out-of-family” properties of the 2019 January observation are inherent to the \((u, v)\) data and are not an artifact of image reconstruction. The reimaging investigation does not address whether this is a physical property of the source at the time of observation or an idiosyncrasy of this particular patchy sampling in the \((u, v)\)-plane.

We hypothesize, without proof, the plausibility of \((u, v)\) coverage issues with the observation. 3C 84 is a very complex source with many components. The \((u, v)\) data sampling is not ideal for such a complex source, as it is being observed with 31–32 other sources over a 24 hr period. The \((u, v)\) coverage is not the same in all epochs. Occasionally, the \((u, v)\) coverage might not be sampled well enough to reconstruct the complex structure adequately or uniquely. We cannot prove whether the image is accurate or adversely affected by patchy \((u, v)\) coverage. Our basic premise is that we cannot vouch for the integrity of the CC models in an individual epoch, but we can detect temporal trends in the bright components. To this point, the results of our analysis do not depend on choosing model 1 over model 2. The estimated separation velocity with the choice of model 1 in Figure 5 was 0.086 ± 0.08c. By comparison, using model 2 (as was done in Figure 13) results in almost exactly the same separation velocity 0.088 ± 0.07c. Thus, our results do not depend on the confusing details of a particular epoch.

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**ORCID iDs**

Brian Punsly 🏈 https://orcid.org/0000-0002-9448-2527
Hiroshi Nagai 🏈 https://orcid.org/0000-0003-0292-3645
Tuomas Savolainen 🏈 https://orcid.org/0000-0001-6214-1085
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