

VLA HIGH-RESOLUTION 1.4 AND 8.4 GHz MAPPING OF THE BARRED GALAXY NGC 3367

J. ANTONIO GARCÍA-BARRETO AND JOSÉ FRANCO

Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264, 04510, México D.F., Mexico

AND

LAWRENCE RUDNICK

Department of Astronomy, University of Minnesota, 116 Church Street, SE, Minneapolis, MN 55455

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ABSTRACT

We report new radio continuum observations with an angular resolution of $2''.1$ at 1.4 GHz (20 cm) and $0''.28$ at 8.4 GHz (3.6 cm) of the barred galaxy NGC 3367. In the map at 1.4 GHz, the central nuclear region connects to the southwest lobe, with a projected structure at a position angle (P.A.) of $\sim 230^\circ$, forming a jet-like structure. The map at 8.4 GHz shows a compact unresolved source (smaller than 65 pc in diameter) associated with emission from the nucleus and several compact sources located within a radius of about 300 pc, forming a circumnuclear structure. The compact core, jet, and lobes form a small, low-power counterpart to radio galaxies, with a flow axis that is out of the plane of the galaxy. The flow axis (P.A. $\sim 230^\circ$) coincides with the P.A. of the major axis of the galaxy and is thus inclined to the rotation axis of the disk. In addition, the flow axis differs by about 20° from the major axis of the stellar bar. Assuming that the stellar bar rotates counterclockwise (i.e., assuming trailing spiral arms), this difference in angle is taken as an argument in favor of having the jetlike structure out of the plane of the disk and not associated with the stellar bar.

Key words: galaxies: clusters: individual (NGC 3367) — galaxies: ISM — galaxies: jets — galaxies: starburst

1. INTRODUCTION

Strong radio continuum emitters, such as radio galaxies or quasars, are identified with elliptical galaxies and recent mergers, and many of them have impressive radio jets with sizes larger than the host galaxy (see Wilson & Colbert 1995). Maps of radio galaxies display fairly straight radio jets with distant lobes, showing the interaction of the jet with the ambient medium and indicating that the jet axis has been stable for thousands or even millions of years. Recent work indicates the presence of lobes at a distance of 100 kpc from a spiral galaxy in a cluster (Ledlow, Owen, & Keel 1998; Ledlow et al. 2001). In normal spiral galaxies, on the other hand, most of the radio continuum emission comes from the disk component (Hummel 1981; Condon 1987; García-Barreto et al. 1993; Niklas, Klein, & Wielebinski 1997). Radio surveys of Seyfert galaxies indicate that the radio continuum emission arises mainly from three components: (1) subkiloparsec emission from the nuclear region, (2) extranuclear kiloparsec-scale emission, and (3) greater than kiloparsec-scale emission associated with the disk (Wilson & Ulvestad 1983; Ulvestad & Wilson 1984; Baum et al. 1993; Colbert et al. 1996; Ho & Ulvestad 2001). In barred spiral galaxies, the radio continuum emission is found from the following: (1) emission from the compact nucleus, (2) emission from the circumnuclear region (≤ 1 kpc), (3) emission from dust lanes in the leading side of the stellar bar, and (4) emission from spirals arms and disk (Hummel, van der Hulst, & Keel 1987; Condon 1987; García-Barreto et al. 1991a, 1991b; Lindblad 1999; Beck et al. 1999). Depending on the central activity, a spiral can be classified as a starburst or an active galaxy. Seyfert galaxies are stronger radio emitters at 1.4 GHz than normal and barred spirals (Condon 1987). The central radio sources are sometimes associated with a pair of extended sources identified as lobes (Ulvestad & Wilson 1984; Ulvestad, Neff, &

Wilson 1987; Baum et al. 1993; Colbert et al. 1996; Ho & Ulvestad 2001). These triple sources (compact nucleus plus lobes) are thought to be small-scale, low-power versions of the large-scale jets and lobes seen in radio galaxies and quasars. The radio continuum emission from the central region of spirals is linked either to star formation, via H II regions and supernova remnants as in starbursts, or to an unresolved compact object, probably an active galactic nucleus (AGN) (Baum et al. 1993). The study of NGC 3367 may be important in order to understand the lobe–central source relationship and may help to clarify the starburst–AGN dichotomy.

The barred spiral NGC 3367 is a mildly active galaxy between a weak LINER and an H II nucleus (Véron, Gonçalves, & Véron-Cetty 1997; Ho, Filippenko, & Sargent 1997) that displays such a triple-source structure. At $15''$ angular resolution, in addition to extended emission from different locations in the disk, it shows an unresolved radio source in the center plus two sources in opposite directions from it (Condon et al. 1990). Maps at $4''.5$ resolution indicated more clearly the presence of the two lobes (García-Barreto et al. 1998). The central source was not resolved at this $4''.5$ angular resolution, and it was unclear if it is a point-like source or an extended circumnuclear structure and whether or not it is really connected with the lobes.

In this paper we present new VLA¹ radio continuum observations of NGC 3367 at 1.4 GHz with a beam of $\approx 2''.1$ and at 8.4 GHz with a beam of $\approx 0''.28$. In § 2 we present the observed properties of NGC 3367, in § 3 we present the new

¹ The VLA is part of the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

radio continuum observations and results, and in § 4 we give a discussion and conclusions.

2. NGC 3367

NGC 3367 is an SBc(s) barred spiral galaxy with a stellar bar structure of diameter $\approx 32''$ (6.7 kpc) oriented at a position angle (P.A.) of $\approx 70^\circ$. The disk of NGC 3367 is inclined with respect to the plane of the sky at an angle between 6° (Grosbøl 1985) and 30° (García-Barreto & Rosado 2001) and has an optically bright southwest structure resembling a half-ring, or a large-scale “bow shock,” at about 10 kpc from the nucleus. This structure is formed by a collection of H α regions that looks like a necklace, and its origin has been ascribed to an off-center impact with an external intruder, most likely a small galaxy (García-Barreto, Franco, & Carrillo 1996a). Indeed, the general arrangement of the H α knots is similar to the elongated rings found in numerical simulations of off-center galaxy collisions by Gerber & Lamb (1994). The expanding density wave created by the collision can trigger the formation of the half-ring of H II regions, and given that the expected wave velocity in the disk is below 100 km s^{-1} , the collision probably occurred a few times 10^8 yr ago. In addition, aside from the radial gas inflows induced by the stellar bar, a galactic collision is also able to drive gas toward the galactic center, inducing circumnuclear star formation as well as nuclear activity. NGC 3367 also shows H α emission from the central region with an unresolved source, most likely a combination of emission from a compact source and circumnuclear structure at a radius of less than 500 pc (García-Barreto et al. 1996a, 1996b).

The disk of NGC 3367 has a normal content of atomic hydrogen, with $M_{\text{H I}} \sim 7 \times 10^9 M_\odot$ (Huchtmeier & Seiradakis 1985), and it is considered an isolated field galaxy, behind the Leo Group of galaxies at a distance of 43.6 Mpc, with its closest neighbor more than 900 kpc away to the northeast (Tully 1988). Its optical spectrum shows moderately broad H α + [N II] lines with FWHM $\sim 650 \text{ km s}^{-1}$, but H β is stronger than [O III] $\lambda 5007$ and there is weak emission of He II $\lambda 4686$, suggesting the existence of W-R stars and weak LINER activity (Véron-Cetty & Véron 1986; Véron et al. 1997; Ho et al. 1997). In addition, its X-ray luminosity is stronger than that of any normal spiral galaxy but weaker than Seyfert or radio galaxies (Gioia et al. 1990; Stocke et al. 1991; Fabbiano, Kim, & Trinchieri 1992). Nonetheless, from the optical line ratios, NGC 3367 is also considered to have an H II nucleus (Ho et al. 1997).

The first radio continuum observation of the region around NGC 3367 was at 178 MHz, with several arcminute angular resolution (Gower, Scott, & Wills 1967). Although the radio emission was identified with NGC 3367 (Caswell & Wills 1967), the bulk of the emission most likely originated from a radio galaxy $\approx 3'$ north of NGC 3367, detected later with better angular resolution (Lawrence et al. 1983). Similarly, observations from Arecibo at 430 and 835 MHz with integrated fluxes of 583 and 365 mJy, respectively, and $\approx 9'$ angular resolution most likely included the flux of the background radio galaxy (Israel & van der Hulst 1983). Green Bank single-dish observations of NGC 3367 at 5 GHz with a resolution of $\sim 3'$ were carried out by Sramek (1975) and Bennett et al. (1986) with integrated fluxes of 35 and 71 mJy, respectively. Israel & van der Hulst (1983)

reported an integrated flux of 18 mJy at 10.7 GHz with an angular resolution of $3'$ from Owens Valley Radio Observatory (OVRO) 40 m. Finally, Dunne et al. (2000) reported a flux of 132 mJy at 350 GHz with $15''$ angular resolution.

The first aperture synthesis map of NGC 3367 at 1.49 GHz, with $15''$ angular resolution, showed diffuse disk emission plus three peaks aligned in the northeast-southwest direction (Condon et al. 1990), and the disk emission was noticed to be edge brightened. A more recent mapping at this same frequency, but now with $4''.5$ angular resolution, shows more clearly the emission from the triple source: emission from the nuclear region in addition to emission from two extended lobes at a distance of $\sim 6 \text{ kpc}$ from the center (García-Barreto et al. 1998). The polarization analysis indicated that only the southwest lobe is polarized, suggesting that it is out of the disk of the galaxy and closer to the observer than the northeast lobe (the emission of the northeast lobe has been depolarized because this emission has passed through the plane of the galaxy; García-Barreto et al. 1998). These observations showed very clearly the presence of kiloparsec-scale lobes from a barred spiral galaxy seen almost face-on, in addition to the weaker emission from a large number of compact sources in the disk.

3. OBSERVATIONS AND RESULTS

We have carried out radio continuum observations at the VLA in New Mexico in the A array at 1.3851, 1.4649, 8.4351, and 8.4851 GHz in 1998 April 23, using 27 antennas with 50 MHz bandwidths and $\approx 3 \text{ hr}$ integration time at 1.4 GHz and $\approx 4 \text{ hr}$ at 8.4 GHz on NGC 3367. We observed 3C 286 as the amplitude and polarization calibrator, 1120+143 as the phase calibrator at 1.4 GHz, and 1051+213 as the phase calibrator at 8.4 GHz. We adopted a flux density for 3C 286 of $S_\nu = 14.554 \text{ Jy}$ at $\nu = 1.4649 \text{ GHz}$ and $S_\nu = 5.1702 \text{ Jy}$ at $\nu = 8.4851 \text{ GHz}$. Several iterations of phase self-calibration were used at 1.4 GHz. No self-calibration was used at 8.4 GHz because the peak emission was only $\approx 1 \text{ mJy beam}^{-1}$.

3.1. The Jets and the Southwest Lobe

Figure 1 shows the total intensity map at 1.4 GHz of NGC 3367 with an FWHM angular resolution beam of $2''.1 \times 1''.8$ at P.A. $\approx -67^\circ$ and an rms noise of $\sim 25 \mu\text{Jy beam}^{-1}$. The emission above the 2σ level clearly shows the central source and lobes. The central source has a peak emission of $11.2 \text{ mJy beam}^{-1}$ and is still unresolved. At the 2σ level, there is no clear connection of the central source and the southwest lobe. There are, however, extensions pointing toward the northeast and southwest lobes, and a faint connection appears at about 1σ (see below). At this new higher angular resolution 1.4 GHz observation, the emission from the lobes starts to be resolved, and the southwest lobe shows the same polarization (not shown here) as in the previous $4''.5$ angular resolution observations, namely, that the eastern side of the lobe shows the strongest polarization (García-Barreto et al. 1998).

The emission from both lobes is mostly diffuse, with some clumpy structure. The morphology of the southwest lobe resembles a bow shock, probably as a result of the interaction of a relativistic jet with a low-density ambient medium. There is faint emission directed from the central radio source toward the southwest lobe, indicating that they are

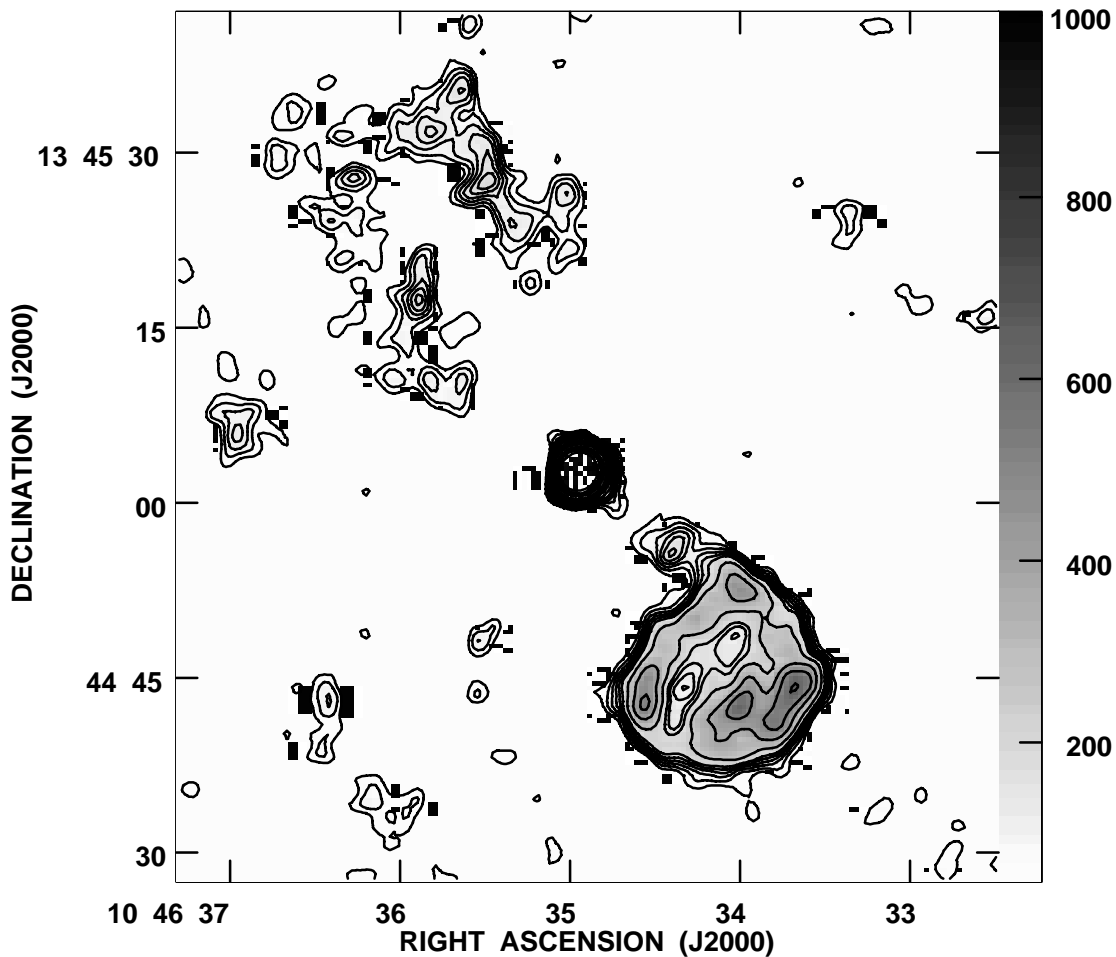


FIG. 1.—Radio continuum emission from NGC 3367 at 1.4 GHz with a beam FWHM $\approx 2''.1 \times 1''.8$ at P.A. $\approx -67^\circ$. The contours are in units of $25 \mu\text{Jy beam}^{-1}$, and the levels are 2, 3, 4, 5, 6, 7, 10, 15, 20, 25, 30, 50, 65, 80, and 120. The weak sources outside the area of the central region plus lobes are real and belong to emission from the disk, as can be seen in lower resolution maps shown in Figs. 2 and 6 of Garcia-Barreto et al. (1998). Gray scale is from $50 \mu\text{Jy beam}^{-1}$ to 1 mJy beam^{-1} .

connected through a low surface brightness continuous structure, $7'' \times 4''$ ($2.5 \text{ kpc} \times 850 \text{ pc}$), perhaps jetlike. The width is probably an upper limit dictated by the restoring beam size. This is seen in Figure 2, which shows the faint emission from the innermost $25''$ central region of NGC 3367 at 1.4 GHz. The contours are drawn starting at a 1σ level and show that the central emission indeed connects to the southwest lobe. Although in Figure 2 there is a minimum of emission midway (i.e., $\alpha \approx 34^\circ 6'$, $\delta \approx 44^\circ 59'$), the 1σ contour surrounds this minimum and connects the central radio emission with the southwest lobe; in order to verify the existence of the structure, we did make several maps with different restoring beams with self-calibration of phase and amplitude, and the structure was there in all maps although with slightly different detailed morphology (not shown here). Therefore, we feel confident that the structure connecting the central radio emission and the southwest lobe really exists; however, the detailed morphology needs to be taken with caution. The average P.A._{rad} of this structure is $\sim 230^\circ$ with a spread of $\pm 10^\circ$. The northeast extension of the central radio source is seen clearly at P.A. $\sim 35^\circ$ and seems to be the starting part of the counterjet that flows toward the northeast lobe. The stellar bar, however, is oriented at P.A._{bar} $\sim 245^\circ \pm 5^\circ$. In the southwest the radio

extension lies to the south of the optical bar, while in the northeast the radio extension lies to the north of the bar (see Fig. 3). There is no radio continuum emission (at the 3σ level of the rms noise) from any dust lane in the leading side of the stellar bar, as is often detected in other barred galaxies (Ondrechen & van der Hulst 1983; Beck et al. 1999). The fact that the southwest lobe is out of the plane of the galaxy suggests that the relative alignment between the radio structure (connecting the central radio source and the southwest lobe) and the stellar bar may be only a projection of the structure onto the galaxy disk and that the structure is out of the plane of the galaxy disk.

3.2. Compact Nucleus and Circumnuclear Structure

Figure 4 shows the radio continuum contours of the emission from the innermost $4''$ central region of the galaxy at 8.4 GHz, with an angular resolution of $0''.28 \times 0''.25$ at P.A. $\sim 1^\circ$ and an rms noise of $11 \mu\text{Jy beam}^{-1}$. The emission is dominated by a still unresolved central source of $0.96 \text{ mJy beam}^{-1}$, at $\alpha(\text{J2000.0}) = 10^{\text{h}}46^{\text{m}}34^{\text{s}}.956$, $\delta(\text{J2000.0}) = 13^\circ45'2''.94$. Its deconvolved diameter is less than 65 pc and is surrounded by several low surface brightness peaks of emission out to a distance of $\approx 300 \text{ pc}$. A rather similar

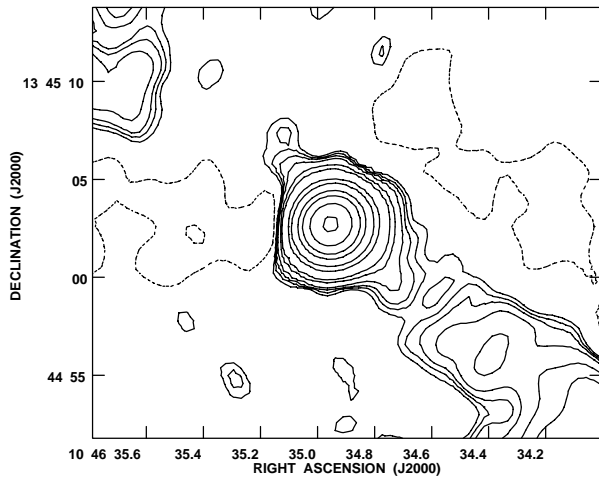


FIG. 2.—Radio continuum emission from the innermost central region at 1.4 GHz from Fig. 1. The P.A. of the radio continuum emission connecting the central source with the southwest lobe is $P.A._{rad} \sim 230^\circ \pm 10^\circ$; the stellar bar P.A. is $P.A._{bar} \sim 245^\circ \pm 5^\circ$; the approaching semimajor kinematical axis is $P.A._{maj} = 231^\circ$. The contours are in units of $25 \mu\text{Jy beam}^{-1}$, and the levels are $-2, 1, 1.5, 2, 3, 6, 10, 30, 50, 100, 150, 250$, and 410 . The second negative contour left of the central emission only indicates a relative local maximum (approximately $-40 \mu\text{Jy beam}^{-1}$) and not a deeper region.

structure is found in the lower resolution map at 1.4 GHz when a central unresolved source is subtracted. At 8.4 GHz, there is a short extension at a P.A. of 230° , the same as seen for the jet on larger scales. No polarization is detected at 8.4 GHz, with an upper limit of 2% for the compact nucleus and a characteristic limit of 25% for the circumnuclear structure. Peak fluxes at various positions in the circumnuclear region are all smaller than $100 \mu\text{Jy beam}^{-1}$.

Figure 5 shows the innermost $10''$ central radio continuum with a superposition of the 1.4 and 8.4 GHz emissions. The emission is clearly dominated by the central source, and an estimate of the spectral index between 1.4 and 8.4 GHz (integrated over the central $3''.5$) gives $\alpha \sim -0.53$ ($S_\nu \propto \nu^\alpha$),

indicating that the radiation is mainly synchrotron emission. The interpretation of spectral index should be taken with caution since the fluxes are the sum of the core plus the circumnuclear sources. The total flux at 1.4 GHz within $7''$ is 16.8 mJy, while the total flux at 8.4 GHz within $4''.5$ is 5.4 mJy.

4. DISCUSSION

We have observed the radio continuum emission from the barred galaxy NGC 3367, with the VLA A array, at 1.4 and 8.4 GHz with $2''.1$ and $0''.28$ spatial resolutions, respectively. The radio maps show emission from the central region, the lobes, and a weak jet. This morphology in NGC 3367 resembles the morphology of more powerful radio galaxies (Fanaroff & Riley 1974; Schilizzi et al. 2001). The power at 1.4 GHz is 2–3 orders of magnitude less than any radio galaxy, and it is more like the power of Seyfert galaxies (see Table 1; see also Fig. 3 of Ho & Ulvestad 2001; Ulvestad & Ho 2001). Nonetheless, this is one of the largest and best-defined triple-source structures ever detected in a galaxy considered to be a normal barred spiral. The triple source is due to emission from the central sources, from a jetlike structure connecting the central emission with the lobes, and from the extended lobes. Other large radio structures have been observed in the Seyfert galaxies, such as Mrk 6 (lobe extent 14 kpc), Mrk 348 (lobe extent 5 kpc), NGC 3516 (lobe extent 8.5 kpc) (Baum et al. 1993), NGC 4235 (lobe extent 9 kpc) (Colbert et al. 1996), and the disk galaxy O313-192 in the cluster A428 (lobe extent 100 kpc) (Ledlow et al. 1998, 2001). The radio continuum jets in other barred galaxies such as NGC 1068 (Wilson & Ulvestad 1987) and NGC 5728 (Schommer et al. 1988) are much smaller in size (of the order of tens to a hundred parsecs). In contrast with O313-192, which has an AGN, and the Markarian galaxies, which are Seyfert 1 and 2 galaxies, NGC 3367 is only a mildly active LINER and, based on optical line emission ratios and widths, is not even considered to be a Seyfert galaxy.

TABLE 1
RADIO CONTINUUM OBSERVATIONS OF NGC 3367

| Frequency (MHz) | Structure | Flux (mJy) | $\log(P/W \text{ Hz}^{-1})$ | Resolution (arcsec) | References |
|--------------------|----------------|--------------------|-----------------------------|------------------------|------------|
| 1490 | Center | 18.40 ^a | 21.6 | 15.0 | 1 |
| 1490 | Southwest lobe | 14.70 ^a | 21.5 | 15.0 | 1 |
| 1425 | Center | 15.80 ^a | 21.5 | 4.5 | 2 |
| 1425 | Triple | 51.50 ^b | 22.0 | 4.5 | 2 |
| 1425 | Center | 11.20 ^a | 21.4 | 2.1 | 3 |
| 1425 | Center | 13.10 ^c | 21.5 | 2.1 | 3 |
| 1425 | Center | 16.80 ^d | 21.6 | 2.1 | 3 |
| 8460 | Center | 0.96 ^a | 20.3 | 0.3 | 3 |
| 8460 | Center | 0.96 ^e | 20.5 | 0.3 | 3 |
| 8460 | Center | 5.1 ^c | 21.0 | 0.3 | 3 |
| 8460 | Center | 5.4 ^f | 21.1 | 0.3 | 3 |

^a Peak flux.

^b Peak flux from center plus integrated fluxes from lobes.

^c Integrated flux from inner $3''.5$.

^d Integrated flux from inner $7''$.

^e Integrated flux from inner $0''.5$.

^f Integrated flux from inner $4''.5$.

REFERENCES.—(1) Condon et al. 1990. (2) Garcia-Barreto et al. 1998. (3) This paper.

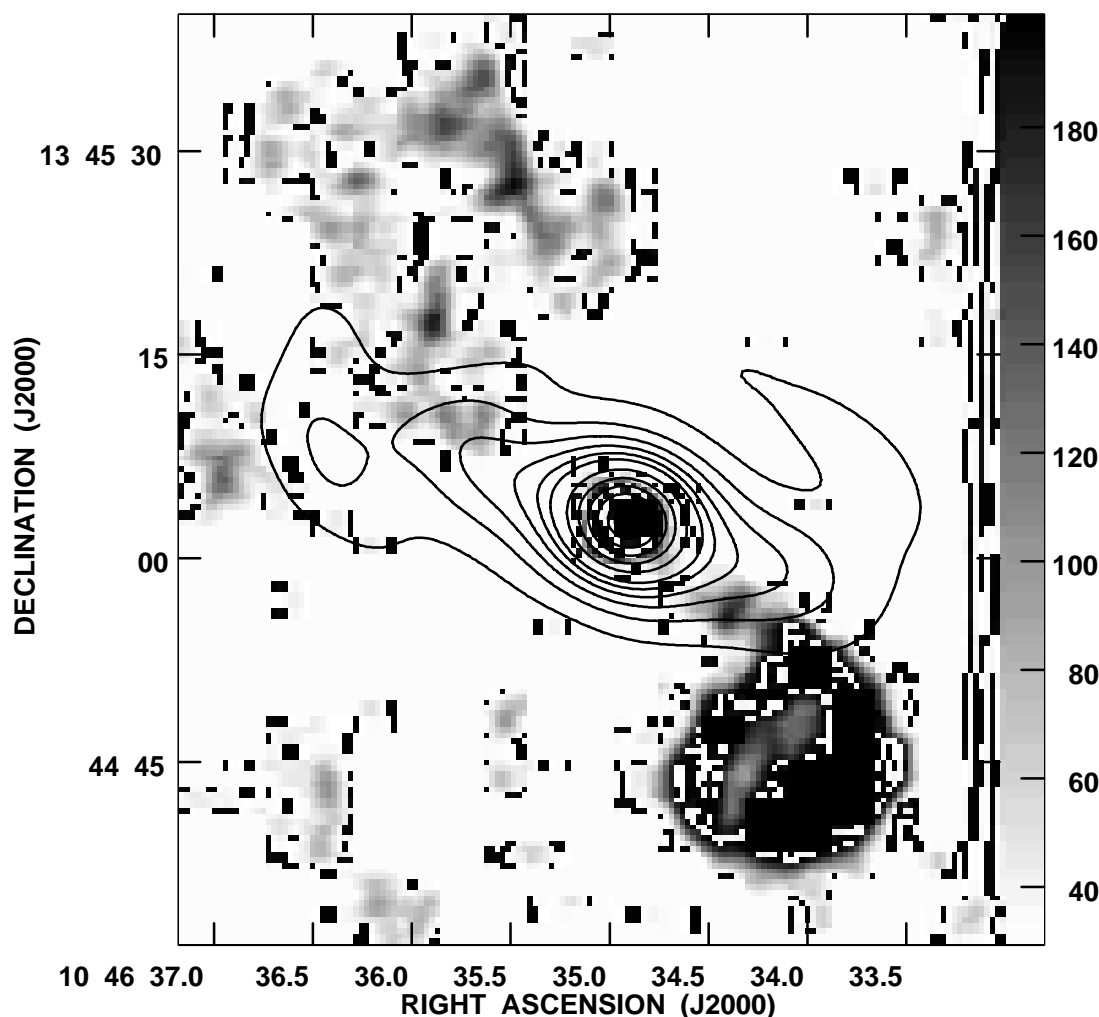


FIG. 3.—Radio continuum emission at 1.4 GHz (gray scale) and the optical continuum (contours; I broadband filter centered at 8040 Å). The contours are in arbitrary units relative to peak showing mainly the bright emission from the central stellar bar.

The $P.A._{jet}$ of the jetlike structure ($\sim 230^\circ \pm 10^\circ$; see Fig. 3) is the same as the $P.A._{maj}$ of the major axis, as determined from $H\alpha$ kinematics (Garcia-Barreto & Rosado 2001). The jet would be considered a low-power one (Massaglia, Bodo, & Ferrari 1996). The direction of the plasma outflow is thus not aligned with the rotation axis of the disk because, if that were the case, the relative orientation of the lobes in NGC 3367 would have to lie closer to the direction southeast-northwest, that is, the projection of the $P.A.$ of the minor axis as expected in the very simple picture that jets emanating from an active nucleus would emerge at right angles to the disk of the host galaxies (Kinney et al. 2000). However, the simple scenario is contradicted by the observations of Seyfert galaxies (Schmitt et al. 1997; Kinney et al. 2000; Ulvestad & Ho 2001). Our observations of NGC 3367 suggest that the outflow axis is inclined with respect to the rotation axis of the galaxy and also inclined to the line of sight. A comparison between the $P.A.$ of the extended radio structures from Seyfert galaxies and the major-axis $P.A.$ of their host galaxies indicates that the radio structures in type 2 Seyfert galaxies are oriented along any direction in the galaxy, and not necessarily along the minor axis (Schmitt et al. 1997; Kinney et al. 2000; Ulvestad & Ho 2001). The directions of the radio jets are consistent with being completely

uncorrelated with the planes of the host galaxies (Pringle et al. 1999; Nagar & Wilson 1999; Kinney et al. 2000). Our observations indicate that NGC 3367 (being a noninteracting late-type LINER/ $H II$ spiral having kiloparsec lobes) presents $P.A._{radio} \approx P.A._{maj}$.

The emission at 8.4 GHz, with the higher resolution, is complex and shows an unresolved nuclear source and several sources surrounding it. The circumnuclear radio sources are at all position angles (see Figs. 4 and 5) and do not align at all with the lobes or with any other optical structure in the galaxy. This implies that the circumnuclear sources are probably located in the plane of the disk and might be identified with a circumnuclear structure at distances of 125–325 pc. The radio emission from the inner $4''.5$ is then most likely a mixture of synchrotron and free-free emission, and the sources are most probably giant $H II$ regions near an inner Lindblad resonance (ILR) (as is the case in other barred galaxies).

An additional hint for the existence of a circumnuclear structure is provided by the $H\alpha$ emission. As mentioned earlier, NGC 3367 shows $H\alpha$ emission from the central region that is unresolved from ground observations (Garcia-Barreto et al. 1996a, 1996b) with a bright emission from a compact source and weak extended emission from within

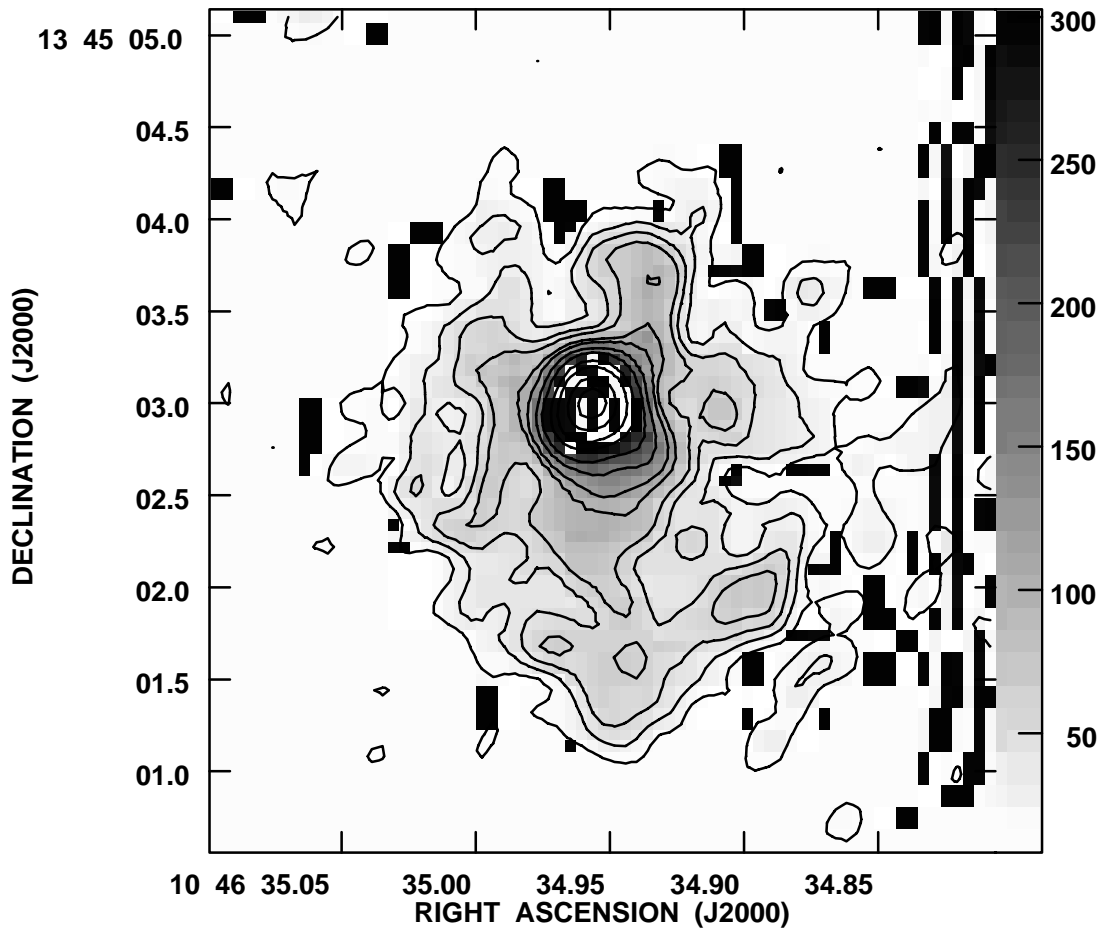


FIG. 4.—Radio continuum emission from the innermost central region at 8.4 GHz. The restoring beam FWHM is $0''.28 \times 0''.25$ (~ 60 pc). The contours are in units of $11 \mu\text{Jy beam}^{-1}$, and the levels are $-3, 1.5, 3, 4.5, 6, 9, 11, 15, 20, 30, 40, 60, 80$, and 100 . Gray scale is from 11 to $300 \mu\text{Jy beam}^{-1}$.

$6''$. Assuming that the peak of $\text{H}\alpha$ coincides with the peak of the 8.4 GHz radio continuum emission, we have subtracted the 8.4 GHz radio continuum emission from the $\text{H}\alpha$ emission in such a way as to have zero emission from the center. The image, $\text{H}\alpha - 8.4$ GHz radio continuum, that is produced is shown in Figure 6; it shows an $\text{H}\alpha$ circumnuclear structure. This $\text{H}\alpha$ image provides no proof of the existence of a circumnuclear structure since we have made several assumptions: (1) that the spatial position of the peak of the $\text{H}\alpha$ emission coincides with the position of the 8.4 GHz emission, (2) that the radio continuum 8.4 GHz is related to the $\text{H}\alpha$ emission in such a way that they are directly proportional to each other through a constant, (3) that the constant of proportionality was chosen in such a way as to have zero emission from the very center, and (4) that the final subtracted image represents emission from the disk of the galaxy where we think the structure lies (near an ILR). The image, however, is very suggestive of the existence of such a structure. If the circumnuclear structure represents regions of massive star formation, one could estimate the supernova rate using the relation (Condon 1992)

$$\frac{\nu_{\text{SN}}}{\text{yr}^{-1}} \sim \frac{L_N / (10^{22} \text{ W Hz}^{-1})}{13(\nu/\text{GHz})^{-\alpha}}. \quad (1)$$

Using the integrated flux within the innermost $3''.5$ at 1.4 GHz and assuming that all of this emission is of nonthermal

origin (which we know is wrong but hope not by much) and a spectral index $\alpha = -0.53$, the expected supernova rate in the circumnuclear region of NGC 3367 is $\nu_{\text{SN}} = 0.03$, which is very similar for other galaxies (Condon 1992). The global star formation rate using the far-infrared (*IRAS*) luminosity and the relation (Condon 1992)

$$\frac{\text{SFR}(M \geq 5 M_{\odot})}{M_{\odot} \text{ yr}^{-1}} \sim \frac{L_{\text{FIR}}/L_{\odot}}{1.1 \times 10^{10}}, \quad (2)$$

with $L_{\text{FIR}} = 2 \times 10^{10} L_{\odot}$ (Soifer et al. 1989), is $\text{SFR}_{\text{NGC 3367}} \sim 1.8 M_{\odot} \text{ yr}^{-1}$, similar to the values found in other galaxies (Condon 1992).

As stated above, the gas in the circumnuclear structure could have been driven inward either by the perturbations induced by the potential of the stellar bar or by a possible off-center collision with a minor intruder. A reason in favor of the active compact radio nucleus is the short extension in the 8.4 GHz map that has a P.A. similar to that of the jetlike structure observed in the 1.4 GHz map that connects the central radio source with the southwest lobe. If the flow were coming from a starburst wind (originating from the circumnuclear structure, which one assumes is in the plane of the galaxy), this wind would be directed (in the most simple case) out of the plane toward the rotation axis of the disk (where the density gradient is largest) and the jets and lobes would be projected in the southeast-northwest direction as

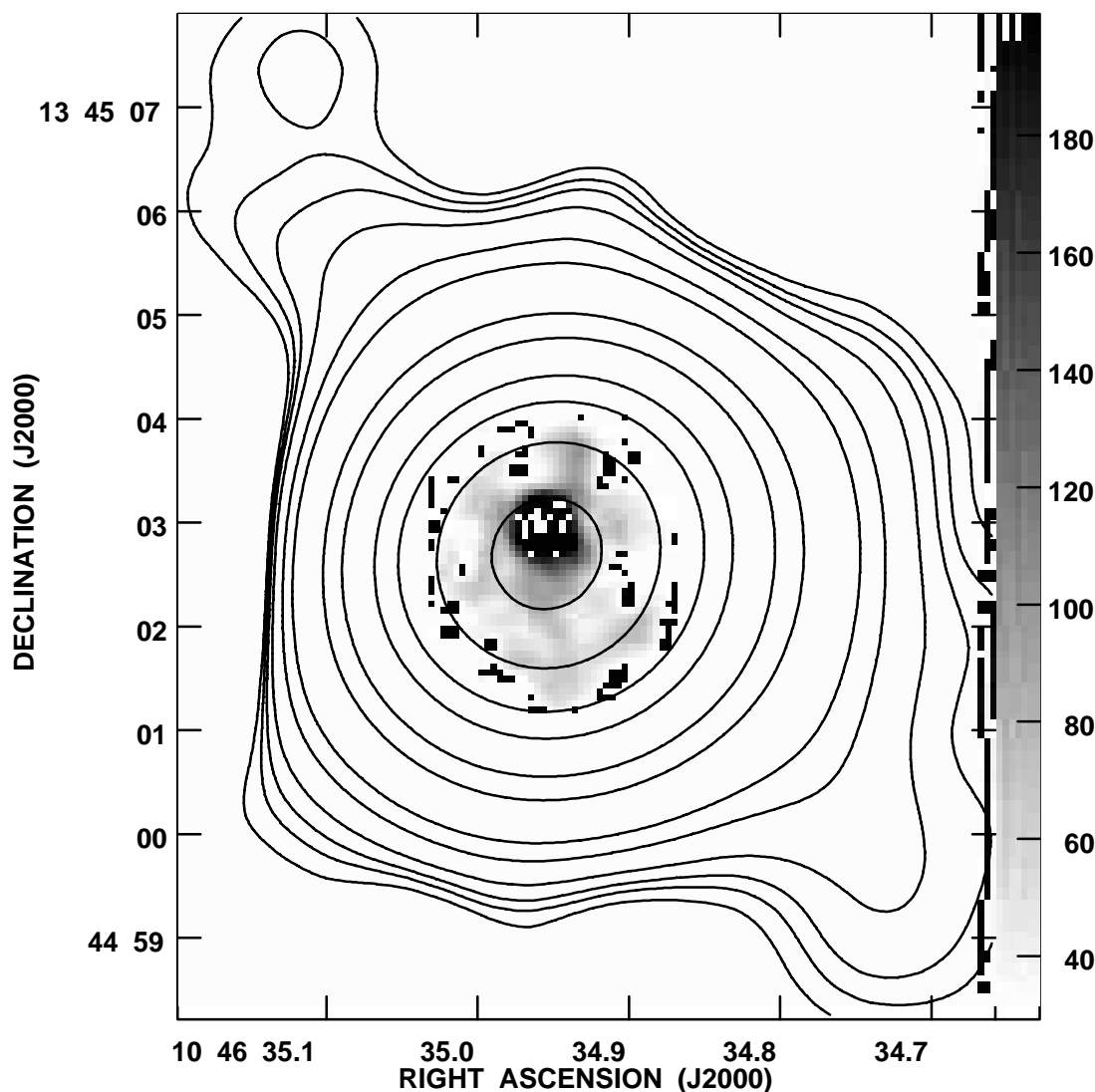


FIG. 5.—Radio continuum emission from the innermost central region at 1.4 (contours) and 8.4 GHz (gray scale). The contours are in units of $25 \mu\text{Jy beam}^{-1}$, and the levels are 1, 1.5, 2, 3, 6, 10, 30, 50, 100, 150, 250, and 390. The gray scale is from 30 to $200 \mu\text{Jy beam}^{-1}$.

mentioned above. Therefore, although an elongated structure is not observed at 8.4 GHz forming a jet, the observations suggest that the plasma flows out from the compact nucleus, possibly directed in the observed orientation as a result of an accretion disk inclined (but not perpendicular) with respect to the plane of the galaxy. One thus could infer that the jet does not interact with the circumnuclear material. The interpretation of the origin of the energy for the jets in NGC 3367 might still be controversial with respect to the global q parameter. The q parameter is the ratio of the far-infrared (*IRAS*) emission to the 1.4 GHz emission (Helou, Soifer, & Rowan-Robinson 1985). Empirically the median $2.2 \leq \langle q \rangle \leq 3.1$ was found for spiral galaxies (Condon, Anderson, & Broderick 1995), while $\langle q \rangle \leq 2$ was found for galaxies powered by an AGN (Condon, Frayer, & Broderick 1991a). In particular, based on the value found for q for NGC 3367 ($q = 2.4$ using the 5 GHz total emission), it was concluded that the dominant energy source in NGC 3367 is stars (Condon et al. 1991a, 1995). If we compute q using the total emission at 1.4 GHz (119 mJy; Condon et al. 1998), we get $q = 1.9$, which might indicate the presence of a mild

AGN according to the convention (Condon et al. 1991a, 1995). We believe that this result involves global emissions (radio and infrared) and not necessarily the energy powering the jets and lobes observed in NGC 3367. This result still needs to be confronted with the current observations of the central radio sources, jets, and lobes in NGC 3367.

This central radio continuum structure (compact source with circumnuclear regions) is very similar to the structure observed in some barred Seyfert 1 galaxies, like NGC 1097 (Hummel et al. 1987) and NGC 7469 (Condon & Broderick 1991; Wilson et al. 1991; Miles, Houck, & Hayward 1994; Mauder et al. 1994; Genzel et al. 1995). The radius of the circumnuclear structure is about 550 pc in NGC 1097 (Hummel et al. 1987) and about 450 pc in NGC 7469 (Condon et al. 1991b). These are similar to the one observed in NGC 3367 (~ 300 pc). None of these Seyfert galaxies, however, show any indication of a large-scale jet or radio continuum extended lobes (Hummel et al. 1987; Wilson et al. 1991). In the case of normal barred galaxies, like NGC 1326 and NGC 4314, they show $H\alpha$ circumnuclear structures with radio continuum emission characteristic of

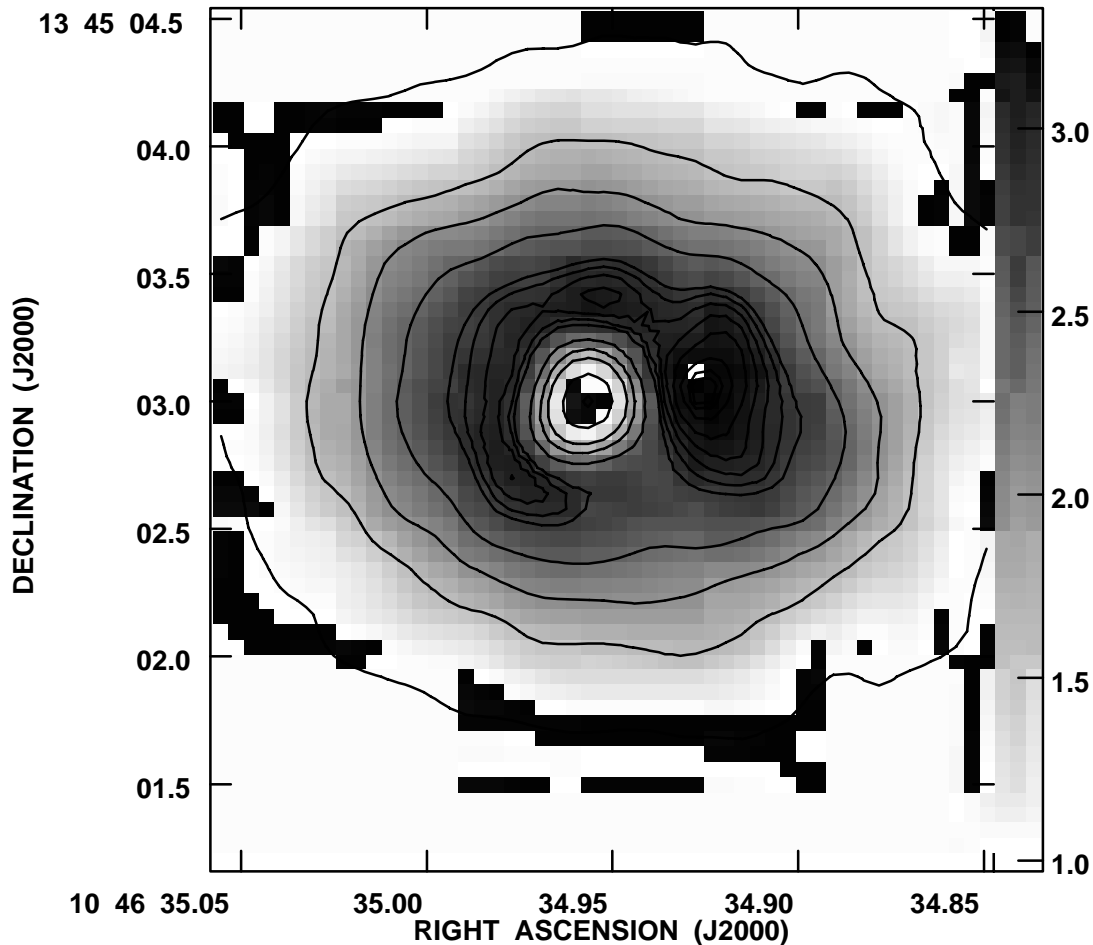


FIG. 6.— $H\alpha$ – 8.4 GHz emission from the innermost $4''$. The contours and gray scale are in arbitrary units relative to the maximum. The structure observed indeed suggests the existence of a circumnuclear structure within the innermost 300 pc ($1'' = 210$ pc). This image was obtained with several assumptions; among them are (1) the spatial location of the peak of the $H\alpha$ emission coincides with the spatial location of the 8.4 GHz emission, (2) both the peaks of $H\alpha$ and 8.4 GHz emission are directly proportional to each other, and (3) the constant of proportionality was chosen as to have zero emission from the center. Although the assumptions seem reasonable, the structure is definitely not a proof, but is very suggestive, of the existence of a circumnuclear structure in $H\alpha$.

regions of star formation at similar radii (400 and 325 pc, respectively). None of them have radio continuum emission from the compact nucleus (García-Barreto et al. 1991a, 1991b) nor any radio continuum extended lobes. These differences in radio continuum emission morphology from barred galaxies probably suggest also differences in disk properties, like the amount of gas in the disk, the strength of the gravitational potential including the nonaxisymmetric component, and possibly different ways of transporting material to the central regions and compact nucleus.

Our main results are as follows:

1. There is a faint structure that connects the central source with the southwest lobe, here identified as a low surface brightness jet. Thus, the lobes are currently being fed by plasma from the compact radio source.

2. At the highest resolution, the 8.4 GHz emission shows an unresolved central peak with several circumnuclear sources. The unresolved source, which is located at the center of the galaxy, is ~ 10 times stronger than individual peaks of emission in the circumnuclear region, and its deconvolved diameter is smaller than 65 pc.

3. The circumnuclear radio sources are most likely not associated with the interaction of the jet and the surrounding medium.

4. An estimate of the spectral index from the innermost region within a radius of $1''.8$ from the center is about -0.53 .

5. The flow of plasma from the nuclear region to the lobes is out of the plane of the galaxy but inclined with respect to the rotation axis of the disk.

6. No emission is detected from the stellar bar.

Our high-resolution imaging has confirmed ideas from earlier work that NGC 3367 is a currently active low-power radio galaxy, continuing to be powered by a weak LINER/ $H\ II$ nucleus. Like other barred spirals, it shows indications of star formation both in the center and on larger scales. The jetlike structure connecting the central source with the southwest lobe is out of the plane of the disk.

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