CENTRAL ACTIVITY IN THE BARRED GALAXY NGC 3367

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ABSTRACT

We report the radio continuum structure of the barred galaxy NGC 3367 with an angular resolution of ~4".5. The radio structure indicates emission from the disk and from a triple source consisting of the nucleus straddled by two extended sources (the lobes). The triple source shows an excess of radio continuum emission compared with the emission expected from the total radio-H α correlation, suggesting a nonthermal origin probably related to activity of an active galactic nucleus (AGN) and not to star formation processes. The triple source is approximately 12 kpc in extent at P.A. $\approx 40^{\circ}$, close to (but not aligned with) that of the stellar bar, P.A. $\approx 65^{\circ}$. Only the southwest lobe is polarized. The polarization asymmetry between the two lobes suggests that the triple-source axis is slightly out of the plane. If the origin of the emission is an outflow of plasma from an AGN, as seen in weak radio galaxies and NGC 1068, then NGC 3367 provides an excellent laboratory object to study a possible interaction of the ejected material and the barred galaxy.

Key words: galaxies: clusters: individual (NGC 3367) — galaxies: structure — intergalactic medium — quasars: emission lines

1. INTRODUCTION

NGC 3367 is a face-on SBc(s) barred spiral galaxy inclined with respect to the plane of the sky at an angle $i \approx 6^{\circ}$ (Grosbøl 1985). It can be considered an isolated galaxy at a distance of 43.6 Mpc with a distant neighbor, NGC 3419, behind the Leo Spur group of galaxies (using $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and assuming that the Milky Way is moving toward the Virgo Cluster at 300 km s⁻¹; Tully 1988). At this distance, an angular diameter of 1" corresponds to ≈ 210 pc. The stellar bar has an angular diameter of $\approx 32''$ (6.72 kpc) oriented at P.A. $\approx 65^{\circ}$, and there is a southwest optical structure resembling a "bow shock," along which lies a half-ring of $H\alpha$ knots at a radius of about 10 kpc from the nucleus (García-Barreto, Franco, & Carrillo 1996a). VLA observations at 15" angular resolution by Condon et al. (1990) at 1.46 GHz show emission from the disk as well as from the nucleus and from two sources straddling the nucleus. NGC 3367 is also an X-ray and farinfrared emitter (Gioia et al. 1990; Stocke et al. 1991; Fabbiano, Kim, & Trinchieri 1992; Soifer et al. 1989). The X-ray emission extends beyond the disk, but peaks some 21" from the compact nucleus in the southwest direction (Gioia et al. 1990; Stocke et al. 1991; Fabbiano et al. 1992). This is coincident with the southwest radio continuum lobe. Its X-ray luminosity is stronger than other normal spirals, but weaker than Seyfert galaxies. It also has strong far-IR emission, of about $L_{\rm FIR} \approx 2 \times 10^{10} L_{\odot}$ (Soifer et al. 1989), with a relatively high dust temperature of $T_p \approx 35$ K (García-Barreto et al. 1993). The nuclear region also shows an H α peak intensity of 2.4 × 10⁻¹³ ergs s⁻¹ cm⁻², with FWHM ~ 650 km s⁻¹, and [O III] $\lambda 5007 \approx \frac{1}{2}$ H β (Véron-Cetty & Véron 1986). All these characteristics are similar to those found in Seyfert galaxies, and thus NGC 3367 has been classified as a Seyfert-like galaxy (Véron-Cetty & Véron 1986).

Radio continuum emission from the central regions of disk galaxies has been detected at low resolution from almost every nearby spiral (Hummel 1980; Gioia, Gregorini, & Klein 1982; Condon 1992; García-Barreto et al. 1993; Niklas, Klein, & Wielebinski 1997), and highresolution studies show that this is usually a result of circumnuclear emission, with a variety of sizes and morphologies. Double, triple, or jetlike radio continuum structures have been found in several barred spirals with well-known Seyfert activity, such as NGC 1068, 4151, and 5728, but only NGC 1068, a Seyfert 2, displays extended radio continuum disk emission and has a central (0.4 kpc) source with two lobes (Wilson & Ulvestad 1987), very much like a small-scale radio galaxy (van der Hulst, Hummel, & Dickey 1982; Wynn-Williams, Becklin, & Scoville 1985; Ulvestad, Neff, & Wilson 1987; Wilson & Ulvestad 1987).

In this paper, we present new VLA² radio continuum observations of NGC 3367 at 1.4 GHz with a beam of ~4".5. The radio continuum image is complex, showing emission from the central region, from many unresolved sources associated with star-forming regions, and from two extended regions straddling the central region. For the purpose of analysis, in this paper we refer to the emission from the central region plus the two extended sources as the *triple source*, and we refer to the emission from the disk emission as *star formation* emission.

2. OBSERVATIONS AND RESULTS

We have carried out radio continuum observations at the VLA, in New Mexico, in the B configuration at 1.3851 GHz

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and at 1.4649 GHz, on 1997 May 18 using 27 antennas with 50 MHz bandwidths, and 7.5 hr integration time on NGC 3367. We observed 3C 286 as the amplitude and polarization calibrator and 1120+143 as the phase calibrator. We assumed a flux density for 3C 286 of $S_v = 14.941$ Jy at v = 1.3851 GHz, and $S_v = 14.554$ Jy at v = 1.4649 GHz. Several iterations of phase self-calibration and one iteration of amplitude self-calibration were used. The final maps of the total intensity of NGC 3367 after 25,000 iterations using the AIPS cleaning task IMAGR have an rms noise of ~18 μ Jy beam⁻¹ and a cleaned beam of 4.51 × 4.34 at P.A. ~ -71°, using uniform weighting. The final maps, however, still have weak ripples in the east-west direction, most likely as a result of phase residuals. The maps in Q and U have an rms of ~10 μ Jy beam⁻¹.

2.1. Total Intensity

Figure 1 shows the total intensity map of NGC 3367. There are four different regions that are apparent in the figure: (1) the unresolved source from the nuclear region, (2)the northeast and the southwest extended emissions, i.e., the lobes (see Fig. 2), which are connected to the nuclear region, (3) many unresolved sources in the disk of the galaxy, and (4) diffuse disk emission. We designate regions 1 and 2 as the "triple source" for later discussion. The total integrated flux density is 89.3 mJy, slightly less than the low-resolution (VLA-D FWHM $\approx 45''$) value of 119.5 mJy, which is more sensitive to diffuse emission (Condon et al. 1998). The central source is slightly resolved, with an approximate deconvolved FWHM size of 1.7×1.6 , at P.A. $\approx 100^{\circ}$. The integrated flux densities of the northeast and southwest lobes are ≈ 13 and ≈ 23 mJy, respectively, and span 12 kpc. The disk emission is generated from at least 55 unresolved sources (each with a peak flux of $\leq 500 \,\mu$ Jy beam⁻¹).

The nucleus is connected to the lobes by extensions at an angle of $\approx 70^{\circ}$, coincident with the position angle of the



FIG. 1.—Radio continuum emission from NGC 3367 with a beam FWHM $\approx 4.5 \times 4.3$ at P.A. $\approx -70^{\circ}$. The contours are in units of 18 μ Jy beam⁻¹ and the levels are -3, 3, 5, 7, 9, 11, 13, 15, 17, 20, 25, 35, 50, 65, 80, 110, 120, 140, and 160. The weak extension from the nuclear source into the southeast and the weak extensions to the west of the galaxy are probably not real, but related to phase problems in the data.



FIG. 2.—Radio continuum emission from the extended regions northeast and southwest of the nucleus. The contours are in units of 18 μ Jy beam⁻¹ and the levels are -3, 7, 11, 15, 19, 21.5, 23, 25, 27, 30, 40, 55, 70, 90, 120, 140, and 160.

innermost contours of the convolved red continuum image of the stellar bar (García-Barreto et al. 1996b). A line joining the two lobes is at P.A. $\approx 45^{\circ}$, and a one-dimensional plot along this line (Fig. 3) shows the brightening toward the outer parts of the lobe, similar to the observed behavior of powerful radio galaxies (Fernini, Burns, & Perley 1997).

2.2. Polarized Intensity

Polarized emission was detected only from the southwest lobe (Fig. 4). The fractional polarization varies through the



FIG. 3.—One-dimensional plot of the total radio continuum emission along the line at P.A. ~ 45° (with center at $\alpha = 10^{h}46^{m}35^{s}1$, $\delta = 13^{\circ}45'04''_{.8}$ [J2000.0]). Note that the flux density increases with distance from the nucleus and has a sharp drop at the end of the lobes. The large central flux is from the nuclear region. Negative distances are toward the southwest lobe.



FIG. 4.—Electric field vectors plotted over the total intensity map of the southwest lobe in NGC 3367. The contours are as in Fig. 2. The length of each vector is proportional to the polarized brightness, with 1" indicating 200 μ Jy beam⁻¹.

southwest lobe from $\approx 4\%$ to $\approx 24\%$. The polarization angle also varies from P.A. $\approx 70^{\circ}$ to $\sim 145^{\circ}$, with no corrections made for Faraday rotation. On average, the polarization in the northeast lobe is lower than $\approx 3\%$.

3. CENTRAL TRIPLE SOURCE

If the extended radio emission in NGC 3367 is a combination of emission related to star formation and to activity of an active galactic nucleus (AGN), then, in principle, it should be possible to separate their contributions by using the distribution of H α emission. The H α emission and the thermal radio emission are proportional to the number of ionizing photons. The ionizing photons come primarily from the most massive OB stars in stellar clusters. In addition, nonthermal emission from star formation regions comes from the supernova remnants (SNRs). We expect a correlation between H α and radio emission, although this can be complicated by differences in extinctions, in the SNR populations, or in magnetic field strengths (see, e.g., Deeg, Duric, & Brinks 1997).

Here we have adopted a more empirical approach and have simply subtracted scaled versions of the H α map, Figure 5 (from García-Barreto et al. 1996b), from the radio map. The exact scaling factor is not relevant for the rest of the discussion. With the aid of these subtracted images (see Fig. 6), we are able to eliminate the contributions to the radio from the brightest H II regions. Then we can make rough estimates of the strength and morphology of the remaining nonthermal emission, which we identify as AGN related.

The residual emission is dominated by the triple source previously discussed, along with long ridges of emission on both sides of this source (see Fig. 7). These ridges are likely to be disk emission and, possibly, associated with cosmicray acceleration in large-scale shocks. They are coincident with optical low surface brightness regions, are relatively weak in H α , and lie outside of the stellar bar. Their locations seem to correspond with locations at which large-scale shocks can be produced by gas flows driven by a bar potential (see Roberts, Huntley, & van Albada 1979 and Fig. 6.28 of Binney & Tremaine 1987). This issue is currently under investigation with a magnetohydrodynamic code, and it will be addressed in a forthcoming paper. At the moment, we center the discussion on the AGN-related emission.

The power of the triple source is about 10^{22} W Hz⁻¹, approximately half the total radio power from NGC 3367 and similar to that of Seyfert 2 galaxies. It is known that both Seyfert and Markarian galaxies can have double or triple radio continuum sources (e.g., NGC 1068, Mrk 3, Mrk 6, Mrk 78, NGC 4151, NGC 5548, and NGC 5728; Ulvestad, Wilson, & Sramek 1981; van der Hulst et al. 1982; Ulvestad & Wilson 1984; Baum et al. 1993), and some edge-on Seyfert galaxies and starburst galaxies show largescale radio continuum structures along their minor axes (Colbert et al. 1996). In the case of barred spirals, the relative orientation of the bar and the double and triple sources varies from galaxy to galaxy. A comparison with other types of galaxies is presented in § 5.

The fact that only one lobe is polarized may indicate that they do not lie on the plane of the disk, but may be inclined with respect to the midplane. If this is the case, the emission from the far lobe (the northeast) will be depolarized by the disk material, and only the near lobe (the southwest) will show some polarization. Their sizes indicate that, in projection, they cover about one-third of the galaxy's diameter.

4. FROM NORMAL BARRED TO SEYFERT GALAXY: IS NGC 3367 IN TRANSITION?

The optical properties of the nucleus and the extended disk of NGC 3367 are similar to those found in both normal spirals and weak Seyfert 2 galaxies: in particular, $[O III] \approx$ $\frac{1}{2}$ H β and [O I] $\approx \frac{3}{10}$ [O III] (Véron-Cetty & Véron 1986). The nuclear optical spectrum suggests a composite spectrum between a normal H II spiral and a weak LINER or a weak Seyfert 2 galaxy (Véron, Gonçalves, & Véron-Cetty 1997). Even though NGC 3367 does not show the optical nuclear characteristics of Seyfert galaxies (with broad Balmer lines with FWHM ≥ 1000 km s⁻¹ and $[O \text{ III}]/H\beta \ge 3$), its radio power at 1.46 GHz is stronger than Seyfert 1 galaxies and is comparable to other Seyfert 2 galaxies. As stated above, the power of the central source plus the lobes is $P_{1.4 \text{ GHz}} \sim 10^{22} \text{ W Hz}^{-1}$. Also, the global spectral index of NGC 3367 is $\alpha \approx -1$, from 1.4 to 4.8 GHz, similar to the spectral index found in other Seyfert galaxies (de Bruyn & Wilson 1978; Condon et al. 1990) and slighty steeper than in normal spirals (Klein & Emerson 1981; Condon et al. 1990; Niklas et al. 1997).

There are several barred galaxies that show similar radio continuum morphologies, and NGC 1068 is probably the best-known example. At a distance of 15.6 Mpc, the power of the inner 13" structure in NGC 1068 at 6 cm is $P_{4.8 \text{ GHz}} \sim$ 3.4×10^{21} W Hz⁻¹ (Wilson & Ulvestad 1987). It also has a central source plus two lobes (parallel to the stellar bar), a bright stellar bar, and a nearly face-on disk (Wilson & Ulvestad 1987; Baldwin, Wilson, & Whittle 1987; Scoville et al. 1988). Elongated radio continuum structures are relatively common in the central parts of barred galaxies with Seyfert-like activity, but the relative orientation between the structures and the corresponding bars does not show any particular type of alignment (Schommer et al. 1988;



Fig. 5.-(a) H α + [N I] continuum-free image of NGC 3367 (García-Barreto et al. 1996a, 1996b), convolved to a Gaussian beam as the clean beam in the radio continuum map (see Fig. 1). The contour units are 6×10^{-16} ergs s⁻¹ cm⁻² arcsec⁻² and the levels are -3, 3, 5, 7, 9, 11, 13, 15, 17, 20, 25, 30, 35, 50, 65, 80, 100, 120, 140, and 160. Note the limb-brightened edge forming a semicircle in the southwest part of the galaxy. (b) Radio continuum emission contours superposed on a gray-scale image of the H α + [N II] continuum-free emission from NGC 3367. The contour units and levels are as in Fig. 1.



FIG. 6.—Map of the radio continuum emission minus the scaled H α image. The scaling factor was 7.2 × 10⁹. Note that (1) more emission from the weak H II region disappeared at the northwest, (2) the streamer starting at the northeast is getting narrower than the emission from the original radio map (see Fig. 1), and (3) the limb-brightened eastern edge of the northeast lobe is more pronounced than the emission from the original radio map (see Fig. 1), and (3) the limb-brightened eastern edge of the northeast lobe is more pronounced than the emission from the original radio map (see Fig. 1). In this map there is negative emission from the bright H α regions in the south and west of the galaxy, indicating that the subtraction was overdone in those areas. The radio continuum emission seen in this map is most likely not directly related to star formation.

Ulvestad et al. 1981; Wilson et al. 1993; Mundell et al. 1995). A summary of the global properties of NGC 3367 and other (normal, Seyfert 2, Seyfert 1, and radio) galaxies is shown in Table 1.

The angular distances on the plane of the sky of NGC 3367 from the central source to the brightest sources in the northeast and southwest lobes are $\sim 33''$ and $\sim 26''$, respectively. These angular distances would correspond to linear

TABLE 1 Properties of NGC 3367 and Other Galaxies

Property	Normal	NGC 3367	NGC 1068	Seyfert 2	Seyfert 1	Radio	References
$\begin{array}{c} \lambda 5007/H\beta \\ L_{\rm [O III]} (W) \\ q(FIR/radio) \\ \log P_{1.4{\rm GHz}}(W{\rm Hz}^{-1}) \\ {\rm Dimensions}^{\rm a} (\rm kpc) \\ \log L_{\rm X}({\rm ergs \ s}^{-1}) \end{array}$		$\begin{array}{c} 0.4 \\ 4 \times 10^{32} \\ 2-2.4 \\ 22.3 \\ 5.5-7 \\ 40.9 \end{array}$		$ \begin{array}{c} \geq 1 \\ 10^{34} - 10^{37} \\ 1.5 - 2.3 \\ 21 - 23.5 \\ 0.5 - 5 \\ \leq 42 \end{array} $	$ \begin{array}{c} \geq 1 \\ 10^{34} - 10^{37} \\ 2 - 2.4 \\ 20 - 22 \\ \leq 0.1 \\ \leq 43 \end{array} $	≥ 1 10^{34} ≤ 1 ≥ 24 ≥ 100 40-44	1, 2, 3 1, 2, 3, 4 5, 6, 7, 8 4, 7, 8, 9 7, 8, 9, 10, 11, 12, 13 14, 15, 16, 17

^a Distances from nucleus to circumnuclear region in normal galaxies, from nucleus to lobe in NGC 1068, NGC 3367, and Seyfert and radio galaxies.

REFERENCES.—(1) Baldwin et al. 1987; (2) Véron-Cetty & Véron 1986; (3) Lawrence et al. 1996; (4) Wilson 1996; (5) Condon 1991; (6) Ledlow et al. 1998; (7) this paper; (8) Condon et al. 1990; (9) Ulvestad & Wilson 1984; (10) Hummel, van der Hulst, & Keel 1987; (11) Wilson & Ulvestad 1987, (12) Baum et al. 1993; (13) Colbert et al. 1996; (14) Fabbiano et al. 1992, (15) Dultzin-Hacyan & Ruano 1996; (16) Wilson 1991; (17) Rhee, Burns, & Kowalski 1994.



FIG. 7.—Optical broadband I ($\lambda \sim 8040$ Å) image (from García-Barreto et al. 1996b) in contours superposed on the total radio continuum emission. Contours are mainly to indicate the extent of the stellar bar and the spatial extent of the disk. The gray scale was chosen to show the emission mainly from the lobes. Note that the innermost radio continuum emission originates in the same position angle as the stellar bar and then slowly deviates from this angle to smaller values in the northeast.

distances of ~ 7 and ~ 6 kpc. For comparison, the northeast lobe in NGC 1068 is only \sim 400 pc from its nucleus. At the other extreme, the distance from the center to the north lobe in the spiral radio galaxy 0313-192 (in the Abell 428 cluster) is ≈ 100 kpc (Ledlow, Owen, & Keel 1998). The extent of the so-called extranuclear emission observed in edge-on Seyfert galaxies ranges from 0.6 kpc, in NGC 4051, to 30 kpc, in Mrk 231, with an average of \sim 4.5 kpc (Baum et al. 1993). Thus, the lobes of NGC 3367 are within the wide range of sizes observed in other active galaxies. The spatial resolution of our observations, however, is not suitable to analyze the structure of the connection between the lobes and the central nuclear source (e.g., jets, plasmoids from a galactic wind, young superbubbles), or to analyze whether any emission originates from the inner regions of the bar. Also, if there is a radio continuum circumnuclear structure in NGC 3367, it must be less than 4" in diameter, and higher angular resolution observations would be needed to resolve it. The central ionized gas structure in $H\alpha$ is also dominated by an unresolved bright source and weak emission extending to about a radius of 2".5 (García-Barreto et al. 1996a).

5. TRIPLE SOURCE-GALAXY RELATION

Several models have been proposed for the radio emission from a Seyfert nucleus (Blandford & Königl 1979; Pedlar, Dyson, & Unger 1985; Wilson & Ulvestad 1987; Taylor et al. 1989). In our case, the key questions are the origin of the triple radio source, its structure, and the polarization asymmetry.

The total gas content in NGC 3367, $M_g \sim 7 \times 10^9 M_{\odot}$ (Giovanardi et al. 1983; Huchtmeier & Seiradakis 1985), is similar to the amount observed in other Sc galaxies. The AGN activity that originates the triple radio source in NGC 3367 was probably triggered by an episode of efficient gas transfer to the innermost central regions. As stated above, gas from large radii can be transferred to the central regions by the action of the nonaxisymmetric gravitational potential (Binney & Tremaine 1987; Friedli & Martinet 1997), or by interaction with another galaxy (Lynds & Toomre 1976; Toomre 1978). In NGC 3367, both scenarios are possible: it has a well-formed bar, and it has a string of H II regions (forming a semicircle) that could have originated in an offcenter collision with an intruder (García-Barreto et al.

1996a). The bar, however, can only drive the gas inflow to the inner Lindblad resonance, and an additional pertubation (e.g., interaction with an intruder) is needed in order to send the gas even closer to the dynamical center (Toomre 1978).

On larger scales, the gas also strongly influences the appearance and structure of the triple radio source. The polarization asymmetry is likely caused by depolarization through an ionized component, such as that seen in X-rays. The limb-brightened outer edges indicate an interaction with a gaseous external medium. Similarly, the S shape of the triple source could result from shears in galactic rotation or gradients in the ambient medium (see, e.g., Henriksen, Vallée, & Bridle 1981). Precession of the jet as a result of torques from infalling material (Tohline & Durisen 1982) could also play a role.

The interactions between the radio plasma and the other gaseous components are worthy of further study, such as searching for molecular and shocked gas at the leading edges or where the jets from the nucleus make large changes in direction. Numerical simulations of jet flows in a barred galaxy would also be of interest.

6. CONCLUSIONS

We have observed, using the VLA's B configuration, the radio continuum emission from the barred galaxy NGC 3367 with 4".5 spatial resolution. The radio continuum emission maps show emission from four distinct regions: (1) the star-forming region, (2) the nucleus, (3) two extended symmetric lobes connected with the nuclear source, and (4) long ridges of emission from the disk that are not coincident with bright Ha regions. Our main results are as follows:

1. The optical and radio characteristics suggest that NGC 3367 is a transition galaxy between normal and Seyfert.

2. The total radio continuum emission from regions of

star formation correlates with the observed $H\alpha$ emission, in agreement with a similar correlation found in other galaxies.

3. The strongest radio continuum emission is from a barely resolved nuclear source and two extended regions symmetrically located opposite the nucleus, forming what we call the triple source, with total extent ~ 12 kpc. The morphology of the triple source is similar to that observed in radio galaxies, and to the structure seen in the inner 0.4 kpc of NGC 1068.

4. The triple source could be the result of nuclear ejecta in the northeast and southwest directions that is inclined with respect to the galactic plane. The S shape of the lobes could be due to interaction with the ambient gas.

5. Only the southwest lobe is found to be polarized. The northeast lobe is probably depolarized as the beam passes through a randomly oriented magnetic field in the disk of the galaxy.

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