

15 GHz COMPACT STRUCTURE IN GALACTIC NUCLEI

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ABSTRACT

We present 0.2 resolution maps of 15 GHz continuum emission in 11 infrared and radio-bright galactic nuclei. The high angular resolution and short wavelength favor the detection of AGNs and other bright compact sources of flat spectral index. We divide the galaxies into three groups. In NGC 2992, NGC 3079, NGC 4151, and NGC 4388, the low-infrared luminosities, high radio-to-infrared luminosities, and small, bright ($T_B > 10^3$ K), centrally located radio sources, are most likely associated with AGNs. In NGC 520, NGC 660, NGC 2146, and NGC 3628, higher infrared luminosities, lower radio-to-infrared luminosity ratios, and multiple compact radio components that are less bright ($T_B < 300$ K), are likely to be produced by star formation, probably in large part by compact H II regions. In the extremely luminous infrared galaxies NGC 6240 and NGC 3690, the high brightness temperatures ($T_B > 10^3$ K) of the radio components, together with their unusually high L_{IR} and relatively low Brackett line fluxes, indicate that the compact knots may be associated with both AGN and star formation.

Subject headings: galaxies: nuclei — interferometry — radio sources: galaxies — stars: formation

I. INTRODUCTION

Ground-based observations and *IRAS* data have revealed that a considerable fraction of galaxies are extremely luminous at infrared wavelengths (Soifer *et al.* 1984, 1987*b*), frequently in the nuclear regions (Rieke and Lebofsky 1978). The infrared continuum emission has been interpreted as evidence of intense bursts of star formation. Extended nonthermal radio continuum emission in these galaxies may be produced by supernovae accompanying the starburst (Rieke *et al.* 1980; Weedman *et al.* 1981).

However, both infrared continuum and extended non-thermal radio emission are indirect probes of star formation. Aligned nonthermal radio structures seen in some spiral nuclei (Wilson and Ulvestad 1982; Ulvestad and Wilson 1984*a, b*; Turner and Ho 1985, hereafter TH) suggest that even extended radio emission may often be attributed to active galactic nuclei (AGN) rather than star formation. Is it possible that the infrared dust emission is also heated by a nonthermal nuclear “engine” rather than simple star formation? High-resolution mapping indicates the presence of compact radio cores in “normal” galaxies, with high brightness temperatures and relatively flat spectra ($T_B > 10^4$ K; $\alpha \sim -0.2$ to -0.4), distinctly different from the larger scale structures ($T_B < 100$ K; $\alpha \sim -0.6$ to -1.2) (Condon *et al.* 1982; Klein and Emerson 1981; Gioia, Gregorini, and Klein 1982; Turner and Ho 1983). Compact radio cores may well be opaque synchrotron emission surrounding an AGN (Kellerman and Pauliny-Toth 1981), perhaps an evolutionary stage following a starburst (Norman and Scoville 1988).

In this paper, we study nuclear activity (starbursts vs. AGNs) in galaxies by looking at compact, flat spectrum radio continuum emission. We test for the presence of AGNs in “normal” galaxies and study the strength, location, and nature of the compact emission in starburst galaxies. Toward this end we made 0.2 resolution VLA observations of the 2 cm emission from 11 galaxies whose infrared or radio continuum emission

show evidence of nuclear structure. Most of the galaxies in the selected sample are interacting galaxies or are morphologically classified as peculiar spirals.

High angular resolution and short wavelengths bias our sensitivity toward bright compact features with relatively flat spectral index. This approach serves to suppress the contribution of extended synchrotron radiation, classical H II regions, and old SNR. Our results provide some clues to the nature of the nuclear activity in these galaxies.

II. OBSERVATIONS AND RESULTS

The observations were made in 1986 May using the NRAO⁴ Very Large Array in its A configuration. We observed with 27 antennas at 14.965 GHz and an effective bandwidth of 100 MHz. Total integration times were 35–50 minutes per galaxy. Absolute position errors are ≤ 0.1 . 3C 286 is the absolute flux calibrator with an assumed flux density of 3.45 Jy (Baars *et al.* 1977). The estimated error in the absolute flux calibration is 5% or less. From the calibrated data we constructed CLEANed maps (Clark 1980). For NGC 3690, NGC 4151 and NGC 6240 the signal-to-noise ratio was sufficiently high to allow the application of self-calibration (Schwab 1980). The synthesized beamsizes are ~ 0.15 (FWHM) and the rms in the maps is 0.05–0.1 mJy beam⁻¹. Lack of short spacings in the A configuration of the VLA results in insensitivity to source components larger than 3".

We detect 10 of the 11 galaxies in the sample. For NGC 2782 we obtain a 3 σ upper limit of 0.3 mJy for the nuclear region. Selected maps have been plotted in Figure 1. In Table 1, we give the beam size, rms noise, and total flux detected on the 15 GHz maps as well as the galaxies, far-infrared (FIR) luminosities, 60 μm to 1.4 GHz flux ratios, and single-dish 2 cm fluxes from the literature. It can be seen that the percentage of mapped radio emission ranges from less than 1% in NGC 2146 and NGC 2782 to 75% in NGC 4151; for most of the galaxies we detect a small percentage of the total 2 cm emission which

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DECLINATION

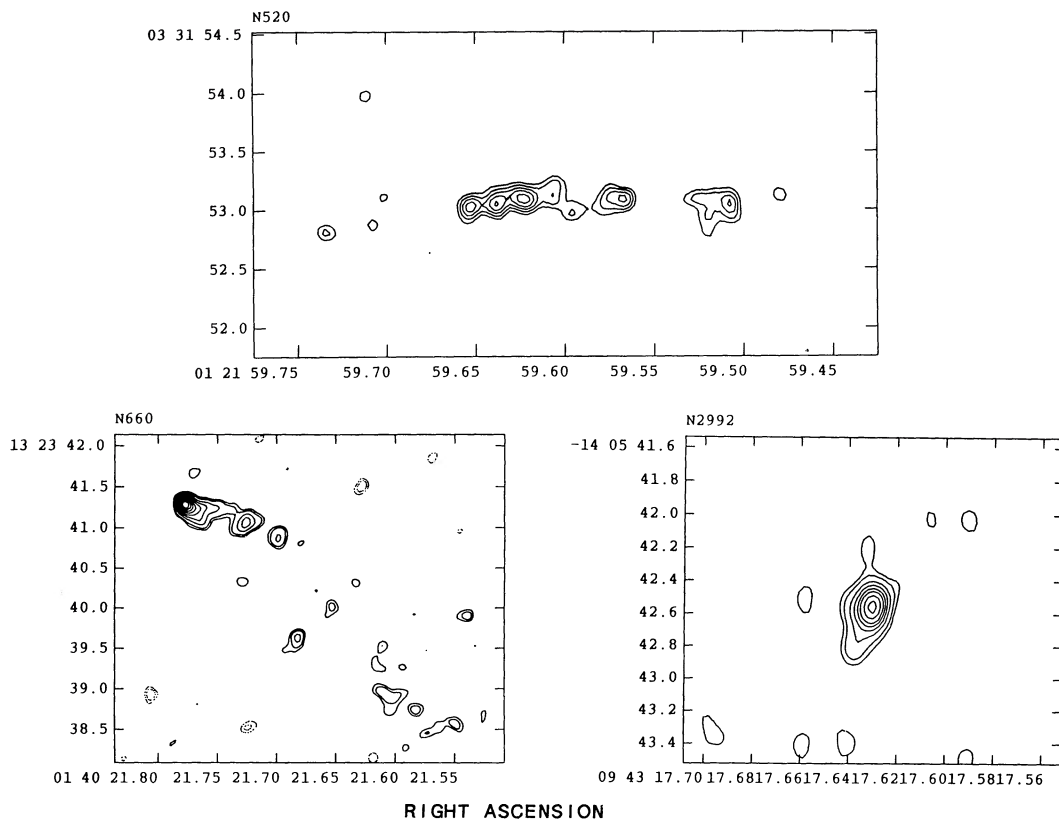


FIG. 1a

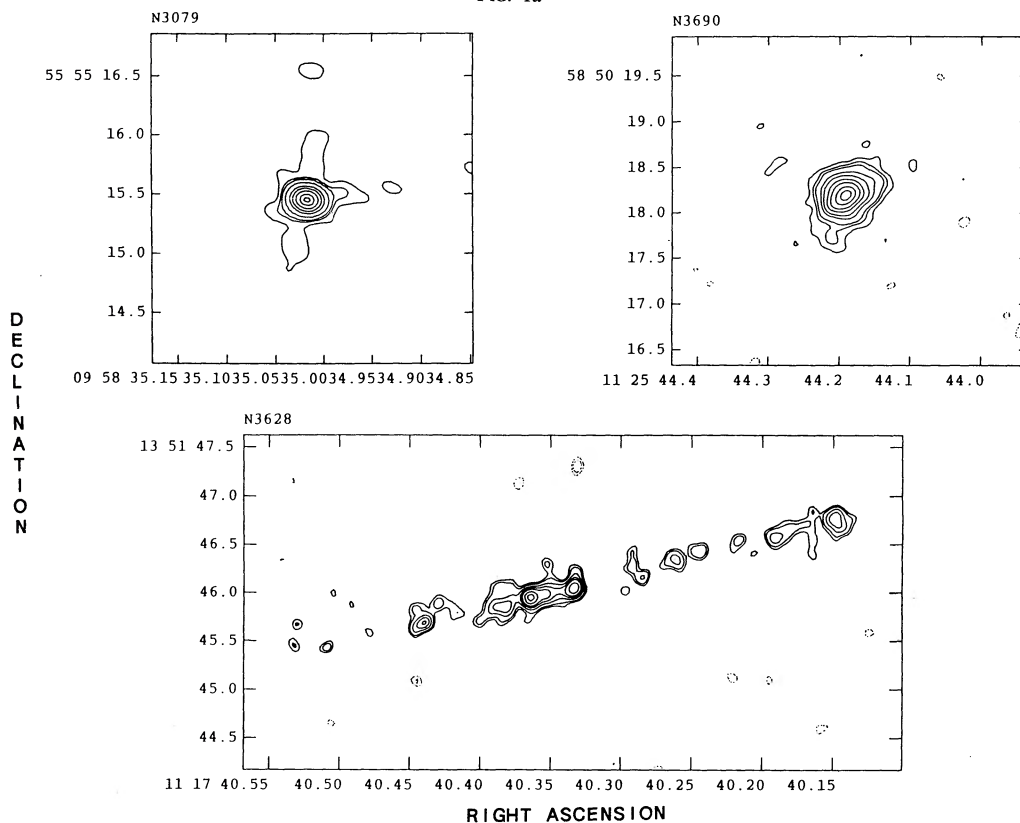


FIG. 1b

FIG. 1.—15 GHz radio continuum maps for selected galaxies in our sample. (a) The contour levels are $-0.21, 0.21, 0.28, 0.35, 0.42, 0.49, 0.56,$ and $0.63 \text{ mJy beam}^{-1}$ for NGC 520; $-0.24, -0.18, 0.18, 0.24, 0.37, 0.49, 0.61, 0.73, 0.85, 0.98,$ and $1.1 \text{ mJy beam}^{-1}$ for NGC 660; $-0.4, -0.2, 0.2, 0.4, 0.8, 1.2, 1.6, 2.0, 2.6, 3.2 \text{ mJy beam}^{-1}$ for NGC 2992. (b) The contour levels are $-0.3, 0.3, 0.9, 1.2, 1.8, 2.4, 3.0, 4.2,$ and $5.4 \text{ mJy beam}^{-1}$ for NGC 3079; $-0.3, 0.3, 0.6, 0.9, 1.8, 2.7, 4.2, 6.0, 9.0,$ and $12.0 \text{ mJy beam}^{-1}$ for NGC 3690A; $-0.28, -0.21, 0.21, 0.28, 0.42, 0.56, 0.7, 0.98,$ and $1.26 \text{ mJy beam}^{-1}$ for NGC 3628. (c) The contour levels are $-0.28, -0.21, 0.21, 0.28, 0.42, 0.56, 0.70, 1.05, 1.4, 2.1, 3.5, 4.9, 6.3, 9.1,$ and $11.9 \text{ mJy beam}^{-1}$ for NGC 4151; $-0.44, -0.22, 0.22, 0.44, 1.32, 1.76,$ and $2.2 \text{ mJy beam}^{-1}$ for NGC 4388; $-0.2, 0.2, 0.4, 0.6, 1.2, 2.0, 3.4, 6.0,$ and $9.0 \text{ mJy beam}^{-1}$ for NGC 6240.

DECLINATION

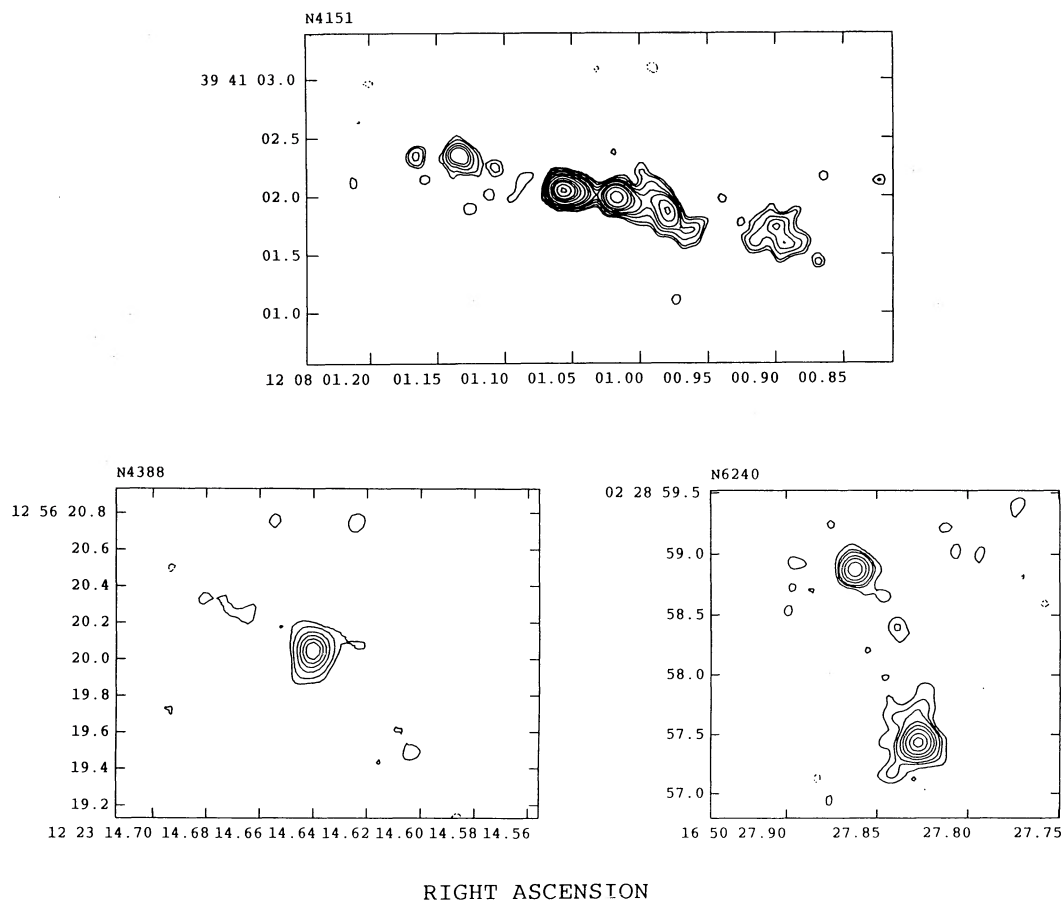


FIG. 1c

TABLE 1

PROPERTIES OF GALAXY SAMPLE AND OBSERVATIONAL PARAMETERS

Galaxy Name	$\alpha(1950)$	$\delta(1950)$	Galaxy Type ^a	Distance ^b (Mpc)	L_{FIR}^c ($10^{10} L_{\odot}$)	u^d	CLEAN Size	Beam P.A.	rms (mJy/ Ω_b)	$S_{15 \text{ GHz}}^e$ VLA (mJy)	$S_{15 \text{ GHz}}^f$ Single Dish (mJy)
N 520	01 ^h 21 ^m 59 ^s .62	03°31'53".2	.P.....	30.1	4.5	2.24	0'.18 × 0.16	29°	0.05	9 ± 2	37
N 660	01 40 21.66	13 23 39.8	.SBS1P.	13.0	1.8	2.16	0.17 × 0.17	...	0.06	12 ± 4	82
N 2146	06 10 41.10	78 22 28.1	.SBS2P.	17.7	6.8	2.08	0.19 × 0.14	7	0.09	1.7 ± 0.3	230
N 2782	09 10 53.65	40 19 15.3	.SXT1P.	40.1	2.2	2.0	0.18 × 0.15	-81	0.09	≤ 0.3	24
N 2992	09 43 17.62	-14 05 42.5	.S..1P.	33.7	1.4	1.3	0.22 × 0.14	-2	0.07	4.6 ± 0.4	90
N 3079	09 58 35.01	55 55 15.5	.SBSS./	19.6	2.9	1.7	0.19 × 0.14	77	0.09	59 ± 2	220
N 3628	11 17 40.35	13 51 46.1	.S..3P/	10.1	0.9	2.7	0.15 × 0.14	-12	0.07	23 ± 2	90
N 3690	11 25 44.18	58 50 18.2	.IB.9P.	48.5	35.2	2.18	0.17 × 0.15	87	0.1	66 ± 4.5	135
N 4151	12 08 01.03	39 41 02.1	.PSXT2*.	20.1	0.4	1.25	0.15 × 0.14	17	0.07	42 ± 3	56
N 4388	12 23 14.63	12 56 19.6	.SAS3*/	19.2	0.7	< 1.8	0.15 × 0.14	18	0.08	3.5 ± 0.4	44
N 6240	16 50 27.83	02 28 58.5	.I.O.*P	97.8	32.1	1.6	0.14 × 0.13	23	0.09	34 ± 4	87

^a Galaxy Types from RCBG 2.^b Distances were determined from redshifts, and derived using the Virgocentric flow of Aaronson *et al.* 1982 (solution 3.1, with $H = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$). For NGC 3079, NGC 3628, and NGC 4388 we used the distances listed in Soifer *et al.* 1987a and modified them for the distance of 18 Mpc adopted for the Virgo cluster.^c From *IRAS* 60 μm and 100 μm fluxes, and the FIR fluxes listed in "Cataloged Galaxies and Quasars Observed in the *IRAS* Survey".^d $u = \log(S_{60 \mu\text{m}}/S_{1.4 \text{ GHz}})$ from Condon and Broderick 1988, for NGC 2992, NGC 4151, and NGC 4388 the radio fluxes were obtained from Ward *et al.* 1980, Condon and Broderick 1988, and Ulvestad and Wilson 1984, respectively.^e Total Flux in our VLA 15 GHz maps.^f Single-dish fluxes for NGC 520, NGC 660, NGC 2782, NGC 3690, and NGC 4151 are extrapolated from 10.7 GHz observations by Urbanick, Gräve, and Klein 1985, Wunderlich, Klein, and Wielebinski 1987, and Gioia, Gregorini, and Klein 1982, with a 70" beam. For NGC 2146, NGC 3079, and NGC 3628 the 10.7 GHz fluxes were measured in a 3' beam (Israel and van der Hulst 1987) and for NGC 6240 the antenna beam was 2.5 (Baan, Güsten, and Haschick 1986). We assumed a spectral index $\alpha = -0.7$ for NGC 3079 and for galaxies with no indices available. NGC 2992 was observed at 1.4 GHz by Ward *et al.* 1980 with a 55" beam and NGC 4388 by Sramek 1975 at 5 GHz with a 2.7 beam. We obtained the 2 cm fluxes assuming spectral indices of -0.55 and -0.7 for NGC 2992 and NGC 4388, respectively. The errors in the single dish fluxes are typically 10%–25%.

must be manifested in structures with diameter greater than $\sim 3''$. In Table 2 we list positions, peak fluxes, and total fluxes for individual components identified in the 15 GHz maps. Source sizes were estimated for the most compact sources by fitting two-dimensional Gaussians to the intensity maps. For more extended sources, we measured directly the 50% contours in the maps. Brightness temperature and total power at 2 cm are also given in Table 2. In this section we describe the results on individual galaxies and in § III we discuss the nature of the observed compact radio emission.

a) Individual Galaxies

NGC 520.—The 6 cm map of NGC 520 by Condon *et al.* (1982; hereafter CCGP) shows a nuclear linear structure $\sim 6''.0 \times 1''.8$ in extent. In our 2 cm map we resolve the 6 cm maximum into three peaks and detect a total of five components aligned at P.A. $\sim 90^\circ$ (Fig. 1). If there is a nuclear source, it is probably associated with components 3, 4, or 5. However, we expect that most of the sources are associated

with star formation, as suggested by the spatial correlation of the radio continuum with the CO emission (Sanders *et al.* 1988; Young *et al.* 1986) and dust feature (Barbieri and di Tullio 1979). If NGC 520 is an interacting pair of galaxies (Stockton and Bertola 1980; Barbieri and di Tullio 1979), the aligned radio emission could be related to disk star formation within one of the galaxies viewed edge-on. Alternatively, NGC 520 could be a single perturbed galaxy (Thuan and Wadiak 1982). This would mean that when deprojected onto the plane of the galaxy at $\sim 120^\circ$ (Stockton and Bertola 1980), the five 2 cm sources are strikingly aligned. This alignment is unlikely to occur if the radio components are distributed at random over the galactic disk. Mechanisms that could produce a linear configuration in this case include large-scale gravitational structures (spiral arms, bars, etc.) or jetlike phenomena as suggested for other galactic nuclei (e.g., NGC 253, TH; NGC 4151, Wilson and Ulvestad 1982).

NGC 660.—This barred peculiar spiral has been mapped at 6 and 20 cm by Condon (1980) and Condon *et al.* (1982). The 6

TABLE 2
OBSERVED PARAMETERS FOR THE 15 GHz COMPACT RADIO COMPONENTS

Galaxy	$\alpha(1950)$	$\delta(1950)$	Peak Flux (mJy/ Ω_b)	Total Flux (mJy)	Size	P.A.	T_B (K)	Power (10^{20} W Hz $^{-1}$)
N 520:								
C1	01 ^h 21 ^m 59 ^s .510	03°31'53".04	0.44	1.6 ± 0.3	$0''.37 \times 0''.29$	90°	81	1.73
C2	01 21 59.566	03 31 53.08	0.45	1.0 ± 0.3	0.3×0.2	90	91	1.08
C3	01 21 59.623	03 31 53.10	0.51	1.6 ± 0.3	0.35×0.16	91	155	1.71
C4	01 21 59.639	03 31 53.03	0.3	0.4 ± 0.1	...	...	>75	0.43
C5	01 21 59.653	03 31 53.01	0.43	0.8 ± 0.1	0.2×0.11	151	198	0.86
N 660:								
C1	01 40 21.726	13 23 41.08	0.42	0.8 ± 0.1	0.25×0.19	145	92	0.16
C2	01 40 21.777	13 23 41.28	1.17	2.0 ± 0.3	0.3×0.2	45	181	0.40
N 2146:								
C1	06 10 39.282	78 22 28.06	0.6	1.3 ± 0.3	0.3×0.16	162	147	0.48
C2	06 10 40.216	78 22 27.82	0.4	...	...	...	>80	0.15
N 2992	09 43 17.629	-14 05 42.56	3.5	4.6 ± 0.4	<0.1	...	$>2.5 \times 10^3$	6.23
N 3079	09 58 35.017	55 55 15.45	48.1	59.0 ± 2	<0.07	...	$>6.5 \times 10^4$	27.0
N 3628:								
C1	11 17 40.148	13 51 46.78	0.69	1.6 ± 0.1	0.24	...	151	0.19
C2	11 17 40.191	13 51 46.57	0.54	1.3 ± 0.1	0.42×0.18	114	94	0.16
C3	11 17 40.216	13 51 46.54	0.35	0.5 ± 0.1	0.26×0.18	146	58	0.06
C4	11 17 40.245	13 51 46.42	0.40	0.6 ± 0.1	0.21	...	74	0.07
C5	11 17 40.261	13 51 46.36	0.49	0.8 ± 0.1	0.22	...	90	0.1
C6	11 17 40.286	13 51 46.15	0.44	1.1 ± 0.2	0.37×0.15	38	108	0.13
C7	11 17 40.333	13 51 46.06	1.25	2.4 ± 0.2	~ 0.21	...	296	0.29
C8	11 17 40.364	13 51 45.94	1.41	2.8 ± 0.2	0.3×0.17	102	302	0.34
C9	11 17 40.383	13 51 45.85	0.69	2.3 ± 0.1	~ 0.3	...	139	0.28
C10	11 17 40.440	13 51 45.67	0.54	1.5 ± 0.1	0.16×0.25	129	204	0.18
N 3690:								
A	11 25 44.192	58 50 18.19	13.5	61.0 ± 4	0.3×0.23	126	4.8×10^3	171.0
B	11 25 41.529	58 50 12.30	2.9	4.7 ± 0.3	0.15×0.09	78	1.9×10^3	13.2
N 4151:								
C1	12 08 00.899	39 41 01.74	0.75	3.9 ± 0.3	~ 0.38	...	147	1.88
C2	12 08 00.980	39 41 01.86	1.49	5.7 ± 0.3	0.31×0.2	28	500	2.74
C3	12 08 01.016	39 41 01.98	4.57	6.6 ± 0.3	0.14×0.064	72	4.0×10^3	3.17
C4	12 08 01.058	39 41 02.04	12.51	17.6 ± 0.9	$0.13 \times <0.07$	81	$>1.0 \times 10^4$	8.46
C5	12 08 01.133	39 41 02.34	1.03	2.6 ± 0.2	0.21×0.16	53	421	1.25
C6	12 08 01.167	39 41 02.34	0.47	0.6 ± 0.1	~ 0.18	...	100	0.29
N 4388	12 23 14.640	12 56 20.04	2.7	3.5 ± 0.4	<0.07	...	$>3.9 \times 10^3$	1.54
N 6240:								
C1	16 50 27.827	02 28 57.43	10.3	14.7 ± 2	<0.09	...	$>1.0 \times 10^4$	167.3
C2	16 50 27.862	02 28 58.87	4.9	5.9 ± 1	<0.06	...	$>8.9 \times 10^3$	67.1

cm map shows a double-peaked elongated structure oriented at P.A. $\sim 45^\circ$ and $7''.2$ in extent. Condon *et al.* suggest that the radio brightness distribution can be understood as a ring seen in projection or as a linear structure produced by a jet. We find the compact 2 cm distribution more consistent with a ring than with a jet. The line joining the three strongest peaks located NE of the map center (see Fig. 1) is oriented at a P.A. $\sim 71^\circ$, unlike the 6 cm radio structure and optical bar ($\sim 37^\circ$; Nilson 1973), as would be expected for a jet-produced morphology. Keel's (1984) positions locate the optical nucleus $\sim 3''$ south of the strongest 2 cm component.

NGC 2146.—At 2 cm, we detected two of the three central components in this peculiar spiral galaxy previously observed by Kronberg and Biermann (1981) at 6 cm. The stronger 2 cm peak does not coincide with the 6 cm maximum but with a secondary peak $\sim 2''.8$ west of it. This indicates significant variations in spectral index in the compact sources.

Kronberg and Biermann suggest that the radio morphology of NGC 2146 and the triple central source could be produced by the projection of a bar, ring, or spiral arm structure on the plane of the sky. Alternatively, nuclear ejection close to the plane of the galaxy could also produce a linear morphology. Neither the optical nuclear spectrum (Heckman *et al.* 1983) nor our 2 cm observations show clear evidence for a central compact nonthermal nuclear source. In addition, there is strong CO emission in the central region of NGC 2146 (Jackson and Ho 1988; Young *et al.* 1988) suggesting that star formation is probably able to account for the compact radio emission.

NGC 2992.—The 2 cm source detected in this narrow-line X-ray galaxy consists of a central unresolved ($< 0''.1$) core plus a "tail" (Fig. 1) that extends SE along the figure-eight seen in 6 cm maps (Ulvestad and Wilson 1984*b*; Wherle and Morris 1988). This "tail" suggests a direct connection between the kiloparsec scale radio morphology and the nuclear source. From the 6 cm flux of the unresolved core and our 2 cm measurement, we obtain a spectral index $\alpha \geq -0.4$ for the compact source.

NGC 3079.—The 2 cm unresolved core in this Sc(pec) galaxy is less than $0''.07$ in size (≤ 6.7 pc, at 19.6 Mpc). The high brightness temperature, $T_B > 6.5 \times 10^4$ K, and flat spectral index ($\alpha_6^2 = -0.09$; 6 cm flux from Duric *et al.* 1988), suggest that the emission mechanism is optically thick synchrotron radiation from an AGN. The optical "Liner" spectrum (Heckman *et al.* 1980; Keel 1983), warm infrared spectrum (Lawrence *et al.* 1985), and central X-ray source (Fabbiano, Feigelson, and Zamorani 1982) are consistent with the AGN interpretation.

NGC 3628.—Maps at 6 cm obtained by CCGP of this edge-on Sbc galaxy show several peaks oriented along the plane of the galaxy. In our higher resolution 2 cm maps, the linear structure breaks into 12 sources with size scales of a few parsecs. The linear radio morphology can be understood in terms of projection effects and the radio components are probably associated with star formation.

NGC 3690.—NGC 3690 and IC 694 (Arp 299) are luminous infrared and radio galaxies. Maps at 20 cm, 6 cm, and $10 \mu\text{m}$ (Gherz, Sramek, and Weedman 1983, hereafter GSW) show three dominant peaks and extended diffuse emission. At 2 cm, compact emission appears in two of these positions, NGC 3690 A and NGC 3690 B (following GSW), that we interpret as being associated with the two galactic nuclei (Telesco, Decher, and Gatley 1985).

In NGC 3690 A we resolve the nuclear source. From the 21, 6, and 2 cm fluxes, we estimate an average spectral index of $\alpha = -0.4$ for the central $3''$. In NGC 3690 B we detect a 4.7 mJy source and estimate $\alpha \sim -0.8$ using the peak fluxes at 6 and 20 cm from GSW. Given the high L_{IR} and extended nature of the emission in the NGC 3690 complex, we expect that star formation is a dominant source of the compact radio emission. This is supported by Brackett line fluxes (Beck, Turner, and Ho 1986). However, an AGN could also be present, in particular in NGC 3690 A, which has an anomalously large radio to Brackett line ratio.

NGC 4151.—This well-studied Seyfert galaxy has been observed at several radio frequencies. At 2 cm we detect an unresolved nuclear source with $T_B > 10^4$ K corresponding to the double VLBI source (Harrison *et al.* 1986; Preuss, Alef, and Pedlar 1987). We detect five other components along a $3''.5$ structure. Three of the peaks in our 2 cm maps appear in the $0''.25$ resolution, 18 cm map by Booler, Pedlar, and Davies (1982). Since these maps have similar resolution we calculate spectral indices between 18 and 2 cm for the 2 cm components (Table 3). The central source (C4) has a relatively flat spectral index, $\alpha_{18}^2 = -0.4$, as compared to $\alpha_{18}^2 \sim -0.6$ to -0.7 for the other components. The flat spectral index and high T_B of the central component is consistent with synchrotron self-absorption associated with an AGN. The striking alignment of the radio components can be explained if the emitting material has been energized from the nucleus. In addition, the radio morphology of the radio components (limb-brightened boundaries and tails) suggest interaction of a jet with the ambient medium (see Wilson and Ulvestad 1982; Booler *et al.* 1982; Harrison *et al.* 1986 for a detailed discussion of the radio morphology at different scales).

NGC 4388.—The high-resolution, 6 cm map of Stone, Wilson, and Ward (1988) of this SB(s)b pec Seyfert 2 galaxy reveal a double-peaked central structure oriented at a P.A. $\sim 25^\circ$. At 2 cm we detect a 3.5 mJy unresolved (< 6.5 pc) source coincident with the strongest 6 cm peak. The optical nucleus is offset from the 6 cm central double source and the $10 \mu\text{m}$ peak (Stone *et al.* 1988) and is $2''.9$ SW of the 2 cm peak; however, the nucleus may be obscured by dust (Phillips and Malin 1982; Corbin, Baldwin, and Wilson 1988; Shields and Filippenko 1988). It is likely that the galactic nucleus is associated with the 2 cm compact source.

NGC 6240.—One of the most luminous infrared galaxies known ($L_{\text{FIR}} \sim 3 \times 10^{11} L_\odot$), NGC 6240 seems to be a strongly interacting pair of galaxies (Joseph and Wright 1985). At 2 cm we detect two unresolved ($\lesssim 45$ pc and 30 pc) sources coin-

TABLE 3
SPECTRAL INDICES FOR THE RADIO COMPONENTS
IN NGC 4151

NGC 4151 component	Distance to C4	$S_{1.7 \text{ GHz}}$ (mJy)	Spectral Index (α_{18}^2)
C1 ^a	1.84	15 ± 4	-0.66 ± 0.14
C2	0.90	26 ± 4	-0.69 ± 0.08
C3 ^b	0.48	34 ± 4	-0.73 ± 0.06
C4 ^c .....	...	43 ± 4	-0.42 ± 0.06
C5	0.9	12 ± 1.2	-0.71 ± 0.06
C6	1.28	1.9 ± 0.2	-0.60 ± 0.08

^a Corresponds to component C in Booler *et al.* 1982.

^b Corresponds to component A₂ in Booler *et al.* 1982.

^c Corresponds to component A₁ in Booler *et al.* 1982.

cident with the peaks in the 6 cm map obtained by CCGP. The separation of the two peaks is 1.5 (~ 700 pc). We also detect diffuse 2 cm emission with a total flux of 34 mJy in a $2'' \times 3''$ box of which 60% is associated with the compact components. Convoluting our map to match the 6 cm map of CCGP, we obtain $\alpha_6^2 \sim -0.6$ and -0.8 for the main and secondary components. These spectral indices are consistent with optically thin synchrotron radiation. The two peaks may be associated with two galactic nuclei as suggested by the correspondence of the radio components with the two near-infrared "nuclei" (Fried and Schulz 1983). The high ratio of $L_{\text{IR}}/L_{\text{Ly}\alpha}$ (> 70) in NGC 6240 as compared to "typical" starburst galaxies (10–20) suggests that an AGN may be an important contributor to the L_{IR} (De Poy, Becklin, and Wynn-Williams 1986). On the other hand, *IRAS* colors are consistent with the fluxes being produced by star formation (Helou 1986).

III. DISCUSSION

a) Candidate Sources for Compact 2 Centimeter Emission

One of the goals of this project is the study of brightness temperatures and morphologies of compact radio sources in galactic nuclei in an effort to distinguish starbursts from AGN activity. Another goal is the study of the characteristics of the radio continuum emission in starbursts. What is the origin of the observed compact 2 cm radio emission? Are the radio components associated with H II regions, supernova remnants, or radio supernovae? What types of H II regions are seen? Or is there evidence that an active nucleus or nuclear jets are responsible for the radio emission?

Because high-sensitivity matched array observations are not possible we cannot derive reliable spectral indices at this resolution. However, because of the high resolution, we do obtain good measures of the brightness temperatures of the individual radio components. Comparing these values with those expected for the possible emission sources can help us to define the nature of the radio emission.

i) H II Regions

As pointed out by Turner and Ho (1983), thermal radio emission from individual H II regions is difficult to detect for galaxies that are more than a few Mpc away. Our 1σ sensitivity is $T_B = 15\text{--}20$ K. For a typical electron temperature of 10^4 K, a classical H II region with emission measure $EM = 10^2\text{--}10^5 \text{ cm}^{-6} \text{ pc}$ and size 1–30 pc (Habing and Israel 1979) will be optically thin at 2 cm with $T_B \lesssim 1$ K. This is below our sensitivity limit even if it is resolved. For compact H II regions $T_B \sim 10^3\text{--}10^4$ K, but beam dilution is severe: $\theta_S^2/\theta_B^2 \leq 10^{-4}(D/10 \text{ Mpc})^{-2}$ for a typical compact H II region of diameter 0.1 pc. However, large complexes of compact H II regions of sizes $\sim 10\text{--}50$ pc, and corresponding excitation parameters of $U \sim 10^3 \text{ pc cm}^{-2}$, although unknown in the Galaxy, may exist in starburst regions. There is evidence for a large collection of compact H II regions in the nearby galaxy M83 (Turner, Ho, and Beck 1987). We can detect complexes of compact H II regions so long as they are larger than a tenth of the beam size, $\sim 0''.02$.

ii) Supernova Remnants

Even the brightest individual supernova remnants (SNR) such as Cas A, where $T_B \sim 50$ K, fall below our sensitivity limit because of beam dilution: $\theta_S^2/\theta_B^2 \leq 0.2(D/10 \text{ Mpc})^{-2}$ for a 3 pc diameter SNR. It is possible that large numbers of SNRs could produce the observed emission. Estimating the required

number of SNRs, however, is tricky. We can apply the Galactic Σ - D relation (Clark and Caswell 1976; Mills *et al.* 1984; Green 1984; Green 1984; Huang and Thaddeus 1985) to estimate the expected SNR diameters and thus the required numbers of SNR from the observed T_B and θ_S . Unfortunately, we are extrapolating to very compact, bright SNRs for which the Σ - D relation may no longer hold (however, see Berkhuijsen 1986); the Σ - D relation has a large intrinsic scatter (Mills *et al.* 1984; Green 1984); and starburst SNR may be quite different from Galactic SNRs. However, lacking a better procedure, we employ both the Σ - D relation and the flux of the radio-bright Galactic SNR Cas A (Baars *et al.* 1977; 381 Jy at epoch 1985.4) in our analysis to obtain two estimates of the number of SNRs required to produce the observed fluxes.

iii) Radio Supernovae

In the nearby starburst galaxies M82 and NGC 253 high-brightness, compact (less than a few pc) radio continuum sources have been detected (Kronberg Biermann, and Schwab 1985; TH; Antonucci and Ulvestad 1988). These objects are more powerful than any known SNRs and are comparable in power with radio supernovae (RSNs) that have been observed in nearby galaxies (Weiler *et al.* 1986). Kronberg *et al.* (1985) postulate that the compact radio sources in M82 are RSNs. Supporting this interpretation are possible flux variations detected in some of the sources (Kronberg and Biermann 1985). However, their angular sizes appear to be larger than one might expect for supernovae (Bartel, Ratner, and Shapiro 1987). The 2 cm mean flux for the brightest 10 sources in M82 is ~ 8 mJy, which is comparable to that of supernova SN 1979C (Weiler *et al.* 1986). We could detect these sources up to a distance of 10 Mpc, and groups of RSN to greater distances.

iv) Synchrotron Cores

Also easily detectable by our observations are optically thick synchrotron cores associated with AGN (Kellermann and Pauliny-Toth 1981). TH associate the central radio source detected in NGC 253 with compact self-absorbed synchrotron emission since $T_B \gtrsim 10^5$ K. The high brightness temperatures associated with opaque synchrotron cores (up to 10^{12} K) allow detection at distances up to 100 Mpc for sources of diameter greater than 10^{-3} pc. A necessary condition for the AGN identification is that it be located at the center of the galactic gravitational potential well, which should coincide with the optical center in the absence of extinction.

b) Nature of Compact Radio Activity in These Galaxies

From the discussion above, we have narrowed the detectable radio activity in these galaxies to (1) large complexes of compact H II regions ($U \gtrsim 500 \text{ pc cm}^{-2}$), (2) groups of SNR, (3) radio supernovae, and (4) opaque synchrotron nuclear sources. Sources 1–3 are representative of star formation and source 4 indicates the presence of an AGN. From the sizes and fluxes and spatial distribution of the 2 cm radio components we have separated the galaxies into three groups.

i) The Moderately Active or Starburst Galaxies

NGC 520, NGC 660, NGC 2146, and NGC 3628 are classified optically as starburst galaxies except possibly NGC 660 (Heckman *et al.* 1983). The 2 cm radio emission shows several components, most of which are resolved. None of the components has a particularly high brightness temperature and small size that can be unambiguously identified as a non-thermal core source. Unlike the extended 6 cm emission

(CCGP), the compact 2 cm structure in these galaxies is asymmetric and clumpy. If both the large-scale radio emission and the compact structure are related to starburst activity, a likely explanation for the asymmetry is that the individual 2 cm components are short-lived compared with the starburst age.

Brightness temperatures of the components range from $T_B \sim 50\text{--}300$ K and sizes from $\sim 5\text{--}50$ pc. If one assumes that these are bright H II regions with $T_e = 10^4$ K and unity filling factor, the measured T_B imply emission measures of $EM = 10^6\text{--}10^7$ pc cm $^{-3}$ and the fluxes imply excitation parameters of $U = 550\text{--}10^3$ pc cm $^{-2}$. Ho, Beck, and Turner (1990; HBT) measured Br α line fluxes in the nuclear ($7''$) regions of NGC 520 and NGC 660, from which they predict $S_{2\text{ cm}} = 5.2$ mJy for NGC 660 and $S_{2\text{ cm}} \gtrsim 5.8$ mJy for NGC 520. The total 2 cm fluxes we measure in compact components are 2.7 and 5.4 mJy, respectively. If the 2 cm sources are indeed H II regions, then an important fraction of the young stellar luminosity is produced in large complexes of compact H II regions.

The second possibility is that the 2 cm compact emission is dominated by synchrotron radiation from SNR. Given the sizable fluxes of the radio components, they must be associated with large groups of SNR. From the Σ - D relation we predict that in NGC 520 we would need of the order of 2000 SNRs to produce the total 2 cm flux, whereas for NGC 660, NGC 3628, and NGC 2146 the required numbers are ~ 200 , 1400, and 200, respectively. An estimate from the distance-scaled 2 cm flux of Cas A yields 1600, 160, 500, and 200 Cas A's for the same galaxies. The presence of so many SNRs implies either a high SN rate or long-lived remnants. In some of these galaxies, we have a constraint on the SN rate from the observed numbers of massive young stars predicted by Brackett line fluxes. Using NGC 520 and NGC 660 Br α line fluxes measured by HBT, adopting the IMF and main-sequence lifetimes from Scalo (1986), with $7 M_\odot$ and $30 M_\odot$ as lower and upper mass cutoffs, we obtain rates of 0.007 SN yr $^{-1}$ and 0.04 SN yr $^{-1}$ for the central 400–1000 pc of NGC 660 and NGC 520. (These numbers depend on the values assumed for the upper cutoff and the uncertainty in the IMF of Scalo [1986], giving uncertainties by factors of a few in the SN rates.) To observe 1600–1900 and 160–200 SNRs at a given time, the SN rates in NGC 520 and NGC 660 would require that the radio-remnants live more than $\sim 10^4\text{--}10^5$ yr. This lifetime may be 10–100 times longer than the ages of Galactic radio SNR (Mills *et al.* 1984). If such old ($10^4\text{--}10^5$ yr) remnants exist, one would expect them to have low brightness and large sizes unlike the radio components in these galaxies. It appears, therefore, that too many SNRs for the observed star formation rates would be required to produce all of the bright compact structure in these galaxies, although SNRs may be responsible for some fraction of the flux.

The third option is that the 2 cm compact sources are associated with RSNs. The total flux measured for each component would then correspond to the contribution of a few RSNs along the line of sight. To estimate the number of RSNs, we averaged the 2 cm fluxes for the 10 brightest sources in M82 to obtain a "typical" flux. Since RSNs are more luminous than SNRs, fewer are needed to explain the observed fluxes. We require ~ 10 RSN per component in NGC 520, giving a total of ~ 50 ; in NGC 3628 we expect 1 or 2 RSN for each component for a total of ~ 15 ; for NGC 2146 and NGC 660, $\sim 5\text{--}6$ RSN are necessary. These numbers are lower limits because of our sensitivity. As before, if these are radio-bright supernovae,

the supernova rate for NGC 520 and NGC 660 predicted by the Brackett fluxes imply that these RSN would have to live $\sim 10^3$ yr to produce the observed emission. This is inconsistent with the observed lifetimes of RSN which are on the order of decades. RSN cannot produce the observed compact emission in those galaxies for which we have estimates of the SN rate.

Low-luminosity self-absorbed synchrotron sources, like the one in the nucleus of NGC 253 (TH) could be present in these galaxies. One would expect no more than one of these sources per galaxy. None of the galaxies in this group has a high brightness, centrally located source that would be an obvious candidate for an AGN. Even if an AGN is present, the dominant emission mechanism for the compact radio emission seems to be star formation, specifically compact H II regions, as discussed above.

ii) *The Active Galaxies*

In NGC 2992, NGC 3079, NGC 4388, and NGC 4151 we detect dominant high-brightness ($T_B \gtrsim 10^3$ K) compact ($\lesssim 15$ pc) cores. The small sizes and high brightness of the radio nuclei strongly suggest that opaque synchrotron sources associated with AGNs are the origin of the compact radio emission. In NGC 3079 the flat spectral index of the core gives additional support to this interpretation (see § II). In NGC 2992 and NGC 4151 the bright radio sources are coincident within the errors with the optical nuclei. In NGC 3079 and NGC 4388 the radio peaks and optical maxima are close but not coincident, possibly due to dust obscuration (Lawrence *et al.* 1985; Stone *et al.* 1988). Different from the galaxies in the first group, the high-brightness radio sources in these active galaxies lie at the center of symmetry of the extended lower frequency radio emission.

It is unlikely that the high brightness compact sources in these galaxies are produced by SNR and/or RSN. The number of remnants like Cas A required to explain the radio fluxes (500–8000) or alternatively the number of RSN (20–250) are too extreme for the small sizes of these sources ($< 6\text{--}15$ pc). The most likely origin of the high-brightness cores in these galaxies is synchrotron emission associated with AGNs. The presence of AGNs in these galaxies is also suggested in studies at other wavelengths (see § II).

iii) *The Powerhouse Galaxies*

For the galaxies NGC 3690 and NGC 6240 the observed infrared luminosities are so high that it is difficult to classify them as either typical Seyferts or starbursts. Our measurements of the compact 2 cm emission indicate that neither starburst nor nuclear sources can be definitely ruled out, but the high brightness in some of the radio components are perhaps more consistent with the AGN phenomenon.

For NGC 6240 we find that more than 60% of the 2 cm flux within the nucleus is concentrated in the two compact cores. The radio flux can be the consequence of either a starburst with associated SNRs or an AGN. The double source morphology and the sizes, brightness temperatures and extreme luminosities of the individual components, are more typical of Seyfert galaxies (Ulvestad and Wilson 1984; Unger *et al.* 1986) than of starburst regions. The power (W Hz $^{-1}$) at 2 cm in these compact components (of diameter < 50 pc), is several times larger than the integrated 2 cm power measured in NGC 253 (Klein and Emerson 1981).

Using the Σ - D relation we predict that $\sim 12,000$ and 4500 SNRs would be required to explain the 2 cm fluxes in components C1 and C2, respectively. The required number of SNR

like Cas A is 50,000 and 20,000 respectively. From the ionizing flux of $N_{\text{Lyc}} = 10^{54} \text{ s}^{-1}$ inferred by DePoy, Becklin, and Wynn-Williams (1986) from Brackett lines, we would predict a supernova rate of 0.6 yr^{-1} . At this rate, the SNR would have to live $\sim 10^4$ – 10^5 yr in these components. Even given the large uncertainties in the Σ - D relation, there is far too much compact radio emission in NGC 6240 to be explained solely by SNR. If the radio emission in the nucleus of NGC 6240 is mainly the consequence of a starburst, the emission must be dominated by compact H II regions. From our observations we obtain $T_B \gtrsim 10^4 \text{ K}$ for the compact components. It seems more likely that such bright compact sources are associated with self-absorbed synchrotron emission from AGNs. VLBI observations are required to confirm the presence of parsec-scale synchrotron cores.

In NGC 3690 A the strong 2 cm emission is extended ($\sim 60 \text{ pc}$), and not dominated by a central source. The total mapped 2 cm flux is consistent with $\alpha = -0.4$ for the central $3''$ which is relatively flat compared to $\alpha \sim -0.6$ to -0.8 typical of extended Galactic synchrotron components (Klein and Emerson 1981; Gioia *et al.* 1982). BTH estimate that $\sim 85\%$ of the flux at 5 GHz within $7''$ comprises nonthermal radiation. Given the steep central concentration of the radio emission in NGC 3690 A (GSW) we estimate that nonthermal radiation will also dominate the 2 cm emission within $3''$.

A possible origin for the radio emission in NGC 3690 A is a complex of SNR with relatively flat spectral index. The number of SNR required would be very high ($\sim 40,000$). From the Br α fluxes in BTH we estimate, as for NGC 520, NGC 660, and NGC 6240, a SN rate of $\sim 0.4 \text{ SN yr}^{-1}$. The remnants within the 60 pc source would need to radiate 10^5 yr to account for the observed 2 cm fluxes and would have to remain bright and flat-spectrum during this time. Since this is unlikely, the compact radio emission from NGC 3690 A must be primarily due to either giant complexes of compact H II regions or an AGN or both.

In NGC 3690 B, $T_B = 1800 \text{ K}$ is consistent with either thermal or non-thermal radiation. The BTH Brackett line fluxes predict that more than $\sim 50\%$ of the 6 cm continuum flux within the inner $7''$ of NGC 3690 B is thermal: for a nonthermal index of -0.7 , the percentage of extended thermal flux at 2 cm increases to 65%. If the compact radio source has a thermal to nonthermal ratio similar to the region sampled by the Brackett observations then the thermal flux at 15 GHz would be 3 mJy which comprises $\sim 20\%$ of the flux predicted by BTH for the central $7''$. The emission measure $EM \sim 10^8 \text{ cm}^{-6} \text{ pc}$ for the thermal component would be typical of ultra-compact H II regions and the observed 2 cm fluxes would then require very large complexes of compact H II regions with 10^5 – 10^6 stars. On the other hand, if a fair proportion of the radio flux is due to SNR, a few times 10^3 SNRs are implied. The supernova rate predicted using BTH Br α observations is 0.8 SN yr^{-1} , requiring remnants of more than $\sim 10^3 \text{ yr}$ old. Star formation, in the form of optically thick emission from H II regions or emission from RSN or SNR could conceivably explain the compact 2 cm emission in NGC 3690 B.

IV. CONCLUSIONS

Using high-sensitivity, high-resolution VLA observations, we mapped the 15 GHz emission from compact ($< 1''$) radio

components in the nuclear regions of 10 galaxies with strong infrared and radio activity in their nuclear regions. Our experiment was designed to probe for the presence of bright compact radio sources that could trace starburst activity or AGNs or radio structures that could give clues to the triggering mechanisms for the activity.

Given the sizes, fluxes, brightness temperatures, and spatial locations of the 2 cm sources in our sample of galaxies, we separate them into three groups. In the first group of moderately active galaxies composed by NGC 520, NGC 660, NGC 2146, and NGC 3628, we do not find extremely bright sources that could be clearly identified as AGNs but multiple compact components of moderate brightness temperature, $T_B \sim 50$ – 300 K . These sources could be associated with giant complexes of compact H II regions, or with bright synchrotron sources, similar to the ones seen in M82. However, comparison with Brackett line fluxes indicate that the emission in these starburst galaxies is not likely to be dominated by SNRs or RSNs, although these may contribute to the 2 cm flux. The compact emission features in NGC 520 and NGC 2146 show linear radio morphology that has not been unambiguously explained. For NGC 660 the alignment of the compact radio sources is consistent with a ring seen in projection. This group has relatively high infrared to radio ratios and high-infrared luminosity $L_{\text{IR}} > 10^{10} L_{\odot}$, probably due to dust heated by the starburst.

The second group, the active galaxies, show high brightness, compact cores likely to be associated with an AGN. This group includes NGC 2992, NGC 3079, NGC 4151, and NGC 4388. The presence of these cores supports the arguments in favor of a connection between the active nucleus and the large-scale peculiar radio morphology of the galaxies in this group. This group tends to have low-infrared luminosities, $L_{\text{IR}} < 10^{10} L_{\odot}$, particularly in comparison with their radio luminosities.

The powerhouse galaxies, NGC 3690 and NGC 6240 seem to fall into a third category overlapping with Seyfert galaxies in the characteristics of their 2 cm radio emission. Their compact, high-brightness 2 cm emission suggest in each case the presence of two nuclei. The characteristics of the compact radio emission, together with extreme infrared luminosities and relatively low Brackett line fluxes suggest AGN activity in addition to starbursts. In NGC 6240, $T_B \gtrsim 10^4 \text{ K}$ for both components; since nuclear activity seems to be an important source of L_{IR} (DePoy, Becklin, and Wynn-Williams 1986), the two compact 2 cm cores are likely to be synchrotron nuclear sources. The radio fluxes are unlikely to be dominated by SNR associated with a starburst unless SNR lifetimes are long ($> 10^4$ – 10^5 yr). In NGC 3690, we see possible evidence for both, flat-spectrum, although extended, nonthermal activity in NGC 3690 A, and starburst activity in NGC 3690 B.

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