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THE STARBURST-AGN CONNECTION: A SENSITIVE VLBI SURVEY OF LUMINOUS *IRAS* GALAXIES

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ABSTRACT

Results of an 18 cm VLBI survey of 31 luminous ($L_{\rm fir} > 10^{11.25}\ L_{\odot}$), radio-compact ($\theta \lesssim 0\farcs25$) infrared galaxies are presented. Over half the sample galaxies show high-brightness temperature emission, with $T_b > 10^5$ K and structure on scales of 5–150 mas. The median VLBI core power for detected sources is log $P_{\rm core}$ = 22.0 (W $\rm Hz^{-1}$), and the ratio of core to total 1.6 GHz flux density $\langle S_{\rm core}/S_{\rm total}\rangle = 0.12$. The limits for nondetected sources are similar, consistent with a picture in which most of these galaxies have compact cores at a level of a few percent of the total radio flux density. Characteristics of the extended radio structure, infrared properties, and optical excitation *are not* good indicators of the detectability of VLBI-scale emission. Structural information and energetic considerations rule out a single supernova interpretation of the compact emission in these galaxies, although we cannot exclude the possibility of several simultaneous extraordinarily luminous radio supernovae within the central few hundred $\rm pc^3$. Our results instead favor the presence of an AGN obscured by starburst-related dust.

Subject headings: galaxies: active — infrared: galaxies: — radio continuum: galaxies

1. INTRODUCTION

There has been increasing interest in recent years in the relationship between active star formation in galaxies, as evinced by high infrared luminosity, and AGN characteristics. This interest has been stimulated by schemes which suggest a causal or evolutionary relationship between the AGN and starburst phenomena (e.g., Perry & Dyson 1985; Sanders et al. 1988; Norman & Scoville 1988). Ideally, we wish to determine whether nuclear starbursts and AGNs typically, or only occasionally, coexist, and whether typical starburst and AGN properties are correlated. The principal difficulty in such a determination is the large optical depth to the nucleus presented by the dusty starburst environment at most observing wavelengths. However, the optical depth at centimeter radio wavelengths is expected to be small, unless very large amounts of ionized material produce large free-free optical depths. By observing such galaxies with a sensitive VLBI array designed to detect high brightness-temperature AGN-related emission, it is possible to conduct a search for AGNs buried in dusty nuclear starbursts. We report here such a survey, which has detected 17/31 galaxies in a sample of compact luminous infrared galaxies, and briefly discuss the implications of these detections under the assumption that they represent buried AGN cores.

In a preliminary search (Lonsdale, Lonsdale, and Smith 1992, Paper I) we detected 3/5 infrared-bright galaxies with VLBI, including the peculiar compact radio source Mrk 297A. This source displays some, but not all, of the characteristics normally associated with radio supernovae (see also Yin & Heeschen 1991), suggesting a new class of exceptionally radio-luminous supernovae as a possible origin of high T_b radio emission in IR-luminous galaxies. Such objects would have typical radio luminosities at peak, log $P_{1.6\ \rm GHz} \approx 21$ (W $\rm Hz^{-1}$), an order of magnitude higher than that of SN 1986J (Rupen et al. 1987), which is the most luminous radio supernova for which a complete light curve is available. The existence of such a class is supported by evidence that an extremely radio-luminous supernova occurred in M82, sometime before 1963 (Wilkinson & deBruyn 1990).

In § 2 we describe the sample, and in § 3 we present the observations. Section 4 deals with the results, and their interpretation as AGNs or supernovae. We adopt H_0 = 75 km $\rm s^{-1}$ $\rm Mpc^{-1}$ throughout this paper.

2. THE SAMPLE

Condon et al. (1991, hereafter CHYT) presented 8.44 GHz VLA images of the 40 most luminous members of the *IRAS* Bright Galaxy Sample (BGS; Soifer et al. 1989) with log $[L_{\rm FIR}/L_{\odot}] \geq 11.25$. Most of the images show nuclear features of angular extent comparable to or smaller than the $0\farcs25$ restoring beam. CHYT were able to resolve nearly all of these features and derived deconvolved sizes for them by assuming an elliptical Gaussian brightness distribution. However, the degree of resolution was typically small, and the data were generally consistent with a large fraction of the flux density originating in regions much smaller than the deconvolved Gaussian sizes quoted in that paper.

We estimated the maximum possible flux density of such compact regions at 18 cm, using the overall galaxy spectral index, and constructed a subsample of 31 objects potentially detectable using the most sensitive VLBI systems. The properties of these 31 galaxies are summarized in Table 1, in which we list the 1950 radio position from CHYT, the distance, the optical spectral classification—AGN (Sy 1-2 or LINER) vs. H II—following Veilleux & Osterbrock (1987), FIR luminosity and 60 μm flux density from the BGS, and 1.49 GHz radio flux

TABLE 1

AGN-Starburst Sample

Source (1)	Radio Position (1950) α (2)	δ (3)	D (Mpc) (4)	Spectral[a] Type (5)	log L_{FIR} ($L_\odot$) (6)	S_{60} (Jy) (7)	Radio Data $S_{1.49}$ (mJy) (8)	$\alpha_{1.49}^{8.44}$ (9)	S_{core} (mJy) (10)	log P_{core} (W Hz^{-1}) (11)	log T_b[b] (K) (12)
Mrk 938	$00^h08^m33^s.40$	$-12°23'08''.9$	77	AGN[c]	11.28	16.08	58.7	0.78	<2.5	<21.25	5.0†
01173+1405	01 17 23.17	+14 05 58.7	131	H II[d]	11.42	6.76	41.9	0.70	7.0	22.16	$\geq$7§
01364−1042	01 36 24.27	−10 42 24.3	187	AGN[d]	11.67	6.53	17.0	0.42	<2.0	<21.92	<5
01417+1651	01 41 47.91	+16 51 06.3	109	H II[d]	11.46	11.86	39.3	0.40	<1.0	<21.15	5.4†
UGC 2369	02 51 15.92	+14 46 03.9	124	H II[e]	11.42	7.68	42.7	0.67	15.	22.44	$\geq$7§
03359+1523	03 35 58.33	+15 23 09.4	140		11.37	5.77	18.9	0.31	3.0	21.85	$\geq$7*
04191+1855	04 19 06.95	−18 55 41.9	123		11.34	5.84	27.3	0.65	<2.5	<21.65	<5
05189−2524	05 18 58.88	−25 24 39.4	166	AGN[f]	11.91	13.95	28.1	0.52	<3.0	<21.99	<5
NGC 2623	08 35 25.27	+25 55 50.2	76	AGN[g]	11.47	25.72	97.8	0.58	9.0	21.79	$\geq$7§
08572+3915	08 57 12.96	+39 15 38.9	236	H II[g]	11.96	7.66	6.5	0.27	<1.5	<22.00	<5
UGC 4881	09 12 38.43	+44 32 29.2	163	H II[d]	11.61	6.53	29.0	0.69	4.0	22.11	$\geq$7*
UGC 5101	09 32 04.78	+61 34 37.0	164	AGN[f]	11.93	13.03	146.	0.59	28.	22.95	$\geq$7§
10173+0828	10 17 22.26	+08 28 39.7	194		11.70	6.08	8.8	0.28	3.6	22.21	6.1†
11010+4107	11 01 05.81	+41 07 10.5	142	H II[d]	11.52	6.95	28.0	0.55	<1.5	<21.56	5.1†
Mrk 171D	11 25 44.19	+58 50 18.2	48	H II[g]	11.74	122	658.	0.67	1.5	20.61	$\geq$7*
12112+0305	12 11 12.48	+03 05 22.1	292	H II[g]	12.18	8.39	22.6	0.47	<1.3	<22.12	<5
Mrk 231	12 54 05.01	+57 08 38.2	173	Sy 1	12.35	35.40	240.	−0.06	115	23.61	$\geq$7§
Arp 238	13 13 41.83	+62 23 17.9	130	H II[g]	11.62	12.01	51.2	0.64	<1.5	<21.48	<5
13183+3243	13 18 17.01	+34 24 04.7	97	H II[d]	11.51	13.69	106.	0.64	<0.9	<21.00	<5
Mrk 266	13 36 15.01	+48 31 54.1	116	H II[g]	11.34	7.19	98.8	0.64	4.5	21.86	6.4*
Mrk 273	13 42 51.71	+56 08 14.3	157	AGN[g]	12.04	22.09	130.	0.63	16.0	22.67	$\geq$7§
14348−1447	14 34 53.30	−14 47 26.1	326	AGN[g]	12.17	6.46	33.2	0.71	<2.5	<22.50	<5
Mrk 848	15 16 19.30	+42 55 38.3	166	H II[d]	11.72	9.15	46.8	0.78	3.5	22.06	7.5*
15250+3608	15 25 03.72	+36 09 01.0	219	AGN[g]	11.88	7.20	12.8	0.11	6.5	22.57	6.2*
Arp 220	15 32 46.88	+23 40 07.7	78	AGN[g]	12.11	103.	301.	0.41	10.5	21.88	$\geq$7§
NGC 6285	16 57 44.99	+59 00 41.7	80	H II[d]	11.27	9.87	142.	0.84	13.0	22.00	7.0§
17132+5313	17 13 13.49	+53 13 49.3	208	AGN[d]	11.79	6.35	28.4	0.67	<1.5	<21.89	<5
22491+1808	22 49 09.09	−18 08 20.6	302	H II[g]	12.02	4.58	6.1	0.41	<4.0	<22.64	5.2†
NGC 7469	23 00 44.41	+08 36 15.8	66	Sy 1.5	11.41	27.68	183.	0.68	12.0	21.79	$\geq$7§
23135+2516	23 13 33.13	+25 17 01.6	111	AGN[d]	11.37	8.75	26.0	0.67	<0.8	<21.07	<5
Mrk 331	23 48 54.03	+20 18 29.2	72	H II[d]	11.27	17.32	67.5	0.66	7.5	21.67	$\geq$7§

[a] Optical spectral types are from spectroscopy by (c) Veilleux & Osterbrock 1987; (d) Paper III; (e) J. Mazzarella 1992, private communication; (f) Sanders et al. 1988; (g) Armus et al. 1989.

[b] Symbols indicate structure in visibility plot; * = simple, § = complex, † = single baseline detection.

density and 1.49–8.44 GHz spectral index from CHYT. The VLBI detectability criterion is primarily a radio flux density limit because detectable compact structure could not be excluded for any object purely on the basis of resolved appearance on the CHYT image. The properties of our subsample will be carefully discussed in a future paper (Smith, Lonsdale, & Lonsdale 1993, hereafter Paper III).

3. OBSERVATIONS

The VLBI observations were performed on 1991 September 29, under the auspices of the US and European VLBI networks, project code GL5. In addition to the most sensitive antennas available, namely Effelsberg (Germany), phased VLA (New Mexico), Greenbank (West Virginia), and Arecibo (Puerto Rico), we used the southwestern US VLBA antennas at Pietown and Los Alamos (New Mexico), Kitt Peak (Arizona), and Fort Davis (Texas), together with the Westerbork tied array (Netherlands) and the Jodrell Bank MkIA telescope (UK) to provide a number of relatively short baselines. The data from each antenna were recorded using the MkIIIA system in standard mode-A, 56 MHz nominal bandwidth. This bandwidth was reduced by a factor of 2 on baselines to the VLBA antennas, and to about 40 MHz on baselines to the phased VLA, due to backend restrictions. For each source, data were recorded at an antenna or correlated on a baseline only if the potential correlated flux density exceeded the relevant theoretical sensitivity, for reasons of resource economy. Due to a variety of practical constraints, including the limited declination range of Arecibo, the baseline coverage and detection thresholds vary substantially from source to source.

The tapes were processed on the MkIIIA correlator at Haystack Observatory, in standard fashion. A variety of problems were encountered, but these led to less than 10% overall data loss. After correlation and fringe searching, the data were exported to the Caltech VLBI suite of analysis programs. Calibration of the correlation coefficients was performed by first using the nominal gain and system temperature measurements supplied with the logs from each antenna, and then refining the gain of each antenna on the basis of measurements of the barely resolved calibrator sources 0235+164 and 1611+343. It is estimated that the correlated flux densities carry a general calibration-related uncertainty of order 10%, rising to 20% on baselines involving Greenbank and Arecibo.

Taking into account all calibration uncertainties, and combining them with estimates of error due to thermal noise, we constructed plots of correlated flux density versus baseline length for all the detected sources, and used these plots to determine approximate size scales for the emission. For sources with detections on sufficient baselines we classified the structure as simple or complex by looking for significant departures from monotonically declining or flat curves on these plots and combining this information with closure phase data. "Complex" classification can generally be taken to imply a lack of circular symmetry, and the strong possibility of multiple peaks in the brightness distribution. Details of the interpretation of the VLBI data in terms of source structure will be deferred to Paper III.

4. RESULTS AND INTERPRETATION

4.1. *VLBI Results Compared with Radio, Infrared, and Optical Characteristics*

The results of the VLBI experiment are summarized in the last three columns of Table 1. Columns (10) and (11) list the maximum correlated flux density and power at 18 cm on baselines of projected length $\geq 10^6 \lambda$. In column (12) we provide an estimate of the source brightness temperature, determined by modeling the emission as a circular Gaussian component of size approximately 0.5 times the fringe spacing, and flux density about 2.5 times the correlated flux density. This minimizes the inferred brightness temperature for a Gaussian component fitting the measurement; in general we cannot rule out regions with T_b significantly higher than quoted. For a few sources the visibility functions are adequately fitted by a single Gaussian component, and we quote the T_b corresponding to this component. For the current data, meaningful estimates of T_b above about 10^7 K cannot be made, and in cases of substantial correlated flux density on very long baselines we have tabulated $T_b \gg 10^7$ K (note that this does not imply pointlike, unresolved structure). The nature of the compact source, simple (*) or complex (§), is also indicated in column (12) of Table 1. It should be emphasized that future, more extensive observations may detect complex structure for sources classified here as "simple," and this classification should not be taken as proof of pointlike structure. A designation of "complex" in Table 1, however, precludes the possibility that the detected emission originates in a single pointlike source.

CHYT modeled their galaxies with ultracompact starbursts involving thermal dust emission at $T \approx 60$–80 K, which are so dense as to be optically thick to free-free absorption at 1.6 GHz and to dust extinction at 25 μm. By invoking a standard "starburst" ratio of thermal to nonthermal emission, they derive an upper limit, $T_b \lesssim 10^5$ K for the brightness temperature of purely starburst-related emission. All 17 sources with measured $S_{\rm core}$ values in Table 1 have detectable compact emission substantially (i.e., more than a factor of 10) exceeding this T_b limit of 10^5 K. Three additional sources showed emission with $5.0 \lesssim \log T_b \lesssim 5.4$, only marginally above the "starburst limit." As anticipated from the CHYT images, most sources showed evidence for considerable emission on the shortest baselines (scales of 0."05 and greater), the interpretation of which will be deferred to Paper III.

The median VLBI core power is $\log P_{\rm core}(\text{median}) = 22.06$ (W Hz^{-1}) for detected sources, with a median ratio of core to toal 1.6 GHz radio power of 12%. The histograms of the VLBI-core power and core fraction *limits* for undetected sources are comparable, with median values $\log P_{\rm core} \lesssim 21.8$ (W Hz^{-1}) and core fraction $\lesssim 6\%$, respectively. We caution that the flux density limits for undetected sources were typically determined on longer baselines than the maximum core flux density measurements for the detected sources. Nonetheless, our results are clearly consistent with the presence of compact cores in all of our sample galaxies and in the majority of the CHYT complete sample, at a power level of $\log P_{\rm core} \lesssim 20.5$ (W Hz^{-1}) (which falls below the typical detection threshold).

This result is apparently at variance with the study of Norris et al. (1990) who detected radio cores in a small fraction of luminous infrared galaxies and preferentially in high-excitation systems. Among the differences between our study and that of Norris et al. are the following: (1) The current study has considerably higher sensitivity. The majority of the sources detected here would fall below the Norris et al. detection threshold. (2) The current study employs a higher luminosity cutoff ($\log [L/L_\odot] > 11.25$ vs. 10). (3) There is greater statistical uniformity of the CHYT/BGS sample. We speculate that detectably strong radio cores preferentially inhabit compact, ultraluminous IR galaxies, which comprise our entire sample, but which are statistically swamped by lower luminosity objects in the Norris et al. sample (only 22% of the Norris et al. galaxies have $\log [L/L_\odot] > 11.25$).

The 17 high-T_b galaxies detected here frequently show evidence for resolution on 10 mas scales, and in many cases the structure can be classified as complex. In only four cases (Mrk 273, NGC 2623, Mrk 171D, and 0335+152) are the correlated flux densities on the long baselines consistent with the high-T_b emission originating entirely from an unresolved point source, and in two of these the apparent consistency is due to the fact that there is a single detection on the most sensitive baseline.

We address here two fundamental questions posed by these results: (1) Are the compact radio cores due to AGN or starburst activity? and (2) What is the relationship between the compact radio core and the more extended radio and infrared emission? Since the inferred core brightness temperatures are typically two or more orders of magnitude higher than the limit, $\log T_b \lesssim 5$, suggested by CHYT for starburst related thermal plus synchrotron emission, the only viable candidates for compact starburst-related cores are extremely luminous radio supernovae (RSNs). Indeed, the early phases of RSNs can reach brightness temperatures, $\log T_b \gtrsim 11$, near the inverse-Compton limit, and we consider this possibility in § 4.2.

We have compared the VLBI core flux densities, $S_{\rm core}$, core powers, $P_{\rm core}$, and 1.6 GHz core fractions, $S_{\rm core}/S_{\rm total}$, with the other known radio, infrared, and optical characteristics of our sample galaxies. These include far-infrared flux density, $S_{\rm FIR}$, and luminosity, $L_{\rm FIR}$; (25 μm/60 μm) color; (60 μm/100 μm) color; 60 μm spectral shape, $C_{60\,\mu{\rm m}}$; FIR to radio ratio, q; radio spectral index, $\alpha^{8.44}_{1.49}$; $L_{\rm FIR}$ to (inferred) H_2 mass ratio; and optical excitation, log ([O III]/Hβ) versus log ([N II]/Hα). A striking aspect of these results is the lack of correlation of VLBI core properties with any of these other characteristics, some of which are indicators of AGN activity. CHYT make particular note of the high infrared and radio optical depths implied by their compact starburst models, therefore we have also compared these observables after making appropriate optical depth corrections following CHYT, with the same null result. We note that if the free-free optical depths inferred by CHYT are correct, then the 1.6 GHz core power, which must be presumed to be coming from the innermost obscured regions of the source, must be corrected upward by a factor of up to 5, as well.

Of particular note is the fact that the emission-line spectrum yields few, if any, clues to the existence of VLBI-scale radio emission. If high excitation and compact radio core were both reliable indicators of the presence of a true AGN, our results would indicate that low-excitation (H II) galaxies differ from their Seyfert brethren only in the quantity or patchiness of dusty material obscuring the high-excitation region from our view. Conversely, if high excitation is caused by extremely massive stars in a dense starburst environment (Terlevich & Melnick 1985), a supernova interpretation of the compact radio cores might still predict a higher incidence of the required extraordinary supernova events in high-excitation galaxies, which is not the case, unless one again appeals to variable optical obscuration.

Considerable support for the CHYT model of ultracompact starbursts can be found in the lack of correlation of VLBI detectability with 8.4 GHz nucleus size and spectral index, and the relatively small fractions of the total nuclear flux density represented by the high-T_b emission. The spectral flattening tabulated by CHYT in many of these nuclei cannot be due to synchrotron self-absorption, and the interpretation of such flattening in terms of free-free absorption seems persuasive. An ultracompact starburst must be considered a leading candidate for the origin of the dense ionized medium responsible for such absorption. We emphasize that our results do not obviate the CHYT model, but rather show that AGN cores are common in compact IR galaxies and must be considered as candidates for some of the infrared luminosity.

There remains the possibility that the more extended radio emission is augmented by lobelike emission from the AGN core. In this case, preservation of the well-known FIR-radio correlation (which incidentally is not especially strong within our subsample) would require that the AGN also contributes substantially to the IR emission. This is a reasonable hypothesis, given the presence of starburst-related dust suitable for reprocessing optical and UV AGN luminosity. Whatever the origin of the extended radio emission, it would seem surprising that its properties or those of a nuclear starburst appear to be unrelated to the strength or existence of milliarcsecond-scale radio structure.

4.2. *Luminous Radio Supernova vs. AGN Interpretation*

It is becoming increasingly clear that luminous radio supernovae show many characteristics of modest-luminosity AGN cores and may, in the extreme, compete as candidates for the compact VLBI cores detected in this study (Wilkinson & de Bruyn 1990; Paper I). We are severely constrained in our interpretation of the VLBI cores in terms of radio supernovae by the phenomenological nature of current RSN models and by our poor understanding of the acceleration of the synchrotron electrons in these models (see Chevalier 1982). Furthermore, most theoretical work in this area has concentrated on the detonation of Type II SNs into a preexisting stellar wind and may not directly apply in the dense environs of starbursting molecular clouds. A brief discussion of RSN models as applied to the case of Mrk 297A is given in Paper I. We note at the outset that the RSN interpretation further pushes the upper bound for energetics of known RSNs: the *median* observed core power is over a factor of 4 higher than the *maximum* observed for Mrk 297A.

Consider, for example, IRAS 01173+1405, a luminous H II galaxy with complex structure, which lies near the median in most IR/radio characteristics. This source has a compact VLBI core with a flux density of approximately 2 mJy on a 5 mas (3 pc) scale, with another 2 mJy distributed over about 10 mas, and additional flux density on 50 mas scales. Assuming optically thin emission with typical spectral index, $\alpha \approx 0.7$, and integrating from 100 MHz to 100 GHz, we obtain a total core luminosity, $L_{\rm core} \approx 10^{39}$ ergs s^{-1}, with comparable luminosity distributed over the central 6 pc. This luminosity is in itself an order of magnitude greater than the most luminous previously studied RSN at radio maximum such as SN 1986J in NGC 891. The resolved core size implies a minimum remnant age of order a few hundred years. A variety of scaling arguments suggest that the luminosity at radio maximum must be in excess of 10^{42} ergs s^{-1}, four orders of magnitude greater than SN 1986J. The total synchrotron emission over the supernova lifetime would then considerably exceed the 10^{51} ergs of mechanical energy allotted by standard theory to a Type II supernova. Such considerations are exacerbated when considering the upper extremes of the core luminosity distribution and the possibility of significant free-free optical depth to the compact source.

Luminous RSN complexes and complexes of young SNRs may be considered as an alternative explanation. The supernova rates inferred from the core luminosities considerably exceed those implied by the star-formation rates inferred from the far-infrared luminosities (Condon & Yin 1990) for conventional RSNs. Similarly, distributions of standard young SNRs are unable to provide the requisite luminosity or extreme brightness temperatures. The only remaining supernova interpretation involves multiple objects belonging to the hypothetical new class of extremely radio-luminous supernovae arising in regions smaller than about 0″.03 or 20 pc. These considerations will be discussed further in Paper III, and we are actively pursuing new observations which will help discriminate between AGNs and multiple luminous supernovae.

4.3. *Conclusions*

Our results suggest that AGN-like cores are common in luminous infrared galaxies, but the lack of correlations with other properties complicates simplistic scenarios in which there is a monotonic evolution from starburst to AGN. It is worth remarking that the compact cores detected in this experiment are comparable in power to the total radio power of typical Seyfert galaxies (Ulvestad & Wilson 1989) or radio-quiet QSOs (Kellermann et al. 1989), but orders of magnitude greater than the compact radio sources seen in quiescent late-type galaxies. [e.g., $\log P_{1.6\,\rm GHz}$(Sgr A) $\lesssim 16$ (W Hz^{-1})]. However indirect the relationship between the compact core source and the infrared emission may be, a relationship of some type does appear to exist. Our interpretation would be considerably strengthened by radio data capable of probing the relationship (if any) between the very compact core and the subarcsecond (VLA) scale emission. Further VLBI and MERLIN observations of selected galaxies are in progress to define accurately the detailed radio structure.

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