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5 GHz observations of isolated and group galaxies

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Summary. We have searched for 5 GHz continuum emission from a sample of 12 isolated galaxies and a control sample of 17 galaxies in small groups with the Westerbork radio telescope array. The selection of these samples is discussed and compared with previous work. Only two nuclei were detected at a level of about 2 mJy, both of them belonging to isolated galaxies. Three point sources possibly located in the galaxy disks were detected, as well as a number of background sources. Extended disk emission was detected with a similar degree of success both in the isolated and the non-isolated samples. We conclude that at this level there is no difference in the radio properties of the two samples. We also rule out the possibility that thermal bremsstrahlung is responsible for the excess U-band radiation observed in the nuclei of the isolated galaxies, unless very high temperatures or densities are invoked.

Key words: galaxies – galactic nuclei – isolated galaxies – nuclear activity – radio continuum

I. Introduction

This paper presents the results of a sensitive interferometer search for radio continuum emission from galaxies belonging to two samples, one of isolated galaxies and the other of galaxies in small groups. This study is part of a wider effort to understand the influence of the environment in determining observable properties of galaxies.

To date, the sample of isolated galaxies (described in the next section) has been studied in several wavelength regions. Brosch and Shaviv (1982) made multiaperture photometric measurements in three colors (U, B, and V). They found that the nuclei of all 12 isolated galaxies exhibit excess U-band radiation, similar to Seyferts (e.g. Weedman, 1973). The integrated colors, however, are normal for spirals.

In Seyfert galaxies the ultraviolet excess extends as a power law into the near infrared (Balzano and Weedman, 1981). This, however, is not true of the six isolated galaxies measured in J-, K-, and L-bands by Brosch and Isaacman (1982). The latter have normal infrared colors, similar to those of a black body with $T \sim 3400$ K (typical of a K star). This apparently rules out the possibility that the nuclear U-band excess comes from a steep-spectrum synchrotron source but is still consistent with bremsstrahlung or with a peculiar population of early stars.

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Meanwhile, Balkowski and Chamaraux (1981) have found an apparent excess of neutral hydrogen gas (H I) in these same isolated galaxies. If the gas is metal-poor and falling into the nucleus, it could be responsible for either a hot thermal plasma or star formation with an initial mass function biased towards massive star formation (Brosch and Isaacman, 1982) both of which could produce the ultraviolet excess. Consistent with the infall picture is the finding by Krumm and Shane (1982) that the H I *diameters* are normal in the two isolated galaxies which they mapped. This suggests that the gas is more centrally condensed in these galaxies, a condition favoring infall to their nuclei.

Radio continuum measurements have previously been made of a different sample, from the list of isolated galaxies compiled by Karachentseva (1973, hereafter KI), and of a sample of isolated *pairs* of galaxies selected by Karachentsev (1972, hereafter KP). We argue in the next section that these samples are contaminated by non-isolated systems, but we note the results of radio studies of them by Adams et al. (1980) and Stoke et al. (1978). They concluded that isolated galaxies are less likely to be strong radio emitters than non-isolated galaxies and that wide pairs show less emission than close pairs. Hummel (1981) reached similar conclusions for the emission originating in the central regions from his 21 cm continuum study of 400 galaxies in all environments.

Besides using a purer sample of isolated galaxies, our study improves on earlier work because of its better sensitivity. By using the Westerbork Synthesis Telescope, we have eliminated the confusion problem and thus reduced the detection limit to about 2 mJy in most cases.

In addition, we have also observed a control sample of galaxies in small groups. In this way we have obtained a uniform set of data for comparing the radio properties of average galaxies to those of the isolated sample.

II. The samples

The criteria by which the KI isolated galaxies and the KP sample of isolated pairs of galaxies were selected from the Zwicky catalogue (Zwicky et al., 1961–8) required that neighboring galaxies of comparable diameter be more distant than a certain factor (10 for KI, 5 for KP) times the diameter of the primary or the separation between the members of the pair. However, Karachentseva (1980) subsequently found that the KI sample is contamined by systems which are non-isolated. This is because the selection criteria used do not exclude certain kinds of neighbors. The contaminating galaxies found by Karachentseva were mostly

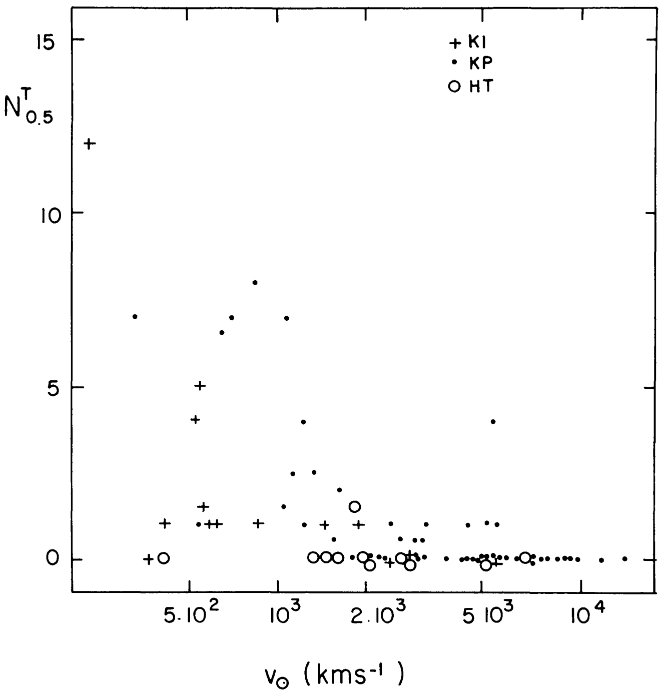

Fig. 1. Number of true companion galaxies vs. the redshift of the subject galaxy

components of pairs with members of widely different apparent magnitudes and/or diameters, or members of groups or clusters of galaxies where only the brightest galaxy had been considered.

We have now applied new criteria to estimate the number of *true* companions $N^T_{0.5}$ of galaxies and pairs in KI and KP subsamples. These subsamples consist of those KI and KP objects detected in radio emission by Adams et al. (1980) and by Stocke et al. (1978), which have radial velocities in Rood (1980). By selecting only galaxies previously detected in radio emission, the comparison is not biased. Note that both KI and KP did not use radio emission criteria in their selection; thus our finding should not be influenced by this. Companions are here defined as those galaxies in the Uppsala General Catalogue (Nilson, 1973) at projected distances less than 0.5 Mpc ($H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) with measured radial velocities differing from that of the primary by less than $150\,\mathrm{km\,s^{-1}}$. The velocities are drawn from Rood (1980). Companions without a measured velocity are missed, thus $N^T_{0.5}$ is a lower limit. A velocity difference of $150\,\mathrm{km\,s^{-1}}$ is about twice the dispersion of field galaxies about the Hubble flow (Tammann and Kraan, 1978; Rivolo and Yahil, 1982) and is comparable with the dispersion of velocities in small groups. A galaxy will travel three times 0.5 Mpc in a Hubble time when its velocity is $150\,\mathrm{km\,s^{-1}}$.

$N^T_{0.5}$ is shown in Fig. 1, as a function of the redshift of the primary system. Clearly, most KI and KP systems *do* have companions (and note that at the larger redshifts companions may be missed because of the magnitude limit of the Uppsala Catalogue). Hence, the assumption that these galaxies have remained undisturbed for a sizable fraction of a Hubble time may not be correct.

For this reason, and also because the KI and KP samples are too large for a detailed study (KI includes 1050 objects), we decided to use the sample of isolated galaxies suggested by Huchra and Thuan (1977). Hereafter this will be called the HT sample. These objects are a subset of the Turner and Gott (1976) field galaxies, selected from the Zwicky catalogue under the constraints that they should be brighter than 14.0 mag., should have no neighbour brighter than 15.7 mag within 45′, and should not be members of any nearby de Vaucouleurs (1975) group. Out of 1088 Zwicky galaxies brighter than 14.0 mag, only 12 satisfy the HT criteria. (Curiously, only five objects overlap with KI.)

Figure 1 shows that the HT galaxies, with one exception, have no companions. Thus the sample is probably less contaminated by non-isolated galaxies than is KI.

We have also selected a sample of comparison galaxies in small groups to check how an enhancement of the local density of galaxies affects their observed properties. These "group galaxies" were chosen from the Turner and Gott (1976) catalogue of groups of galaxies, the de Vaucouleurs (1975) list of groups, and a list of galaxies with measured rotation curves, supplied by Vera Rubin. The actual selection of objects from these lists was somewhat arbitrary. We needed a sample comparable to the HT sample, covering a similar range of apparent magnitudes, angular sizes, and morphological types. We further required that their radial velocities be known, and that they would not be members of rich clusters. Finally, we insisted that each chosen group galaxy have at least three companions, in the above sense. Radio properties of the galaxies played no role in the selection criteria, either here or in the master lists, so the sample is unbiased in that sense.

The galaxies in the HT and group galaxy (GG) samples are listed in Tables 1a and 1b. It is clear that the two samples span the same range of parameters.

Radio continuum information already available in the literature for these galaxies is presented in Table 2. We will not discuss individually the numerous discrepancies in observations, but it appears that confusion is an important problem for single dish observations and even for synthesis observations composed of only one short cut.

Table 1a. Isolated galaxies

Name	Type	m_{pg}	a × b (blue) [arcmin]	V_0 [km s⁻¹]	Distance [Mpc]
N 2684	S	13.4	0.9 × 0.8	2858	29
N 2712	SBb	12.3	3.5 × 1.7	1807	18
Z 0902+36	S0	14.0	1.3 × 1.1	7090[a]	71
N 3622	S?	13.7	1.3 × 0.5	1335[a]	15
N 3682	S0/a	13.4	2.3 × 1.6	1515[a]	17
N 4566	S	13.9	1.2 × 0.8	5290	54
N 5301	Sc	13.0	4.2 × 0.8	1490	16
N 5448	SBb	12.7	4.3 × 2.0	2023	22
N 5832	SBc	13.3	3.7 × 2.5	448[b]	7
N 5987	Sb	13.3	5.1 × 1.8	3018	32
Z 1549+47	S	13.6	1.4 × 0.7	5971[a]	61
N 6012	SBa	13.1	2.1 × 1.6	1848	19

[a] J. Huchra (private communication)
[b] Balkowski and Chamaraux (1981)

All information is from Nilson (1973), except velocities which are from Rood (1980), unless otherwise noted. Distances are derived asuming a galactocentric correction of $300 \sin l^{\mathrm{II}} \cos b^{\mathrm{II}}\,\mathrm{km\,s^{-1}}$ and $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Table 1b. Group galaxies

Name	Type	m_{pg}	a × b (blue) [arcmin]	V_0 [km s^{-1}]	Distance [Mpc]	$N^T_{0.5}$
N 3003	SB?c	12.3	5.7 × 1.7	1481	14	3
N 3067	Sa-b	12.7	2.2 × 0.8	1506	15	3
N 3245 A	SBb	15.4	3.6 × 0.3	1327	13	3
N 3430	Sc	12.2	4.5 × 2.4	1594	16	3
N 3593	SO	11.8	5.2 × 2.1	621	5	3
N 3893	Sc	10.6	4.6 × 2.5	977	10	8
N 3898	Sa	11.7	3.6 × 2.1	1174	13	4
N 3938	Sc	11.0	5.4 × 5.1	812	9	7
N 3982	S	11.6	2.4 × 2.2	1110	12	5
N 4062*	Sc	11.9	4.8 × 2.0	769	8	4
N 4369*	SO/a	12.3	2.4 × 2.4	1052	11	3
N 4448*	Sa	11.9	4.0 × 1.5	693	7	6
N 5350*	SBb/c	12.4	3.4 × 2.7	2316	24	4
N 5676*	Sc	11.7	4.0 × 1.7	2117	23	7
N 5879*	Sb	11.9	4.8 × 1.7	775	10	4
N 5905	SBb	13.6	4.7 × 3.6	3393	35	4
N 5908	Sb	13.5	3.0 × 1.3	3309	35	4

Columns 2, 3, 4 are from Nilson (1973). Column 5 is from Rood (1980). Column 6 is derived assuming a galactocentric correction of $300 \sin l^{II} \cos b^{II}$ km s^{-1} and $H_0 = 100$ km s^{-1} Mpc^{-1}. See the text for $N^T_{0.5}$ Galaxies with an asterix after their NGC number have been observed only once (single cut)

Table 2. Previous radio continuum observations

Galaxy	Frequency (GHz)	Flux (mJy)	Ref.	Remarks
N 2712	1.4	12	H 80	Center
	1.4	<50	H 80	Total
	1.4	5 ± 0.8	KS 82	Center, unresolved
	1.4	3.2 ± 2.3	KS 82	Disk, center subtracted
	5.	< 20	AJS	Beam = 2.′5
N 3003	1.4	< 10	H 80	Center
	1.4	< 50	H 80	Total
	2.38	19 ± 4	DC	Beam = 2.′7
N 3067	1.4	< 10	H 80	Center
	1.4	< 60	H 80	Total
	2.38	<150	DC	Beam = 2.′7, confused
N 3430	1.4	< 10	H 80	Center
	1.4	< 50	H 80	Total
	2.38	28 ± 6	DC	Beam = 2.′7
N 3593	1.4	45	H 80	Center
	1.4	93	H 80	Total
	2.38	64 ± 4	DC	Beam = 2.′7
	5.	67 ± 17	S	Beam = 2.′7
N 3893	1.4	< 20	H 80	Center
	1.4	162	H 80	Total
	1.5	20	HBC	Center
	2.695	75 ± 14	STKK	Beam = 5.′0
	5.	43 ± 12	STKK	Beam = 2.′7
	5.	4	HBC	Center
	5.	45 ± 9	S	Beam = 2.′7

Table 2 (continued)

Galaxy	Frequency (GHz)	Flux (mJy)	Ref.	Remarks
N 3898	1.4	< 2	H 80	Center
	1.4	<100	H 80	Total
	1.4	< 3	VDK	Center
	1.5	< 2	HBC	Center
	5.0	< 11	HBC	Center
N 3938	4.8	20±3	GGK	Beam=2:4
	10.7	13±7	GGK	Beam=1:2
N 3982	1.4	40	H 80	Center } dynamic range problem
	1.4	< 50	H 80	Total } dynamic range problem
	4.8	35±4	GGK	Beam=2:4
	10.7	25±14	GGK	Beam=1:2
N 4062	1.4	< 10	H 80	Center
	1.4	< 50	H 80	Total
	2.38	4±3	DC	Beam=2:7
	5	< 20	AJS	Beam=2:5
N 4369	1.4	< 15	H 80	Center
	1.4	< 50	H 80	Total
N 4448	1.4	< 10	H 80	Center
	1.4	< 50	H 80	Total
	2.38	0±4	DC	Beam=2:7
N 4566	5.	< 20	AJS	Beam=2:5
N 5301	1.4	< 15	H 80	Center
	1.4	< 50	H 80	Total
	1.4	< 1	KS 82	Center
	1.4	7.2±1.5	KS 82	Disk
	2.7	70±50	P 80	Beam=0:9
N 5350	1.4	< 10	H 80	Center
	1.4	60	H 80	Total
N 5448	1.4	< 10	H 80	Center
	1.4	< 50	H 80	Total
N 5676	1.4	< 20	H 80	Center
	1.4	140	H 80	Total
	1.5	< 3	HBC	Center
	4.8	35±5	GGK	Beam=2:4
	5.	33±7	S	Beam=2:7
	5.	< 12	HBC	Center
	10.7	19±3	GGK	Beam=1:2
N 5879	1.4	< 10	H 80	Center
	1.4	< 50	H 80	Total
	4.8	9±5	GGK	Beam=2:4
	10.7	< 4	GGK	Beam=1:2
N 5905	1.4	20	H 80	Center
	1.4	< 50	H 80	Total
	1.4	13.2	M 82	Center
N 5908	1.4	29	H 80	Center
	1.4	< 50	H 80	Total
	1.4	27.2	M 82	Whole disk
	5	17±6	S	Beam=2:7
N 6012	2.38	12±5	DC	Beam=2:7
	5	< 15	AJS	Beam=2:5

References to Table 2

AJS, Adams, Jensen and Stocke, 1980
DC, Dressel and Condon, 1978
GGK, Gioia, Gregorini and Klein, 1982
H 80, Hummel, 1980
HBC, Heckman, Balick and Crane, 1980
KS 82, Krumm and Shane, 1982
M 82, van Moorsel, 1982
P 80, Pfleiderer et al., 1980
S, Sramek, 1975
STKK, Stocke et al., 1978
VDK, van de Kruit, 1972

III. Observations and reductions

The observations were performed at 5 GHz with the Westerbork Synthesis Radio Telescope (WSRT) in 1980 and in 1981. The telescope and the data reduction programs have been described in detail elsewhere (Hogbom and Brouw, 1974; Baars and Hooghoudt, 1974; van Someren-Greve, 1974; Bos et al., 1981). The performance of the system is summarized in Table 3.

Table 3

Frequency		4.995 GHz
Bandwidth		10 MHz
Number of interferometers		40
Baselines[a]		36 (72) 2700 m
	or	72 (72) 2700 m
Synthesized beam FWHM[b]		3″.5 × 3″.5 cosec δ
Primary Beam FWHM		11′
Size of CLEANed map		9′.6 × 9′.6
Typical RMS Noise[c]		0.6 mJy/beam
Typical distance to first grating ring[d]		2′.9

[a] Shortest baseline (increment) longest baseline
[b] For a 12 h observation
[c] For 3 × 20 min integration
[d] Minor axis, for system parameters as above, calculated as described in Bos et al. (1981)

A typical observation of one galaxy consisted of three integrations (or cuts) of 20 min each, at widely-spaced hour angles. This was in most cases sufficient to exclude confusing sources, but not to map the galaxies. Two galaxies, NGC 3067 and NGC 5832, are close to powerful radio quasars and in their cases limitations of the dynamic range of the observations degrade the sensitivity. Three galaxies were observed with only two cuts, and six with only one. The latter, all from the GG sample, are identified in Table 1b with an asterix after their NGC number.

The observations were used to create two-dimensional maps which were processed using the CLEAN algorithm (Hogbom, 1974), by which multiple delta functions convolved with the synthesized beam are fitted to extended sources. In most cases the maps were cleaned to 2.5 mJy. The final rms residuals averaged about 0.6 mJy. The individual residual value produced for each map was adopted as the standard deviation of the detected fluxes and as the 1σ detection limit for that map. The distribution of the residuals in a single map is non-Gaussian because of the incomplete hour angle coverage and the presence of remnants of grating rings and faint sources. There are more large-amplitude residuals than would be expected for a Gaussian distribution. Considerable care has therefore been exercised in selecting the detection criteria so as not to claim spurious detection on the one hand, nor discard good information on the other.

The criteria for claiming a detection of a *nuclear point source* were (a) that its position be within 10″ of the optical nucleus (Dressel and Condon, 1976 for GG's and Brosch, 1982 for HT's), and (b) that its flux be higher than that of 99.865% of the points in the map (corresponding to a three sigma level for a Gaussian

Table 4a. Point sources – isolated galaxies

Galaxy	Survey source	α(1950)	δ(1950)	Galactocentric coordinates		Flux (mJy)	Optical identification
				ϱ	ψ		
N 2684	–	–	–	–		<2.1	Nucleus
	51 W 01	8h51m28s.8	+49°20′00″	1′.3	143°	19.6	G:N 2686a
N 2712	–	–	–	–	–	<2.1	Nucleus
Z 0902+36	51 W 02	9 02 37.3	36 33 17	0	0	5.3	Nucleus
	51 W 03	9 02 58.7	36 35 45	4.9	60	22.6	E
N 3622	–	–	–	–	–	<1.9	Nucleus
N 3682	–	–	–	–	–	<2.1	Nucleus
	51 W 08	11 24 40.1	66 51 48	0.5	−101	3.8	D
	51 W 09	11 24 43.8	66 52 24	13.5	41	280	D
N 4566	–	–	–	–	–	<2.2	Nucleus
N 5301	–	–	–	–	–	<2.3	Nucleus
	51 W 13	13 44 33.7	46 21 45	2.1	79	72.8	E
N 5448	–	–	–	–	–	<2.1	Nucleus
	51 W 14	14 00 55.6	49 24 03	0.7	−178	3.9	D
N 5832	–	–	–	–	–	<65.3	Nucleus
	51 W 17	14 58 56.7	71 52 11	6.8	− 85	10539.0	Q:3C309.1
N 5987	–	–	–	–	–	<2.2	Nucleus
	51 W 19	15 39 31.9	58 13 09	5.5	104	41.6	S
Z 1549+47	51 W 20	15 49 40.3	47 24 14	0	0	7.6	Nucleus
N 6012	–	–	–	–	–	<2.5	Nucleus
	51 W 21	15 52 06.9	14 49 25	5.4	32	12.3	E

Table 4b. Point sources – group galaxies

Galaxy	Survey source	α(1950)	δ(1950)	Galactocentric coordinates		Flux (mJy)	Optical identification
				ϱ	ψ		
N 3003	–	–	–	–	–	<2.3	Nucleus
N 3067	–	–	–	–	–	<11.3	Nucleus
	51 W 04	$9^h55^m25^s.4$	+32°38′23″	1′.8	– 4°	1165.2	Q:3C232
N 3245A	–	–	–	–	–	<2.4	Nucleus
	51 W 05	10 24 05.8	28 58 11	4.6	– 19	34.6	S
N 3430	–	–	–	–	–	<2.3	Nucleus
	51 W 06	10 49 12.6	33 13 11	2.4	– 88	8.7	G
N 3593	–	–	–	–	–	<2.5	Nucleus
	51 W 07	11 12 00.3	13 08 33	3.1	6	7.1	G
N 3893	–	–	–	–	–	<2.2	Nucleus
N 3898	–	–	–	–	–	<2.2	Nucleus
	51 W 10	11 46 30.3	56 22 47	1.4	– 38	3.8	D
	51 W 11	11 46 42.0	56 23 51	2.3	20	3.9	E
N 3938	–	–	–	–	–	<2.2	Nucleus
N 3982	–	–	–	–	–	<2.3	Nucleus
N 4062	–	–	–	–	–	<2.4	Nucleus
N 4369	–	–	–	–	–	<4.1	Nucleus
N 4448	–	–	–	–	–	<2.4	Nucleus
	51 W 12	12 25 50.5	28 52 24	1.7	146	5.5	E(*)
N 5350	–	–	–	–	–	<2.5	Nucleus
	51 W 14	13 51 04.7	40 39 22	3.4	– 35	14.2	E(*)
N 5676	–	–	–	–	–	<2.5	Nucleus
	51 W 16	14 31 03.2	+49 42 19	1.6	10	4.7	S(*)
N 5879	–	–	–	–	–	<9.6	Nucleus
	51 W 18	15 08 44.3	57 13 59	3.3	39	338.1	S(*)
N 5905	–	–	–	–	–	<3.2	Nucleus
N 5908	–	–	–	–	–	<3.6	Nucleus

Notes to Tables 4a and 4b
Identifications: G = galaxy image (fuzzy on Palomar prints); S = stellar image (sharp on Palomar prints); E = empty field; D = source within disk of galaxy observed; Q = identified quasar; (*) = one cut only; position uncertain. The expected number of background sources at 5 GHz is very small (~0.5 per map; see Willis and Miley, 1979b). The chance that a D source would be contributed from this background is then

$$0.5 \times \frac{\text{solid angle subtended by galaxy}}{\text{solid angle subtended by field}}$$

or about 0.005, thus negligible

distribution). *Non-nuclear point sources* were identified if they were within three arcmin of the galaxy center and were stronger than five sigma (5/3 times the above three sigma value). In addition, any source in the cleaned field stronger than 5.0 mJy (before correction for primary beam attenuation) was noted.

All detected sources and upper limits for the non-detected nuclei are listed in Tables 4a and 4b. The sources are identified by their Westerbork survey numbers. The present list of sources is survey number 51; the sources are numbered sequentially in order of increasing right ascension.

An impression of the accuracy of the fluxes given for the detected sources can be obtained from the upper limits presented for the non-detections; these are three sigma values as explained above. We have tried to identify the detected sources on the prints of the Palomar Sky Survey, and we give the results in the last column of Tables 4a and 4b. All fluxes have been corrected for

Table 5a. Extended emission – isolated galaxies

Galaxy	Flux integral [mJy]	
	1′.2 diameter circle	2′.4 diameter circle
N 2684	<8.2	<11.6
N 2712	<8.2	17.6±3.9
Z 0902+36	11.5±2.5[a]	18.8±3.5[a]
N 3622	<8.4	<11.9
N 3682	10.9±3.2[b]	<13.4
N 4566	<9.2	<12.9
N 5301	<8.8	<12.5
N 5448	<9.9±2.9	<11.9[b]
N 5832	<292.9	<414.3
N 5987	<9.3	<13.2
Z 1549+47	11.3±3.0[a]	17.7±4.2[a]
N 6012	<5.6	<8.3

Table 5b. Extended emission – group galaxies

Galaxy	Flux integral [mJy]	
	1′.2 diameter circle	2′.4 diameter circle
N 3003	<7.9	15.1±3.7
N 3067	<38.1	<53.9
N 3245A	<7.7	15.5±3.6
N 3430	<7.8	<11.0
N 3593	<5.5	<7.7
N 3893	25.9±2.9	41.1±4.1
N 3898	<9.2	<13.1
N 3938	<8.5	14.0±4.0
N 3982	15.9±3.2	34.8±4.5
N 4062	<8.0	<11.4
N 4369	<15.0	<21.3
N 4448	<7.7	<10.9
N 5350	<9.3	<13.1
N 5676	<10.0	<14.2
N 5879	<40.4	<57.2
N 5905	<13.4	<19.0
N 5908	<15.0	<21.3

Notes to Tables 5a and 5b:
Upper limits are 3σ; Errors on detections are 1σ; [a] Nuclear source subtracted; [b] Disk source subtracted

primary beam attenuation using the function

$$f(R) = \exp(-0.0245\,R^2)\,, \quad (1)$$

where R is the distance to the field center in arcmin (Willis and Miley, 1979a).

We have also looked for *extended emission* in both samples of galaxies. For this purpose we summed the flux density within circles of diameter 1.2 and 2.4 arcmin, centered on each galaxy. As Tables 1a and 1b show, these circles encompass a wide region in most galaxies, if not all the galaxy. The reason for choosing a distance-dependent area of integration is due to the wide range of redshifts in both samples coupled with the fact that with a minimum baseline of 72 m (Table 3) the WSRT is blind to extended emission larger than ~two arcmin. The flux density sums were normalized by the corresponding sums of the antenna patterns. The results are shown in Tables 5a and 5b. We give there also the detection limit corresponding to each measurement, obtained by multiplying the three sigma noise per beam by the square root of the number of beams per circle scaled by the effective number of interferometers used. This assumes that the noise and residuals within each integrating area are uncorrelated (hence the scaling to the number of beams); this may well not be the case.

Table 6. Extended radio emission

1′.2 Circle		$\chi^2 = 0.0121$	
		HT sample	GG sample
$S > 10$ mJy	observed	3	2
	expected	2.4	2.6
$S < 10$ mJy	observed	8	10
	expected	8.6	9.4
2′.4 Circle		$\chi^2 = 0.0191$	
		HT sample	GG sample
$S > 15$ mJy	observed	3	4
	expected	3.3	3.7
$S < 15$ mJy	observed	8	8
	expected	7.7	8.3

IV. Discussion

The observational results may be summarized as follows:

(a) Nuclear radio sources were found in only two of the 12 HT galaxies and in none of the group galaxies. Point sources possibly originating in the disks were found in two HT galaxies and one GG.

(b) Extended emission was found in five isolated galaxies and in five group galaxies. The detection statistics for extended radio emission are summarized in Table 6. The hypothesis that the proportion of detections among HT galaxies and the GG sample is similar was tested with the χ^2 test, with the conclusion that there is no difference in this aspect between the samples.

A comparison between our 5 GHz fluxes and previously published single dish values (Table 2) shows that in a number of cases our detection or upper limits are much lower than the other measurements. This is probably an indication of some missing flux due to the lack of interferometer spacings shorter than 72 m. In general, however, our upper limits and the other published values are in reasonable agreement.

Result (a) above casts doubt on the thermal bremsstrahlung model for the nuclear U-band excess in isolated galaxies, since such a process should produce detectable radio emission. The mean nuclear brightness of the isolated galaxies measured by Brosch and Shaviv (1982) is 15.5 U-magnitudes, or about 1 mJy

Table 7. Bremsstrahlung model[a]

Plasma temperature	Flux at 5 GHz
$0.8\,10^5$ K	15.1 mJy
1.0	6.3
1.5	2.9
2.0	2.0
5.0	1.0

[a] Assumes $S(3500\,\text{Å}) = 0.2$ mJy

(Johnson, 1966). The bremsstrahlung spectrum of an optically thin source is

$$S_\nu \propto g(\nu, T) \exp(-h\nu/kT) \quad (2)$$

(Lang, 1974). Here, T is the plasma temperature, ν is the frequency of observation, and g is the Gaunt factor. In Table 7 we have used Eq. 2 to calculate the expected flux at 5 GHz, assuming that *only* 20% of the U-band light (0.2 mJy) is bremsstrahlung. The observed upper limit to the 5 GHz flux of about 2 mJy for most of the galaxies in Tables 4a and 4b is thus incompatible with the bremsstrahlung model unless the temperature is quite high ($T \gtrsim 2\,10^5$ K). Maintaining such high temperatures requires a powerful energy source and probably a low-metallicity plasma (so that cooling is inefficient). A strong gravitational field is also needed to bind the plasma to the nucleus.

Lower temperatures (down to a few times 10^4 K) can be allowed if the electron density or path length is large enough that radio emission is *self-absorbed*. The "cut off" frequency where the optical depth reaches unity is given by

$$\nu_c = 0.3(T^{-1.35} E_m)^{1/2} \quad (3)$$

(Lang, 1974). Here ν_c is in GHz, T is the electron temperature in Kelvins, and E_m is the emission measure, defined as

$$E_m = \int n_e^2 dl .$$

n_e is the density of electrons (in cm^{-3}) and dl is an element of path length along the line-of-sight (in pc). Self-absorption at 5 GHz requires that

$$E_m \gtrsim 7\,10^7 (T/10^4\,\text{K})^{1.35}\,\text{cm}^{-6}\,\text{pc} . \quad (4)$$

Such large emission measures in our own Galaxy are found only in small regions, such as planetary nebulae and "hot spots" of H II regions. By comparison, more than 2600 unobscured O5 stars would be necessary to account for the nuclear U-band light in NGC 2712 (Allen, 1973).

A second possibility suggested by Brosch and Isaacman (1982) to explain the U-band excess is an unorthodox mixture of stars, in which intermediate types (B – K) are absent. This suggestion is consistent with the general lack of radio emission which we observe.

The complete absence of nuclear radio sources in the GG sample as well as the similarity of the extended emission properties are also noteworthy. Clearly, the higher density of galaxies in small groups is not sufficient to trigger more 5 GHz emission than in isolated galaxies. (The opposite conclusion suggested by our data, namely that group galaxies are *less* likely to show emission than isolated galaxies, is probably not warranted, since (a) the samples are small, and (b) the two detected HT galaxies are not very representative, having the two largest redshifts in the samples.) Apparently, it is only when one looks at close pairs of galaxies, where interaction has occurred recently or is presently occurring, that enhanced radio emission is likely.

Conclusions

It appears that isolated galaxies generally do not have nuclear radio sources, nor do they display extraordinary disk emission. In these respects they resemble ordinary galaxies in small groups, represented by the GG sample. Only in galaxy pairs (studied by others) are nuclear sources more frequent, suggesting that such activity is short-lived.

In failing to find a radio counterpart to the excess U-band emission from the nuclei of isolated galaxies, we have ruled out the thermal bremsstrahlung model, unless very high temperatures or densities are invoked. We hope that forthcoming observations of the nuclear spectra of the HT galaxies, along with aperture photometry of the GG sample, will resolve the mystery of this emission.

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