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SOME PROPERTIES OF THE IR–RADIO RELATIONSHIP OF LUMINOUS INFRARED GALAXIES

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Results of radio continuum observations of 25 luminous IRAS galaxies at 3.95 GHz are presented. The correlation between the radio continuum and far–infrared (FIR) emission is discussed. It is argued that the relationship between the radio and FIR emission in different galaxy scale structures is different. The FIR–radio correlation is much tighter in the core region of the galaxy than in its disk region. While the FIR luminosity is independent of the FIR to radio ratio, the core radio luminosity of the galaxy is decreasing as this ratio is increasing.

1. *Introduction.* The IRAS survey has discovered many extragalactic objects with high far–infrared (FIR) luminosities. The well–established correlation between the radio and FIR luminosities in galaxies is one of the most interesting results of the IRAS survey [1–4]. Furthermore, in some nearby objects where the FIR emission of the galaxies was spatially resolved, it was established that radio continuum and FIR emission have almost the same spatial distribution [5,6]. Because of the large beam size ($\sim 1'$) of the IRAS little is known about the spatial distribution of the FIR emission in the galaxies.

Carico et al. [7] based on near–infrared colours of a subset of luminous infrared galaxies suggested that most of the IR emission originates from the nuclear region of these galaxies. Statistical analysis of FIR bright galaxies also indicates that most of infrared and radio power appears to be originated within nuclear regions [8]. The close linear radio–FIR correlation strongly suggests that the radio and FIR emission of the galaxy spatially coincide with each other.

A striking results were obtained by Lonsdale et al. [9], namely AGN–like cores are common among luminous infrared galaxies, but VLBI core radio properties are not correlated with the known infrared and optical characteristics of these galaxies.

The lack of well-established correlations between radio and FIR properties in the milliarcsecond-scale structure suggests that there is not a simplistic scenario in evolution of the galaxies from starburst to AGN [9].

We address here two questions: (1) What is the relationship between radio and FIR emissions in different galaxy scale structures? and (2) In what scale structure the radio-FIR correlation is tighter? For this purpose we will compare radio-FIR correlation coefficient of luminous far-infrared galaxies for core component ($<1''$) with the correlation coefficient of more extended structure ($\sim 1'$).

In Section 2 we briefly describe the sample and radio continuum observations of galaxies at 3.95 GHz. Section 3 deals with the results and their interpretations. Section 4 presents discussion of the results. We adopt $H_0 = 75$ km/s Mpc in this paper.

2. *The sample and observations.* The sample of galaxies observed during two different epochs (June 1989 and October 1990) using the RATAN-600 radio telescope has been selected from three sources [10-12]. The sample contains 25 galaxies 18 of which are OH megamaser galaxies. Besides radio-FIR relation analysis, initially our intention was optical and radio investigation of megamaser galaxies as well. The preliminary results of these observations we have reported earlier [13]. The details of relations between OH, FIR and radio continuum luminosities of megamaser galaxies will be discussed elsewhere [14].

The radio continuum observations of galaxies were obtained at a frequency of 3.95 GHz on the North sector of RATAN-600. The parameters of the radio telescope and reduction procedure have been described by Aliakbarov et al. [15]. Beam size of the North sector of the radio telescope is $\sim 1'$ in the E — W direction. The receiver system at 3.95 GHz was described by Berlin et al. [16]. We adopted the flux density scale of Kuhr et al. [17]. Typical rms noise level was 5 — 6 mJy.

3. *Results.* The radio data and some global parameters of detected at 3.95 GHz IRAS galaxies are listed in Table 1. The description of the Table is the following: Column 1: IRAS name. Column 2: Measured total flux density at 3.95 GHz, in mJy. Column 3: Estimated flux density at 3.95 GHz for core component ($<1''$), in mJy. Flux densities of core c omponents were c alculated on the base either 5 or 1.49 GHz, assuming a radio spectral index ($S \sim \nu^{\alpha}$) of $\alpha = -0.6$, which is a mean value of spectral indices for core component of infrared luminous galaxies according to [4]. Column 4: Ratio of core and total flux densities. Column 5: Distance in Mpc. Column 6: Logarithm of the FIR luminosity, in solar luminosity. Column 7: Logarithm of the monochromatic core radio luminosity at 3.95 GHz, in W/Hz.

Column 8: Logarithm of the monochromatic total radio luminosity at 3.95 GHz, in W/Hz. Column 9: References for distances, FIR luminosities and measured flux densities of core components.

Table 1

PARAMETERS OF DETECTED SOURCES AT 3.95 GHz

Name	S_t [mJy]	S_c [mJy]	S_c/S_t	D [Mpc]	$\log L_{ir}$ [$L_\odot$]	$\log L_c$ [W/Hz]	$\log L_t$ [W/Hz]	Ref.
01417+1651	37 [7]	28	0.76	109	11.46	22.6	22.7	[4]
0353+261	48 [9]	3	0.06	706	11.75	23.3	24.5	[11]
0356+217	60 [6]	3	0.05	102	10.11	21.6	22.9	[11]
0406+085	20 [6]	7	0.35	48	10.15	21.3	21.7	[11]
0413+081	56 [8]	9	0.16	24	9.55	20.8	21.6	[11]
0421+040	84 [10]	26	0.31	176	10.54	23.0	23.5	[11]
11010+4107	28 [6]	18	0.64	142	11.52	22.6	22.8	[4]
12112+0305	24 [6]	15	0.63	292	12.18	23.2	23.4	[4]
12240-0036	41 [7]	24	0.59	34	11.00	21.5	21.8	[4]
13097-1531	44 [6]	22	0.5	91	11.41	22.3	22.6	[12]
15107+0724	48 [9]	29	0.6	52	11.17	22.0	22.2	[4]
15327+2340	255 [13]	202	0.79	78	12.11	23.2	23.3	[4]
16399-0937	31 [4]	15	0.48	107	11.42	22.3	22.6	[12]
23135+2516	31 [6]	17	0.55	111	11.37	22.4	22.7	[4]

Table 2 presents the list and parameters of non–detected galaxies. The description of the Table 2 is identical with Table 1.

When one considers the correlation between two luminosities in different spectral ranges the Malmquist bias causes oftenly for unreal correlations and it should be taken into account. One of the methods which may correct the possible effect of Malmquist bias is the partial correlation analysis [18,19].

Correlation matrix, means, errors and standard deviations for the sample of galaxies are listed in Table 3. Table 4 presents correlation coefficients, slopes and their significance levels after correction for Malmquist bias where, for example, (ir, c. D) means the partial correlation coefficient between logarithms of infrared and core radio luminosities for fixed value of distance. It is obvious that correlation between infrared and core radio luminosities is much tighter and significant than between total radio and infrared luminosities, which means that when it considers the radio–FIR correlation between luminosities of the IRAS galaxies, the contribution of the core component is much higher than that of disk component. The mean value of the fraction of the core radio flux density (S_c/S_t) is 0.46. The correlation coefficient between FIR emission and S_c/S_t is 0.93 which also indicates on the close relationship between FIR and core radio emission.

Table 2

PARAMETERS OF NON–DETECTED SOURCES AT 3.95 GHz

Name	S_c [mJy]	D [Mpc]	$\log L_{ir}$ [$L_\odot$]	$\log L_c$ [W/Hz]	$\log L_t$ [W/Hz]	Ref.
03056+2034		108	11.18		<22.3	[12]
04332+0209		48	10.43		<21.6	[12]
05100-2425		133	11.28		<22.5	[12]
10173+0828	7	194	11.70	22.5	<22.8	[4]
12018+1941		702	12.36		<24.0	[12]
1653-012	10	168	11.24	22.6	<22.7	[11]
1715+117	4	120	10.65	21.8	<22.4	[11]
20491+1846		118	10.87		<22.4	[12]
20550+1656		145	11.76		<22.6	[12]
22025+4205		58	11.04		<21.8	[12]
22491-1808	4	302	12.02	22.6	<23.2	[4]

Table 3

CORRELATION MATRIX FOR 25 IRAS GALAXIES

	D	$\log L_{ir}$	$\log L_c$	$\log L_t$
D	1	0.55	0.61	0.82
$\log L_{ir}$		1	0.83	0.58
$\log L_c$			1	0.87
$\log L_t$				1
Mean	167	11.21	22.31	22.73
Error	35	0.14	0.16	0.21
StD	176	0.69	0.69	0.78

The same result has been obtained when ranks of luminosities instead of their values have been used. The upper limits of $\log L_t$ (Table 2) were used and ranked in such a way as to minimize the corresponding Spearman rank correlation coefficients.

The Spearman rank correlation coefficient between core radio and FIR luminosities is 0.63 with significance level 99.7%. The minimum of Spearman rank correlation coefficient between total radio and FIR luminosities is 0.1. In both cases the effect of Malmquist bias has been taken into account.

Table 4

CORRELATION COEFFICIENTS AND SLOPES FOR 25 IRAS GALAXIES AFTER CORRECTING MALMQUIST BIAS

	Corr.	Slope	Confidance (%)
[ir,c].D	0.78	0.74	99.99
[ir,t].D	0.47	0.48	95.00

Fig. 1 plots $\log L_t$ against $\log L_{ir}$ for 25 galaxies. Detected galaxies at 3.95 GHz and upper limits are plotted by different symbols. It is evident that galaxies with upper limits should decrease correlation coefficient and slope because the directon of their movement is downwards. In Fig. 2 the relation between core radio luminosities and FIR luminosities for 18 galaxies is plotted. So the infrared emission of IRAS galaxies is much tighter correlated with core radio emission than with radio emission of disk component of the galaxy. Therefore for the following discussions we will deal with core radio emission only.

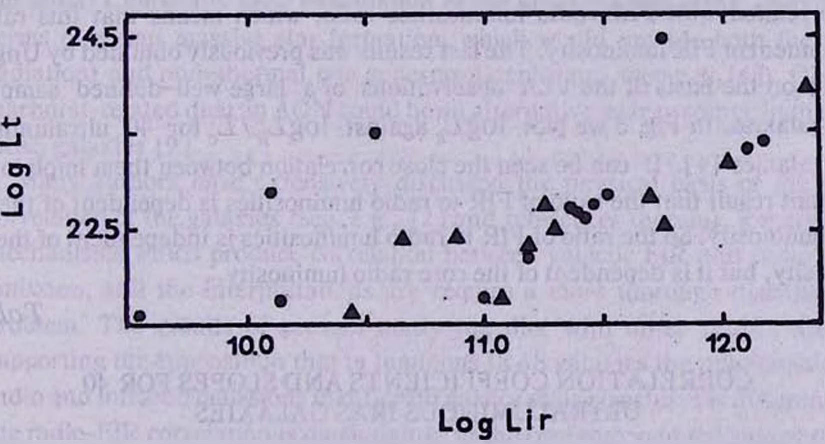

Fig. 1. Relation between radio (total at 3.95 GHz) and FIR lumunosities for 25 IRAS galaxies. Radio detected galaxies are marked by circles and non–detected galaxies are marked by triangles.

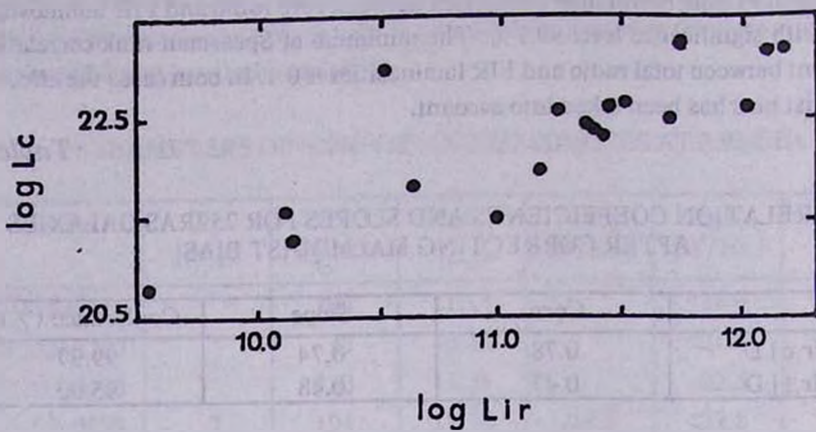

Fig.2. Estimated core radio luminosity (at 3.95 GHz) plotted against FIR luminosity for 18 IRAS galaxies.

Condon et al [4] have observed 40 IRAS ultraluminous galaxies with $\log L_{ir} \geq 11.25$ at 8.44 GHz using VLA. Most of the images have nuclear features of angular extent comparable to or smaller than $0.25''$. We have applied same correlation analysis to their data and results are presented in Table 5. The most striking result is the tight correlation between core radio luminosity and ratio of infrared to core radio luminosities. But the infrared luminosity of IRAS galaxies does not correlated with FIR–radio luminosities ratio, which means that this ratio is independent of FIR luminosity. The last results was previously obtained by Unger et al. [2] on the basis of the VLA observations of a large well–defined sample of IRAS galaxies. In Fig. 3 we plot $\log L_c$ against $\log L_{ir}/L_c$ for 40 ultraluminous IRAS galaxies [4]. It can be seen the close correlation between them implying the important result that the ratio of FIR to radio luminosities is dependent of the core radio luminosity. So the ratio of FIR to radio luminosities is independent of the FIR luminosity, but it is dependent of the core radio luminosity.

Table 5

CORRELATION COEFFICIENTS AND SLOPES FOR 40 ULTRALUMINOUS IRAS GALAXIES

	Corr.	Slope	Confidance (%)
[ir,c].D	0.7	0.77	99.99
[c,ir/c].D	-0.73	-0.93	99.99

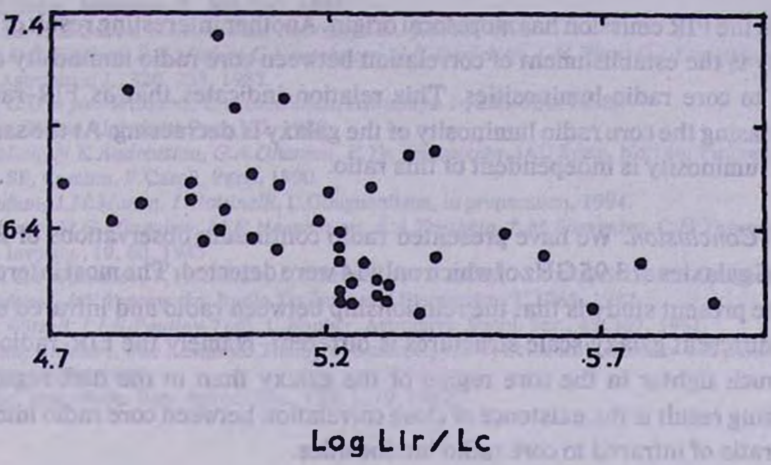

Fig.3. Relation between core radio luminosity (at 1.49 GHz [4]) and FIR to core radio ratio for 40 ultraluminous IRAS galaxies.

4. *Discussion.* It is generally accepted that strong infrared emission is one of the indicators of the star formation activity in the galaxies and the thermal processes are responsible for infrared emission. Radio continuum emission in IRAS galaxies is due to non–thermal synchrotron radiation rather than to thermal bremsstrahlung. What is the physical connection between the thermal (FIR) and non–thermal (radio) emission? Commonly used explanation of the observed radio–FIR correlation is in terms of recent massive star formation, which would provide both thermal (dust radiation) and non–thermal (via supernova explosion) (see e.g., [4]). Obscured by starburst-related dust an AGN could be an alternative energy source in the luminous IRAS galaxies [9].

Many authors have extensively discussed the physical basis of the radio-FIR correlation of the galaxies (see, e.g., [2] and references therein). Regardless of the mechanisms which produce correlation between galactic FIR and radio cintinuum emission, still the interpretations are require a more thorough discussion of this problem. The results of present study together with other studies are strongly supporting the supposition that in luminous IRAS galaxies the relationship between radio and infrared emissions in different galaxy scale structures is different. Namely the radio-FIR correlation is much tighter in the core region of the galaxy than in the disk region. On the other hand, according to Lonsdale et al. [9] in the milliarcsecond-scale structure of IRAS galaxies there is an absence of radio-FIR correlation. It means that in luminous IRAS galaxies the radio emission is spread out almost everywhere, while the FIR emission has more local origin. Another interesting result of the present study is the establishment of correlation between core radio luminosity and ratio of FIR to core radio luminosities. This relation indicates that as FIR-radio ratio is increasing the core radio luminosity of the galaxy is decraesing. At the same time the FIR luminosity is independent of this ratio.

5. *Conclusion.* We have presented radio continuum observations of 25 luminous IRAS galaxies at 3.95 GHz of which only 14 were detected. The most interesting result of the present study is that the relationship between radio and infrared emissions in the different galaxy scale structures is different. Namely the FIR-radio correlation is much tighter in the core region of the galaxy than in the disk region. Another striking result is the existence of close correlation between core radio luminosity and the ratio of infrared to core radio luminosities.

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НЕКОТОРЫЕ СВОЙСТВА ИК—РАДИО СВЯЗИ ЯРКИХ ИНФРАКРАСНЫХ ГАЛАКТИК

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Приведены результаты радионаблюдений 25 IRAS галактик на частоте 3.95ГГц. Обсуждаются некоторые свойства ИК—радио связи IRAS галактик. Установлено, что связь между радио и инфракрасным излучением галактик различна в различных участках галактики. Эта связь намного сильнее в ядерной области галактики, чем в области диска. В то время, как инфракрасная светимость не зависит от отношения инфракрасной и радио светимостей, радиосветимость ядра галактики уменьшается с увеличением этого отношения.

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