АСТРОФИЗИКА

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MULTIWAVELENGTH STUDY OF 230 IRAS FSC GALAXIES

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A sample of 230 galaxies has been compiled based on their IRAS FSC fluxes to study their multiwavelength properties and carry out comparative analyses with other similar samples. To understand the nature of these galaxies a comparison with a sample of bright ULIRGs having fluxes at 60 μm $f_\nu > 1$ Jy and 14 optically faint IRAS FSC galaxies is presented. This comparison shows that galaxies found by IRAS are not always strong infrared sources and that the objects from the sample of ULIRGs represent a sample of extreme galaxies, which are very powerful infrared sources. We have confirmed the consistency between Star Formation Rates (SFRs) calibrated based on luminosities of the PAH feature at 7.7 μm and radio 1.4 GHz flux densities. We have estimated the extinction for our 230 objects using SFRs calibrated from the PAH feature compared to ultraviolet flux, which shows that only 1% of the ultraviolet continuum typically escapes extinction by dust within a starburst.

Key words: *galaxies:multiwavelength study*

1. *Introduction*. After the launch of the Infrared Astronomical Satellite (IRAS) in 1983 [1], a new class of objects was found: Ultra Luminous Infrared Galaxies (ULIRG), which have quasar like luminosities emitted primarily in infrared (IR), i.e. $L(\mathrm{IR}) \geq 10^{12}\, L_\odot$ (erg s^{-1}) [2]. The spectral and morphological studies showed that the strong infrared emission is caused by the presence of active galactic nuclei (AGN) and/or circumnuclear starburst activities (starburst, SB) [3]. The study of infrared spectra revealed that the ultraviolet (UV), optical and near IR emission of AGN or young stars are absorbed by the dust and re-emitted in IR. Observations with the Infrared Space Observatory (ISO) [4] showed that the number of these objects increases rapidly with redshift [5]. Unfortunately the sensitivity of the ISO instruments were not enough for studying objects at high redshifts ($z > 2$). This became possible only after the launch of the Spitzer Space Telescope (SST) having instruments with 1000 times higher sensitivities [6].

The data from IRAS mainly are presented in two catalogues: IRAS Point Source (IRAS PSC) [7] and Faint Source Catalogs (IRAS FSC) [8]. Many objects from the IRAS FSC were observed with Spitzer but there are many IRAS FSC objects which still are not studied and their nature until now is not clear. We present a study of 230 IRAS FSC galaxies, which have optical

classifications. To understand their IR nature we have compared them with a sample of bright ULIRGs having fluxes at 60 μm $f_\nu > 1$ Jy [9-11] and 14 optically faint IRAS FSC sources [12,13], having spectra obtained with the Spitzer Infrared Spectrograph (IRS) [14].

2. *Sample selection and description.* To create our sample, we first cross-correlated the IRAS FSC catalog with the FIRST radio catalog [15]: as a result 2310 objects were selected having confident associations. As shown in [12], the IRAS detections having $\log f_\nu(25) < 1.75$ mJy may not be true detections. To eliminate false detections, objects having $\log f_\nu(25) < 1.75$ mJy were excluded from the sample. Finally, for further multiwavelength studies, only objects having detections from the near-infrared 2MASS catalog and optical classifications and redshifts based on Sloan Digital Sky Survey (SDSS) DR7 [16] spectra or NASA Extragalactic Database (NED) were included in the sample. The final sample contains 230 objects. SDSS spectra were available for 222 sources, and for 8 objects the data from NED were used. Our optical classification of objects is based on the diagnostic diagrams using $f_\lambda(\lambda5007)/f_\lambda(H\beta)$, $f_\lambda(\lambda6583)/f_\lambda(H\alpha)$ and $f_\lambda(\lambda6300)/f_\lambda(H\alpha)$ flux ratios [17,18]. For optical SDSS and NED spectra, 46 objects are classified as AGN, 173 objects are classified as SB galaxies, and 4 objects show both activities in their spectra so were classified as objects having composite spectra (Comp.) [19]. In case of 7 objects a strong absorption is present in spectra and it was difficult to have a correct classification. In case of such objects for classifications a label "em+abs" is used.

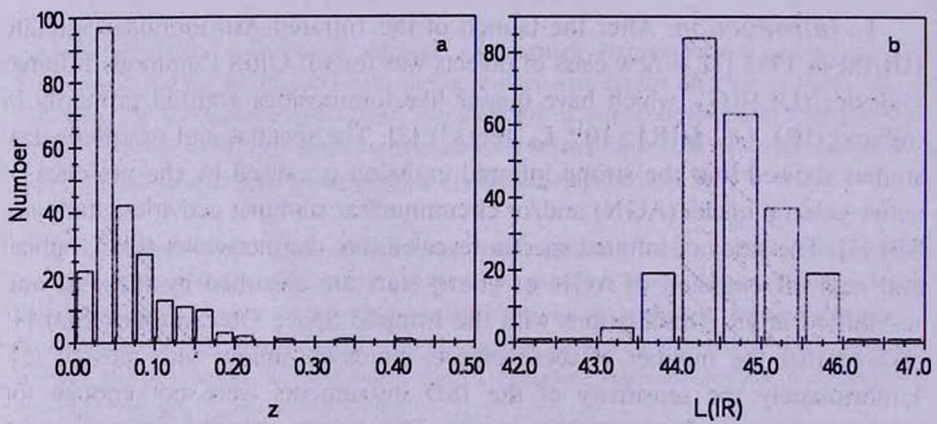

Fig.1. Distributions of 230 sources by redshifts (a) and IR luminosities (b). The luminosities are given in logarithms (erg s^{-1}); calculations are explained in the text.

Distributions of objects by redshifts and IR luminosities are presented in Fig.1a and b. They span the range of $42.46 < \log L(IR) < 46.55$ (erg s^{-1}) and $0.003 < z < 0.421$: the median redshift and median IR luminosity for our sample are 0.0466 and 44.59, respectively.

For IR luminosity calibration the following equation was used [20]

$L_{IR}(L_\odot) = 312700 \cdot D^2 \cdot 1.8 \cdot (13.48 \cdot f_\nu(12) + 5.16 f_\nu(25) + 2.58 \cdot f_\nu(60) + f_\nu(100))$, where the $f_\nu(12)$, $f_\nu(25)$, $f_\nu(60)$ and $f_\nu(100)$ are corresponding IRAS fluxes in units Jy at 12, 25, 60 and 100 μm, D is the luminosity distance in Mpc, calculated using electronic cosmological calculator [21].

Additional 14 FSC sources, but having fainter optical magnitudes from [12] are also used in our comparison discussed below. This sample in the plots is labeled as "optically faint sample". The median redshift and median IR luminosity for these objects are 0.2545 and $1.5 \cdot 10^{12}\ L_\odot$. All these objects are classified as AGN [13].

The major goal of our study is to compare IR samples having different flux limits.

3. *Comparison with other IR samples.* The IR properties of our 230 IRAS FSC galaxies are compared with a sample of 111 nearby bright ULIRGs defined by the IRAS 1Jy survey, which means that the IRAS fluxes at 60 μm are $f_\nu(60) > 1$ Jy (69 are AGN, 12 show composite spectrum, 30 are SB galaxies) [9-11]. The median redshift is 0.1383 and the median IR luminosity is $1.12 \cdot 10^{12}\ L_\odot$. This sample was chosen because the optical and IR spectra are very well studied.

The measure of how much a source is dominated by dust absorption and dust continuum luminosity can be calibrated by the ratio of mid-infrared to optical or near-infrared flux. For this as a near-infrared flux we have used the flux at 1.25 μm (J band) from 2MASS survey [22] and the IRAS flux at 25 μm

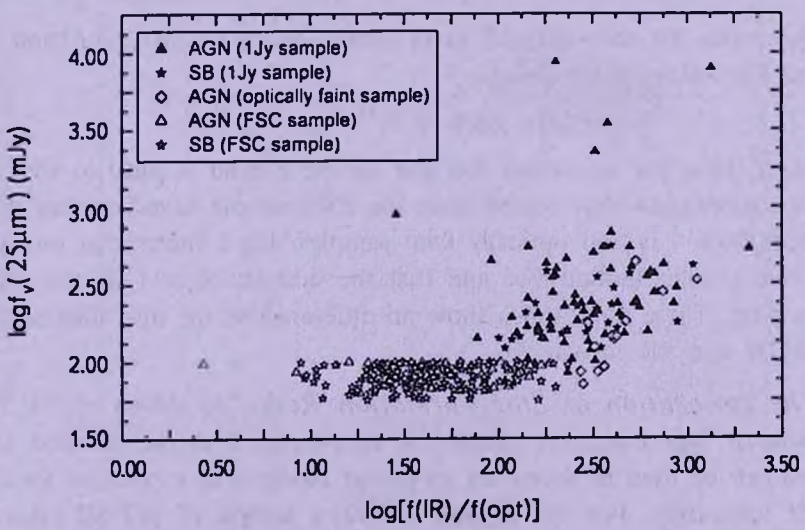

Fig.2. Comparison of the observed IR 25 μm flux densities with the infrared to optical flux ratios. The filled triangles and stars represent the AGN and SB galaxies from the 1 Jy sample. AGN from the optically faint sample are shown with diamonds. AGN and SB galaxies from the FSC sample are shown with open triangles and stars.

was used as an IR flux. The comparison of the optical and IR flux ratios with observed IR flux at 25 μm and IR luminosities are shown in Fig.2 and Fig.3. The filled triangles and stars represent the AGN and SB galaxies from the 1 Jy sample. AGN from the optically faint sample are shown with diamonds. The AGN and SB galaxies from the FSC sample are shown with open triangles and stars.

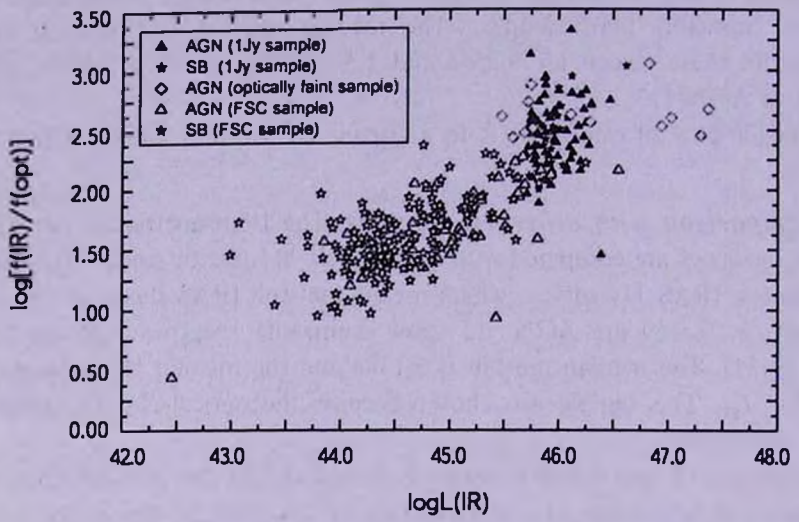

Fig.3. Comparison of the infrared to optical flux ratios with IR luminosities. Designations are the same as in Fig.2.

To determine the near-infrared fluxes corresponding to 2MASS *J* band we have used the following formula:

$$f_\nu(J) = f_\nu(0) \cdot 10^{(-m(J)/2.5)},$$

where the $f_\nu(0)$ is the zero point flux and for the *J* band is equal to 1594 Jy.

These figures show that objects from the FSC sample have less dust than the galaxies from 1 Jy and optically faint samples. Fig.3 shows that our 230 objects have smaller luminosities and that the dustiest objects are the most luminous ones. These figures also show no difference in the dust distribution among AGN and SB galaxies.

4. *The calibration of Star Formation Rates.* As shown in [23] the comparison of Star Formation Rates (SFR) measured in the infrared and ultraviolet can be used to derive an empirical estimate of extinction for the ultraviolet luminosity. For this purpose in [23] a sample of 287 SB galaxies with $z < 0.5$ was used having Spitzer IRS observations. As an infrared flux the mid-infrared 7.7 μm polycyclic aromatic hydrocarbon (PAH) luminosity [SFR(PAH)] was used. To determine the SFR measured in ultraviolet [SFR(UV)]

for the same objects, the far-ultraviolet observations with the Galaxy Evolution Explorer (GALEX) [24] peaked on 1528 Å were used. The ultraviolet fluxes were not corrected for dust extinction. The comparison of these two SFRs indicated that only 2% of the ultraviolet continuum typically escapes extinction by dust within a starburst [23].

To estimate the extinction for our FSC sample we at first need to calibrate the SFR(PAH), but our objects do not have Spitzer IRS observations. To estimate the 7.7 μm fluxes for our objects we have used the median ratios of the IRAS fluxes at 25 μm to fluxes at 7.7 μm estimated for each $41.0 < \log L(\mathrm{IR}) < 41.9$, $42.0 < \log L(\mathrm{IR}) < 42.9$, $43.0 < \log L(\mathrm{IR}) < 43.9$, $44.0 < \log L(\mathrm{IR}) < 44.9$ and $45.0 < \log L(\mathrm{IR}) < 45.9$ luminosity bins, using the objects from [25]. In [23] it is shown that the SFR(PAH) and SFRs calibrated from radio 1.4 GHz continuum flux densities [SFR(1.4 GHz)] of the radio FIRST survey, give the same values: that is, the median SFR(PAH)/SFR(1.4 GHZ) = 1. To check the accuracy of estimation using the median numbers of the $f_\nu(25\mu\mathrm{m})/f_\nu(7.7\mu\mathrm{m})$ fluxes we compared the SFR(PAH) with SFR(1.4 GHz). This comparison is shown in Fig.5, where for comparison the SB galaxies from [23] also are plotted (asterisks). In the case of FSC SB galaxies the median of SFR(PAH)/SFR(1.4 GHz) = 1.36 or log[SFR(PAH)/SFR(1.4 GHz)] = 0.13. This difference is small compared to the dispersion, which is equal to 0.2 and confirms the similar values of SFR(PAH) and SFR(1.4 GHz). Fig.4 shows that the scatter for the FSC sample is the same as for the Spitzer sample.

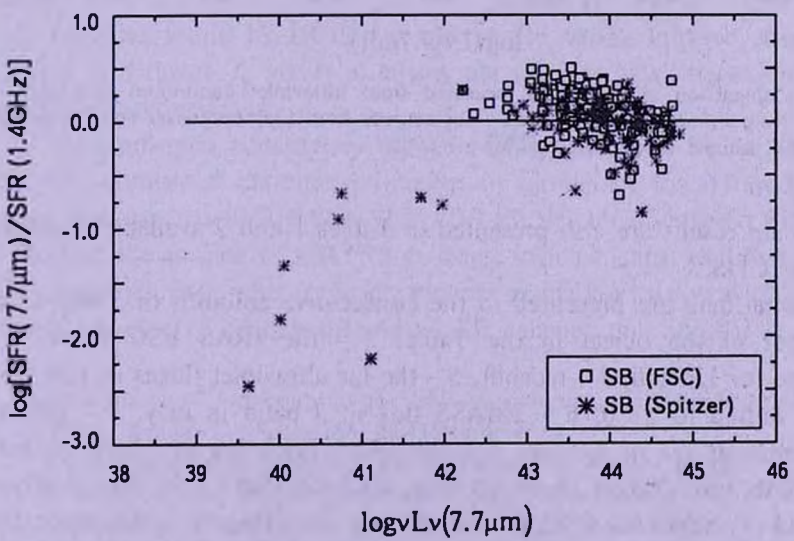

Fig.4. Comparison of SFR(1.4GHz) measured from radio 1.4 GHz continuum luminosity to SFR(PAH) from 7.7 μm PAH luminosity for objects from [23] (asterisks) and SB galaxies from the FSC sample (open squares). Horizontal line is the median value of 0.0, indicating no offset in SFR(PAH) compared to SFR(1.4GHz) for the SB galaxies from [23].

Fig.5 shows the comparison of the SFR(UV) measured from ultraviolet continuum luminosity to SFR(PAH) from infrared PAH luminosity. For comparison, we also presented the objects from [23] (asterisks): the FSC SB galaxies are the open squares. This figure shows that the FSC SB galaxies are mostly dustier than Spitzer discovered SB galaxies from [23]. The median SFR(PAH)/SFR(UV) for Spitzer discovered SB galaxies is ~50, which means that only 2% of the UV continuum escapes extinction by the dust. In case of the FSC SB galaxies this number is ~115, which means that less than 1% of the ultraviolet continuum typically escapes extinction by dust within a starburst.

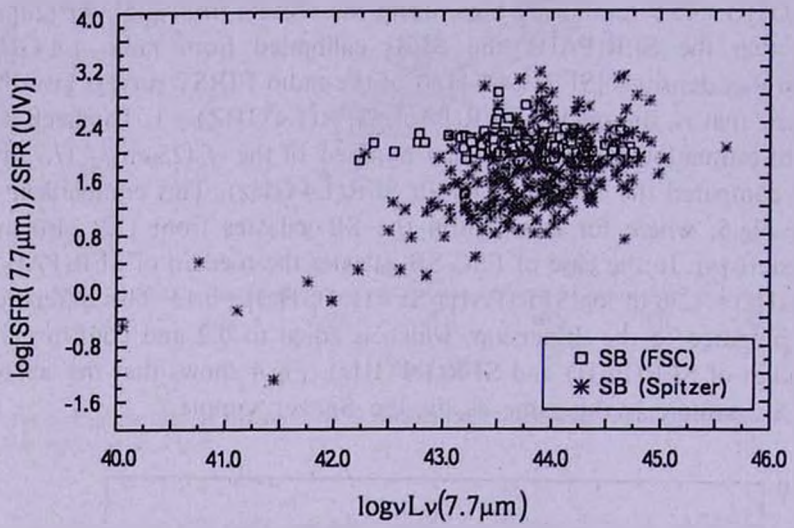

Fig.5. Comparison of SFR(UV) measured from ultraviolet continuum luminosity to SFR(PAH) from infrared PAH luminosity for sources from [23] (asterisks) and SB galaxies from the FSC sample (open squares).

The main results are also presented in Tables 1 and 2 available electronically from CDS.

Following data are presented in the consecutive columns of Table 1: 1 - the number of the object in the Table, 2 - the IRAS FSC name, 3 - coordinates for J2000.0, 4 - redshift, 5 - the far ultraviolet fluxes in μJy from GALEX, shifted to $z=0$, 6 - 2MASS flux in *J* band in mJy, 7 - infrared fluxes in mJy at 7.7 or 8.0 μm , 8 - the IRAS FSC flux at 12 μm in mJy, 9 - the IRAS FSC flux at 25 μm in mJy, 10 - the IRAS FSC flux at 60 μm in mJy, 11 - the IRAS FSC flux at 100 μm in mJy, 12 - the radio flux in mJy at 1.4 GHz from radio FIRST catalog, shifted to $z=0$, 13 - infrared to optical flux ratios, 14 - the activity type, "agn"-for active galactic nuclei, "sb"-for starbursts, "comp"-for objects with composite spectrum, "em+abs"-for

objects with weak emission features and strong absorption features in the spectrum.

In Table 2 are presented: 1 - the number of the object in the Table, 2 - the IRAS FSC name, 3 - Star Formation Rate calibrated from far ultraviolet fluxes in $M_\odot$ year^{-1}, 4 - Star Formation Rate calibrated from infrared fluxes at 7.7 μm in $M_\odot$ year^{-1}, 5 - Star Formation Rate calibrated from radio fluxes in $M_\odot$ year^{-1}, 6 - the logarithm of far ultraviolet luminosity in erg s^{-1}, 7 - the logarithm of infrared luminosity at 7.7 or 8.0 μm in erg s^{-1}, 8 - the logarithm of radio luminosity in erg s^{-1}, 9 - the logarithm of total infrared luminosity in erg s^{-1}, 10 - the activity type, "agn"-for active galactic nuclei, "sb"-for starbursts, "comp"-for objects with composite spectrum, "em+abs"-for objects with weak emission features and strong absorption features in the spectrum.

5. *Summary.* From the cross-correlation of the IRAS FSC catalog with the radio FIRST catalog, 230 IR galaxies were selected having optical classifications and redshifts from SDSS and NED. To understand the nature of these objects we have compared them with a sample of bright ULIRGs with fluxes $f_\nu > 1$ Jy at 60 μm and with 14 optically faint IRAS FSC galaxies. This comparison gives the following results:

1. Infrared-selected sources which are most luminous are also dustier. This conclusion is shown by the comparison of the optical and IR flux ratios with IR luminosities.

2. We found no difference in the dust distribution among AGN and SB galaxies.

3. Galaxies found by IRAS not always are strong infrared sources; the ULIRGs with fluxes $f_\nu > 1$ Jy at 60 μm are extreme galaxies, which are very powerful infrared sources.

4. We confirmed consistency between SFR(PAH) and SFR(1.4 GHz).

5. We confirmed extreme extinction in ultraviolet for infrared-selected sources. The median SFR(PAH)/SFR(UV) for Spitzer discovered SB galaxies is ~50, and 115 in case of FSC SB galaxies, which means, that less than 1% of the ultraviolet continuum typically escapes extinction by dust within an FSC starburst (in case of Spitzer discovered SB galaxies this number is ~2%).

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МНОГОВОЛНОВОЕ ИССЛЕДОВАНИЕ 230 IRAS FSC ГАЛАКТИК

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Для исследования многоволновых свойств и проведения сравнительного анализа с другими подобными выборками, на основании IRAS FSC-потоков составлена выборка из 230 галактик. Для понимания природы этих галактик представлено сравнение с выборкой ярких ULIRG, имеющих потоки на 60 μm $f_\nu > 1$ Jy и с 14 оптически слабыми IRAS FSC-галактиками. Это сравнение показало, что галактики, найденные IRAS, не всегда являются сильными инфракрасными источниками и что объекты из выборки ULIRG представляют выборку экстремальных галактик, являющихся очень мощными инфракрасными источниками. Подтверждено соответствие между темпами звездообразования (SFR), откалиброванными на основании светимостей спектральных признаков PAH на 7.7 μm , с одной стороны, и радио 1.4 GHz потоков, с другой. Используя SFR, откалиброванные на основании PAH признаков и ультрафиолетовых потоков, оценена экстинкция для наших 230 объектов, показывающая, что в галактиках со вспышкой звездообразования почти 1% ультрафиолетового континуума обычно избегает экстинкцию со стороны пыли.

Ключевые слова: *галактики:многоволновое исследование*

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