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Recent results of studies of IR galaxies

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Abstract

Infrared galaxies are among the most important extragalactic objects for studying the formation and evolution of galaxies, star formation and SFR in galaxies, morphology, interacting and merging galaxies, variety of types of active galaxies (many Seyferts, LINERs, Starbursts and Composites), the luminosity function of galaxies (at higher redshifts), radiation mechanisms / energy sources, cosmological role of active galaxies, interrelationship between Starburst, AGN and interaction/merging phenomena, etc. We have carried out several studies of IR galaxies, including their revelation by optical identifications of IR sources and creation of Byurakan-IR Galaxies (BIG) sample of 1179 galaxies, redshift survey, study of pairs and multiples among the BIG objects, compilation of a IRAS PSC/FSC Combined Catalogue of 345,163 IR sources and distinguishing extragalactic objects among them, study of IR luminosities and IR/opt flux ratios, search and discovery of 114 ULIRGs and HLIRGs in the mentioned sample, their activity types from SDSS, morphology and X-ray, UV, optical and radio properties of IR galaxies, study of SEDs of IR galaxies by 17 photometric measurements from 1.25μ to 160μ range using 2MASS, WISE, IRAS and AKARI IRC and FIS catalogues.

Keywords: *Infrared astronomy, Infrared galaxies, AGN, Starburst galaxies, IRAS, ULIRGs, pairs and multiples*

1. Byurakan-IRAS galaxies (BIG), optical and spectral identifications

About half of all IRAS sources are still not identified and there is a need for optical identifications. Since 1995, a project of optical identifications has been carried out in the Byurakan Astrophysical Observatory (Mickaelian, 1995), in order to detect new galaxies with bursts of star formation in their central regions (SB, or Starburst galaxies) (Weedman et al., 1981), galaxies with active nuclei (AGN, active galactic nuclei) (Ambartsumian, 1958), interacting pairs, and galaxies with high IR luminosity (ULIRG, Ultra-Luminous IR Galaxies), which resulted in revealing 1179 galaxies and 299 stars, named Byurakan-IRAS Galaxies (BIG) (Mickaelian & Sargsyan, 2004) and Byurakan-IRAS Stars (BIS) (Mickaelian & Gigoyan, 2006), respectively. Identifications using low-dispersion spectra of the First Byurakan Survey (FBS or Markarian survey) (Markarian et al., 1989) and its digitized version, DFBS (Massaro et al., 2008, Mickaelian et al., 2007) guaranteed better selection of optical counterparts compared to other identification works.

BIG objects have been studied spectroscopically using BAO 2.6 m (Mickaelian et al., 2003, Sargsyan & Mickaelian, 2006), Special Astrophysical Observatory (SAO, Russia) 6 m (Balayan et al., 2001, Mickaelian et al., 1998), Observatoire de Haute-Provence (OHP, France) 1.93 m (Mickaelian, 2004) telescopes and the Sloan Digital Sky Survey (Abolfathi et al., 2018, Mikayelyan et al., 2018). Altogether 257 BIG objects have been studied and classified. The spectroscopic studies of BIG objects facilitate the concurrent solution of several problems. These problems range from confirming the extragalactic nature of objects and determining their redshifts to detailed analyses of the objects' structure, which proved to be of greatest interest, such as galaxies with enhanced IR luminosities and/or with nuclear or starburst activity.

A total of 257 BIG objects were observed; of these 149 were identified as galaxies with star formation regions, 42 as AGN, 28 as galaxies with a composite spectrum (referred below to Composite or Comp), 21 as "Em" galaxies (this type refers to a spectrum with signs of emission without the possibility of a more precise determination of the activity class of the galaxy), 13 as galaxies represented as Norm (galaxies for which the rate of star formation does not exceed the normal), 3 as absorption galaxy and one object without

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the possibility of classification (unknown). In Table 1 the distribution of all objects by activity types is given.

Table 1: The distribution of 257 BIG objects by activity types

Activity type	Number of objects	%	Activity type	Number of objects	%
HII	149	58.0	AGN	13	5.1
Composite	22	8.6	Em	21	8.2
HII / LINER	4	1.5	Norm	13	5.1
HII / Sy	2	0.8	Abs	3	1.1
LINER	12	4.6	Unknown	1	0.4
Sy	17	6.6	**All**	**257**	**100.0**

2. IRAS PSC/FSC Combined Catalogue

To increase the efficiency of using IRAS PSC and FSC, which contain a lot of common sources, one needs a joint catalogue of all IRAS point sources with improved data based on both catalogues. However, cross-correlation of the catalogues is not so easy, as the association of many sources is relative, and not always it is obvious, whose source from one catalogue corresponds to the other one in the second catalogue. This problem exists in case of using standard cross-correlation tools. Therefore, Abrahamyan et al. (Abrahamyan et al., 2015) have created a tool for cross-matching astronomical catalogues and they have applied it to IRAS PSC and FSC. Using this tool they have carried out identifications with a search radius corresponding to 3-σ of errors for each source individually rather than a standard radius for all sources. As a result, authors obtained 73,770 associations. In addition, cross-correlations with AKARI-IRC, AKARI-FIS and WISE catalogues have been done. Authors created a catalogue of 345,163 IRAS sources with high positional accuracy and with 17 photometric measurements from 1.25 to 160 μ range, providing a detailed catalogue for IRAS point sources.

Catalogues	IRAS-PSC	IRAS-FSC	AKARI-IRC	AKARI-FIS	WISE
Year	1986	1989	2010	2010	2012
Wavebands (μm) Wavelengths (μm)	12, 25, 60, 100 8–120	12, 25, 60, 100 8–120	9, 18 6.7–25.6	65, 90, 140, 160 50–180	3.4, 4.6, 11.6, 22.6, 1.25, 1.65, 2.17 2.6–28
Resolution (″) Sensitivity (Jy)	40 0.25, 0.25, 0.4, 1.0	20 0.1–0.5	0.3 0.05, 0.12	0.8 ~0.55	0.5 0.00008–0.006
Sky area Coverage (%)	All-sky 96	$\|b\| > 10°$ 83	All-sky 94	All-sky 98	All-sky 99
Source number	245,889	173,044	870,973	427,071	563,921,584

Figure 1. Main characteristics of IRAS-PSC, IRAS-FSC, AKARI-IRC, AKARI-FIS, and WISE catalogues

3. Discovery of new bright ULIRGs and their classification by activity types

From the IRAS PSC/FSC Combined Catalogue (Abrahamyan et al., 2015), we have taken sources that were checked by WISE (Cutri et al., 2013) considering that the accuracy of the WISE coordinates is significantly higher (< 1") than the coordinates of the two other AKARI catalogues (Ishihara et al., 2010, Yamamura et al., 2010). The selected sample was cross-correlated with SDSS DR14 (Abolfathi et al., 2018). Considering that the accuracy of WISE coordinates is ~1", and the accuracy of SDSS coordinates is ~0.1", the cumulative accuracy will be:

$$\sigma = \sqrt{\sigma_{WISE}^2 + \sigma_{SDSS}^2}$$
$$\sigma = \sqrt{1^2 + 0.1^2} \approx 1.005$$

Corresponding 3σ was taken as the search radius. Only the SDSS objects that had spectroscopical data and were the only optical counterparts in the radius of 3σ were taken from the results of cross-correlation. This way 6,346 objects were found; galaxies brighter than 17.77^m.

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For the calculation of the IR luminosities of the sources the flux densities for each source in 12, 25, 60 and 120 μ bands that are given in IRAS PSC/FSC Combined Catalogue are necessary. Therefore, from the 6,346 objects only those were chosen that had the data on the flux densities in all four bands. Only 6,270 sources had such data. The IR and FIR luminosities were calculated by the following formulae (Duc et al., 1997):

$$L_{IR} = 5.6 \times 10^5 R^2 (13.56 f_{12} + 5.26 f_{25} + 2.54 f_{60} + f_{100}) L_\odot$$
$$L_{FIR} = 5.6 \times 10^5 R^2 (2.58 f_{60} + f_{100}) L_\odot$$

where the R is the distance of the object in Mpc and $f_{12}, f_{25}, f_{60}, f_{100}$ are the flux densities given in IRAS PSC/FSC Combined Catalogue in 12, 25, 60, 100 μ bands, respectively. Out of 6,270 objects only those were selected having IR luminosities greater than $10^{12} L_\odot$ (the lower limit of ULIRG's luminosity) and having stellar magnitudes in r band greater than 17.77^m (the spectroscopic limit for SDSS galaxies).

As a result, 114 extragalactic objects were selected that have high IR luminosity and correspond to ULIRG/HLIRG classes (Mikayelyan et al., 2018).

The classification of the sample by activity types (Mikayelyan et al., 2019a) was done "by eye" - by studying the SDSS spectra, since most spectra of 114 objects have different lines lost in noise, which makes it impossible to construct diagnostic diagrams. Also, by eye, one can take into account the width of the emission lines and notice the wide components that play an important role for the Seyfert subclasses 1.0 – 1.9. Moreover, without removing the components of the wide lines, it is impossible to calculate the ratios of the narrow lines, and the measured data in the table refer to the total intensities of the summed lines. We distinguish different types of active galaxies with narrow lines according to the following criteria:

- Seyferts from LINERs: $[OIII]/H_\beta > 3$
- AGN from HII: $[NII]/H_\alpha > 0.6, [OI]/H_\alpha > 0.1$

As a result of classifying the sample by activity types, the following types of galaxies were discovered.

- BLL/QSO – 3 (BL Lac, QSO, NLQSO)
- BLS (Seyferts with broad lines) – 28 (S1.0, NLS1.0, S1.2, NLS1.2, S1.5, NLS1.5)
- NLS (Seyferts with narrow lines) – 6 (S1.8, S2.0)
- NLAGN (AGN with narrow lines – Seyfert or Liner) – 9 (NLAGN, S1.9/LINER)
- LINER – 14
- Composite (NLAGN/HII) – 11 (S1.9/HII, LINER/HII)
- HII – 36
- Em (with emission lines) – 3
- Abs (with absorption lines) – 3

4. The Extragalactic Sample of Combined IRAS PSC/FSC Catalogue

To build the IRAS full extragalactic sample, we have applied several approaches (Mikayelyan et al., 2023). First of all we have cross-correlated the IRAS PSC/FSC Combined Catalogue with optical catalogues of already known galaxies, quasars and blazars. The search radius was taken differently for each catalogue, depending on its own positional errors. After cross-correlation only the single matches in given search radius were taken as genuine ones. Below in Table 2 are the catalogues with their object quantities, search radii and the numbers of single matches after cross-correlations:

The next step was cross-correlating the IRAS PSC/FSC Combined catalogue with catalogues giving data, which can be used to determine galaxy candidates, for example data about point like and extended objects, ellipticity of objects, etc. Below are the catalogues with their object quantities, data which was used to determine galaxy candidates, search radii and the numbers of single matches after cross-correlations:

- Sloan Digital Sky Surveys (SDSS), Release 16 (DR16, Ahumada et al., 2020) containing 1,231,051,050 objects. SDSS marks all extended objects as galaxies, so we take them as galaxy candidates. The search radius was taken 3 arcsecs; 46,396 single matches were found.
- HYPERLEDA. I. Catalog of galaxies (Paturel et al., 2003) containing 983,261 objects. This catalogue is the new Principal Galaxies Catalogue (PGC2003), which contains candidates of galaxies. The search radius was taken 1 arcmins; 33,309 single matches were found.
- The APM-North Catalogue (McMahon et al., 2000) containing 166,466,987 objects. APM gives the data about ellipticity of objects (1-a/b, where "a" is the minor axis diameter and "b" is the major axis diameter). When the ellipticity is bigger than 0.5, we consider them as galaxy candidates. The search radius was taken 3 arcsecs; 37,232 single matches were found.
- Gaia DR3 Part 2. Extra-galactic (Gaia Collaboration, 2022a) containing 11,491,504 objects. In this catalogue all extended objects have been separated from Gaia DR3. The search radius was taken 3 arcsecs; 21,599 single matches were found.

Table 2. Optical catalogues of already known galaxies, quasars, blazars and cross-correlation results with IRAS PSC/FSC Combined Catalogue.

Catalogues and references	**Number of objects**	**Search radius**	**Associations with IRAS PSC/FSC**
Catalogued Galaxies and Quasars observed in the IRAS Survey, Version 2 (Fullmer & Lonsdale, 1989)	11,444	10 arcsecs	5,377
NGC 2000.0, The Complete New General Catalogue and Index Catalogue of Nebulae and Star Clusters by J.L.E. Dreyer (Sinnott, 1988)	13,226	2 arcmins	4,006
Third Reference Catalogue of Bright Galaxies (RC3, de Vaucouleurs et al., 1995)	23,011	2 arcmins	7,956
A catalogue of quasars and active nuclei 13th edition (Véron-Cetty & Véron, 2010)	168,940	10 arcsecs	1,271
The Roma BZCAT - 5th edition (Massaro et al., 2015)	3,561	10 arcsecs	40
Astrometric Catalogue 5, LQAC-5 (Souchay et al., 2019)	592,809	3 arcsecs	1,364
SDSS quasar catalog, sixteenth data release (DR16Q, Lyke et al., 2020)	750,414	3 arcsecs	111
QSOs selection from SDSS and WISE (Richards et al., 2015)	1,604,577	3 arcsecs	180

In addition, we have cross-correlated our catalogue with radio catalogues, considering that sources having strong radio emission are most likely extragalactic. Below are cross-correlation results with radio catalogues:

- 1.4GHz NRAO VLA Sky Survey (NVSS, Condon et al., 1998) containing 1,773,484 sources. The search radius was taken 75 arcsecs; 42,072 single matches were found.
- The FIRST Survey Catalog (Helfand et al., 2015) containing 946,432 sources. The search radius was taken 15 arcsecs; 6,640 single matches were found.

The last step was cross-correlation of IRAS PSC/FSC Combined Catalogue with GAIA DR3, which gives data about proper motions of objects, so we can consider the objects having real proper motions as stars and exclude them from the sample:

- Gaia DR3 Part 1. Main source (Gaia Collaboration, 2022b) containing 1,811,709,771 objects. The search radius was taken 3 arcsecs; 217,385 single matches were found.

If all data show the same type of object, then we give it as a genuine one, and if there is an ambiguity, we give the most probable type with a flag.

In Figure 2 we show our preliminary results after cross-correlations. The first column shows 183,168 star candidates for which Gaia DR3 gives proper motions with the ratio of proper motion and its error bigger than 3. In the second column there are 80,998 unknown sources that have no matches after all cross correlations (most probably, these sources may appear either faint galaxies or false sources, ex. cirruses). In the third column we have 68,940 galaxy candidates and the last column shows 12,057 confirmed or genuine galaxies or QSOs.

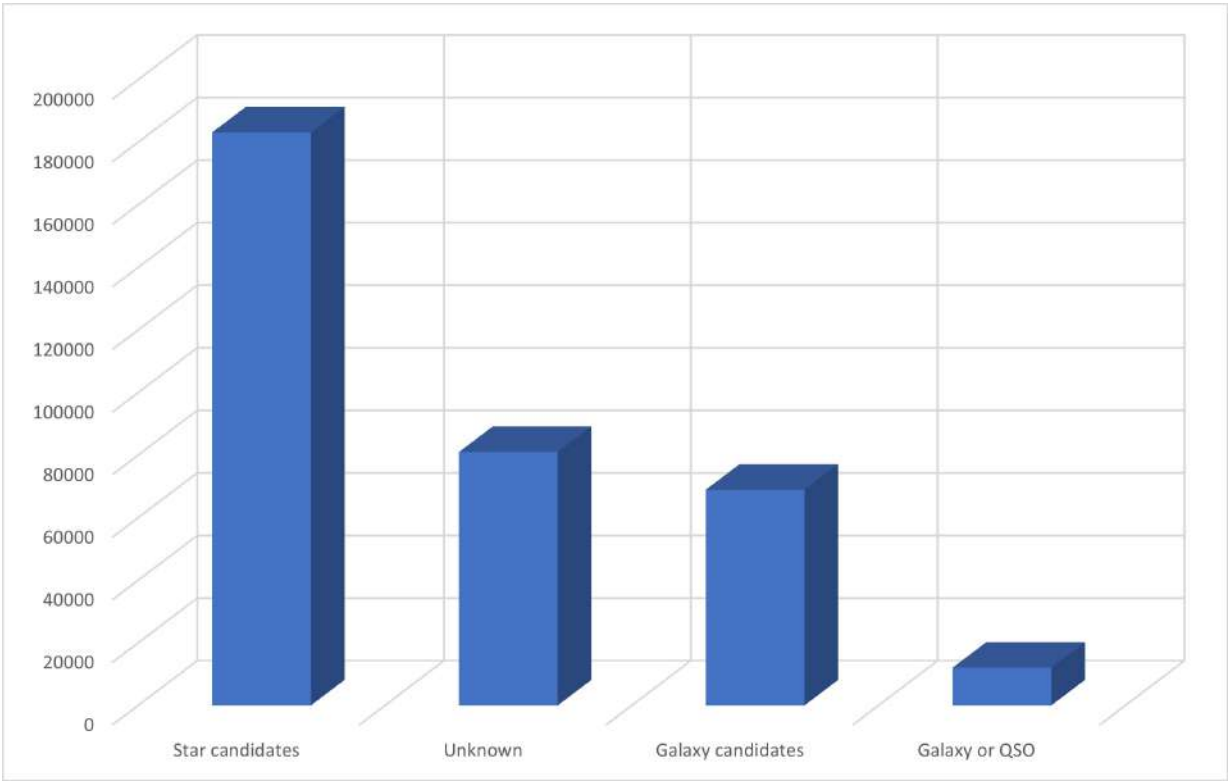

Figure 2. The distribution of the number of objects by type

Our next step is to finalize the results of the cross-correlations and decide with the nature of objects: star, galaxy, quasar, unknown (which may also include nebulae, ex. planetary nebulae). We will publish the Extragalactic Sample of IRAS.

5. BIG Pairs and multiples

Besides isolated galaxies, BIG objects include some binary and multiple systems. This makes it possible to establish their physical coupling, to determine the true IR source more precisely (as an individual galaxy or the system as a whole), and to study the interrelation between star formation activity, the interactions of galaxies, and the activity of their nuclei.

Altogether 361 groups with 907 counterparts of pairs and multiples were found, from which only 31 groups with 77 counterparts have 2 or more counterparts observed spectroscopically. In Figure 3 are examples of BIG pairs and multiples from SDSS.

The work is still in process, the preliminary results are: the IR coordinates have been significantly refined using the IRAS PSC/FSC combined catalog (with WISE coordinates); optical coordinates have been corrected using DSS2; the distance from the IR source was calculated for each galaxy; for each group, a member responsible for the IR source has been determined, in some cases the IR source is the pair or the entire group; the IR and far-IR luminosities have been calculated.

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Figure 3. Examples of BIG pairs and multiples from SDSS

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