Building the Largest Sample of IR Galaxies. Preliminary Results

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Abstract

To build the IRAS full extragalactic sample (including both point-like sources - QSOs, and extended ones - galaxies), we have applied several approaches. Cross-correlation of IRAS PSC/FSC Combined Catalogue with optical catalogues of already known galaxies, quasars and blazars such as The NGC 2000.0 Catalog, Third Reference Catalogue of Bright Galaxies, The Roma BZCAT, Astrometric Catalogue 5 and many others. Cross-correlation of IRAS PSC/FSC Combined Catalogue with optical catalogues giving data, which can be used to determine galaxy candidates, for example Sloan Digital Sky Survey (SDSS, contains data about point like and extended objects), The APM North Catalogue (contains data about ellipticity of objects), etc. Cross-correlation of IRAS PSC/FSC Combined Catalogue with GAIA DR3, which gives data about proper motions of objects (we can consider the objects having real proper motions as stars and exclude them from the sample). 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. All this will lead to construction of a confident sample of optical counterparts of extragalactic objects of IRAS PSC/FSC: galaxies and quasars. We also will study IR/opt flux ratios, which may serve as one more characteristic to reveal galaxies with very high SFR. We will carry out calculation of IR luminosities for all IR galaxies. We expect revelation of many new ULIRGs and HLIRGs and building their largest samples.

Keywords: *IR - IR Galaxies - ULIRG - Catalogues - Galaxies - AGN - Starburst*

1. Introduction

Astronomy is now in its multiwavelength era, however most interesting results are being obtained in the infrared (IR), especially Far-IR (FIR), and especially considering the recent ground-based surveys and space missions. Astronomical IR sources contain a number of interesting cosmic objects: quasars and other Active Galactic Nuclei (AGN), late-type stars, planetary nebulae (PN), variables, etc. Infrared galaxies (galaxies of this type were discovered in 1983 by the InfraRed Astronomical Satellite, IRAS) appear to be single, gas rich spirals whose infrared luminosity is created largely by the formation of stars within them. However, some galaxies' luminosity come from an AGN. These AGNs reside in compact regions at the centers of galaxies and have higher than normal luminosity. In addition, many IR galaxies appeared to be interacting/merging systems.

The Activity of Galaxies as predicted by Ambartsumian (1958, 1961) and further developed by many other authors, may be nuclear and starburst. The first one relates to the nuclei of galaxies and these objects are called AGN. It is revealed by the non-thermal emission, which is present from γ-ray to radio. The accretion on Super-Massive Black Hole (SMBH) at the central part of the galaxy is considered as the original source of energy. Starburst activity is related to high Star Formation Rates (SFR) at short periods of evolution. Typical SFR is a few $M_\odot$ yr^{-1}, but may reach up to 103 $M_\odot$ yr^{-1}. Thus, high-luminosity galaxies may be fed also by fast burst of star formation (Starburst, SB). It is established that interrelationship between these two types is important for formation and evolution of galaxies, star-formation and metal enrichment history of the Universe. Still, there are significant controversies around the question whether there is a physical relation between SB and AGN and which of these two causes the other one.

There are some especially powerful IR galaxies, called Luminous InfraRed Galaxies (LIRG); their luminosity may come from starburst, and also an AGN. These galaxies contain more energy in the IR portion of the spectrum. The energy given off by LIRGs is comparable to that of a quasar, which before were

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doi: https://doi.org/10.52526/25792776-23.70.2-321

known as the most energetic objects in the Universe. LIRGs are galaxies with luminosities above 10^{11} $L_\odot$ (100 billion times that of our Sun; Sanders & Mirabel 1996). LIRGs are more abundant than starburst galaxies, Seyfert galaxies and quasars at comparable luminosity. IR galaxies emit more energy in the IR than at all other wavelengths combined. Galaxies with luminosities above 10^{12} $L_\odot$, are Ultra-Luminous Infrared Galaxies (ULIRG's). Many of the LIRG's and ULIRG's are showing interactions and disruptions. In many of these types of galaxies the SFR is about 100 per year as compared to Our Galaxy which has SFR only 1 star per year; this creates the high level of luminosity. More luminous than ULIRGs are the HLIRG, Hyper-Luminous Infrared Galaxies ($>10^{13}$ $L_\odot$). The most luminous class is the ELIRG, Extremely Luminous Infrared Galaxies.

Optical identifications of the IRAS sources from both IRAS Point Source Catalogue (PSC, IRAS 1986) and Faint Source Catalogue (FSC, Moshir et al. 1990) are rather complicated and uncertain due to the positional errors and many doubtful detections. IRAS PSC and IRAS FSC provide photometric information of fluxes at wavelength bands centered at 12, 25, 60 and 100 μm. IRAS PSC contains 245,889 sources from the whole sky and IRAS FSC contains 173,044 sources at galactic latitudes $|b| > 10°$. Abrahamyan et al. (2015) cross-matched these two catalogues and created IRAS PSC/FSC Combined Catalogue. In frame of the Armenian Virtual Observatory (ArVO), they created a software through which they made cross-correlations (Knyazyan et al., 2011). IRAS PSC/FSC Combined Catalogue contains 345,163 sources. To obtain accurate positions and fluxes in other IR bands the authors carried out cross-correlations with recent catalogues: AKARI IRC (Ishihara et al., 2010), AKARI FIS (Yamamura et al., 2010) and AllWISE (Cutri et al., 2013) also having J, H, and K data from 2MASS (Cutri et al., 2003). We give in Table 1 the main characteristics of the catalogues IRAS PSC, IRAS FSC, AKARI IRC, AKARI FIS and AllWISE.

Table 1. Main characteristics of IRAS PSC, IRAS FSC, AKARI IRC, AKARI FIS and AllWISE catalogues.

Catalogues	**IRAS-PSC**	**IRAS-FSC**	**AKARI-IRC**	**AKARI-FIS**	**AllWISE**
Year	1986	1989	2010	2010	2013
Wavebands (μm)	12, 25, 60, 100	12, 25, 60, 100	9, 18	65, 90, 140, 160	3.4, 4.6, 11.6, 22.6, 1.25, 1.65, 2.17
Wavelengths coverage (μm)	8-120	8-120	6.7-25.6	50-180	1.2-2.2, 2.6-28
Resolution (")	40	20	0.3	0.8	0.5
Sensitivity (Jy)	0.25, 0.25, 0.4, 1.0	0.1-0.5	0.05, 0.12	~0.55	0.00008-0.006
Sky area	All-sky	$\|b\| > 10°$	All-sky	All-sky	All-sky
Sky coverage (%)	96	83	94	98	99
Number of sources	245,889	173,044	870,973	427,071	747,634,026
Reference	IRAS (1986)	Moshir et al. (1990)	Ishihara et al. (2010)	Yamamura et al. (2010)	Cutri et al. (2013)

There have been a number of studies on identifications of IRAS galaxies since the release of IRAS catalogs: IRAS Revised Bright Galaxy Sample (Sanders et al., 2003); Far-InfraRed (FIR) sources (Bertin et al., 1997); IRAS galaxies towards the Boötes void (Strauss & Huchra, 1988); IRAS point sources in the area of Fornax, Hydra I and Coma clusters (Wang et al., 1991); IRAS 1.2 μm survey (Fisher et al., 1995); IRAS galaxies in Virgo cluster area (Yuan et al., 1996); and some others.

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 1178 galaxies and 399 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) (Mickaelian et al., 2018). Altogether 255 BIG objects have been studied and classified. The spectroscopic studies of BIG objects facilitate the concurrent solution of

doi: https://doi.org/10.52526/25792776-23.70.2-321

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.

Until now IRAS remains the only all-sky survey giving data in Far-IR (namely 60 and 100 mum). There also is AKARI FIS catalog, however there are doubts in the correctness of its flux calibration. In IRAS PSC/FSC Combined Catalogue, out of 345,163 sources, there are 145,902 (42.3 %) candidate galaxies to be checked by cross-correlations with optical catalogues. In this project we investigate this sample to create a large list of genuine IRAS-selected galaxies. Having the largest sample, we can achieve the best understanding of many properties of IR galaxies.

2. Research methods

To build the IRAS full extragalactic sample, we have applied several approaches. 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 refrences and object quantities, search radii and the numbers of single matches after cross-correlations:

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

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

doi: https://doi.org/10.52526/25792776-23.70.2-321

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, 2022) 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.

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 the cross-correlation of IRAS PSC/FSC Combined Catalogue with GAIA DR3, which gives data about proper motions of objects, so that 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, 2022) 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. The order of the catalogs by their priority is the following: 1. Catalogued Galaxies and Quasars observed in the IRAS Survey, Version 2; NGC 2000.0; RC3; A catalogue of quasars and active nuclei 13th edition; The Roma BZCAT - 5th edition; Astrometric Catalogue 5, LQAC-5; SDSS quasar catalog, sixteenth data release; QSOs selection from SDSS and WISE; 2. SDSS DR16; 3. Gaia DR3 Part 2. Extra-galactic; 4. The APM-North Catalogue; 5. HYPERLEDA. I. Catalog of galaxies; 6. NVSS; FIRST.

3. Preliminary results

In Figure 1 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.

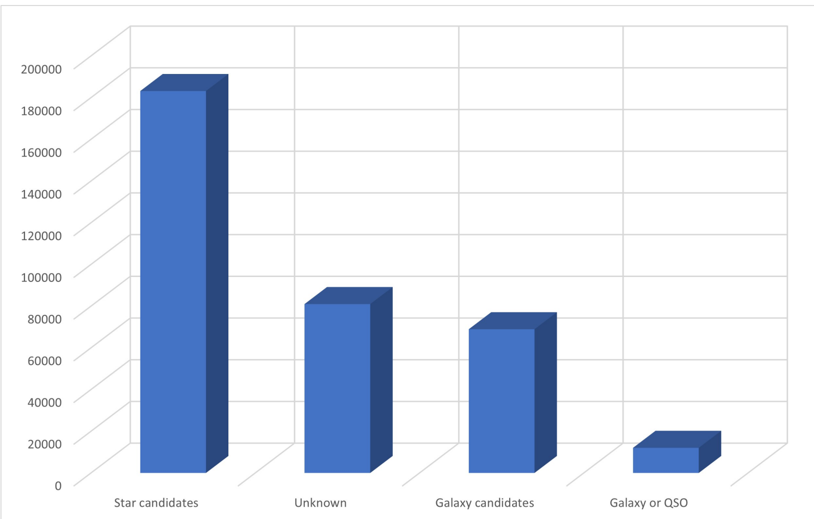

Figure 1. The distribution of the number of objects by type

doi: https://doi.org/10.52526/25792776-23.70.2-321

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.

4. Future studies

High Luminosity Infrared Galaxies. Using the IRAS PSC/FSC Combined Catalogue containing 345,162 sources with improved astrometric data and SDSS spectroscopy for redshifts and luminosities, we have found 114 very high luminosity IRAS galaxies; HLIRGs and ULIRGs (Mikayelyan et al., 2018). Having the confirmed extragalactic sample, we will carry out calculation of IR luminosities for all IR galaxies. We expect revelation of many new ULIRGs and HLIRGs and building their largest samples. Figure 2 shows an analysis of their IR luminosities *vs.* redshifts. A few objects show obvious deviation from the standard sequence for most of the objects and have much higher luminosities. We will search for such objects to see if this is a rule or exception; in both cases we will find either a sample of such objects or extremely unique ones.

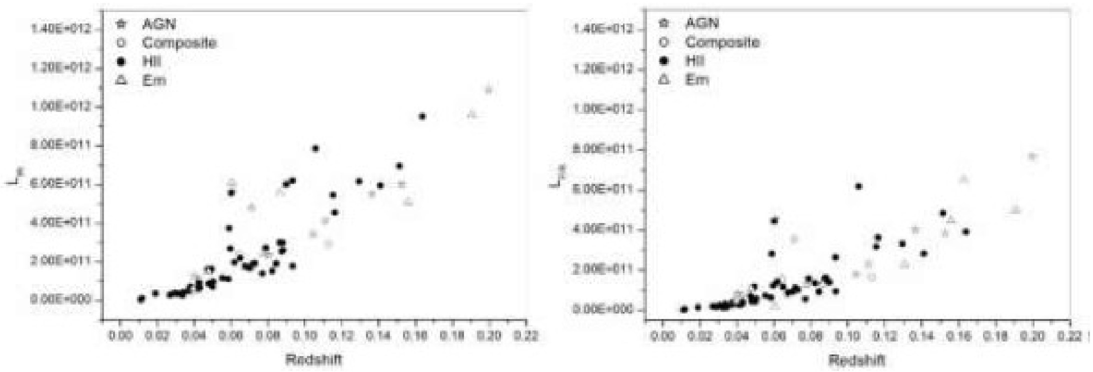

Figure 2. IR luminosities against redshifts for 70 IR galaxies showing a few of them outlying the standard sequence for most of galaxies. These are probably ULIRGs.

Another issue is the study of the highest IR luminosity of a single galaxy, as most of high luminosity IR galaxies show interaction and merging features. The preliminary studies show that this limit is near 10^{12} Solar luminosities.

Study of IR/optical flux ratios. The IR luminosity alone is not the only relevant parameter to reveal interesting IR galaxies. The IR/optical flux ratio may serve as an additional characteristic to reveal galaxies with very high SFR. We aim at the revelation of very high IR/opt flux ratio objects among the IRAS PSC/FSC Combined Catalogue involving objects with detected Far-IR (IRAS 60 and 100 μm). Among the goals of this study may be the revelation of objects with very high IR/opt flux ratio, so called IR-excess galaxies and the distribution of IR/opt flux ratios to reveal the possible limit between the normal and IR galaxies, as well as the detailed study of IR/opt for different types of AGN and Starburst galaxies.

Morphological study of IR galaxies. SDSS images are reliable for morphological study of the images of IR galaxies; to carry out morphological classification and to reveal interacting pairs/multiples and mergers. IR galaxies at higher luminosities show strong features of interactions and merging. For our sample it will be rather important to have statistics between single galaxies and pairs/multiples, as well as mergers. We give in Figure 3 examples of SDSS images of interacting/merging IR galaxies.

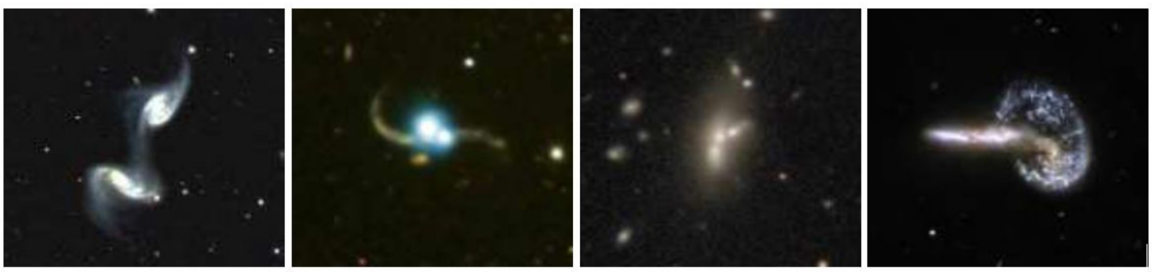

Figure 3. SDSS images showing interacting/merging IR galaxies

doi: https://doi.org/10.52526/25792776-23.70.2-321

5. Summary

We have cross-correlated IRAS PSC/FSC Combined catalogue with optical catalogues of already known galaxies, quasars and blazars (Catalogued Galaxies and Quasars observed in the IRAS Survey, Version 2; NGC 2000.0, The Complete New General Catalogue and Index Catalogue of Nebulae and Star Clusters by J.L.E. Dreyer; Third Reference Catalogue of Bright Galaxies; A catalogue of quasars and active nuclei 13th edition; The Roma BZCAT - 5th edition; Astrometric Catalogue 5, LQAC-5; SDSS quasar catalog, sixteenth data release; QSOs selection from SDSS and WISE), catalogues giving data, which can be used to determine galaxy candidates (Sloan Digital Sky Surveys DR16; HYPERLEDA. I. Catalog of galaxies; The APM-North Catalogue; Gaia DR3 Part 2. Extra-galactic), radio catalogues (1.4GHz NRAO VLA Sky Survey; The FIRST Survey Catalog) and GAIA DR3. After cross-correlation out of 345,163 IR sources we have revealed 12,057 galaxies, quasars or blazars and 68,940 galaxy candidates. Due to cross-correlation with GAIA DR3 we have revealed 183,168 stars. However, 80,998 IRAS sources still remain unknown.

Acknowledgements

This research was partly accomplished by the Republic of Armenia Science Committee for the Advanced Research Grant 21AG-1C053 Revelation of Early Stages of Galaxy Evolution by Means of MW Study of Active Galaxies (2021-2026).

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