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DATA ON 2-D SPECTROSCOPY

Observations of *IRAS* galaxies with the 6 m telescope

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Abstract. Spectroscopic follow-up observations of the Byurakan–IRAS Galaxies (BIG) have been carried out with the Special Astrophysical Observatory (SAO, Russia) 6 m, Byurakan Observatory (BAO, Armenia) 2.6 m, and the Observatoire de Haute-Provence (OHP, France) 1.93 m telescopes to measure their redshifts and classify them. Some of the most interesting galaxies and interacting systems have been observed with the SAO Multi Pupil Fiber Spectrograph (MPFS) for more detailed study.

Key words: methods: observational — techniques: spectroscopic — galaxies: individual: IRAS galaxies

1. Introduction

Multiwavelength studies of extragalactic objects, particularly AGNs, bring to discovery of important links between sources of different ranges and better understanding of star-formation, AGN, evolutionary phenomena in galaxies. Therefore it is rather important to match radio, IR, UV, X- and gamma-ray sources with optical objects of known types, i.e. make optical identifications. Extragalactic infrared sources (infrared galaxies) represent starbursts, AGNs, interacting pairs and groups; in addition, many IR galaxies are radio and X-ray sources too, thus proving their importance for study of all above mentioned phenomena. The Infrared Astronomical Satellite (IRAS) has detected more than 250,000 infrared point sources in 12μm, 25μm, 60μm and 100μm bands. They are cataloged in the IRAS Point Source Catalog (PSC) and the IRAS Faint Source Catalog (FSC). Cross-identifications have been made for these sources with the main available catalogs, revealing bright stars, nebulae, QSOs, galaxies, and other objects as their optical counterparts. As the IR data are very useful for investigation of objects, many papers have been devoted to optical identifications of the IRAS sources. For separation of star and galaxy candidates, IR colors and the galactic latitude are being used. However, half of the IRAS sources still remain without any identification and their physical nature is unknown.

Beginning with the first published data of the IRAS surveys, work has been done on construction of various samples of the IRAS galaxies. They include mainly bright galaxies limited in IR fluxes and area of the sky. More than 20 different samples of IRAS galaxies are known already (Soifer et al., 1987; Spinoglio & Malkan, 1989; Rush et al., 1993; Fisher et al., 1995; Clements et al., 1996, etc.). However, only systematic identifications of all IRAS point sources in a large area can reveal all IRAS galaxies and allow investigation of their population and properties with respect to their luminosity and distances. A program of optical identifications of all IRAS PSC sources at high galactic latitudes and construction of a new IRAS galaxy sample was conducted in the Byurakan Observatory in 1995 (Mickaelian, 1995). The First Byurakan Survey (FBS) (Markarian et al., 1989), the largest existing low-dispersion survey, formed a basis for such work.

2. The *FBS* and the Byurakan–*IRAS* galaxy sample

The First Byurakan Survey (FBS) was carried out with the Byurakan 1m Schmidt telescope and 1.5 deg objective prism. It consists of 1133 $4^\circ \times 4^\circ$ fields and covers an area of 17,000 deg^2 at high galactic latitudes, ($|b| > 15^\circ$). All the Northern sky and part of the Southern sky ($\delta > -15^\circ$) is covered at these galactic latitudes. The dispersion is 1800 Å/mm near Hγ and the spectral range is 3400–6900 Å, so that one can notice some absorption and emission lines (such as Balmer lines, molecular bands, He, N_1+N_2, broad emission lines of QSOs, etc.), follow the spectral energy distribution and compare the blue and red parts of the spectrum. This gives a possibility of distinguishing different types of objects and making their preliminary rough classification. Since 1987, surveys of blue stellar objects and red stars are being carried out on the basis of this observational material (Mickaelian, 2001b, and references therein).

The program of mass optical identifications of all IRAS sources in a large (1487 deg^2) area on the basis of low-dispersion spectra was conducted in the region with $+61° < \delta < +90°$ (at galactic latitudes $|b| > 15°$). All the unidentified IRAS point sources in this area have been checked for associations by the NED and SIMBAD databases. In all, 1577 IRAS PSC sources have been included in the identification program. Positions of all the IRAS sources have been examined on the POSS O and E charts, FBS plates and DSS (McGlynn et al., 1994) images. The ultimate selection of the optical counterpart is being made on the basis of many parameters, including the IR fluxes and colors, optical images, the low-dispersion spectra, optical magnitudes and colors. The following results have been obtained. Optical identifications have been made for these IR sources (Mickaelian, 2001a, and references therein). Optical coordinates have been measured, V magnitudes, B–V colors have been estimated, and rough classification has been made for all the objects. Among the identified optical counterparts, there appeared to be late-type stars, planetary nebulae, QSO candidates, single, multiple galaxies and small groups. There is no optical counterpart near the positions of some 50 sources even in the DSS, and taking into account their IR colors typical of galaxies, they must be very faint galaxies at the optical wavelengths.

The identified galaxies can be considered as the most interesting counterparts of the IR sources. The identifications resulted in construction of a new sample of IRAS galaxies: the Byurakan-IRAS Galaxy (BIG) sample, containing 1967 objects, including 789 previously known in this area and 1178 newly identified ones. For them angular sizes and position angles have been determined, morphological classification have been made in addition to the above mentioned main parameters. The galaxies have different nature, structure and appearance (Fig. 1): compact galaxies, interacting pairs and groups (with tails and bridges between the objects), "mergers", radio and X-ray sources, etc. Study of the sample gives a better understanding of star-formation, nuclear activity, interactions, and connections between these phenomena.

3. Spectral study of the *BIG* objects

Studies of the BIG objects include: spectroscopic follow-up for the brighter ($<18^m$) objects (aimed at measuring their redshifts and classification); discovery and study of new AGNs; discovery and study of new ULIGs; 2D spectroscopy of interacting/merging systems; search for obscured IRAS galaxies; study of starburst/AGN/interaction phenomena and their interrelationship, etc.

Medium-dispersion spectral observations were carried out for the BIG objects during 1997–2000 and are being continued using the Special Astrophysical Observatory (Russia) 6 m, Observatoire de Haute-Provence (France) 1.93 m, and the Byurakan Astrophysical Observatory (Armenia) 2.6 m telescopes (Mickaelian et al., 1998; 1999; Balayan et al., 2001). The redshift survey is the first task. These observations are aimed at the investigation of space distribution of IRAS galaxies and their IR luminosity function, discovery and selection of AGNs, high luminosity IR galaxies, composite spectrum objects, and their study in more details. Statistics of observations of the BIG objects carried out up to now is given in Table 1: telescopes, equipment and the receivers, years of observations, number of IRAS sources with observed counterparts, number of observed galaxies, number of obtained spectra. Dispersions of 1.8–5.8 Å/pix have been used and a spectral resolution of 5–14 Å with a S/N ratio up to 1:50 have been achieved. Study of the objects with different telescopes and observational methods (e.g. MPFS — a multi-pupil spectrograph) is more efficient both for quick fulfillment of the program and better quality of classifications. The spectra have been reduced by IRAF, MIDAS and/or a package of programs worked out at the SAO (Vlasyuk, 1993).

The observational programs for the SAO 6 m telescope consist of two stages: spectroscopic observations with the UAGS spectrograph and the 2D spectroscopy with the MPFS. The UAGS is a long slit spectrograph (LSS) mounted at the prime focus of the 6 m telescope (Afanasiev et al., 1995). Two CCDs have been used with the UAGS: 580×530 pix and 1024×1024 pix. Depending on the grating angle we have recorded one of the two spectral ranges with the first CCD: 4500–7800 Å or 3800–7000 Å with a spectral resolution of ~16 Å: and with the second CCD, 3600–8000 Å with a slightly higher resolution of 14 Å. The MPFS is a spectrograph intended for 2D spectrophotometry of the extended objects with medium spectral resolution. The detector used is CCD TK 1024×1024, with 24×24 μm/pix. The recorded data make a cube of 16×15×1024 elements. Spectrograph is mounted in the prime focus of the 6 m telescope. A spectral range of 3600–9600 Å can be obtained, the dispersion is 1.35–5 Å/pix, realized by a set of grat-

Table 1: *Statistics of Observations of the BIG Objects in 1997–2000*

Telescope	Equipment	Receivers	Dates	IRAS sources	BIG objs.	Sp.
BAO 2.6 m	ByuFOSC	TM1060×514	Apr98-Dec99	45	56	75
SAO 6 m	UAGS	K 585×530	Feb97-Feb99	48	64	84
		TK 1024	Mar99			
SAO 6 m	MPFS	TK 1024	Sep98-Dec00	42	46	109
OHP 1.93 m	CARELEC	TK 1024	Oct97	64	69	74
		EEV 2048	Jan99			
All observations				175*	216*	342

* Some objects have been observed several times with different telescopes

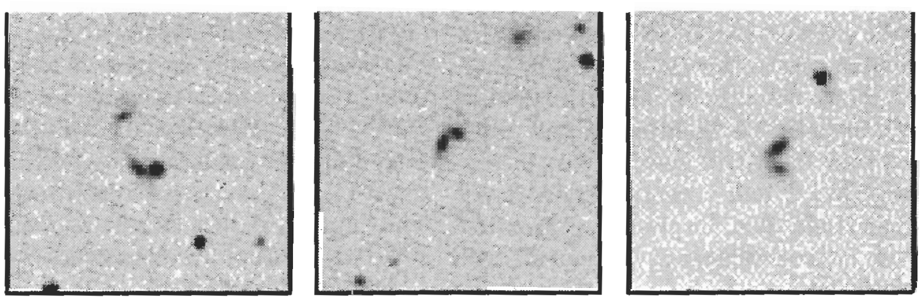

Figure 1: *Examples of galaxies from the BIG sample.*

ings of 300–1200 g/mm, and the resolution is FWHM ~ 2.5 pix over the entire field of view.

4. Obtained results

In all, 216 galaxies associated with 175 IRAS sources have been observed spectroscopically (some sources have more than one association, and all components have been observed to check their nature and find out which of them is responsible for the IR). Spectral observations revealed new AGNs and high-luminosity infrared galaxies. Redshifts for all the observed galaxies have been measured (z=0.008÷0.173, brighter galaxies of the sample have been observed having V magnitudes $12^m \div 18^m$ and larger redshifts are not expected yet), the distances are 80÷1041 Mpc, the absolute magnitudes are in the range $-17.5^m \div -23^m$ and the calculated infrared luminosities are in the range $3 \cdot 10^9 L_\odot < L_{IR} < 7.5 \cdot 10^{12} L_\odot$ (for H_0=50 km/s/Mpc), including some 30 LIGs and two ULIGs already revealed (IRAS 07479+7832a and IRAS 10252+7013).

The objects have mostly emission-line spectra with strong Balmer lines (Hα and/or Hβ are in the observed range), [OIII] 5007Å and 4959Å, [NII] 6584Å and 6548Å, [SII] 6717Å and 6731Å lines. [OI] 6300Å and 6363Å, [OII] 7320Å and 7330Å. HeI 5876Å, [FeVII] 6087Å emission lines, and NaI 5896Å and MgI 5175Å absorption lines are often present. Activity type of the galaxies have been estimated using well-known diagnostic diagrams (Baldwin et al., 1981, Veilleux & Osterbrock, 1987) in the cases of presence of the corresponding data. In the cases with fewer data, we used the adapted scheme for spectral classification working on the basis of intensity ratios of the forbidden and permitted lines as well (see, for example, Balayan et al., 2001), mainly [NII]λ6584Å/Hα, and/or [OIII]λ5007Å/Hβ to differentiate galaxies of star formation activity in different stages — HII, and objects with nuclear activity — Sy type galaxies, LINERs, composite AGNs (Véron et al., 1997). Most of the objects (143) classified already are of HII nature, 21 are Sy2 galaxies, 3 are LINERs, 7 are of composite AGN nature. Among them, six interacting systems contain objects showing AGN features, interesting for further studies. The diagnostic diagrams for a subset of BIG objects observed with the UAGS spectrograph at the 6 m telescope are given in Fig. 2.

The activity zones separated show the distribution of objects of different types. Objects having a composite spectrum (two distinct emission nebulae, for instance a HII region and a Seyfert, being superimposed on the slit) should be observed with higher resolution (<3 Å) to study the profile of the different emission lines and to identify the nature of the emission nebulosities present in the spectra. Fig. 3 gives spectrum of one of the Sy2 galaxies from the diagram.

5. Subsamples of the *BIG* objects

Morphology and obtained spectra allow separation of different interesting subsamples for a further detailed study. They are important for understanding of certain processes taking place in galaxies, and evidence of activity, starburst and/or interactions in the same object allows one to study connections between these phenomena. Here are the main subsamples of BIG objects attracting attention:

- AGNs. The nuclear activity in galaxies is not finally understood yet. Numerous types of active galaxies, making an "AGN zoo" are not fitted well in the unified scheme. Hence, discovery of more AGNs helps to solve this problem. IRAS galaxies contain a large fraction of AGNs, and it grows up with IR luminosity. Are all high-luminosity IR galaxies AGNs at higher redshifts? BIG objects provide a number of interesting AGNs, too. Many of them are radio (NVSS: Condon et al., 1998) and X-ray (ROSAT: Voges et al., 1999) sources as well.
- Composite spectrum objects. As it was mentioned, a number of galaxies show simultaneously features of two different types of objects: e.g. HII and Sy2, or HII and LINER. Such objects are important for study of different emission-line regions and their co-existence in the same galaxy (Véron et al., 1997).
- High-luminosity IR galaxies: LIGs, ULIGs and HLIGs (Sanders & Mirabel, 1996; Clements et al., 1999). Fainter galaxies in our BIG sample should appear to be such objects, as they have nearly the same IR fluxes as brighter galaxies (0.4–1.5 Jy at 60μm and 1–3 Jy at 100μm), but are much fainter in the optical range and, hence, much farther. 30 IRAS sources seeming to be real extragalactic objects (not cirruses) have no optical counterparts at the IR positions. There must be objects with optical magnitudes beyond the DSS limit.
- Interacting galaxies and mergers. Revealed by the DSS images, they are subject for a further detailed study by 2D spectroscopy (MPFS observations have already been made for a number of them), which gives the velocity field of such objects and understanding of their relative motions. Is always the high IR radiation due to merging process? (Clements et al., 1996).
- Distant groups. Cross-correlations of the IRAS sources with higher positional accuracy radio catalogs (particularly, the NVSS: Condon et al., 1998) allowed selection of a correct optical counterpart among the several candidate objects (Mickaelian et al., 2001). 766 NVSS sources coincide with the IRAS sources in the investigated region. By matching with the APS database (Pennington et al., 1993), most of them coincide with a certain optical object. However, in a number of cases, the IR radiation comes from a group of galaxies as a whole. Many of these groups are compact.

6. 2D spectroscopic study of the *BIG* objects

One of the most important subsamples of the BIG objects are interacting/merging galaxies. The 2D spectroscopy of interacting/merging systems is aimed at study of their velocity fields and dynamics. The MPFS is being used for this purpose. However, a number of individual objects have been observed too.

Fig. 4 shows images in Hα with superposed velocity field for two galaxies observed with MPFS. Data obtained for IRAS 17493+6626, which is a galaxy of intermediate luminosity ($L_{IR}{\sim}10^{11}L_\odot$) except for spectral features give the details of the motions of its two components. IRAS 12395 +6238 was preliminarily classified as a composite galaxy with the value of redshift z = 0.0342 on the basis of previously obtained with LSS slit spectra (Mickaelian et al., 1998). Data obtained with the MPFS in about the same spectral range for this object of $L_{IR}{\sim}10^{10}L_\odot$ luminosity reflect the main picture of the processes ongoing here. The spectra of each of the two components composing this complex integrated separately do not show any AGN features, showing only emission lines conforming to star forming mechanism.

7. Future plans

The main aim of the program is to make a systematic study of the complete sample of ultraluminous interacting IRAS galaxies to understand the interrelationship between AGN and starburst activity induced by galaxy merging and follow the evolutionary processes in these objects. The optical identification program has produced a new IRAS galaxy sample — BIG. The following studies of these objects are planned:

- study of the sample contents. In particular, the availability of optical and IR (in 4 bands) data for many galaxies will help to clarify the classification principles as well (relation between ULIG and activity types);
- detailed optical study (morphology: study of interactions, fine structure of central regions; and spectroscopy: determination of redshifts and activity classes) of the newly identified IRAS galaxies and groups of galaxies;
- near-infrared (mainly for some brighter galaxies) and millimeter radio (for galaxies and QSOs) observations of newly identified objects;

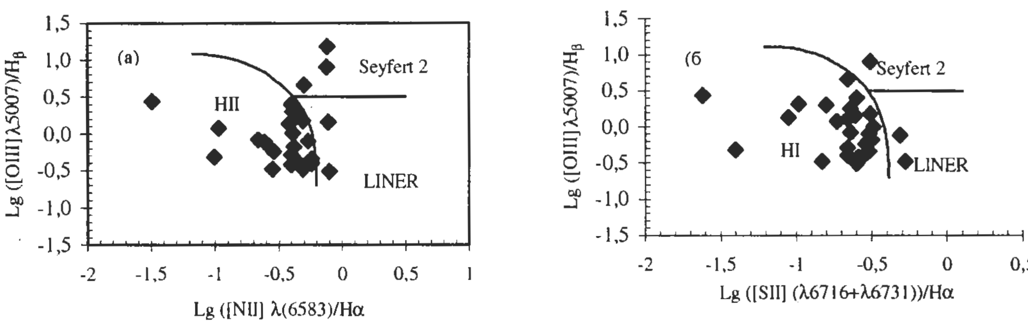

Figure 2: *Diagnostic diagrams for BIG galaxies observed with the 6 m telescope.*

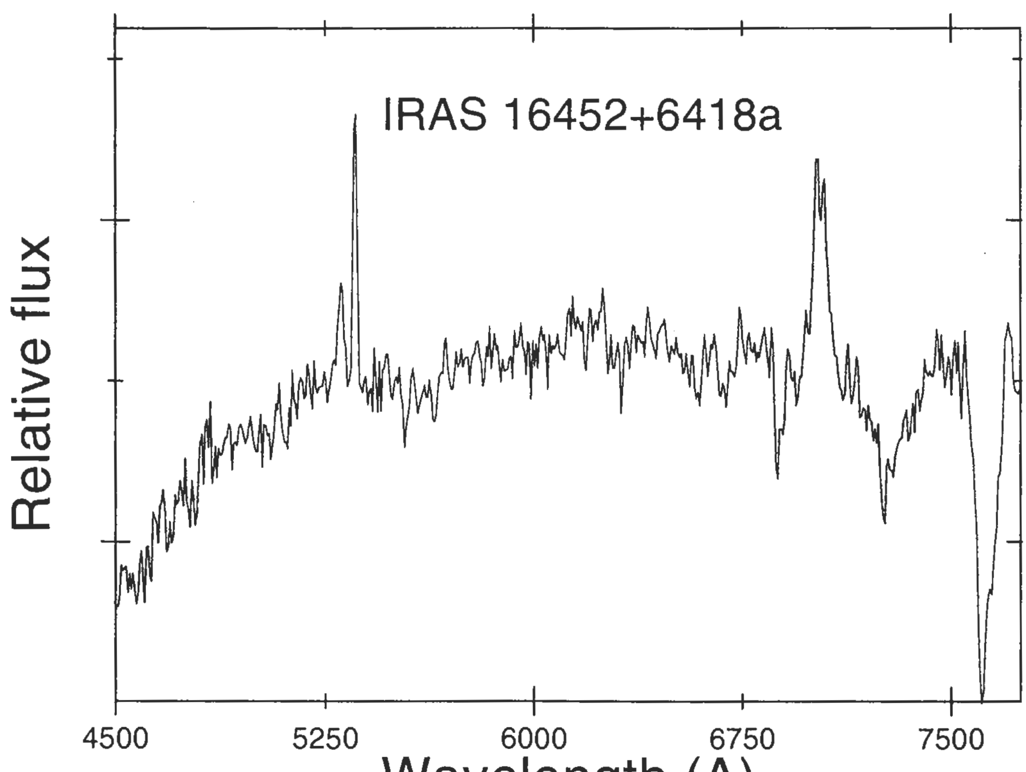

Figure 3: *The slit spectrum of a Sy2 galaxy from the BIG sample observed with the 6m telescope.*

- overall statistical study of the area, including previously identified IRAS sources: space distribution and density of IRAS galaxies in the field, their luminosity function and their connection with AGNs will be investigated. Study of the sample of all the galaxies in the field, including previously known and newly identified ones, will give the most complete picture of the nearby Universe;
- comparison with the existing samples of IRAS galaxies and their statistical properties on space density, evolution, star-formation rate and status of the IR galaxies.

Taking into account that this program gives a complete sample of IRAS galaxies in a large area, we hope to obtain the real distribution pattern of extragalactic IR sources in the Local Universe. The large number of interesting objects (active galaxies, interacting systems, QSOs, planetary nebulae, variable stars, etc.) among the IRAS sources makes important investigations in this field, as their study leads to understanding of evolutionary phenomena and processes taking place both in stars and galaxies.

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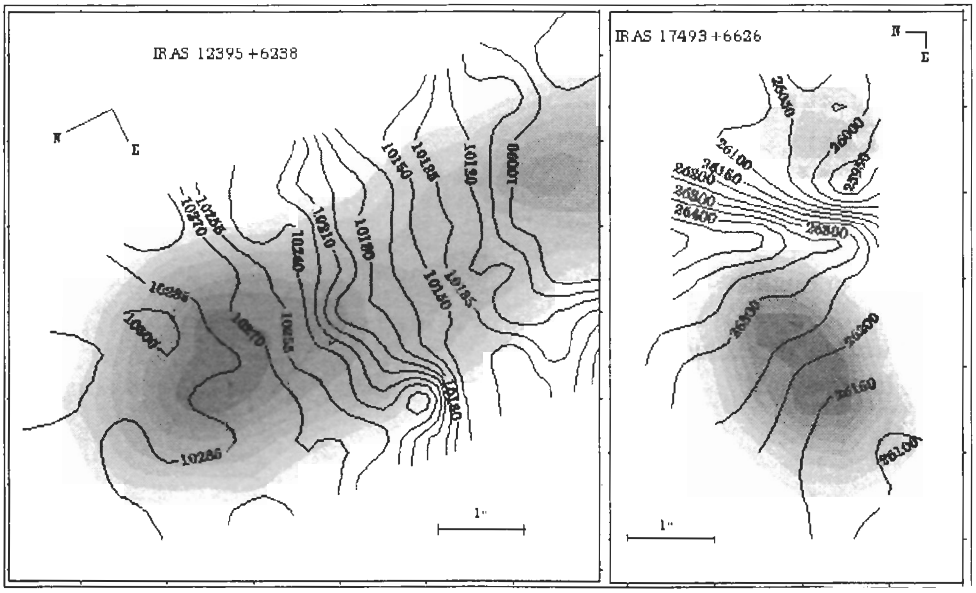

Figure 4: *Velocity field of IRAS 12395+6238 and IRAS 17493+6626 superposed on Hα image.*

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