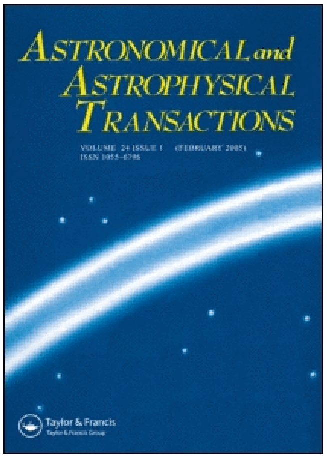

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Statistical properties of the sample faint early-type galaxies: Possible effects of evolution

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GALACTIC AND EXTRAGALACTIC ASTRONOMY

STATISTICAL PROPERTIES OF THE SAMPLE FAINT EARLY-TYPE GALAXIES: POSSIBLE EFFECTS OF EVOLUTION

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Early-type galaxies from CfA catalogue were associated with IRAS FSC sources. In this sample, IR and optical properties were used to obtain a classification of these objects. The existence of significant classes can evidence for the presence of one main type of dust in each galaxy. Physical interpretation of the obtained classes is discussed. The dust mass in two classes of galaxies can be calculated using evolution modelling. Thus, we can estimate the chemical composition and the initial mass function in these galaxies.

1 INTRODUCTION

The availability of an enormous amount of infrared data, obtained in the IRAS experiment, makes it possible to analyze statistical properties of samples of various celestial objects, including those in which the components of IR emission are expected to be fairly weak. In particular, galaxies of early morphological types (E and SO) may be placed into the latter category. Although the first release of the IRAS Point Source Catalog contained only a small number of such galaxies, the application of additional processing techniques allowed to form a large sample of such objects and to investigate statistical properties of various physical parameters of galaxies, obtained both from IR data and from data derived in other spectral regions (Knapp *et al.* [1], Bally & Thronson [2]). The release of the next catalog of IR sources (Faint Source catalogue **2**, FSC-2, Moshir *et al*, [3]) justifies studies of general sample properties of early-type galaxies, associated with the sources of this catalog. These studies are also useful because the objects in the IRAS Point Source Catalog (PSC) and FSC-2 Catalog are subject to various selection effects and may exhibit various physical properties. In this work, such an investigation was performed using objects from the CfA catalog (Huchra, [4]), which has associations in the FSC-2 catalog. For the derived sample, the objects were classified by means of the cluster analysis, and physical interpretation of the obtained classes was made.

2 DATA AND DATA HANDLING

To analyze possible associations with the Faint Source Catalog, the largest available catalog of galaxies – the CfA catalog – was used, which containes 38909 objects; morphological type is given for 17008 objects, 4596 objects from them are early-type galaxies (the cataloged type $t < 0$). To apply the identification procedure, the following selection criteria were used for objects: the separation between the objects in the CfA and FSC-2 catalogs must be within 60 arcsec; the object must show a statistically significant flux (parameter $FQUAL > 2$) in one of the far-IR bands (60 or 100 μm); there must be no associations for the source in the FSC-2 catalog with other, closer objects from catalogs of other objects. The applied procedure resulted in a sample of 539 galaxies, which was used in the subsequent analysis; 11 galaxies from this list had no previous associations with IR sources. A group of galaxies with statistically significant IR measurements in, at least, three IRAS bands and with measured apparent magnitudes in Johnson's UBV system, as well as with known redshifts, was selected from the general sample. These data were available for 166 E and SO galaxies. Such selection is required to classify objects by, at least, three parameters. As it is desirable that the selected parameters were independent of the galaxy distance, the flux ratio at 25, 60, 100 μm, and in the B band (f_{25}/f_{60}, f_{100}/f_{60}, f_B/f_{60}) were used for the classification.

Hierarchical clustering algorithm, involving a sequential agglomeration of objects or of groups of objects (clusters) using a criterion of any kind, was applied for object classification. After the agglomeration of objects into a single cluster, the maximum number of statistically significant clusters is determined using a criterion of any kind (a set of criteria). In this case of a software program of hierarchical cluster analysis taken from the STATLIB library (compiled by Murtagh [5]), minimal increase in residual mean square (RMS) in a cluster during agglomeration (Ward's criterion was used as a criterion for cluster agglomeration; this leads to breaking the hyperspherical form (in classification parameter space) into clusters. To estimate the significance of breaking into clusters, a semi-empirical criterion was applied, based on an analysis of the "dissimilarity – number of cluster" relationship (Mojena & Wishart [6]); according to this criterion, the agglomeration must stop when the growth rate of RMS increases during cluster agglomeration. The requirement that the separation between clusters be larger than RMS within each cluster was used as an additional criterion. The application of both these criteria resulted in breaking the sample into four clusters (object classes), which were subsequently subject to further analysis.

3 RESULTS OF DATA PROCESSING

To analyze the derived classes of galaxies, some additional physical parameters for each sample object were calculated, including the dust distribution in temperature, dust masses, and the contribution of IR emission to overall emission from galaxies.

Table 1.

Parameter	*Cluster 1*	*Cluster 2*	*Cluster 3*	*Cluster 4*
Redshift z	0.017±0.001	0.010±0.003	0.019±0.003	0.009±0.004
Type t	-2.86±0.21	-2.32±0.25	-2.56±0.26	-2.78±0.35
$\log(f_B)/f_{60})$	-0.36±0.09	1.34±0.13	0.49±0.11	3.35±0.21
$\log(f_{25})/f_{60})$	-0.86±0.01	-0.49±0.02	-0.49±0.03	-0.49±0.03
$\log(f_{100})/f_{60})$	0.23±0.01	0.41±0.01	0.20±0.02	0.53±0.03
$T^{(2)}_{\rm dust}$	66.41±0.41	69.89±2.02	81.54±1.50	94.49±4.81
$\log(M_{\rm dust})$ in $M_\odot$	7.60±0.09	7.15±0.15	7.52±0.12	6.51±0.21
"Hot"/"Total"	0.37±0.02	0.27±0.05	0.38±0.03	0.13±0.02

The limited number of photometric requires a simple dust model to describe the observational IR photometry:

$$I_\nu = \tau_\nu B_\nu(T_{\rm dust})$$

where $\tau_\nu \propto \nu^\alpha$ is the optical depth, and $B_\nu(T_{\rm dust})$ is the Plank function. Unfortunately this approximation cannot give meaningful results for a large number of galaxies in the sample. As a consequence, we have to use a multicomponent dust model:

$$I_\nu = \sum_{i=1}^{n} \tau_\nu^{(i)} B_\nu(T^{(i)}_{\rm dust}).$$

A two-component ($n = 2$) model of dust was employed to evaluate the temperature distribution. As three measurements are not enough to determine the complete set of parameters for such a model, the spectral index α in the dependence of absorption coefficient on the frequency and the temperature of one of the components ($T^{(1)}_{\rm dust} = 28$ K) were fixed parameters. As a result of the modelling, the temperature of the "hot" component, as well as the "hot"-to-"cold" component ratio were calculated. The "hot" component with temperature $T^{(2)}_{\rm dust} > 60$ K is present virtually in all galaxies, its contribution to overall emission being in the range from 1% to 60%. The mass of dust, as in the paper by Greenhouse et al. [7], was calculated from the emission in the wavelength range of 25 to 300 μm, taking into account the two-component model of dust. Statistical data on classification parameters ($\log(f_B)/(f_{60})$, $\log(f_{25})/(f_{60})$, $\log(f_{100})/(f_{60})$) and additional physical parameters quoted above ($T^{(2)}_{\rm dust}$, $\log(M_{\rm dust})$), the contribution of "hot" component to overall emission, as well as the redshift z and the morphological type t), were obtained for each selected class of galaxies and are given in Table 1. To interpret some physical properties of galaxies of various types, the available observations traces of interaction (possible associations with objects from Vorontsov-Vel'aminov's catalog of interacting galaxies), traces of an active nucleus (possible associations with objects from Veron's catalog), and the presence of radio emission, were collected. As a result of the comparison of the above signs, the following interpretation may be provided for the division of early-type galaxy sample into classes:

- Class 1: Galaxies with high abundance of moderate-temperature dust; this class includes all interacting galaxies, galaxies with giant HII zones, and a number of sources emitting in a high-frequency range; the above signs imply outbreaks of star formation in this class of galaxies and the existence of UV photons - the main source dust heating.

- Class 2: Differs from the previous by a considerably lower dust abundance and by a minimum number of peculiar properties (there are weak traces of nuclear activity in a number of cases); this class appears to include "normal" ellipticals.

- Class 3: Contains mainly galaxies with active nuclei, high-temperature dust (when the amount of optical emission, reradiated in infrared, is small), galaxies with synchrotron radio sources. The dust properties being close to IR properties of galaxies implies that the dust surrounding the nucleus is the contributor of IR emission in this class of galaxies.

- Class 4: This class of objects has the same properties as class-2 galaxies, except that their dust is warmer. To establish the nature of the additional dust-heating source for this class of galaxies, a more thorough investigation of their observed properties in a variety of spectral regions may be required. Another explanation can be offered, if we assume that the spectral index α in the dust model is large. Since α is determined by the size distribution of dust grains, the destruction of large dust particles takes place in these objects. The negative correlation between the temperature and mass of the dust favors the second explanation.

4 DUST AND HISTORY OF GALAXIES

As a result of previous considerations, we can see that a set of galaxies without significant star formation, nuclear activity, and interaction can be selected using clustering methods. For these objects, we can suggest late-type stars in each galaxy as ultimate source of interstellar dust in this galaxy. It allows us to write relation between stellar evolution and dust mass in a galaxy. If the galactic mass is generated mainly in atmospheres of late stars, dust mass can be estimated as:

$$M_{\rm dust} = \zeta(Z) t_{\rm dust} \dot{M}_{\rm gas}$$

where $\zeta(Z)$ is the content of dust in the stellar wind (depending on chemical composition Z, $t_{\rm dust}$ is lifetime of dust grains, $\dot{M}_{\rm gas}$ is stellar mass loss rate, determined as:

$$\frac{\dot{M}_{\rm gas}}{M_{\rm gal}} = \int\limits_{M_{\rm min}}^{M_{\rm max}} \frac{\dot{M}(M_*)}{M_*} \phi(M_*)\, dM_*$$

where $M_{\rm gal}$ is total galactic mass, $M_{\rm min}$, $M_{\rm max}$ are minimal and maximal stellar masses, and $\phi(M_*) \propto M_*^{-\alpha}$ is stellar mass function. Since $\zeta(Z)$ and $\dot{M}(M_*)$ can be obtained from stellar models, dust mass obtained from IR-observations can be a useful tool to estimate the chemical composition and stellar mass function in the galaxies.

CONCLUSIONS

1. It is possible to obtain statistically significant groups of galaxies on the basis of IRAS photometry. This fact can be considered as evidence for the existence of one main type of dust in each galaxy.

2. The derived classes of galaxies can be interpreted as: - galaxies with active star formation (class 1); - galaxies with strong nuclear activity (class 3); - "normal" E/SO galaxies (class 2); - galaxies with large index in the size distribution of grains (class 4).

3. Many galaxies show appreciable (up to 80% of the overall dust mass) amount of hot ($T_{\rm dust} > 60$ K) dust.

4. For galaxies from classes 2 and 4 we have an opportunity to estimate the chemical composition and initial mass function from the dust mass.

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