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SPECTROSCOPICAL AND PHOTOMETRICAL ANALYSIS OF NEARBY GALAXIES OF DIFFERENT MORPHOLOGICAL TYPE

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Abstract. Galaxies show high degree of organization, proven by numerous scaling relations. However, most of these relations hold either for early- or late- type galaxies. There is a need for a study of galactic properties regardless of their morphological type, but driven from the sample representative of the galactic morphology in the local Universe. HI blind surveys sample galaxies based solely on their gas content, regardless of their luminosity in the optical. This is why we have extracted our sample from the latest HI blind survey, the Arecibo Legacy Fast ALFA Survey (ALFALFA). The first data release referring to the 40% of the planned survey was the alfa.40 catalog (Haynes et al. 2011), counting about 10 000 extragalactic sources. We have cross-matched this catalog with the sixth data release of the Galex Evolutionary Explorer (GALEX) and Two Micron All-Sky Survey (2MASS) catalogs to add ultraviolet and near-infrared photometry. Our final sample counts 2180 galaxies with radio and optical spectroscopy and ultraviolet through optical to near- infrared photometry.

Numerous empirical relations between galactic properties imply that there is a final number of parameters whose continuous change is responsible and may describe diversity of galactic types in the local Universe. The question that naturally arises is how many independent parameters are sufficient to describe galaxies we see today, i.e. the dimensionality of the problem and whether there is a single driving force responsible for their present distribution. To this end, we have applied the principal component analysis in order to reveal the true dimensionality of the problem. This method was applied earlier by Disney et al. 2008 on the sample of 200 galaxies chosen from the earlier HI blind survey, the HI Parkes All-Sky Survey (HIPASS). The authors analyse six galactic properties: dynamical mass, HI mass, luminosity, Petrosian radii R50 and R90 and the colour and find that there is a single dimension that is statistically significant. We have explored larger parametric space, including in addition: stellar mass, age, metallicity, colours with both ultraviolet and near infrared components, velocity dispersion, maximal rotational velocity and the mass of the dark halo. The parameters measured in the thesis are: dynamical mass, velocity dispersion, age and metallicity. Other parameters are taken from the existing catalogs. We have successfully reduced our parametric space to ten parameters: dynamical mass, stellar mass, HI mass, age, luminosity, colour with ultraviolet component, velocity dispersion, maximal rotational velocity and two Petrosian radii enclosing 50% and 90% of the flux, respectively. As the result of the principal component analysis, we have found *three* statistically significant components (dimensions), the first being the "size" of the galaxy, the second being the galaxy colour and the third being the galaxy age. The fourth component, although not statistically significant is dominated by the maximal rotational velocity. To conclude, there are at least three and possibly four "driving forces" that could explain the diversity of galaxies we see today.

1. INTRODUCTION

Pioneering studies of galactic properties with measured rotation curves (Brosche 1973; Bujarrabal et al. 1981; Whitmore 1984) were severely biased in several respects - galaxies were chosen a priori, for they optical luminosity and were all spiral and moderately irregular. In these early statistical studies, galaxy samples were heterogenous and very moderate (< 100 galaxies). However, applying statistical analysis (principal component analysis), previous workers found that the multidimensional space populated with very broad range of galactic properties may be reduced to only two fundamental and independent (uncorrelated) dimensions, i.e. properties – the first being the "size" of the galaxy and the other being the "aspect" of the galaxy.

With the advent of all-sky HI surveys, that mapped the whole sky in the radio L-band (1420 MHz), all the astronomical objects with measurable gas content were imaged, regardless on their optical luminosity. The first such a blind HI survey was the HI Parkes All Sky Survey (HIPPAS; Meyer et al. 2004) that mapped ~ 30000 deg^2 of the sky with the 64m Parkes radio-telescope and detected ~ 5000 objects with gas masses $M_{\rm HI} > 10^7 M_\odot$. Disney et al. 2008 applied the principal component analysis on a subsample of about 200 galaxies from this survey and found that there is a single galactic property guiding the variety of galaxies, with very different morphologies and colors. This property is equally well correlated with the galaxy mass, luminosity, Petrosian radii etc. and cannot be identified with a single property.

The second and the latest, most sensitive radio survey is the Arecibo Legacy Fast ALFA Survey (ALFALFA; Giovanelli et al. 2005) that detected more then 30000 extragalactic HI line sources with masses as low as $10^6 M_\odot$ out to z$\sim$0.06. The first data release (α.40; Haynes et al. 2011) was used in this contribution which describes my PhD thesis (defended in 2016 at the Department of Astronomy, University of Belgrade) in synergy with other wide area surveys conducted at other wavelengths to explore the widest range of galactic properties and to reduce the number of dimensions of this multiparametric space to the smallest number of statistically significant dimensions, given the unbiased and large sample of galaxies.

2. GALAXY SAMPLE

To build a large sample of galaxies without optical bias, we used α.40 catalog that is already cross-matched with the Sloan Digital Sky Survey (SDSS DR7; Abazajian et al. 2009) spectroscopic catalog. This catalog was further cross-matched to the Galaxy Evolution Explorer (GALEX GR6), Two Micron All Sky Survey (2MASS XSC; Jarrett et al. 2003) and the SDSS DR7 catalogs to add a multiwavelength photometry to the radio and optical spectroscopy originally provided with the α.40 catalog. The final sample has 2180 galaxies and we will refer to it as an α- sample, hereafter. α-sample has radio and optical spectroscopy and photometry from the ultraviolet, trough the optical to the near-infrared passband.

Morphological distribution of galaxies, based on the concentration index alone (C_{95}), suggests that there is about 1/3 of early-type galaxies in the α-sample for which $C_{95} > 2.6$ (Fig. 1). The ratio 1:3 reflects the contribution of early-type galaxies to the galaxy population in the local Universe (Shimasaku et al. 2001). On the other hand, Huertas- Company et al. (2011) made an automatic morphological classification of all the galaxies from the SDSS DR7, dividing them into two canonical types (early

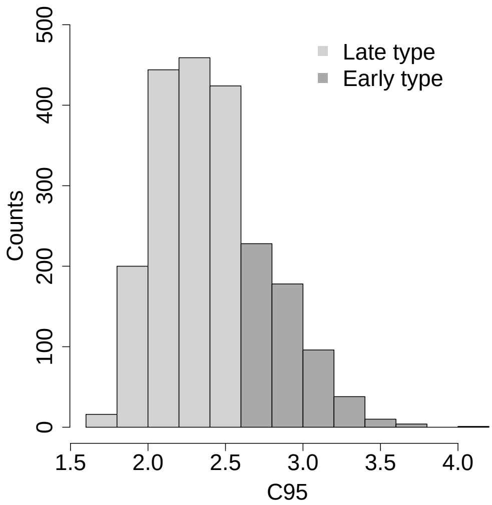

Figure 1: Morphological classification of galaxies based on the concentration index C_{95} (see Vudragović et al. 2016.): $C_{95} \leq 2.6$ are late-type galaxies (lighter) and $C_{95} > 2.6$ are early-type galaxies (darker).

and late) and then each of these types into two subtypes: ellipticals and lenticulars as subtypes of early-type galaxies and spiral Sab and Scd as subtypes of late-type galaxies. The affiliation is given as a continuous probability, normalized to the unity. For example, a galaxy is an early-type galaxy if pE> 0.5, with all different non-zero probabilities probabilities normalized to unity (pE + pS0 + pSab + pScd = 0.7 + 0.2 + 0.05 + 0.05 = 1). According to this classification, α-sample has 13% of early- and 87% of late-type galaxies.

For all the galaxies in the α-sample, we have measured velocity dispersions, Sersic indices and effective radii to obtain dynamical mass of galaxies. Also, we have measured the Lick indices since some of them are good proxies to galaxies' ages and metallicities. These parameters will be used in the final statistical analysis.

3. STELLAR KINEMATICS

Line-of-sight velocity distribution (LOSVD, hereafter) function is the distribution of stellar velocities in the galaxy spectrum responsible for the final shape of the spectral lines and reflects the motion of stars in the gravitational potential field defined by the dark matter distribution. The LOSVD function may often be well represented with the Gaussian function, but in early-type galaxies and bulges of late-type galaxies, when random velocity component takes over the rotationally supported component of velocity of stars binned to the disk, the Gaussian approximation breaks down and additional velocity components are needed to describe the LOSVD function accurately. van der Marel & Franx (1993) proposed decomposing the LOSVD function into orthogonal polynomials (see also Gerhard 1993), the so-called Gauss-Hermite series: introducing two new parameters describing asymmetric (h_3) and symmetric (h_4) departures from the Gaussian function.

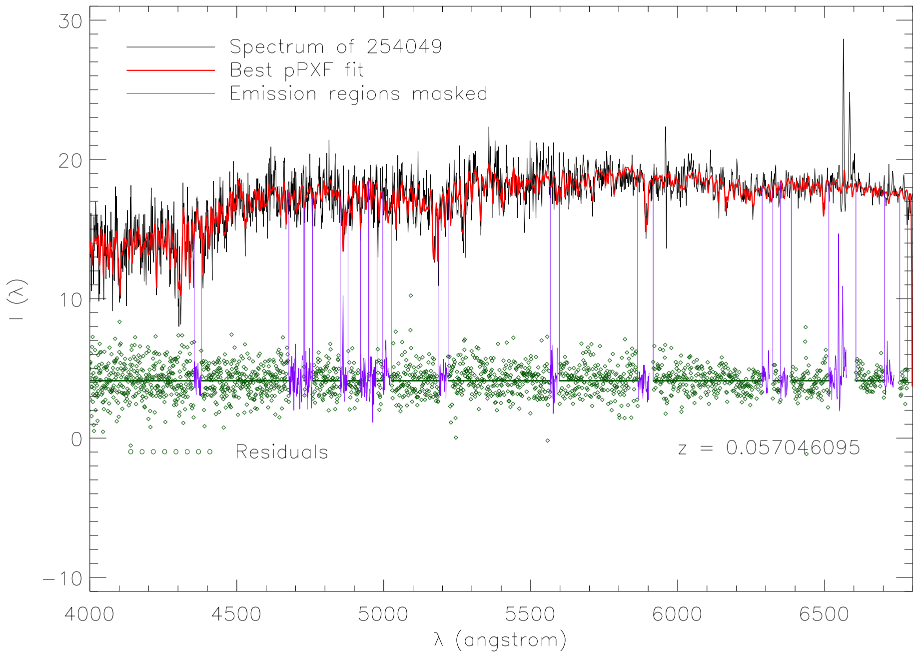

Figure 2: Spectrum of one of the galaxies (Alfalfa 254049) with the best fitting model overplotted. The residuals are given by dots at the bottom. Emission lines are masked (regions between vertical lines). The redshift is indicated in the bottom right.

Using the publicly available penalized piXel Fitting (pPXF) code (Cappellari & Emsellem 2004), we have measured velocity dispersion and the two higher moments (h_3 and h_4) from the LOSVD function represented with the Gauss-Hermite series, using the empirical Elodie stellar library (Prugniel et al. 2007) of 998 stars in total. We have tested several empirical and one synthetic stellar library to choose the Elodie library for its better agreement with the literature.

The measured velocity dispersion and the h_4 Gauss-Hermite coefficient will be used in dynamical mass calculation. The velocity dispersion needs to be aperture corrected (Jorgensen et al. 1995), but also corrected ($\sigma_{\rm corr}$) for the departure of the Gaussian function trough:

$$\sigma_{\rm corr} = \sigma^{\rm GH}(1 + \sqrt{6}\ {\rm h}_4^{\rm GH}), \tag{1}$$

where $\sigma^{\rm GH}$ is the uncorrected velocity dispersion and ${\rm h}_4^{\rm GH}$ Gauss-Hermite coefficient.

Given the sample size, we were able to study the behavior of the Gauss-Hermite coefficients across the Hubble sequence. We have established an increasing trend in h_4 parameter going from late- to early-type galaxies (Fig. 3), i.e. going from $\rm pE0 = pE + pE0 = 0$ to $\rm pE0 = 1$. The results are obtained using the empirical stellar library. This implies the dominance of radial orbits in early-type galaxies.

Also, we have applied several statistical tests to the Gauss-Hermite h_4 coefficient

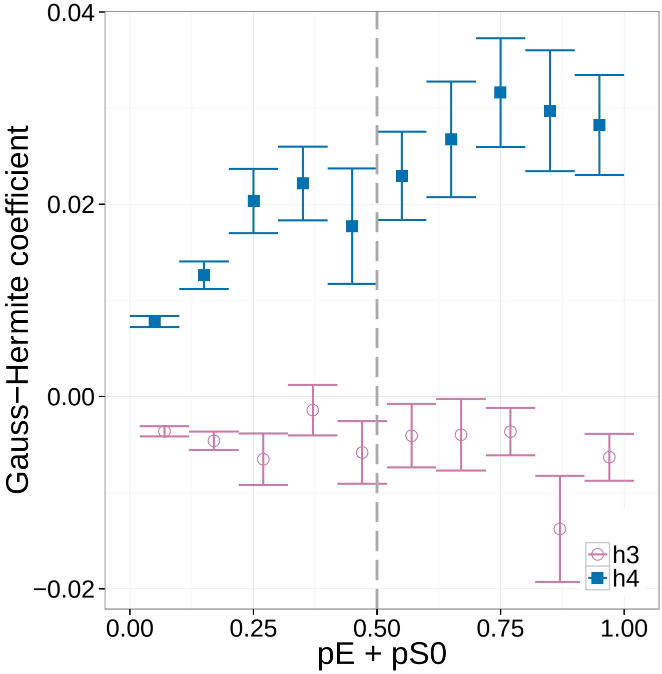

Figure 3: Measured Gauss-Hermite coefficients along the Hubble sequence (see Vudragović et al. 2016): h_3 (open circles) and h_4 (full squares). pE + pES0 $\equiv$ pE0 is the probability that galaxy belongs to early-type galaxies if pE + pES0 = pE0 > 0.5. Vertical dashed line is splitting late- from early-type galaxies.

going from the null hypothesis that early- and late-type galaxies share the origin. Also, we have confronted all subtypes in this way, e.g. E vs. S0 and S0 vs. Sab and Sab vs. Scd. The following statistical tests were performed: Anderson-Darling (Scholz & Stephens 1987; Darling 1957; Anderson & Darling 1952), Kolmogorov-Smirnov (Hoel 1971) and Cramer-von Mises (Anderson 1962). The results give a hint that elliptical and lenticular galaxies have the same origin, unlike all other (sub)types, for which the results were negative.

4. THE LICK INDICES

Two fundamental properties of galaxies, age and metallicity may be estimated from the width of specific absorption lines. To find those specific lines, we have measured all 25 Lick indices (Faber et al. 1985; Worthey & Ottaviani, 1997). On the other hand, we did full spectral fitting with the publicly available `ulyss` code (Koleva et al. 2008, 2009), that fits linear combination of single stellar populations of various ages and metallicities and finds a global χ^2 minimum that corresponds to a single age and metallicity.

Comparing the Lick indices to the measured (modelled) ages and metallicities, we have found that $<\mathrm{Fe}>'$=1/3 (Fe_{5015} + Fe_{5270}+Fe_{5335}) best correlates with metal-

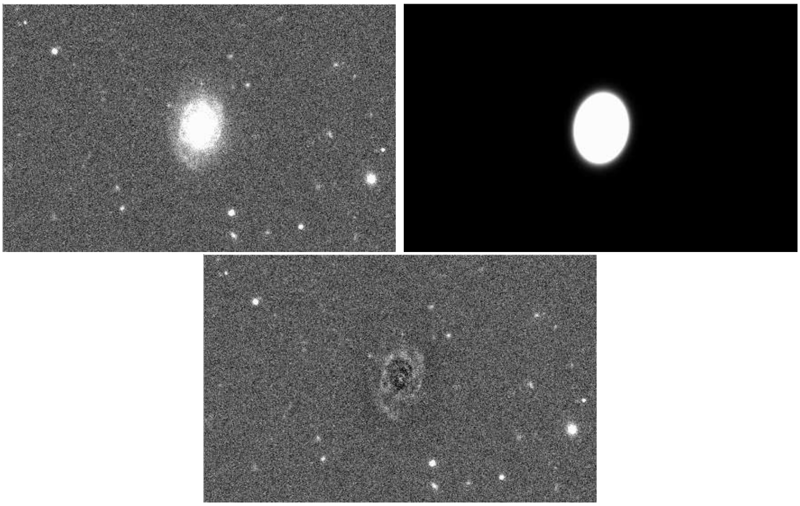

Figure 4: Surface brightness modelling trough steps. Up: input galaxy image (left) and galaxy model (right). Down: the fitting residuals from the modelling with the Sersic law.

licity and H_β best correlates with age. These two Lick indices ($< \mathrm{Fe} >'$ and H_β) will be used in the final statistical analysis as proxies for galaxy metallicity and age, respectively.

5. SURFACE BRIGHTNESS MODELLING

Surface brightness modelling with the Sersic law (Binney & Merrifield, 1998) was done using publicly available `galfit` code (Peng 2012), that is based on the non-linear least square method iteratively searching for the solution (global minimum). An example is given in the Fig. 4.

We needed to calculate Sersic index (n) and effective radius (r_{eff}) of all the galaxies from the α-sample for dynamical mass derivation, following (Taylor et al. 2010):

$$GM_{\mathrm{dyn}} = K_V(n)\sigma_0^2 r_e,\ K_V(n) = \frac{73.32}{10.456 + (n - 0.95)^2} + 0.954, \quad (2)$$

where σ_0 is the central velocity dispersion, corrected for the departure from the Gaussian function (Eq. 1) and also aperture corrected, n Sersic index and r_e effective radius.

6. PRINCIPAL COMPONENT ANALYSIS

One of the main goals of the thesis is the reduction of the multidimensional space of galactic properties to the smaller number of dimensions, sufficient to describe them. To this end, the principal component analysis (Venables & Ripley 2002) was applied on the large set of galactic properties: Petrosian radii R_{50} and R_{90}, colors made from all the combinations of magnitudes from ultraviolet to near-infrared, luminosity in g-band L_g, gas mass M_{HI}, the width of HI line at 20% of the peak W_{20}, dynamical mass of the galaxy M_{dyn}, Lick indices $< Fe >'$ and H_β as indicators of galaxy's metallicity and age and velocity dispersion σ.

After applying regression analysis where all the parameters except for the colors and the Lick indices were put in the logarithmic scale, the linear relations that were too tight were used to exclude redundant parameters. Ten galactic properties were chosen in the final set: Petrosian radii R_{50} and R_{90}, NUV-r color that well correlates with the specific star formation rate, M_{dyn} dynamical mass, M_k stellar mass, M_{HI} gas mass, luminosity in g- band L_g, Lick index H_β as a proxy for galaxy ages, maximum rotation velocity V_r as an indicator of a specific angular momentum and velocity dispersion σ.

The principal component analysis gave the same number of components as in the input parametric set, with "amplitudes" describing how relevant is the contribution of each of the input parameters to that very component. Given that only those eigenvectors with eigenvalues $\lambda > 1$ (Guttman 1954) are statistically important, there are only three independent and statistically significant components: the first one being the "size" of the galaxy that has an equal contribution from Petrosian radii, dynamical, stellar and gas masses and luminosity, the second one being the "aspect" of the galaxy with the color NUV-r as the one that most contributes and is poorly correlated with any of the other properties and the third one being the age of the galaxy (H_β).

7. RESULTS

For the sample of 2180 galaxies, selected from the HI blind survey after cross-matching with several photometric and one spectroscopic catalog, we assembled various information on galactic properties from radio and optical spectroscopy and ultraviolet, optical and near-infrared photometry. The sample is morphologically representative in the local Universe. For all the galaxies in this sample we measured velocity dispersions and higher moments of the line-of-sight velocity distribution function (3^{rd} and 4^{th} moment), the Lick indices and Sersic law parameters (Sersic index and effective radius). We have created the largest catalog of full stellar kinematics including higher moments of velocity distribution function. The sample size enables us to perform various statistical tests to make insights into galactic properties in the local Universe. The main points are:

- The increasing trend of Gauss-Hermite h_4 parameter along the Hubble sequence suggests that stellar orbits are dominantly radial and this trend increases going from late- to early- type galaxies.

- We confirm an indication that elliptical and lenticular galaxies share the origin from the statistical analysis of h_4 parameter.

- We have found a new combination of iron indices that better correlates with metallicity of galaxies than the one used in the literature ($< Fe >$).

- There are three dimensions of multidimensional space of galactic properties responsible for the present day galaxy distribution. The first two are more descriptive and may be understood as the "size" and the "aspect" of the galaxy and the third one can be identified with the galaxy ages.

In the near future, we plan to use facilities at the Astronomical Station Vidojevica, in particular the Milanković telescope, to obtain deeper photometry to study nearby galaxies in more detail.

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References

Abazajian, K. N., Adelman-McCarthy, J. K., Agueros, M. A. et al.: 2009, *Astrophys. J. Supp.*, **182**, 543.
Anderson, T. W.: 1962, *Ann. Math. Statist.*, **33**, 1148.
Anderson, T. W. and Darling, D. A.: 1952, *Ann. Math. Statist.*, **23**, 193.
Binney, J. and Merrifield, M.: 1998, *Galactic Astronomy*, Princeton University Press.
Brosche, P.: 1973, *Astron. Astrophys.*, **23**, 259.
Bujarrabal, V., Guibert, J. and Balkowski, C.: 1981, *Astron. Astrophys.*, **104**, 1.
Cappellari, E. and Emsellem, M.: 2004, *PASP*, **116**, 138.
Darling, D. A.: 1957, *Ann. Math. Statist.*, **28**, 823.
Disney, M. J., Romano, J. D., Garcia-Appadoo, D. A. et al.: 2008, *Nature*, **455**, 1082.
Faber, S. M., Friel, E. D., Burstein, D. et al.: 1985, *Astrophys. J. Supp.*, **57**, 711.
Gerhard, O.: 1993, *Mon. Not. R. Astron. Soc.*, **265**, 213.
Giovanelli, R., Haynes, M. P., Kent, B. R. et al.: 2005, *Astrophys. J.*, **130**, 2613.
Guttman, L.: 1954, *Psychometrika*, **19**, 149.
Haynes, M. P., Giovanelli, R., Martin, A. M. et al.: 2011, *Astron. J.*, **142**, 170.
Hoel, P. G.: 1971, *Introduction to Mathematical Statistics.* Wiley, New York, 4th ed.
Huertas-Company, M., Aguerri, J. A. L., Bernardi, M. et al.: 2011, *Astron. Astrophys.*, **525**, 157.
Jarrett, T. H., Chester, T., Cutri, R. et al.: 2003, *Astron. J.*, vol125, 525.
Jorgensen I., Franx, M. and Kjaergaard, P.: 1995, *Mon. Not. R. Astron. Soc.*, **276**, 1341.
Koleva, M., Prugniel, P., Ocvirk, P. et al.: 2008, *Mon. Not. R. Astron. Soc.*, **385**, 1998.
Koleva, M., Prugniel, P., Bouchard, A. et al.: 2009, *Astron. Astrophys.*, **501**, 1269.
Meyer, M. J., Zwaan, M. A., Webster, R. L. et al.: 2004, *Mon. Not. R. Astron. Soc.*, **350**, 1195.
Peng, C. Y., Ho, L. C., Impey, C. D. et al.: 2012, *Astron. J.*, **124**, 266.
Prugniel, P., Soubiran, C., Koleva, M. et al.: 2007, *VizieR Online Data Catalog: ELODIE library V3.1.*
Scholz, F. W. and Stephens, M. A.: 1987, *J. American Statist. Assoc.*, **82**, 918.
Shimasaku, K., Fukugita, M., Doiet, M. et al.: 2001, *Astron. J.*, **122**, 1238.
Taylor, E. N., Franx, M., Brinchmann, J. et al.: 2010, *Astrophys. J.*, **722**, 1.
van der Marel, R. P. and Franx, M.: 1993, *Astrophys. J.*, **407**, 525.
Venables, W. N. and Ripley, B. D.: 2002, *Modern Applied Statistics with S.* Springer-Verlag New York.
Vudragović, A., Samurović, S., Jovanović, M.: 2016, *Astron. Astrophys.*, **593**, 40.
Whitmore, B. C.: 1984, *Astrophys. J.*, **278**, 61.
Worthey, G. and Ottaviani, D. L.: 1997, *Astrophys. J. Supp. S.*, **111**, 377.