Galaxy properties

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We discuss the basic properties of galaxies, our present view of relations between them and their evolution.

1 Introduction – galaxies in the cosmological context

In the framework of the model which currently best fits the data, the ΛCDM model, we live in a Friedmann universe (uniform and isotropic) which is dominated by its dark sector: dark matter and dark energy (e.g., Planck Collaboration et al., 2015). At the same time, practically all the observational data related to the near and far Universe originates from baryonic matter, which corresponds to less that 5% of the total matter-energy balance of the present-day Universe.

More concretely, most of this information comes from observations of galaxies, whose stars contain only $\sim$ 10% of baryons present in the today's Universe (e.g., Fukugita & Peebles, 2006).

The distribution of galaxies in our local Universe is quite well known thanks to present-day large spectroscopic surveys, like 2dF (Colless et al., 2001) and SDSS (e.g., Eisenstein et al., 2011). However, to understand the evolution of galaxies and co-evolution of their properties and the large scale structure of the Universe, we need much deeper spectroscopic surveys. The presently-existing large and deep spectroscopic surveys, like VVDS (Le Fèvre et al., 2013), DEEP2 (Newman et al., 2013), zCOSMOS (Lilly et al., 2007), VIPERS (Guzzo et al., 2014), GAMA (Driver et al., 2012) reach at least to redshift $z \sim 1.5$, and some, like VVDS or VUDS (Le Fèvre et al., 2015) even up to $z \sim 5$.

In this short note we give a very brief and superficial introduction to some basic terms related to galaxy structure and evolution. We refer the interested reader to some excellent books on the subject, among which we list here only two: Mo et al. (2010); Schneider (2006).

2 Galaxies – basic ingredients

The basic ingredients of present-day galaxies are stars—usually hundreds of millions of them. Apart from stars, galaxies contain interstellar gas and dust see (e.g. Binney & Merrifield, 1998). In the framework of the ΛCDM model, they are immersed in much larger haloes of dark matter. The central parts of galaxies (at least of the massive ones) usually harbor a supermassive black hole, whose activity may be detected through the phenomenon known as the active galactic nucleus (AGN) (e.g. Magorrian et al., 1998). As such, galaxies are quite complex systems.

The main processes which drive galactic evolution are related to the evolution of their stellar, gaseous and dusty content. However, galaxies do not live alone—another important factor in their evolution are different types of galaxy interactions, starting from relatively mild ones, like stripping or harassment, to mergers of different galaxy systems. The role of the central supermassive black hole in galaxy evolution is also more and more in the center of interest (e.g. Rodighiero et al., 2015).

3 Morphological classification of galaxies in the present-day Universe and in the past

The easiest description of galaxies is the one referring to their visible shapes and structure, but this can only be done in detail for local galaxies, for which detailed imaging can be easily done.

The main "building blocks" of galactic structure are disks and bulges (otherwise known as ellipsoidal or spheroidal components). Other components which play a role in visual galaxy classification are their cores (active or composed from stars), bars (sometimes also found in the cores), spiral arms, rings and pseudo-rings, lenticles and dust lanes (e.g. van den Bergh, 1998; Buta, 2013).

The best known and most widely used system of morphological classification of galaxies is the revised Hubble sequence, or "tuning fork diagram", not much different from the form introduced originally by Edwin Hubble (Hubble, 1926). In this diagram, galaxies are divided into two main groups, which are usually referred to as early type and late type galaxies (even if—as we know today—the Hubble sequence does not itself represent any evolutionary trend).

"Early type" galaxies are elliptical, characterized by their elliptical or spheroidal shape. In Hubble's classification they have the symbol Ex, where $x = 10(a-b)/a$, with a and b being the major and minor axis of an ellipse. The values of x range from 0 to 7, with E0 galaxies being almost spheroidal, and E7 galaxies being the most flattened. Typically elliptical galaxies have no internal structure and little rotation is observed. They do not contain significant amount of gas and dust, and they do not have any ongoing star formation. They are composed mainly of old stellar populations.

"Late type" galaxies are otherwise known as spiral galaxies. They consist of a central bulge (in many aspects similar to a miniature elliptical galaxy) and a disk with spiral arms. In the Hubble classification they are denoted by a letter S, and divided into two main classes: normal spiral galaxies, consisting of a nearly spherical bulge and a disk with spiral arms, and barred spiral galaxies (SB), which contain a bar—an elongated bulge with spiral arms starting at its ends. Both these types of spiral galaxies can be additionally divided into a few classes (a, b, c) depending on the level of development of their spiral arms. Spiral galaxies of Sa, SBa type are characterized by a bright bulge and tightly wound spiral arms. Galaxies of Sb, SBb type have a dimmer bulge, the spiral arms more loose, and more stellar associations are visible. Finally, Sc, SBc galaxies have a yet dimmer bulge, open spiral arms, more dust, and more stellar associations and clusters visible. Additionally, the latest type is Sd: galaxies with a dim or almost no bulge, loose spiral structure (sometimes barely detectable), a lot of dust, gas and young stars.

A typical feature of spiral galaxies is on-going star formation in the spiral arms.

They contain dust (sometimes visible as dusty lanes), and gas. They contain young stars, but also old stellar populations are present (Roberts & Haynes, 1994).

As mentioned above, a separate intermediate type are lenticular galaxies: S0 (L). They are characterized by the ellipse axis ratio $b/a < 0.3$. Similarly to elliptical galaxies, they have no internal structure. However, they resemble spiral galaxies by the presence of a bulge (sometimes barred) and disk (without spiral arms). They are found almost solely in clusters and many studies suggest that they are not simply an intermediate type but rather the result of a different course of galaxy evolution than both spiral and elliptical galaxies, possibly affected by their environments (van den Bergh, 2009).

One more galaxy type are irregular galaxies (Irr). These are not symmetrical, they have no visible internal structure (Irr) or very weakly detectable one (Irr I). They are chaotic, and usually undergoing processes of active star formation.

After Hubble, a number of more refined classification schemes appeared. The most notable among them is a generalization of the tuning fork diagram proposed by Gerard de Vaucouleurs (which is partially visible in the presently most-often used version of the Hubble diagram, de Vaucouleurs, 1959). However, the basic division line for large bright galaxies still lies between "early type" and "late type" or "spheroidal" and "disky" galaxies, and the Hubble diagram remains the most practical classification scheme for galaxies.

According to de Vaucouleurs (1963), among local bright galaxies the most common ones are spiral S ($\sim 60\%$) and lenticular L or S0 ($\sim 22\%$) galaxies. Elliptical galaxies E are much less abundant ($\sim 13\%$). The number of irregular galaxies among large bright galaxies is very low ($\sim 4\%$), but it rises significantly for fainter galaxies, and it is speculated that they may be the dominant type at the lowest luminosities.

Of course, a large variety of "special" types of galaxies can also be listed. Among them, we can mention all the family of active galaxies: from classical quasars (QSOs), and active galactic nuclei (AGNs), which include Seyfert galaxies, radio galaxies etc. Peculiar galaxies are the ones which bear a trace of a recent intergalactic interaction which resulted in their disturbed their morphology. Also, dwarf galaxies can be regarded as a separate (in the dynamical sense as well) family of galaxies; among them, we can distinguish star-forming dwarfs like dwarf irregular galaxies (dIrr) or Blue Compact Dwarfs (BCDs), and dwarf galaxies with no star formation, like dwarf elliptical (dE) and dwarf spheroidal (dSph) galaxies.

Among "peculiar" types of galaxies we can list also low surface brightness galaxies, Starburst and post-starburst galaxies, nucleus-dominated N-type galaxies, cD galaxies (supermassive elliptical surrounded by stellar haloes, found in the centers of large clusters, and a whole zoo of galaxies whose spectrum is dominated by radiation from wavelength ranges other than the optical: [ultra]luminous infrared galaxies ([U]LIRGs), dust obscured galaxies (DOGs), sub-millimeter galaxies (SMGs) etc. (e.g. Sanders & Mirabel, 1996).

One of the main questions in present-day extragalactic astrophysics is how far, in space and time, the morphological segregation exists. The best available images of distant galaxies are those made by HST; however, they are available for limited areas of the sky only. The best available ground-based observations have visibly lower quality. Since images of distant objects are much dimmer and much more difficult to obtain, we cannot usually rely on a classification made "by eye". Consequently, the tools usually applied to classify distant galaxies are based either on colors or their luminosity profiles (like Sérsic or Gini parameters: e.g. Lotz et al., 2004).

The main question is, however: how early did disk/elliptical segregation form in the Universe? Observations indicate that basic morphological types might have started to form early—in the Hubble Deep Fields (Williams et al., 1996) we find $z < 2$ galaxies of various shapes, but not exactly similar to today's ones. More specifically, studies of the galaxies in the Hubble Ultra Deep Field (Beckwith et al., 2006) indicate that $2.2 < z < 3$ galaxies are typically smaller, bluer, and more asymmetric than their descendants. This often found asymmetry is most likely due to much more common mergers (Conselice et al., 2008). Recent studies (Mortlock et al., 2013) indicate that the massive systems acquired their shapes earlier; the elliptical formed earlier than spirals, and their relative fraction was stabilized earlier (which indicates that the formation of spiral galaxies was more prolonged in time).

4 Basic galaxy properties

As seen from the above discussion, in galaxy description we cannot rely solely on morphological features. Below, we list a few more "basic" but important properties of galaxies.

4.1 Galaxy luminosities

Our Galaxy—the Milky Way—contains $\sim 10^{11}$ stars of average luminosities $\sim 2 \times 10^{10} L_{\odot}$. The absolute luminosity of the Sun is ~ 5.48, which implies the absolute luminosity of Milky Way being ~ -20.3. Our neighbouring Andromeda Galaxy, M31, is somewhat more luminous (-20.8), while the Magellanic Clouds have luminosities ~ -18 and ~ -16.5. Luminosities of massive elliptical galaxies can exceed even $M \sim -24$. On the faint side, the faintest dwarf elliptical and irregulars are as faint as $M \sim -8$. The faintest known dwarf spheroidal galaxy has a luminosity of only $\sim 10^5 L_{\odot}$, but the faintest galaxies are, obviously, the most difficult to detect.

4.2 Angular sizes of galaxies

Galaxies are diffuse objects and they do not have clear boundaries or edges: their surface brightness gradually fades with increasing distance from the center. Then, the size of a galaxy is a matter of convention. For this purpose, we define a so-called effective radius of a galaxy, R_e, as the radius of a circle from within which half the total flux of a galaxy originates. It is most often used as a proxy of galaxy angular size.

4.3 Luminosity profiles of galaxies

Luminosity profiles describe how the surface brightness I of galaxies changes with the distance r from their centers. Typically, galaxies are bright in the center and gradually faint towards outer boundaries. However, this change of surface brightness is different for different types of galaxies.

In particular, luminosity profiles of elliptical galaxies follow the so-called de Vaucouleurs $r^{1/4}$ law (de Vaucouleurs, 1948):

$$\log_{10}\frac{I(r)}{I(R_e)} = 3.3307\left[\left(\frac{r}{R_e}\right)^{1/4} - 1\right]. \tag{1}$$

Luminosity profiles of spiral and lenticular galaxies can be divided into two regimes. Their bulges usually follow de Vaucouleurs' $r^{1/4}$ law. Disks, in contrast, are best described by the exponential formula:

$$I(r) = I_0 \exp\left(-\frac{r}{h}\right), \tag{2}$$

with h being the characteristic disk scale (e.g. for the Milky Way $h = 3$ kpc); and I_0 the central surface brightness.

A generalization of these two formulae is the Sérsic formula (Sérsic, 1963), which describes both elliptical and disk galaxies:

$$\log_{10}\frac{I(r)}{I(r_e)} = b_n\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]. \tag{3}$$

Here, n is known as the Sérsic index. It can be easily noticed that for $n = 4$ we obtain de Vacouleurs' law, while the case with $n = 1$ corresponds to the exponential relation.

In practice, the values of n are, indeed, not discrete. Galaxies display a clear bimodality in the value of the Sérsic index (e.g. Baldry et al., 2004; Driver et al., 2006) with the maxima around $n = 4$ and $n = 1$, but both peaks are very broad and they partially overlap. This bimodality in the Sérsic index is also observed seen at least up to $z \sim 1$ (e.g. Tasca et al., 2009; Krywult et al., 2014).

5 Relations between different galaxy properties

What is interesting from the cosmological point of view are not simply the properties of single galaxies, but common relations between these properties. Looking for relations between different galaxy properties, like luminosities, sizes, velocity dispersion of stars in them, surface brightnesses, morphologies, metallicities, can be used for at least two important cosmological tasks.

One of them is to find distance-independent relations between these properties. If such a relation is found, it can be used to calibrate cosmic distances and turn a specific class of galaxies into standard candles. On the other hand, relations between different galaxy properties and their evolution with time is crucial to understanding galaxy origins, formation and the relationship of the related processes to the properties of the underlying dark matter density field.

Among different relations between basic galaxy properties, there are two which are historically particularly famous and important: the Faber-Jackson relation for elliptical galaxies, and the Tully-Fisher relation for spiral galaxies.

5.1 Elliptical galaxies

5.1.1 The Faber-Jackson relation

The Faber-Jackson relation is a nearly linear relation between the velocity dispersion of stars in a galaxy (measured by the width of its absorption lines) and its absolute luminosity (Faber & Jackson, 1976). It may be used to roughly estimate distances, but in practice it is not very accurate because of the large scatter of this relation, which reaches ~ 2mag.

5.1.2 The fundamental plane

Such a large scatter might imply that just two parameters are not sufficient to describe the elliptical galaxy. What if more fundamental parameters are involved? Dressler (1987); Djorgovski & Davis (1987) proposed to introduce a three-dimensional (at least) parameter space in order to try to establish the basic relations between elliptical galaxy properties.

Such a 3D space may be composed of the galaxy effective radius, luminosity, velocity dispersion, but also central surface brightness μ and other parameters. And indeed, it was empirically shown that the relations in the 3D hyperplane are much tighter than when only a 2D plane is used. The scatter in the 2D relations, among others in the Faber-Jackson relation, results from a twist of the hyperplane in 3D. The exact physical interpretation of these relations is still not very clear; it is related to the processes of evolution of elliptical galaxies.

5.2 Spiral galaxies

5.2.1 The Tully-Fisher relation

In the case of spiral galaxies, there is a well known relation between their rotation velocity and luminosity. It is known as the Tully-Fisher relation (Tully & Fisher, 1977), relating the optical luminosity in the B filter, L_B to the rotation velocity ΔV to a certain power a:

$$L_B \propto (\Delta V)^a \tag{4}$$

The value of ΔV is measured by the width of galactic lines, and the value of a is usually ~ 4. In practice, the tightest relation, most widely used nowadays, is provided by ΔV measured as the width of the hydrogen 21cm line (Han, 1992) corrected for the galaxy's tilt with respect to the line of sight. This relation is the most accurate and yields the accuracy of luminosity estimation up to 0.3 mag. This accuracy allows it to be used for distance calibration.

5.3 Galaxy color bimodality – red sequence and blue cloud

Colors in astronomy are defined as a difference of fluxes measured in two different filters. In spite (or may be rather because) of their simplicity, color-color and color-magnitude diagrams are an important tool in describing and classification of astronomical objects, in particular in galaxy classification.

Similarly to stars, galaxies form a clear sequence on optical color-color diagrams, with elliptical galaxies being "red" (more flux in red than blue filters), and spiral galaxies – "blue" (more flux in the blue than red part of the spectrum).

Hence we define two main galaxy populations: "red sequence" (often nicknamed "old, red and dead"—spheroidal massive galaxies with no star formation) and "blue cloud" (star forming, less massive, disk-like galaxies). The histogram of galaxy colors has a form of two Gaussian curves corresponding to these two populations. This is known as galaxy color bimodality.

This bimodality is easily observed in the local Universe, and it remains visible at least until $z \sim 1.5$ (Franzetti et al., 2007). Interestingly, the bimodality observed in the distribution of the Sérsic index is highly consistent with those seen in the color distribution. There are, however, exceptions: star-forming elliptical galaxies or dusty spiral galaxies. They are not common but distinguishing these usually types requires additional information, e.g. observations in the infrared (Arnouts et al., 2013).

An additional intermediate class, named the *green valley*, has been observed, especially at $z \sim 1$ (Baldry et al., 2004). There is still an on-going discussion if it is real or spurious. And, if it is real, what is its composition? If real, most likely it is not a uniform class of galaxies but a mixture of different categories: genuine intermediate types, dusty ellipticals, inactive spirals and interacting systems (see e.g. Schawinski et al., 2014).

5.4 Interpretation of correlations between different galaxy properties

As was said before, galaxy types are strongly correlated with colors. Elliptical galaxies are red, which is reflected in the higher value of their $B-V$ color. Spiral galaxies are blue (low $B-V$ color value). However, between different spiral galaxies colors can strongly vary—it would be difficult to classify subtypes of spiral galaxies based only on colors.

When it comes to sizes, both elliptical and spiral galaxies are larger than irregular galaxies. In the optical range, elliptical and early spiral galaxies are more luminous than the spiral and irregular ones. Elliptical and early spiral galaxies are also more massive than late spiral and irregular galaxies. The mass to light ratio (M/L, indicating a ratio of the total—dark and baryonic—mass to the luminous mass) is the highest for elliptical galaxies and very low for extreme irregular galaxies. We refer the reader to the classical but still very instructive paper by (Roberts & Haynes, 1994).

Different physical properties of different morphological types of galaxies can be interpreted in terms of their different histories of star formation. The optical color results from a mixture of all populations of stars present in a galaxy. Thus, it tells us about the past history of star formation in this galaxy. The presence of areas of ionized hydrogen (HII, abundant in low mass disk and irregular systems, is an indicator of galaxy's present star formation activity. Finally, the amount of neutral hydrogen, HI, is prognostic of the galaxy's future star forming activity.

6 Galaxy types vs environment

Galaxy of different morphological types are not distributed randomly in space. As demonstrated by Dressler (1980), and confirmed later by numerous studies (Giovanelli et al., 1986; Hogg et al., 2004), in the local Universe, at $z \sim 1$ (Guzzo et al., 2014) red galaxies tend to live in dense environments (i.e. in places where the galaxy number densities are the highest—like the centers of clusters). Blue galaxies seem to prefer less dense areas. Interestingly, lenticular galaxies appear practically only in clusters (very often in their outskirts) which is a confirmation that they are not a simple intermediate galaxy type but rather a result of some more complex evolutionary processes.

7 Evolution of galaxy types

This galaxy environmental segregation is observed at least up to $z \sim 1$ (e.g. Cucciati et al., 2006). However, it is clear that at some point in the past red galaxies must have produces their stars—i.e. in this period they must have been blue. There is a rich literature (starting from Cowie et al., 1996) dedicated to the observations of downsizing—a process of gradual shift of galaxy formation from larger to smaller galaxy systems. A natural consequence of this process is the relocation of star formation from the galaxy clusters to the areas of low density, populated by less massive galaxies. However, to trace and understand this process, we need large and unbiased samples at $z \gg 1$.

8 Galaxy spectral properties and their origin

8.1 Redshift

A redshift z is defined as the relative difference between the observed (λ_{obs}) and emitted, or rest-frame (λ_{em}) wavelength of features observed in the electromagnetic spectrum of an object:

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}. \tag{5}$$

Redshift can be caused by (1) the Doppler effect (when it is related to the movements of the galaxy in a space), (2) gravitational interactions (light distorted in a strong gravitational field) and (3) most importantly, by the cosmological effects (related to the expansion of the space itself). It is important to keep in mind that the cosmological redshift does not have an interpretation in terms of the Doppler effect, in spite of superficial similarities.

8.2 Galaxy spectra

Spectra of different galaxy types contain different features which make them clearly distinguishable Kennicutt (see 1992).

Spectra of elliptical galaxies are characterized by strong absorption lines, which appear because of the presence of metals in the stellar atmospheres of the old stellar population. Emission lines appear rarely ([OII]3727A and/or [NII]6583A can be occasionally present), if some weak star formation was induced recently, i.e. by the inter-galactic interactions. But since there are no young stars and no gas, usually no emission lines are visible.

In contrast, spectra of spiral galaxies are characterized by strong emission lines, produced in gas clouds surrounding hot young stars. These emission lines are superimposed on absorption features originating from the older, underlying stellar population.

In the spectra of irregular galaxies we usually find strong emission lines, which are due to hot young stars and regions of ionized hydrogen HII which around them.

9 How did it form?

An important question in galaxy studies is whether the fact that we observe elliptical and disky galaxies can be related to their initial properties, or rather to their surroundings. No simple answer has yet been found to this problem. In particular, there are two main scenarios, whose competition is sometimes nicknamed “nature or nurture”, using the term taken from behavioral sciences (Whitmore, 1990).

In the hierarchical model of large scale structure formation galaxies form and grow in dark matter haloes, due to accretion and mergers. But the dynamics of this process and its dependence on the exact properties of the DM halo and small- and large-scale environment is still a matter of debate. Why are some galaxies red and some blue? When was this bimodality established and which are the fairest tracers of the dark matter field at different redshifts?

In the “nature” scenario, the present appearance of a galaxy is related to the dynamics of the gas infall in the very beginning of its existence, and it is controlled by its initial halo mass. In particular, in the case of the most massive haloes we expect a fast infall of gas from all directions, which causes a sudden and strong burst of star formation in the very beginning, and at the same time defines its spheroidal shape. However, the strong starburst is followed by the production of a significant number of supernovae in a short time; the feedback from these supernovae—namely, the galactic wind—sweeps out all the remaining gas from the galaxy and its vicinity and stops its star formation forever. In the case of the low mass haloes, the infall of gas is much slower, much more prolonged in time, and (at concrete moments) asymmetric. This results both in much more prolonged star formation, with no effective supernova feedback which would be able to stop it, and in the disky shape and angular momentum of a galaxy.

Such a scenario is also supported by galaxy evolutionary population synthesis models, which nicely demonstrate how different scenarios—of a strong early starburst or a prolonged star formation—lead to the formation of elliptical- and spiral-type galaxy spectra Bruzual A. & Charlot (1993)

However, galaxies do not live separated from the others: many processes can occur between them. They not only merge, but also interact in many ways when passing by each other: strip each other from gas and stars, disturb each others’ morphologies and so on. Simulations confirm that galaxy interactions can speed up the transition of a galaxy towards an elliptical type. And, indeed, elliptical galaxies are found in dense environments where the chances of interactions are high.

Then, is the fact that we observe elliptical and disc galaxies related to their initial properties or rather to their surroundings? There is no simple answer to that. Both mechanisms mentioned above tend to work in a similar direction. Most probably, in reality we have a mixture of both scenarios. However, to construct a precise scenario we need much more solid data from early epochs of galaxy formation.

10 Summary

Galaxies come in many shapes and varieties. The basic division is between non-star-forming red elliptical galaxies and star-forming blue disk-like galaxies. Galaxy properties are correlated, which is a reflection of their histories. Their detailed scenarios may depend both on their birth site (the initial properties of their host dark matter halo) and their interactions with surrounding galaxies and the intergalactic medium. We need more refined observatories than we have now to reach the epoch of galaxy formation.

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