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Evolution of galaxies: inside-out? outside-in?

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In this review I discuss the directions of building up galaxies – from their central parts towards the periphery or by gas inflow into the center starting from outer disks towards central bulges and nuclei. I stress that particular evolutionary mechanisms also shape morphological types of galaxies, so the galaxies of different types can have different directions of build up. Recent observations of various samples of galaxies, including those at high redshifts as well as nearby galaxies in different environments, allow us to conclude that elliptical galaxies evolve inside-out, while lenticular galaxies in groups and clusters evolve outside-in. The evolution of spiral galaxies is complex and depends on a sequence of gas aquisition events. The most common way is continuous formation of thin stellar disks at intermediate distances from the center.

Keywords: Galaxies: evolution

1 Introduction

Scenaria of galaxy formation and evolution are thought to be various, depending strongly on morphological type of the galaxies under consideration. Elliptical galaxies in the nearby Universe are old stellar spheroids with slow rotation and anisotropic distribution of chaotic motions; their surface brightnesses and sizes are related closely with their masses by so-called scaling relations; so scenaria of their formation and evolution must include violent loss of initial momentum and cessation of star formation. Disk galaxies – S0 and spiral ones – have more complex structure: in zero approximation, they consist of dynamically hot, centrally concentrated stellar spheroids – bulges, – and large-scale stellar disks dominated by regular circular rotation. Spiral galaxies, besides stellar populations, also contain rather abundant gaseous component, and their star formation proceeds just now revealing current building of some parts of these galaxies. Just for the description of the evolution of spiral galaxies a term of "inside-out formation" of their disks was invented, implying continuous building of the galaxies starting from their innermost parts toward the outermost regions. However, the question: what part of a galaxy, inner or outer one, was completely

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shaped first? can be posed in relation to any type of galaxies. There are observations of galaxies at high redshifts, up to 2–2.5, which witness that 10 Gyr ago the typical sizes of massive galaxies were much smaller than now, and the difference in size of disk galaxies was not so prominent or pronounced as the difference in size of elliptical galaxies (see e.g. Trujillo et al. (2007)). So in this review I will consider the preferred directions of galaxy construction for all morphological types of contemporary galaxies by referring to fresh observational data. Also the meaning of these observational findings will be put into the context of the LCDM cosmological model prescribing very particular ways of galaxy evolution depending on their morphological type. I will show that this popular cosmological scenario cannot reproduce all trends of galaxy evolution observed so far.

2 Elliptical galaxies

Since everybody believes that initially collapsed (dark-matter) structures possessed rotation momentum (Peebles 1969; Doroshkevich 1970; White 1984) and since contemporary giant elliptical galaxies lack this, the most popular scenario of the elliptical galaxy formation to date is major merging: violent relaxation accompanying it destroys regular rotation perfectly. However, a critical amount of discrepancies between the predictions of major-merger scenario and real observational data on various characteristics of nearby and distant elliptical galaxies is already accumulated. The LCDM model of the galaxy evolution requires an hierarchical sequence of major mergers, and their timescale is such that the most massive elliptical galaxies had to experience the last major merger quite recently. For example, Kaviraj et al. (2009) give a model estimate for the look-back time of the last merger event in the life of an elliptical with the absolute magnitude of $M_V = -22$ of only 2–5 Gyr (the redshift 0.1–0.6), while for a $M_V = -20$ elliptical look-back time of the last major merger of 10 Gyr is allowed. A major merger of two spiral galaxies results in their gas inflowing into the very center of the final merger product, and a subsequent star formation burst is inevitable, so the age of the stellar populations in the centers of massive elliptical galaxies must be also rather young. However, there exists a direct *correlation* between the luminosity and stellar population age in the center of elliptical galaxies, so that the most luminous ellipticals possess the oldest stellar population, namely, the ellipticals with $M_V = -22$, or stellar velocity dispersion of about 300 km s^{-1}, are older than 10 Gyr old (Nelan et al. 2005). To solve this contradiction, an idea of "dry" merging was proposed, so that only the merger of two elliptical galaxies, without gas, could produce another, more massive elliptical galaxy. However, this variant of major merger scenario is also not successful: it does not provide a well-known correlation between the metallicity and galaxy mass (Trager et al. 2000), and in general the total amount of massive elliptical galaxies does not change with time while the amount of small ellipticals rises towards the present epoch (Ferreras et al. 2009) that is inconsistent with proposed rapid recent transformation of a large number of small ellipticals into giant ellipticals.

Another strong restriction of the scenario of elliptical galaxy formation is posed by the data on radial stellar metallicity gradients. Numerical simulations of the evolution of elliptical galaxy ensemble in the frame of LCDM cosmology (Kobayashi 2004) have

allowed us to compare final stellar metallicity gradients in the galaxies without major merger events after $z = 2$ (during the last 10 Gyr) and ellipticals having suffered such events after $z = 2$. The first scenario, though allowing merging at very high redshifts, is in fact some analogue of "monolithic collapse" as an alternative to hierarchical assembling. Simulations have revealed strong dependence of the metallicity gradients on the presence of major merger evolutionary stages. If the galaxy has experienced major merger after $z = 2$, violent relaxation has smoothed any radial dependencies, and the metallicity gradient can be only more shallow than –0.3 dex per dex in radius. If we observe a steeper gradient, it is a certain proof that the galaxy evolution was quiescent during the last 10 Gyr. We (Lyskova et al. 2014) have measured extended radial metallicity gradients with a high precision and fine spatial resolution in a handful of nearby giant elliptical galaxies. All *inner* metallicity gradients, within $0.5R_e$, have appeared to be very steep, steeper than –0.4 dex per dex in radius. In the outer parts, at $R > R_e$, some galaxies demonstrate much more shallow gradients. By obtaining for the first time such "broken" metallicity gradients we (Baes et al. 2007) had immediately concluded that they give evidence for a two-stage process of formation for our elliptical galaxies: the inner parts were formed at very high redshifts in some kind of "monolithic collapse" providing steep metallicity gradient while the outer parts were built up later by multiple minor mergers. If these minor mergers were predominantly "wet" or "dry", a variety of stellar population *age* gradients would arise; this variety is observed indeed (Petty et al. 2013). Later other observations of broken metallicity gradients, with a steep inner part and shallow outer one, have been published for some other elliptical galaxies (Pu et al. 2010; Coccato et al. 2010), and the scenario of multi-stage elliptical galaxy formation excluding major mergers have become more and more popular.

But an even stronger impulse to the revision of the scenario of elliptical galaxy formation was given by a discovery of the strong size evolution for a population of very massive quiescent ("passive") elliptical galaxies at $z \approx 2$ to $z = 0$: during these 10 Gyr the typical radius of a massive, $M_* \geq 10^{11}$ solar masses, galaxy has grown by a factor of 4–5 (see e.g. Trujillo et al. 2007, Toft et al. 2007, van Dokkum et al. 2008 among many others). It means that the volume density of stellar matter in elliptical galaxies was larger by two orders of magnitude at $z \geq 2$! To explain such extreme evolution, several hypotheses were proposed. For example, in Bezanson et al. (2009) three possible ways of rapid evolution of the sizes of elliptical galaxies, among those – major ("equal-mass") merging and multiple minor merging ("accretion" of satellites), are considered. Major merger as a common way for elliptical galaxy evolution is rejected because major merger events lead to the size growth proportional to the mass growth. If majority of elliptical galaxies have increased their size by a factor of 4–5 during the last 10 Gyr, the population of 2×10^{11} solar mass ellipticals at $z = 2$ would become now a population of $>10^{12}$ solar mass ellipticals, similarly numerous. However, such massive ellipticals as a population are absent in the present-day Universe. Also, to match the population of massive ellipticals at $z = 2$ to that at $z = 0$ one needs to drop their stellar velocity dispersion while major mergers do not change this characteristic of a final-product galaxy. In Bezanson et al. (2009) a comparison of the evolution of the very central parts of the galaxies, $R < 1$ kpc, and the evolution of the galaxies as a whole, $R < R_e$, is made, and much milder evolution of the galactic cores is found. The only scenario that satisfies all these complex observational data on the evolution

of sizes, densities, and dynamical state of the elliptical galaxies, resolved along their radius, is the scenario of multiple minor mergers. It results in size growth proportional to the square of the mass growth so providing strong size evolution under quite mild mass evolution, and it affects mostly outer parts of galaxies. If some minor mergers are "wet" and accompanied by gas inflow into the center and by formation of young, dynamically-cold stellar populations, they would diminish stellar velocity dispersion in accordance with the observational direction of the elliptical galaxy evolution. So the scenario of "inside-out" formation of elliptical galaxies through multiple minor merging is now mostly accepted by the extragalactic community.

3 Lenticular galaxies

Lenticular galaxies resemble spiral galaxies by their global structure: they have large-scale stellar disks and centrally concentrated bulges. However, they lack spiral arms and so they usually lack large-scale star formation. This evident difference has provoked the simplest approach to the S0 galaxy formation scenario: they are believed to form from spirals by so-called "quenching" star formation in their disks. A variety of physical mechanisms are proposed to quench star formation in a galactic disk, and all of them require dense environments: tidal "harassment", ram pressure by intergalactic hot medium, "starvation" of star formation due to outer gas reservoir stripping, all these mechanisms work only in clusters and rich X-ray groups. There are some observational evidences in favour of this scenario. Dressler (1980) found that S0 galaxies constitute the dominant population, up to 60% of all galaxies, in nearby galaxy clusters, and later tracing the galaxy populations in clusters and groups up to redshifts of 0.5–0.8 with the Hubble Space Telescope he has confirmed the Butcher–Oemler effect: at $z \approx 0.4$ S0 population in clusters and groups is replaced by blue (spiral?) one (Fasano et al. 2000; Wilman et al. 2009). The natural conclusion was made that at $z \approx 0.4$ we see transformation of spirals into lenticulars in the process of cluster assembling. But it means that only 4 Gyr ago nearby lenticulars were spirals, and experienced star formation in their disks. Also since before $z \approx 0.4$ star formation in spiral disks – progenitors of S0s – had to proceed during several Gyrs, we would expect the solar abundance ratios in the stars of nearby S0 disks.

These consequences of the commonly accepted scenario of S0 galaxy origin are verifiable, and I have undertaken an observational project suitable for this purpose at the 6-m telescope of the Special Astrophysical Observatory. Deep long-slit spectral data for a sample of nearby S0s observed with the reducer SCORPIO (Afanasiev & Moiseev 2005) have been acquired, and the ages, metallicities and magnesium-to-iron ratios of the stellar populations resolved along the radius have been obtained through calculations of the Lick indices Hβ, Mgb, Fe5270, and Fe5335 (Sil'chenko et al. 2012). The most of S0s under consideration belong to groups, with a few galaxies from the Virgo cluster, and only one is quite isolated. We have found that the large-scale disks of our targets are mostly old, with the mean stellar age of 60% galaxies larger than 10 Gyr. Moreover, their stars are prominently magnesium overabundant that means that these disks were formed with a very brief timescale – less than 1 Gyr. All these findings contradict completely to the expectations inspired by the commonly accepted scenario of spiral transformation into S0s during accretion onto the clusters

and groups at the redshifts of $z < 0.5$. Interestingly, the bulges in our sample have appeared to be mostly younger than the disks of the same galaxies. We have suggested that the central parts of S0 galaxies may be rejuvenated just during their accretion onto the clusters and groups 4–7 Gyr ago because all the mechanisms proposed so far to cease star formation in spiral disks in dense environments result indeed in the gas inflow and its concentration in the centers of the galaxies affected. The subsequent nuclear star formation bursts seem to be very probable, and blue galaxies seen in clusters and groups at $z > 0.4$ by Fasano et al. (2000) and Wilman et al. (2009) are perhaps those caught just during their bulge rejuvenation.

The effect has appeared to be strongly dependent on the environment, and just in the sense expected in the frame of our suggestion. Recently a study by Johnston et al. (2014) of the stellar populations in the bulges and disks of S0 galaxies – members of the Virgo cluster – has been published. In their sample, the bulges are almost always younger than the disks (only two galaxies fall off this relation), and the magnesium-to-iron ratios are higher in the disks than in the bulges. Meantime, our study of the sample of strictly isolated S0 (Katkov et al. 2014, 2015) has revealed the rough equality of the ages between the disks and bulges, and both the ages of the bulges and the ages of the disks are homogeneously distributed from 1 to 15 Gyr, so implying the absence of particular epoch of S0 formation in extremely rarified environment.

By summarizing these properties of the stellar populations in the disks and bulges of nearby S0 galaxies in different environments, we discard their shaping by recent quenching of star formation in the disks of spirals and propose instead a new scenario of general evolution of disk galaxies. We think that *all* disk galaxies started their careers as lenticulars. Indeed, at redshifts of $z > 1.5$–2 violent star formation in clumpy gaseous disks of early disk galaxies is observed (Elmegreen & Elmegreen 2005); the timescale of this star formation governed by gravitational instabilities in very gas-rich disks has been measured to be shorter than a few hundred billion years (Genzel et al. 2008). After these brief violent starforming events stopped by gas depletion and feedback from supernovae just thick stellar disks with magnesium overabundant stellar populations are expected to be formed some 10 Gyr ago. In our own Galaxy, the thick stellar disk has the age of 10–11 Gyr, magnesium-overabundant stellar population (Bernkopf & Fuhrmann 2006; Schuster et al. 2006), and since there is a gap in stellar ages between the thick and the thin disks (Fuhrmann 1998), evidently, after the formation of the thick disk, for 2–3 Gyr, or between $z = 2$ and $z = 1$, our Galaxy was a *lenticular* one. At $z < 1$ galactic disks become dynamically colder, thinner, bar-unstable (Kraljic et al. 2012), and their star formation is supported mainly by gas accretion from outside. So their subsequent evolution, including the morphological one, is fully prescribed by the outer conditions of cold gas accretion. Since in clusters, with their deep gravitational potential well and hot intergalactic medium, possibilities to retain cold gas reservoir or to attract cold cosmological filament supply are negligible, the primordial lenticular galaxies in clusters remain lenticulars forever providing the dominant population of today clusters. The most galaxies in the field, like our own Galaxy, start cold gas accretion onto their disks at $z < 1$, cool the dynamical state of the stellar component, ignite star formation, and become spirals.

Taking into account that the majority of nearby S0s populate groups and clusters and that just in those types of environments their bulges look younger than the large-scale disks, we conclude that lenticular galaxies formed *outside-in*.

4 Spiral galaxies

It is just for spiral galaxies that the "inside-out" scenario was proposed firstly some twenty years ago. Initially it was a purely theoretical, analytical approach: in Wang & Silk (1994) it was argued that under the assumption of flat rotation curve (that is consistent with observational statistics) the timescale of gravitational instability development grew with radius, being related to the epicyclic frequency of the differential rotation; and so star formation timescale had to grow along the radius too. The inside-out scenario arose naturally in Wang & Silk (1994), without any outer gas supply involvement. However already in 1997 the inside-out scenaria of the structural *and* chemical evolution of stellar disks in spiral galaxies were developed where the inside-out direction of the disk building was related to the inside-out increase of the outer gas accretion timescale (Bouwens et al. 1997; Chiappini et al. 1997). It was a very natural idea: the accretion rate is higher in the center of a galaxy because the local gravitation is stronger there. However this idea looks natural only if we consider *hot* gas accretion: being homogeneously distributed over full volume of the spheroidal dark halo, this virialized gas sinks vertically onto the disk due to energy losses and momentum conservation, and in addition the low-momentum gas is more abundant than the high-momentum gas (Bullock et al. 2001) providing higher amount of the gas supply for the inner parts of galactic disks. Meantime, the direction of gas accretion may be quite different from this, if the bulk of the accreted gas is *cold* and comes from narrow cosmological filaments – this accretion mode is proposed and propagated by Avishai Dekel (Dekel & Birnboim 2006; Cattaneo et al. 2006; Genel et al. 2012). The cold gas accretion is thought to proceed along highly collimated streams and reaches firstly the outer parts of galactic disks feeding star formation there. So if the dominant gas accretion mode in the disks of spiral galaxies is the *cold gas accretion*, the disk formation "outside-in" seems to be preferable. Presently there is no concordance between cosmologists-theoreticians about the dominant mode of outer gas accretion in spiral galaxies, especially taking into account the unlucky circumstance that the expected outer gas accretion is not observed up to now at all.

As for observational evidences for the direction of the disk building, they are numerous and contradictory. For example, by studying the evolution of the disk truncation radius in spiral galaxies over the last 8 Gyr, Trujillo and Pohlen (2005) have found that it has increased by some 1–3 kpc with cosmic time; it is mild evolution, and it is directed inside-out. Also very rich information allowing us to refine the picture of the present star formation processes in galactic disks was provided by the observations of the ultraviolet space telescope GALEX. With surveying UV images of nearby spiral galaxies, the team of GALEX has discovered so-called eXtended Ultra-Violet (XUV) disks (Thilker et al. 2007) prominent star formation proceeds beyond the optical borders of galaxies in about 30% of all nearby disk galaxies. At first glance, we see just present building of the outermost parts of galactic disks so the inside-out scenario works. But in course of studying XUV-disks, the common view shifts more and more from smooth expansion of star formation inside-out through the disk, in its equatorial plane, to wet merger events – drastic gas accretion from outside onto the outer disk borders, or something like cold gas accretion from filaments. Kinematics of HI tracing XUV-disks is often decoupled from the kinematics of the gas in the inner parts of galaxies. The gas metallicity demonstrates a sharp drop at the edges of

optical (stellar) galactic disks, with subsequent flat distributions at rather low level (Bresolin et al. 2009; Lehner et al. 2013); in Lehner et al. (2013) a low metallicity, [Z/H]≈ -1.5, of some LLS ("Lyman-limit Systems") seen in spectra of distant quasars as systems of absorption lines at intermediate redshifts, is attributed to primordial gas accreted onto the outer parts of galactic disks, at radii more than 25 kpc. More and more facts are accumulated in favour of domination of cold gas accretion from cosmological filaments.

A very interesting field of spiral disk investigation is that of surface photometry and colour profiles construction. The early investigation by Bakos et al. (2008) has revealed that the bluest radius in late-type spiral galaxies is that of "break", where the truncation of the surface brightness profile starts. If we suggest that the colour in the disks of late-type galaxies reflects star formation intensity, and calibrate mass-to-light ratio of stellar population with the evolutionary synthesis models, we obtain surface *baryon mass density* profiles lacking any breaks or truncation. Recent publication of a much more extended survey Pan-STARRS1 has confirmed that truncated surface brightness profile appearance is mostly caused by a ring of star formation superimposed on an older extended stellar disk (Zheng et al. 2015). The mass density profiles represent mostly single unbroken exponentials. Hence, the disks of spiral galaxies are built neither inside-out, nor outside-in; they grow middle parts of their disks in ring-like zones of enhanced star formation.

5 Conclusions

By inspecting typical structures and stellar population properties in the extended bodies of nearby galaxies of different morphological types, we have established that elliptical galaxies built up their bodies inside-out, through minor merging; and lenticular galaxies, though being early-type as ellipticals, but quite different dynamically, evolve outside-in and rejuvenate their bulges recently, after shaping completely their outer stellar disks at $z > 1$. As for spiral galaxies, their evolution depends probably very strongly on the regime and geometry of the outer gas accretion; in many cases they can grow their disks instaneously at any radius, without definite order, through star formation in ring-like zones at intermediate radii.

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