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The present stellar populations and the origin of galaxies

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I discuss the present state of our knowledge on the properties of stellar populations in galaxies of various types at various redshifts and restrictions which these data pose on the scenaria of galaxy formation. Up to date, observations contradict the hierarchical paradigm which is the part of the modern ΛCDM cosmological model. There are some promising ideas how to eliminate discrepancies, and these ideas are also discussed in the present review.

Keywords: Galaxies: evolution

1 Introduction

There are two ways to study the evolution of galaxies. One can study in detail properties of stellar populations in nearby galaxies of different sizes and morphologies and to try to reconstruct the sequence of events resulting just in such present stellar populations. This approach is evidently model dependent. Another way may seem to be more direct: we can look at galaxies at different redshifts which are in fact the galaxies *in the past*. Indeed, when we look at galaxies at $z = 0.5$, we see the galaxies 5 Gyrs ago; when we look at galaxies at $z = 1$, we see the galaxies 8 Gyr ago, etc. By observing the full range of redshifts, we would observe in fact the full range of time moments of the galaxy evolution. However, it is a true illusion that this approach is direct and model independent. The galaxies at high redshifts *are not the same* as the galaxies around us; they have often quite different appearance and characteristics, dissimilar to those of nearby galaxies. To reconstruct an unified evolutionary sequence, we must connect the nearby galaxies and the high-redshift galaxies. The task is not trivial; and of course, all the solutions are model dependent.

The most popular model which is now used to connect the galaxies at different redshifts into one evolutionary sequence is the cosmological ΛCDM concept including the so called hierarchical paradigm. The central point of the ΛCDM concept is the dominance of dark matter over the baryon matter. The whole evolution of the Universe structure including galaxy formation is governed by gravitational interaction of the dark matter clumps which are called 'dark halo' after they are shaped at last.

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Baryons must follow the dark matter. The hierarchical way of galaxy formation is inevitable in the frame of the ΛCDM concept: small dark-matter clumps must collapse first, and later, in the course of multiple mergers of smaller units, larger dark haloes form. The baryons are thought to be coupled with the dark matter, so large luminous galaxies must form much later than the dwarf ones. Also there are rigorous limitations on the dominant morphological type of galaxies at different moments of the Universe evolution imposed by the dynamical consequences of galaxy mergers which are the key points of the galaxy evolution under the ΛCDM concept.

The morphological classification of galaxies which is used presently is so called 'fork' of Hubble [1]; the historical terms 'early-type galaxies' and 'late-type galaxies' reflect the evolutionary sense of the Hubble morphological sequence which he himself put into the 'fork'. A galaxy is thought to be composed of two main large-scale structure components: extended stellar disk and centrally-concentrated stellar spheroid, a bulge. Elliptical galaxies which are at the left end of the Hubble morphological sequence represent a naked spheroid. Hubble [1] thought them to be the initial stage of galaxy evolution so they were called 'early-type galaxies'. When going to the right, the stellar disk contribution increases, and the most 'right' galaxies have **only** disks. They were called 'late-type galaxies' because Hubble thought that it took long time to form extended stellar disks with a lot of subtle features, and that the galaxies with large disks were formed the last.

The present view on the evolutionary sense of the Hubble morphological sequence is opposite to the opinion of Hubble himself. Now cosmologists think that the disks form first, by the halo gas cooling and smooth accretion onto the rotation plane with subsequent star formation, so 'pure-disk' galaxies must form earlier than elliptical ones. The stellar disks are rather fragile, they cannot survive major mergers, so ellipticals form later, by major mergers of late-type galaxies. In principle, this scheme is very simple and may be calculated quantitatively in the frame of the adopted ΛCDM concept. Parry et al. [2] give the following mean moments of the last major merger: $z = 1.3$–1.4 for spirals and $z = 0.4$–0.5 for ellipticals, both types brighter than $M_B = -18.7$. Cosmologists can also calculate exactly the 'morphological mix' at every moment. But here we meet a discrepancy between the theory and observations. Around us, at $z = 0$, late-type galaxies represent a majority (excluding very dense environments like clusters). For example, Loveday [3] mentions the following proportions among his nearby galaxy sample consisting of about 15000 field galaxies of the southern sky: E:S0:S:Irr=0.12:0.18:0.56:0.04 (the remaining 10% have uncertain morphological classification). But according to the calculations of the ΛCDM concept, massive pure-disk galaxies cannot exist at all: every galaxy with the typical mass of 10^{11} solar masses, like the Milky Way, must suffer at least one major merger during the last 8 Gyr, and its old thin stellar disk must be destroyed. However, they exist. It is a puzzle confusing cosmologists, the problem which has no solution yet. The other problem is that the theory predicts too many dwarfs at low redshifts and too few giant galaxies at $z = 1$–2; for example, Conselice et al. [4] demonstrate that the galaxies with $\log(M/M_\odot) > 11.5$ are predicted by the famous Millenium Simulations (e.g. [5]) with the deficit of 1.5 orders at $z = 1$ and with the deficit of 2 orders at $z = 2$. The hierarchical paradigm contradicts obviously the observational results on the luminosity and mass density of the most massive galaxies at high redshifts.

Elliptical and spiral galaxies as they are seen around us preserve their appearance

up to $z = 1$; during the last 8 Gyr the Hubble 'fork' is in place. But at higher redshifts the galactic morphologies change dramatically. The high-resolution, deep imaging made by the Hubble Space Telescope for several 'Hubble deep fields', HDFs, has revealed quite different morphologies of galaxies at $2 < z < 3$ [6]: they are much more compact than the nearby galaxies, with the typical sizes less than 1 kpc, and are assembled often into 'chains' and 'nests' implying common galaxy interaction at these redshifts. At the first glance, we see merging as predicted by the hierarchical paradigm. But the space densities at $z = 0$ and at $z = 3$ are not directly consistent: the number of star-forming galaxies at $z = 3$ is roughly equal to the number of massive spheroids at $z = 0$ while if the star-forming galaxies at $z = 3$ are condemned to merge, the products of merging must be obviously less numerous by several times. In any case, morphological types of high-redshift galaxies – Lyman-break galaxies (LBG) at $z = 3$–5, distant red galaxies (DRG) without star formation or blue star-forming BzK at $z = 1.5$–3 – have to evolve into ellipticals and spirals by some ways, and these ways are far from being clear now.

2 Elliptical galaxies

Elliptical galaxies are thought to form through so called 'major merger', or by merging galaxies of comparable masses, with the mass ratio not less than 1:4. The very idea was claimed 30 years ago by Beatrice Tinsley and Richard Larson [7] after long insuccessful efforts of Larson to 'form' *non-rotating* elliptical galaxies by a monolithic collapse: due to moment conservation, the monolithic collapse gave stellar disks with fast rotation, and only after merging two rotating disks one could obtain a spheroid whose kinetic energy was confined to chaotic stellar movements, in accordance with observations. Later the idea of multiple mergers has found its central place in the ΛCDM concept because with the massive dark haloes surrounding every galaxy the mergers became dynamically inevitable in any pair or bound group.

Elliptical galaxies as an ensemble have some common properties and so called scaling relations which must be reproduced by any viable scenario of their formation. One of the key property is rather slow rotation discovered by Illingworth [8] which requires major merger (but see also the recent alternative results by the SAURON team on the 'slow' and 'fast rotators' among nearby elliptical galaxies [9]). The other property is luminosity-colour correlation [10] which is treated traditionally as a mass-metallicity relation: more massive elliptical galaxies are supposed to have more metal-rich stars. In 70th, when the scenario of monolithic collapse was popular as a formation mechanism for elliptical galaxies, the mass-metallicity relation was explained by the onset of galactic wind phase after star formation burst and supernova feedback: in massive elliptical galaxies with a deep potential well the gas had to be retained till its full exhaustion, star formation had to last long, and more metals had to be produced with respect to dwarfs which could not retain their gas inside their shallow potential wells. When Tinsley and Larson [7] proposed major merging instead of monolithic collapse to form slow-rotating elliptical galaxies, they introduced star formation bursts accompanying every merging, to force additional heavy-element production to be related with the galaxy mass growth. But when this merger mechanism has been incorporated into the ΛCDM concept imposing very certain time scales to

all gravitational processes, the most massive elliptical galaxies have been claimed to be formed the last, quite recently, by major mergers at $z = 0.4$–0.5 [2], and this has meant that they must have rather young stellar populations, and more younger stellar populations must inhabite more massive elliptical galaxies.

Meantime, observational data contradicts this point severely. The statistics on the nearby early-type galaxies shows that there exists an opposite correlation: the more luminous galaxies have the older stellar populations ([11–13] and many others). In general, elliptical galaxies have much older stellar populations than spirals, though according to the ΛCDM concept they must form later. To solve this problem, cosmologists have proposed major mergers producing giant elliptical galaxies to be 'dry'; the hypothesis of 'dry mergers' is discussed for the last years with enthusiasm. Indeed, if the merging galaxies have no gas at all, their merger would not be accompanied by a star formation burst, and though the giant elliptical galaxy is 'formed' (shaped) recently, it would consist of old stars born long ago in the smaller galaxies which later have merged into a big one. The scenario of 'dry merger' solves the problem of old stellar populations in giant elliptical galaxies; but unfortunately it eliminates completely the mass–metallicity relation.

However, this mass–metallicity relation is in general a puzzle. An old idea about a role of galactic winds does not work now, because studies of detailed chemical composition of the stellar populations in giant elliptical galaxies have shown their magnesium overabundance [14] which has been explained by a very brief duration of the main star formation episode, much shorter than 1 Gyr. Moreover, observational statistics has revealed a correlation between the magnesium (alpha-elements) overabundance and the mass of the galaxy [11, 13, 15]. It means that in more massive galaxies the main star formation event is shorter – quite opposite to the predictions of scenaria with galactic winds. To retain the mass-metallicity relation, we must suggest that star formation in massive galaxies is much more efficient than in low-mass ones; but physical reasons for such correlation are quite unclear [16].

Some quite recent observational data on nearby ellipticals put in doubt the very major merger as a basic mechanism to form elliptical galaxies. Besides the mentioned above statistics of the SAURON on the stellar rotation in elliptical galaxies, these are also data on the metallicity gradients. The common view is that typical metallicity gradients in elliptical galaxies are of order of $\Delta[\mathrm{m/H}]/\Delta \log r = -0.2$ dex per dex, the stellar metallicity decreasing along the radius. Such shallow metallicity gradients are consistent with the scenario of major merger [17]: merging makes shallower all initially steep radial dependencies by violent star mixing. But these metallicity gradients have been estimated mostly from broad-band photometry and line-index analysis within the radii less than one effective radius. Recently Baes et al. [18] have published metallicity gradients in 4 giant elliptical galaxies upto 1.5–3 effective radii. We have found that the dependencies of [m/H] on $\log r$ are not linear over the full radial extension of the galaxies. Instead, a break of these dependencies is typically present at $r \sim 0.5 r_e$: within $0.5 r_e$ the gradients are steep, $\Delta[\mathrm{m/H}]/\Delta \log r < -0.5$, inconsistently with the major merger scenario, and beyond $0.5 r_e$ the metallicity gradients are negligible or even inverted implying perturbance of the outermost regions of elliptical galaxies, the most probably by minor merging small satellites of various stellar ages and gas contents.

3 Spiral galaxies

Spiral galaxies possess much more complex structures than the elliptical ones; they are multi-component stellar systems. Our own Galaxy consists of the thin stellar disk, the thick stellar disk, the bulge and the extended stellar halo. The former two subsystems are 'flat', in the sense that their thickness is much smaller than the radial extension; but the thin disk is dynamically cold and possesses spiral arms while the thick disk is dynamically hot. The latter two subsystems are spheroids: the bulge is centrally concentrated, with the radius of a few kiloparsec, and the halo is extended, up to 20–50 kpc. Interestingly, the properties of the stellar populations are almost identical in the thick disk and in the bulge; both are old, ~ 10 Gyr. The halo is even older and much metal-poorer; the thin disk is the only subsystem possessing a lot of young stars. But the oldest stars of the thin disk have the age of about 9–10 Gyr (for example, the open clusters NGC 6791 and Berkeley 17 [19] or some field stars [20]), and so no severe dynamical perturbations have heated our thin disk starting from $z = 1$.

But whereas our Galaxy has a some kind of bulge (though, according to some last opinions, it may be a pseudobulge, not a real spheroid!), there exist spiral galaxies of later morphological types, which have no bulge at all. Cosmologists do not know how to form pure disk galaxies; there is no place for them within the ΛCDM concept. Cold stellar disks are very fragile. Major merger destroys them completely. Let us even suggest that major mergers are a rather rare event, and not all disk galaxies suffer it during the last 8 Gyr. But minor mergers are very common, and the lesser mass ratio, the more frequent these events are. Minor mergers 'heat' stellar disks, make them thick and featureless. Moreover, such a large dark halo as the dark halo of the Milky Way is itself a product of multiple merging and consequently contains a lot of 'substructures' – dark-matter clumps, the remnants of smaller haloes which have been merged. These dark-matter clumps being distributed over the dark halo volume have elongated orbits within the common gravitational potential; they impact the stellar disk many times during the lifetime of a galaxy, and again, they heat it. Old thin stellar disks cannot survive for several Gyr.

Observational data give evidence for the presence of full-size spiral galaxies at $z = 1$; the size evolution of spiral galaxies between $z = 1$ and $z = 0$ is negligible [21]. And the last cosmological simulations have succeeded to form full-size disks just to the required moment, 8 Gyr ago; but there is no ideas how to save these thin stellar disks between $z = 1$ and $z = 0$.

Another long-standing problem of the spiral galaxy formation in the frame of the modern cosmological concepts is a correct reproduction of the Tully-Fisher (TF) relation. The Tully-Fisher relation [22] is an observational correlation between the galaxy luminosity and the maximum rotation velocity. This correlation is not a trivial fact because the luminosity characterizes the stellar (baryonic) component of the galaxy, and the rotation velocity refers to the dark matter content since just the dark matter gives the dominant contribution into the galaxy mass. The slope of the relation is close to 4 in the near-infrared photometrical bands. Cosmological simulations reproduce the TF relation with the correct slope, but there exist problems with the zero-point and with the scatter of the individual galaxies around the common relation. In general, the model galaxies have a smaller moment for their luminosity than it is

found in reality [23]. The only effective method to overcome this discrepance known up to now is to tune finely supernova feedback after star formation burst. One of the most successful simulations of the TF relation in the frame of the ΛCDM concept is the work by Governato et al. [24]. The combination of UV background and SN feedback has provided realistic exponential radial density distributions of stars in the disks, increasing moment and decreasing a number of 'satellites' (clumps) inside the galaxy dark-matter halo. However, everything must be paid: an intense SN feedback, in its turn, heats the stellar disk and makes it thicker. The problem of improbability of old thin stellar disk existence within the ΛCDM concept remains unsolved.

An interesting issue is a presence of non-axisymmetrical perturbations in the stellar disks – namely, the presence of bars. Bars are rotating wave patterns. Now dynamical models allow to form a bar within the gravitational well of a (live) dark halo. But after the rotating bar forms, it is condemned to decelerate soon due to dynamical friction with the dark halo [25]. Meantime, all the bars studied to date in the nearby galaxies are the fast bars [26]. This requires the central density of the dark haloes to be very low, insignificant with respect to the central density of baryons. This requirement is in line with the known discrepance between the simulated dark matter density profiles demonstrating central cusps [27] and observed rotation velocity curves implying isothermic density cores in the centers of disk galaxies. This discrepance is another unsolved problem of the ΛCDM concept.

4 'Downsizing' and feedback

The correlation between the stellar age and the mass of an elliptical galaxy mentioned in the Section 2 reflects the common situation with the galaxy evolution observations in the Universe: it is referred in the literature as 'downsizing'. The downsizing is in fact an opposite direction of the evolution with respect to the hierarchical paradigm: the massive galaxies are first to form, consequently, at $z = 0$ they seem to be the oldest, whereas dwarf galaxies continue their star formation up to now, so they are lasting their birth and shaping up to $z = 0$. The downsizing reveals numerous manifestations. In particular, the direct counts at 3.6–4.5 μm with the cosmic infrared telescope Spitzer [28] shows that the space mass density of the most massive galaxies, $M > 10^{12} M_{\odot}$, at $z = 3$ is exactly equal to their space mass density at $z = 0$, so they are completely assembled during the first 1–2 Gyr of the Universe life. Less massive galaxies, $10^9\, M_{\odot} < M < 10^{11} M_{\odot}$, have assembled about the half of their stellar mass at $z < 0.4$, or during the last 4 Gyr. If one consider localization of the intense star formation in various epochs, here one see again downsizing. Presently, star formation is concentrated mostly in low-mass galaxies. And up to $z = 2.5$ the 'mean' star-forming galaxy is less massive than the 'mean' quiescent galaxy; but at $z > 2.5$ the situation changes, there the space number density of the massive galaxies with intense star formation exceeds such for the low-mass star-forming galaxies [29]. One can say that the bulk star formation, starting in the most massive galaxies whose formation has been fast and effective, has later moved into the dwarfs where it continues at much lower level up to now.

Is it possible to establish consistency between the 'downsizing' observed and the hierarchical paradigm required by the cosmological theory? Yes, there are proposi-

tions which make it possible. The most popular idea of the last years is feedback of active galactic nuclei. Indeed, a correlation is known from the observations between the mass of the nuclear black hole and the mass of the galaxy stellar spheroid [30, 31], so the presence of an active nucleus is a privilegy of massive luminous galaxies, predominantly of early morphological types. Central black holes accumulated their mass at very early stages of galaxy evolution: the quasars at $z \sim 3$ have the same mass, $\sim 10^9 M_\odot - 10^{10} M_\odot$ [32], as the most massive central black holes at $z = 0$. So a very promising idea is that a central black hole in an early-type galaxy has had a burst of its activity just after the main burst of star formation in the galaxy which provided it with a fuel, namely, with the gas having lost its moment in a violent turbulence accompanying the star formation burst. The burst of quasar-like activity had to heat the remaining gas and to stop the star formation leaving all the stars to evolve passively from $z \sim 3$ to now. The idea that the nuclear activity can heat the ambient gas over the full volume of a giant galaxy has come from the study of cooling flows in the centers of giant elliptical galaxies and galaxy clusters where just the nuclear activity is thought to prevent strong gas cooling and the star formation which is failed to be found despite the great efforts [33–35]. The idea has been incorporated into the cosmological simulations of galaxy formation, and indeed, has given an appearance of downsizing in the global star formation distribution at high and intermediate redshifts [36, 37]. Since the most massive black holes inhabit the largest galaxies, at least, in the nearby Universe, one may expect that the scenario reproduces qualitatively the correlation between the mean age of the stellar populations and the mass of elliptical galaxies. However, the discrepance between the theoretical and observed timescales of the galaxy formation remains: no cosmologist can explain 100 times more numerous massive galaxies at $z > 2$ than it has been predicted by the ΛCDM simulations. The parameters of the present ΛCDM model are tightly restricted by the data on the cosmic microwave background anisotropy, so the timescales of galaxy formation (or, more exactly, of the dark halo mass distribution evolution) are restricted too. Together with the other problems of the ΛCDM model, such as the existence of long-lived thin stellar disks, the problem of rapid complete shaping of massive galaxies remains to be solved by the cosmological theory.

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