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The origin of morphological types of galaxies *

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Contents

Abstract. **Galaxies in the modern Universe demonstrate very diverse shapes. They can be one-component stellar spheroids (elliptical galaxies) or complex systems including compact stellar spheroids in the centers and extended flat stellar disks (spiral and lenticular galaxies). The morphology of the galaxies is related with other physical parameters: rotation velocities, current star formation rates, and stellar population ages. The problem of morphological type origin is persistently discussed for the last hundred years, and the dominant paradigm changes every time. Last years it becomes clear that the main agent of galaxy evolution is nonstop outer matter accretion; hence it is just the time to associate the morphological type origin with the properties of this outer accretion and with its secular change during billion years of the Universe evolution.**

Keywords: evolution of galaxies, morphology of galaxies, astronomical observations

1. Introduction

Extragalactic astronomy as a field of research of everything beyond the Milky Way is a very young science compared to physics and astronomy 'in general:' it is only 100 years old. Exactly 100 years ago, Edwin Hubble proved that some of the nebulae long observed by astronomers and recorded in catalogs are in fact giant star–gas systems located far beyond our Galaxy. They look as nebulae precisely because they are very distant and are not resolved into individual stars — the stars of which they consist merge into a general nebula when observed from Earth. And at the same time, 100 years ago, Hubble, following the trail of his discovery, proposed a scheme of morphological classification of galaxies — a classification of their structure and external appearance. He formulated the first principles of division into types in 1926–1927 [1, 2], and the final form of the 'Hubble tuning fork' was given in his book The Realm of the Nebulae [3]. Since then, despite attempts by many generations of astronomers to improve this scheme, it has not changed much and still looks approximately as it did 90 years ago in the Hubble's original book (Fig. 1).

Having compiled statistics of external views of 400 nearby galaxies in his work [1], Hubble had firstly divided them into elliptical and spiral. The difference between the first and second was the most obvious: elliptical galaxies (the handle of Hubble's tuning fork) were spheroids with a homogeneous red stellar population, while spiral galaxies are dominated by extended, rather thin stellar disks, in which a lot of small-scale details associated with star formation regions were visible. First and foremost, the most noticeable structures in the disks were spiral arms, and secondarily — central triaxial concentrations, bar-like structures. Next, the long 'prongs' of Hubble's tuning fork were divided into three parts: 'early' (Sa), 'intermediate' (Sb), and 'late' (Sc). As he stated in [2] — exclusively for statistical convenience. The three main criteria by which spiral galaxies were classified into 'early,' 'intermediate,' or 'late' were [2]:

- the size of the central spheroidal stellar component — the bulge;
- the degree of openness of the spiral arms;
- the degree of smoothness (clumpiness?) of the spiral arms.

And finally, in 1936, an intermediate type appeared between elliptical and spiral galaxies — the S0 (lenticular) galaxies (see Fig. 1) [3]. Lenticular galaxies resemble spirals by their large-scale structures — they also have extended stellar disks and concentrated central spheroidal bulges. But in the disks of lenticular galaxies, spiral arms are absent, and in general, by their smooth reddish appearance (and, probably, in Hubble's opinion, by the properties of their stellar population), lenticular galaxies more closely resemble elliptical ones.

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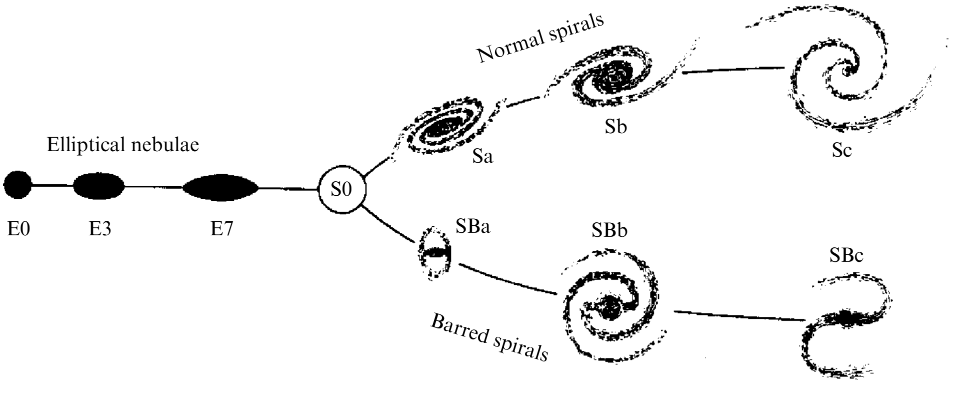

Figure 1. Classification of morphological types of galaxies by Hubble — as it was proposed by him in the 1936 book [3].

Before moving on to a modern assessment of the differences between elliptical, lenticular, and spiral galaxies, it is worth noting once more that despite the designation 'early,' 'intermediate,' or 'late' types of galaxies, Hubble categorically denied that his classification scheme carries an evolutionary sense. He proposed it exclusively for the convenience of ordering statistical properties of structures in galaxies. However, the provocation was too strong — practically immediately astronomers began trying to imbue Hubble's scheme with evolutionary meaning. Indeed, perhaps at first 'early' spheroids appeared, and then around them grew extended disks with spiral arms? After all, the stellar population of the bulges of spiral galaxies is older than that of the disks of late-type galaxies! But subsequently, when statistics accumulated on the characteristics of galaxies, it turned out that spiral galaxies are on average less massive than ellipticals [4]; that is, if something were to grow around massive elliptical galaxies, the final result would in no way correspond to the average characteristics of spiral galaxies. And thanks to cosmologists who formulated their picture of the world by the 1990s, the exactly opposite direction of galaxy evolution emerged: first, during the initial events of gas conversion into stars, stellar disks were supposed to be born (because protogalaxies had an initial angular momentum), and then later, in the process of collisions and merging of these disk galaxies, spheroids should have appeared [5]. This sequence of transformations was subsequently also rejected — due to a whole set of observational facts contradicting it.

So how do elliptical, lenticular, and spiral galaxies differ on a global scale?

2. Dynamics is linked to structure; but what determines star formation?

The 1970s were the golden age of observational extragalactic astronomy. A huge number of breakthroughs in understanding galaxies were associated with qualitatively new observations and their interpretation. In particular, by the end of the 1970s, the first long-slit spectra of elliptical and disk galaxies had been obtained, with which one could study their stellar kinematics [6]; and the kinematics of spiral galaxies from spectral observations of the gas in galactic disks began to be studied even earlier [7]. It turned out that disk galaxies rotate rapidly — practically all the kinematic energy of their stars is concentrated in ordered circular rotation of the disks. But the rotation of the stellar component of elliptical galaxies, if it could be measured, turned out to be much slower in galaxies of the same luminosity — the main intrinsic kinematic energy of spheroids is associated with chaotic motions of stars over the full extension of the galaxy, or with the so-called velocity dispersion. The construction of stellar dynamical models for elliptical galaxies proved that only some of the spheroidal galaxies demonstrate a ratio of ordered rotation velocity of the stellar component to the velocity dispersion of stars corresponding to their shape (so-called oblate spheroids). In the most massive elliptical galaxies, their three-dimensional structure is defined by the shape of the ellipsoid of velocity dispersion: the fastest chaotic motions are oriented along the longest axis; in general, these galaxies can be triaxial [8, 9].

Using accumulated statistics on rotation velocities of the stellar component of galaxies of various types, Michael Fall in 1982 presented to the astronomical community a correlation of the specific angular momentum of the stellar body of a galaxy to its stellar mass — the so-called 'Fall relation' [10]. As it turned out, a tight power-law dependence of the specific angular momentum on the stellar mass of the galaxy is observed, with a slope in logarithmic units of about 0.6, and such a correlation with such a slope is observed within all morphological types of galaxies. But the zero point of these dependencies is different for different morphological types: the highest moment at fixed mass is for spiral galaxies, followed by lenticulars, and the lowest is for ellipticals [11]. Moreover, if we distinguish only the disk component of lenticular galaxies, the disks of S0 galaxies in terms of their dynamics turn out to be the same as spiral ones — the reduced angular momentum of the latter is due to the presence of massive spheroidal bulges.

Thus, the main physical difference between disk galaxies and spheroidal ones is precisely in the difference of their specific angular momenta. Any evolutionary mechanism describing the origin of disk or spheroidal morphology of galaxies must ultimately yield this difference.

Within the broad class of disk galaxies, the main difference between spiral and S0 galaxies is in the presence or absence of large-scale star formation in the disk. In everything else — in general structure and dynamics — these types of galaxies are similar. Moreover, if we turn to another well-known scaling relation linking the integrated star formation rate in a galaxy to its stellar mass, the so-called 'main sequence' of galaxies [12], then at the same stellar mass, lenticular galaxies are located significantly below spiral ones [13]. About them it is said that star formation in them is 'quenched.'

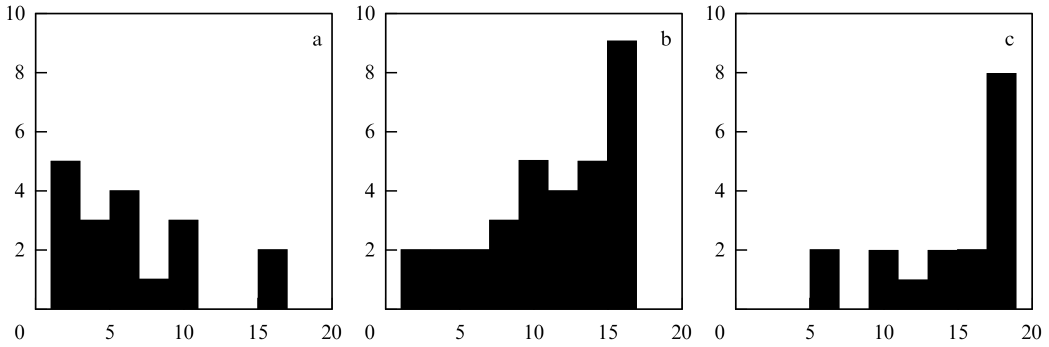

Figure 2. Histograms of age estimates (in Gyr) for the stellar disks of lenticular galaxies in environments of different density: (a) isolated galaxies [25], (b) galaxies in poor groups [73], (c) galaxies in the Virgo cluster ([23] and [73]).

As a result, even at the dawn of extragalactic astronomy, a scenario of the origin of lenticular galaxies from spiral ones by gas removal from the disk was popular [14, 15]. Indeed, if no gas — no star formation, since stars form from gas. When statistics on the prevalence of morphological types was accumulated, and it turned out that it was precisely lenticular galaxies that made up the majority in the densest environments — in galaxy clusters, right there and then the mechanism of gas removal from spiral galaxies which might transform a spiral into lenticular, was specified associated with the dense environment: either gravitational tidal effects [17], or gas-dynamical influence — ram pressure of the hot intergalactic medium [18, 19]. However, over time, observational data cast doubt on such a simple way to 'make' a disk galaxy without star formation. First, in many lenticular galaxies, gas is still present [20], but star formation is somehow weakened, and its level does not correspond to the measured amount of cold gas. Second, most lenticular galaxies live not in clusters but in the field, and some of them are completely isolated. The realization of this fact provoked a current 'multiplication' of proposed mechanisms for stopping star formation in the disks of lenticular galaxies: for S0s in clusters this mechanism may be one, and for S0s in the field — another.

But even if we focus only on lenticular galaxies in clusters, the idea that these are former spiral galaxies that lost their gas and stopped star formation precisely when they fell into a cluster, into the very massive dark halo that exists only in the modern Universe, encounters difficulties. Under the leadership of Alan Dressler in the 1990s, a key project was carried out on the Hubble Space Telescope to study the morphology of galaxies in clusters at redshifts up to $z \approx 0.8$, to trace the evolution of the cluster morphological content. And indeed, it was detected what was expected to be seen within the classical scenario: at $z < 0.4$, lenticular galaxies dominate in clusters, while at $z \approx 0.5$, the morphological composition of clusters changes abruptly: the majority begin to be blue (spiral?) galaxies, while the fraction of lenticulars drops to 15% — just as in the sparse field [21, 22]. At the same time, the fraction of elliptical galaxies did not evolve. An obvious interpretation had arisen: precisely at $z \approx 0.5$, when within the standard cosmological model massive gravitationally bound systems (galaxy clusters) begin to 'assemble', spiral galaxies accrete onto clusters from surrounding field areas (where spiral galaxies represented the majority), and then, already in the dense environment and within the hot gas medium, they lost their gas and transformed into quiescent S0s. This scenario has left a possibility to be observationally checked. At $z \approx 0.5$ we observe galaxies such as they were 5 billion years ago (because the light speed is finite). This means that in the nearby Universe, at $z = 0$, in lenticular galaxies, stellar disks should be relatively young — after all, according to the classical scenario, star formation in them occurred only 5 billion years ago. To measure the age of the stellar population in the disks of lenticular galaxies in nearby clusters is not very difficult — one only needs to obtain deep spectra and to model them. And for nearby clusters Virgo and Fornax this was done. It turned out that the age of the stellar population in the disks of lenticular galaxies in nearby clusters is old, basically about (or more than) 10 Gyr [23, 24]. These galaxies could not have been spirals at $z = 0.5$. Moreover, the denser the present environment of lenticular galaxies, the older their disks are (our compiled statistics is shown in Fig. 2). A young stellar population can be found in the disks of some *isolated* lenticular galaxies [25], and these lenticular galaxies could in principle have been spiral only a few billion years ago. But isolated lenticular galaxies have no nearby neighbors of noticeable mass, to ensure gravitational tidal influence, or hot intergalactic medium around them to suffer ram-pressure; and consequently, the origin of their morphological type has nothing to do with dynamical mechanisms operating in a dense environment.

3. Modern scenarios of the origin of lenticular galaxies

In fact, after 2010, the classical scenario of removing primordial gas from the disks of spiral galaxies to make them lenticulars ceased to be so relevant, because the global paradigm of the evolution of disk (mainly spiral) galaxies changed. If previously it seemed that all evolution of disk galaxies consists in gradually converting their primary gas into stars, then after 2010, it was recognized that globally the gas content of disk galaxies is constantly changed — by an accretion (gas inflows) from outside and in less extent by galactic winds (gas outflows); and, accordingly, it is the balance of accretion and outflows that determines the rate of star formation in the disk.

The very idea of the necessity of continuous laminar inflow of cold gas from outside arose from the combination of observational data. Here it is worth mentioning, first of all, the peculiarities of the chemical evolution of the thin stellar disk of the Milky Way, in which the average metallicity of stars did not grow over the last 8 billion years [26], which was most naturally explained [27, 28] by a continuous inflow from outside of metal-poor gas, which mixes with the galaxy's own gas and dilutes the continuously forming products of stellar

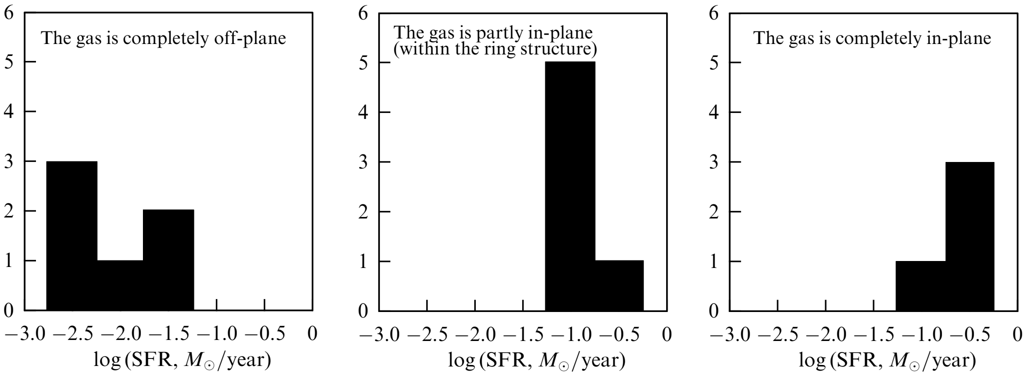

Figure 3. Histograms of estimates of integrated star formation rates (by the ultraviolet luminosities from the NED database) for lenticular galaxies with different orientation of global gas disks relative to their stellar disks.

nucleosynthesis, inevitable in the case of continuing star formation in the disk. It had also a strong effect for the paradigm that a very short time scale of gas depletion in the disks of spiral galaxies in the nearby Universe was discovered if to consider current star formation rates [29]. Should all star formation stop after 2 Gyr (the current gas depletion time in spiral galaxies) after the current gas reservoirs in galactic disks are exhausted? The idea of laminar gas accretion was approved very much by cosmologists, in whose models the gravitating centers (galaxies in the hearts of dark haloes) always accrete surrounding dark matter — and where dark matter inflows, baryons must follow. Observations of distant galaxies allowed establishing the evolution of both the rates of star formation and the times of gas depletion in galaxies for this star formation [30]. And the observed evolution of both the one and the other quite fit into numerical calculations of hierarchical 'assembly' of galactic matter over the last 13 Gyr of the Universe's evolution — at least, their power-law dependencies on $(1+z)$ turned out to be similar [31, 32]. Harmonious scenarios of the equilibrium state of galactic disks throughout their entire existence appeared: as much gas flows in per unit time, so much is spent on star formation, minus the galactic wind [33]. As a result, to the first main factor of galaxy evolution — stopping star formation in massive galaxies under the influence of a possible internal mechanism associated with the mass of the galaxy — a second no less important factor was added: the continuous inflow of gas from outside. Now it becomes necessary to explain for lenticular galaxies why the inflow of gas into the disk, if it is the same as in spiral galaxies, does not lead to the resumption of star formation.

Modern scenarios of the origin of lenticular galaxies are multiple. In various studies based on statistics of global properties of S0 galaxies in the nearby Universe, whole sets of scenarios are proposed, associated with:

- gravitational tidal interaction of galaxies in medium-density environments, namely in groups [34, 35]; this interaction perturbs gas in galactic disks, turbulizes it, as a result of which under the action of viscosity the gas clouds lose angular momentum and fall into the center of the galaxy, where they are quickly spent on a burst of star formation within the bulge region;
- galaxy merging — most often, with satellite accretion (minor merging), but in certain orbital configurations and with major merging — which dynamically heats the disks, both stellar and gaseous, thickens them, so reducing the volume density of gas, and ultimately leading to the suppression of star formation [36, 37];
- and, finally, with the peculiarities of accretion regime, first of all — with its geometry.

We [38] found that in the case of inclined gas inflow into the disk of a lenticular galaxy, star formation on average is lower than if all the gas lies and rotates inside the stellar disk of the galaxy (Fig. 3). At the same time, the integrated star formation rate in the galaxy turns out to be an order of magnitude lower than expected for the observed gas mass in it. The reason for this may be that in the gas flow, arriving at an angle into the potential well of the stellar disk, a shock wave develops, which heats the gas and prevents its cooling to the star formation regime. In recent years, in connection with the acquisition of large statistics on galaxies with decoupled kinematics of gas and stars in the MaNGA survey, ideas have been actively developing that if a so-called counter-rotating gas arrives into the disk of a galaxy, the orbital spin of which differs by 180 degrees from the spin of the galactic disk, then its collision with the 'native' gas of the galaxy leads to the disappearance of angular momentum for both, their fall into the center of the galaxy with subsequent exhaustion on the central burst of star formation [39–41].

The question of whether any significant role of the galaxy's environment remains in this is actively discussed, and so far has no unambiguous solution. In some works, the role of the environment is denied [37, 42]. In some statistics, the role of the density of the environment, specifically, the role of clusters and groups, is still revealed [35, 43]. We ourselves once noted that in clusters, within the hot X-ray gas halo, external cold flows do not survive, and accretion becomes impossible, which allows once-formed lenticular galaxies to preserve their morphological type for billions of years [44]. This is directly related to the dependence of the age of stars in the disks of modern lenticular galaxies on the density of the environment (see Fig. 2). Nine to ten billion years ago, at redshifts greater than unity — as is figuratively expressed in the literature, at the 'noon of cosmic star formation' — thick gaseous disks, correspondingly forming thick stellar disks [45–47], are observed in galaxies; and the characteristic times of gas depletion and fading of star formation at $z = 2$ are only about half a billion years [30]. This means that 10 billion years ago in massive disk galaxies, structures were already forming that after half a billion years looked like typical lenticular galaxies. In our own Galaxy, in the Milky Way, there is such a large-scale substructure — a thick stellar disk of old stars, older than 10 billion years, with an enhanced ratio of magnesium to iron, which means a very short epoch of its formation 10–11 billion years ago [48]. But the thin stellar disk in the Milky Way began to form only 8–9 billion years ago. This means that between $z = 2$ and $z = 1$ the Milky Way was a lenticular galaxy. Further, after $z = 1$, the fate of any disk galaxy depends on whether it will encounter a source of accretion of external cold gas. If it falls into a cluster, into a hot intergalactic medium, it will not have the opportunity to accrete cold gas, build its thin stellar disk, and will forever remain lenticular.

However, most lenticular galaxies still live outside clusters. From general considerations it seems that within similar environments and at similar masses they should be able to accrete external cold gas, just like spiral galaxies. So what factors have a decisive influence on the impossibility of laminar star formation in their disks and prevent the formation of thin stellar disks, in which spiral structure could develop? One factor we [38] have already proposed and substantiated — this is the geometry of gas arrival, more precisely, the inclination, relative to the stellar disk, of the direction of arrival of the external gas flow. A second variant of the external cold gas accretion regime, which does not lead to noticeable star formation in the disk, is proposed as a scenario by Peng and Renzini [49]. The external focused gas inflow carries with it angular momentum, and this is its orbital angular momentum. If it turns out to be large — that is, if the accretion flow falls not directly onto the center of a galaxy, but as if bypasses the center — then this gas cannot get into the inner region of the disk, it accumulates at the periphery, forming an extended gas disk beyond the stellar one. It is precisely such gas disks that are observed in giant lenticular galaxies [50]! The fact that this gas is not 'pressed' by the potential of the stellar disk, leads again to increased thickness and to decreased volume density of the gas; and these factors suppress star formation in the equatorial plane of the galaxy.

Peng and Renzini [49] expressed the idea; and we recently found a real lenticular galaxy that fits exactly into this scenario [51]. This is the S0 galaxy NGC 6798. The galaxy is known as absolutely isolated [52]: it is not in clusters or groups. By morphological classification it is a lenticular galaxy. However, it has an extended neutral hydrogen disk [53], and in the framework of a panoramic spectroscopic survey of early-type galaxies by the ATLAS-3D project, it turned out that in the central region there is a gas disk — both as an ionized hydrogen disk and as a cold gas disk, neutral and molecular — counter-rotating relative to the stellar disk [54]. Further study of this galaxy continued in the direction of increasing the field of view — ideally it was desired to reach the edge of the neutral hydrogen disk, that is, to a radius of more than 3 arcminutes, or about 30 kpc. So far, the main stellar disk of the galaxy could not be traced by spectroscopic methods; but throughout the entire extent of the disk, which was covered by the analysis, the gas strictly counter-rotates relative to the stars [55, 56]. We [51] according to our data and archival radio interferometer WSRT observations traced the spatial orientation of the gas rotation plane: it exactly coincides in space with the plane of the stellar disk; but the gas rotates against the stars, and the angle between their spins is exactly 180 degrees. This means that the gas was accreted into the plane of the galaxy — but with an orbital angular momentum turned by 180 degrees relative to the galaxy's own angular momentum. The analysis of the two-dimensional line-of-sight gas velocity field, within the model of circular rotation, has shown that the radial gas inflow velocities beyond the radius of 5 kpc are strictly equal to zero [51, 57]. This is precisely what means that the accreted gas does not fall into the inner disk of the galaxy, remaining on its periphery. Why does it occur? In [58] it was shown that the specific angular momentum of the gas of NGC 6798 exceeds several times the expectations from the measured content of cold gas in this galaxy (according to another scaling relation for galaxies). That is, this is precisely the case that Peng and Renzini [49] wrote about: the accreted gas inflow brings too much orbital momentum. And since the gas does not fall into the region compressed by the gravitational potential of the stellar disk, star formation in it is also significantly weaker than expected — NGC 6798 falls on the lower edge of the 'green valley' [51]. Here it is the real observational confirmation in the nearby Universe for the occurency of scenario by Peng & Renzini [49] for the origin of isolated lenticular galaxies and for the possibility to keep their morphological type despite the significant cold gas supply in the disk.

4. Modern scenario of origin of elliptical galaxies

Starting from the late 1970s [59] and until the end of the 2000s, the main scenario for the origin of elliptical galaxies was so-called major merging — the merger of two disk galaxies of comparable masses. Such a scenario provided both the predominance of chaotic stellar motions over ordered rotation [60], and the correlation of mean metallicity of stars with the mass of the galaxy through the secondary star formation bursts during the galaxy coalescence [59]. This scenario was especially liked by cosmologists [5]: in the classical model of hierarchical clustering of matter in the Universe, such mergers were the main event in the life of every massive elliptical galaxy [61, 62]. However, everything changed at the end of the 2000s: new observational data appeared that resulted in a complete revision of the concept.

First, in 2007 we published a study of metallicity gradients of the stellar population in a sample of giant elliptical galaxies with round isophotes [63]. This study was based on deep spectral observations at the Russian 6-meter telescope BTA of the Special Astrophysical Observatory; and it was precisely the depth of these data and the high accuracy of the measured characteristics of the stellar population that allowed us for the first time to see a break in the radial decrease of metallicity. Until then, due to insufficient accuracy of measurements, researchers fitted a single power-law dependence over the entire extent of the galaxy, and the obtained in logarithmic coordinates the slopes of −0.2–0.3 dex per dex (that is, a decrease in metallicity by about 2 times at a distance of 10 times from the center of the galaxy) that did not contradict the popular scenario. We have seen that in the center the gradients are steep, steeper than −0.4 dex per dex, and beyond half the effective radius they flatten out, almost to zero. By that time, extensive samples of model elliptical galaxies with detailed calculations within the LCDM cosmology with spatially resolved properties of the stellar population and selected features of evolutionary paths already existed. A PhD student of the Munich center, where these calculations were explored, Chiaki Kobayashi, had already published a work [64], where she showed that major merging always 'washes out' radial metallicity gradients — if the metallicity gradient is steeper than −0.2 dex per dex, this galaxy could not pass through major merging, at least in the last 10 billion years (that is, after the completion of the formation of the stellar population). And if we compare our results with the results of the LCDM modeling, we made a conclusion in [63] that the giant elliptical galaxies we studied could not have formed as a result of major merging. We proposed a two-stage scenario: first, the galaxy forms its inner part of the stellar body as a result of the so-called monolithic collapse, that is, by a collapse of a single gas cloud with effective rapid star formation during this collapse; and then onto this compact stellar 'seed' multiple small satellites accrete, which get stuck in the outer regions due to their orbital angular momentum. With such a course of evolution, merging-related evolution is limited to the outer regions of galaxies, and it is precisely there that we see the flat metallicity gradients, while in the inner region a steep gradient inherited from the monolithic collapse is preserved [65]. At the same time, it is desirable that the accreting satellites be without gas, so as not to rejuvenate the stellar population in the inner region of the galaxy.

By pure coincidence, precisely in 2007–2008, other observational arguments appeared which required rejecting the scenario of single major merging in favor of a scenario of multiple minor merging for the typical evolution of elliptical galaxies. These arguments were based on observational studies of the size evolution of a typical massive elliptical galaxy. Photometric data for massive galaxies with stellar masses up to 2×10^{11} solar masses, with elliptical morphology, at redshifts of 2–3, that is, for giant elliptical galaxies as they were 10–11 billion years ago, were obtained; and these galaxies, by the way, were already without star formation at this early epoch. These distant galaxies turned out to be compact, with typical effective radii of about 1 kpc [66, 67]. That is, over the last 10 Gyr, massive elliptical galaxies, without experiencing star formation, increased their size by 5 times, almost without increasing their stellar masses. They grew faster than disk galaxies with star formation! And such rapid growth also contradicted the major merging scenario — because in a major merger, the size of a stellar system, of course, also grows, but it grows strictly proportionally to the mass. That is, to increase the size of the stellar system by 5 times with major merging, one needs to increase its mass by 5 times (which requires 5 consecutive major mergers). And then for a system that had a mass of 2×10^{11} solar masses at $z = 2$, the final stellar mass would be more than 10^{12} solar masses. Such elliptical galaxies in the nearby Universe do not exist — perhaps, only a few central cluster galaxies may be so massive, but not a bulk of ellipticals in the field. One had to abandon the major merging scenario as the main track of formation for modern elliptical galaxies. And already from this new side, with this new argumentation, one could turn to a two-stage scenario, in which over the last 10 billion years the main mechanism of evolution of elliptical galaxies was multiple minor merging.

Three basic mechanisms that could lead to an increase in the size of a stellar system without additional star formation in it were considered by Bezanson et al. [68]. These three mechanisms are: major merging (mergers of galaxies of comparable masses), minor merging, and an explosion in the center of the galaxy of active nucleus, preferably with a kinematic nature of activity (with a jet), which by the injection of additional energy into the surrounding stellar system would increase the equilibrium (virial) size corresponding to the depth of the gravitational potential well. For each mechanism, on the scaling relations for elliptical galaxies, known for $z = 0$ as well as for $z = 2$, arrows were drawn — directions of evolution. It was shown that the only mechanism that successfully 'stretches' distant massive elliptical galaxies to modern size scales is multiple minor merging. It is enough over 10 billion years to 'swallow' 8 satellites, each with a mass of 10% of the host galaxy, to provide it with the necessary evolution of size at modest evolution of mass.

Multiple minor merging — or accretion of satellites with a mass less by 10 times, or more, than the mass of the main host galaxy — as a dynamical mechanism of evolution, has a whole series of advantages over major merging. As shown in [69], the size of the stellar system in multiple minor merging grows proportionally to the square of the mass: to increase the size by 4 times, it is enough to gather additional stellar mass so as to double the original one. And if we assume that the satellite is not swallowed whole, but is preliminarily disrupted by tidal forces into small parts and swallowed already in parts — then the factor of size growth with respect to the mass growth increases to 2.4. In multiple minor merging, as in real massive galaxies in accordance with the observational evidences [70], the outermost regions of the galaxy are rebuilt, preserving the inner part of the massive elliptical galaxy intact, such as it formed in the primary burst of star formation at $z > 5$ — that is, the initially steep metallicity gradient in the inner half of the galaxy is not erased by violent relaxation of the stellar system (inevitable in major merging). And finally, dynamical 'heating,' that is, a decrease in the specific angular momentum of the system, associated with ordered rotation of stars, is several times more effective precisely in multiple minor merging than in major merging [11].

As a result, for the complete evolution of giant elliptical galaxies, a scheme is now adopted (Fig. 4). Somewhere in a very early epoch, at redshifts $z > 5$, what the classics described as 'monolithic collapse' occurs: in fact, inside a massive dark halo, a gas cloud with the mass of the protogalaxy breaks into clumps, and these clumps then within the framework of dissipative collapse merge, fall into the center and very effectively form a stellar system — with a mass of up to 10^{11} solar masses. Violent star formation turbulizes the gas, it loses angular momentum and flows onto the central black hole, providing fuel for nuclear activity; in the center of the galaxy a quasar ignites, which heats and drives gas around itself and thus stops star formation. This is now the key moment of all models of formation of massive galaxies, built into all LCDM models; this is beautifully called 'feedback' from an active nucleus. The point is that in modern elliptical galaxies the stellar

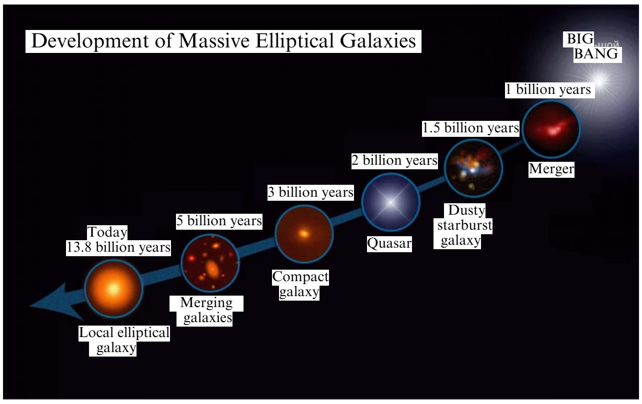

Figure 4. Modern scenario of evolution of giant elliptical galaxies (illustration is taken from the public collection NASA Image Galleries).

population in the center is old; and the more massive the galaxy, the older the stellar population, and the higher the ratio of magnesium abundance in stars to iron one (this ratio characterizes the duration of the main epoch of star formation — the shorter it is, the higher this ratio). The idea is very good: there exists a tight correlation between the stellar mass of an elliptical galaxy and the mass of its central black hole; consequently, the more massive is the galaxy, the brighter is the quasar that flashed in its center, the faster and more effectively it stopped star formation. As a result, by the epoch $z \approx 3$ we obtain a compact stellar system without star formation. All main events in that early epoch, $z \approx 4-5$, proceed in the very center of the galactic nucleus — and, accordingly, the 'puffed up' passive stellar system also has a characteristic size of 1 kpc. And since then, for the last 11 billion years, small satellites, purely stellar, without gas, fall onto this seed, and in this — the entire evolution of a giant elliptical galaxy (see Fig. 4).

5. Conclusion: the morphological type of galaxies is fully determined by the regime of external gas accretion

As for the accretion of external gas onto spiral galaxies, many arguments give evidence in favor of the fact that it must occur on a long-term steady basis strictly in the plane of the galactic disk, with an orbital spin strictly co-directed with the internal spin of the galaxy. In the paper by Peng and Renzini [49], in order to obtain a qualitative estimate, the authors multiplied three evolutionary dependencies of parameters of spiral (disk) galaxies on redshift: the growth of stellar mass (due to star formation), the observed growth of radius and growth of rotation velocity (allocated from the evolution of the Tully–Fisher relation through the 'disk support by rotation' dependency on z in [71]). They obtained that over the last 10 billion years the angular momentum of spiral galaxies grew from 30 to 200 times — depending on the adopted cosmic history of star formation. This is an observational estimate obtained from observed trends of evolution of scaling relations for galaxies. To theoretically justify such rapid evolution of the angular momentum of spiral galaxies over the last half-life of the Universe, it is precisely the assumption of accretion of narrow gas flows from outside strictly in the plane of the galaxy that is required. Only such an accretion regime provides the observed growth of the momentum, and it also provides steady star formation in the plane of the galactic disk and the formation of a dynamically cold thin stellar disk, in which internal instabilities can develop and both spiral arms and central bars can form.

Thus, as a result of considering empirical scenarios of evolution of galaxies of different morphological types, we come to the conclusion that the modern morphological type of a galaxy is fully determined by the regime of accretion onto it of external cold gas over the last 10 billion years.

- Elliptical galaxies are produced till $z = 0$ if purely stellar small satellites, devoid of gas, accrete onto them; the direction of accretion can be any, and the actual distribution in space of the directions of satellite infall will determine the final shape of the elliptical galaxy — spherical in the case of isotropic distribution and triaxial in the case of several selected directions of satellite arrival.
- Spiral galaxies arise at $z = 0$ if gas flows accrete onto them strictly in the plane of the galactic disk, with a small orbital spin, co-directed with the galaxy's own spin.
- And, finally, lenticular galaxies are obtained in all other cases: either when accretion of cold gas does not occur at all (for example, in galaxy clusters), or when it occurs, but not in the plane of the galactic disk, or when it occurs in the plane of the galactic disk, but with too large an orbital moment, preventing the accreted gas from reaching the central part of the stellar disk. Also, 'wet' minor merging — accretion of satellites containing besides stars also gas — also leads to the formation of lenticular galaxies.

Actually, the frequency of galaxies of different morphological types in the nearby Universe — Sp:S0:E = 0.75:0.15:0.06 [72] — obviously reflects the prevalence of different types of accretion, which, in turn, probably should be associated with the geometry and composition of elements of the large-scale structure of the Universe (nodes, filaments, etc.).

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