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Recent revolutions and unsolved problems in the galaxy evolution paradigm

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Due to the fast development of observational techniques, observations of high-redshift galaxies and detailed studies of nearby galaxies bring surprises every week. Many quite unexpected discoveries have been made over the last years, which have changed our views about galaxy formation and evolution substantially. I review some of the most important and unexpected observational facts, which bring changes even to paradigms.

1 Introduction

Galaxy evolution studies represent a very rapidly evolving branch of our knowledge about the most general properties of the Universe. In the 1990s, cosmological theory played a leading role in shaping the most general frameworks of the galaxy evolution scenarios – those of the LCDM cosmology. However, after the VLT and other 8 m–10 m-class telescopes have started their work, the priorities have changed. Every year, fundamental observational discoveries appear that transform substantially our primary concepts. In this review, I discuss the most unexpected and troubling things that become known or that have been understood in the last years. I will touch upon the following points:

– fast evolution of the sizes of quiescent (elliptical) galaxies between $z = 2$ and $z = 1$;
– prolonged star formation histories of dwarf spheroidal galaxies in the Local Group;
– apparent lack of external sources of cold gas accretion for the nearby spiral galaxies;
– old stellar ages and magnesium overabundance of the large-scale disks of nearby lenticular galaxies.

None of these points has been predicted in the framework of physically and cosmologically motivated galaxy evolution scenarios; their discovery changes substantially our views on the entire picture of the evolving Universe.

2 Formation and evolution of elliptical galaxies

Morphological and metric studies of galaxies now extend out to $z > 2$ and beyond (i.e., to lookback times of more than 10 Gyr). High spatial resolution and sensitivity of imaging demonstrated by 8 m-class telescopes with adaptive optics make it possible to resolve and measure the radii of very distant galaxies. Several years ago, the unexpectedly fast evolution of the sizes of red ("quiescent") galaxies was discovered at redshifts $z > 1.5$. These red galaxies observed at $z = 1.5$–2.5 and lacking obvious star formation are shown to possess de-Vaucouleurs' surface brightness profiles (Szomoru et al. 2012) and therefore to be bona-fide elliptical galaxies. At $z = 2$, the most massive of them, with the stellar masses of about 10^{11} $M_\odot$, look extremely compact, $R_{\rm eff} \sim 1$ kpc, which means that to match the modern scaling relations for elliptical galaxies, they must have undergone at least a factor of four size evolution over the last 10 Gyr (Trujillo et al. 2006, 2007; van Dokkum et al. 2008).

Given the similarity of the total mass range between the nearby and high-redshift quiescent elliptical galaxies, this also implies a two order of magnitude evolution in their intrinsic stellar volume density. This discovery has challenged the recognized scenarios of elliptical galaxy evolution. Indeed, the most popular scenario of the formation of massive elliptical galaxies has been that of a major merger, which can of course result in the expansion of the stellar system; however, the law of this expansion implies that the effective radius should be proportional to the final mass of the galaxy. It promises a huge number of nearby elliptical galaxies with stellar masses exceeding 10^{12} $M_\odot$ if all the observed compact ellipticals at $z = 2$ evolved in such a way. Massive ellipticals are not observed in such numbers in the Local Universe. Furthermore, it is interesting that stellar velocity dispersion inside these massive elliptical galaxies evolves only mildly between $z = 1.5$–2 and $z = 0$ (Cenarro & Trujillo 2009; van Sande et al. 2011). After trying various scenarios, extragalactic researchers are now inclined to accept that elliptical galaxies grow between $z = 2$ and $z = 0$ mostly via multiple minor mergers, which result in the size increasing as the square of the mass (Naab et al. 2009), and

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can therefore bring about considerable size growth with a moderate mass change. Furthermore, minor mergers are the very mechanism capable of organizing the growth of elliptical galaxies in the "inside-out" direction: the resolved estimates of the stellar densities in the quiescent galaxies at $z \sim 2$ are indicative of less evolution in the central kiloparsec compared to what is observed in the whole stellar system (Bezanson et al. 2009). This fact is inconsistent with the scenarios of major merger or AGN-triggered expansion, but agrees with multiple minor merger contributions.

When publishing our measurements of stellar metallicity gradients in a small sample of round elliptical galaxies, we (Baes et al. 2007) proposed a two-step scenario of the formation of elliptical galaxies as a class. We found the metallicity gradients in the inner parts of elliptical galaxies, $R < 0.5R_{\rm eff}$, to be very steep, steeper than –0.4 dex per dex in radius, and to become shallow and in some cases consistent with zero in the outer parts. Given that formation of an elliptical galaxy via major merger cannot result in metallicity gradients steeper than –0.3 (Kobayashi 2004), we concluded that the inner parts of elliptical galaxies must have formed via a kind of fast monolithic collapse of a gas-rich protogalactic cloud at a high redshift. Later, during the last 10 Gyr, or at $z < 2$, the elliptical galaxy continues to build its outer part by multiple minor mergers of satellites that may be gas-poor or gas-rich dwarfs, thus providing final zero metallicity gradients and quite various radial stellar-population age gradients that we observed. We now see that the scenario with multiple minor mergers during the last 10 Gyr to form contemporary elliptical galaxies gets support from very different observational findings.

3 Star formation histories of dwarf galaxies

Over the past 40 years, all the scenarios of early star formation in spheroidal galaxies were based on the simple physical argument by Larson (1974b) and later by Dekel & Silk (1986) that galactic winds that expunge all the gas and thereby suppress star formation developed much earlier and more effectively in low-mass protoclouds (dark halo), in other words – in dwarf galaxies; and that the fainter they are now, the higher is the fraction of baryons they lost at the beginning of their life. This is because their shallow gravitational-potential well cannot retain the gas heated by young massive stars (by their stellar winds) and by supernova explosions. Particularly, this mechanism explained well the known mass-metallicity relation for galaxies of early morphological types. However, the same mechanism predicts not only the correlation between the mass and total metallicity of stellar populations in early-type galaxies, but also anti-correlation between the mass and magnesium-to-iron ratio, because the shorter is the main epoch of star formation, the higher must be the magnesium-to-iron ratio approaching that of the core-collapse SNe nucleosynthesis output. At the same time, observations of dwarf elliptical galaxies show them to have solar magnesium-to-iron ratio (Sansom & Northeast 2008; Spolaor et al. 2010), whereas giant ellipticals are strongly magnesium overabundant (Worthey et al. 1992). In other words, what is observed is a strong correlation between the galaxy mass and magnesium-to-iron ratio of its stellar population (Trager et al. 2000). It means that star formation in dwarf ellipticals has to last for more than 2–3 Gyr in order to provide solar magnesium-to-iron ratio.

The nearest early-type galaxies – dwarf spheroidal members of the Local Group – allow individual stars inside them to be measured. In particular, spectroscopic studies of the individual stars – members of the dSphs – and their chemical composition analysis have shown that stars in dSphs reach the solar alpha-element to iron abundance ratio during their chemical evolution; the sequence of dSph stars on the [Mg/Fe] vs. [Fe/H] diagram reaches the [Mg/Fe]$= 0$ level already at [Fe/H]$= -1.5 \ldots -1.0$, whereas halo stars of our Galaxy are still magnesium-overabundant at these metallicities (Tolstoy et al. 2003; Geisler et al. 2005; Koch et al. 2008). This fact can be interpreted as evidence for weak prolonged star formation in the dSphs of the Local Group.

Direct measurements of star formation histories in nearby dwarf spheroidal galaxies, where stellar populations can be resolved and the CMDs can be solved, have shown that indeed star formation has been very prolonged in these galaxies. The nice review by Tolstoy et al. (2009) collects individual star formation histories of dwarf galaxies in the Local Group demonstrating that practically all of them formed their stars during ages. The most massive dSph members of the Local Group – Fornax and Carina, which are located at a distance of about 100 kpc from our Galaxy, formed their stars just a few Gyr ago. In particular, traces of distinct star formation bursts can be seen at the lookback time of 4 Gyr (Hurley-Keller et al. 1998; Coleman & de Jong 2008).

Fainter dSphs have older stellar populations; however, the reconstruction of star formation histories in these systems shows their star formation timescales to be about 2–3 Gyr in the distant dSph Cetus (Monelli et al. 2010), and in the nearby Draco (Aparicio et al. 2001) and Sextans (Lee et al. 2009) galaxies. Among a dozen of dSphs of the Local Group, only Ursa Minor looks like we expected: with the star formation duration of less than 1 Gyr and homogeneously overabundant alpha-elements (Cohen & Huang 2010). In most cases, galactic wind seems not to work properly during the main star formation episodes in dwarf galaxies, and their gas appears not to go outside, beyond the potential wells. The current lack of gas and star formation in dwarf spheroidal galaxies is not due to galactic winds; now the most popular explanation of this fact is tidal stripping in the field of a larger (host) galaxy (Kazantzidis et al. 2011) or in the field of a group or cluster.

4 Where are the sources of external gas accretion?

The chemical evolution of spiral galaxies cannot be understood without permanent external gas accretion onto the disks over the whole disk life. Indeed, the mean metallicity of thin-disk stars in our Galaxy did not change during the last 11 Gyr (e.g. Karatas et al. 2005), and the famous "G-dwarf problem" discovered by van den Bergh (1962) fifty years ago (all the G-dwarfs in the Galactic disk have the same solar metallicity within the errors of estimates!) requires an inflow of about 1 $M_\odot$ of gas with pristine chemical composition per year to compensate stellar nucleosynthesis of heavy elements (Larson 1974a). Interestingly, the required gas accretion rate is roughly equal to the star formation rate observed. This is another important role of the external gas accretion: it is to maintain the nearly constant level of star formation during the last 10 Gyr in late-type disk galaxies. Dividing the present gas content of a typical spiral galaxy by the star formation rate observed in its disk yields a uniform timescale of about 2–3 Gyr (Kennicutt et al. 1994; Saintonge et al. 2011). It means that the gas contained in the galactic disks is not sufficient to sustain star formation during 10 Gyr: external gas accretion is needed. The global picture of the Universe evolution obtained in the framework of the LCDM concept appeared to solve the problem of permanent external gas accretion: in the case of a 10-kpc disk embedded in a 100-kpc dark halo, most of the baryons must be in a very hot ("X-ray") gas phase corresponding to the virial temperature of the massive dark halo and distributed over the whole volume of the dark halo. In the halo, it cools through radiation and settles to the disk, and thereby seems to provide quite a natural source of external gas.

However, despite constant progress in the sensitivity and spatial resolution of the X-ray observations, so far no massive X-ray gaseous haloes have been found around spiral galaxies. All what was found is a small amount of metal-rich hot gas within a few kiloparsecs above the disk planes, which spatially corresponds to the sites of intense star formation in the disks – this gas obviously belongs to the so-called "galactic fountains" and is not the pristine gas of the massive haloes (Strickland et al. 2004). Quite recently, the first claims about discoveries of extended X-ray gaseous haloes around the most massive spiral galaxies have appeared in the literature (Anderson & Bregman 2011; Dai et al. 2012), but the total mass of these haloes does not compensate the so-called "missing baryons" (the deficit of baryons in spiral galaxies with respect to the mean cosmological baryon fraction). Furthermore, the estimated cooling rates are by an order of magnitude lower than the star formation rates in the disks, and therefore this gas cannot provide the external gas accretion rate required by the chemical evolution models. Alternative sources of cold gas supply for steady star formation may be cosmologically motivated cold gas flows along the filaments of the large-scale structure (Fumagalli et al. 2011); however, they also have not yet been observationally discovered in the nearby Universe around massive spiral galaxies. The problem of cold gas supply for the disks of spiral galaxies remains unsolved so far.

5 The origin of modern lenticular galaxies, in clusters and beyond

Among the scenarios of various galactic morphological types shaping, the scenario of S0 formation seemed to be the most stable among others up to now: it was formulated in its essential part over the late 1970s – early 1980s, when a so called Butcher-Oemler effect was discovered. Butcher & Oemler (1978a,b) compared colour statistics in nearby and distant ($z \approx 0.4$) highly concentrated rich galaxy clusters. While in the nearby clusters S0 galaxies dominate, and their colours are red, in the distant clusters the fraction of blue ("spiral-like") galaxies rises and reaches 30–50 %. They suggested that their observations revealed transformation of spiral galaxies into lenticulars having proceeded between $z \approx 0.4$ and $z \approx 0.0$. Immediately, a fundamental study by Dressler (1980) followed where a "morphology-environment" relation was established and a fraction of S0s in nearby clusters was found to be as high as 60 %. The proper scenario of spiral transformation into S0s appeared also in 1980: Larson et al. (1980) proposed to remove outer gas reservoirs from spiral galaxies by tidal stripping during their infall into clusters in the course of hierarchical assembly. Without the external reservoirs, the cold gas of spiral disks had to be exhausted by star formation during some 2 Gyr (see the previous section), after which the star formation would stop, and the spiral galaxy would transform into a S0. This scenario is now known as "starvation"; since 1980 many other mechanisms have been proposed to transform a spiral into S0, but the main idea remains intact: all these mechanisms are related to dense environments and their gravitational and gasdynamical effects. Later, when morphological studies of galaxies in distant clusters were undertaken with high spatial resolution at the Hubble Space Telescope, the epoch of the S0 sudden emergency in clusters and groups was established exactly: it is indeed $z = 0.4$ (Fasano et al. 2000; Wilman et al. 2009).

But at $z = 0.4$ we see galaxies 4 Gyr ago. If nearby S0s have been formed from spirals at $z = 0.4$, it means that only 4 Gyr ago there have been star formation in their large-scale disks. It means that if we measure the mean ("SSP-equivalent") ages of stellar populations in the disks of nearby S0s, we should see ages younger than 8 Gyr (Smith et al. 2009; Allanson et al. 2009). Just this feature has been checked by us with the long-slit spectrograph SCORPIO of the Russian 6-m telescope (Afanasiev & Moiseev 2005) for a small sample of 20 nearby S0s homogeneously distributed over luminosities and environment densities. The results have appeared to be quite unexpected: two thirds of our S0s have stellar disks older than 10 Gyr, and furthermore, their stellar populations are magnesium overabundant. We conclude that star formation in the disks of nearby S0s has stopped at $z \approx 2$, and the duration of this star formation had been very short, less than 1 Gyr (Sil'chenko et al. 2012). This conclusion disproves completely the commonly accepted scenario of S0 formation from spirals at intermediate redshifts. Spirals and lenticulars may be relatives, but judging on their disk stellar population properties, it is spirals that have emerged from lenticulars, and not vice versa.

Basing on our results concerning the stellar populations of the outer stellar disks in nearby S0s, I have invented a new scenario of disk galaxy evolution in general. At $z > 2$, more than 10 Gyr ago, all disk galaxies were born as S0s during brief effective star formation bursts in clumpy highly-turbulent large-scale gaseous disks. Later, at $z < 1$, or < 8 Gyr ago, many of them got profit of some sources of cold gas accretion from outside; those became spirals. Concerning the sources of external gas accretion, there are some ambiguities yet – see the previous section. I like the idea of systems of gas-rich satellites to be such sources. Then the necessary condition for a disk galaxy to grow a thin disk and to become a spiral must be angular momentum alignment between the galaxy itself and its satellite system; in the case of multiple orientations of the satellite orbits, their accretion would heat the disk, and the galaxy would remain a lenticular in sparse environment. Within dense environments, in clusters and massive groups with their hot intracluster/group medium, however, it is difficult to hold external reservoirs of cold gas whatever they be – so most of primary S0s in clusters and groups have to remain S0s up to now. The environment effects have to provide S0 dominance in clusters and rich groups at the present epoch.

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