VARIABLE STARS, THE GALACTIC HALO
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Formation Mechanisms for Spheroidal Stellar Systems

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Abstract. Spheroidal stellar systems on various scales include elliptical galaxies, dwarf spheroidal galaxies, and globular stellar clusters. Elliptical galaxies are thought to be formed by major mergers of disk galaxies: it is the easiest way to create dynamicallly hot stellar systems without rotation, whose shape is supported only by anisotropic chaotic motions (by stellar velocity dispersion). However some recent observational findings have put into doubt this commonly accepted scenario. Some features of elliptical galaxies structure can only be explained if minor merging has mostly shaped these spheroidal stellar systems. The dwarf spheroidal galaxies represent quite certainly former disk galaxies shaped and transformed by tidal interactions with their large host galaxies. Globular clusters differ from the (dwarf) spheroidal galaxies by an absence of their own dark matter component. So they cannot be either downscaled version of galaxies nor the direct precursors of elliptical galaxies during the hierarchical gravitational clustering of baryons. However they are the oldest stellar systems in the Universe – it is an observational fact. The formation mechanisms of the oldest globular clusters represent a puzzle yet.

1. Introduction

Spheroidal stellar systems have a very wide range of luminosities. They include dwarf spheroidal galaxies, $-4 > M_B > -14$, globular star clusters, $-6 > M_B > -10$, diffuse elliptical galaxies, $-14 > M_B > -18$, and 'normal' elliptical galaxies, $-16 > M_B > -24$. The various families of spheroidal stellar systems obey to different scaling relations; in particular, the famous Kormendy's relation reveals the connection between the size and surface brightness of a galaxy, such that in elliptical galaxies the larger size implies the lower surface brightness while in diffuse ellipticals and in spheroidal dwarfs the opposite is true. Globular clusters lie parallel to the spheroidal dwarf sequence at the diagram 'μ_0 vs M_B' but are much more compact and so are shifted to higher surface brightnesses (an updated version of this scaling relation can be found in Kormendy et al., 2009). The typical properties of stellar populations, such as metallicity and age distributions, are also very different in spheroidal stellar systems of various types. But there are also similarities related obviously to their similar shapes: all the spheroidal systems are dynamically hot so their rotation is insignificant compared to the contribution of the chaotic stellar motions (stellar velocity dispersion) to the total kinematic energy. The formation scenaria which are constructed daily for different types of spheroidal stellar systems have then some similar features despite the different timescales and the varying roles of dark matter and diffuse baryon matter during the violent stages of the systems' shaping.

2. Globular clusters

Globular clusters are spheroidal stellar systems with typical masses of some 10^5–10^6 solar masses. Their distinction with respect to the same-mass spheroidal galaxies is that they have no dark halos: the dynamical mass-to-light ratios agree well with the population-synthesis predictions (e.g. McLaughlin & van der Marel 2005). Many galaxies, from giant ellipticals to dwarf spheroidals, possess globular cluster populations; and many globular clusters are old stellar systems, perhaps the oldest ones in the Universe, though young globular clusters exist also, mostly in interacting galaxies.

The presence of massive young clusters in violently interacting galaxies, such as the Antennae (NGC 4038/4039), inspires ideas that globular clusters may form during galaxy merging since dynamical simulations imply high pressure and so high star-formation efficiency during these violent events. For example, recent high-resolution simulations by Bournaud et al. (2008) demonstrate that gas-rich galaxy merger produces a wide mass spectrum of newly born 'tidal dwarfs', starting from $10^5\,M_\odot$ up to a few $10^8\,M_\odot$. The tidal dwarf galaxies, with the masses of some 10^8 solar masses, and massive star clusters are forming inside tidal arms, arcs, tails, and bridges; and these dwarf spheroidal systems are long-lived being good candidate-progenitors for globular clusters. Though the main attention has been paid up to now to major mergers which are extensively simulated, however observations provide us also with a lot of evidences for massive star clusters forming during minor mergers (e.g. UGC 10214, or VV 29, Tran et al. 2003) and even during a mere interaction (NGC 6872, or VV 297, Bastian et al. 2005).

Now significant statistics is acquired on the observational properties of globular clusters in external galaxies (see the review by Brodie & Strader 2006). A wide-spread feature which is found in very different host galaxies is a bimodal colour distribution of globular clusters: there are two well-separated Gaussian-like peaks, at $V-I \approx 0.9$ and $V-I \approx 1.2$. This colour difference is attributed to the metallicity difference while the ages of both red and blue globular clusters are thought to be old (Cohen et al. 1998, Larsen et al. 2001, Kuntschner et al. 2002). Besides the age, the blue and red globular clusters share also the same mass and size distributions. However, there are also some distinctions: the red clusters concentrate more tightly to the centers of their host galaxies and follow the underlying galaxy diffuse halo surface brightness distributions while the blue clusters behave more 'independently'. Interestingly, the smaller (fainter) host galaxies have often only red (metal-rich) globular clusters (Forte et al. 2009).

These properties of globular cluster populations must be explained in the frames of the cosmological galaxy formation scenaria. The common view is that red globular clusters may form during merger events which accompany the whole evolution of spheroidal galaxies according to the hierarchical paradigm. This point of view is based on the rather strong correlation between the peak colour (metallicity) of the clusters and the stellar velocity dispersion (the masses) of the host galaxies. The origin of the blue clusters is less concorded. Some people think that the same merger events may produce both red and blue clusters (e.g. Gnedin 2009). However, there is a striking difference between the red and blue clusters demonstrated recently by Harris (2009): the colour (metallicity) of the blue clusters correlates with *their own* luminosity while red clusters do not show such correlation. It means that the formation of blue globular clusters must be somewhat similar to the formation of dwarf galaxies for which their luminosity-metallicity relation is attributed to the potential regulation of the star formation duration by the own potential of the dark-matter halo: the more massive halo collapses, the higher fraction of gas heated (and enriched) by young stars can it retain, and so self-enrichment degree is proportional to the system mass. This fact, together with the very old age of the globular clusters, confirms the point of view that metal-poor globular clusters may be primordial stellar systems, and so to serve building blocks for the more massive, later formed galaxies. Some cosmological simulations provide this possibility (Mashchenko et al. 2006).

3. Dwarf spheroidal galaxies

Almost the same luminosities but the sizes larger by an orders are appropriate to dwarf spheroidal galaxies which are especially well studied in the Local Group. In fact, most of them are close companions of the large galaxies, Milky Way and the Andromeda, and so they are thought to be former disk (irregular) galaxies which have been morphological transformed by tidal forces.

After the seven SDSS survey data release, now we know 23 dwarf spheroidal satellites of the Milky Way, with the luminosities from about a thousand to about a billion solar ones; however, the mass range is much narrower than the luminosity range, some authors suppose even that all the dSphs have the same mass, of $\sim 10^7$ solar masses (Strigari et al. 2008). It means that all of them are strongly dark-matter dominated. One must only note that all the mass estimates are based on the assumption of the stellar velocity dispersion isotropy and of the virial equilibrium; the obvious presence (superposition) of tidal tails and the possibility of even weak tangential anisotropy reduces the mass estimates substantially (e.g. Lokas 2009). Despite the close masses and environments, the star formation histories of the dwarf spheroidal satellities of our Galaxy are strongly different: Draco, Sextans, and Sculptor are very metal poor, and each has a single old stellar generation, while Carina and Fornax demonstrate wide ranges of stellar ages, and their metallicities differ by an order.

An interesting feature is a magnesium-to-iron ratio in the stars of the dSphs. The most metal-poor stars of dSphs demonstrate magnesium overabundance, [Mg/Fe]$\approx +0.4 - +0.5$, just as stars in the halo of our Galaxy. But the Galactic halo and our thick disk demonstrate constant (flat) magnesium overabundance over the star metallicity range of $-3 <$ [Fe/H] $- 0.5$, while in dSphs the magnesium-to-iron ratio comes to zero already at [Fe/H]$= -2 - -1.5$ (for the summary of the data, see Cohen 2009). Since the magnesium-to-iron ratio traces the duration of the starforming process becoming solar after 2–3 Gyr of continuous star formation (e. g. Matteucci 1994), the abundance pattern in the dSphs implies that their star formation has been prolonged and inefficient. Recent simulations by Revaz et al.(2009) have succeeded to reconstruct various star formation regimes which can produce such diversity of chemical and age patterns among the stellar populations of dSphs. They simulate a dwarf spheroidal in isolation, and depending on the initial mass and on the initial star formation intensity, the galaxy may form its stars in the regimes of "full gas consumption" (the star formation ceases), of "the outflow" (the star formation ceases later), and of "self-regulation" (star formation bursts repeat several times). The real satellites of the Milky Way are reproduced nicely in these simulations, and only the residual gas has to be removed 'by hands' to match observations.

The problem with the gas removing implies a necessity of including effects of tidal interaction and/or intergalactic hot gas ram pressure within the outer dark halo of the large host galaxy for a dwarf spheroidal to form at last. Recent considerations by Klimentowski et al. (2009) and Mayer (2009) describe dynamical mechanisms to solve this problem. Initially, a dwarf galaxy under consideration represents a small disk irregular galaxy, with the width-to-radial scalelength ratio of $c/a = 0.3$. During the tidal interaction with the host galaxy, the dwarf disk develops a bar which is buckling in the vertical direction and heat the stellar component of the disk. The gas is removed by ram pressure. After 5 cycles of orbital motion, or after about 10 Gyr of evolution, the axis ratio becomes $c/a \approx 0.6 - 0.7$, and the disk transforms into a spheroid.

4. The origin of elliptical galaxies

The large elliptical galaxies are traditionally thought to form by merging. The most popular current scenario for the elliptical galaxy formation is major merging, or a merger of two disk galaxies of comparable masses. Historically, the scenario has been proposed by Beatrice Tinsley and Richard Larson (1979) to explain simultaneously the lack of rotation and the mass-metallicity relation for nearby elliptical galaxies: every merger event heats the stellar system dynamically while a star formation burst which must accompany merging if a significant gas fraction is present in merging subsystems provides the metallicity increase roughly proportional to the mass increase. The scenario has been explored enthusiastically by cosmologists because it is in line with their paradigm of hierarchical assembly of dark matter together with baryons into larger and larger gravitationally bound structures (starting from the paper by White & Rees, 1978, go on).

However, when the scenario has been inserted into the global picture of the Universe evolution in the frame of the concordant cosmological model (the LCDM one currently), it begins to contradict multiple observational data. Since the merging must proceed hierarchically, the largest elliptical galaxies are predicted to form the last and so must possess the youngest stellar populations among all ellipticals, if merging is accompanied by star formation bursts. The redshifts of the last major merger events for ellipticals more luminous than, say, $M_B \sim -21^m$ are well below 1 in the LCDM simulations (Kaviraj et al. 2009a) so the ages of stars dominating their integrated spectra must be well below 8 Gyr. Meantime the observations of nearby ellipticals demonstrate much older stellar ages, larger than 10 Gyr, and the strong age-mass correlation (e.g. Howell 2005, Smith 2005). The latter effect has been called 'downsizing'. Downsizing seems now to be the dominant tendency of many evolutionary phenomena observed in the real Universe: the largest galaxies are the oldest, the earliest supermassive black holes (in quasars) are the most massive, and so on. It costs hard efforts for cosmologists to consent the hierarchical paradigm with the observed downsizing.

A popular idea invented to avoid difficulties with the old stellar populations in giant elliptical galaxies is the idea of 'dry' merging. 'Dry' merging means merging without dissipative component, so without gas at all and without the consequent star formation burst which should rejuvenate stellar population in centers of the merger products. This idea has some theoretical arguments in favour of it. Indeed, the gas content of galaxies decreases *on average* with decreasing redshift, and among the most massive galaxies the early-type *gasless* galaxies dominate. So, it is highly probable that the *last* merger of the *most* massive galaxies would be the recent merger of two early-type gasless galaxies, so the recent dry merger. The idea was quite good; but it eliminated almost completely the resulting mass-metallicity relation for the most luminous elliptical galaxies (Pipino & Matteucci 2008) – the relation which inspired Tinsley and Larson to invent the major merger scenario of elliptical galaxy formation. Moreover, the kinematical structure of nearby elliptical galaxies contradicts strongly to their origin in dry mergers: the generally non-Gaussian shape of their line-of-sight velocity distributions (LOSVDs) requires significant dissipation during formation, and so does the high fraction of *rotating* elliptical galaxies, with their rotation axes aligned with the minor axes of isophotes (Cox et al. 2006). And finally, the observed frequency of close early-type galaxy pairs at redshifts of 0–1 which should be considered as potential major dry merger frequency, is much below the needed one to explain all the population of nearby elliptical galaxies, and its evolution with redshift is quite weak (Bundy et al. 2004, 2009). So the dry mergers cannot alone explain the present population of giant elliptical galaxies, with all their scaling relations.

We (Baes et al. 2007) have used another approach to identify a typical mechanism of elliptical galaxy formation. We studied stellar metallicity gradients along the radii which appeared to be good discriminators of the galaxy origin. Indeed, Kobayashi (2004) has simulated a variety of evolutionary histories of elliptical galaxies in the frame of the concordant LCDM cosmological model, from a monolithic collapse of a single gas cloud at one extreme to a major merger at the other extreme. She has found that while the monolithic collapse can produce metallicity gradients as steep as $\Delta \log Z/\Delta \log r \sim -1$, elliptical galaxies formed by major merger cannot possess metallicity gradients steeper than $\Delta \log Z/\Delta \log r \sim -0.35$: major mergers wash out any gradients due to provoking development of radial stellar orbits. An observed statistical (averaged) estimate of the typical metallicity gradient in a large elliptical galaxy is commonly accepted to be $\Delta \log Z/\Delta \log r \sim -0.2 - -0.3$ (Carollo, Danziger, & Buson 1993; Davies, Sadler, & Peletier 1993; Mehlert et al. 2003), and so at first glance it confirms the paradigm of major mergers. However, the most measurements up to date were confined to the inner parts of galaxies, $r < r_e$, where a linear dependence of $\Delta \log Z$ on $\Delta \log r$ was forced to fit the data because of their insufficient accuracy. We have observed 5 elliptical galaxies with the long-slit spectrograph of the Russian 6-m telescope to obtain deep spectroscopy, up to $3r_e$ in a few cases. When the absorption-line index profiles have been traced by us toward 1.5-3 effective radii of the galaxies under consideration, we have revealed breaks in the index profiles, typically around $0.5r_e$, which prevent us from fitting the metallicity radial dependencies by a single linear law. The inner metallicity gradients, within $r < r_e$, have all appeared to be steep, $\Delta \log Z/\Delta \log r \sim -0.4 - -0.9$, while the outer metallicity gradients are consistent with being nearly zero. By having found such two-tiered metallicity profiles in all our 5 elliptical galaxies, we have critically examined the best spectroscopic measurements by other authors, in particular, the Keck observations by Sanchez-Blazquez et al. (2007), and we have assured that the metallicity gradient breaks at $0.3 - 0.5\,r_e$ are commonly seen in elliptical galaxies, in the sense that the inner gradients are always steeper. However, noboby but us has paid an attention to this fact upto now. We have concluded that such two-tiered structure of metallicity distributions in present-day elliptical galaxies evidences for a complex formation mechanism which may include early monolithic collapse for the inner parts formation and subsequent built-up of the outer galactic parts by multiple minor mergers.

In fact, an idea about the importance of minor mergers in elliptical galaxy formation becomes now very popular; minor mergers have to be much more frequent than major mergers because of a larger number of small galaxies in the Universe, and they are able to provide a necessary population of well-shaped elliptical galaxies to $z \sim 1$ (Bournaud et al. 2007). Quite various observational statistics favour the dominant role of minor mergers. For example, the large scatter in the ultraviolet colours of early-type galaxies in the nearby Universe which has been found by GALEX recently can be explained by low-level star formation in their centers as a result of minor merging, or accretion, of gas-rich dwarf satellites (Kaviraj et al. 2009b). Just multiple minor mergers can provide gravitational heating of protoelliptical galaxies at $z \sim 2$ that turbulizes gaseous disks, stops wide-spread star formation and transforms stellar disks into stellar spheroids without the need of any feedback from supernova or AGN (Johansson et al. 2009). Tidal features – shells, loops, low-contrast arms and tails – which are seen around a large fraction of nearby giant ellipticals can hardly be simulated by dissipationless ('dry') major merging; instead they are well reproduced in the models of accretion of small kinematically cold disk galaxies (Feldmann et al. 2008). But the most impressive argument in favour of minor merging as a dominant mechanism to form elliptical galaxies is perhaps its application to the explanation of early-type galaxy size evolution.

Recently deep photometric surveys undertaken together at the VLT and the HST (GEMS, GOODS, et al.) have provided statistics on the sizes of early-type red ('quiescent') galaxies at $z > 1.5 - 2$. These galaxies have appeared to be very compact with respect to the nearby ellipticals, their effective radius being smaller by about a factor of 4–6 for the same luminosity, so their surface mass density is higher by an order or two (Trujillo et al. 2006, Zirm et al. 2007, Trujillo et al. 2007). How can these distant progenitors of the massive old galaxies be connected to the nearby ellipticals with their well-known scaling relations, in particular, to the Kormendy's relation between the size and surface brightness? We need mechanisms of dynamical evolution which increase strongly the sizes but only modestly – the stellar velocity dispersion. Among the mechanisms initially proposed there have been dry major merging – but it gives too many extramassive present-day elliptical galaxies – and active nucleus feedback. But the close inspection reveals that the only suitable mechanism which moves the high-redshift compact massive galaxies to the area of present-day ellipticals at the diagram 'size-density' is minor merging (Naab et al. 2009, Bezanson et al. 2009).

5. Conclusions

1. Dwarf spheroidal galaxies have been formed from disk galaxies by some external mechanisms of secular evolution.

2. Globular clusters may form during merger events, but the extreme metal-poor globular clusters may represent the primordial population.

3. The formation mechanisms of elliptical galaxies are now quite unclear, but the combination of some early monolithic collapse of a gas cloud with the later minor mergers seems to be the most promising scenario.

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