Formation and Evolution of Galaxy Bulges
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Age and metallicity of the bulges in lenticular galaxies

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Abstract. Panoramic spectroscopy of the sample of 80 nearby lenticular galaxies is presented. The SSP-equivalent ages, [Z/H], and [Mg/Fe] are determined through the Lick indices Hβ, Mgb, and $\langle$Fe$\rangle$ separately for the nuclei and for the bulges. About a half of the sample contain chemically distinct nuclei, more metal-rich and younger than the bulges. The statistics of stellar population properties for the nearby S0s is discussed.
Keywords: galaxies: elliptical and lenticular, cD; galaxies: bulges; galaxies: evolution

1. Introduction

Lenticular galaxies are perhaps the only class of nearby galaxies which is certainly formed rather recently. Direct observations of galaxy clusters at various redshifts have shown that the fraction of S0s in clusters has risen from 0–10% to 50%–60% between the lookback times of 6 and 2 Gyr (Fasano et al. 2000, Desai et al. 2007). The common point of view is that S0s galaxies are transformed from spirals due to some external action related to dense environment and/or hot intergalactic medium. Theoretical considerations propose a lot of mechanisms for this transformation: ram pressure by hot intracluster medium (Quilis et al. 2000), tidal stripping and heating (Larson et al. 1980, Byrd & Valtonen 1990), harassment (Moore et al. 1996), minor merger... Probably, different mechanisms may play role in different environment types, because in fact you can meet lenticular galaxies in any environments, from field to clusters. An interesting thing is that many of these mechanisms lead to gas concentration in the very centers of the galaxies at the moment of their transformation. It means that we can expect secondary nuclear star formation bursts and intermediate-age stellar populations in the nuclei of nearby S0s. Also, the statistics on bulge-to-disk luminosity ratios show that nearby S0s have on average more massive bulges than nearby spirals (e.g. Trujillo et al. 2002), so their transformation must include some process of bulge growth. It means that the bulges must have suffered some rejuvenation during the last 5 Gyr, and their stellar populations may be on average younger than those in nearby ellipticals. So there are good reasons to extract S0 galaxies from the wider samples of 'early-type' and 'red-sequence' galaxies and to search for particular properties of their stellar populations.

2. Sample

We consider a sample of 80 nearby S0s in the wide range of luminosity. Our sample is not complete but rather representative. We have undertaken a retrieval over the HYPERLEDA with the following restrictions:

- $v_r < 3000$ km/s;
- $-3 \leq t \leq 0$, where t is the numerical morphological-type indicator;
- $\delta(2000.0) > 0$;

- $B_T^0 \leq 13.0$.

Strong Seyfert nuclei or nuclear star bursts were excluded. The search gave us a list of 148 S0s, with 50 Virgo members among them. We have observed 66 targets from this list, including 10 Virgo members. Also a few more distant luminous galaxies as well as nearby fainter ones were added to the sample to expand the range of luminosities.

By following NOG survey of groups (Giuricin et al. 2000), we put our galaxies into four types of environments: those belonging to clusters (Virgo and Ursa Major), group central galaxies (the brightest galaxies in groups), group second-rank members, and field galaxies. Finally, we have 13, 22, 33, and 12 galaxies in every class.

The novelty of our approach to bulges is that we do not use *aperture* spectral data focused onto the centers of galaxies. Inspired by the panoramic spectroscopy benefits, we consider separately unresolved stellar nuclei and bulges taken as rings between $R = 4''$ and $R = 7''$; the latter R corresponds to 1.3 kpc for the most distant galaxies.

3. Observations and data reduction

All the observations have been made with the integral-field spectrograph of the Russian 6-m telescope, Multi-Pupil Field/Fiber Spectrograph (MPFS). The spectrograph had several modifications. In 1994–1998 it was a TIGER-mode spectrograph, with the fields of view of about 10×16 square elements, of $1.3''$ each. The spectral range was tight, and the spectral resolution, on average about of 5 Å, varied strongly over the field of view. In 1998 this spectrograph was replaced by another MPFS, which contained fibers transmitting light from the microlenses to the slit (Afanasiev et al. 2001). From 2002 upto now we observe with the field of view of 16×16 elements, of $1''$ each, the spectral range of 1500 Å, and the working spectral resolution of about 3 Å that permits to obtain reliable kinematical data in addition to the absorption-line indices.

Two spectral ranges are used: the green one, 4200-5700 Å, which provides Lick indices and stellar kinematics, and the red one, 5800-7200 Å, where strong emission lines can be found to study ionized-gas kinematics. We co-added the bulge elementary spectra over the rings to get index accuracy for the bulges comparable to that for the nuclei. Stellar velocities and velocity dispersions have been calculated by cross-correlation with template star spectra, gas velocities – by measuring baricentres of emission lines. The Lick indices Hβ, Mgb, Fe5270, and Fe5335 are measured for every nucleus and bulge. The Lick index system is calibrated by observing a sample of standard Lick stars (Worthey et al. 1994). Having observed a dozen galaxies more than once, we have assured that internal precision of the indices is 0.15 Å for Hβ and iron indices, and 0.1 Å for Mgb.

4. Results

Three characteristics of stellar populations, age T, global metallicity [Z/H], and magnesium-to-iron ratio [Mg/Fe], are determined separately for the nuclei and for the bulges by using the models of old stellar populations by Thomas et al. (2003). SSP approach (single-burst one-metallicity population) is applied, so the parameters determined are close to luminosity-averaged ones. The age T and metallicity [Z/H] are determined firstly, by confronting Hβ to [MgFe]$=$ (Mgb$\langle$Fe$\rangle$)$^{1/2}$ (insensitive to the Mg/Fe ratio), and then the abundance ratio [Mg/Fe] is determined by confronting $\langle$Fe$\rangle$ to Mgb for a given T. The detailed tables can be partly found in my recent paper (Sil'chenko 2006).

By starting our study of nuclei and bulges of early-type galaxies with the MPFS, we discovered immediately that the (unresolved) nuclei differ strongly from the surrounding bulges as concerning the absorption-line indices, namely, the nuclei demonstrated

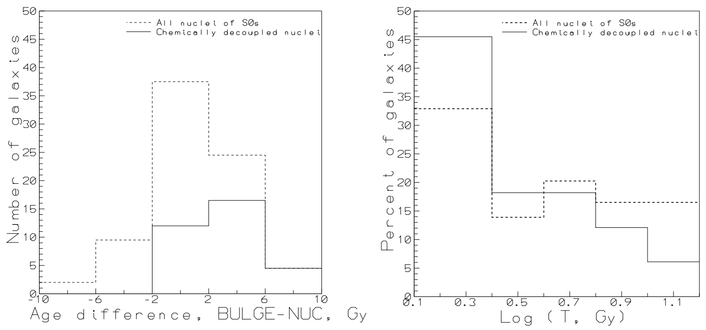

Figure 1. The results on mean stellar ages for the chemically distinct nuclei in comparison to the total sample of the nuclei in lenticular galaxies. (*a*) the histogram of the stellar age difference between the nuclei and the bulges; the chemically distinct nuclei are **always** younger than the surrounding bulges; (*b*) the distributions of the absolute values of the SSP-equivalent ages for the nuclei; the chemically distinct nuclei are separately shown by a solid line.

stronger metal absorption lines (Sil'chenko et al. 1992). Now, with our sample of 80 lenticular galaxies observed with the MPFS, we can state that about half of them have chemically distinct nuclei. If we select the galaxies where the nuclei are more metal rich than the bulges by +0.3 dex and more (by a factor of 2 and more), we come to the estimate of 42%. The limit put by us onto the metallicity difference to select chemically distinct nuclei is rather conservative and is defined by the fact that current estimates of the metallicity gradients in spheroidal galaxies are about 0.2–0.3 dex per radius dex. The chemically distinct nuclei selected by us have the *same* metallicity drop inside the radius equal to *one or two* resolved spatial elements. By comparing the subsample of the S0s with the chemically distinct nuclei to the total sample of nearby S0s (Fig. 1), we have assured that the chemically distinct nuclei are **always** younger than the surrounding bulges: the mean age difference between the chemically distinct nuclei and their surrounding bulges is 2.8 Gyr while the age difference between the nuclei and the bulges for the whole sample is only 1 Gyr. The age distribution of the chemically distinct nuclei peaks strongly at $T = 2$ Gyr whereas the total nuclear age distribution is rather flat between $T = 1$ and $T = 12$ Gyr.

So it is necessary to separate the nuclei and the bulges before making any conclusions about the properties of any of them. Nuclei and bulges have quite different evolution and differ as concerning their present stellar populations. Further we consider the bulges as taken in the rings between the radii of $4''$ and $7''$ – within the areas of bulge domination but beyond those affecting by the nuclei influence due to seeing effects.

By observing a representative sample of nearby S0s, we have tried to cover homogeneously all types of environments. We have more than ten galaxies in every environment class, so we are able to reveal any difference of stellar population parameters due to the environment type. However, at all diagnostic diagrams 'index vs index' the cluster S0s occupy just the same area as the group center galaxies, and group second-rank members are indistinguishable from the field galaxies. So we unite all the galaxies in two big groups: S0s in dense environments, namely, in clusters and group centers, and S0s in sparse environments, namely, in field and off-centered in groups. We see some difference between these two groups. In particular, at the diagram 'Hβ vs [MgFe]' which serves for age and metallicity determination, the bulges of S0s in dense environments are concentrated as compact point cloud, elongated from the parameter combination ($T = 12$ Gyr, [Z/H]= 0.0 dex) toward the combination of ($T = 5$ Gyr, [Z/H]= +0.3 dex), while the bulges of the galaxies in sparse environments are spread over all the ages, from 1 to 15

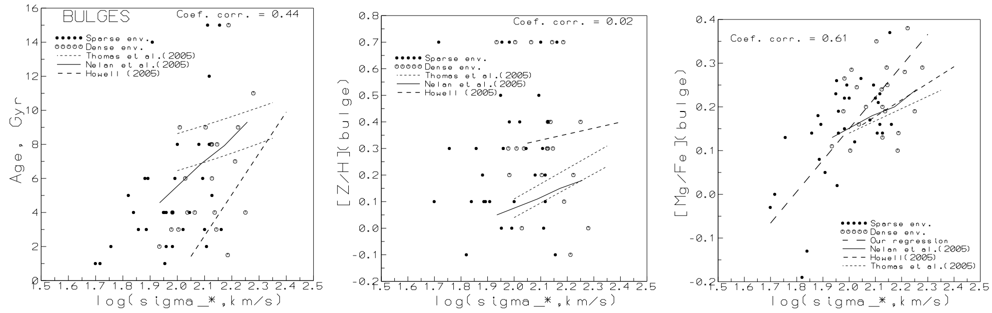

Figure 2. Correlations between the stellar population parameters and the logarithm of the local stellar velocity dispersion for the bulges of nearby lenticular galaxies. Local relations for various samples of early-type galaxies from the literature are also shown. (*a*) the SSP-equivalent age vs $\log\sigma_*$; (*b*) the total metallicity vs $\log\sigma_*$; (*c*) the magnesium-to-iron ratio vs $\log\sigma_*$.

Gyr, in the metallicity band of $0.0 - +0.3$ dex. The median stellar ages of the bulges are 4.0 Gyr in sparse environments and 6.7 Gyr in dense environments; the corresponding estimates for the nuclei are 2.4 and 4.1 Gyr, so the nuclei are on average younger than the bulges in any types of environments. To test if the age differences due to environment density is real, we must analyze age correlation with the stellar velocity dispersion.

Such relations are well-studied for elliptical galaxies in numerous works. We can compare our results obtained for the bulges of S0s, first of all, with these data. But as we separate the nuclei and the bulges when studying the properties of stellar populations, similarly, we wish to measure stellar velocity dispersion separately in the very centers ('inside the nuclei') and in the bulges, at $R \sim 5''$. Indeed, the results reveal again distinction between the nuclei and the bulges: the stellar velocity dispersion in the nuclei is typically larger than that in the bulges, and sometimes the difference reaches 70–80 km/s, with the mean of 27 km/s. To make a fair comparison, we confront the stellar population parameters to the *bulge* stellar velocity dispersion. This reduces our sample to 52 galaxies, because accurate stellar velocity dispersion mapping in the full mass range over the full field of view becomes possible only with the spectral resolution of 3 Å, after 2002. Below we analyze the correlations over the range of $\sigma_* = 50 - 200$ km/s.

In Fig. 2 we show dependencies of T, [Z/H], and [Mg/Fe] on $\log\sigma_*$, in comparison with the recent results for early-type galaxies in various types of environment from Thomas et al. (2005), Nelan et al. (2005), and Howell (2005) which have been obtained for more massive galaxies, with $\sigma_* > 100$ km/s typically. One can see that the age and metallicity dependencies on $\log\sigma_*$ are consistent with those for elliptical galaxies. The age correlates with $\log\sigma_*$, and the metallicity does not (Howell 2005). However, the correlation of the abundance ratio [Mg/Fe] with $\log\sigma_*$ is the strongest, and the slope of the regression is much steeper than the slope which is consistently found by several groups of investigators for elliptical galaxies. What does it mean? If we treat the correlation of [Mg/Fe] with the mass of spheroid as an evidence for more effective (and brief) star formation in deeper potential well, we may suggest that the relation found for the bulges of S0s is fundamental for some early formation process. Consequently, the flatter relation for ellipticals may be a result of later 'dry mergers' which increase the mass of spheroids leaving the properties of stellar population corresponding to the masses of smaller progenitors.

5. Conclusions

Unresolved stellar nuclei in early-type disk galaxies have their own evolution: 42% of nearby S0s have Δ[Z/H](nuc-bul)= +0.3 dex and more and the mean ΔT(nuc-bul)= −2.8 Gyr. The difference of the stellar velocity dispersion $\Delta\sigma_*$(nuc-bul) may reach 70 km/s, with the mean of 27 km/s. So to study bulges, one needs to measure off-nuclear zones.

In sparse environments there is a much larger spread of ages than in clusters and group centers. However when correlating the ages, metallicities, and Mg/Fe ratio with the stellar velocity dispersion, there is no separation due to the environment type. The SSP-equivalent ages correlate with the local stellar velocity dispersions, while the SSP-equivalent metallicities do not. But the age spread rises to larger σ_* - unlike ellipticals (Caldwell et al. 2003). The abundance ratio [Mg/Fe] correlates strongly with the stellar velocity dispersion, and the relation slope is much steeper than for ellipticals.

Acknowledgements

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Discussion

Pipino: Why do you think that the bulges of S0s have not experienced mergers?

Silchenko: S0 galaxies have large-scale stellar disks, and these disks are old. It means that recent major merger can be excluded because they have to destroy stellar disks.