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Young Nuclei in Dwarf Elliptical Galaxies

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Abstract—We report the discovery of young embedded structures in three diffuse elliptical galaxies (dE) in the Virgo cluster: IC 783, IC 3468, and IC 3509. We performed 3D spectroscopic observations of these galaxies with the MPFS spectrograph at the 6-m Special Astrophysical Observatory telescope and obtained spatially resolved distributions of kinematic and stellar population parameters by fitting high-resolution PEGASE.HR synthetic single stellar populations (SSP) in pixel space. In all three galaxies, the luminosity-weighted age of the nuclei (∼4 Gyr) is considerably younger than that of the population in the outer regions of the galaxies. We discuss two possibilities for the formation of such structures—a dissipative merger event and a different ram pressure stripping efficiency during two consecutive crossings of the Virgo cluster centre.

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1. INTRODUCTION

Diffuse (or dwarf) elliptical galaxies are a numerically dominating population in dense regions of the Universe, but their origin and evolution still remain unknown. These galaxies exhibit a great variety of kinematic and stellar population properties (Simien and Prugniel 2002; Geha et al. 2002, 2003; De Rijcke et al. 2004; van Zee et al. 2004a, 2004b), posing a number of questions to the current theories of galactic evolution. In the past, based on a photometric analysis, dE galaxies were believed to be old metal-poor objects that are building blocks for larger systems. This was consistent with the hierarchical merger scenario. However, spectroscopic studies (Geha et al. 2003; van Zee et al. 2004b) pointed to fairly young luminosity-weighted ages (∼3 Gyr) of the stellar populations of bright dE galaxies in the Virgo cluster, with the total absence of objects older than 10 Gyr.

The kinematics of dE galaxies is also fairly complex. A number of objects exhibit kinematically decoupled nuclei (De Rijcke et al. 2004; Geha et al. 2005; Thomas et al. 2006).

Recently, high-quality HST imagery became available for a large sample of early-type galaxies (from dwarfs to giants) in the Virgo cluster (Côté et al. 2004). Compact blue nuclei were discovered in many low- and intermediate-luminosity galaxies (Ferrarese et al. 2006). The $g' - z'$ colors of these nuclei correspond either to young ages or to reduced metallicities compared to their host galaxies.

Young stellar nuclei are a common occurrence in giant early-type galaxies (Sil'chenko 1997; Vlasyuk and Silchenko 2000) observed in both clusters and groups (Sil'chenko 2006). However, no young circumnuclear structures have been detected in dwarf elliptical/lenticular galaxies, probably because they are difficult to observe due to their low surface brightness. To achieve high signal-to-noise ratios sufficient for a stellar population analysis by the classical method of measuring Lick indices (Worthey et al. 1994), the integration time must be of the order of several hours even when large telescopes are used. In addition, integral field spectroscopy, an essential technique for reliable detection of such structures, has not yet been used to observe even small samples of dE galaxies, except for several individual objects (Geha et al. 2005).

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Several years ago, we initiated a project of observing a sample of dE galaxies in clusters and groups with the Multi-Pupil Fiber Spectrograph at the 6-m BTA telescope.

2. OBSERVATIONS AND DATA REDUCTION

The spectroscopic data that we analyze were obtained with the MPFS integral field spectrograph. The idea of integral field spectroscopy was suggested by G. Courtès in the late 1960s (for a description of the instrumental idea, see, e.g., Bacon et al. 1995). It allows a set of spectra to be simultaneously taken in a wide spectral range for an extended region in the sky.

The Multi-Pupil Fiber Spectrograph (MPFS) operating on the 6-m Special Astrophysical Observatory BTA telescope is a fiber-lens instrument with a microlens unit containing 16 × 16 square spatial elements, each with a size of $1'' \times 1''$ (Afanasiev et al. 2001). We used a setup of the instrument that provided an intermediate spectral resolution varying between $R = 1300$ and $R = 2200$ over the field of view and the selected spectral range (4100–5650 Å). Parameters of our observations are given in Table 1.

The data reduction for 3D spectroscopy is a fairly complex procedure. See our previous paper (Chilingarian et al. 2006) for a detailed description of this procedure. The results of the data reduction are flux-calibrated spectra and a parametrized line spread function (LSF) of the spectrograph for each spatial element at each wavelength.

We apply a Voronoi 2D adaptive binning procedure (Cappellari and Copin 2003) to achieve a signal-to-noise ratio sufficient for extracting the stellar kinematics and stellar population parameters ($S/N = 10\ldots20$) by degrading the spatial resolution of the data. The adaptive binning procedure yields a set of 1D spectra for which all the subsequent steps of our analysis are done independently.

Besides, for each of the objects, we apply an alternative procedure of tessellation of the data sets containing only two bins ("2-points"): a central young embedded structure and the rest of the galaxy.

For two galaxies, IC 3468 and IC 3509, we used the results of analysis of ACS images from the HST archive, proposal 9401, "The ACS Virgo Cluster Survey" (P.I.: P. Côté), presented in Ferrarese et al. (2006). For IC 783, we used the light and color profiles accessible in the GOLDMine database (Gavazzi et al. 2003).

To estimate the stellar population parameters, we apply a new technique developed by our team. Its basic idea is a simultaneous determination of the stellar population and kinematic parameters by fitting the observed spectra of galaxies in pixel space by high-resolution PEGASE.HR synthetic spectra (Le Borgne et al. 2004) in which the spatial resolution is degraded according to the line spread function (LSF) of the MPFS spectrograph to simulate the observing conditions. A description of the method and the first results of its applications are given in Chilingarian et al. (2005) and Prugniel et al. (2005); its stability and error analysis for MPFS observations are described in detail in Chilingarian et al. (2006). General kinematic and stellar population parameters for the three galaxies are presented in Table 2.

Table 1. Parameters of the observations

Object	Date	Total exposure time, h	Seeing
IC 783	May 21 and 23, 2004	3.5	$2''$
IC 3468	March 20, 2004	2.5	$1\overset{''}{.}5$
IC 3509	May 10 and 12, 2005	3.5	$1\overset{''}{.}7$

3. STELLAR POPULATIONS AND INTERNAL KINEMATICS

IC 783. A remarkable spiral structure was found in this galaxy (Barazza et al. 2002). IC 783 exhibits rotation ($v_{\rm rot} \sim 20$ km s^{-1}; see also Simien and Prugniel 2002). The velocity dispersion field is flat ($\langle\sigma\rangle = 35 \pm 10$ km s^{-1}) and shows no significant features (Fig. 1).

We have discovered a young nucleus in this galaxy with the following luminosity-weighted stellar population parameters: $t = 3.3 \pm 0.4$ Gyr and $Z = -0.35 \pm 0.04$ dex; compare with the main body (containing a spiral structure): $t = 12.8 \pm 4.0$ Gyr and $Z = -0.79 \pm 0.12$ dex. The young nucleus in IC 783 cannot be resolved spatially. According to Worthey (1994), the B-band mass-to-light ratios for the stellar populations are $(M/L)_{B*} = 2.1 \pm 0.2$ for the nucleus and $(M/L)_{B*} = 5.2 \pm 1.5$ for the rest of IC 783.

IC 3468. The galaxy is known to contain an embedded structure (Barazza et al. 2002). The question about the nature of this structure remained open, because long-slit spectroscopy by Simien and Prugniel (2002) revealed no rotation in this galaxy. However, we see complex kinematics in the integral field spectroscopic data (Fig. 2)—rotation along two nonperpendicular directions (NW–SE and NE-SW) separated by ~60° in position angle, none of which coincides with the slit position from Simien and Prugniel (2002). Unsharp masking of the HST ACS images reveals an elongated structure in the central region of the galaxy. Various parts of this structure can be

Table 2. Luminosity-weighted parameters of the stellar populations in three dE galaxies: ages, metallicities $[Z/H]$, and mass-to-light ratios for the stellar populations according to the models by Worthey (1994)

Object	Age, Gyr	$[Z/H]$, dex	$(M/L)_{B*}$
IC 783 (nucleus)	3.3 ± 0.4	-0.35 ± 0.04	2.1 ± 0.2
IC 783 (outer part)	12.8 ± 4.0	-0.79 ± 0.12	5.2 ± 1.5
IC 3468 (disk)	5.3 ± 0.4	-0.40 ± 0.05	2.8 ± 0.4
IC 3468 (outer part)	8.6 ± 0.9	-0.60 ± 0.05	4.0 ± 0.6
IC 3509 (nucleus)	4.1 ± 0.4	-0.05 ± 0.05	3.1 ± 0.4
IC 3509 (outer part)	7.8 ± 0.8	-0.40 ± 0.10	4.3 ± 0.5

identified by varying the smoothing radius for unsharp masking.

An elongated substructure with an age of $t = 5.3 \pm 0.4$ Gyr coincident with one of the rotating components (NW—SE) is clearly seen in the map of a luminosity-weighted stellar age. It is approximately 3.3 Gyr younger than the rest of the galaxy ($t = 8.6 \pm 0.9$ Gyr). A "blue stripe" can also be clearly seen in the velocity dispersion distribution (lower by $\sim$10 km s^{-1} than the mean values) at the same location. Based on these results, we conclude that the NW—SE rotation corresponds to a moderately inclined stellar disk ($i \sim 60^\circ$). The rotational velocity is 17 ± 4 km s^{-1} at 7 arcsec from the center, but we cannot be sure that the rotation maxima are reached—wider-field observations are needed.

Interestingly, this disk has virtually no effect on the metallicity distribution. The luminosity-weighted metallicity exhibits a relatively smooth behavior ($[Z/H] = -0.60 \pm 0.05$ dex) with a slight gradient toward the center (up to $[Z/H] = -0.40 \pm 0.05$ dex).

The B-band mass-to-light ratios for the stellar populations are $(M/L)_{B*} = 2.8 \pm 0.4$ for the disk and $(M/L)_{B*} = 4.0 \pm 0.6$ for the outer parts. Our estimates of the luminosity-weighted age and metallicity at the center of IC 3468 correspond to the $g' - z'$ color of a compact nucleus (averaged within the host galaxy over the aperture corresponding to the seeing conditions) given in Ferrarese et al. (2006)

IC 3509. When we selected the objects for observations, we chose IC 3509 as the "prototype" of a dE galaxy without a nucleus classified in this way by Binggeli et al. (1985). We did not expect to see unusual kinematics and/or stellar populations in this object. However, we detected a kinematically decoupled central region rotating ($v_{\rm rot} \sim 10$ km s^{-1}) in a direction perpendicular to the major axis; significant rotation ($v_{\rm rot} \sim 20$ km s^{-1}) along the photometric major axis is also seen in the outer regions (Fig. 3). This kinematically decoupled internal structure also exhibits a dip in the stellar velocity dispersion distribution (50 km s^{-1} compared to 75 km s^{-1} at 4 arcsec from the center) and a metallicity gradient of about 0.2 dex. The stellar population of the galaxy is relatively old and metal-poor ($t = 7.8 \pm 0.8$ Gyr, $[Z/H] = -0.40 \pm 0.10$ dex, $(M/L)_{B*} = 4.3 \pm 0.5$). At the very center of the galaxy, we see a spatially unresolved young ($t = 4.1 \pm 0.4$ Gyr) metal-rich ($[Z/H] = -0.05 \pm 0.05$ dex) nucleus ($(M/L)_{B*} = 3.1 \pm 0.4$).

We applied unsharp masking to the HST images available from the Virgo ACS Survey (Cotê et al. 2004) with various smoothing radii. No embedded structures were found.

A kinematic manifestation quite similar to IC 3509 was observed previously in giant early-type galaxies, for example, in NGC 5982 (Statler 1991). An explanation that did not require the presence of dynamically decoupled structures was offered—the projection of orbits in a triaxial potential. Based on the fairly regular (except the very center) maps of stellar population parameters for IC 3509, we conclude that the galaxy outside the nuclear region can be represented by a single-component triaxial ellipsoid.

As in the case of IC 3468, the $g' - z'$ color for the nucleus of IC 3509 presented by Ferrarese et al. (2006) is consistent with our estimates of the stellar population parameters.

4. DISCUSSION

Since the first discovery of chemically (Sil'chenko et al. 1992) and evolutionarily (Sil'chenko 1997; Vlasyuk and Silchenko 2000) decoupled nuclei in giant early-type galaxies, no attempts have been made to quantitatively model their formation and evolution. A usual qualitative explanation of this phenomenon is a dissipative merger event. Whereas a merger is a universally accepted scenario for the formation of giant early-type galaxies, it is generally considered to be unlikely for dwarfs because of their small sizes and masses.

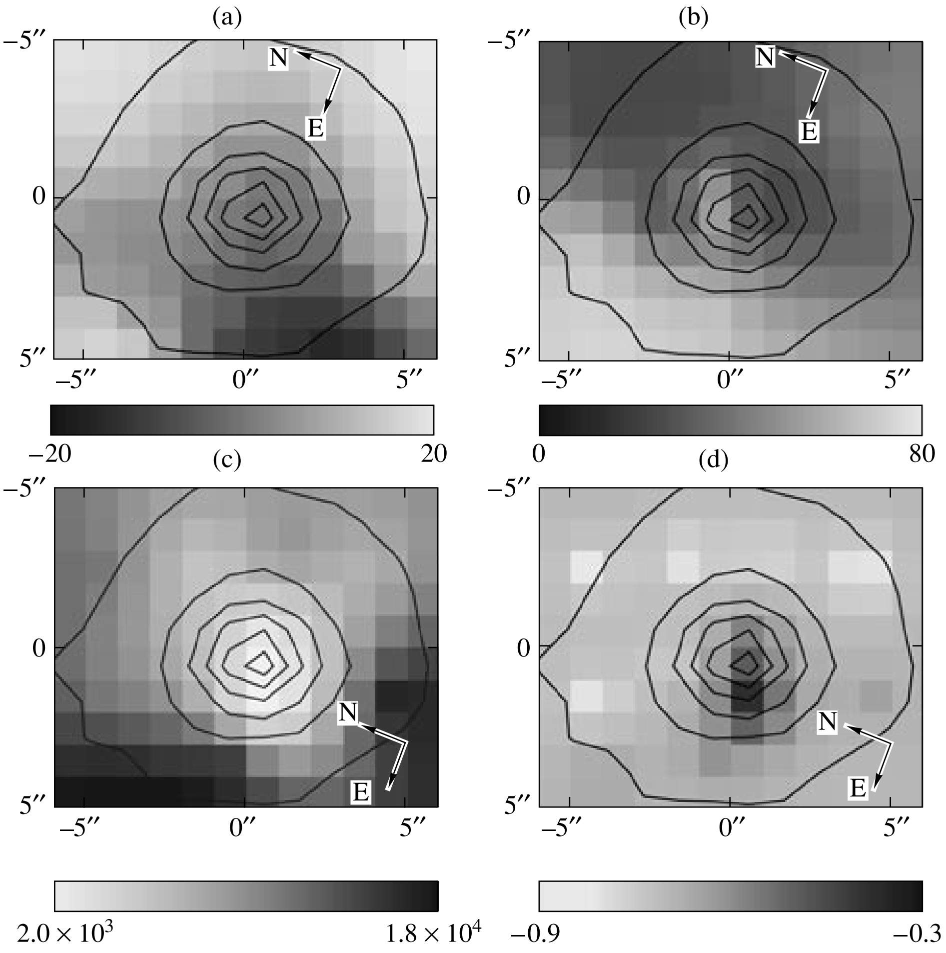

Fig. 1. Kinematics and stellar population of IC 783. The maps of internal stellar kinematics and stellar population parameters were constructed for Voronoi tessellation with a target S/N ratio of 15. (a) Radial velocity (km s^{-1}), (b) stellar velocity dispersion (km s^{-1}), (c) luminosity-weighted age (*M*yr), and (d) luminosity-weighted metallicity (dex, with respect to the Sun on a logarithmic scale).

However, the presence of an embedded disk in IC 3468 is an important argument for the merger scenario. Kinematically decoupled structures associated with a young metal-rich stellar population can be formed precisely through a dissipative merger of gas-rich galaxies several Gyr ago. Such a dissipative merger is expected to trigger a starburst at the galactic center, with the gas of the merging galaxies serving as the material for it. Several Gyr later, this starburst will give rise to a kinematically decoupled nucleus in the form of a circumnuclear stellar disk that will be younger than the host galaxy.

Another possibility is the process of ram pressure stripping by the hot intergalactic medium. The efficiency of this phenomenon depends on the density of the region in the galaxy being stripped of the gas: higher densities result in a lower efficiency (Gunn and Gott, 1972; Abadi et al. 1999). Thus, it may happen that the intergalactic medium will “blow off” the gas only from the galactic periphery, while the gas in the dense nucleus of a dwarf galaxy will not be removed. A similar phenomenon of gaseous disk truncation is observed in giant spiral galaxies in the Virgo cluster (Cayatte et al. 1994; Kenney and Koopmann 1999). It was explained and modeled by Abadi et al. (1999). The gas survived at the galactic center and additionally compressed by the ram pressure from the hot intergalactic medium can rapidly turn into stars and produce a circumnuclear stellar disk.

Multiple crossings of the cluster center are a possible scenario for the formation of the structure observed in IC 783 (the total absence of gas and a compact young nucleus without clear evidence of being kinematically decoupled). IC 783 is located at a projected distance of 1.1 Mpc from the center of the Virgo cluster. Thus, its orbital period is at least 4.5 Gyr (assuming the cluster mass to be $10^{14} M_{\odot}$). The gas of IC 783 can be removed from its disk

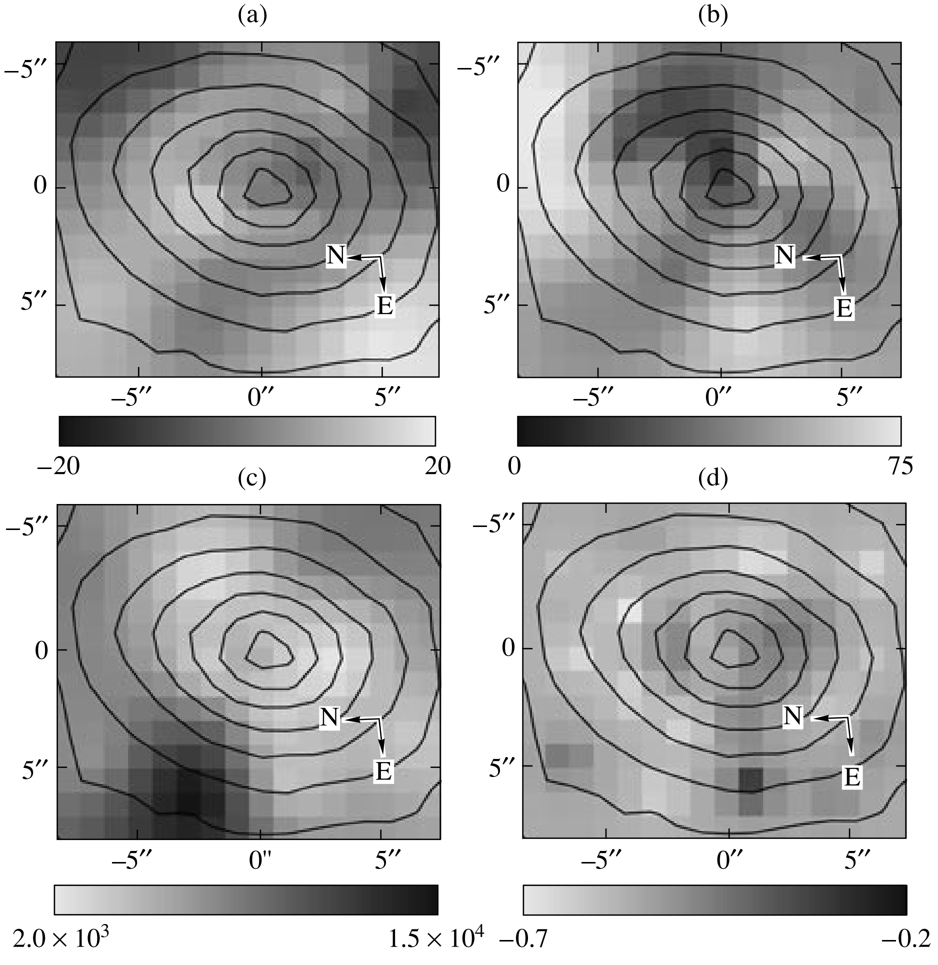

Fig. 2. Same as Fig. 1 for IC 3468.

during the first crossing of the cluster center, but it will be retained in the inner dense galactic nucleus, because the intercluster medium density and/or the galaxy velocity may be not enough for the gas to be removed completely. To remove the gas and to stop the star formation in the nucleus, we may assume that during the second crossing several Gyr later, the intracluster orbit of the galaxy can be transformed into a slightly more elongated one, say, due to a chance encounter with a massive galaxy. Consequently, $v_{\rm cross}$ will increase (as will ρ, because the galaxy will pass closer to the cluster center); as a result, the ram pressure $P = \rho v^2$ will reach a value sufficient to strip the galactic nuclear region of the gas and to stop the star formation.

An alternative possibility of the variation in ram pressure stripping efficiency for IC 783 can be explained by its belonging to the Messier 100 group. IC 783 is located at a projected distance of 90 kpc from M 100 and their radial velocity difference of $\sim$270 km s^{-1} is an argument for the interaction. Assuming that the M 100 group is currently passing through its apocentre, its orbital period in the cluster is about 5–8 Gyr; thus, the last crossing of the cluster center could take place 3–4 Gyr ago and the previous one could occur 8–12 Gyr ago. On the other hand, the orbital period of IC 783 with respect to M 100 should be about 1 Gyr. Thus, if the orbital velocity of IC 783 was counter-directed to the orbital motion of M 100 in the cluster during the first crossing of the center and co-directed during the second crossing, then the ram pressure $P = \rho v^2$ could change by a factor of 3.5 (assuming the maximum velocity of M 100 with respect to the Virgo intracluster medium to be $\sim$1000 km s^{-1} and the orbital velocity of IC 783 with respect to M 100 to be $\sim$300 km s^{-1}). The coincidence of the crossing times of the cluster center by the M 100 group with the ages of the two populations in IC 783 is a strong argument for this scenario.

The ram pressure stripping during repeated crossings of the cluster center may be considered as a possible explanation of the young metal-rich nuclei in dwarf early-type galaxies. Depending on the orbital parameters of a specific galaxy in the cluster, one

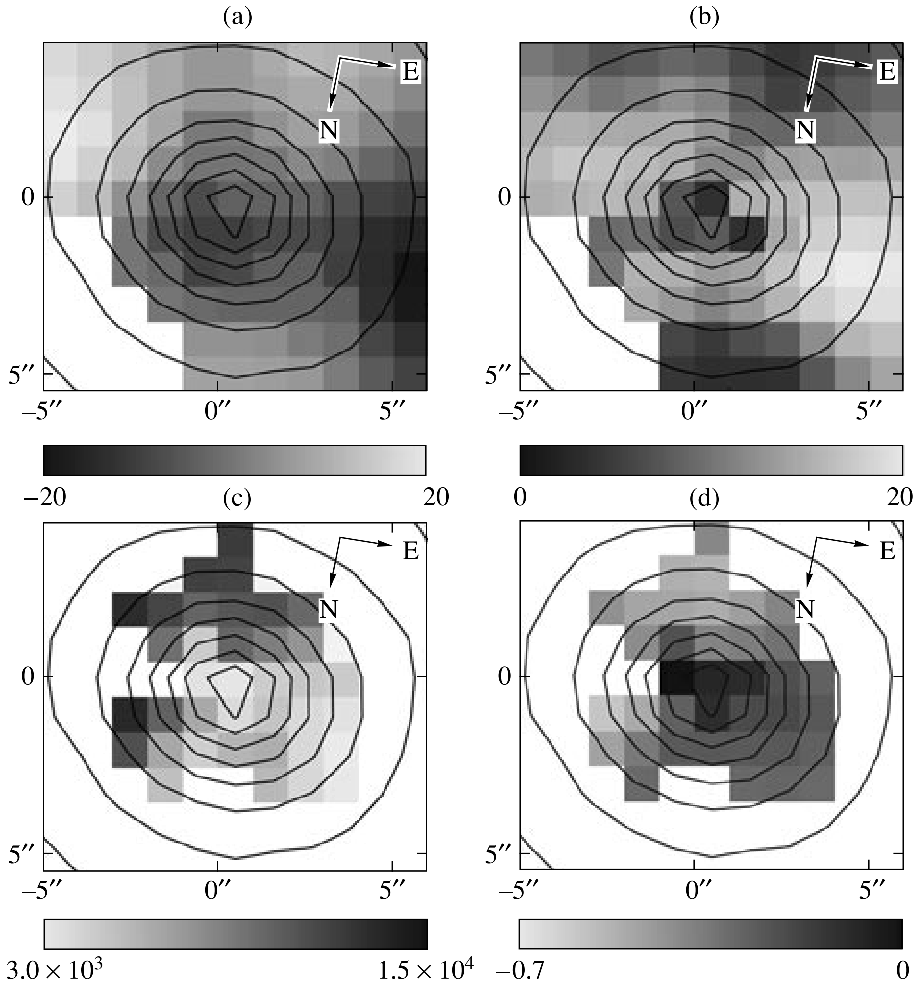

Fig. 3. Same as Fig. 1 for IC 3509.

might expect a large scatter of ages/metallicities of these substructures with respect to their host galaxies. This effect can explain the increase in the scatter of mean ages and metallicities of early-type galaxies toward low-massive objects, as reported by Caldwell et al. (2003) based on multi-object spectroscopy.

Good agreement between the model colors obtained from our estimates of the stellar population parameters and the $g' - z'$ colors of the compact nuclei in IC 3468 and IC 3509 may be considered as evidence for the presence of young metal-rich stellar populations in all compact blue nuclei of dE galaxies (Côté et al. 2006). However, this hypothesis can be confirmed only by future observations.

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