HOMOGENEITY OF STELLAR POPULATIONS IN EARLY-TYPE GALAXIES WITH DIFFERENT X-RAY PROPERTIES

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Received 1999 August 19; accepted 2000 March 14

ABSTRACT

We have found that the stellar populations of early-type galaxies are homogeneous with no significant difference in color or Mg\(_2\) index, despite the dichotomy between X-ray–extended early-type galaxies and X-ray–compact ones. Since the X-ray properties reflect the potential gravitational structure and, hence, the process of galaxy formation, the homogeneity of the stellar populations implies that the formation of stars in early-type galaxies predates the epoch when the dichotomy of the potential structure was established.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — galaxies: ISM — galaxies: stellar content

1. INTRODUCTION

ASCA X-ray observations of NGC 4636 (Matsushita et al. 1998) and some other giant early-type galaxies (Matsushita 1997) show that early-type galaxies can be classified into two categories in terms of X-ray extent. Some early-type galaxies have a very extended dark matter halo characterized by X-ray emission out to \(\sim 100\) kpc from the galaxy center, while others have a compact X-ray halo. The galaxies with an extended X-ray emission can be interpreted as sitting in larger scale potential structures, such as galaxy groups, subclumps of clusters, or clusters themselves, as well as sitting in the potential well that is associated with each galaxy.

Potential structure must have played a big role in the course of galaxy formation. If the difference in potential structure had already been established before the bulk of stars formed, we would expect some differences in stellar populations, such as in their mean age or metallicity, as well. A deeper potential well would keep the gas more effectively against the thermal energy input by supernova (SN) explosions, the chemically enriched gas could be recycled more efficiently, and the galaxy would end up with higher mean stellar metallicity (Larson 1974). Therefore, we would expect that the X-ray–extended galaxies have higher metallicities than the X-ray–compact ones at a given stellar mass. Furthermore, considering that the higher density peaks collapse earlier in the universe, which is likely to be the case for the X-ray–extended galaxies sitting in the local density peaks, we would also expect them to be older than the X-ray–compact ones. Both of these effects would make the colors of the X-ray–extended galaxies redder. The central question of this paper is, therefore, how this dichotomy in X-ray properties, and hence the potential structure, is related to the optical properties that trace the stellar populations in galaxies.

Another interesting issue is whether the number of globular clusters per unit optical luminosity of galaxy correlates with the X-ray extent of the galaxy. This is because, if the X-ray–extended galaxies are the products of galaxy mergers as they are located in the center of larger scale potential structures, and if a considerable number of new globular clusters form during galaxy mergers, as suggested by Zepf & Ashman (1993), we would expect more globular clusters in the X-ray–extended galaxies for a given optical luminosity.

Matsushita (2000, hereafter M2000) has recently compiled the X-ray properties of 52 nearby early-type galaxies from ROSAT data. Together with the archival data of various optical properties, we now compare the optical properties with the X-ray properties to examine the correlation between them.

The structure of this paper is the following. In §2 we summarize the X-ray properties of our sample of early-type galaxies, highlighting the dichotomy of the potential structure. In §3 we present their optical properties, including integrated colors and Mg\(_2\) index. We show the homogeneity of the stellar populations despite the dichotomy in X-ray properties. We discuss the impact of this result on the formation of early-type galaxies in §4 and conclude the paper in §5. We use \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) throughout this paper.

2. X-RAY PROPERTIES

We use the same sample of early-type galaxies presented in M2000. The sample is composed of 52 bright early-type galaxies, of which 42 are ellipticals and 10 are S0 galaxies. M2000 have selected all the early-type galaxies observed by the Position Sensitive Proportional Counter (PSPC), available in the ROSAT archival data, whose B-band magnitudes are brighter than 11.7. The environment of the sampled galaxies varies from cluster environment (Virgo, Fornax, and Centaurus Clusters) to galaxy groups and the field.

Figure 1 shows the X-ray luminosity of the interstellar medium (ISM) within a radius of \(4r_e(L_{\text{IS}M})\) against \(L_B\sigma^2\) for all the sample galaxies, where \(r_e\), \(L_B\), and \(\sigma\) indicate the effective radius in the optical profile, the galaxy luminosity in the B band (taken from Tully 1988), and the central velocity dispersion of stars, respectively. In order to exclude the contribution from low-mass X-ray binaries and the active galactic nuclei, the ROSAT PSPC spectrum (0.2–2.0 keV) is fitted with two components, soft (\(\sim 1\) keV) and hard (10 keV), and only the soft component is used to determine the ISM X-ray luminosity (M2000). The quantity \(L_B\sigma^2\) is proportional to the kinetic energy of the gas supplied from

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stellar mass loss and heated up by random stellar motions. The solid line, \( \log L_X/L_B \sigma^2 = 25.15 \) (constant), corresponds to the energy balance between the cooling by X-ray emission and the heating by stellar mass loss, assuming a relation between mass loss rate and \( L_B \) (Ciotti et al. 1991; M2000). There is a considerable scatter in \( L_X \) for a given \( L_B \sigma^2 \). Many galaxies follow the solid line, suggesting that their X-ray luminosities can be simply explained by the energy input from stars through mass loss. However, some galaxies have significantly higher \( L_X/L_B \sigma^2 \) ratios, requiring an excess energy to explain such high X-ray luminosities. Many of these \( L_X \) bright galaxies are classified as X-ray–extended galaxies in M2000 (crosses) as they show spatially extended X-ray emission. They are likely to have more extended dark matter halos residing on larger scale structures, such as a group or a cluster of galaxies, as well as on its own galaxy. Furthermore, the X-ray–extended galaxies show significantly higher ISM temperatures at \( r > r_e \) than do the X-ray–compact ones as a result of their extended potential. In fact, their mean ISM temperature within 4\( r_e \) is about a factor of 2 higher than the others at a given \( \sigma \) (M2000). We reproduce this plot in Figure 2. We refer to these differences as a dichotomy of X-ray properties. Therefore, we will use a quantity \( F_X = \log L_X/L_B \sigma^2 - 25.15 \), the excess energy in \( L_X \), as a measure of the “X-ray extent” later, in § 3. A larger \( F_X \) means that a galaxy has a deeper and more extended potential. The galaxies that are classified as X-ray–extended ones in M2000 are the following nine: NGC 4406 (bright galaxy in Virgo Cluster), NGC 4472 (brightest galaxy in Virgo), NGC 4486 (cD in Virgo), NGC 4636 (bright galaxy in Virgo), NGC 4696 (cD in Centaurus Cluster), NGC 1399 (cD in Fornax Cluster), NGC 1407 (group center), NGC 5044 (group center), and NGC 5846 (group center).

3. OPTICAL PROPERTIES

We have compiled the optical properties of our sample galaxies from various sources. The integrated colors are taken from de Vaucouleurs et al. (1991, hereafter RC3). Following Schweizer & Seitzer (1992), we defined \((U-V)_{e,0}\) as

\[
(U-V)_{e,0} = (U-V)_{e} + [(U-V)_{T,0} - (U-V)_{T}],
\]

where subscript \( T \) denotes global colors, subscript 0 indicates colors corrected for Galactic extinction and redshift, and subscript \( e \) denotes average colors within the effective radius \( r_e \). \((B-V)_{e,0}\) is also defined in a similar way. The integrated colors within \( r_e \) in the Cousins system, \((V-R)_{e}\) and \((V-I)_{e}\), are taken from Buta & Williams (1995). Galactic extinction is corrected for using the extinction in the \( B \) band \((A_B)\) from RC3 and the extinction curve from Rieke & Lebofsky (1985). The reddening-corrected colors are denoted as \((V-R)_{e,0}\) and \((V-I)_{e,0}\). The reason we use colors within \( r_e \) rather than the total colors is that there are more galaxies available with \( r_e \) apertures. This improves the statistics. Furthermore, the colors within \( r_e \) would be more reliable than the total colors, although no errors are given in the literature for the total colors. However, we have checked that the results in this paper did not change even if we used the total colors. The central line index \( M_g \), central velocity dispersion \( \sigma \), maximum rotation velocity \( V_{\text{max}} \), and deviation from the fundamental plane \((\Delta F_P)\) are obtained from Prugniel & Simien (1996). A velocity dispersion for NGC 4096 is added from Faber et al. (1989). The globular cluster specific frequency \( (S_h) \), which is the number of globular clusters per unit galaxy luminosity, is acquired.
from Ashman & Zepf (1998). Finally, the $a_4$ index, which is the fourth cosine coefficient of the Fourier expansion of isophotal deviation from a pure ellipse, and the ellipticity ($e$) are taken from Bender et al. (1989). We will use these values later in this section. The number of galaxies that have optical properties available are 44 ($U-V$), 47 ($B-V$), 32 ($V-R$), 32 ($V-I$), 43 ($\text{Mg}_2$), 49 ($\Delta FP$), 44 ($V_m$), 23 ($S_N$), and 25 ($a_4$) out of a total of 52 galaxies in our X-ray sample.

In the top three panels of Figure 3, we have plotted $U-V$, $V-I$ colors and the $\text{Mg}_2$ index against log $\sigma$. The error bars indicate 1σ measurement errors. The error bars for $\text{Mg}_2$ are not shown but are negligibly small (<0.005). The typical error for log $\sigma$ is ∼0.02 (Prugniel & Simien 1996). We find the scaling relations for the early-type galaxies as a whole, which are shown by the solid lines. The linear regression lines are fitted to the data excluding the X-ray–extended galaxies in order to see the difference between the X-ray–extended galaxies (crosses) and the X-ray–compact ones (the others), if present. For comparison, the same relations taken from Bower, Lucey, & Ellis (1992) and Burstein et al. (1988) are also reproduced by the dashed lines in the top panel and the third panel, respectively. Our regression lines agree very well with those in the literature. Most important, none of the $U-V$, $V-I$, and $\text{Mg}_2$ indices of the X-ray–extended galaxies looks different from those of the X-ray–compact ones, being well within the scatter at fixed $\sigma$.

$S_N$ is plotted against log $\sigma$ in the bottom panel of Figure 3. The error bars correspond to 1σ. Again, the X-ray–extended galaxies do not have systematically different $S_N$ values, except the two circled galaxies, NGC 1399 and NGC 4486 (the former has a larger $\sigma$), which have a factor of 2–3 as many globular clusters for a given optical galaxy luminosity. These are both cD galaxies in nearby clusters, which might have had rather different mechanisms of globular cluster formation, such as secondary formation in the cooling flows (Richer et al. 1993, but see also Holtzman et al. 1996 for an objection), capture of globular clusters from other galaxies through tidal stripping (Côté, Marzke, & West 1998), or the debris of cannibalized nucleated dwarf galaxies (Bassino, Muzzio, & Rabolli 1994). Apart from these cD galaxies, the number of globular clusters seems comparable between the X-ray–extended galaxies and the X-ray–compact ones. The consequence of this result will be discussed in §4.

In order to compare the optical properties against the X-ray properties in a more general manner, we use $E_X$ as a measure of the X-ray extent or the depth of the potential (§2). To subtract the underlying metallicity effect as a function of galaxy mass (or $\sigma$) that is present in early-type galaxies (e.g., Kodama et al. 1998), we measured the deviations from the color–$\sigma$ and the $\text{Mg}_2$–$\sigma$ relations (Fig. 3, solid lines) for each galaxy and plotted them against the X-ray extent ($E_X$) in Figure 4. The raw values of $S_N$ are replotted in the bottom panel. There is no clear trend that any of the optical quantities scale with the X-ray extent. Our result is consistent with White & Sarazin (1991), who found no correlation between the excess of X-ray luminosity for a given optical luminosity and the residual from the scaling relations in $U-V$ color and $\text{Mg}_2$ index.

To test the above results statistically, we calculate the mean deviations in four colors, the mean deviations in the $\text{Mg}_2$ index, and the mean $S_N$ for the X-ray–extended galaxies and the X-ray–compact ones separately. The results are summarized in Table 1. The standard deviation within

![Fig. 3.—Integrated colors within an effective radius ($U-V_{c,0}$) and ($V-I_{c,0}$), central $\text{Mg}_2$ index, and globular cluster specific frequency $S_N$. (from top to bottom) are plotted against the central stellar velocity dispersion $\sigma$. Vertical error bars (1σ) are shown except for the $\text{Mg}_2$ index. Crosses indicate the X-ray–extended galaxies, and those surrounded by big circles are the cD galaxies. The galaxies in cluster environments are shown by filled symbols, while those in the field or in small groups are shown by open symbols. Ellipticals are indicated by circles, while S0 galaxies are indicated by triangles. The solid lines are the linear regression lines fitted to the data excluding the X-ray–extended galaxies. The dashed lines show the relations taken from the literature (Bower et al. 1992; Burstein et al. 1988).](image)

| Index                | X-Ray Compact | X-Ray Extended | Probability of the Difference (%) |
|----------------------|---------------|----------------|----------------------------------|
| $\Delta (U-V)_{c,0}$ | 0.00 ± 0.07   | −0.04 ± 0.05   | <90                              |
| $\Delta (B-V)_{c,0}$ | 0.00 ± 0.03   | −0.01 ± 0.02   | <80                              |
| $\Delta (V-R)_{c,0}$ | 0.00 ± 0.01   | −0.01 ± 0.02   | <80                              |
| $\Delta (V-I)_{c,0}$ | 0.00 ± 0.03   | −0.01 ± 0.03   | <50                              |
| $\Delta \text{Mg}_2$ | 0.00 ± 0.02   | 0.00 ± 0.02    | <50                              |
| $S_N$                 | 3.80 ± 2.33   | 5.25 ± 1.73    | <80                              |
| $\Delta FP$           | −0.10 ± 0.19  | 0.07 ± 0.09    | >99                              |
| $a_4/a_0 \times 100$ | 0.25 ± 0.98   | −0.30 ± 0.26   | >95                              |
| $(V_m)^*$             | 0.59 ± 0.40   | 0.24 ± 0.18    | >99                              |

Notes.—The average values are shown for, from top to bottom, the deviations from the scaling relations of the four colors and $\text{Mg}_2$ against log $\sigma$, $S_N$ deviation from the fundamental plane, boxy/dislike index, and anisotropy index. Standard deviations are given following the ± signs as the measure of scatters around the average values. The two cD galaxies, NGC 1399 and NGC 4486, are excluded in calculating the averaged $S_N$ value and the scatter for the X-ray–extended galaxies.
We will discuss this point in the future with the same stellar mass form in various potential depths. A small dynamical mass-to-light difference is always smaller than 90%, and the hypothesis of only a dynamical mass difference is rather homogeneous below this level despite the variety of X-ray extent. If a difference of more than 0.078 in U - V or 0.023 in Mg, had been present between the two groups, it should have been detected at the significance level in this statistical test and found that none of these optical quantities show significant difference between the X-ray-extended galaxies and the compact ones. The probability of the difference is always smaller than 90%, and the hypothesis that we draw both samples from the same parent group cannot be rejected.

If a difference of more than 0.078 in U - V or 0.023 in Mg, had been present between the two groups, it should have been detected at the significance level in this statistical test. This corresponds to the difference in stellar populations of only $\Delta \log Z = 0.1$ or $\Delta \log T = 0.15$ for old galaxies (Kodama & Arimoto 1997). Therefore, the stellar populations of the early-type galaxies should be homogeneous below this level despite the variety of X-ray extent. The above upper limit for the metallicity difference is rather small compared with the expected difference if the galaxies with the same stellar mass form in various potential depths. We will discuss this point in § 4.

We also plot the deviation from the fundamental plane, $\Delta$FP, in the top panel of Figure 5 as a function of $E_X$. $\Delta$FP is a measure of the difference of the dynamical mass-to-light ratio from that of the “normal” early-type galaxies with the same dynamical mass (Prugniel & Simien 1996). This indicates the deviations in stellar populations and/or dynamical mass including dark matter. A positive value of $\Delta$FP corresponds to a larger mass-to-light ratio. The X-ray-extended galaxies generally have a high $\Delta$FP, while the X-ray-compact ones show a considerable spread toward lower values. Since we have found that the stellar populations are quite homogeneous against $E_X$, the above result is indicative of the presence of more dark matter in the X-ray-extended galaxies, as expected.

Finally, we compare the isophotal shape and the velocity anisotropy against the X-ray properties. We first use the $a_d/a$ index, where $a_d$ is the fourth cosine coefficient of the Fourier expansion of the deviations from a pure ellipse and $a$ is the semimajor axis of the isophote (Bender & Möllenhoff 1987). A positive value of $a_d/a$ means a disklike isophote, while a negative value corresponds to a box-shaped isophote. The other index, $V_m/\sigma$, is a ratio between maximum rotation velocity ($V_m$) and central velocity dispersion ($\sigma$), which is transformed to the anisotropy index by taking into account the ellipticity ($e$) as

$$V_m/\sigma^* = (V_m/\sigma)/\sqrt{e/(1-e)},$$

following Bender (1988). There are clear trends that the X-ray-extended galaxies have a negative $a_d/a$ and small ($V_m/\sigma^*$) with relatively small scatters. These effects should come partly from the dependence of $a_d/a$ and ($V_m/\sigma^*$) on galaxy luminosity (Bender 1988; Bender et al. 1989), because the X-ray-extended galaxies are generally bright. However, it is notable that all of the X-ray-extended galaxies have boxy shapes and weak rotations. These findings
are similar to what Bender (1988) and Bender et al. (1989) found; i.e., the $a_{\alpha/\alpha}$ index correlates with the X-ray luminosity excess that comes from the surrounding hot gas halos and also with the velocity anisotropy. Some attempts have been made to understand this kinematical dichotomy of elliptical galaxies in the context of galaxy-galaxy merging using dynamical simulations (Bekki & Shioya 1997; Naab, Burkert, & Hernquist 1999). Naab et al. (1999) showed that major mergers produced boxy ellipticals with anisotropic velocity, while minor mergers produced the disklike ones. Considering also that the X-ray–extended galaxies are located at the local density peaks, they are possibly the products of major mergers.

After all, although the clear dichotomy in X-ray properties correlates with the isophotal shape and the velocity structure of galaxies, the stellar populations and globular cluster properties are still found to be quite homogeneous.

4. DISCUSSION

We estimate how much metallicity difference is expected between the X-ray–extended galaxies and the X-ray–compact ones at a given stellar mass (or $\sigma$) if the dichotomy of the potential structure has already been established at the time of star formation. The hydrostatic equilibrium for the ISM gives the galaxy potential of

$$\Phi \propto T \left( \frac{\log \rho}{\log r} + \frac{\log T}{\log r} \right), \quad (3)$$

where $\rho$ is the density of matters including the dark matter. Since the density gradient $\log \rho/\log r$ should not differ much between the two galaxy categories (X-ray extended and X-ray compact) within optical radius and the ISM temperature gradient $\log T/\log r$ is negligible compared with the density gradient (Forman, Jones, & Tucker 1985; Trinchieri et al. 1994; Boute & Canizares 1994), the potential $\Phi$ approximately scales with the ISM temperature $T$. Given that there is a factor of 2 difference in $T$ within $4r_e$ between the two galaxy categories for a given $\sigma$ ($\S$ 2), the X-ray–extended galaxies could have experienced twice as many supernova explosions and recycled twice as much metal into the same amount of stars before the gas was expelled. Therefore, we could expect that the mean stellar metallicity of the X-ray–extended galaxies is twice as high as that of the X-ray–compact ones for a given $\sigma$. This big difference in metallicity should have been detected in the statistical test in $\S$ 3, if it was present. As opposed to what we expect, however, we do not detect any significant difference in stellar populations between the two. This means that the potential structure of early-type galaxies during the major star formation epoch was quite different from what it is today. Gravitational potential must have been homogeneous. It must not have produced more than only 0.1 dex difference in mean stellar metallicity at a given stellar mass. Later on, after the epoch of major star formation, some galaxies became incorporated into larger scale potentials by infalling into the bottom of the local potential and/or by accumulating the surrounding materials and augmenting their gravitational potential, which eventually resulted in the variety of X-ray extents seen at the present day.

This picture is consistent with what people have found as to the formation of early-type galaxies: most of the “stars” in early-type galaxies should form at significantly high red-shifts ($z > 2$) (e.g., Bower et al. 1992; Ellis et al. 1997; Stanford, Eisenhardt, & Dickinson 1998; Kodama et al. 1998; van Dokkum et al. 1998; Kodama, Bower, & Bell 1999), while the “mass” of early-type galaxies can successively grow because of the accretion and/or merging even well below $z < 2$ in the course of hierarchical assembly (e.g., Kauffmann 1996; Baugh et al. 1998; Bower, Kodama, & Terlevich 1998; van Dokkum et al. 1999).

From our results, we speculate that the chemical abundance of ISM in $z$-elements (such as O, Mg, Si, and S, which come mainly from Type II SNe) should be quite uniform at a fixed stellar mass of the central galaxy regardless of its X-ray extent. The individual potential structure of a galaxy is independent of the larger scale potential and should be similar at the time of major star formation. Davis & White (1996) and Loewenstein et al. (1994) claimed that galaxies with lower ISM temperature or compact X-ray halos tend to have lower chemical abundance of the ISM. However, it is not yet clear whether there is such a correlation for the $z$-element abundance (Matsushita, Makishima, & Ohashi 2000). The new X-ray satellite XMM will solve this problem. On the other hand, the contribution from Type Ia SNe can be much different, because the potential structure would vary at the time of a SN Ia explosion because of the time delay of the explosion (Yoshii, Tsujimoto, & Nomoto 1996). The X-ray–extended galaxies would have acquired deeper potential wells by then and would keep the SN Ia ejecta more efficiently and, hence, show relatively iron-enhanced ISM abundance compared with the X-ray–compact ones. This is what we actually observe with ASCA.

Although the ISM abundance of the X-ray–compact galaxies is still uncertain, if we assume the same $z$-element abundance as the X-ray–extended systems, the Fe abundance is about a factor of 2 smaller than that of the X-ray–extended objects (Matsushita et al. 2000).

Considering that the X-ray–extended galaxies are sitting in the center of larger scale potential structures and that dynamical friction drives satellite galaxies toward the center, these galaxies are more likely to be produced by galaxy mergers. The fact that the X-ray–extended galaxies tend to have boxy shapes and weak rotation might support this hypothesis. If this is really the case, and if a considerable number of new globular clusters form during galaxy mergers, as suggested by Zepf & Ashman (1993), we should expect higher $S_N$ for the X-ray–extended galaxies on average. However, there is no significant difference in $S_N$ except for the cD galaxies. This may imply that, apart from the cD galaxies, the secondary globular clusters do not generally form by recent galaxy mergers and that most of the globular clusters around the X-ray–extended galaxies are likely to form very early when the major star formation takes place in their host galaxies.

5. CONCLUSIONS

The stellar population makeup in early-type galaxies does not correlate with their present-day global potential structure. Early-type galaxies form stars at early epochs in their own potential wells independently, and some of the galaxies become incorporated into larger scale potential structures (clusters/groups) later on. This idea naturally explains the homogeneity of the stellar populations despite the variety of X-ray properties.
This work was supported by the Japan Society for the Promotion of Science (JSPS) through its Research Fellowships for Young Scientists. We thank K. Pimbblet for carefully reading the paper and polishing up the English as well as giving us some useful comments.

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