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THE STAR FORMATION HISTORY OF EARLY-TYPE GALAXIES

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RESUMEN

La luz ultravioleta (UV) es un trazador efectivo para las estrellas jóvenes. Utilizando datos UV recientes de GALEX asociados a galaxias cercanas brillantes de tipo temprano encontramos que el 30% de ellas presentan un flujo UV que es demasiado fuerte para explicar, sin invocar un 1–3% (en masa estelar total), la tasa de formación estelar de los últimos mil millones de años. Esto implica que la formación estelar residual de bajo nivel fue común durante los últimos mil millones de años en galaxias brillantes de tipo temprano. Aquí discutimos las implicaciones que se tienen para la formación y evolución de galaxias de tipo temprano. Este artículo es un resumen del trabajo más reciente que hemos realizado (Yi et al. 2005; Schawinski et al. 2006; Kaviraj et al. 2006).

ABSTRACT

The UV light is an effective tracer for young stars. Base on the recent GALEX UV data of nearby, bright early-type galaxies, we find that 30% of them show a UV flux that is too strong to explain without invoking a 1–3% (in total stellar mass) star formation rate in the last billion years. This implies that low-level residual star formation was common during the last few billion years even in bright, early-type galaxies. We discuss the implications for the formation and evolution of early-type galaxies. This article is a summary of our recent work (Yi et al. 2005; Schawinski et al. 2006; Kaviraj et al. 2006).

Key Words: **GALAXIES: ELLIPTICAL AND LENTICULAR, CD — GALAXIES: EVOLUTION — GALAXIES: FORMATION — GALAXIES: FUNDAMENTAL PARAMETERS**

1. INTRODUCTION

Color-magnitude diagrams (CMDs) have been widely-applied tools for studying the star formation history (SFH) in early-type galaxies and, in turn, for placing constraints on galaxy formation scenarios, e.g., monolithic vs. hierarchical. In optical colors, brighter early-type galaxies are generally redder.

The short wavelength light of an integrated population is a good tracer of recent star formation (RSF). The scatter in the CMD is critical for understanding the significance of the RSF activities. The scatter is found to be small in UBV CMDs of early-type galaxy clusters (Bower et al. 1992). Because the U-band light is relatively sensitive to the presence of young stars, Bower et al. interpreted the small scatter as evidence for absence of major star formation activities in early-types since $z \sim 2$. This result seemed to be solid supporting evidence for the monolithic scenario.

The near-UV (NUV) light is 20 times more sensitive to the presence of young stars than the U-band is, and thus is a better tracer of RSF history. The GALEX UV satellite (Martin et al. 2005) is obtaining a large sample of nearby, early-type galaxies that is statistically significant. It is our goal to derive the first NUV−optical CMD for the present and for recent epoch early-type galaxies based on this data set and to investigate their RSF history. This study is an extension of the earlier work of Yi et al. (2005).

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2. THE NUV−OPTICAL CMD

We use the GALEX Medium Imaging Survey (MIS) data that reach limiting magnitudes of 22.6AB and 23.0AB in the FUV (1344–1786Å) and NUV (1771–2831Å), respectively. These limits safely detect $M(r) \lesssim -21.5$ at $z \lesssim 0.1$. We first find early-type galaxy candidates from the SDSS DR3 database applying (1) $Frac\_Dev(gri) > 0.95$, (2) visual inspection and (3) the Baldwin-Phillips-Terlevich AGN diagnostics (Baldwin et al. 1981). Then we search for GALEX detections of these galaxies (Schawinski et al. 2006). Of our bright sample of $M(r) < 16.8$ for which visual inspection is thought to be reliable, roughly 17% of galaxies are rejected via the visual inspection and another 10% by the AGN diagnostics. The final number of non-active, early-type galaxies in the volume-limited ($M(r) \leq -21.5$ at $z \leq 0.1$) sample is 986.

Figure 1 shows the optical and $NUV - r$ CMDs for a part of our sample. The left panel shows

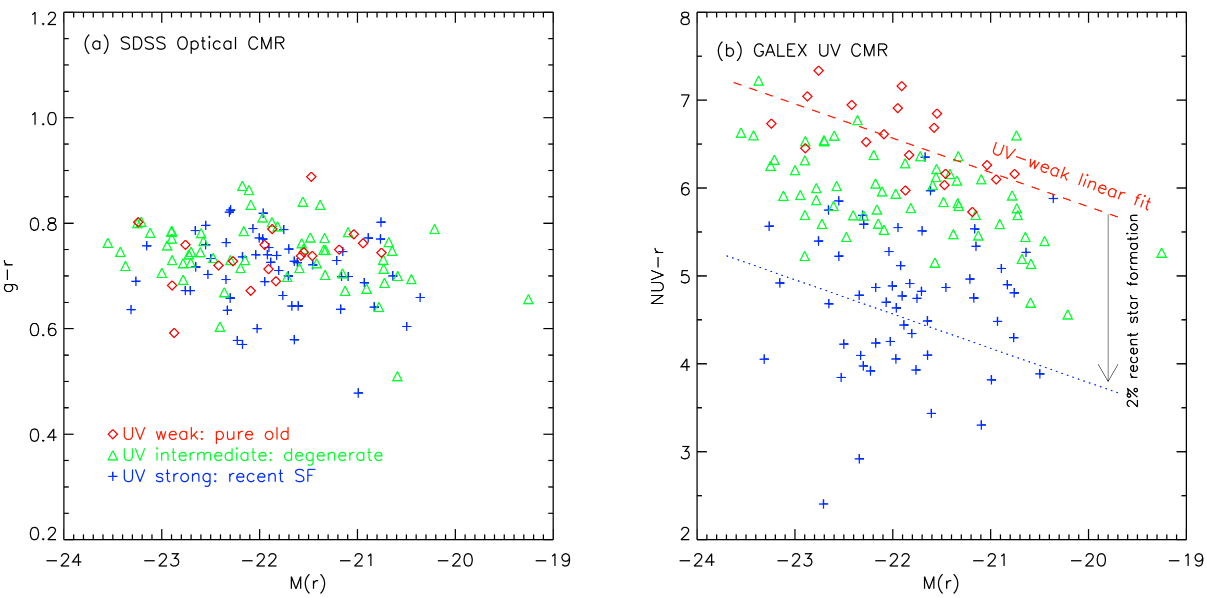

Fig. 1. The first NUV CMD for a subset of our nearby bright ($M[r] < -22$) early-type candidates in GALEX MIS fields. Symbols denote UV-weak (*diamonds*), UV-intermediate (*triangles*) and UV-strong (*crosses*) galaxies, respectively. The optical data are from the SDSS database. The same galaxies are shown in both panels. Note that the NUV CMD shows 20 times more scatter than the optical CMD. UV blue galaxies are completely hidden in optical CMDs. In the right panel, a linear fit to the "UV-red envelope" (i.e., UV-weak) galaxies is shown as a dashed line. The lower dotted line is a rough model of a case where 2% of the stars in the red-envelope galaxies are young ($t \sim 0.2$ Gyr).

the $g - r$ CMD. We classify our sample galaxies into three types. (1) UV-weak galaxies (*diamonds*) have photometric properties (using FUV and NUV from GALEX, and *ugriz* from SDSS) based on the χ^2 test (Kaviraj et al. 2006). Old, passively-evolving early-type galaxies would show such properties. (2) UV-strong galaxies (*crosses*) have a UV flux that is too strong to be consistent with an old, passively-evolving galaxy of any metallicity. (3) UV-intermediate galaxies (*triangles*) have a moderate UV flux and thus are consistent either with an old, passively-evolving galaxy showing a UV upturn (Burstein et al. 1988) or with an old passively-evolving galaxy with a very small number of young stars. This degeneracy is difficult to break and is even worse if one of the two UV bands is not available, which is often the case. Readers may refer to figure 3 of Yi et al. (2005) for the spectral shapes of these categories.

Despite the high significance of the χ^2 test results on the UV–Optical data (Kaviraj et al. 2006), the three types are indistinguishable in the optical CMD (Figure 1, left panel). On the contrary, these three types are clearly separated in the NUV CMD (Figure 1, right panel). To begin with, the most notable feature in the NUV CMD is its large scatter. The scatter in the NUV CMD (≈ 1 mag) is 20 times greater than that found in optical CMDs. For example, the Bernardi et al. (2003) SDSS optical sample shows a $g - r$ scatter of $\sigma_{RMS} = 0.05$ mag. Only part of this scatter can be attributed to the photometric uncertainty (0.1 mag in the NUV) and the k-correction of the colors (0.15 mag at $z = 0.2$).

The UV-weak galaxies form a narrow sequence, which we call the "UV-red envelope". A linear fit to the UV-red envelope (that is UV-weak) galaxies is shown as a dashed line. Similar to the optical red envelope (Kodama & Arimoto 1997), this too is probably a metallicity sequence of the bulk of the stellar population. When we use simple stellar population models for giant ellipticals with proper chemical enrichment prescriptions, we reproduce this slope rather easily. In principle, one can compare the rest-frame NUV-optical colors of various samples (e.g., distant galaxies) to this slope to investigate the significance of their recent star formation activities (e.g., Ferreras & Silk 2000).

The "UV-strong group" shows a strong UV flux either in the NUV and/or in the FUV in a manner that is unlikely to have come from old stars. A third of them show a much stronger FUV flux compared to nearby red ellipticals even considering the

UV upturn. The χ^2 test using 2-component (old and young) composite models on these galaxies indicates a recent starburst age of $t \sim 0.2\,\mathrm{Gyr}$ having 1–3% of the total mass (Kaviraj et al. 2006). For this test, we assumed that the dominant underlying population formed at $z = 5$ and of solar metallicity. The other two-thirds show an unusually strong NUV flux, which suggests the presence of moderately young ($t \sim 0.5\,\mathrm{Gyr}$) stars. Similar RSF signatures in early-type galaxies have been reported by Deharveng et al. (2002) who used the FOCA data.

As a visual guide, the lower dotted line in the right panel of Figure 1 shows a rough model of a case where 2% of the stars in the red-envelope galaxies are young ($t \sim 0.2\,\mathrm{Gyr}$). This shows that a 2% recent star formation rate explains the photometric properties of UV-blue galaxies without modifying their optical colors. A more rigorous statistical age-mass derivation is available in Kaviraj et al. (2006).

Hence, we wonder what fraction of these galaxies show a RSF signature. In order to answer this question, we need to use our volume-limited sample whose UV-red envelope has been detected. For the galaxies of $M[r] < -21.5$ and $z < 0.1$, GALEX reached their UV-red envelope, that is, their predicted NUV magnitudes assuming they have no substantial number of young stars or UV-upturn (old core-helium-burning) stars. Out of nearly a thousand such nearby, bright galaxies, roughly 20–30% are classified as UV-strong. We consider this as a lower bound mainly because we have excluded all the AGN candidates despite the fact that not all AGNs dominate the galaxy UV flux and also because our internal reddening treatment is very conservative (Schawinski et al. 2006).

3. DISCUSSION

Both monolithic and hierarchical galaxy formation scenarios suggest that large ellipticals form the bulk of their stars at high redshifts. Residual star formation is more common in hierarchical models because mergers between gas-rich galaxies probably induce residual star formation. The tiny mass fraction for the RSF population derived in our study ($\sim 1\%$) is consistent with both views. Although it seems inconsistent with extreme versions of monolithic models where all stars form exclusively at high redshifts, such extremes are probably unrealistic anyway. In this regard, we can call our "recent" SF a tail of "residual" SF caught immediately after or in the act. In this framework, the next question is naturally what causes such residual star formation in bright early-type galaxies.

Recent semi-analytic models based on a Λ-CDM hierarchical picture appear to be compatible with our scenario. For example, Kaviraj et al. (2005) suggested that roughly 5–10% of the entire star formation in all (bright and faint) early-type galaxies happened at $z < 1$. The residual SF fraction is predicted to depend strongly on the galaxy mass and environment: a larger residual SF is expected in a less massive galaxy and in a less dense environment. The merger rate is predicted to be higher in the more distant past (Khochfar & Burkert 2001), and thus the amount of residual SF may also be expected to be a sharply-increasing function of redshift. If this is true, and if galaxy mergers were the main driver of the residual star formation in ellipticals, then the cumulative RSF for the last several billion years (that is during $z < 1$) would easily be up to 10% or more, even though our estimate of RSF mass fraction at $z \sim 0$ is found to be only $\sim 1\%$ in 25% of the sample galaxies. This is significant and would leave no room for strict versions of monolithic models. Interestingly, as shown in Figure 2, we find that the blue galaxy fraction is indeed a function of local density (x-axis) as expected from the hierarchical models (see Schawinski et al. 2006 for details). But the dependence on the stellar mass is not obvious.

On the other hand, residual star formation may be possible even in a monolithic scenario if we relax our star formation prescription a bit. For instance, gas cooling/infalling onto old ellipticals is routinely observed. Some of the cooling gas seems to be lost, perhaps due to star formation (e.g., Knapp et al. 1989), and this has been suggested as an effective channel for residual star formation in elliptical galaxies (Mathews & Brighenti 2003). In addition, the mean stellar mass loss rate for old populations is typically 40%! Unless this gas is lost immediately out of the galaxy potential or heated very quickly (perhaps by AGN), it would be natural to expect that some of it cools to form stars. Such young stars would be very metal-rich and low in the α element abundance. The question is whether residual star formation occurring in such a scheme would be consistent with various stellar photometric and spectroscopic properties of elliptical galaxies. Detailed tests of such relaxed, monolithic models are performed by Kaviraj et al. (2006).

An important result is that such gas cooling in a passive mode would also apply to the hierarchical picture — whether galaxy mergers happen or not! Is the active RSF history predicted in the semi-analytic models in a hierarchical universe really caused by

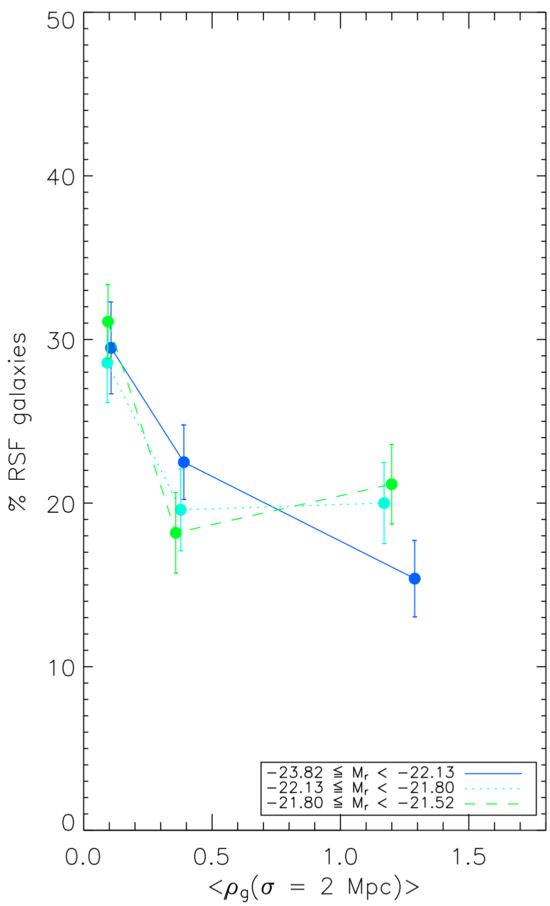

Fig. 2. The number fraction of residual star-formation (RSF) galaxies as a function of local galaxy number density. The sample are broken into three groups by the r-band luminosity (a proxy to stellar mass) in order to investigate the mass dependence as well. The overall trendseems statistically significant neither in mass nor in density. But notable is that the galaxies in the lowest density regions show high fractions and the most massive galaxies in the highest density regions show markedly low fractions.

mergers or simply by gas cooling? A detailed study is warranted.

Another interesting investigation regards "fine structure". If it is mergers that cause RSF, some UV-strong galaxies with a very young RSF might show morphologically-disturbed features. An investigation is underway.

To be conservative, we have excluded all the AGN candidates from our sample. However, weak AGNs, such as those found in our initial sample, do not necessarily dominate the galaxy UV light. In fact, it is an interesting issue whether AGN have a positive or negative impact on the residual star formation in early-type galaxies. A comprehensive theoretical investigation is called for.

In terms of the galaxy morphology, we believe our sample is dominated by ellipticals rather than lenticulars because of our extreme $Frac\_Dev(gri) >$ 0.95 criteria. But if lenticulars are really different animals from ellipticals, our analysis using a sample containing both would be misleading.

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