GALAXY EVOLUTION EXPLORER ULTRAVIOLET COLOR-MAGNITUDE RELATIONS AND EVIDENCE OF RECENT STAR FORMATION IN EARLY-TYPE GALAXIES

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ABSTRACT

We have used the Galaxy Evolution Explorer UV photometric data to construct a first near-UV (NUV) color-magnitude relation (CMR) for the galaxies preclassified as early-type by Sloan Digital Sky Survey studies. The NUV CMR is a powerful tool for tracking the recent star formation history in early-type galaxies, owing to its high sensitivity to the presence of young stellar populations. Our NUV CMR for UV-weak galaxies shows a well-defined slope and thus will be useful for interpreting the rest-frame NUV data of distant galaxies and studying their star formation history. Compared to optical CMRs, the NUV CMR shows a substantially larger scatter, which we interpret as evidence of recent star formation activities. Roughly 15% of the recent epoch (z < 0.13) bright [M(r) < −22] early-type galaxies show a sign of recent (≤1 Gyr) star formation at the 1%–2% level (lower limit) in mass compared to the total stellar mass. This implies that low-level residual star formation was common during the last few billion years even in bright early-type galaxies.

Subject headings: galaxies: evolution — galaxies: formation — ultraviolet: galaxies

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1. INTRODUCTION

Color-magnitude relations (CMRs) 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 (monolithic vs. hierarchical). In optical colors, they show that brighter early-type galaxies are generally redder (Baum 1959; Sandage & Visvanathan 1978). It is often attributed to a metallicity sequence in the sense that brighter early types are more metal-rich (Larson 1974; Bressan et al. 1994; Kodama & Arimoto 1997); but different scenarios, where age plays an important role, have also been proposed (Kauffmann & Charlot 1998; Kaviraj et al. 2004).

The UV light of an integrated population is a good tracer of recent star formation (RSF). Thus, finding the local CMR is important: we can derive the SFH in early types by comparing it to the galaxies at various redshifts (Bower et al. 1992; Stanford et al. 1998; van Dokkum et al. 1999; Ferreras & Silk 2000; Menanteau et al. 2001). The scatter in the CMR is also important. It is found to be small in optical CMRs (Bower et al. 1992). Because U-band light is relatively sensitive to the presence of young stars, Bower et al. (1992) interpreted the small scatter as evidence of the absence of recent major star formation activities in early types. This result seemed to be solid supporting evidence for the monolithic scenario.

The near-UV (NUV) light is far more sensitive to the presence of younger stars than the U band and thus traces RSF history better. The first internal-release data (IR0.2) from the Galaxy Evolution Explorer (GALEX) project (Martin et al. 2005) contain the NUV data of nearby galaxies that are large enough for statistically significant investigations. It is our goal to derive a first NUV versus optical CMR for the present and recent epoch early-type galaxies based on this data and investigate their RSF history.

2. SAMPLE

GALEX is undertaking two wide-area surveys of different depth (Morrissey et al. 2005). The All-sky Imaging Survey (AIS) reaches limiting magnitudes of 19.9 AB in the far-UV (FUV: 1344–1786 Å) and 20.8 AB in the NUV (1771–2831 Å), while the Medium Imaging Survey (MIS) reaches 22.6 and 22.7 AB in the FUV and NUV, respectively. For nearby galaxies, GALEX operates in the Nearby Galaxy Survey (NGS) mode applying the MIS exposure time. As an illustration, the colors of objects detected in one MIS field are displayed in Figure 1. Stars (dots mainly in the vertical sequence in the lower right) are separated from galaxies (crosses) clearly. The big galaxy clump in the upper middle of the plot shows various galaxies currently star-forming, while quiescent early-type galaxies would be located in the lower part of the figure in and around the square box. The various symbols
show the expected colors from the Kinney-Calzetti Spectral Atlas of Galaxies (Calzetti et al. 1994) for redshift 0–0.5 from right to left (arrow). If early types are quiescent, as often assumed, it would be an easy task to find them in this two-color diagram.

In order to construct a sample unbiased by any specific search criterion, we search for *GALEX* detections of galaxies already classified as being early type by one of the major Sloan Digital Sky Survey (SDSS) studies (Bernardi et al. 2003a). The Bernardi et al. classification is mainly based on concentration index, luminosity profile, and spectra with principal component analysis classification. We use SExtractor’s MAG_AUTO (total) magnitudes from the *GALEX* catalog and Bernardi et al.’s *model* (total) magnitudes for optical bands. Our initial cross-identification of sources between the Bernardi et al. sample and the *GALEX* catalog results in 207 matches. We have removed eight and 37 matches for having a close neighbor within 6″*H*11033 in *GALEX* and SDSS images, respectively. As a result, we have a total of 162 matches (133 from MIS, 18 from AIS, 11 from NGS). Of these, 62 have both FUV and NUV detections. Typical errors are 0.1 mag in NUV and 0.2 mag in FUV. These galaxies are at *z* = 0–0.25. It is from this final sample that we construct our NUV CMR.

3. UV CMR

We use the SDSS *r* (Fukugita et al. 1996) and *GALEX* NUV photometry to construct our CMRs (Fig. 2). The top panel shows the whole sample, while the others show galaxies in different redshift bins. The absolute magnitudes are computed based on the distance derived from redshift, assuming (Ω, Λ, *H*0) = (0.3, 0.7, 70). The uncertainty in the redshift is 0.001–0.002, and thus the uncertainty in the derived distance is negligible (Bernardi et al. 2003a). Extinction is from the Galactic correction of Schlegel et al. (1998); we make no correction for internal extinction. Because we do not assume to know the spectral shapes of these galaxies a priori, we apply *k*-corrections based on the luminosity distance only. The *k*-corrections on the colors would be 0.1–0.2 mag. The fitting function to the whole and binned samples and the scatter (the standard error between the fit and the data), based on the first-order polynomial fitting, are shown at the bottom of each panel. At first sight, it appears that the slope (dashed line) gets monotonically steeper with redshift. But, this is an artifact due to the limiting magnitude affecting the completeness of the data. The data are roughly consistent with the global slope in all bins. The change of the slope is an important issue for studying the SFH of galaxies, but the sample needs to reach deeper to assert it. The most notable feature in the UV CMR is its large scatter. The scatter in the NUV CMR (≈1 mag) is far greater than that found in any previous optical CMRs; e.g., the Bernardi et al. sample shows a *g* − *r* scatter *σ* = 0.05 mag (Bernardi et al. 2003b). Only part of this scatter can be attributed to the photometric uncertainty (0.1 mag in NUV) and the *k*-correction on the colors (0.15 mag at *z* = 0.2). In order to understand the cause of the scatter, we divide the whole sample into three groups based on the NUV and FUV fluxes compared to the optical flux. Figure 3 summarizes our spectral classification scheme. The horizontal lines in the UV for the continuum fitting (right panels) show the criteria.

The first group, the “UV-weak” galaxies, shows a low UV
flux: that is, \( F(NUV)/F(r) < 0.08 \) and \( F(FUV)/F(r) < 0.08 \). This originates from the upper bound in the NUV flux measured from the Burstein et al. (1988) nearby quiescent elliptical sample and to a flat UV spectrum. Twenty out of 62 galaxies with both FUV and NUV data are classified in this group. They form the “red envelope” in the UV CMR (circles in Fig. 3, top left panel). The first-order polynomial fit to the UV-weak galaxies is also shown and can be described as

\[
M(NUV) - M(r) = -0.23(\pm 0.16) M(r) + 0.95, \tag{1}
\]

which is consistent with the expected position of the quiescent elliptical galaxies shown as a box in Figure 1. The standard error between the fit and the data is 0.58 mag. One can compare this quiescent early-type galaxy UV CMR to the observed optical CMR of high redshifts and derive the SFH. The spectral energy distribution (SED) of an example galaxy is shown in the top middle row.

![Fig. 3](image_url)

**Fig. 3.**—Three groups of early-type galaxies based on the UV spectral shape: UV-weak (top row), UV-intermediate (middle row), and UV-strong (bottom row). A linear fit to the UV-weak galaxies is shown in the top left panel and described in eq. (1). In each panel, crosses are the whole sample and circles are the galaxies in each group; large circles are those with both FUV and NUV detections. In the right panels (shown in \( \lambda \) vs. \( F \), format), typical example galaxy data (GALEX UV and SDSS optical photometry) for each group are shown. The reference SEDs are those of M32 (dotted line) and of NGC 4552 (solid line). [See the electronic edition of the Journal for a color version of this figure.]

The last “UV-strong group” shows strong UV flux (bottom right panel) either in the NUV or in the FUV in a manner that is unlikely to have come from old stars: that is, \( F(NUV)/F(r) > 0.08 \) or \( F(FUV)/F(r) > 0.16 \). Forty-four galaxies are classified to be in this group, while four of them had no FUV detection. A subgroup of galaxies shows a UV-upturn-type spectral slope, i.e., strong in the FUV and weak in the NUV, but a far stronger UV flux than any present epoch elliptical galaxy exhibits. An example is shown in Figure 3 (bottom right panel). Note that the optical photometric data of this galaxy are close to those of typical elliptical galaxies, but its UV flux is significantly brighter. Such galaxies would not appear abnormal in optical CMRs but make themselves conspicuous in the UV CMR. A two-component (old and young) \( \chi^2 \) test on the GALEX and SDSS data indicates a recent starburst age of 0.2 Gyr having 1.2% of the total mass. For this test, we assumed that the dominant underlying population formed at \( z = 5 \) and had solar metallicity. Their high UV flux seems to be hinting at the presence of young (on the order of 100 Myr) stars. A larger fraction of galaxies, in fact, show a strong NUV flux, indicating the presence of 0.3–1 Gyr old populations. The UV spectral slope (FUV – NUV) tells us the age of the RSF; and it is clear that the UV-strong galaxies are the prime culprit of the scatter in the UV CMR. Such a star formation signature in early-type galaxies has been suggested by Deharveng et al. (2002), who used the FOCA data.

Then, we wonder what fraction of our galaxies are showing an RSF signature. In order to answer this question, we need to define a subsample whose red envelope has been detected. Figure 4 shows only the bright \( |M(r) - 22| \) galaxies from GALEX MIS fields. For \( z < 0.13 \), GALEX reached their red envelope, that is, their predicted NUV magnitudes assuming they are UV-weak. Out of 41 such close bright galaxies, eight (20%) are classified as UV-strong. The crosses denote their quiescent positions corresponding to their \( r \) magnitudes adopting the UV-weak galaxy CMR in Figure 3. Their departure from the quiescent models (vertical arrows) can be explained by a low-level RSF. As supporting evidence, six of these eight galaxies show a weak H\( \alpha \) emission line (see also Salim et al. 2005).
Since galaxy catalogs are in general subject to contamination of classified objects (Gavazzi et al. 2000; Shimasaku et al. 2001), we visually inspected the SDSS $r$-band images of all our galaxies. We find most of our UV-weak and UV-intermediate galaxies have early-type morphology but roughly 30% of UV-strong galaxies show ambiguous morphology, while still fitting the de Vaucouleurs profile. More distant galaxies are obviously more difficult to classify. For example, two of the eight UV-strong galaxies in Figure 4 appear to be spiral. Some galaxies, which clearly appear to be early type, show minor nonsmooth features. Such features warn us about galaxy misclassification but might also be expected if the early-type galaxies experienced a merger event that caused RSF. Further investigation of their morphology, especially using multiband data, seems essential. When the two spiral-looking galaxies are removed from the UV-strong sample, our UV-strong fraction becomes 15% (6/39).

The NUV spectral signature as a sign of RSF remains apparent only for 1.5 Gyr or so. In other words, our NUV flux analysis detects only roughly a 1.5 Gyr or younger starburst. The typical mass fraction of the young populations in these RSF galaxies is 1%–2%, based on our simple two-starburst analysis. If the recent burst was not instant but extended, the 1%–2% estimate should increase. In this regard, this value is a lower limit.

4. DISCUSSION

We have constructed a first UV CMR at present and recent epochs at $z = 0.0-0.25$. One can now compare this empirical UV CMR to higher redshift early-type galaxy data and derive their SFH. Based on our sample, roughly 15% of bright $M(r) < -22$ early-type galaxies show an RSF signature in the UV continuum. This effectively rules out extreme versions of monolithic galaxy formation models where all stars form at high redshifts. The 15% estimate is a lower limit in the sense that our sample relies on the Bernardi et al. (2003a) classification, which excluded galaxies showing strong emission lines (Fukugita et al. 2004). In addition, the internal extinction, which we ignored in this study, must have reduced the UV flux in some galaxies.

Recent semianalytic models based on ACMD dynamics appear to be compatible with our discovery. For instance, Kaviraj et al. (2004) suggested that roughly 5%–10%—depending strongly on the galaxy mass and environment—of the entire star formation in all (bright and faint) early types happened at $z < 1$. The merger rate and the amount of residual star formation are predicted to be a sharply increasing function of redshift (Khochfar & Burkert 2001), which is supported by observational studies (Menanteau et al. 2001; Bell et al. 2004). A detailed test against galaxy evolution models using GALEX data will be presented shortly.

An obvious next question is what triggers residual star formation. If it is a merger event, some UV-strong galaxies with a very young RSF might show morphologically disturbed features, as shown in the H I gas map of the nearby elliptical galaxy Cen A (Schiminovich et al. 1994). A follow-up investigation would be called for.

The strength of the UV CMR study is that it can detect even sub-1% level RSF events very easily. During its 28 month mission, GALEX will collect an order of magnitude larger and deeper data than used here and provide critical information on the recent SFH in early-type galaxies.

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