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THE LOOK-BACK TIME EVOLUTION OF THE UV UPTURN PHENOMENON

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Abstract. In order to investigate the origin of the far-UV (FUV) flux from early-type galaxies, *Galaxy Evolution Explorer* (GALEX) is collecting the UV data for the elliptical-rich clusters at moderate redshifts ($z < 0.25$) where the dominant FUV source is predicted to be hot horizontal-branch (HB) stars and their post-HB progeny. The early results show that the FUV flux of quiescent early-type galaxies *does* evolve substantially during the last 1–2 Gyr of look-back time, and the observed UV fading is consistent with the variation predicted by the population synthesis models where the mean temperature of HB stars declines rapidly with increasing look-back time.

Key words: galaxies: elliptical – galaxies: evolution – galaxies: stellar content – ultraviolet: galaxies

1. INTRODUCTION

It is now well established that the far-UV (FUV) flux ("UV upturn") of nearby early-type galaxies originates from a minority population of old hot helium-burning horizontal-branch (HB) stars (O'Connell 1999; Brown et al. 2000b). Stellar evolution models of HB predict that the mean temperature of HB distribution declines rapidly with decreasing age (e.g., Lee et al. 1994), and therefore the FUV flux from ellipticals should fade rapidly with look-back time (Greggio & Renzini 1990; Tantalo et al. 1996). Population synthesis models of Yi et al. (1999) also indicate that careful observations for the UV look-back time evolution could also discriminate two alternative HB solutions on the origin of UV flux, i.e., "metal-poor" and "metal-rich" HB models, which predict different ages for giant ellipticals.

The *Hubble Space Telescope* (HST) has obtained FUV images for several elliptical-rich clusters in the redshift range of $0.3 < z < 0.6$ (Brown et al. 2000a, 2003), but stellar evolution models (Lee et al. 1999; Yi et al. 1999) predict that hot HB stars must be absent at these relatively high redshifts, as no stars of low enough mass have yet evolved. Therefore, UV observations covering a lower redshift range ($z < 0.25$) are still required, in order to test the look-back time evolution effect of HB stars in giant ellipticals. Here we present the early results from the *Galaxy Evolution Explorer* (GALEX) UV observations for the Abell clusters in this redshift range, and also for the Fornax cluster as a local calibrator.

2. GALEX UV OBSERVATIONS

GALEX UV deep imaging survey for the UV upturn early-type galaxies aims at the elliptical-rich Abell clusters at $z < 0.25$. The first deep imaging target for this study was Abell 2670 at $z = 0.076$. Figure 1 shows the GALEX FUV and optical images of the early-type galaxies successfully identified within 25 arcmin^2 field of view centered on the brightest giant elliptical galaxy, a19 (Lee et al. 2005a). From a subsequent observation, we also successfully detected several early-type galaxies in Abell 951 at $z = 0.143$ in the GALEX UV images (see Figure 2; Ree et al. 2005). In most cases, their FUV lights are concentrated in the central region of the red galaxies without recent massive star formation, which is analogous to the smooth UV profiles of the quiescent UV upturn galaxies in the local Universe (Ohl et al. 1998; O'Connell 1999), with a few exceptions discussed below. The multi-orbit deep imaging UV observations with GALEX dedicated for more other elliptical-rich clusters at moderate redshifts are ongoing.

In order to compare the remote targets at various redshifts with the local samples without any systematic effect that may arise from the different aperture sizes used in the photometry, we should measure the total luminosities with sufficiently large, variable apertures. The total luminosities of those cross-matched early-type galaxies in remote clusters were measured by the elliptical aperture photometry (MAG_AUTO) with SExtractor image analysis package (Bertin & Arnouts 1996) in both FUV and optical passbands. The Galactic foreground extinctions were then corrected with $R_V = 3.1$, $R_{FUV} = 8.16$ (Cardelli et al. 1989). We do *not* convert the observed values into the restframe ones, as the *empirical* k-corrections may cause uncertainties in the comparison between the data samples at different redshifts. Instead, we will compare the apparent values with the model synthetic spectra redshifted to the target distances.

Nearby clusters of galaxies, e.g., Fornax, Virgo and Coma, are the best places to find the local early-type galaxies with various UV strengths, and they provide constraints to the model parameters in the local Universe. GALEX observations for the early-type galaxies in the Fornax cluster are presented in Figure 3. Their FUV magnitudes were measured from the surface photometry using ellipse fitting. The FUV surface brightness profiles extend smoothly, out to $r > 80''$ in the case of NGC 1399 and NGC 1404. In order to minimize the aperture effect induced by UV/optical radial gradient (Ohl et al. 1998), we estimated the FUV total magnitudes by integration of the radial profiles. We have also corrected for the Galactic foreground extinctions ($A_{FUV} = 0.09 - 0.14$), and their total magnitudes in V-band were adopted from the Third Reference Catalog of Bright Galaxies (RC3; de Vaucouleurs et al. 1991). Our FUV photometry for the elliptical galaxies in the Fornax cluster, when measured within the *International Ultraviolet Explorer satellite* (IUE) aperture ($20''\times 10''$), agrees well with the IUE measurements (Burstein et al. 1988) to within 0.01–0.06 mag.

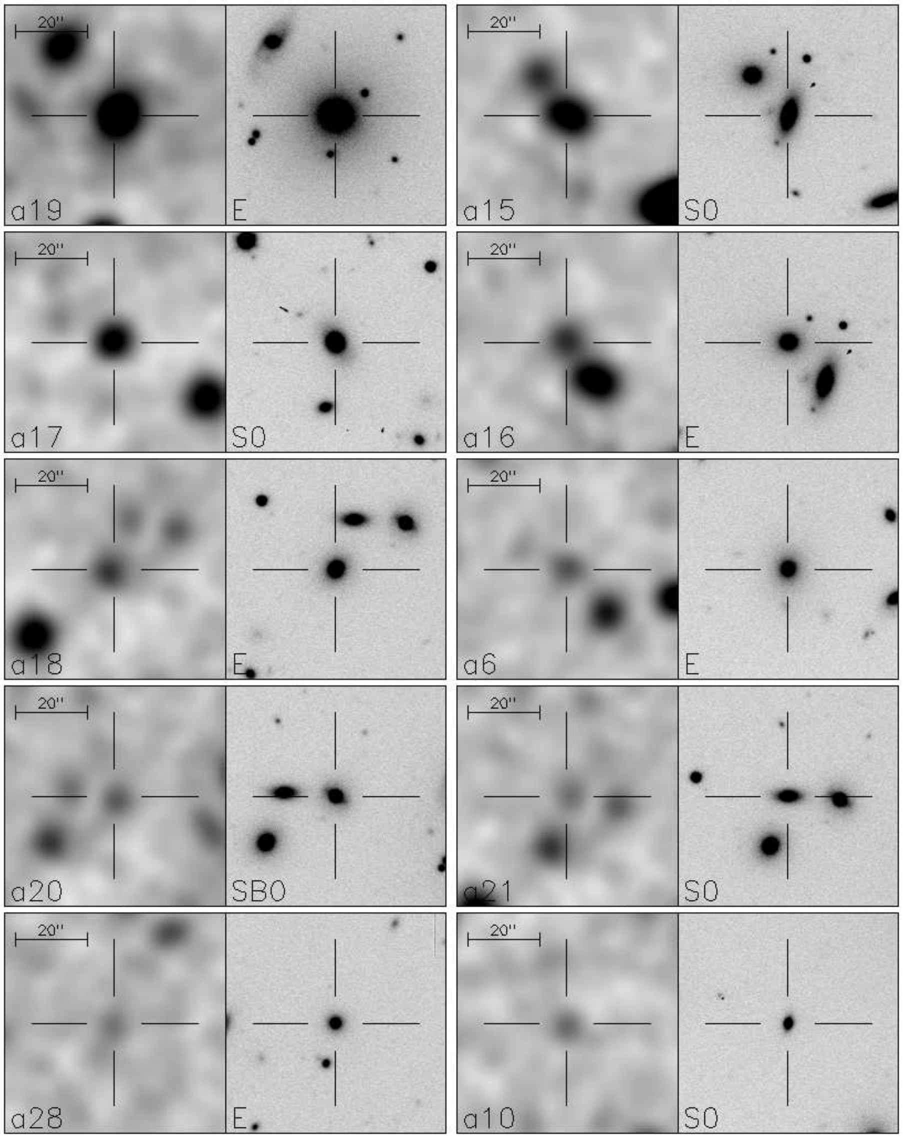

Fig. 1. GALEX FUV (*left panels*) and optical r-band (*right panels*) images ($1' \times 1'$) of the early-type galaxies in Abell 2670 ($z = 0.076$). The optical images are from Fasano et al. (2002). For some of UV-strong galaxies here, a15 and a16, there are strong evidences of young populations based on strong near-UV flux or Hα emission feature due to the residual star formation (Lee et al. 2005a).

3. MORE DISTANT CLUSTERS

Even the most massive giant elliptical galaxies ($M_V \leq -22$) should be fainter than 25th magnitude (AB) in FUV at $z > 0.3$. It would be very difficult to detect such faint *red* galaxies at high redshift with a small telescope like GALEX.

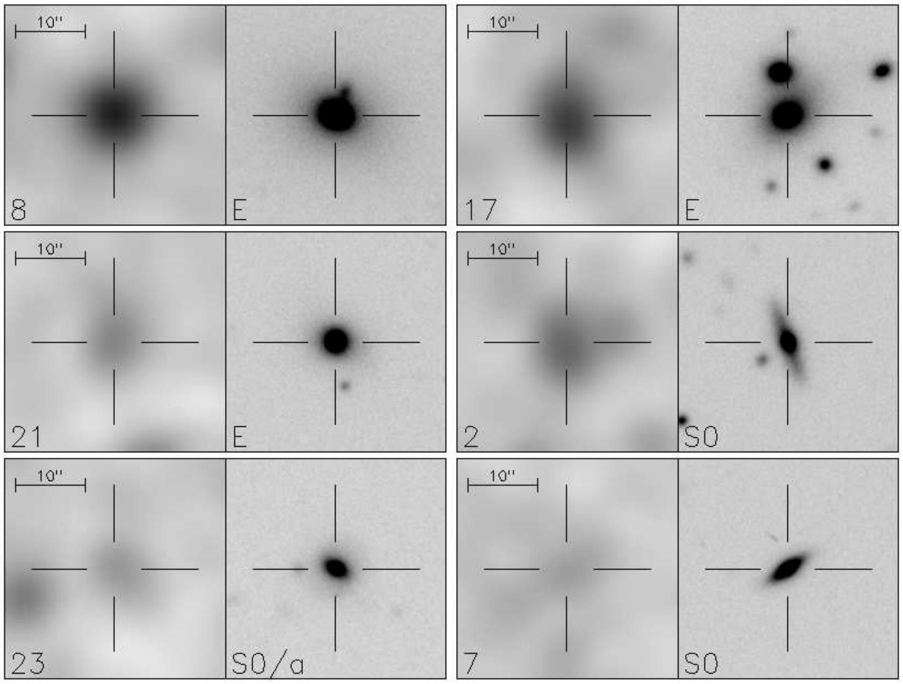

Fig. 2. GALEX FUV (*left panels*) and optical r-band (*right panels*) images ($30'' \times 30''$) of early-type galaxies in Abell 951 ($z = 0.143$). The optical images are from Fasano et al. (2000). Optical spectroscopic follow-ups are underway searching for the recent star formation signatures, if any, in these galaxies.

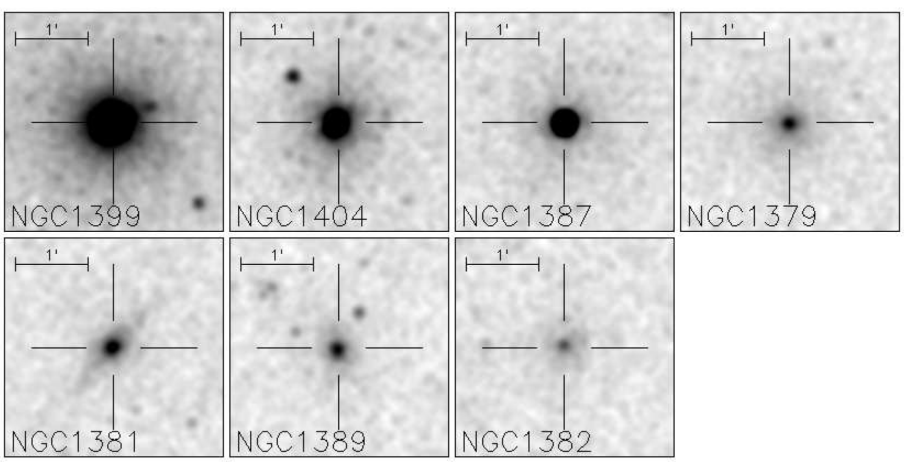

Fig. 3. GALEX FUV images ($3' \times 3'$) of the early-type galaxies in the Fornax cluster as a local calibrator. Their FUV lights are concentrated in the central region, and the radial profiles extend smoothly to $r > 1'$ for UV-strong galaxies.

However, there are several HST UV observations for the distant galaxy clusters at $0.3 < z < 0.6$ with the *Space Telescope Imaging Spectrograph* (STIS). From the literatures, we have taken the photometric measurements for the early-type galaxies in two distant clusters, Cl 1358+62 at $z = 0.33$ and Cl 0016+16 at $z = 0.55$, observed in UV by Brown et al. (2000a, 2003) and in optical passbands by van Dokkum et al. (1998) and Smail et al. (1997), respectively. The HST *Faint Object Camera* data for Abell 370 at $z = 0.375$ (Brown et al. 1998) are not included here, as they may have significant systematic errors according to Brown et al. (2003).

For the comparison with GALEX data, we converted those HST measurements to the AB magnitude system using the photometric zero-points and pivot wavelengths defined in the HST image headers ($m_{\rm AB} = m_{\rm ST} - 5\,log\,\lambda_p + 18.6921$). Model spectral energy distributions (SEDs) redshifted to $z = 0.33$ and 0.55 were then used to estimate the systematic difference between the HST and GALEX filter systems. Since the aperture radii in their analyses ($0.4''$ in FUV for both clusters, and $1.5''$ in V for CL 1358+62) are not large enough to represent total magnitudes, we applied appropriate aperture corrections, –0.32 (FUV) and –0.22 (V) for CL 1358+62. For the galaxies in CL 0016+16, we applied a correction only in FUV (–0.17 mag), as we adopted the total V magnitude from the catalog in Smail et al. (1997). The aperture correction values were obtained by utilizing the FUV (Lee et al. 2005a) and V (Marcum et al. 2001) radial profiles of NGC 1399, assuming that these clusters are at 75 (CL 1358+62) and 117 (CL 0016+16) times the distance of the Fornax cluster adopting the currently favored cosmological parameters (Ω_M, Ω_Λ, H_0) = (0.3, 0.7, 70). Finally, foreground extinction corrections are applied.

4. DISCUSSION

From the extinction-corrected apparent total magnitudes in both FUV and V passbands, we have derived the $FUV - V$ colors of the early-type galaxies in clusters, measured by GALEX (Fornax, Abell 2670 and *preliminary* analysis of Abell 951) and by HST (CL 1358+62 and CL 0016+16). The apparent redshift evolution of the observed $FUV - V$ colors is then presented in Figure 4, along with the two alternative model predictions. The "metal-poor HB model" suggests that the dominant FUV sources are very old ($t > 12$ Gyr) hot metal-poor HB stars and their post-HB progeny, and the FUV flux is expected to increase with age due to the smaller main-sequence turnoff and HB envelop masses. In the "metal-rich HB model", on the other hand, the dominant sources are old (t = 10–12 Gyr) hot super metal-rich HB and post-HB stars, and the FUV flux is predicted to increase with metallicity due to the enhanced helium enrichment and mass-loss. Even if these two alternative models are almost equally capable of reproducing the observed $FUV - V$ colors in present-epoch giant ellipticals, their evolutionary predictions are quite different from one another (see Yi et al. 1999).

The models in Figure 4 are specifically constructed to match the $FUV - V$ color of the local giant elliptical galaxy NGC 1399, the brightest galaxy in the Fornax cluster, and then passively evolved with look-back time. The model spectra and colors are then redshifted and the look-back times are converted to the equivalent redshift values, with the cosmological parameters above. Therefore, the foreground extinction-corrected observed data can be directly compared with the models. Since the NGC 1399 is a typical FUV-strong giant elliptical galaxy in the local

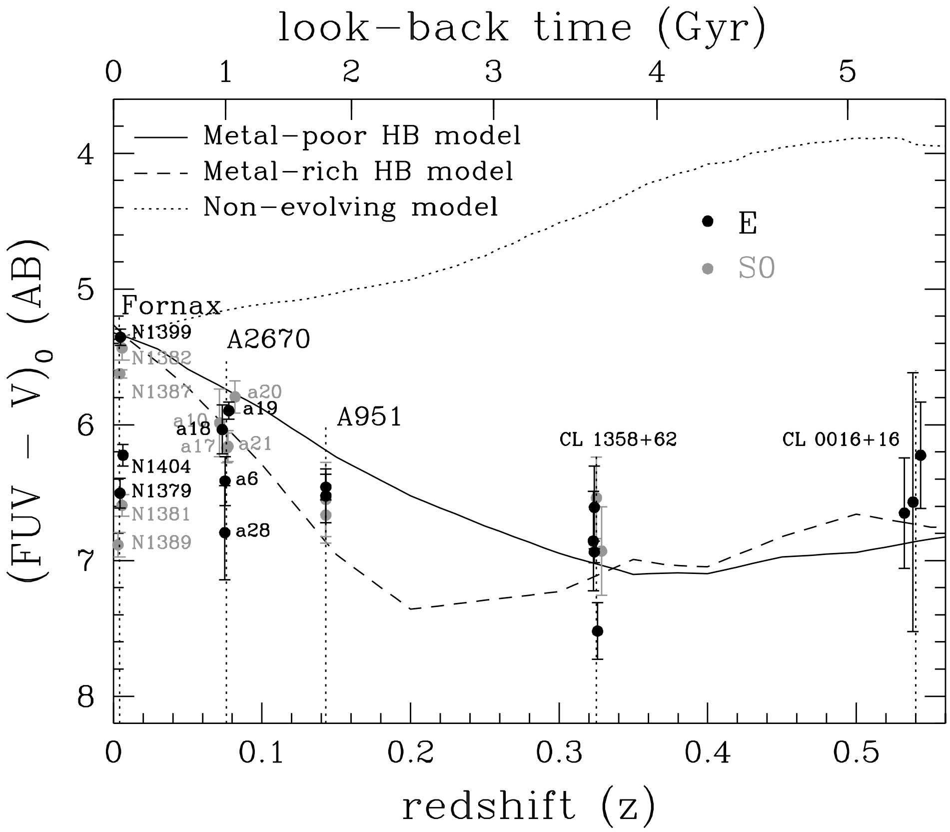

Fig. 4. Evolution of the UV upturn as a function of redshift. The observed apparent $FUV - V$ colors of the early-type galaxies in clusters at various redshifts are compared with the "metal-poor" (*solid*) and "metal-rich" (*dashed*) HB evolutionary models. The *dotted* line is for the case that the model spectrum of NGC 1399 is redshifted with no stellar evolution considered. Only the *quiescent* type of galaxy samples, without any strong star-formation signatures, are plotted (see text).

Universe, the model lines would represent the redshift (look-back time) evolution of giant ellipticals, and hence should be compared with the brightest ellipticals in each cluster. Note that there is a distinguishable amount of difference between the two alternative evolutionary models, up to ~ 1 mag. in $FUV - V$ color at $z \approx 0.2$, for the massive giant elliptical galaxies ($M_V \approx -22$).

It is clear from Figure 4 that we have detected the fading of the UV upturn expected at moderate redshifts. Compared to NGC 1399, the nearby giant elliptical galaxy in the Fornax cluster, an apparent extinction-corrected $FUV - V$ color of the giant elliptical galaxy (a19) in Abell 2670 gets redder by ~ 0.55 mag at $z = 0.076$ (look-back time ~ 1.0 Gyr). For the restframe $FUV - V$ color, this corresponds to 0.70 mag, which is consistent with the variation predicted by the models (Lee et al. 2005a). A preliminary analysis for Abell 951 ($z = 0.143$) confirms this by showing a similar amount of evolution again in the $FUV - V$ color of UV-strong giant elliptical galaxies between the look-back time of 1 and 2 Gyr. In these models, the dominant FUV source is hot HB stars for $z < 0.25$, and therefore the FUV flux fades rapidly with look-back time (redshift) as the HB temperature distribution becomes cooler with decreasing age (increasing look-back time).

For $z > 0.3$, the HST data also appear to be in reasonable agreement with our model predictions, to within the errors. Note, however, that the models become more uncertain at these relatively higher redshifts, as the dominant FUV source changes from hot HB stars to post-asymptotic giant branch (PAGB) stars for $z > 0.25$. In particular, Lee et al. (1999, see their Fig. 1) predict that the HB contribution to the total FUV flux becomes almost negligible for $z > 0.4$. At relatively higher redshifts, the total FUV flux would therefore increase as the mass of PAGB stars decreases because their lifetimes correlate inversely with their mass. Consequently, the available HST data may provide no direct test of HB evolution effect. Nevertheless, they provide a useful test on the adopted mass (0.565 $M_{\odot}$) of PAGB stars in our models.

Although we are witnessing the growing body of evidence indicating the FUV flux of quiescent early-type galaxies evolves substantially at moderate redshifts ($z < 0.25$) as the deep imaging survey with GALEX UV telescope continues, there are some issues to be solved. On the observational side of this study, UV blending and contamination by young stars are serious issues. With the given spatial resolution of GALEX (1.5 ″/pixel), it becomes difficult to de-blend properly the UV lights purely from the old stellar population in elliptical galaxies and the possible UV contaminations by neighboring dwarf galaxies, as we reach out to $z \sim 0.2$. Furthermore, some early-type galaxies show contamination from the residual star formation in their UV spectra (Burstein et al. 1988; Yi et al. 2005), and therefore it is important to check whether our sample galaxies are not affected by a minority population of young stars. As described in Lee et al. (2005a), we found two of the UV-strong early-type galaxies in Abell 2670, a15 (S0) and a16 (E), show the evidence of young populations inferred by unusually strong near-UV flux or by strong Hα emission. Some of HST data samples also show unexpectedly strong UV flux. All of these abnormal galaxies with recent star-forming signatures are excluded in Figure 4. The optical follow-up spectroscopy continues for the other GALEX target clusters in order to discriminate such star-forming red galaxies.

On the theoretical side, the nature of extreme HB (EHB) stars and their contribution to the UV flux should be understood. The effect of EHB stars are *not* fully included in the current population synthesis models presented here. Particularly, the excessively large age (up to 30 % older than the Galactic globular clusters) required for the local giant ellipticals in the "metal-poor" HB model would be reduced significantly, if the EHB stars are explained as the minority population of super helium-rich stars (Lee et al. 2005b). In any case, the observed rapid evolution of FUV flux with look-back time at moderate redshifts, if confirmed by further observations, would infer the strong age dependency in the evolution of UV sources in old stellar systems (Lee et al. 1994; Yi et al. 1999).

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