STELLAR AGE VERSUS MASS OF EARLY-TYPE GALAXIES IN THE VIRGO CLUSTER

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ABSTRACT

The flux excess of elliptical galaxies in the far-ultraviolet can be reproduced by population synthesis models when accounting for the population of old hot helium-burning subdwarf stars. This has been achieved by Han and coworkers through a quantitative model of binary stellar evolution. Here, we compare the resulting evolutionary population synthesis model to the *GALEX* far−near ultraviolet colors (FUV−NUV) of Virgo cluster early-type galaxies that were published by Boselli and coworkers. FUV−NUV is reddest at about the dividing luminosity of dwarf and giant galaxies, and becomes increasingly blue for both brighter and fainter luminosities. This behavior can be easily explained by the binary model with a continuous sequence of longer duration and later truncation of star formation at lower galaxy masses. Thus, in contrast to previous conclusions, the *GALEX* data do not require a dichotomy between the stellar population properties of dwarfs and giants. Their apparently opposite behavior in FUV−NUV occurs naturally when the formation of hot subdwarfs through binary evolution is taken into account.

Subject headings: galaxies: clusters: individual (Virgo) — galaxies: dwarf — galaxies: elliptical and lenticular, cD — galaxies: stellar content — subdwarfs

1. INTRODUCTION AND MOTIVATION

What can we learn from the ultraviolet light of early-type galaxies that longer wavelengths cannot tell us? Mainly from spectrophotometric analyses in the optical and near-infrared, a picture emerged in which the stars of massive early-type galaxies formed during a short period of intense star formation at early epochs (Bower et al. 1992; Ellis et al. 1997; Thomas et al. 1999). On the other hand, studies of their stellar mass or number density evolution with redshift imply that a substantial fraction of them must have formed within the last gigayears (Bell et al. 2004; Ferreras et al. 2005). Both above statements were found to depend on galaxy mass: at lower masses, star formation lasted longer (Nelan et al. 2005; Thomas et al. 2005) and the number density shows a stronger evolution with redshift (Cimatti et al. 2006).

While optical spectral line indices are a commonly used tool to derive estimates for the (mean) ages and metallicities of early-type galaxies, they still leave room for discussion. Larger values of the H_β index were interpreted by de Jong & Davies (1997) with lower mean ages, caused by the presence of a relatively young stellar population on top of an old one that dominates the mass. However, Maraston & Thomas (2000) found that a large value of H_β can alternatively be explained by the contribution of old metal-poor stars. Nevertheless, Caldwell et al. (2003) derived substantially lower mean ages, as well as a larger age spread, for early-type galaxies with lower velocity dispersions (i.e., lower masses), even when taking into account the approach of Maraston & Thomas (2000).

To what extent recent or residual star formation does

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play a role in shaping present-day early-type galaxies can be explored with the ultraviolet (UV) data of the *Galaxy Evolution Explorer* (*GALEX*; Martin et al. 2005), since the contribution of young stars is much stronger in the UV than at optical wavelengths. From these data, Kaviraj et al. (2007a) and Schawinski et al. (2007) concluded that about 30% of massive early types at low redshift have experienced some star formation less than 1 Gyr ago. Similar results were obtained at higher redshifts, for which the rest-frame UV can be probed with optical surveys: Kaviraj et al. (2007b) found "compelling evidence that early-types of all luminosities form stars over the lifetime of the Universe". Again, less massive objects were found to have formed most of their stellar mass later than more massive galaxies (also see Ferreras & Silk 2000).

The above mentioned studies, while covering each a range of masses and luminosities of early-type galaxies, did not reach into the dwarf regime. Based on a study of *GALEX* far−near UV (FUV−NUV) color of early-type galaxies in the Virgo cluster, Boselli et al. (2005) reported a pronounced dichotomy between dwarf and giant early types: while giants become bluer with *increasing* near-infrared H luminosity, dwarfs do so with *decreasing* luminosity. The former can be understood with a stronger presence of the well-known FUV flux excess ("UV-upturn") at higher masses (Gil de Paz et al. 2007), while the latter was interpreted by Boselli et al. (2005) with residual star formation in early-type dwarfs. These observations were of particular importance, for they appeared to settle an issue that has never been conclusively resolved in the optical regime: the question of whether or not dwarf and giant early-type galaxies follow the same color-magnitude relation (de Vaucouleurs 1961; Secker
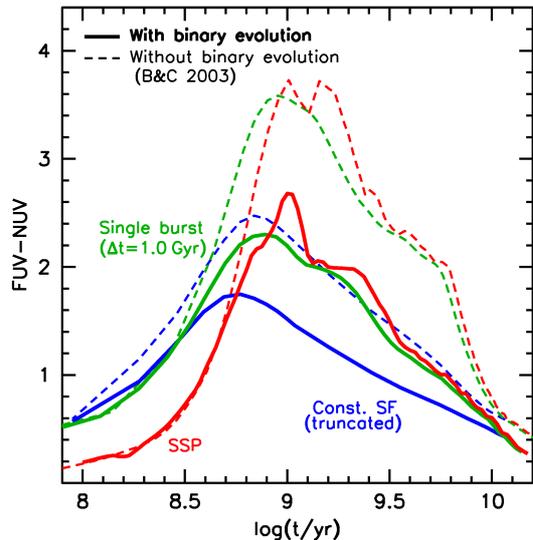
FIG. 1.— **Binary vs. single stellar evolution.** Time evolution of FUV−NUV color of various synthetic stellar populations, computed with the binary model of Han et al. (2007, solid lines) and the single-star model of Bruzual & Charlot (2003, dashed lines). For each of the two models, we show the color evolution of a simple stellar population (SSP, red or black), a stellar population formed in a single 1-Gyr period ("Single burst", green or light grey), and a population formed through continuous star formation that is truncated at a certain epoch ("Const. SF", blue or dark grey; see text for details). The "age" t is defined for all cases as the time since the end of star formation.

et al. 1997; Conselice et al. 2003).

Interpretations of integrated galaxy light hinge critically on the availability of appropriate stellar population synthesis models that can be compared to the data. A crucial issue is the availability of a quantitative prescription for the cause of the FUV excess. Commonly used models, which are based on single stellar evolution, do describe a rise in the FUV at old stellar population ages (e.g. Maraston & Thomas 2000; Bruzual & Charlot 2003). However, the approach of Kaviraj et al. (2007a), who preferred to use the spectral energy distribution of a single galaxy as empirical template for the FUV excess, demonstrates the need for further improvement in modelling its cause.

While it is believed that hot helium-burning subdwarf B (sdB) stars on the Extreme Horizontal Branch (EHB, Heber 1986) and their progeny (Stroeer et al. 2007) are the main cause of the FUV excess (Brown et al. 1997, 2000), until recently the formation of these stars was only poorly understood (Heber et al. 2002; Edelmann et al. 2003; Lisker et al. 2005). Since close binary evolution was known to play a major role in it (Maxted et al. 2001), a binary stellar evolution model for the formation of hot subdwarfs was developed by Han et al. (2002, 2003), which is able to account for the observed range of stellar parameters (Lisker et al. 2005). This model was integrated into an evolutionary population synthesis model by Han et al. (2007), which, as we shall demonstrate below, is not only able to explain the observed UV colors of Virgo cluster early-type galaxies, but also provides a simple explanation for the apparent dichotomy between dwarf and giant early types.

2. THE BINARY POPULATION SYNTHESIS MODEL

By incorporating the binary model of Han et al. (2002, 2003) for the formation of hot subdwarfs into evolution-ary population synthesis modelling, Han, Podsiadlowski & Lynas-Gray (2007, hereafter HPL07) obtained an "a priori" model for the UV-upturn of elliptical galaxies. Their study indicated that the UV-upturn is most likely the result of binary interactions. In the model, HPL07 used their binary population synthesis code to evolve millions of stars (including binaries) from the zero-age main-sequence to the white dwarf stage or a supernova explosion. The spectra of hot subdwarfs were calculated with the ATLAS9 stellar atmosphere code (Kurucz 1992), while the spectra of other stars were taken from the latest version of the comprehensive BaSeL spectral library (Lejeune et al. 1997, 1998). The model simulates the evolution of the colors and the spectral energy distribution of a simple stellar population (SSP).

The rest-frame FUV−NUV color evolution of the SSP is shown in Fig. 1 (solid red or black line). Its main characteristic is the rather sharp turnaround at an age of $t \approx 1\,\mathrm{Gyr}$, at which the hot subdwarf stars start to contribute to the FUV flux and thus cause a subsequent bluening of FUV−NUV. We compare the binary model to the single stellar evolution model of Bruzual & Charlot (2003, hereafter BC03; dashed red or black line), since it is one of the most commonly used models in stellar population studies of galaxies. The BC03 model reaches to much redder FUV−NUV colors than does the HPL07 model, but it eventually also becomes bluer due to post-AGB stars (Bruzual & Charlot 2003). See Sect. 3.2 for a comparison to other models.

From each SSP we computed the evolution of a stellar population with a star formation history that, compared to the SSP's single instantaneous burst, is somewhat more realistic: a single star formation period of finite length, and continuous star formation that is truncated at a certain epoch. For the first case, we adopt a 1-Gyr period of constant star formation rate ("Single burst", green or light grey lines in Fig. 1). For the second case, we adopt a constant star formation rate since $12.6\,\mathrm{Gyr}$[1] until a point of time when star formation is being truncated ("Const. SF", blue or dark grey lines in Fig. 1). In order to have a uniform definition of "age" for these different model populations, we adopt the time t that has passed since the *end* of star formation as a proxy for age. Actually, t directly indicates the age of the youngest stellar component, which will be helpful for the discussion in Sect. 4.

The above computation was done with the *csp_galaxev* tool of Bruzual & Charlot, which uses the method of isochrone synthesis (see Bruzual & Charlot 2003). Since the HPL07 binary model is based on a chemical composition of $X = 0.78, Y = 0.20, Z = 0.02$, we use the BC03 model with the same composition, based on 'Padova 1994' isochrones (Alongi et al. 1993; Bressan et al. 1993; Fagotto et al. 1994a,b; Girardi et al. 1996) and adopting a Chabrier (2003) IMF.

3. COMPARISON OF MODELS AND OBSERVATIONS

3.1. *Binary versus single-star model*

The *GALEX* UV colors of Virgo early-type galaxies were presented by Boselli et al. (2005) in relation to their near-infrared H luminosity. A dividing luminosity of dwarfs and giants (as classified by Binggeli et al. 1985)
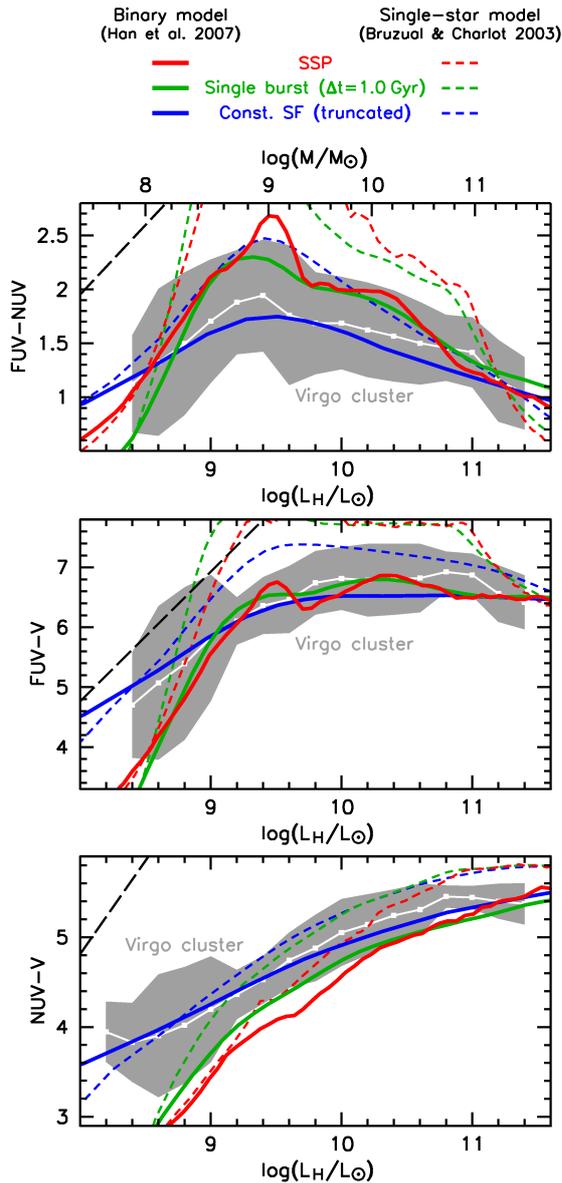
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[1] We actually use $10^{10.1}\,\mathrm{yr} = 12.59\,\mathrm{Gyr}$

can be roughly defined at $\log(L_H/L_\odot) \approx 9.6$ (Boselli et al. 2005, their Fig. 1). Here, we compare these data to synthetic colors from the HPL07 binary model, as well as the BC03 single-star model. Our intention is to investigate whether the models are able to simultaneously match the observed range in FUV−NUV, FUV−V, and NUV−V, and whether the observed relation of color and luminosity could be explained with an age variation only.

Fig. 2 shows the observed colors as binned averages (white line and dots), along with the respective RMS scatter (grey shaded area). Colors were corrected for Galactic extinction by assuming an average $E(B-V) = 0.03$ (Gil de Paz et al. 2007), leading to $A_{\rm FUV} = A_{\rm NUV} = 0.24$, $A_V = 0.10$ (Schlegel et al. 1998). Color values are given in the AB magnitude system (Oke & Gunn 1983). No internal extinction correction was applied: for the minor population of Virgo cluster early type galaxies with ongoing central star formation, a typical value for $E(B-V)$ of 0.1 was found for their centers (Lisker et al. 2006b), thus being much smaller for the galaxies as a whole, and certainly negligible for the vast majority of the sample.

For each synthetic stellar population shown in Fig. 1, we selected an age range such that the time evolution of the model FUV−NUV color traces best the relation with luminosity (top panel of Fig. 2). The matching was performed visually by allowing age steps of 0.05 dex. The age range was then kept fixed for the other colors (middle and bottom panel).

We see from the top panel of Fig. 2 that the SSP of HPL07 exceeds the observed color range at intermediate ages. This is no surprise, though: since the reddest color of the SSP is reached during a very brief period, any realistic population – with a finite duration of star formation rather than a delta-peak – can never become so red, since not all of its stars reach this period at the same time. Indeed, the model population that formed from a single burst of finite length lies within the observed color range, although still somewhat offset from the mean values. The best match is provided by the model population that formed through a constant star formation rate with a varying truncation time, which lies relatively close to the observed mean values.

In reality, we might expect that the most massive galaxies did not only form earlier, but also needed less time to make their stars. Therefore, one might prefer the SSP or single burst model at high luminosities, whereas in the dwarf regime, continuous and rather recently truncated star formation might appear more plausible. In any case, the binary model is able to explain the observed turnaround in FUV−NUV, as well as the apparently different slopes of dwarfs and giants, in a simple and straightforward way, by only varying the average stellar population age. Moreover, the model with constant star formation is able to simultaneously match the observed range of colors in FUV−V and NUV−V. For the SSP and the single burst population, no match is achieved in NUV−V except for the high-mass end. Note that we are regarding the H luminosity as a proxy for the stellar mass of a galaxy. A transformation into mass is shown as the uppermost abscissa in Fig. 2, using the mass-to-light ratio in H as given by the HPL07 SSP.

As for the BC03 models, both the SSP and the single-burst population exceed the observed FUV−NUV color

FIG. 2.— **Models vs. observations.** Each panel shows the colors and near-infrared H luminosities of Virgo cluster early-type galaxies. Average color values (white dots) are calculated within a luminosity interval of ± 0.3 dex, and are given every 0.2 dex, connected by the white line. The grey shaded area represents the RMS scatter. The data were extracted from Boselli et al. (2005) using the *Dexter* tool (Demleitner et al. 2001), and comprise 76 galaxies in FUV−NUV (top), 70 in FUV−V (middle), and 97 in NUV−V (bottom). The average number of galaxies contained in each bin is 13 (top and middle) and 16 (bottom); bins with less than 5 galaxies are excluded. The black dashed lines in the upper left of each panel mark the detection limit given by Boselli et al. (2005). The upper axis of the top panel gives the stellar mass that has been determined from the H luminosity using the SSP mass-to-light ratio evolution of HPL07. The time evolution of synthetic stellar populations is shown with the same line styles as in Fig. 1. For these, the age ranges used for plotting were chosen to provide the best visual match to the observed FUV−NUV colors, allowing age steps of 0.05 dex. The resulting age ranges for the HPL07 binary model are $8.6 \leq \log(t_{\rm SSP}/{\rm yr}) \leq 9.75$, $8.1 \leq \log(t_{\rm Single}/{\rm yr}) \leq 9.6$, and $8.4 \leq \log(t_{\rm Const}/{\rm yr}) \leq 9.4$, and for the single-star model of Bruzual & Charlot (2003), $8.6 \leq \log(t_{\rm SSP}/{\rm yr}) \leq 10.0$, $8.1 \leq \log(t_{\rm Single}/{\rm yr}) \leq 9.95$, and $8.35 \leq \log(t_{\rm Const}/{\rm yr}) \leq 9.8$. Note that the "age" t denotes, for all model populations, the time since the *end* of star formation. The given interval boundaries correspond to the low and high luminosity end of the grey-shaded area in the upper panel, not to the boundaries of the figure. The same age ranges were used for the middle and bottom panel.
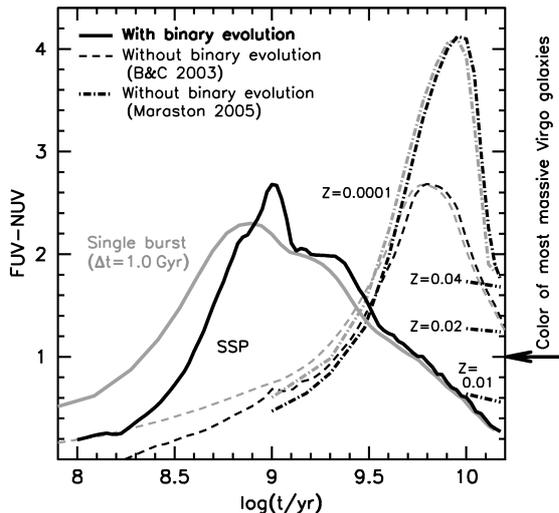
FIG. 3.— **Alternative models.** Time evolution of FUV−NUV color of various synthetic stellar populations, computed with the binary model of Han et al. (2007, solid lines) for solar metallicity ($Z = 0.02$) and with the single-star model of Maraston (2005, dash-dotted lines) with blue horizontal branch morphology for metallicities $Z = 0.0001$ (1/200th solar), $Z = 0.01$ (1/2 solar), $Z = 0.02$ (solar), and $Z = 0.04$ (2 times solar). Note that for the models with $Z \geq 0.01$, Maraston (2005) only computed SSPs for the age of 10 and 15 Gyr. For comparison with the low-metallicity model of Maraston, we also show the Bruzual & Charlot (2003) model for $Z = 0.0001$ (dashed lines). The FUV−NUV color reached by the brightest Virgo early-type galaxies is indicated by the arrow.

range by far. This is not only the case for the comparison with Virgo cluster galaxies: in fact, only three out of 874 galaxies of the *GALEX* UV atlas of nearby galaxies (Gil de Paz et al. 2007) are redder than a FUV−NUV value of 2.6, whereas the BC03 models reach much redder values. Nevertheless, the BC03 model colors for continuous star formation just fall within the observed RMS scatter, and could thus provide a similar interpretation as the HPL07 model. In contrast to the binary model, though, none of the BC03 populations is able to provide a simultaneous match to all three colors.

3.2. *Comparison to other models*

The observed mass-to-light ratio evolution of early-type galaxies with redshift has been found to be reproducible with the population synthesis models of Maraston (2005), but not with those of Bruzual & Charlot (2003), possibly due to the different AGB treatment (van der Wel et al. 2006). Moreover, the Maraston models have been shown by Maraston & Thomas (2000) to match the UV and optical spectra of a sample of early-type galaxies when a metal-rich stellar population with red horizontal branch (HB) morphology is combined with a small contribution of an old metal-poor population with blue HB morphology. It therefore appears worthwhile to compare these single-star models to the HPL07 binary model.

Maraston & Thomas (2000) point out that, while the minor population of old metal-poor stars is able to account for observed large values of H_β, it is the dominant metal-rich population that reproduces the observed $1500−V$ color. However, as can be seen from their Fig. 5, this metal-rich population does not show an uprise of the spectral slope in the FUV, and does thus not exhibit blue FUV−NUV colors, which are at the focus of our present study. Only the metal-poor population exhibits such an
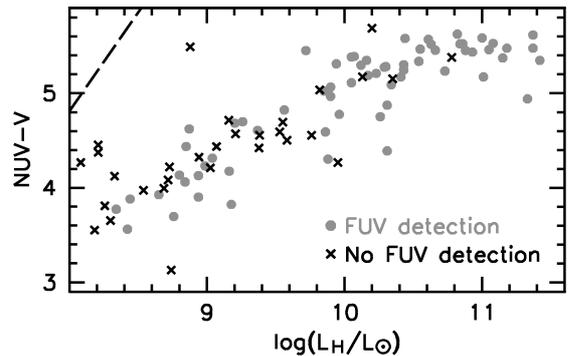

FIG. 4.— **Assessing a possible color selection effect.** NUV−V color versus near-infrared H luminosity of Virgo cluster early-type galaxies, as given in Boselli et al. (2005). Grey circles denote objects that have a FUV detection, whereas black crosses are objects with no FUV detection. The black dashed line marks the detection limit given by Boselli et al. (2005).

uprise. We therefore show in Fig. 3 the time evolution of the model of Maraston (2005) with $Z = 0.0001$ and blue HB morphology (using a Salpeter (1955) IMF), without combining it with a metal-rich population of red HB morphology. It can be seen from the figure that this model reaches FUV−NUV colors that are even redder than the solar metallicity model of BC03 (Fig. 1), and also redder than the BC03 model with $Z = 0.0001$. Moreover, at large ages, the model is not able to account for the blue FUV−NUV values that are observed for the Virgo cluster galaxies at the high-mass end.

Since Maraston & Thomas (2000) emphasized that *metal-rich* populations with blue HB morphologies could provide another alternative to explaining large H_β values without invoking young ages, Maraston (2005) computed models with blue HB morphology also for high metallicities. These models, which were only computed for ages of 10 and 15 Gyr, are shown in the figure as the short lines on the right-hand side. Only the population with metallicity $Z = 0.01$ reaches colors that are blue enough to account for the observed ones. However, if it were to fully explain the FUV−NUV colors of the most massive early-type galaxies, this population would have to be the predominant one in any composite population, which appears unlikely given its subsolar metallicity.

Another model that was shown to match the UV properties of early-type galaxies is the single-star model of Yi et al. (1998). While at old ages, its FUV−NUV colors are blue enough to match the values of the Virgo galaxies (as are the BC03 colors), at intermediate ages it reaches comparably red colors in FUV−NUV and FUV−V as the BC03 model. It is thus also not able to match the observations with a single sequence like the HPL07 model does. See Han et al. (2007) for a discussion of this and other models that were proposed to explain the UV-upturn.

3.3. *A possible color selection effect?*

The NUV and FUV photometry presented by Boselli et al. (2005), which we use here, is only available for galaxies that were detected by *GALEX* in NUV and FUV, respectively. This could cause a color selection bias, in the sense that galaxies with redder FUV−NUV would be too faint in the FUV to be detected. Since the sample of Boselli et al. becomes bluer in FUV−NUV towards the faint end (Fig. 2), it is important to assess

whether this could be purely due to a selection effect.

In Fig. 4 we show the NUV−V color of all galaxies, as given in Boselli et al. (2005). Those that are detected in the FUV, and therefore enter the FUV−NUV and FUV−V diagrams, are shown as grey circles; all others are denoted by black crosses. The dwarf galaxy regime starts at about $\log(L_H/L_\odot) \approx 9.6$, thus spanning 4 magnitudes ($\Delta \log(L_H/L_\odot) \approx 1.6$) in this sample. At the faintest luminosities, a handful of galaxies are redder than the apparent mean relation, and these are indeed not detected in the FUV. However, down to $\log(L_H/L_\odot) \approx 8.4$, only a mild offset – if at all significant – is seen between FUV-detections and non-detections, of the order of ~ 0.1 mag.

If the UV emission is caused by a young stellar population, then an offset of ~ 0.1 mag in NUV−V would correspond to an offset of not more than ~ 0.15 mag in FUV−NUV. This can be seen from Fig. 2 when considering by how much the model colors change per luminosity interval. This translation from one color into the other is possible because a young stellar population exhibits blue colors in both NUV−V and FUV−NUV. For an old stellar population showing a UV-upturn, this would of course be different — but the presence of a strong UV-upturn at these faint luminosities is neither deduced in previous studies nor in this work.

We summarize that the above investigation points towards a mild selection effect only, which does not support the interpretation of the bluening of FUV−NUV in the dwarf regime as an artificial feature. We also point out that only a relatively small fraction of Virgo cluster early-type dwarfs was found to exhibit ongoing star formation (Lisker et al. 2006b); see Sect. 4.3 for a discussion of this point. Nevertheless, from Fig. 2 it can be seen that the detection limits are closest to the bulk of the data in FUV−V, where faint red galaxies might be missed. This could indirectly lead to a selection effect in FUV−NUV to some extent, even if the detection limits given for FUV−NUV itself appear to be less disturbing. Certainly a more comprehensive assessment of the limitations of GALEX photometry for different stellar populations, which is beyond the scope of the present study, would be necessary to obtain precise estimates of the number and colors of potentially undetected galaxies.

4. DISCUSSION AND SUMMARY

4.1. *The UV colors of early-type galaxies*

From an analysis of GALEX data for over 6000 galaxies with the (single-star) models of Bruzual & Charlot (2003), Salim et al. (2005) concluded that "the star formation history of a galaxy can be constrained on the basis of the NUV−r color alone". However, our Fig. 2 shows that FUV−NUV contains important information on the stellar population of an early-type galaxy: by taking into account the formation of hot subdwarf stars that contribute significantly to the FUV flux, the binary model of Han et al. (2007) can easily explain the observed FUV−NUV colors of Virgo cluster early-type galaxies with a younger stellar population age at lower luminosities. This continuous sequence in luminosity – and hence, galaxy mass – also provides a natural interpretation of the observed anticorrelation between FUV−NUV and B − V for nearby early-type galaxies (Donas et al. 2007). Similarly, the findings of Rich et al. (2005), that

"quiescent" early-type galaxies are bluer in FUV−NUV than "star-forming" early types, can be straightforwardly explained with the latter having formed the majority of their stars later than the former.

It needs to be stressed that the dependence of FUV−NUV on the stellar population age differs from the behavior of the actual UV-upturn, depending on the definition of the latter. If the UV-upturn is defined as the slope β of the FUV spectrum, it remains at an almost constant value soon after the onset of the formation of hot subdwarfs in a galaxy, and does not change with age (Han et al. 2007). Consequently, different definitions of the UV-upturn in the literature need to be carefully distinguished. For example, Rich et al. (2005) adopt FUV−r color as the UV-upturn – similar to the 1550−V color analyzed by Burstein et al. (1988) – for which the corresponding age evolution of the binary model is very different from that of both β and FUV−NUV (Fig. 2; Han et al. 2007).

Our findings do not necessarily contradict the claims of recent star formation in a significant fraction of early types (Kaviraj et al. 2007a; Schawinski et al. 2007): these and similar studies mainly used solely the NUV flux as indicator for the presence of young stars (also see Yi et al. 2005). It is important to point out that these studies primarily focus on whether a *small fraction* of young stars is present, whereas we have considered the average age of the *whole* stellar population of a galaxy. Therefore, not surprisingly, the statement of Kaviraj et al. (2007a) that galaxies with NUV−r < 5.5 (roughly NUV−V < 5.2) are very likely to have experienced *some* recent star formation translates into a younger *overall* stellar age in our study (cf. Fig. 2, bottom).

4.2. *Residual or recent star formation in dwarfs?*

While the degeneracy between a somewhat younger mean age or a small fraction of young stars on top of an old population is unavoidable to some extent, we would like to emphasize the difference between *recent* and *residual* star formation. In Fig. 2, the time since the end of star formation for the binary model with constant star formation rate ranges from $\log(t/\mathrm{yr}) = 8.4$ at the low-mass end to $\log(t/\mathrm{yr}) = 9.4$ at the high-mass end. Therefore, when defining "recent star formation" as having some fraction of stars younger than 1 Gyr (cf. Kaviraj et al. 2007a; Schawinski et al. 2007), all galaxies with $\log(L_H/L_\odot) \lesssim 10$ would count in this scenario as objects that experienced recent star formation. In contrast, the term "residual star formation" (cf. Boselli et al. 2005, 2008) refers to a small amount of *ongoing* star formation activity, which should not be confused with the former.

VCC 1499, a morphologically early-type-like object (Binggeli et al. 1985; Lisker et al. 2006b) but having post-starburst characteristics (Gavazzi et al. 2001), is significantly bluer in FUV−NUV than the average value at its luminosity (Boselli et al. 2005), with the offset being about 2 times the RMS color scatter. Lisker et al. (2006b), who identified Virgo early-type dwarfs with blue central g − i colors, showed that the inner colors of VCC 1499 are bluer than those of all early-type dwarfs having a blue center. In that study, the weakest blue centers that could still be identified as such exhibit a g − i color difference of 0.1 mag between inner and outer galaxy regions, whereas the value for VCC 1499 is 0.5

mag. VCC 1499 thus stands out at least as clear in the optical Sloan Digital Sky Survey data (Adelman-McCarthy et al. 2007) as it does in the *GALEX* data, partly because both the signal-to-noise ratio and the resolution are much better in the former. It is therefore not necessarily the case that residual or very recent star formation activity can be identified down to lower levels with *GALEX* than with optical data.

In the sample of Lisker et al. (2006b), VCC 1499 is the only galaxy for which the population synthesis model fits to the spectrum of the very central region yielded a mass fraction of young stars ($< 500\,\mathrm{Myr}$) of more than 10%. The other early-type dwarfs with a blue central region – of which several show H_α emission from ongoing star formation (Lisker et al. 2006b; Boselli et al. 2008) – were deduced to have several thousandths of their mass in very young stars ($< 10\,\mathrm{Myr}$), and several percent of their mass in stars younger than $500\,\mathrm{Myr}$. These objects make up $\sim 15\%$ of early-type dwarfs among the brightest two magnitudes. We would thus expect that the majority of Virgo early-type dwarfs has a lower fraction of young stars that could not be identified by Lisker et al. (2006b). Let us therefore consider the age ranges that were adopted in Fig. 2 (specified in the caption). For the SSP and the single burst model, more than one third of the stars were formed less than 500 Myr ago at low galaxy masses. If this was the real situation, Lisker et al. (2006b) should have detected recent star formation like in VCC 1499 in the vast majority of early-type dwarfs. However, both the SSP and the single burst model do *not* match the NUV$-V$ color (Fig. 2, bottom), for the very same reason: in case of significant recent star formation, NUV$-V$ would be much bluer than what is actually observed. (VCC 1499 does have such a very blue NUV$-V$ color). Only the model with constant star formation is able to match the observed colors at the faint end. For this model, only 2% of all stars formed less than 500 Myr ago, which, given the above considerations, would indeed not have been detected by Lisker et al. (2006b), leading to a consistent picture.

This scenario is also in accordance with the indications for just a small color selection effect in FUV$-$NUV (see Sect. 3.3), which should be much larger if most of the FUV-detected galaxies contained a significant amount of young stars. Furthermore, we would like to remark that only a very small fraction of early-type galaxies in the Virgo cluster contain a significant amount of neutral hydrogen (di Serego Alighieri et al. 2007; Gavazzi et al. 2008), again in agreement with the above picture.

4.3. *From dwarfs to giants*

Do dwarf and giant early-type galaxies form one continuous parameter sequence, despite the rather different formation scenarios suggested for them (e.g. Bell et al. 2006; Boselli et al. 2008)? Their overall shapes follow a structural continuum with luminosity (Jerjen & Binggeli 1997; Graham et al. 2003; Gavazzi et al. 2005). In nearby galaxy clusters, early-type dwarfs were reported to follow the color-magnitude relation (CMR) of giant early types, at least on average (Secker et al. 1997; Conselice et al. 2003; also see Andreon et al. 2006). Smith Castelli et al. (2008) recently presented a well-defined optical CMR of early-type dwarf and giant galaxies in the Antlia cluster, which shows no change in slope within a range of 9

magnitudes. However, from *GALEX* UV colors, a pronounced dichotomy seemed to be present between Virgo cluster dwarf and giant early types (Boselli et al. 2005), hinting at systematic differences in their star formation histories. With our above analysis, which takes into account the FUV flux of hot subdwarf stars, we have shown that this color behavior can be naturally explained with a continuous sequence of longer duration and later truncation of star formation at lower galaxy masses, all the way from giants to dwarfs. These results do point towards a fraction of relatively young stars in early-type dwarfs (see Sect. 4.2); however, residual star formation activity, as suggested by Boselli et al. (2005, 2008), is not necessary to account for the observed colors. While a number of Virgo cluster early-type dwarfs with central star formation activity are known (Lisker et al. 2006b), these only constitute a minor subpopulation (Lisker et al. 2007).

A continuous sequence of longer star formation duration at lower galaxy masses has been found by Thomas et al. (2005) for giant early-type galaxies, in agreement with the larger mass fraction of young stars at lower galaxy masses reported by Ferreras & Silk (2000). Given the apparent continuity of the optical CMR down to early-type dwarfs, and the reproduction of the turnaround in FUV$-$NUV by the HPL07 model, it appears reasonable that this trend in the star formation history might simply be continued to the dwarfs. Along these lines, a clear relation of longer duration of star formation at lower H luminosity was found by Gavazzi et al. (2002, their Fig. 11) in their spectrophotometric study of Virgo cluster early-type dwarfs and giants. A continuous star formation with rather late truncation for dwarfs would also be in agreement with the study of Boselli et al. (2008), who compared multiwavelength observations of Virgo cluster dwarf galaxies to chemo-spectrophotometric models and concluded that the majority of early-type dwarfs could have been formed recently through ram-pressure stripping of late-type galaxies.

How plausible would a continuity between the star formation histories of giant and dwarf early-type galaxies appear in the light of the recent infall of the dwarf progenitors – following the scenario proposed by Boselli et al. (2008) – as opposed to the dynamically relaxed and centrally concentrated population of giant early types (cf. Conselice et al. 2001)? The fact that for giant early-type galaxies, significant stellar population differences are found between clusters and the field (e.g. Thomas et al. 2005), but not between different clusters (e.g. Bower et al. 1992; Andreon 2003), indicates that the environmental density played an important role already at early epochs. Would we thus expect a continuity of cluster giants and dwarfs if the progenitors of the latter just recently arrived from a low-density environment? One key to this question might be in the recent identification of several early-type dwarf subclasses that have significantly different shapes, colors, and/or spatial distributions within the Virgo cluster (Lisker et al. 2007). Early-type dwarfs with weak disk features (Lisker et al. 2006a), with blue central regions (Lisker et al. 2006b), as well as those without a bright stellar nucleus all have a rather flat shape and populate a similar density regime as the late-type cluster galaxies do. Only the ordinary

nucleated early-type dwarfs fit into the classical image of dwarf elliptical galaxies, in that they have a spheroidal shape and are concentrated towards the cluster center (Lisker et al. 2007). Moreover, they exhibit somewhat older and/or more metal-rich stellar populations than the other subclasses. This diversity renders a common formation mechanism for all early-type dwarfs highly unlikely (Lisker et al. 2008). One can thus speculate whether those nucleated early-type dwarfs have resided in the cluster since a long time already (Oh & Lin 2000), along with the giant early types, and might therefore be responsible for the above picture of a continuum from giants to dwarfs — after all, they constitute the majority of the early-type dwarf population. The other dwarf subclasses might be those that formed through transformation of infalling galaxies, as suggested by Boselli et al. (2008). Future studies need to investigate in more detail the characteristics of the different subclasses of early-type dwarfs, as well as their relation to giant early types, in order to gain further insight into the physical mechanisms responsible for their formation.

While still being relatively simple, the binary model of Han et al. (2007) is able to account for the observed range of FUV−NUV color of Virgo cluster early-type galaxies, and provides a natural explanation for its behavior with luminosity. We thus believe that it will become an important tool in future studies of the ultraviolet light from galaxies. Further development of the model, such as an extension to various metallicities, is in progress. Moreover, the diagnostic UV-optical color-color diagrams presented by Han et al. (2007) enable us to study the star formation histories of early-type galaxies in a more detailed way than presented here, which will be subject of a forthcoming paper.

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