COLOR PROFILES OF DISK GALAXIES SINCE z ∼ 1: PROBING OUTER DISK FORMATION SCENARIOS

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ABSTRACT

We present deep color profiles for a sample of 415 disk galaxies within the redshift range 0.1 < z ≤ 1.1, and contained in HST ACS imaging of the GOODS-South field. For each galaxy, passband combinations are chosen to obtain, at each redshift, the best possible approximation to the rest-frame u − g color. We find that objects which show a truncation in their stellar disk (type II objects) usually show a minimum in their color profile at the break, or very near to it, with a maximum to minimum amplitude in color of ≤0.2 mag arcsec^{-2}, a feature which is persistent through the explored range of redshifts (i.e., in the last ∼8 Gyr). This color structure is in qualitative agreement with recent model expectations where the break of the surface brightness profiles is the result of the interplay between a radial star formation cutoff and a redistribution of stellar mass by secular processes.

Subject headings: galaxies: evolution — galaxies: high-redshift — galaxies: structure

Online material: color figure

1. INTRODUCTION

Systematic studies of the fainter outer parts of stellar disks in galaxies show that there are three distinct modes of behavior. All disk galaxies show radial exponential decay in their surface brightness profiles (Patterson 1940; de Vaucouleurs 1959), although in some cases this exponential may change its slope (i.e., scale length) at a defined galactocentric radius. First there are the pure type I profiles, with no change of slope in their surface brightness profile out to 5 and even 10 scale lengths (Bland-Hawthorn et al. 2005; Pohlen & Trujillo 2006; Erwin et al. 2008); second, the type II profiles, with a shallower inner exponential followed by a steeper outer exponential (Freeman 1970; Erwin et al. 2005, 2008; Pohlen & Trujillo 2006). A subset of this type are the so-called stellar disk truncations (van der Kruit 1979), where the change in slope takes place in the outermost parts of the disks (see also Pohlen et al. 2004). Finally, there are the type III profiles, seen in Courteau (1996) and in Matthews & Gallagher (1997) but first systematically measured by Erwin et al. (2005) and observed in many galaxies by Pohlen & Trujillo (2006) and Erwin et al. (2008). Type III profiles have a steeper inner exponential and a shallower outer profile and have been termed “antitruncations.”

In understanding why and how these differences among profiles arise, the application of stellar population analysis techniques throughout stellar disks may prove very useful. This kind of analysis, for example, sheds light on when stars formed in different parts of the disk of galaxies, thus giving hints on the stellar mass buildup process. When we can apply these tools to objects at different redshifts, we can see how changes in the spatial distribution of stellar mass in the disks actually take place. Color gradients have been extensively used in the literature as a way to extract information on both ages and metallicities through the galaxy radial profiles in the local universe (e.g., MacArthur et al. 2004). However, an interesting point these previous works missed was the connection between the color distribution and the break phenomenology. The reason for this is that although truncations in edge-on galaxies have been known of for quite some time, a systematic exploration showing the different galaxy profile types (i.e., types I, II, and III) in low-inclination galaxies is relatively new, as accounted for above. At higher redshift (0.5 < z < 3.5), color distribution has also been studied (e.g., Moth & Elston [2002] in the HDF-N or Tamm & Tenjes [2006] in the HDF-S), showing for a general mixed population (ellipticals, spirals, and irregulars) a small to a constant color gradient. But again, these previous works were not focused at all on the break phenomenology. In a significant step toward tackling this problem, we present here the analysis of color profiles for 415 disk galaxies taken from the GOODS-South field with profile types I, II, and III in the redshift range 0.1 < z ≤ 1.1. The observed HST ACS bands were selected to best approximate rest-frame u − g, for maximum uniformity in interpretation. The results put useful constraints on models of disk formation in general, and for profile truncations in particular.

Throughout, we assume a flat Λ-dominated cosmology (Ωm = 0.30, ΩΛ = 0.70, and H0 = 70 km s^{-1} Mpc^{-1}). All magnitudes are in the AB system.

2. DATA, SAMPLE SELECTION, AND COLOR PROFILES

In Azzollini et al. (2008, hereafter ATB08) we presented a detailed and extensive analysis of surface brightness profiles for a sample of 505 late-type galaxies with redshifts 0.1 < z ≤ 1.1, within the GOODS-South field. The final set of 435 galaxies in ATB08 that were suitable for analysis constitutes our parent sample. These galaxies were selected from the catalog published in Barden et al. (2005) which relies on the Galaxy Evolution from Morphologies and SEDs imaging survey (GEMS; Rix et al. 2004). Barden et al. (2005) provided morphological analysis of that sample of galaxies by fitting Sérsic r^{1/4} (Sérsic 1968) profiles to their surface brightness. Also, photometric redshift estimates [with errors δz/(1 + z) ∼ 0.02] and absolute B-band magnitudes of the objects were available thanks to the photometric catalog from COMBO-17 (Classifying Objects by Medium-Band Observation in 17 filters; Wolf et al. 2001, 2003). ATB08 selected those objects from the Barden et al. sample which fell within the following ranges of parameters: Sérsic index n ≤ 2.5 to isolate disk-dominated galaxies (Ravindranath et al. 2004); axial ratio q > 0.5 to select...
objects with inclination $<60^\circ$; and $M_B < -18.5$ mag, as in Trujillo & Pohlen (2005). Moreover, only objects with $z < 1.1$ were selected in order to maintain the analysis in the optical rest-frame bands. The observational basis for this work and ATB08 is imaging data from ACS observations of the GOODS-South field (Giavalisco et al. 2004). The data set consist of imaging data from ACS observations of the GOODS-South field (Giavalisco et al. 2004). The data set consist of images in the F435W, F606W, F775W, and F850LP HST passbands, hereafter referred to as $B_{435}$, $V_{606}$, $i_{775}$, and $z_{850}$. As in ATB08, we divide the redshift range covered by the objects in three redshift bins: “low,” $0.1 < z \leq 0.5$; “mid,” $0.5 < z \leq 0.8$; and “high,” $0.8 < z \leq 1.1$. All objects are classified as being of type I, II, or III, following ATB08. This classification was obtained by inspection of the GOODS band image which best approximates to rest-frame $B$ band in each redshift bin.

In order to make the best comparisons of the color profiles in different redshift ranges we use the images in the filter sets which give the closest approximations possible to rest-frame $u$ - $g$, which are, for $0.1 < z \leq 0.5$, $B_{435} - V_{606}$; for $0.5 < z \leq 0.8$, $V_{606} - i_{775}$; and for $0.8 < z \leq 1.1$, $V_{606} - z_{850}$.

The parent sample of 435 galaxies was further reduced by eliminating probable SO’s and those type II profiles where the change in slope clearly occurs in the inner disk (i.e., in the region inner to the spiral arms). We were also forced to remove 10 galaxies (4 of type I and 6 of type II) in the nearest redshift bin for which there is no $B_{435}$ image, since the field for this filter is slightly smaller than for the others. The final sample for this study has 415 galaxies.

### RESULTS AND DISCUSSION

Using our color profiles for the 415 sample galaxies we computed the median color profiles for subsamples of types I, II, and III, divided into bins of low, mid, and high redshift, all displayed in Figure 2. We show these profiles for all nine subclasses, with their error bars, and also, coded in color, median profiles for galaxies in higher and lower ranges of stellar mass $M_\ast$ (see caption for details).

In Figure 2 we see that in all three redshift bins the type II

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**TABLE 1**

**Sample Distribution by Profile Type and Redshift Ranges**

| Redshift Range | I   | II  | III | Total | Total$_{ATB08}$ | Discarded |
|----------------|-----|-----|-----|-------|-----------------|-----------|
| $0.1 < z \leq 0.5$ | 13  | 33  | 10  | 56    | 67              | 11 (10)   |
| $0.5 < z \leq 0.8$ | 74  | 133 | 20  | 227   | 234             | 7         |
| $0.8 < z \leq 1.1$ | 52  | 66  | 14  | 132   | 134             | 2         |
| Sum ................. | 139 | 232 | 44  | 415   | 435             | 20 (10)   |

**Notes.**—The total number of objects in each redshift bin is given in col. (5). In col. (6) we give the number of objects within each redshift bin of the parent sample (from ATB08), and in col. (7) how many were discarded to according to the described selection process.

Details of how the radial brightness profiles were derived can be found in ATB08, and the color profiles were subsequently produced as the difference between the surface brightness profiles in the two appropriate bands. The surface brightness profiles were radially scaled using a scale radius $R_s$, whose definition depends on the profile type, to give a uniform radial coordinate $R$. Objects of type II or III have $R_s$ equal to the break radius $R_b$. For type I objects $R_s$ is defined as a factor $f_s$ times the disk scale length $h$. ATB08 measure $R_b/h$ for type II galaxies of intermediate redshift as $1.4$, where $h$ is the inner scale length, while for nearby galaxies Pohlen & Trujillo (2006) measure a median value of 2.4 for this ratio. These values led us to choose $f_s = 2$ so that the radial scaling is comparable for types I and II. To give a sense of typical apparent/proper sizes of the galaxies under study, for the subset of type II objects, the median values of $R_b$ are $1.33^\prime/5.25$ kpc, $0.75^\prime/5.17$ kpc, and $0.64^\prime/5.07$ kpc within the low, mid, and high redshift bins, respectively. We have also checked the effect of the different ACS PSF wing properties on our color gradients, finding basically no influence on our results.

To illustrate our procedure, in Figure 1 we present an example color profile for one of the objects in the sample. It is a type II galaxy (ATB08) at $z = 0.59$. There is a broad but clear minimum (bluer) color at the position of the break ($R < 1$).

![Figure 1](image1.png)

**Fig. 1.**—Illustrative example of the kind of analysis performed on the galaxies of the sample under study, for a type II galaxy at $z = 0.59$. Top left panel: Surface brightness profiles in the bands $i_{775}$ and $V_{606}$. Bottom left panel: The $i_{775} - V_{606}$ color profile, showing a clear minimum in color around $R = 1$ (corresponding to $R_b$). On the right panel we show the $i_{775}$ image of the galaxy from GOODS-South–HST ACS. The ellipse marks the position of the break in the surface brightness profile. The horizontal line is 1” long at the given scale. [See the electronic edition of the Journal for a color version of this figure.]
profiles show color minima at the break radius. The differences \( \Delta C \) in median color index \( C \) between \( R = 0 \) and 1 are, for the three bins, in increasing redshift 0.14 ± 0.05, 0.17 ± 0.02, and 0.20 ± 0.05 mag arcsec\(^{-2} \), respectively, a marginal increase with \( z \). The reported errors \( \delta \Delta C \) are \( \sqrt{2} \) times the median of the error in the median color index median (\( \delta C \)) for each radius. The factor \( \sqrt{2} \) comes from the propagation of the error in the median color index when obtaining \( \Delta C \) as a difference in color.) The error in the median color index \( \delta C \) is obtained as the standard deviation of the color profiles at each radius, divided by the square root of the number of profiles. These differences in color index \( \Delta C \) are 2.6, 7.3, and 3.9 times higher than the errors \( \delta \Delta C \), in the respective bins, and so the (blue) minima are clearly significant. The minimum values are found in color profiles for each subsample, and the error bars give the error in those estimations. The error in the median color profile \( \delta C \) is defined as \( \delta C = c_i/N \), where \( c_i \) is the standard deviation in the distribution of color at the given radius, and \( N \) is the number of galaxies taken into account, which is also shown in the panels.

There is a large scatter between individual profiles for all types and bins. Among the possible causes are the quite wide range of \( z \) within each bin, causing a scatter in the effective bandpasses; the range of inclinations, causing different amounts of dust reddening; and intrinsic scatter due to different evolutionary stages for the galaxies in a bin. We could check among these by plotting the color at \( R = 1 \) against the parameters (1) \( 1/q \), where \( q \) is the axis ratio of the ellipse best fitting the disk; (2) redshift; (3) \( M_B \) (absolute B magnitude); and (4) the stellar mass \( M_\star \) of the galaxy. Parameters 3 and 4 are from Barden et al. (2005). The strongest dependences of \( C(R = 1) \) are on the stellar mass, \( M_\star \), for most profile types and at all redshifts (the only exception being for type I galaxies in the “low” redshift bin, a sample with \( N = 13 \)). We have also tested for the relations between \( C(R = 1) \) and average B-band luminosity surface density \( (L_\odot/kpc^2) \) and average stellar mass surface density \( (M_\odot/kpc^2) \), both within the radius corresponding to \( R = 1 \). These relations are not stronger than, although in the case of stellar mass surface density comparable to, that found with stellar mass. Thus, the color scatter is due mainly to differences in stellar mass, and not to the inclination range or to omitting k-corrections for the range of \( z \) within each bin.

This is illustrated in Figure 2, where we have plotted separately, where meaningful (not in the “low” redshift bin for types I and III, where the samples were too small), median color profiles for objects with \( M_\star \leq 10^{10} M_\odot \) (blue squares) and \( M_\star > 10^{10} M_\odot \) (red squares), superposed on the plots of
the full samples (black dots). The full profiles lie close to the “low mass” profiles, while the “high mass” profiles lie well above the other two. Our sample is dominated by the lower mass objects, and there are significant differences between low- and high-mass galaxies. However, the segregated plots for the type II profiles all reproduce the color minima shown by the full plots. We note that in the highest redshift bin the type III profiles of high-mass objects are very much redder than those of the less massive ones, possibly indicating contamination of this subsample with early-type galaxies.

The most interesting feature of our results is the minimum in the color profile at the break for type II galaxies, with similar amplitude over the full redshift range and for the stellar mass range explored. This seems to confirm that truncation is a phenomenon related to the stellar populations of the galaxies, and not a purely structural or geometrical effect.

Proposed models to explain the occurrence of truncations in stellar disks can be grouped in two branches: (1) models related to angular momentum conservation in the protogalactic cloud (van der Kruit 1987) or angular momentum cutoff in cooling gas (van den Bosch 2001); and (2) models which appeal to thresholds in star formation (Kennicutt 1989) or star-forming properties of distinct ISM phases (Elmegreen & Parravano 1994; Schaye 2004; Elmegreen & Hunter 2006). More recently, N-body simulations in which secular dynamics is considered have been devised in an attempt to better fit observational results (e.g., Debattista et al. 2006). In this same line, Roškar et al. (2008) presented a model in which the breaks are the result of the interplay between a radial star formation cutoff and a redistribution of stellar mass by secular processes. In this model, stars are created inside the break (threshold) radius and then move outward due to angular momentum exchange via spiral arms. Our results fit qualitatively their prediction that the youngest stellar population should be found at the break radius, and older (redder) stars must be located beyond that radius. It is not easy to understand how “angular momentum” or “star formation threshold”/“ISM phases” models alone could explain our results. Thus they pose a difficult challenge for these models. However, it will also be necessary to check whether the Roškar et al. (2008) models are able to reproduce quantitatively the results shown here.

There are also other possible causes of the color minima which cannot be ruled out, but at this stage are less satisfactory. Radially falling dust thickness out to the break plus older stars outside it could give this result for the color, but does not explain the break itself. More subtly, a change in metallicity gradient at the break could explain the color profile, but again this would need incorporating into a predictive model to yield a break.

The color profiles for types I and III are less easy to interpret. Type I profiles are flat in the lower redshift bins, and rising in the farthest bin. In the latter case this could imply a greater star formation rate near the centers. Type III profiles are falling in the nearest bin, flat in the intermediate bin, and rising with a downturn at the break in the highest redshift bin, this latter being the inverse of the behavior of the type II profiles. We do not feel that it is worth hazarding even qualitative interpretations for type I and type III profiles, certainly not within the scope of this Letter and especially given the small or moderate numbers involved. But the results, when strengthened statistically, will surely lead to useful constraints on disk evolution models, preferably when compared with similar results from more local samples (as in, e.g., J. Bakos et al., in preparation).

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