ON THE COLOR MAGNITUDE RELATION OF EARLY-TYPE GALAXIES

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ABSTRACT

In this letter we present a study of the color magnitude relation of 468 early-type galaxies in the Virgo Cluster with Sloan Digital Sky Survey imaging data. The analysis of our homogeneous, model-independent data set reveals that, in all colors ($u − g$, $g − r$, $g − i$, $i − z$) similarly, giant and dwarf early-type galaxies follow a continuous color magnitude relation (CMR) that is best described by an S-shape. The magnitude range and quality of our data allows us to clearly confirm that the CMR in Virgo is not linear. Additionally, we analyze the scatter about the CMR and find that it increases in the intermediate-luminosity regime. Nevertheless, despite this observational distinction, we conclude from the similarly shaped CMR of semi-analytic model predictions that dwarfs and giants could be of the same origin.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: dwarf — galaxies: fundamental parameters — galaxies: clusters: individual: (Virgo Cluster)

1. INTRODUCTION

That early-type galaxies form a well-defined Color Magnitude Relation (CMR) was first recognized by Baum (1959). Extensive studies by Visvanathan & Sandage (1977) and Sandage & Visvanathan (1978b,a) compared the CMR of nine galaxy clusters and of field galaxies. They found them to be astonishingly similar. In combination with other studies comparing the CMR for E and S0, within clusters, groups and the field (Faber 1973; Bower et al. 1992) a high degree of universality was shown for the relation.

The CMR is typically explained by an increase of mean stellar metallicity with increasing galaxy mass as the dominant effect. The common underlying idea is that more massive galaxies have deeper potential wells, which can retain metal-enriched stellar ejecta more effectively and subsequently recycle the enriched gas into new stars (Kodama & Arimoto 1997; Ferreras et al. 1999; Gallazzi et al. 2006; Chang et al. 2006). Another factor could be a variable integrated galactic initial mass function, with more massive stars in more massive galaxies, and thus a more substantial enrichment (e.g. Matteucci et al. 1998; Köppen et al. 2007).

An alternative explanation was given with a change of the mean age (see e.g. Poggianti et al. 2001, and some observational support for it in Rakos & Schombert 2004). The question of which explanation to favor is not totally settled yet due to the ambiguity introduced by the age-metallicity degeneracy. But data from clusters at higher redshift show that the CMR is in place ever since, favoring the mass-metallicity relation to be the dominant effect (Kodama & Arimoto 1997).

From early on, it was discussed whether the universality of the CMR also holds over the whole range of galaxy masses, i.e. whether dwarf and giant early-type galaxies follow the same CMR. Studies of different clusters show consistency with one common CMR for dwarfs and giants, albeit with a significant increase in the scatter at

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low luminosities (Secker et al. 1997 for Coma, Conselice et al. 2002 for Perseus, Karick et al. 2003 and Mieske et al. 2007 for Fornax, Smith Castelli et al. 2008 for Antlia and Misgeld et al. 2008 for Hydra I). More explicitly, Caldwell (1983) stated that there is a common linear relation. But his Fig. 3 might hint at a change of slope from high to low luminosities, similar to what de Vaucouleurs (1961) suggested. Interestingly, visual examination of the diagrams presented by most of the above-mentioned studies indicates consistency also with a change of slope – yet linear relations were fitted in most cases (see, however, Ferrarese et al. 2006; see Sect. 5). In this letter we revisit the question of the universality of the CMR for dwarfs and giants.

2. SAMPLE SELECTION AND DATA

The sample is based on the Virgo Cluster Catalog (VCC; Binggeli et al. 1985). All early-type galaxies therein with a certain cluster member status and $m_B < 18.0$ mag are taken into account, which is the same magnitude limit up to which the VCC was found to be complete. This translates into $M_B < −13.09$ mag with our adopted distance modulus of m-M=31.09 mag (d=16.5 Mpc, Mei et al. 2007). We treat uncertain classifications as in Janz & Lisker (2008) and exclude possible irregulars. Seven further galaxies are exluded due to their low S/N in u and z.

The Sloan Digital Sky Survey (SDSS) Data Release Five (DR5) (Adelman-McCarthy et al. 2007) covers all but six early-type dwarf galaxies of the VCC. Since the quality of sky level subtraction of the SDSS pipeline is insufficient, we use sky-subtracted images as provided by Lisker et al. (2007), based on a careful subtraction method. The images were flux-calibrated and corrected for galactic extinction (Schlegel et al. 1998).

For each galaxy, we determined a "Petrosian semi-major axis" (Petrosian 1976, hereafter Petrosian SMA, a_p), i.e., we use ellipses instead of circles in the calculation of the Petrosian radius (see, e.g., Lotz et al. 2004). The total flux in the r-band was measured within $a = 2a_p$, yielding a value for the half-light semimajor axis, $a_{hl,r,uncorr}$. This Petrosian aperture still misses
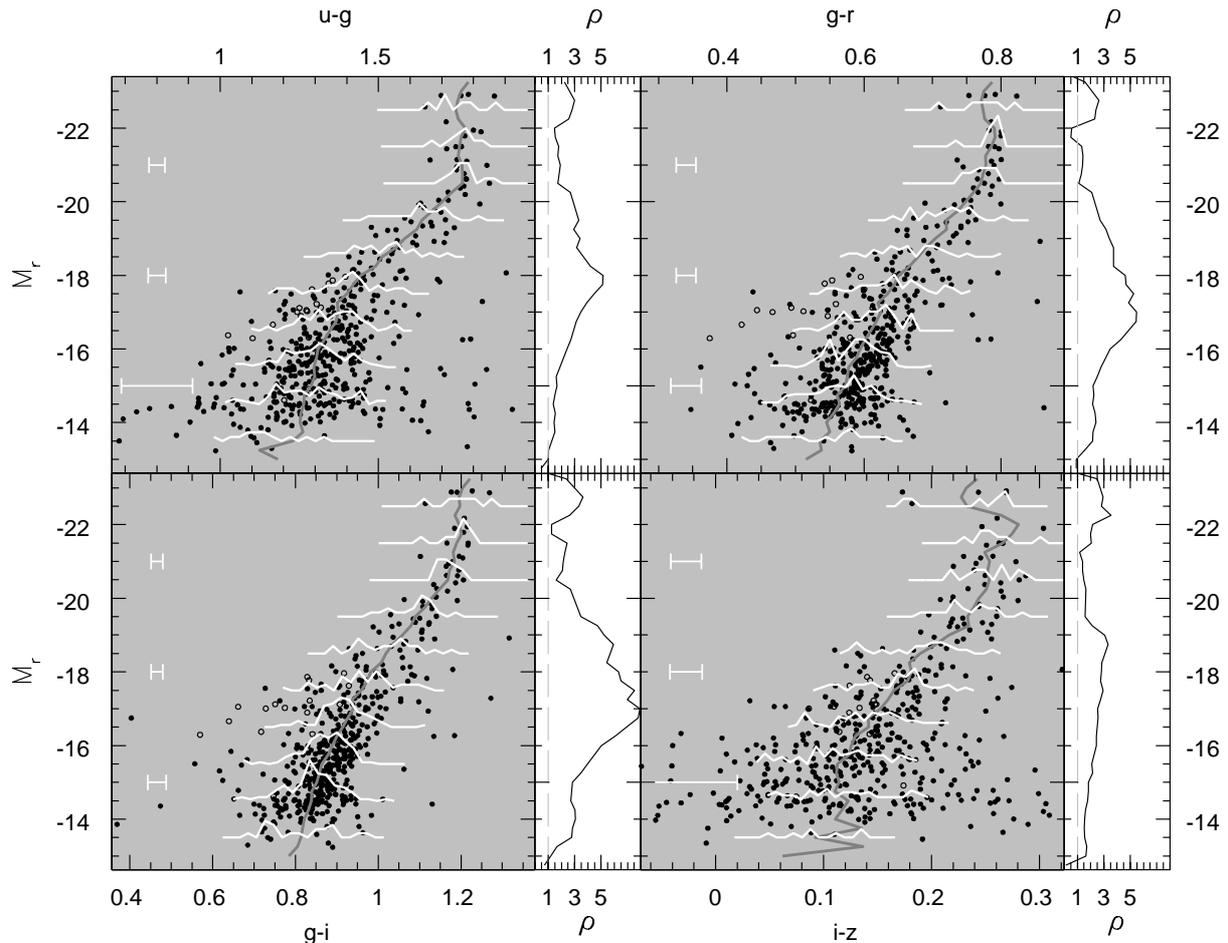
FIG. 1.— Color Magnitudes Relations for the colors $u - g$, $g - r$, $g - i$, and $i - z$. *Open circles* show dEs with blue cores and *filled circles* all the other galaxies in the sample. Limits for the x-axes are scaled to the mean color of galaxies fainter than $M_r > -15$ mag and brighter than $M_R < -21$ mag. The gray line indicates the "running histogram" as found in successive magnitude bins with a width of 1 mag and steps of 0.25 mag, clipped one time at 3σ. We limit the drawing range for the line to the region with at least three galaxies in a bin. The white histograms show the distributions in bins of the same width, normalized to the square root of the number of galaxies in the bin, shown for every fourth step. The white errorbars indicate typical photometric errors at the respective brightness. In the panels right to the color magnitude diagrams a measure for the intrinsic scatter is given by the ratio of the RMS of the scatter and of the photometric error in the same running bins (see text).

some flux, which is of particular relevance for the giant galaxies (Trujillo et al. 2001). The brightness and the half-light SMA were corrected for this missing flux according to Graham et al. (2005).[2] Axial ratio and position angle were then determined through an isophotal fit at $a = 2a_{hl,r}$. Colors were measured within the elliptical r-band half-light aperture for each filter. Errors were estimated from the S/N and calibration uncertainties (which we estimate to have a *relative* effect of 0.1 mag in each band, which is smaller than the absolute values given by SDSS), as described in Lisker et al. (2008).

Our data constitute a very homogeneous set of measurements for galaxies in one cluster, obtained and reduced with the same instrument, setup, and software.

3. THE CMR OF EARLY-TYPE GALAXIES

[2] The correction is computed with the assumption and fitting of Sérsic profiles as in Janz & Lisker (2008). But the effect on the CMR is small: for a de Vaucouleurs profile it leads to a difference of 0.2 mag in brightness and practically no difference in color, since the correction to the radius has a minute effect due to the small color gradients.

From the five SDSS filter bands we choose four representative colors: $u - g$, mostly sensitive to age; $g - r$ with the highest S/N; $g - i$ with the longest wavelength baseline at good S/N; and $i - z$, mostly sensitive to metallicity.

First of all, the impression one can get by examining just the *black points* in Fig. 1 is that there is not one common linear relation from the faint to the bright galaxies. In all colors the overall shape appears more like "S" shaped. The brightest ($M_r < -21$) galaxies have almost constant color, i.e. no correlation between color and brightness; the very brightest galaxies show a larger scatter. These were reported before to be *morphologically* different from the other galaxies in more detailed studies of the inner light profiles (e.g. Ravindranath et al. 2001; Trujillo et al. 2004; Ferrarese et al. 2006; Lauer et al. 2007; Kormendy et al. 2009). For the remaining galaxies several descriptions seem to be plausible, ranging from just an offset between two relations with similar slopes up to a curved relation.

With the non-linear shape, it seems not very favorable to fit a straight line. This would not describe the data
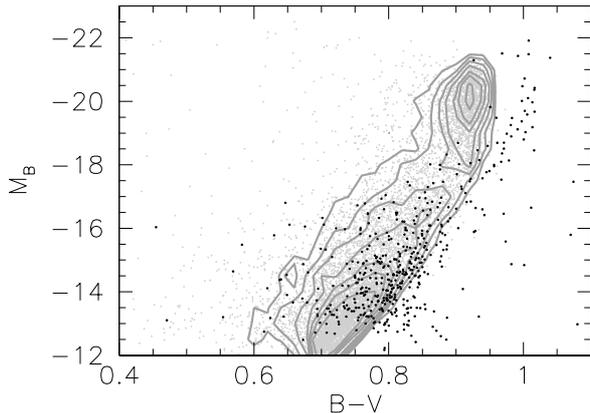
FIG. 2.— Color Magnitude Diagram, comparison to the semi-analytic model. Virgo cluster galaxies are shown with black symbols and model galaxies from the Numerical Galaxy Catalog (Nagashima et al. 2005) as gray dots (we selected galaxies with $B/T > 0.6$ and with higher effective surface brightness than 25.5 mag arcsec^{-2}). Contours were calculated using model galaxy abundances in bins of 0.5 mag in brightness and 0.02 mag in color. The contour levels, relative to the lowest level, are 2, 3.4, 5, 7.5 10, and 15.

well, and there is no theoretical prediction what other function is expected. So at first, we want to make the overall shape more clearly visible, using continous, overlapping magnitude bins, in which mean and scatter are calculated. In Fig. 1 these derived relations are shown with grey lines. The first impression is confirmed: one common linear relation for dwarfs and giants cannot be seen. Moreover, the white histograms showing the galaxy distributions in the bins are clearly peaked towards the bright and the faint end, while they are rather flat at intermediate luminosity.

If the notion of two separate relations with an overlap is correct, this should become evident through an increased scatter about the relation around the intersection, relative to the photometric error. Therefore we calculate the RMS of the scatter around the mean in running bins (clipping one time at 3σ) and divide it by the RMS of the photometric errors

$$\rho \equiv \text{RMS-ratio} \equiv \frac{\text{rms}_{\text{scat}}}{\text{rms}_{\text{err}}} = \frac{\sqrt{\sum_i (c - \langle c \rangle)^2}}{\sqrt{\sum_i \sigma_i^2}},$$

with color c and mean color $\langle c \rangle$, averaging over the galaxies in the respective bin. Here we exclude dEs with blue cores, since they are known to have different colors (Lisker et al. 2008). This RMS-ratio should be one if the scatter is only due to the measurement errors and larger than one if there is an intrinsic scatter.[3] In Fig. 1 we show the CMRs along with the RMS-ratio ρ.

Indeed, the RMS-ratio is enhanced between -20 mag $< M_r < -16$ mag, indicating an intrinsically increased scatter, which could in principle be explained by a transition between two separate relations. But the change is steady. Thus also alternative

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[3] With the binning this is not completely true anymore, since flatter relations with the same amount of scatter will show a larger RMS-ratio. But if the relation becomes significantly flatter, either two relations intersect with an offset anyway, or there is a transition region with a flatter CMR; in both cases it is different from the relations faint- and brightward.
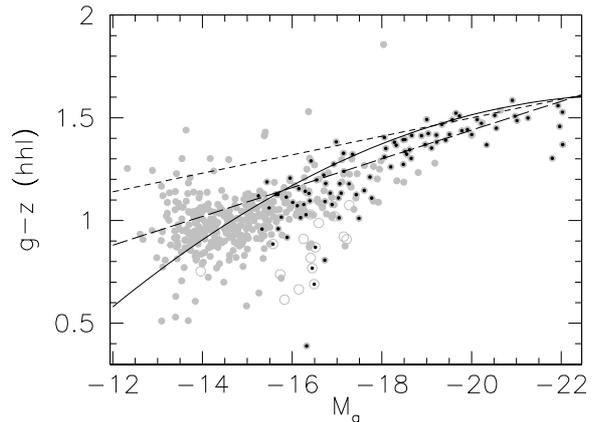

FIG. 3.— Comparison to the data of Ferrarese et al. (2006). Shown are all galaxies in our sample with *gray* symbols, again the blue-core dEs with *open circles* and the other galaxies with *filled circles*. Galaxies common to both samples are indicated by an additional *black dot* in the middle of the other symbol. The axes are changed in comparison to Fig. 1 and colors are measured in smaller apertures to most closely resemble their Fig. 123. The black lines indicate their fits to their data, the *short dashed* and *long dashed line* linear fits to a brighter ($M_g < -18$) and fainter subsample ($M_g > -18$), respectively. The solid line displays the parabola they fitted to the whole sample. There is a systematic offset of about 0.1 mag towards bluer colors of the color derived in our study in comparison to Ferrarese et al.

explanations, such as a more varied star formation history with decreasing galaxy mass, seem plausible – although the decrease in the scatter for the faintest dwarfs would still need to be explained.

One can argue about the significance of the RMS-ratio increase for the brightest galaxies, since it is just a handful of them – nevertheless, this larger scatter might be related to the absence of a well-defined CMR at the brightest magnitudes.

4. COMPARISON TO SEMI-ANALYTICAL MODEL

The Numerical Galaxy Catalog of Nagashima et al. (2005) is based on a high resolution N-body simulation in a ΛCDM universe (Yahagi 2005). The dark-halo merger trees of the N-body simulation are taken as input for a semi-analytical model (SAM) of galaxy formation (here a modified version of the Mitaka Model, Nagashima & Yoshii 2004). The SAM models physical processes of galaxy formation and evolution such as gas radiative cooling, star formation, heating by supernova explosions (supernova feedback), mergers of galaxies, population synthesis, and extinction by internal dust and intervening HI clouds. In particular, the model takes into account the dynamical response to starburst-induced gas removal after gas-rich mergers (also for cases intermediate between a purely baryonic cloud and a baryonic cloud fully supported by surrounding dark matter as in Yoshii & Arimoto 1987). The gravitational well is shallower for the dwarf galaxies and thus they suffer a more substantial gas loss than giants. This process is not only important for the galaxy sizes, but also for their metal enrichment histories.

In the comparison of the CMR of the Virgo galaxies with the SAM (Fig. 2), the shapes of the distributions are fairly similar, and the model CMR is indeed not well represented by a linear relation. In Janz & Lisker (2008) we presented an analogous comparison for the scaling re-

lation of radius and brightness and found that the model qualitatively agrees with distribution of the galaxies in that diagram. Both the CMR and the relation between size and brightness do not show a linear, nor one common behaviour for dwarfs and giants. Nevertheless, in the framework of the SAM both can be explained by the same physical processes, which govern ΛCDM structure formation, and thus both can be of cosmological origin (see also Chilingarian 2009).

Beside the good agreement in the overall shape, an offset is observed. This offset could partly be due to uncertainties of the adopted synthetic stellar population model.[4] Furthermore, the relative number of bright galaxies exceeds the observed one and the luminosity function is clearly different, which could possibly be explained with model input physics.

5. SUMMARY AND DISCUSSION

In the literature, there is no consistent view of commonness or distinctness of the color magnitude relation of dwarf and giant early-type galaxies. Some studies find a linear relation over the whole range of brightness, others find a change of slope.

We studied the CMR of Virgo cluster early-type galaxies, based on the wealth of SDSS imaging data in multiple filter bands. Our main result is that the dwarfs and giants do not follow one common *linear* relation. The appearance in the different colors, from $u-g$ to $i-z$, is very similar, suggesting that age and metallicity go hand in hand: the CMR at shorter wavelengths is more sensitive to changes in age, while it is more sensitive to changes in metallicity at longer wavelengths. Recent studies indeed claim that a combination of the effects of age, metallicity and also α-enhancement shape the CMR (Köppen et al. 2007; Lisker & Han 2008).

The most direct comparison with other data is possible with Ferrarese et al. (2006), who studied early-type galaxies in the Virgo Cluster with the Hubble Space Telescope's Advanced Camera for Surveys (ACS) in the ACS Virgo Cluster Survey. In their Fig. 123 they show the CMR in $g-z$, using smaller apertures for the color measurements. For comparison we repeat the plot and indicate galaxies common to both samples with black dots in the symbols (Fig. 3). We also show their fits (to their data): two linear fits to a brighter and fainter subsample and one parabola for the whole sample. While a qualitatively good agreement is found, the small offset to

bluer colors of our data is likely explained by a combination of the effect of different apertures, the atmosphere, and different physical filters. While we agree with Ferrarese et al. that the CMR is not linear over the whole range, the faint dwarfs in our sample, which they do not reach (cf. Fig. 3), do not lie on the extrapolation of their parabolic fit, but rather define an overall "S"-like shape. Furthermore, some of the galaxies that might drag their CMR to the blue side, at their faint end, display blue cores from recent star formation activity (Lisker et al. 2006), which we excluded.

We found an increase of the scatter about the CMR at intermediate brightness, visible in Fig. 1 through a broadening of the color distributions within the respective magnitude bins. This confirms the result that dwarfs and giants do *not* share one common *linear* CMR. For the brighter and fainter galaxies the scatter is closer to the photometric errors.

Bernardi et al. (2005) concluded that the CMR is a result of two more fundamental relations: the Faber-Jackson relation and a relation between color and velocity dispersion. Given the slope change of the Faber-Jackson relation from giants to dwarfs (Matković & Guzmán 2005; de Rijcke et al. 2005) a change of slope of the CMR would actually be expected.

It is important to emphasize that the curved shape of the CMR, and the possible existence of two adjacent relations does *not* necessarily imply different formation scenarios of dwarfs and giants. This is in accordance with previous claims of no distinction between them (Graham & Guzmán 2003; Gavazzi et al. 2005; Ferrarese et al. 2006; Misgeld et al. 2008). Instead, from the good qualitative agreement of the observed CMR shape with a semi-analytic model, we conclude that a common origin within the framework of ΛCDM structure formation appears plausible for both giant *and* dwarf early types. A more detailed multiparameter comparison of dwarfs and giants will be communicated in a forthcoming paper.

[4] The offset might here also be influenced to some degree by the transformations to Vega magnitudes in the Johnson-Cousins filter system. In a diagram of $i-z$ vs. M_i (for which no transformations are needed) the observed galaxies lie bluewards of the model ones with an smaller absolute offset than in $B-V$ vs. M_B, but the scatter of the observed galaxies is larger due to the lower S/N in the z-band.

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