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INTERNAL COLOR GRADIENTS AND THE COLOR-MAGNITUDE RELATION OF EARLY-TYPE GALAXIES

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ABSTRACT

The traditional use of fixed apertures in determining the well-known color-magnitude (CM) relation of early-type galaxies, coupled with the presence of radial color gradients within these systems, introduces a bias in the CM relation itself. The effect of this bias is studied here, deriving a CM relation that is based on color measurements carried out homogeneously within an aperture of radius equal to that of the galaxy effective radius. A sample of 48 giant early-type galaxies in the Coma Cluster, with CCD observations in the U and V band, is used for this derivation. It is found that internal radial color gradients in early-type galaxies cannot be neglected when discussing the colors of these systems, and that the CM relation derived using color measurements within the effective radius is significantly flatter than those based on fixed-aperture color measurements. With the currently available data, it is impossible to determine whether the relation is completely flat, or whether a small correlation is still present between galaxy color and luminosity.

Key words: galaxies: elliptical and lenticular, cD — galaxies: fundamental parameters — galaxies: stellar content

1. INTRODUCTION

It has long been known that the colors of early-type galaxies correlate with their absolute magnitudes (see, e.g., Baum 1959; de Vaucouleurs 1961; McClure & van den Bergh 1968; Lasker 1970). This color-magnitude (CM) relation was demonstrated to be a universal property of early-type galaxies by Visvanathan & Sandage (1977), and has become one of the most common tools used to constrain the epoch of formation and the star formation history of these systems. Bower, Lucey, & Ellis (1992a, 1992b; hereafter collectively BLE92) were the first to study the CM relation using photometric data based on CCD observations, which exhibited an even smaller scatter around the mean relation than previous determinations. More recently, the CM relation has been shown to be present in clusters up to $z \sim 1$ (see, e.g., Stanford, Eisenhardt, & Dickinson 1998; Kodama et al. 1998; Gladders et al. 1998), and to have similar properties in distant and nearby clusters.

These observations, when interpreted within the framework of a rapid, dissipative, galactic collapse (see, e.g., Larson 1974) and with the help of synthetic stellar population models (see, e.g., Buzzoni 1989; Bruzual & Charlot 1993; Worthey 1994; Tantalo et al. 1996; Kodama & Arimoto 1997) yield an estimate for the epoch of early-type galaxy formation of $z \sim 4.5$, with a fairly limited star formation activity taking place afterward (Bower, Kodama, & Terlevich 1998). The systematic change in color as a function of luminosity in these models is interpreted as the result of systematic changes in the mean metallicity as a function of galaxy mass. These results currently provide what is probably the strongest argument against the otherwise quite successful models of hierarchical galaxy formation (but see Kauffmann & Charlot 1998 for a different point of view).

The seemingly straightforward exercise of deriving a CM relation observationally is complicated by the presence of systematic radial color gradients within giant early-type galaxies. It is now well established that these objects are reddest in their cores and become bluer toward their peripheries (see, e.g., de Vaucoleurs 1961; Sandage & Visvanathan 1978; Frogel et al. 1978; Franx, Illingworth, & Heckman 1989; Peletier et al. 1990a; Peletier, Valentijn, & Jameson 1990b), most likely as a result of radial metallicity gradients within their stellar populations (see recent analysis by Tamura et al. 2000 and Saglia et al. 2000). Since the galaxy colors used in almost all studies of the CM relation are measured within apertures of a fixed radius, different portions of a galaxy are used to derive these colors, depending on the galaxy's intrinsic size (and therefore on its luminosity). As a result, a spurious correlation between galaxy luminosity and color is produced, even in the absence of systematic changes of the global stellar population as a function of galaxy luminosity. This problem has been recognized for quite some time, and a number of attempts have been made to take it into consideration. For example, Sandage & Visvanathan (1978) corrected their color measurements to a constant fraction of each galaxy's isophotal radius [$\theta/D(0) = 0.5$], but this correction does not solve the problem, since isophotal radii include a variable fraction of galaxy light, depending on the galaxy luminosity. Other correction schemes have been attempted on the modeling side, for synthetic stellar population models (see, e.g., Kodama et al. 1998; Kauffmann & Charlot 1998). In this case, mean radial color gradient values are used to convert model-based total magnitudes into aperture magnitudes, for a direct comparison with the observations. However, given the large scatter that is observed for the intensity of radial color gradients (see, e.g., Peletier et al. 1990a, or § 4), it is not appropriate to use a mean value to characterize this property of the galaxy population. It would be clearly preferable to derive the CM relation observationally, using variable size apertures measuring galaxy colors at a fixed fraction of the galaxy light.

In this work, a sample of 48 early-type galaxies in the Coma Cluster with photometric observations in the U and V band and measurements of the galaxy effective radius in

the V and I band, all available from the literature, is used to derive a CM relation that is based on color measurements within the effective radius for each galaxy in the sample. This newly obtained relation should be directly comparable with the model predictions based on synthetic stellar population models. The data set used in this work is described in § 2, the derivation of the traditional "fixed aperture" and of the new "fixed light fraction" CM relations is described in § 3, color gradients within individual galaxies are discussed in § 4, and § 5 presents the discussion and the conclusions of this work.

2. THE DATA

A sample of early-type galaxies in the Coma Cluster was chosen for this work for a number of practical and astrophysical reasons. The Coma Cluster is among the richest nearby clusters and therefore has a large population of early-type galaxies. Due to its proximity, accurate morphological information and a large set of photometric and spectroscopic observations are available. Being a rich cluster, it also represents a fair local counterpart to the distant clusters currently being used to study the processes of formation and evolution of early-type galaxies. The Coma Cluster is, however, too distant to allow an expansion of the study of the CM relation to dwarf galaxies. This exercise will be described in a future work (Scodeggio et al. 2001), which is based on a sample of early-type galaxies in the Virgo Cluster.

The data set being used here consists of U- and V-band CCD photometry observations of E and S0 galaxies in the Coma Cluster, taken from BLE92, supplemented by determinations of each galaxy's effective radius r_e (the radius within which half of the galaxy light is contained), taken from Lucey et al. (1991) and Scodeggio, Giovanelli, & Haynes (1998; hereafter SGH98). BLE92 obtained observations for 81 galaxies at the 2.5 m Isaac Newton Telescope (INT) in La Palma. For each galaxy, these authors provide a series of aperture magnitude measurements, carried out within synthetic apertures with radii ranging from 4″ to 60″. The typical accuracy of these measurements is 0.03 mag. Of these 81 objects, 56 were observed in both the U and V band, and they are those used here. Total galaxy magnitudes in the V band, V^T, are also provided by BLE92, who recalibrated the original data from Godwin & Peach (1977).

Effective radius measurements for a subset of these galaxies were presented by Lucey et al. (1991), based in part on independent V-band photometric observations also carried out at the INT and in part on BLE92 V-band data. The effective radius was measured at the "half-light" point of the growth curve of each galaxy. Unfortunately, only 21 galaxies of the 56 with U- and V-band photometry are in the Lucey et al. sample. A much larger fraction of these are in the I-band sample presented by SGH98, based on CCD photometry observations carried out with the 0.9 m telescope at the Kitt Peak National Observatory. These r_e measurements are based on $r^{1/4}$ profile fits (see SGH98 for details) that were extended from an inner radius twice as large as that of the seeing disk to an outer radius chosen to match the radial extent of the galaxy spheroidal component: for E galaxies this radius is the one of the outermost reliable isophotes, while for S0 galaxies, it is the radius at which the disk component begins to dominate the galaxy surface brightness. Independent measurements for a number of these galaxies were also presented by Jørgensen, Franx, & Kjærgaard (1995) and Saglia et al. (1997). The statistical uncertainty in the determination of r_e is approximately 6%, but significantly larger systematic uncertainties could be produced by the particular fitting method used to derive r_e and the galaxy's effective surface brightness, leading to differences that, on a given object, can be as large as 50% (see, e.g., the discussion in SGH98). While a complete discussion on the reliability of effective radius measurements is beyond the scope of the present work, it is interesting to verify the possibility of using the larger set of I-band r_e measurements instead of the smaller set of V-band ones, despite the significant wavelength difference. Since there is considerable overlap between the Lucey et al. and SGH98 samples, it is possible to make a detailed comparison between the two. The two sets of r_e measurements appear to be in rather good agreement, as shown in Figure 1 in which the fractional difference $\Delta r_e/r_e$ is plotted as a function of both r_e and galaxy total magnitude for the 55 galaxies that are common to the Lucey et al. and SGH98 samples (this overlap includes galaxies that are not in the BLE92 sample used here). The average fractional difference is 0.092, with an rms scatter of 0.183, but a nonzero difference could be expected as a consequence of having used different photometric bands and different methodologies to carry out the measurements. The important finding is that the differences between r_e's measured in different bands do not depend on galaxy luminosity or size, and therefore using r_e as measured in the I-band, as will be done hereafter (unless specifically stated), does not introduce any luminosity- or color-related bias in the following analysis.

For each galaxy, aperture magnitudes at r_e were derived independently in the two bands, interpolating (or using a very small extrapolation where necessary) the relative growth-curve data. Given the good sampling of each

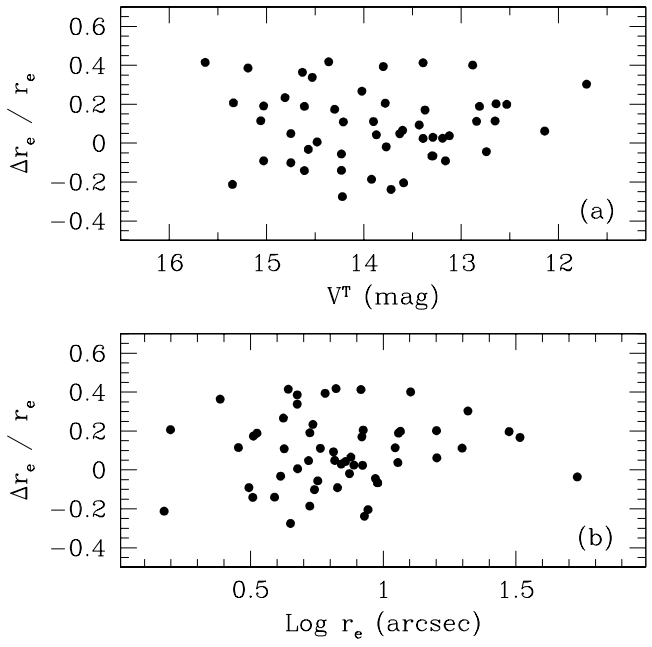


FIG. 1.—Differences in the values of effective radius as measured in the V (Lucey et al. 1991) and I band (Scodeggio et al. 1998). In the two panels, the ratio of the difference between the r_e measurements in the I and V band with respect to their mean is plotted as a function of the (*a*) galaxy total magnitude and (*b*) the logarithm of the I-band measurement.

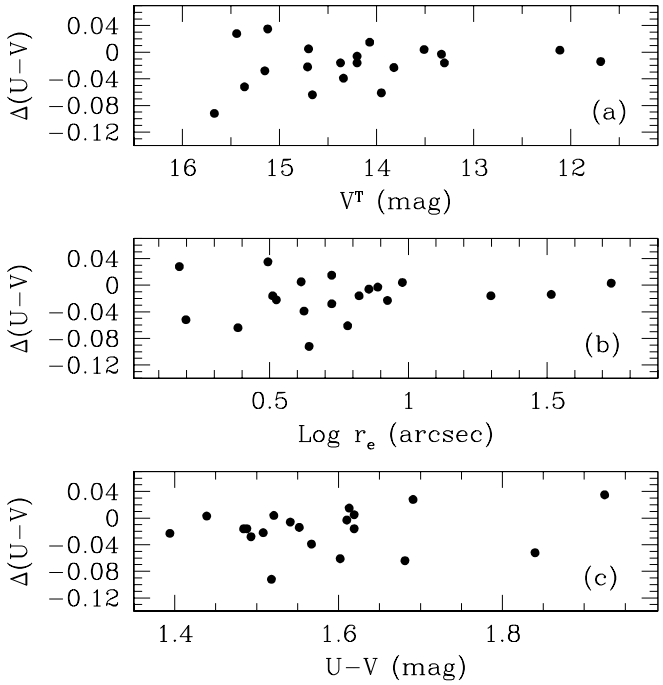


FIG. 2.—Differences in the values of the $U-V$ color, as measured within an aperture of radius the V- and I-band effective radius. In the three panels, the difference between the color measured within the I band and the V-band r_e is plotted as a function of (*a*) the galaxy total magnitude, (*b*) the logarithm of the I-band effective radius, and (*c*) the $U-V$ color measured within that radius.

galaxy's growth curve and the fact that for most galaxies the virtual aperture with radius r_e is tightly bracketed by a pair of aperture measurements, simple linear relations between aperture magnitude and the logarithm of the aperture radius were used for the interpolation and/or extrapolation. Only 8 of the 48 objects in the sample required an extrapolation of the measurements to derive aperture magnitudes at r_e. In all cases, this was an extrapolation to a radius smaller than the smallest aperture radius used for the measurements (4″). This procedure was preferred to the intuitively simpler one of just dividing the total flux measured for a given galaxy [which would be equivalent to defining $m(r_e) = m_T + 0.753$] by 2, because the latter always requires relatively large extrapolations to be carried out to derive total fluxes. This extrapolation process would undoubtedly become the largest source of color measurement uncertainty, while the procedure adopted here only adds the uncertainty on the determination of r_e, which is significantly smaller (see § 3.2), to the original photometric uncertainty. Galaxy colors within r_e were obtained by taking the difference between the relative aperture magnitudes. As a consistency check, colors were also obtained by interpolating and/or extrapolating a linear relation between the color and the logarithm of the aperture radius. Differences between the two techniques show an rms scatter of 0.018 mag, when only interpolation between observations is required to derive the color within r_e. Only colors derived from the difference of aperture magnitudes are used in the following analysis.

Among the 55 objects with r_e measurements in both V and I band, 20 are also in the BLE92 sample, and for them it was possible to obtain a color measurement within apertures of the radius r_e, as determined in the two bands. The differences between these two measurements are shown in Figure 2 as a function of galaxy magnitude, effective radius, and color. As could be expected from the above discussion on the differences between effective radii measured in the two bands, no significant difference is present between the two sets of color measurements, except for a small offset introduced by the somewhat larger values of r_e as determined in the I band. The average difference between the $U-V$ colors is -0.018 mag, with an rms scatter of 0.032 mag. The measured scatter is in good agreement with the expected uncertainty in the color measurements introduced by measurement errors in r_e (see also § 3.2). The fact that the color difference is independent from galaxy luminosity and color means that no bias is introduced in the $(U-V)$–V CM relation by the choice of measuring colors within an aperture having a radius equal to the I-band effective radius.

The sample used in the following analysis is therefore composed of 48 galaxies with magnitude measurements in both U and V band and a measurement of r_e in the I band. Morphological types for all objects are available from Dressler (1980): 23 of them are classified as elliptical galaxies, and 25 as S0. The sample is limited to galaxies brighter than $V \simeq 15.8$ but does not obey any strict completeness criterion. Assuming a distance modulus for Coma of 34.75, the limiting magnitude corresponds to $M_V \simeq -19.0$, or equivalently, $M_B \simeq -18.0$.

3. THE COLOR-MAGNITUDE RELATION

3.1. *Standard Fixed-Aperture Relation*

The standard fixed-aperture CM relation was derived using two slightly different approaches. First, the relation was obtained in the form that is most often used in the analysis of high-redshift clusters, i.e., using both color and magnitude measurements within a given fixed aperture (see, e.g., Bower et al. 1998; Kodama, Bower, & Bell 1999; Gladders et al. 1998). In the second approach, which was introduced to facilitate the comparison with the fixed light fraction relation discussed in § 3.2, colors measured in fixed apertures were correlated with magnitudes measured within the aperture of radius r_e and with total magnitudes. This approach is very similar to that used by BLE92 and Stanford et al. (1998).

The two procedures produce very similar results, except for the fact that using a fixed aperture for both the color and magnitude measurement introduces bias related to sampling different portions of a galaxy depending on its luminosity (and therefore also on its color) in both quantities, and this makes the observed CM relation steeper. This is illustrated in Figure 3, in which the $(U-V)$–V CM relation, obtained when measuring the colors within an aperture of 10″, and the magnitudes within the same 10″ aperture, within r_e, and when using total magnitudes, are compared. The slope obtained when using total magnitudes is -0.074 ± 0.008, which is in good agreement with that previously reported by BLE92 (-0.082 ± 0.008).

One should also note that the slope of the fixed-aperture CM relation is marginally related to the size of the fixed aperture used for the color measurements, becoming slightly flatter for larger aperture radii. This flattening, although not statistically significant in the present sample, is in good agreement with a similar result reported by Okamura et al.

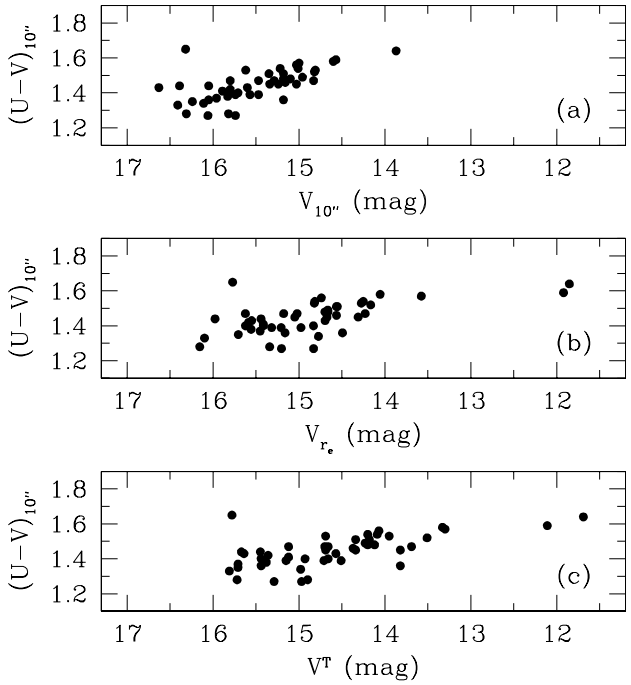


FIG. 3.—Fixed-aperture color-magnitude relations. The $(U-V)$–V relation is plotted in three different formats: (*a*) both color and magnitude are measured within a 10″ aperture; (*b*) and (*c*) the color is the same as in (*a*), but the magnitudes are of those measured within an aperture of radius (*b*) the galaxy effective radius and (*c*) the total magnitude.

(1999), based on $B-R$ color measurements also in the Coma Cluster.

Table 1 presents a summary of the linear least-square fits to the CM relations discussed in this work. All fits are direct fits, in which the fitting procedure minimizes the vertical distances between the data points and the best-fit line, taking into account only error measurements in the independent variable—the color in this case. This fitting procedure was adopted because for the total magnitude measurements individual uncertainty estimates are not available, and because the main goal of this paper is to illustrate the relative changes in the CM relation when different methods are used to derive it more than to derive the ultimate value of the relation parameters. It is certainly possible that such a very simplistic approach to the fitting of the CM relation might bias the result toward flatter slopes, especially when measurements errors are large. This might be happening within the present data set, as shown by the comparison between the correlation involving magnitudes measured within a 10″ aperture (first line in the table; accurate measurements) and the correlation involving total magnitudes or magnitudes within r_e (second and third line in the table; less accurate measurements). Uncertainties in the value of the best-fit slope and zero point were obtained with the statistical jackknife method. With a sample of N data points, the fit is repeated N times using $N-1$ points, each time excluding a different point, to derive an estimate of the parent population from which the parameter under examination is derived. With the present data set, formal uncertainties on the best-fit slopes are approximately 1 order of magnitude smaller than those based on the statistical jackknife. However, one must keep in mind that the two given uncertainties are highly correlated and cannot be used independently to asses the global uncertainty affecting the fit. An approximate estimate of the zero-point uncertainty component that is statistically independent from the slope uncertainty is given by the accuracy with which one can measure the average value of the residuals from the best-fit line, which is typically of 0.02 mag. The scatter in the CM relation reported in the last column of the table is the rms scatter of the differences between the measured color and that predicted by the fit.

TABLE 1

DERIVED $(U-V)$–V COLOR-MAGNITUDE RELATIONS

Apertures[a]	Slope	Zero Point	Scatter (mag)
10″, 10″	-0.119 ± 0.026	3.28 ± 0.40	0.080
10″, r_e	-0.072 ± 0.012	2.50 ± 0.21	0.086
10″, total	-0.074 ± 0.008	2.52 ± 0.11	0.059
r_e, total	-0.016 ± 0.018	1.73 ± 0.28	0.136

[a] The format for this column is the aperture used for the color measurement and the aperture used for the magnitude measurement separated by a comma.

3.2. *Relation at a Fixed Galaxy Light Fraction*

As discussed in § 1, if there are radial color gradients within galaxies, the use of fixed apertures for color measurements introduces a bias in the CM relation, since more luminous galaxies have larger r_e (see, e.g., Fish 1964; Guzmán, Lucey, & Bower 1993; Pahre, Djorgovski, & de Carvalho 1998) and therefore larger overall extent. Since radial color and line-strength gradients are commonly present within giant early-type galaxies (see, e.g., de Vaucouleurs 1961, Sandage & Visvanathan 1978, Frogel et al. 1978, Franx et al. 1989, and Peletier et al. 1990a, 1990b about the color gradients; and Couture & Hardy 1988, Gorgas, Efstathiou, & Aragón-Salamanca 1990, Davies, Sadler, & Peletier 1993, and Carollo & Danziger 1994 about the line-strength gradients), one can expect the fixed-aperture CM relation discussed in the previous section to provide a biased view of the color properties of early-type galaxies.

To quantify the relevance of this effect, a fixed light fraction CM relation was derived, using the colors measured within each galaxy's effective radius. With this procedure, it is always a fixed fraction of the galaxy light that contributes to the color measurements, allowing a more meaningful comparison between galaxies of different luminosities. Contrary to what appeared to be the implicit assumption in most previous works on the CM relation, the bias introduced by the use of fixed apertures appears to be significant. Figure 4 shows a comparison of the CM relations obtained when using color measurements within a fixed aperture of 10″ and within r_e. It is clear that any correlation between galaxy color and luminosity largely disappears when colors are measured within each galaxy's effective radius. The slope of the best-fitting linear relation between color and magnitude goes from -0.074 ± 0.008 (as measured for the fixed-aperture relation) to -0.016 ± 0.018, which is statistically compatible with a completely flat relation. A similarly shallow slope for the CM relation, derived measuring galaxy colors homogeneously at the effective radius, was previously reported by Prugniel & Simien (1996) and van Dokkum et al. (1998), although these authors do not

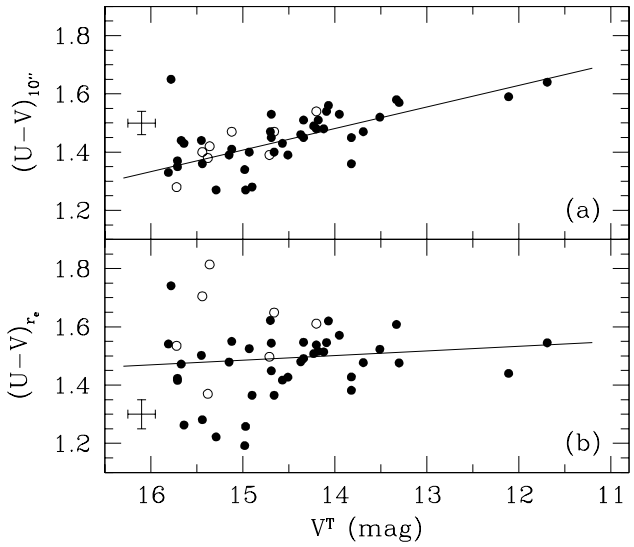


FIG. 4.—Comparison between fixed-aperture and fixed light fraction color-magnitude relations. (*a*) Color measured within a fixed 10″ aperture. (*b*) Color measured within the galaxy effective radius. In both cases, the magnitude is the galaxy total magnitude. Open symbols identify those galaxies that required an extrapolation of their growth curve to derive the color measurement at the effective radius. The solid lines represent the best fit to the relation discussed in the text. The plus signs identify typical uncertainties in the plotted colors and magnitudes.

comment specifically on the significance of this point. In addition, Fioc & Rocca-Volmerange (1999), using total galaxy magnitudes and colors, obtained a relation without a significant slope.

Some concern about the reality of this result might be raised by the fact that color measurements within r_e are affected by larger uncertainties than those within a fixed radius aperture because of the uncertainty in the determination of r_e itself. As discussed in § 2, the statistical uncertainty in the determination of r_e for the present sample is approximately 6% (SGH98), but much larger systematic uncertainties could be present, introduced by the specific fitting procedure used to derive the value of r_e from a galaxy's surface brightness profile (see, e.g., Figs. 4–6 in SGH98). Therefore, a total uncertainty of approximately 20%–30% might be a better estimate of the error budget involved in the determination of r_e. However, the impact on the present color measurements of a conservative 20% r_e uncertainty estimate (the scatter between V- and I-band measurements discussed in § 2 would lead to an estimate of approximately 10%–12%) is only ± 0.025 mag, on average. Since this uncertainty is always smaller than, or comparable to the intrinsic uncertainty of the currently available photometric measurements, it does not have a significant impact on the results presented here. The 0.03 mag uncertainty quoted by BLE92 for their magnitude measurements translates into a 0.042 mag uncertainty in the fixed-aperture color determinations, and the addition of the contribution from r_e determination uncertainties brings the total fixed galaxy fraction color uncertainty to approximately 0.05 mag. These uncertainties are reported in Figure 4, together with a somewhat arbitrary estimate of 0.15 mag for the uncertainty in the total magnitude measurements.

4. RADIAL COLOR GRADIENTS

The significant changes in the CM-relation properties described in the previous section point toward the relevance of internal color and stellar population gradients within early-type galaxies for a detailed understanding of their properties and evolutionary histories. The average color gradient, $d(U-V)/d(\log r)$, measured in the sample used here is -0.15 mag dex^{-1} in radius, with an rms scatter around this mean value of 0.15 mag dex^{-1} in radius. This is in very good agreement with the findings of Peletier et al. (1990a), who report an average gradient of -0.16 ± 0.11 mag dex^{-1} in radius. Note that the use, in both cases, of a simple power-law method to measure the color gradients makes the comparison meaningful, although different methods are used to measure the color points.

In agreement with previous studies, no significant correlation is found between the strength of the color gradient and the galaxy luminosity (see Fig. 5). There is, however, a marginal indication that the scatter in gradient strength might be smaller for the brighter objects in our sample. This result is somewhat in contrast with the claim presented by Peletier (1993) that early-type galaxies fainter than $M_B = -19.5$ have significantly smaller color gradients than those observed in more luminous galaxies. Unfortunately, the number of bright galaxies in the present sample is too small to allow a clear determination of this effect.

The rather large scatter observed globally for the values of the color gradient is responsible for the larger scatter measured in the fixed galaxy fraction version of the CM relation with respect to the fixed-aperture version. This fact points toward a very high photometric accuracy requirement for future measurements aimed at measuring with good accuracy the slope of the CM relation. In addition, it becomes quite clear that using an average gradient value to correct color measurements derived from either observations or theoretical models is not appropriate. In fact, the scatter in gradient values observed among real galaxies is comparable in magnitude with the mean value itself, instead of representing a small additional uncertainty superposed to the main effect one is considering. Therefore, when using

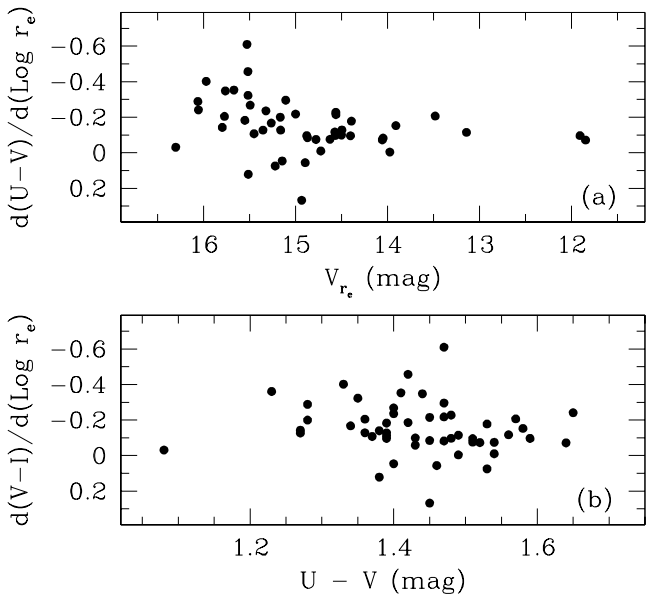


FIG. 5.—Strength of the radial internal color gradient, $d(U-V)/d \log r$, as a function of galaxy luminosity (represented here by the integrated magnitude within the (*a*) galaxy effective radius and (*b*) galaxy color.

a mean gradient value for the color corrections, one would neglect the effects of the relatively strong gradients, which are present in a significant fraction of the galaxy population.

5. DISCUSSION AND CONCLUSIONS

The results presented above show that internal radial color gradients in early-type galaxies cannot be neglected when discussing the colors of these systems. The strength of the gradients measured here is in agreement with other measurements previously reported in the literature, although differences in samples and in the photometric bands used by different authors make a detailed comparison difficult. It is confirmed that for giant early-type galaxies, the strength of the color gradient is not correlated with the galaxy luminosity. In addition, a fairly large scatter in this strength is observed at all luminosities, although there is an indication in the present data set that this scatter might be smaller for the brightest objects.

One point of concern with the present data set is the rather heterogeneous nature of the observations and data reduction procedures adopted to derive magnitudes and effective radii. However, one should note that a substantial flattening of the CM relation, when colors are measured consistently at the galaxies effective radius, is obtained also when considering I- and H-band data, with effective radii measured homogeneously within the same data set (Scodeggio et al. 2001). Very shallow fixed light fraction CM relation slopes have also been published by Prugniel & Simien (1996), van Dokkum et al. (1998), Fioc & Rocca-Volmerange (1999).

While it is found that colors measured within the effective radius depend less strongly on the galaxy luminosity than previously believed, it is not possible to accurately determine whether a small correlation is still present between the two quantities, or whether giant E and S0 galaxies all have the same color, within a small scatter. Because only small differences in color are involved, a larger, more homogeneous data set, composed of data of higher photometric accuracy than those used here, will be required to settle this point. In any case, the present result implies that some modification of the models of galaxy formation currently discussed in the literature is necessary. The shallower slope (if not the complete flatness) of the CM relation and the consequential somewhat larger scatter allowed in the colors of early-type galaxies with respect to that measured in the fixed-aperture relation, should significantly relax some of the tight constraints taken into account so far in discussing the allowed star formation histories of these systems and the processes that led to their formation.

The present results apply only to giant E and S0 galaxies, since with this data set one can sample only the bright end of the early-type galaxies' luminosity functions (spanning an interval of approximately 5 mag). The picture appears to become more complex when one also considers dwarf systems. We are currently extending our analysis to the Virgo Cluster to build a sample that also includes dE and dS0 galaxies (Scodeggio et al. 2001). Our preliminary finding is that a global blueing trend with decreasing luminosity is present among early-type galaxies. The trend is significant for the global sample of Virgo Cluster galaxies, spanning an interval of more than 10 mag in luminosity, but becomes vanishingly small at the bright end of the distribution, in agreement with the results presented here. This would suggest the possibility of a CM relation that is divided into two different regimes, one for the giant galaxies and one for the dwarf galaxies.

It would be quite natural to extend the conclusions reached here to other well-known scaling relations for early-type galaxies, such as the metallicity-luminosity relation, exemplified primarily by the Mg_2-σ relation (see, e.g., Bender, Burstein, & Faber 1993). In this case once again, the measurements are made using a fixed aperture. The typical size of the aperture is comparable with the galaxy r_e for the small, low-luminosity and low-σ galaxies, while it is 1 order of magnitude smaller than r_e in the case of the large, luminous, high-σ galaxies. Since there are radial gradients in the strength of the Mg_2 index, the approach may introduce a significant bias in the inferred mass-metallicity relation. However, a recent analysis of a relatively large set of measurements of such gradients has led Kobayashi & Arimoto (1999) to conclude that a metallicity-mass relation is present among elliptical galaxies even when mean metallicities are considered.

The conclusion is that the interpretation of the CM relation of bright early-type galaxies, as well as that of similar relations with galaxy luminosities that might suffer from the same "fixed-aperture plus internal gradient" bias, may need to be revised. This could lead to a significant change in the overall observational picture of early-type galaxies. In particular, it could no longer be required to have a very strong correlation between galaxy luminosity (which is approximately equivalent to mass) and mean metallicity, allowing for a more significant contribution from random events (such as mergers, or a number of star formation episodes besides the original burst) in the formation and evolutionary processes that shape these objects.

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