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THE INFRARED COLOR-MAGNITUDE RELATION FOR EARLY-TYPE GALAXIES IN VIRGO AND COMA

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ABSTRACT

Recently published infrared photometry of early-type galaxies in Virgo and Coma is used to investigate the IR color-magnitude (C-M) relations in these clusters. The motivation for this study was the hope that, by using $u - K$ colors, the C-M method of obtaining relative cluster distance moduli could be improved, since both $u - V$ and $V - K$ colors correlate with luminosity to a comparable degree. We find that the relative distance moduli between Virgo and Coma derived from the $u - V$, $u - K$, and $V - K$ colors are $\Delta m = 3.5 \pm 0.2$, 3.0 ± 0.2, and 2.6 ± 0.3 mag, respectively. Although based on only two clusters, the differences in these values provide evidence that the C-M effect does not have a universal form. The $u - K$ and $V - K$ moduli yield a Local Group infall toward Virgo whose large size seems out of the question, implying that it is the infrared and not the ultraviolet energy distributions which are different between the clusters. At fixed $u - V$ color, galaxies in Coma (especially the S0s) are bluer in $V - K$ than those in Virgo by ~ 0.1 mag in the mean. The scatter in the $u - K$ and $u - V$ C-M relations is compared, and it is shown that the scatter is dominated by intrinsic variation and not by observational error.

To explain these results, we speculate that many Coma galaxies lost their gas content before the formation of a cool, stellar component found in Virgo (and galaxies not in rich clusters) could occur. This cool component might consist either of very metal-rich stars or very red intermediate-age giants.

Subject headings: galaxies: clusters of — galaxies: photometry — galaxies: stellar content — infrared: general

I. INTRODUCTION

The optical colors of early-type galaxies are well correlated with their luminosities (e.g., Baum 1959; Sandage 1972; Visvanathan and Sandage 1977, hereafter VS), an effect whose primary causal origin is usually attributed to metallicity changes (see Faber 1977). The color-magnitude (C-M) relation thus provides an empirical test for galaxy formation models (cf. Larson 1974) and for galaxy synthesis models calibrated as a function of [M/H] (Tinsley 1978; Aaronson *et al.* 1978). A further use of the C-M relation is the determination of relative distance moduli, a technique whose success depends on whether or not the C-M relation has a universal form. Two applications of the method to the Virgo and Coma clusters have been carried out by Sandage (1972) using *UBV* photometry and VS using *uV* photometry.

Recent observations in the near-infrared show that the $V - K$ colors of E and S0 galaxies also correlate with luminosity to a degree comparable with that seen in $U - V$ (Frogel *et al.* 1978, hereafter FPAM; Persson, Frogel, and Aaronson 1981). A natural question, providing the original motivation for this work, is whether by using $u - K$ or $U - K$ colors the sensitivity of the C-M relative distance method can be improved because of increased leverage on the effect. In the present study, we investigate this issue by using published optical and IR photometry for a sample of galaxies in Virgo and Coma drawn from Sandage (1972) and VS.

The ultimate usefulness of IR colors for measuring distance moduli depends on two considerations. First, do early-type galaxies follow a universal C-M relation in the IR, as they appear to in the optical? Second, is the magnitude scatter less than what is measured using optical data alone? After presenting the data in § II, we address these questions in § III and find evidence for significant differences in the color distributions of Virgo and Coma galaxies. Possible explanations of this result are discussed in § IV.

II. THE DATA

In this analysis we restrict the galaxy sample as much as possible to the very homogeneous *uV* data set of Sandage and Visvanathan (1978*b*, hereafter SV2) and the infrared

TABLE 1

VIRGO CLUSTER DATA

(1) NGC	(2) Type	(3) V_{26}^{KE} (mag)	(4) $K_{-0.3}^{KE}$ (mag)	(5) $(u - K)_{-0.6}^{KE}$ (mag)	(6) Notes
4124	S0	11.48	8.82	5.01	
4179	S0	10.87	7.90	5.63	
4261	E3	10.53	7.46	5.71	1
4264	S0	12.71	10.39	5.17	
4270	S0	12.24	9.48	5.18	
4365	E3	9.98	6.85	5.74:	
4371	S0	10.73	7.97	5.61	
4374	E1	9.37	6.50	5.73	
4377	S0	11.73	8.99	5.19	
4382	S0	9.28	6.59	5.18	2
4387	E5	12.24	9.42	5.32	
4406	E2	9.20	6.51	5.65	
4435	S0	10.67	7.56	5.94	
4442	S0	10.32	7.26	5.48	
4458	E1	12.01	9.62	5.18	
4459	S0	10.54	7.43	5.65	
4464	E3	12.50	9.49	5.32	
4468	E4	12.99	10.58	4.95	
4472	E2	8.56	5.70	5.77	
4473	E5	10.28	7.14	5.58	
4476	E5	12.28	9.67	5.13	
4478	E2	11.28	8.43	5.46	
4479	S0	12.57	10.18	5.26	
4486	E0	8.79	6.08	5.85:	
4486B	dE	-----	10.07	6.04:	1,2
4550	E7/S0	11.31	8.66	5.20:	
4552	E0	9.95	6.90	5.80	
4578	E3	11.15	8.58	5.32	
4621	E5	9.88	6.86	5.64	
4636	E0	9.82	6.99	5.83:	
4649	E2/S0	8.90	6.03	5.84:	
4660	E6	10.97	7.97	5.41	
4754	S0	10.40	7.45	5.58	
M100 - Chart 1	dE	14.5	11.8	4.59	2,3
M100 - Chart 2	dE	16.5	12.2	4.42	2,3
M100 - Chart 4	dE	15.0	12.8	4.25	2,3

NOTES

1) u - V transformed from U - V in Table 4 of Frogel et al. (1978).

2) Galaxy given 0 weight in regressions.

3) u - V transformed from U - V given in Sandage (1972).

photometry of FPAM and Persson, Frogel, and Aaronson (1979, hereafter PFA). The infrared and optical data are corrected for reddening and redshift, as indicated by the superscript *KE* for all colors and magnitudes. These corrections are discussed fully in the above references. Thirty-six Virgo galaxies are then available for establishing the $u - K$ C-M relation; the data are summarized in Table 1. The V_{-26}^{KE} galaxy magnitudes were taken directly from column (4) of Table 1 of SV2. In order to look at possible differences in the C-M relations arising from different galaxy magnitude scales, we have included $K_{-0.3}^{KE}$ magnitudes determined from infrared photometry and a standard galaxy growth curve as discussed in PFA.[1] For 32 galaxies $K_{-0.3}^{KE}$ was taken directly from column (6) in Table 8 of PFA. The $(u - K_{-0.6}^{KE}$ colors were formed by simply adding column (2) of Table 8 in PFA to column (6) in Table 1 of SV2. Four additional Virgo galaxies (NGC 4261, 4464, 4486B, and 4649) were added to the sample using data in Table 4 of FPAM, after first converting these data to the diameter system of de Vaucouleurs, de

[1] We follow here the notation of SV2, except our subscript refers to the log of the isophotal aperture size in the system of de Vaucouleurs, de Vaucouleurs, and Corwin (1976), e.g., $(u - K_{-0.6}^{KE}) = (u - K)^{KE}$ at $\log A/D(0) = -0.6$.

Vaucouleurs, and Corwin (1976, hereafter RC2) adopted here. Finally, several $u - V$ colors were obtained from $U - V$ colors given in Sandage (1972) using the transformation equations in Sandage and Visvanathan (1978*a*, hereafter SV1). We note that the reference isophote of our colors samples roughly one-third of the galaxy light. For a typical Virgo galaxy (e.g., NGC 4473), the corresponding projected aperture is $\sim$ 5 kpc in diameter.

In the analysis that follows, five Virgo galaxies have been excluded—the tidally stripped dwarf elliptical NGC 4486B, the peculiarly blue S0 NGC 4382, and the three M100 dwarfs. Unlike VS, we eliminate the M100 dwarfs because (a) their (UBV) colors and magnitudes have large observational errors; and (b) they are bluer than any other galaxies in the Coma or Virgo samples. Inclusion of the M100 dwarfs does not significantly change the results, as shown below.

For the Coma cluster, there are 13 galaxies in SV2 with measured infrared magnitudes. To increase the Coma sample further, we have added nine more galaxies having infrared photometry. The $u - V$ colors for these nine were obtained from the SV1 transformation equations and the UBV photometry of Sandage (1972). The $V - K$ colors were taken from Table 9 of PFA, and the resulting $(u - K)^{KE}_{-0.6}$ colors are summarized in Table 2. Note that $K^{KE}_{-0.3}$ magnitudes in Table 2 are not given in PFA, but were obtained from the observed K magnitudes in Table 4 of PFA using the K magnitude growth curve of FPAM, after adjusting this curve to the RC2 diameter system.

The morphological types in Tables 1 and 2 are adopted from SV1 and Sandage (1972). Uncertainties in these types, which in most cases are based on newer plate material (see SV1), are small and should not affect the conclusions of this work.

TABLE 2

COMA CLUSTER DATA

(1) Name	(2) Type	(3) V^{KE}_{26} (mag)	(4) $K^{KE}_{-0.3}$ (mag)	(5) $(u - K^{KE}_{-0.6}$ (mag)
N 4874	S0	12.63	9.62	5.61
N 4881	E0	13.62	10.79	5.55
N 4883	SB0	14.25	11.13	5.53
N 4886	E0	14.00	11.45	5.28
N 4889	E4	11.75	8.84	5.77
N 4906	E3	...	11.34	5.41
N 4921	SBb	...	10.04	5.57
N 4923	E0	13.84	10.70	5.51
I 3998	SB0	14.63	11.55	5.50
I 4011	E0	15.09	12.52	5.15
I 4012	E3	14.98	11.94	5.49
I 4021	E0	...	12.26	5.44
I 4026	SB	14.80	11.76	5.40
I 4042	SB0	14.29	10.87	5.49
RB 37	SB0	16.83	14.51	4.74
RB 38	S0	...	13.18	4.98
RB 40	S0	...	12.84	4.92
RB 42	S0	15.80	13.19	5.05
RB 45	E0	...	12.66	5.39
RB 46	S0	...	12.92	4.96
RB 74	S0	...	13.17	4.75
RB 85	S0	...	15.06	4.93

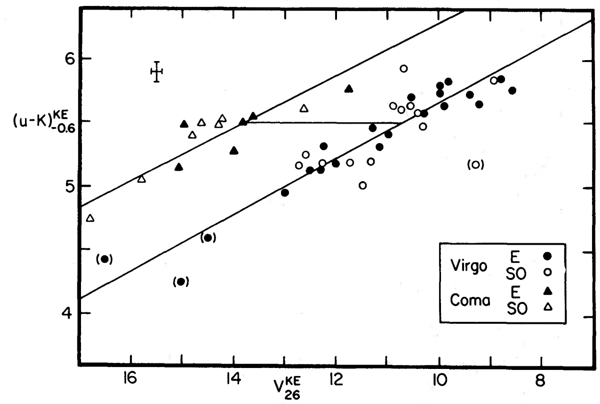

FIG. 1.—The ($u - K$, V) color-magnitude relation for galaxies in Virgo and Coma. Parameters of the least-squares lines shown are given in Table 3. The horizontal line is 3.05 mag in length. Points in parentheses were assigned zero-weight in the regressions.

III. ANALYSIS

Figure 1 plots the ($u - K$, V) C-M diagram for the Virgo and Coma clusters, and lines (1) and (2) of Table 3 summarize the least-squares fits corresponding to the straight lines drawn in on the figure. In these regressions, the coefficients a and b were obtained by first treating the magnitude and then the color as the independent variable and averaging the results. This is a reasonable procedure because the errors in the plotted quantities are comparable. It is important to note that the C-M relation is probably curved (Sandage 1972) and that our adoption of a linear fit to the distribution may therefore not be the best representation of the effect. However, we are not attempting here to ascertain the *form* of the C-M relation, but only to look at the relative distance moduli from the $u - K$ colors in a manner identical to that for the optical colors (SV2). Linear fits should suffice for this purpose.

Figure 2 displays the ($u - K$, K) C-M relations for Virgo and Coma, where now the full Coma sample of 22 galaxies can be used. Lines (3) and (4) in Table 3 give the corresponding least-squares solutions.

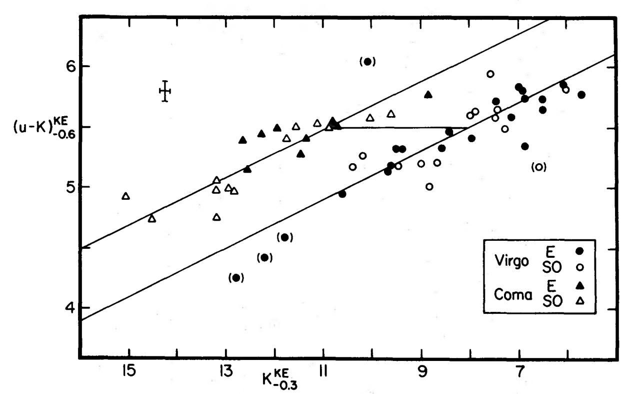

FIG. 2.—The ($u - K$, K) color-magnitude relation for galaxies in Virgo and Coma. Parameters of the least-squares lines shown are given in Table 3. The horizontal line is 2.91 mag in length. Points in parentheses were assigned zero-weight in the regressions.

TABLE 3

LEAST-SQUARES SOLUTIONS TO $y = a + b(x - c)$

Sample	N	x	y	a	b	c	r	$s_{y/x}$	$s_{x/y}$
(1) Virgo	31	$u - K$	V	10.76	−4.50	5.5	−0.85	0.69	0.153
(2) Coma	13	$u - K$	V	13.81	−4.80	5.5	−0.87	0.68	0.141
(3) Virgo	31	$u - K$	K	7.99	−4.98	5.5	−0.88	0.68	0.137
(4) Coma	22	$u - K$	K	10.90	−5.04	5.5	−0.88	0.76	0.150
(5) Virgo	31	$u - V$	V	10.50	−8.81	2.3	−0.86	0.66	0.075
(6) Virgo	31	$V - K$	V	11.08	−8.57	3.2	−0.77	0.87	0.102

a) *Estimates of the Relative Cluster Distance Modulus*

To obtain an estimate of the relative Virgo-Coma distance modulus Δm, we can simply difference the intercepts a in Table 3. We note that the magnitude intercept is defined at a $u - K$ color of 5.5, which is close to the median color of the galaxy sample. The result is $\Delta m = 3.05$ mag from the ($u - K$, V) relations, and $\Delta m = 2.91$ mag from the ($u - K$, K) relations. Inclusion of the three M100 dwarfs in the regressions changes these results insignificantly; the values become 3.04 and 2.98 mag, respectively.

Another method of determining Δm, which does not depend on exact knowledge of the intercept at a single color, is to calculate a relative Virgo distance modulus for each individual Coma galaxy by comparing the observed Coma galaxy magnitude with that predicted by entering the Coma galaxy color into the Virgo least-squares solution. The results of this test are given in column 2 of Table 4, which shows that the two methods of finding the relative distance modulus are in good agreement, and we adopt $\Delta m(u - K) \approx 3.0 \pm 0.2$ mag[2].

We turn now to a comparison of the distance moduli obtained from the $u - V$ and $V - K$ colors separately. The $u - V$ and $V - K$ moduli were found by entering the Coma galaxy colors into the Virgo solution, as was done for $u - K$. Columns 3 and 4 of Table 4 show the surprising result that the quantity Δm is a strong function of color. The $u - V$ and $V - K$ regressions give moduli that are discrepant by ~ 0.9 mag, corresponding to a 3σ effect. The $u - K$ moduli lie roughly half-way between the modulus of ~ 3.5 mag from $u - V$ and the modulus of ~ 2.6 mag from $V - K$. This must mean that the uVK colors of the Virgo and Coma galaxies are systematically different, and indeed this can be seen in Figure 3, which shows a direct plot of the $V - K$ and $u - V$ colors. Most of the Coma galaxies are seen to lie to the right of the least-squares line, which has been fit to the Virgo data only, the effect being especially pronounced for the Coma S0 galaxies.

Before going on to a discussion of these results, let us consider the various possible sources of systematic error:

Instrumental effects in the infrared photometry have been discussed extensively by FPAM and PFA. The most

TABLE 4

MAGNITUDE DIFFERENCE BINNED BY COLOR

Magnitude	Δm from ($u - K$) (mag)	Δm from ($u - V$) (mag)	Δm from ($V - K$) (mag)
V	3.10 ± 0.18	3.56 ± 0.17	2.61 ± 0.31
K	2.90 ± 0.16	3.41 ± 0.17	2.51 ± 0.25

serious worry for the present purpose is related to the fact that the V and K magnitudes are measured through physically distinct apertures. For instance, a 10% mismatch in aperture size would lead to an error of ~ 0.25 mag in relative distance modulus determined from $u - K$ colors. There is, however, simply no evidence for any such mismatch.

The redshift correction is only $0.4z$ for $u - V$ (SV1), while it is $5.3z$ for $u - K$ (FPAM). A conservative estimate of the error in the latter correction is 20%, which

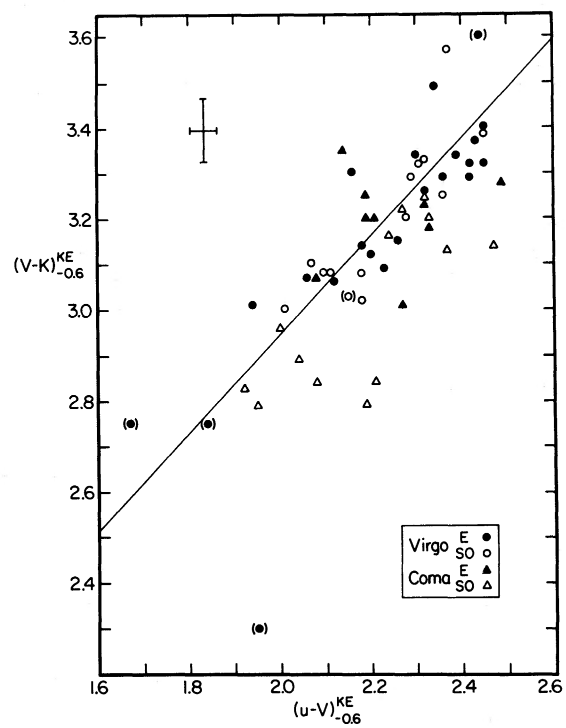

FIG. 3.—The ($V - K$, $u - V$) color-color relation for galaxies in Virgo and Coma. Points assigned zero-weight are in parentheses.

[2] We do not understand the value of 3.66 ± 0.35 mag quoted by Tammann, Sandage, and Yahil (1980), which these authors say is based on the same $u - K$ C-M data discussed here.

would translate here into an uncertainty of only 0.10 mag in relative distance modulus.

Reddening presents the most serious source of systematic error. A difference of only 0.01 mag in $E(B - V)$ results in a change of ~ 0.18 mag in distance modulus with $u - V$ colors and a change of ~ 0.22 mag with $u - K$ colors. The reddening model of SV1 has been adopted here, for which $E(B - V) = 0$ for both Virgo and Coma, but this may not be the case. On the other hand, a reddening differential of $\Delta E(B - V) > 0.1$ mag between Virgo and Coma would be required to explain the color difference discussed above. By demanding that the mean nuclear $B - V$ colors of the 10 brightest galaxies in Virgo and Coma be the same, Weedman (1976) suggested that Coma has an $E(B - V)$ color excess 0.01 mag greater than Virgo, which would *decrease* the relative distance modulus measured here. This finding is surprising in view of Coma's higher galactic latitude. A different result is obtained by Burstein and Heiles (1981) using galactic H I column densities. They find variations in A_B from 0.0 to 0.12 mag for the Virgo galaxies studied here. Their mean extinction to our Virgo sample is $A_B = 0.05$ mag, though, an amount very close to their Coma value of $A_B = 0.04$ mag.

As a further check on our results, we replotted the C-M relations after applying the individual galaxy reddening corrections of Burstein and Heiles (1981). No decrease in scatter was found, and the relative Virgo-Coma modulus remained unchanged. We conclude that reddening uncertainties in the present sample do not pose a serious problem.

Bias of an unknown amount may be present due to the unequal distribution of points sampled in Virgo as compared with Coma in the C-M plane. One obvious difference between our Virgo and Coma samples is the distribution and ratio of E and S0 galaxies: the Coma sample contains a larger fraction of S0s. We have tested for possible bias from this effect by computing the relative distance modulus for the E and S0 galaxies separately. Table 5 shows that, to within the uncertainties, the E and S0 galaxies give values of Δm that are the same. The 0.37 mag difference found from the $(u - K, K)$ relation is due to the larger shift for S0s visible in Figure 3.

b) Scatter in the IR C-M Relation

The data set for Virgo is sufficiently large, homogeneous, and accurate to permit a detailed and worthwhile comparison of the scatter in the optical and IR. To facilitate the discussion, we list in the final two lines of Table 3 regressions calculated from Virgo $u - V$ and $V - K$ colors separately. As expected, the size of the C-M effect, as measured by the slope b, is nearly halved in these solutions as compared with $u - K$. However, the magnitude variance $s_{V/u-K}$ is about equal to $s_{V/u-V}$, indicating that with the present $u - K$ colors no advantage in deriving distances can be gained by extending the wavelength baseline into the near-infrared. Let us consider the reasons for this. VS discuss possible sources of color scatter in the Virgo C-M relation and conclude that the only significant sources are observational errors in the colors and magnitudes themselves and the depth effect of the cluster. After accounting for these, VS find substantial residual scatter which they interpret as real intrinsic scatter in the C-M effect. From Table 3, the total color scatter is seen to be 0.153, 0.075, and 0.102 mag in $u - K$, $u - V$, and $V - K$, respectively. Adopting errors of 0.03 mag and 0.1 mag in $(u - V)^{KE}_{-0.6}$ and V^{KE}_{-26} (VS), 0.07 mag in $(V - K)^{KE}_{-0.6}$ (PFA), and a 0.23 mag depth for Virgo (see VS), the resulting residual scatter is 0.121, 0.063, and 0.068 mag, in $u - K$, $u - V$, and $V - K$.

Now, if there were no correlation between *individual* galaxy $u - V$ and $V - K$ color residuals, as might be expected if the residual $u - V$ and $V - K$ scatter were completely dominated by observational errors, we should find the residual color scatter in $u - K$ to be ~ 0.065 mag. On the other hand, if there were complete correlation in the individual color residuals, which might be expected if the residual scatter were controlled entirely by intrinsic variation, with galaxies redder in $u - V$ also being redder in $V - K$, we should find the residual color scatter in $u - K$ to be ~ 0.13 mag, in good agreement with the residual scatter actually seen. In fact, the individual galaxy color residuals about the mean $u - V$ and $V - K$ C-M relations do weakly correlate ($r = 0.54$). We conclude that the residual scatter does indeed reflect true cosmic variation, in agreement with VS. This conclusion of course rests on the assumption that the observational errors have been accurately estimated. That this is so is suggested by the similar residual scatter seen in both $u - V$ and $V - K$. To summarize, it appears that because scatter in the C-M effect is dominated by real intrinsic variation and not by observational error, no gain is made in going from $u - V$ to $u - K$ colors. Even if the observational errors in $V - K$ could be reduced to the level seen in $u - V$ (0.03 mag), it follows from the above discussion that the magnitude scatter would decrease only by $\sim 20\%$. The origin of the intrinsic scatter would appear to be only indirectly related to the cause of the systematic differences found in § III*a*, because with the former the optical and IR are both changed in step, while with the latter only the IR seems affected, as we show below.

TABLE 5

MAGNITUDE DIFFERENCE BINNED BY TYPE

X (mag)	Y (mag)	Δm Total Sample (mag)	Δm E Galaxies (mag)	Δm S0 Galaxies (mag)
$u - K$	V	3.10 ± 0.18	2.94 ± 0.30	3.23 ± 0.21
$u - K$	K	2.90 ± 0.16	3.12 ± 0.24	2.75 ± 0.20

IV. DISCUSSION

The striking result of the analysis so far is that the Virgo/Coma magnitude difference Δm at fixed color strongly depends on the choice of color. Clearly, interpretation of the quantity Δm as a distance modulus cannot be made until this effect is understood. Either the $u - V$ or $V - K$ colors, on average, are systematically different in the two clusters. Which color is the "correct" one? To help answer this question, we appeal to the difference in relative modulus predicted from the ratio of cluster redshifts. Adopting a redshift of 1019 ± 51 km s^{-1} for Virgo (Mould, Aaronson, and Huchra 1980), and a redshift of 6952 ± 61 km s^{-1} for Coma (Tifft and Gregory 1976), the modulus predicted by the ratio of redshifts is 4.17 ± 0.08 mag. We actually want to compare the C-M modulus with the redshift modulus *corrected* for the infall velocity of the Local Group toward Virgo, currently a somewhat controversial subject. Recent analyses of the velocity field in the Local supercluster by Tammann, Sandage, and Yahil (1980) and by Schechter (1980) yield an infall velocity $\lesssim 200$ km s^{-1}. A larger value, 400–500 km s^{-1}, is indicated by the microwave background anisotropy experiments (Smoot and Lubin 1979) and by the IR/H I distance method (Aaronson *et al.* 1980). In any event, the true infall velocity probably lies somewhere between 200 and 500 km s^{-1}. If the infall is only 200 km s^{-1}, then the corrected redshift modulus is ~ 3.75 mag, and if it is as large as 500 km s^{-1}, then the modulus is ~ 3.50 mag.

Now the relative modulus suggested by the $u - K$ colors, $\Delta m = 3.0$ mag, would imply an infall velocity of ~ 950 km s^{-1}, which seems unquestionably too large; an even greater infall is implied by the $V - K$ colors alone. The best agreement is found from the $u - V$ modulus, which, at 3.5 ± 0.2 mag, is consistent to within the uncertainties with the entire range of corrected redshift modulus. This agreement supports the idea of a universal optical C-M relation, as argued by VS, although some authors (e.g., Burstein 1977) have challenged even this latter claim. With regard to the IR colors, the simplest conclusion we can draw is that the $V - K$ colors of Coma galaxies are systematically different from those in Virgo, i.e., *the infrared C-M effect does not have a universal form.* It should be stressed that this result is not an artifact of the slope in the IR C-M relation being different between the two clusters. As seen in Table 3, the slope b for Coma agrees well with the slope found for Virgo, whether V or K magnitudes are used. Rather, the problem seems to rest with the zero-point. In particular, at fixed $u - V$ color (and absolute magnitude), Coma galaxies are bluer in $V - K$ than Virgo galaxies by ~ 0.10 mag in the mean.

We are led to the view that the stellar populations in the two samples of galaxies are not identical, but that the difference is showing up mostly in the infrared and cannot easily be seen in the visible part of the spectrum (at least from the broad-band colors). It would seem that a second parameter is required to fully describe the C-M effect. What might this second parameter be?[3] A clue is provided by remembering that the color shift in Figure 3 is greatest for Coma S0 galaxies. A further point is illustrated in Figure 4, which compares the $(V - K, U - V)$ two-color distributions for Virgo, Coma, and a large sample of field galaxies, the last being taken from PFA. (The term "field" is used loosely here, referring to all galaxies not located in rich clusters.) The field galaxies fall along a relation similar to that for the Virgo galaxies; if anything, the brighter field S0s have somewhat *redder* $V - K$ colors than those in Virgo. This latter effect does

[3] Terlevich *et al.* (1980) have also suggested that a second parameter, related to axial ratio, is needed to fully describe the optical C-M effect for ellipticals. How their result is related to the discussion here is presently unclear.

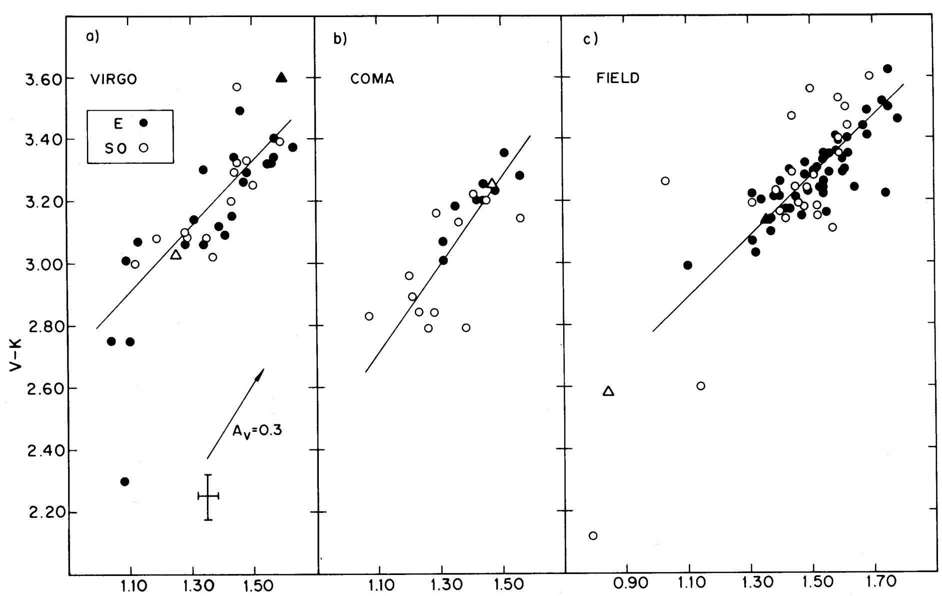

FIG. 4.—The $(V - K, U - V)$ color-color relation for three samples of galaxies. Objects marked with special symbols include the tidally stripped dwarf ellipticals NGC 4486B (Virgo panel) and M32 (field panel), the peculiarly blue S0s NGC 4382 (Virgo panel) and NGC 5102 (field panel), and the Sb galaxy NGC 4921 (Coma panel).

not appear to be due simply to dust, as the reddening line virtually parallels the two-color relation in Figure 4. To summarize, Coma galaxies (especially S0s) tend to be missing a cool stellar component found in Virgo and field galaxies and perhaps enhanced in field S0s.

That the color changes seen here are greatest for S0 galaxies is especially interesting in view of the current debate related to the evolutionary status of these objects. One point of view (e.g., SV2) holds that environmental effects do not play a significant role in determining the formation and evolution of S0s. The opposite viewpoint is that some (if not most) S0s are, in effect, stripped spirals. Serious objections to the stripping hypothesis have recently been raised by Dressler (1980), among others. However, Larson, Tinsley, and Caldwell (1980) have proposed a less extreme form of the stripping mechanism which appears to overcome these objections; in their model, an outer gas envelope rather than collapsed disk gas is stripped. Thus, the absence of a cool red component in Coma galaxies could be explained if they were stripped of gas (via the Larson *et al.* model) before the formation of such a component could occur.

The identification of this cool red component remains. One possibility is that a minority population of very metal-rich stars present in the bright Virgo galaxies is missing in Coma. A more intriguing possibility is that Virgo and field galaxies have a contribution from an intermediate-age population containing very red upper asymptotic giant branch stars, which have long since evolved away in Coma. It is interesting in this regard that evidence for an intermediate age population has been presented for M32 by O'Connell (1980) and for the Fornax dwarf spheroidal by Aaronson and Mould (1980). Also, in an H I study of six clusters, Sullivan *et al.* (1980) find evidence for significant gas deficiency only in Coma spirals. Quantitative estimates of the effects of small numbers of asymptotic giant branch stars upon the infrared colors of composite systems should be obtainable in the near future from observations of intermediate age clusters in the Magellanic Clouds (Persson *et al.* 1981).[4]

Aaronson *et al.* (1978) and Frogel, Persson, and Cohen (1980) have intercompared the infrared colors of globular clusters, early-type galaxies, and theoretical isochrone models. Their studies show that very red stars, not seen in galactic globular clusters, must be present in the galaxies. At a given $U - V$ color, the shift in $V - K$ color of the galaxies compared to the globulars (and the best fitting models) is ~ 0.3 mag on average. It thus seems plausible that galaxy-to-galaxy variation of this same red component, whatever its precise nature, accounts for the systematic color shift between Virgo and Coma.

It is clear that discovery of a second parameter in the C-M relation has substantial bearing on our understanding of the processes governing the star formation history and chemical evolution in early-type galaxies. Additional optical and infrared photometry in Coma and other rich clusters is crucially needed to confirm the existence of such a parameter.

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[4] We note that while changes in the numbers of cool stars grossly affects distances estimated from the C-M technique using IR colors of early-type galaxies, it has little bearing on the IR/H I distance method used by Aaronson *et al.* (1980) for spirals. This is because in the latter method only a magnitude term with slope unity enters, whereas with the former method a color term with large slope ($\sim$ 5–9) is involved.

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