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THE INFRARED COLOR-MAGNITUDE AND COLOR–GAS CONTENT RELATIONS FOR CLUSTER SPIRALS

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ABSTRACT

Using multiaperture optical and infrared magnitudes of 164 spirals in nearby galaxy clusters, we explore the utility of the spiral color-magnitude relation as an accurate distance indicator. In combination with H I line widths, we find there to be a well-defined relationship between the observed $(B-H)_{-0.5}$ color of spirals and their observed 20% line width. This relation demands there to be a wavelength-dependent slope in the Tully-Fisher relation. However, there are important variations in the zero point of the color–line width relation for individual clusters which lead directly to zero-point differences in their corresponding color-magnitude relation. Thus, while individual clusters are shown to yield color-magnitude relations which have a scatter of 0.4–0.5 mag, we show that the spiral color-magnitude relation may be impossible to calibrate due to the lack of a well-defined zero point. In particular, although various clusters can be constrained to fit the same slope in the $B-H$ versus H plane, there appears to be no universal zero point for that given slope. On this basis, we cannot advocate the use of the $B-H$, H relation as an accurate distance indicator. Finally, we compare the H I content of these cluster spirals to the Local Supercluster sample. The locus of points in the infrared color–gas content relation defined by the field sample is virtually identical to that of the cluster sample. Once again, we can find no evidence that any of the cluster spirals that have been used in establishing the IR Tully-Fisher distance scale are H I deficient with respect to field spirals.

Subject headings: galaxies: clustering — galaxies: photometry — radio sources: 21 cm radiation

I. INTRODUCTION

The color-magnitude (*C-M*) relationship for elliptical galaxies has become well established (Visvinathan and Sandage 1977; Griersmith 1980; Caldwell 1983). Its underlying cause is often explained by appealing to a systematic decrease in mean metal abundance with decreasing galaxy luminosity (Faber 1973). Decreasing metal abundance can affect the broad-band colors due to (1) a shift in the mean effective temperature of the giant branch, (2) a decrease in the amount of line blanketing in the atmospheres of red giants, and (3) a possible shift of the horizontal-branch population toward hotter temperatures. Recent work by Mould, Kristian, and Da Costa (1983), Bothun and Caldwell (1984), and Aaronson and Mould (1985) have now extended the mass-metallicity relationship for early-type stellar systems down to an absolute magnitude of $M_B = -8$.

Use of this relation as a distance indicator, however, is rendered difficult due to the steepness of its slope. Small errors in color can translate into significant errors in absolute magnitude. Moreover, the universality of this relation has been called into question. Aaronson, Persson, and Frogel (1981) have presented evidence that the *C-M* relation for early-type galaxies is environment dependent. Such a situation is indeed probable as the eventual mean giant metallicity should depend upon the amount of internal processing that has occurred in the subsequent stages of galaxy evolution. Metallicities could either be diluted due to delayed infall of primordial intracluster gas or through the removal of interstellar gas prior to the time of nearly complete processing. An environmentally dependent *C-M* relation would further negate its usefulness as a distance indicator.

For the case of spirals, if the star formation rate (SFR) varies smoothly with time, then such galaxies can be well represented by some linear combination of stellar populations of differing ages (see Boroson 1980). Since a well-defined *C-M* relation does exist for galaxies that are dominated by an old population, then it would be reasonable to expect that a *C-M* relation should also exist for spirals. However, the corresponding optical *C-M* relation (e.g., $U-V$ vs. V) for spirals is washed out due to active star formation that causes a stochastic variation in the U magnitude. Hence, for spirals one should concentrate on efforts to find *C-M* relations utilizing magnitudes that are sensitive to the amount of old population.

For instance, if the slope of the spiral IR Tully-Fisher relation is wavelength dependent, then it necessarily follows that there must exist a relation between (blue − infrared) color and infrared luminosity. Wyse (1982) has investigated this simple consequence in some detail, and Tully, Mould, and Aaronson (1982) (hereafter TMA) have presented a preliminary, empirical relationship between the $B-H$ color of spirals and their absolute IR luminosity. Similarly, Whitmore (1984) has found that $B-H$ color is highly correlated with luminosity and suggests that this index is one of the more fundamental parameters of

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spiral galaxies. Consistent, though less optimistic, conclusions have also been reached by Bothun (1984).

In this paper we test the applicability of the spiral *C-M* relation as a distance indicator by presenting *C-M* diagrams of spirals in various clusters. These clusters are the same ones used in extending the IR Tully-Fisher relation (Aaronson *et al.* 1984) so consistency checks on relative cluster distances are possible. Section II describes the observations, choice of sample, and possible selection effects which may differentiate this sample from various field samples (e.g., that of Rubin *et al.* 1982). Section III discusses some of the parameters that can influence and alter the $B-H$ color of spirals. Here we present *C-M* diagrams of individual clusters and derive relative distances between clusters. In § IV we compare the IR color–gas content relation for this cluster sample with that of the field sample of Bothun (1984), in order to search for alleged H I deficiencies that plague cluster spirals.

II. OBSERVATIONS AND CHOICE OF SAMPLE

a) *Choice of Sample*

Following the initial work of Sullivan *et al.* (1981) and Schommer, Sullivan, and Bothun (1981) on the H I properties of cluster spirals, and that of Aaronson *et al.* (1980) on the infrared Tully-Fisher relation, our studies of clusters of galaxies continued with particular (though not complete) emphasis on selecting edge-on spirals. In order to be efficient at the telescope, H magnitudes were only measured for edge-on spirals that were previously detected in H I. This is an important selection effect. The sample that is used in the IR Tully-Fisher relation does not contain H I–poor galaxies. Since H I content and bulge-to-disk ratio (B/D) are correlated (see Bothun 1982), this sample is practically devoid of large B/D spirals. In fact, if B/D ratio is an important second parameter in the Tully-Fisher relation (as has been indirectly claimed by Rubin *et al.* 1982), neither this sample nor the Local Supercluster sample of Aaronson and Mould (1983) would readily reveal that secondary dependence.

Our much larger sample differs primarily from the sample of Rubin *et al.* (1982) in that it has a paucity of large B/D galaxies and has a wide range of star formation rates (i.e., $B-V$ and $U-B$ colors) at a given H I content. The main differences in these two samples arise from the simple fact that one sample is H I selected (and therefore blind to the aesthetic qualities of the particular spiral) while the other is optically selected. Optical selection criteria are much more cognizant of morphology than our H I selection criteria (i.e., it is difficult to optically select an H I–rich spiral with a low present-day star formation rate). As discussed by Whitmore (1984), these differences in sample selection are responsible for most of the controversy regarding the importance of morphological type in the Tully-Fisher relation.

b) *Observations*

The acquistion and reduction of this data is described in detail in a catalog of observations of cluster spirals (Bothun *et al.* 1984*b*). Inclination corrected 20% velocity widths (see Aaronson *et al.* 1980) and isophotal $(B-H)_{-0.5}$ colors have been taken directly from that catalog. Suffice it to say that these isophotal $(B-H)_{-0.5}$ colors have been derived by calculating $B_{-0.5}$ from an aperture-magnitude relation similar to the one depicted in de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter RC2). This value of $B_{-0.5}$ is then corrected for reddening as discussed below. $H^c_{-0.5}$ magnitudes are derived from a linear interpolation of multiaperture measurements of each individual galaxy and are then corrected for foreground reddening and redshift in the manner outlined by Aaronson *et al.* (1980).

The reason for this differentiation is that the optical photometry was typically done through large apertures [e.g., log $A/D(0) > -0.3$], while the IR photometry was done through small apertures [log $A/D(0) < -0.3$]. However, there are a number of cases where B and H magnitudes have been obtained with apertures of similar size. These apertures usually correspond to $-0.7 <$ log $A/D(0) < -0.3$. Within that region, gradients in $B-H$ with amplitudes larger than 0.2 mag are not observed. These common aperture measurements are the preferred way to determine $(B-H)_{-0.5}$ and have been used whenever available. In addition, they can be used to check the consistency of $(B-H)_{-0.5}$ that is derived from the aperture-magnitude relation.

Variations of a particular galaxy from the mean growth curve is then a source of uncertainty in the $(B-H)_{-0.5}$ color. An additional source of uncertainty is due to reddening. The reddening corrections adopted by Bothun (1981) and used here set an upper limit to internal absorption at B of 0.6 mag. The reddening corrections of Tully and Fisher (1981) have a limit of 1.0 mag while those of Burstein (1983) have a limit of 2.5 mag. While the correct expression for internal reddening has yet to be found, we note that the fairly large values adopted by Tully and Fisher, and especially by Burstein, yield $B-H$ colors that are very blue (e.g., <2.0 mag) and quite difficult to model. For instance, the $B-H$ color of the Sun is about 2.0 and the giant-dominated light from galaxies is much cooler.

Thus, the $(B-H)_{-0.5}$ colors of highly inclined spirals should be regarded as uncertain. It is difficult to estimate this uncertainty, but given our adopted reddening corrections coupled with the dispersion of the aperture-magnitude relation, a reasonable guess is 0.2 mag. While this is a large uncertainty, it is small in comparison to the total range of at least 2 mag which is spanned by spiral $(B-H)_{-0.5}$ colors.

III. COLOR-MAGNITUDE DIAGRAMS OF CLUSTERS

a) *What Does $B-H$ Measure?*

Before delving into relationships involving $B-H$ it is important to understand what factors actually control and determine this color. $B-H$ is ultimately a measure of the giant-to-dwarf ratio, or, more specifically, is a measure of the relative luminosities of the giant branch, at a given effective temperature, and the upper main sequence. Therefore, changes in $B-H$ will result from processes that control the mean effective temperature of the giant branch (e.g., metallicity and contribution from AGB stars), and alter the population of the upper main sequence (e.g., star formation and disk turn-off age). The differential sensitivities of $B-H$ to present day star formation, mean giant metallicity, and disk turnoff age can best be ascertained through detailed modeling. The modeling procedure fully discussed by Bothun *et al.* (1984*c*) and to some extent by TMA offers the following insights:

1. In mature galaxies (those that have reached their maximum H luminosity), current star formation that replenishes the population of the upper main sequence does not greatly alter the J, H, or K magnitudes in a constant SFR galaxy. Star formation can only significantly influence J, H, and K during that brief evolutionary phase when M super-

giants are present. Most galaxies will not be observed at this phase since it is quite short ($<10^7$ yr). Over the time range 10^7–10^9 yr (when the B light is most affected), the contribution of AGB stars to the integrated disk light can also be considered to be minor. For instance, large aperture J, H, and K observations of actively star forming disk galaxies in Pegasus and Pisces do not reveal many $H-K$ excesses that can be directly attributed to luminous AGB stars that dominate the light (see Bothun *et al.* 1984*c*). In addition, Blanco and McCarthy (1983) show that the contribution of carbon stars to the total bolometric luminosity of the LMC is less than 4%. These various observations suggest that, in most galaxies, the contribution at 2 μm from AGB stars younger than 2 or 3 Gyr is $<20\%$ (see also Persson *et al.* 1983).

Thus, the change in $B-H$ resulting from star formation is equivalent mostly to the enhancement of B from hot stars. The amount of this enhancement can be constrained by deducing the current SFR from either integrated $U-B$ colors or the equivalent width of the Hα line (see Kennicutt 1983) and using population synthesis models to derive the relationship between ΔB and $\Delta(U-B)$. The great majority of the disk galaxies in the present sample are not sufficiently blue in $U-B$ for star formation to have increased their blue luminosity by more than 1 mag (0.5 mag is a more typical value).

2. $B-H$ is potentially sensitive to metallicity since the presence of M giants serves to increase the luminosity at H relative to B. In a related study, Bothun *et al.* (1984*c*) have discovered a near-IR *C-M* relation in the sense that the $J-K$ colors of disk-dominated galaxies become systematically bluer with decreasing IR luminosity. Since $J-K$ is largely determined by the effective temperature of the giant branch, this correlation implies that there must exist an underlying mass-metallicity relationship for disk galaxies. If metallicity is correlated with the ratio of K-to-M giants, then even at fixed mass, metal-rich systems, by virtue of having more M giants, will be redder in $B-H$ and more luminous at H than metal-poor systems.

The observations of Bothun *et al.* (1984*c*), in combination with population synthesis models, suggest that $(B-H)_{-0.5}$ can decrease by 1 mag over the observed range in $J-K$ due solely to a decreasing ratio of K-to-M giants. Additional observational support for this result comes from measurements of low-luminosity ellipticals in Virgo and Fornax whose $B-H$ colors are approximately 0.8 mag bluer relative to giant ellipticals (see Bothun and Caldwell 1984 and Caldwell and Bothun 1984). In fact, if luminosity and metallicity are tightly correlated in disk galaxies, then curvature in the IR Tully-Fisher relation (see Aaronson and Mould 1983) would naturally arise since the mass-to-light ratio at H would systematically decrease with increasing H luminosity.

3. Since $B-H$ is directly related to the giant-to-main-sequence star ratio, then it ultimately evolves redward with time in any population. The rate of this evolution, however, depends strongly on the contribution to the H light from AGB stars. For instance, the observations of Persson *et al.* (1983) of intermediate-age star clusters in the Large Magallenic Cloud indicate them to be quite red in $J-K$ and $H-K$, presumably due to this AGB contribution to the integrated light. Thus, while population synthesis models that ignore this AGB contribution (see Bothun *et al.* 1984*c*) show that for a reasonable range of metallicity and IMF, a 5 Gyr population is 0.5–1 mag bluer in $B-H$ relative to a 10 Gyr population, in reality, the difference could be appreciably less. Better understanding of the evolution of the AGB star luminosity function is vital in ascertaining the correct response of $B-H$ or $V-K$ to aging stellar populations.

A final complication is the sensitivity of $B-H$ to reddening. $B-H$ becomes increasingly uncertain for more edge-on galaxies and therefore observations of face-on galaxies are appropriate. Unfortunately, given the historical nature of this sample (see § II*a*), very few face-on galaxies have measured $B-H$ colors. The few that do are not appreciably bluer, for their luminosity, compared to the dereddened colors of more edge-on spirals; that is, there is no residual correlation between $B-H$ color and inclination. Nevertheless, likely variations in internal reddening limit the accuracy to which $(B-H)_{-0.5}$ can be ascertained (see § II*b*).

b) The Color–Line Width Relation

One of the principal results of TMA was the discovery of a color–line width relation for spirals. This relation is important as its mere existence demands that there is a flatter slope in the blue Tully-Fisher relation than in its infrared counterpart (see also Aaronson and Mould 1983). The color–line width for our cluster sample is shown in Figure 1*a*. A least-squares fit to that data, treating line width as the independent variable, yields the following relation ($r = 0.83$):

$$\log \Delta V = 0.18 \pm 0.01 * [(B-H)_{-0.5} - 3.0] + 2.54 \pm 0.01 .$$

The scatter about this relation is 0.07 in $\log \Delta V$ or 0.31 mag in $(B-H)_{-0.5}$.

Because TMA employed a different set of corrections for internal reddening than used here, and because their color index involves the difference between the total blue magnitude and $H_{-0.5}$, it is difficult to compare our cluster color–line width relation to theirs. However, we can compare this relationship to the one derived from the 93 spirals in the Local Supercluster sample of Bothun (1984), where $(B-H)_{-0.5}$ was calculated in virtually the same manner as done for the cluster sample (this field sample is, in fact, identical to the one used by TMA). The relation for the Local Supercluster sample is the following ($r = 0.87$):

$$\log \Delta V = 0.18 \pm 0.01 * [(B-H)_{-0.5} - 3.0] + 2.59 \pm 0.01 .$$

The scatter about this relation is 0.06 in $\log \Delta V$ or 0.34 in $(B-H)_{-0.5}$. Note that there is a small difference in the intercepts between the cluster relation and the Local Supercluster relation. The reason for the difference is straightforward.

The Local Supercluster sample has reddening- (internal and foreground) corrected B magnitudes that have been lifted from RC2. The reddening corrected B magnitudes of the cluster sample come from Bothun *et al.* (1984*b*) whose prescription for foreground reddening follows that of Burstein and Heiles (1978, 1982) and not RC2. There is approximately 0.25 mag difference in A_B between RC2 and the results of Burstein and Heiles for galaxies at high galactic latitude. The differences in zero points thus can be reconciled by applying a correction of $-E(B-H) = 0.25$ mag to the Local Supercluster sample. This will decrease the intercept by $0.18 * 0.25 = 0.045$. Thus, within the errors, the slopes and zero points of the field and cluster relations are the same. Does this imply that the line width–color relation is universal?

Table 1 summarizes the individual line width–color relations that each cluster defines. These fits were made after one cycle through the data rejected all 2 σ points. In practice, this procedure dropped less than 10% (1–2) of the data points per cluster. Column (1) gives the cluster. Columns (2)–(3) give the

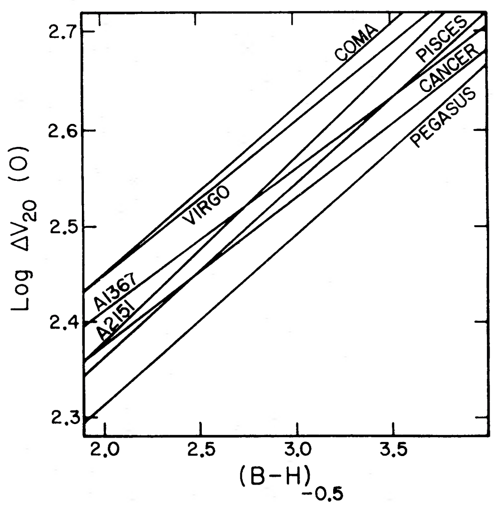

FIG. 1*a*

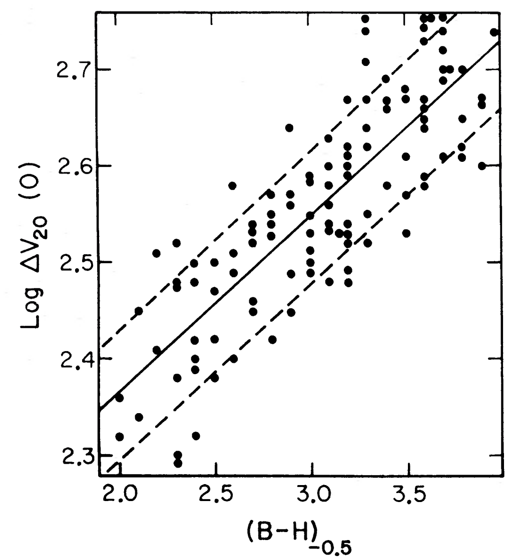

FIG. 1*b*

FIG. 1.—(*a*) The color–line width relation defined by this sample. Solid line represents the best least-squares fit to the data and has a slope of 0.18. Dashed lines indicate $\pm 1\ \sigma$ deviations. The colors and line widths have been corrected for inclination effects. (*b*) Graphical representation of the parameters tabulated in Table 1. Note the large difference in zero point between Pegasus I and Coma.

slope and intercept (evaluated at $B-H = 3.0$) and their associated errors. Column (4) gives the 1 σ scatter about the fit, and column (5) gives the correlation coefficient. Columns (6) and (7) give the number of galaxies used and the number of galaxies that were rejected by the 2 σ criterion. For the field and total cluster samples, the additional line in Table 1 indicates the results obtained when line width, instead of color, was treated as the independent variable.

Within the errors, the individual cluster relations have identical slopes (0.18), but the zero points show important differences. Pegasus I has the lowest zero point (i.e., the smallest line width at a given color) while Coma and Virgo have the highest. Figure 1*b* plots the individual color-line width relations defined by each cluster (from entries in Table 1). The disparity in zero points is obvious.

These zero-point differences have important implications regarding the utility of the $B-H$, H relation as a distance indicator. In particular, if the slope of the H, $\log \Delta V$ relation is 10, then differences of 0.1 in $\log \Delta V$ at a fixed $B-H$ color lead to differences in 1 mag in H at that same color. Indeed, such differences will be seen in the respective cluster $B-H$, H relations (see § III*c*).

The depression of the zero point of the Pegasus color–line width relation with respect to Coma and Virgo might imply that the foreground reddening has been underestimated. Using the methodology employed by Sullivan *et al.* (1981), which is based on the Burstein-Heiles recipe, leads to an absorption of $A_B = 0.18$ in the direction of Pegasus I (we assume $A_B = 0.0$ toward Coma and Virgo). However, even if this value were doubled (and there is no evidence from the Burstein-Heiles maps that this should be the case), the zero point of the color–line width relation would only increase by 0.04 in $\log \Delta V$. In general, uncomfortably large variations in foreground reddenings at high galactic latitude would be required in order to bring all of the zero points into accord.

At first glance, the correlation between color and line width for disk galaxies is somewhat surprising but may be related to the color–velocity dispersion relation observed for elliptical galaxies (see Wirth and Gallagher 1984). For instance, in the color–line width plane, evolution can only occur in color since

TABLE 1

COLOR–LINE WIDTH RELATION

Sample (1)	Slope (2)	Intercept at $B-H = 3.0$ (3)	1 σ Scatter (4)	R (5)	N Used (6)	N Rejected (7)
Pegasus	0.18 ± 0.02	2.49 ± 0.01	0.06	0.88	20	1
Cancer	0.15 ± 0.03	2.53 ± 0.02	0.05	0.90	8	0
Pisces	0.18 ± 0.03	2.54 ± 0.02	0.07	0.90	16	2
A1367	0.15 ± 0.05	2.56 ± 0.02	0.07	0.74	14	1
Coma	0.17 ± 0.05	2.62 ± 0.02	0.06	0.72	12	0
A2151	0.19 ± 0.04	2.57 ± 0.02	0.06	0.88	9	0
Virgo	0.16 ± 0.02	2.61 ± 0.01	0.04	0.97	12	0
Total	0.18 ± 0.01	2.54 ± 0.01	0.07	0.83	113	0
	3.48 ± 0.25	-5.84 ± 0.03	0.31	0.83	113	0
Field	0.18 ± 0.01	2.59 ± 0.01	0.06	0.82	93	0
	3.70 ± 0.27	-6.71 ± 0.03	0.34	0.83	93	0

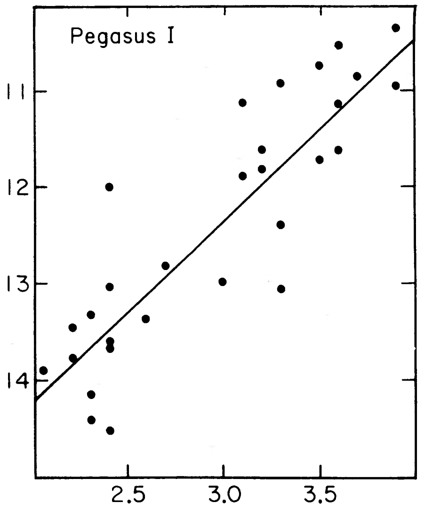

FIG. 2*a*

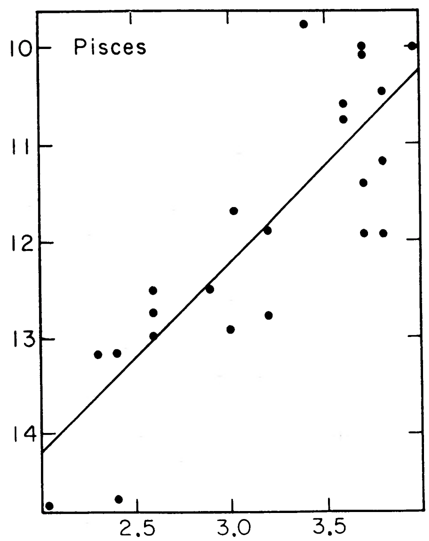

FIG. 2*b*

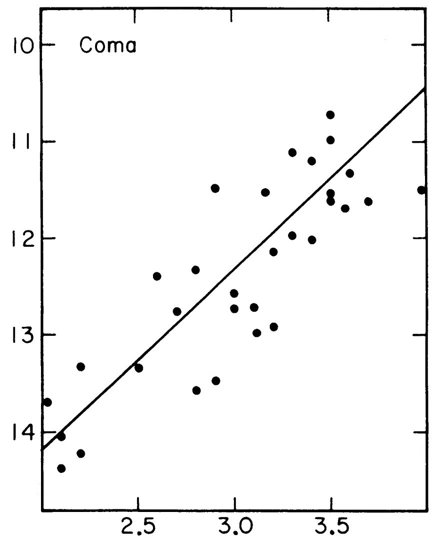

FIG. 2*c*

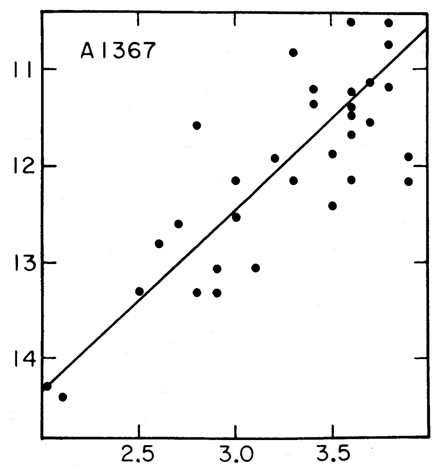

FIG. 2*d*

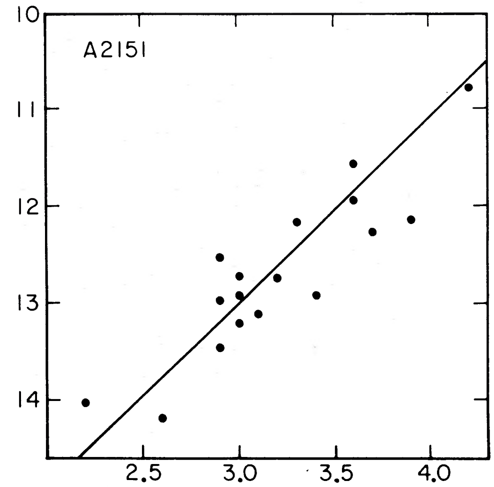

FIG. 2*e*

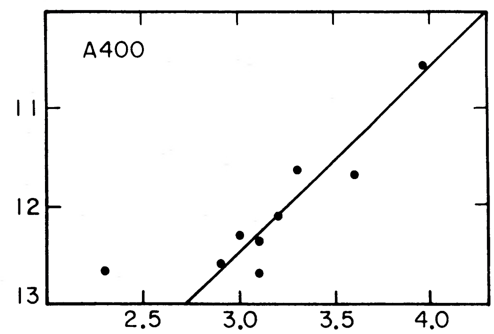

FIG. 2*f*

FIG. 2.—The observed color-magnitude relations for individual clusters. In all figures, the abscissa is $(B-H)_{-0.5}$ color and the ordinate is apparent $h_{-0.5}$ magnitude. The solid line represents the slope of the Virgo relation.

the line width presumably does not evolve with time (except possibly through mergers). Thus, the foundation of this relation rests upon luminosity-dependent factors that alter $B-H$. Systematic changes in mean giant metal abundance, mean disk age, and SFR with luminosity could account for the observed trends (see also Bothun *et al.* 1984*c*). The differences in color–line width zero point may then be related to cluster-wide variations in mean ages, internal reddening, specific star formation rates, and/or mean metallicity of the member disk galaxies.

Whatever the specific cause of these cluster to cluster differences, Figure 1*b* shows that galaxies of the same line width (mass) can have systematic color differences of 0.5 mag in $B-H$ depending upon the cluster in which the galaxies are found. In other words, a galaxy can have a $B-H$ color that is representative of a galaxy in another cluster that is 1 mag brighter or fainter. These results would seem to dispel the notion of a uniform color distribution function in clusters (although this still may hold for optical colors) and suggests that further study of relatively nearby clusters is required in order to understand the color distribution of galaxies in more remote clusters.

c) The Real Color-Magnitude Relations

Figures 2*a*–2*h* present color-magnitude diagrams of the clusters Pegasus I, Pisces, A1367, Coma, Hecules (A2151), A400, Cancer, and Virgo. The Virgo data comes from the H magnitudes listed in TMA, the reddening-corrected B magnitudes listed in RC2, and assumes no foreground reddening toward Virgo. The solid line superposed on Figures 2*a*–2*g* represents the relation defined by the Virgo sample that will be used for calibration (see below). We emphasize that these *C-M* relations involve a color index that is completely different in nature than the one used by TMA, whose color index is defined as the difference between the total blue magnitude and $H^c_{-0.5}$ (Our *C-M* relation is more similar to the one constructed by Wyse 1982, although that conversion from B_T to $B_{-0.5}$ is in error by 1.3–1.5 mag.

As is evident, $(B-H)_{-0.5}$ does correlate with $H^c_{-0.5}$, with a

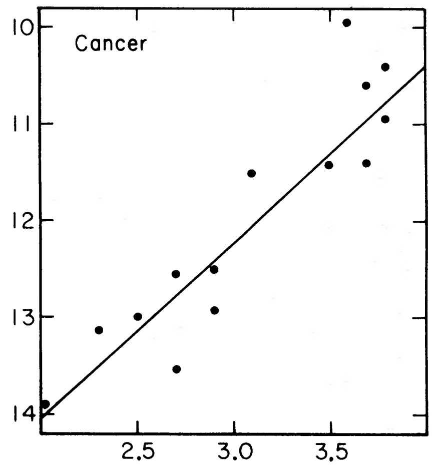

FIG. 2g

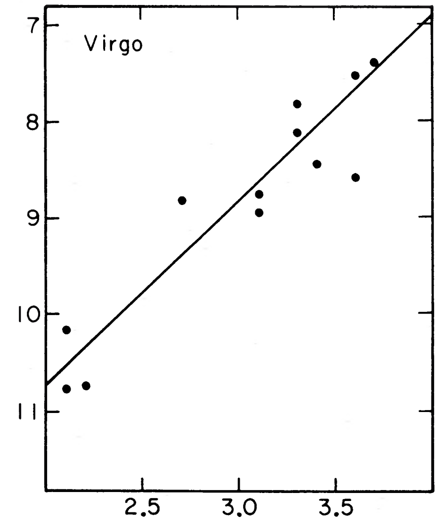

FIG. 2h

scatter of 0.4–0.5 mag in $H^c_{-0.5}$. This, of course, is expected since $H^c_{-0.5}$ is also correlated with line width. Table 2 summarizes the least-squares fit to the data obtained by treating $(B-H)$ color as the independent variable and the rms scatter of the residuals about that fit. The entries in Table 2 are as in Table 1, and the results of changing the regression variables are listed on the second line for each sample. The fit to the Cancer data was made only for those galaxies that Bothun *et al.* (1983) identified to be members of the Cancer cluster proper. The fit to the 12 calibrating galaxies used by TMA is also listed. The intercept of the local calibrator relation is absolute magnitude. Note that the slope of the relation is the steepest for these calibrators and flattest for the A2151 sample, which is the most distant. Possibly this may indicate that as galaxies of increasingly fainter absolute H magnitude are sampled, the slope of the $B-H$, H relation steepens.

To rigorously test the reliability of the C-M relation as a distance indicator, we will use the relationship defined by Virgo to derive relative cluster moduli.. The slope of the Virgo relation, -1.85, is within 1 σ of the slope of the relations defined by the other clusters and is essentially the same as the slope obtained for the combined cluster sample. Examination of Figures 2*a*–2*g* also shows that the slope of Virgo relation is an adequate fit to the data. Note that if we use the Local Calibrator C-M relation, we derive a distance modulus to Virgo of 30.94 ± 0.14, in good agreement with that found by TMA.

Relative cluster moduli are best derived by calculating the relative modulus for an individual cluster member, using the Virgo slope and intercept, and then forming the mean of all cluster members. This method is more reliable than merely shifting intercepts and is the same procedure employed by

TABLE 2

COLOR-MAGNITUDE RELATION

Sample (1)	Slope (2)	Intercept (3)	1 σ Scatter (4)	R (5)	N Used (6)	N Rejected (7)
Pegasus	-2.05 ± 0.17	18.41 ± 0.10	0.51	0.93	27	2
	-0.42 ± 0.03	8.13 ± 0.10	0.23			
Pisces	-2.00 ± 0.25	18.30 ± 0.15	0.68	0.88	22	1
	-0.38 ± 0.05	7.76 ± 0.10	0.30			
Cancer	-1.74 ± 0.19	17.44 ± 0.15	0.42	0.94	13	1
	-0.51 ± 0.06	9.18 ± 0.10	0.22			
A1367	-1.90 ± 0.19	18.22 ± 0.10	0.45	0.89	28	4
	-0.41 ± 0.04	8.26 ± 0.05	0.21			
Coma	-1.79 ± 0.18	17.78 ± 0.10	0.50	0.88	30	1
	-0.43 ± 0.04	8.36 ± 0.10	0.25			
A400	-1.72 ± 0.22	17.64 ± 0.10	0.23	0.95	8	0
	-0.53 ± 0.07	9.61 ± 0.05	0.13			
A2151	-1.63 ± 0.20	17.86 ± 0.10	0.37	0.91	16	1
	-0.53 ± 0.07	9.95 ± 0.05	0.22			
Total	-1.79 ± 0.09	...	0.68	0.84	158	6
	-0.40 ± 0.02	...	0.29			
Virgo	-1.85 ± 0.22	14.37 ± 0.10	0.43	0.94	12	0
	-0.48 ± 0.05	7.20 ± 0.07	0.22			
Local	-2.22 ± 0.07	-15.43 ± 0.05	0.25	0.99	11	1
	-0.44 ± 0.01	-6.84 ± 0.05	0.11			

TABLE 3

VIRGO-RELATIVE DISTANCES TO CLUSTERS USING THE *C-M* METHOD

		$(m-M)$	
CLUSTER (1)	V (2)	*C-M* Method (3)	Redshift Ratio; Infall Corrected (4)
Pegasus	4200	3.46 ± 0.09	2.14 ± 0.21
Cancer	4600	3.39 ± 0.11	2.68 ± 0.21
Pisces	5300	3.41 ± 0.13	2.78 ± 0.21
A1367	6400	3.63 ± 0.11	3.40 ± 0.21
Coma	6900	3.53 ± 0.10	3.58 ± 0.21
A400	7800	3.69 ± 0.08	3.61 ± 0.21
A2151	11000	4.20 ± 0.09	4.51 ± 0.21

Aaronson, Persson, and Frogel (1981). Table 3 summarizes the distance moduli, relative to Virgo, that are obtained using this procedure. Column (1) gives the cluster name, and column (2) gives the approximate mean cluster redshift from Aaronson *et al.* (1984). Column (3) gives the relative cluster modulus obtained using the Virgo *C-M* relation, while column (4) lists the relative modulus that would be expected on the basis of cluster redshift ratios, assuming an infall velocity of the Local Group towards Virgo of 400 ± 100 km s^{-1}. The uncertainty in column (4) arises from this adopted uncertainty in infall velocity. We assume that the individual clusters themselves do not partake in this Virgocentric infall. This is a reasonable assumption, given their distances, provided that the mass density falls off from Virgo faster than r^{-2}.

A glance at Table 3 makes it quite clear that, although the *C-M* relation establishes a distance to Virgo which is in excellent agreement with that using the IR Tully-Fisher relation (see Aaronson and Mould 1983), it fails to produce uniform agreement among the other clusters. In particular, only the Virgo-relative distances of A1367, Coma, A400, and A2151, are within 1 σ of the expected value (e.g., col. [4]). The relative modulus to Pisces is discrepant by 2.5 σ, while the relative moduli to Pegasus I and Cancer are highly discrepant ($> 3.5\ \sigma$). These results remain unchanged if the regression variables are interchanged.

Given the observed differences in zero point of the respective cluster color–line width relations, then this observed nonuniformity regarding relative cluster moduli is not surprising. For instance, the Virgo-relative distance of Coma is the one which is most consistent with the expected value, and indeed it is Virgo and Coma which have identical zero points in the color–line width relation. Thus, it would seem that in order to effectively apply the *C-M* relation as a distance indicator, the color–line width relation must first be formulated and inspected to see if it is similar to the relation defined by the calibrators (in this case the Virgo cluster). This, of course, restricts the sample to edge-on systems and thus defeats one of the main advantages of the *C-M* method, namely, its application to face-on galaxies where corrections for internal reddening are minimized.

There is, however, a disturbing systematic trend present in this data. Examination of column (2) compared to column (3) indicates that the *C-M* method yields distances that are too far from the three nearest clusters (Pegasus, Cancer, and Pisces) and too close for the most distant cluster (A2151). This becomes even more apparent by comparing Pegasus to A2151. The relative distance modulus implied by the ratio of cluster redshifts is 2.38 ± 0.21, while the *C-M* method yields a relative distance of only 0.74 ± 0.13, a difference that is significant at the 7 σ level! It would thus appear that the zero point of the *C-M* relation is also varying from cluster to cluster, in a manner that may depend upon cluster redshift.

Thus, if all the clusters are combined, the scatter in the *C-M* relation will increase because of the differing zero point. This is demonstrated in Figure 3. For purposes of this figure, absolute magnitudes are calculated from the mean cluster velocity and a uniform Hubble flow. The exact value of the Hubble constant is irrelevant, and the use of a Virgocentric flow model does not significantly change the results as the infall of the Local Group is only a 10% perturbation upon the distance moduli of these relatively distant clusters. The formal 2 σ rejection fit to the data yields the following relation ($r = 0.84$):

$$H_{-0.5} = -1.79 \pm 0.10 * (B-H)_{-0.5} + \text{constant} .$$

The scatter about this relation is 0.68 mag which is significantly larger than the scatter in any individual cluster (see Table 2), but is actually somewhat smaller than the scatter in the Local Supercluster *C-M* relation of Bothun (1984).

Clearly the systematic shifts in the zero point in both the color–line width relation and the *C-M* relation advises that caution must be exercised in using the *C-M* method as a distance indicator. As mentioned previously, one possibility for the origin of these shifts appeals to systematic errors in the adopted foreground reddening. In general, if there is an 0.05 uncertainty in cluster reddening in $E(B-V)$, there is an uncertainty of 0.18 in $E(B-H)$ or 0.35 in *C-M* modulus. However, to bring the Virgo-relative *C-M* moduli for the nearest cluster into accord would again require uncomfortably large changes in foreground reddening toward these clusters.

Conceivably, a portion of the zero point shift in the *C-M* relation is the result of systematic errors, with redshift, in the diameters tabulated by Nilson (1973) that are transformed to the diameter system defined by Aaronson, Mould, and Huchra (1980). Errors in diameters more strongly affect the $H^c_{-0.5}$ mag-

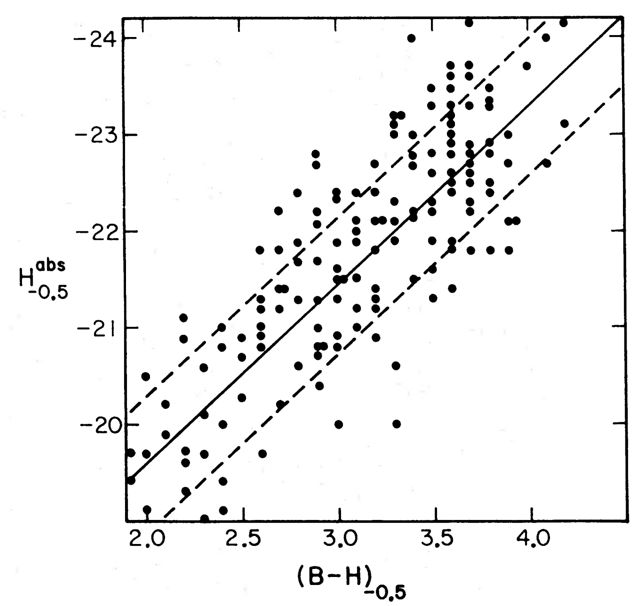

FIG. 3.—The color-magnitude relation for the entire sample. Ordinate scale is derived using a uniform Hubble flow with a Hubble parameter of 100. Solid line represents the best least-squares fit to the data and has a slope of 1.79. Dashed lines indicate $\pm 1\ \sigma$ deviations.

nitude than the $(B-H)_{-0.5}$ color since $B-H$ color gradients with amplitudes larger than 0.2 mag are not observed over the range $-0.7 < \log A/D(0) < -0.3$. However, since the slope of the aperture-magnitude relation at H is approximately 2 mag $\log A/D(0)^{-1}$, the diameter errors would have to be gross in order to account for the magnitude of the observed zero point shift. Furthermore, diameter errors would have little or no effect on the zero point of the color–line width relation which we also observe to vary from cluster to cluster.

On the basis of these results, we conclude that the spiral *C-M* relation could never provide distance moduli that were both unambiguous, due to an ill-defined zero point, and accurate to <0.7 mag. A case in point is provided by the Sc I data of Bothun *et al.* (1984*a*). Those data occupy a limited range in the $(B-H)$, H plane (e.g., $3.1 < (B-H)_{-0.5} < 3.9$), and application of the Virgo relation shows that while nine out of 17 cases yield distances that agree to within 20% of the infrared Tully-Fisher distances, the remaining eight are discrepant by 30%–100%. It would thus seem that the spiral *C-M* relation does not fulfill its initial promise (cf. TMA) as an accurate distance indicator.

IV. THE H I CONTENT OF CLUSTER SPIRALS

There have been indications in various clusters that the member spirals are H I deficient with respect to field spirals (see review by Haynes, Giovanelli, and Chincarini 1984). However, counter to this trend, Bothun, Schommer, and Sullivan (1984*a*, *b*) provide examples of spiral galaxies in clusters that are sometimes embarassingly H I rich. The situation is far from being resolved and, to many, the resolution is critical in order to establish the credibility of the IR Tully-Fisher distance scale. The primary reason for the present difference of opinion in the literature boils down to different techniques of analysis, sample incompleteness and the fact that, like spiral themselves, no two clusters of galaxies are completely alike. Notions that cluster spirals must somehow be different than field spirals just have not been borne out from the data on clusters other than Virgo or Coma (cf. Bothun, Schommer, and Sullivan 1982*b*).

Virgo may not be an especially good representation of the typical cluster of galaxies for it seems to be remarkable in many of its properties (see Kennicutt 1983). Moreover, its galaxy content may be significantly modified due to infall from the Local Supercluster (Tully and Shaya 1984). In fact, Tully and Shaya (1984) argue that there may not be any H I deficiency in Virgo after all, although the H I diameter observations of Giovanardi *et al.* (1983), Giovanelli and Haynes (1984), and van Gorkom *et al.* (1984) would seem to indicate otherwise. In the same vein, Coma is certainly not typical as it is arguably the densest cluster with $z < 0.2$ in the Abell catalog. Indeed, Bothun, Schommer, and Sullivan (1984) do find a strong H I deficiency in Coma. Similar H I deficiencies may exist in the dense cores of other clusters (e.g., A262, A2147—see Haynes, Giovanelli, and Chincarini 1984).

Spirals, particularly those of small B/D, however, tend to avoid regions of high local density (Dressler 1980; Postman and Geller 1984) so an observed H I deficiency in that regime is not surprising. We stress, however, that in the environment that we have sampled, a general spiral H I deficiency is not observed (see Bothun, Schommer, and Sullivan 1982*a*, *b*). This is likely a signature of the dynamical youth of most clusters (e.g., Geller and Beers 1982).

In order to reemphasize this rather fundamental point, Figure 4 shows the IR color–H I content relation of the spirals that Aaronson *et al.* (1984) have used in constructing their distance scale. The solid line superposed on that relation is the least-squares fit of the Local Supercluster data, adjusted by $+0.2$ magnitude in $(B-H)_{-0.5}$ due to the zero-point differences between RC2 and Bothun (1981) for foreground reddening. The dashed lines outline the $\pm 2\ \sigma$ deviations from the mean relation. Clearly, the locus of points inhabited by the

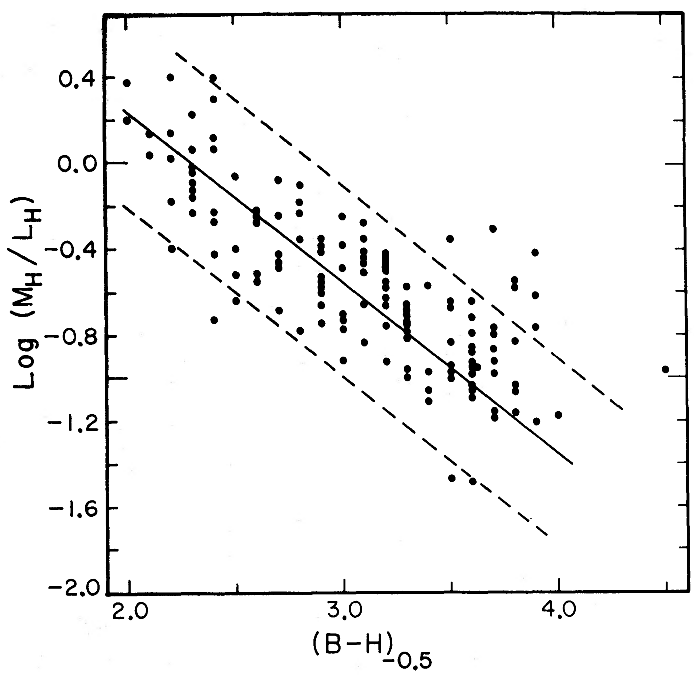

FIG. 4.—The infrared color–H I content relation defined by this sample. The solid line is *not* a fit to the data but instead represents the slope of the relation defined by the Local Supercluster sample of Bothun (1984). The dashed lines indicate $\pm 2\sigma$ deviations from that mean relation.

TABLE 4

COMPARISON OF H I CONTENT OF CLUSTER SAMPLE WITH LOCAL SUPERCLUSTER SAMPLE

$(B-H)_{-0.5}$	LOG $M_H/L_{H_{-0.5}}$ Cluster	Field
2.0–2.2..........	0.13 ± 0.06	0.19 ± 0.04
2.3–2.5..........	-0.07 ± 0.06	-0.02 ± 0.05
2.6–2.8..........	-0.35 ± 0.05	-0.38 ± 0.06
2.9–3.1..........	-0.56 ± 0.04	-0.58 ± 0.06
3.2–3.4..........	-0.73 ± 0.04	-0.82 ± 0.04
3.5–3.7..........	-0.88 ± 0.04	-0.99 ± 0.06

sample of spirals that have been used to define the IR Tully-Fisher distance scale is nearly identical with that locus defined by the Local Supercluster spirals. The only appreciable difference is that the scatter is somewhat larger in the cluster sample, primarily because it contains a component of spiral galaxies with relatively high H I content yet very red optical and infrared colors (see Schommer and Bothun 1983).

Table 4 summarizes the comparisons of the distant cluster sample and the Local Supercluster sample. Column (1) gives the $(B-H)_{-0.5}$ color range, while columns (2)–(3) give the log $M_H/L_{H_{-0.5}}$ value of the cluster and field samples, respectively. While a small difference is present for the two reddest bins, the distant cluster spirals are not H I deficient with respect to the Local Supercluster sample (this sample includes the Local Calibrators). Thus, we can find no evidence that H I deficiencies exist in the spirals that Aaronson *et al.* (1984) use in the construction of their distance scale.

V. SUMMARY

We have examined the color-magnitude and color–gas content relations for a large number of cluster spirals using $B-H$ color as the color index. Our main conclusions are the following:

1. The H I content of the spirals that have been used in constructing the IR Tully-Fisher scale define a locus of points in the IR color–gas content relation that is indistinguishable from the one defined by field spirals. There is no evidence whatsoever that this sample of cluster spirals is H I deficient with respect to Local Supercluster spirals.

2. There is a well-defined relationship between the observed $(B-H)_{-0.5}$ color of spirals and their observed 20% line width. Its particular form implies that if the slope of the Infrared Tully-Fisher relation is fixed to be 10, then the slope of the blue Tully-Fisher relation must be 5. The scatter in line width at a given color is 0.07 in the Log (17%). If the slope of the H magnitude–line width relation is 10, then this scatter implies a scatter of at least 0.7 mag in the color-magnitude relation which is consistent with what is observed in Figure 3.

3. The observed systematic differences in zero point of the color–line width relation lead directly to systematic errors in distance moduli obtained by using the C-M relation. These systematic errors are obvious in this data set in that, although the spiral C-M relation produces a consistent distance to the Virgo Cluster, it fails to provide a homogeneous set of distances to other clusters, even though the other clusters are adequately fit by the slope of the Virgo C-M relation. Thus, use of the spiral C-M relation as a distance indicator is restricted to those cases where the zero point of the cluster color–line width relation can be verified to be similar to that of the calibrating relationship. This, unfortunately, negates its main advantage in that the method cannot be reliably applied to face-on galaxies in distant clusters.

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