PREPRINTS
OF THE
STEWART OBSERVATORY
THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA

PREPRINT NO. 40

THE CORRELATION OF REDSHIFT WITH MAGNITUDE
AND MORPHOLOGY IN THE COMA CLUSTER

by

W. G. TIFFT

Steward Observatory
University of Arizona
Tucson, Arizona

Submitted August, 1971

THE CORRELATION OF REDSHIFT WITH MAGNITUDE
AND MORPHOLOGY IN THE COMA CLUSTER

by

W. G. TIFFT

Steward Observatory
University of Arizona
Tucson, Arizona

Preprint No. 40

Submitted August, 1971

ABSTRACT

Redshifts and magnitudes for 93 faint galaxies in the core of the Coma Cluster are now available. The sample is nearly complete to seventeenth nuclear region magnitude (central 4.8 arc second spot). Nuclear region magnitudes show a good correlation with redshift in the sense that galaxies fall in bands sloping fainter with increasing redshift. A magnitude decrease of 0.6 magnitudes per 1000 km/sec redshift increase is observed. The deviation from the expected random correlation of nuclear region magnitude and redshift is significant at a probability less than 10^{-3} by χ^2 testing. It is further observed that nearly all of the higher redshift galaxies in the Coma Cluster are nonelliptical. This is not expected from a normal dynamical model and is remarkably similar to the pattern in the Virgo Cluster where the spiral galaxies show a distinctly greater redshift than the ellipticals.

The observed redshift-magnitude pattern reality is further tested by comparison with two outlying concentrations of galaxies in the Coma Cluster which show nearly identical patterns slightly shifted in redshift. The pattern is also used to predict the m - $\log z$ diagram for field galaxies. Observed field galaxies are shown to fit the predicted pattern and to deviate from the normal velocity dispersion model.

After allowance for magnitude and redshift uncertainties it is shown that a residual true Doppler velocity dispersion in the Coma Cluster cannot exceed about 140 km/sec, and the cluster is not dynamically unstable. In the presence of an intrinsic unexplained redshift which produced the observed pattern, the mean redshift of a group of galaxies need not be the same as the Hubble velocity of the cluster. Systematic trends in the deviation of the Hubble velocity from the mean redshift are possible due to selection with distance and may explain the local apparent anisotropy in the Hubble law.

INTRODUCTION

According to the usual dynamical picture of clusters of galaxies, internal motion is governed by the gravitational potential of the cluster and the redshift is assumed to represent true systemic motion. Within this dynamical model, depending upon the type of orbital motion assumed and the degree of dynamical relaxation present, there may be a dependence of velocity dispersion on cluster radius or galaxy mass where mass is replaced in practice by total luminosity by assuming known or uniform mass to luminosity ratios. No highly structured patterns in the redshift-magnitude or redshift-morphology relationships are permitted within the dynamical model. A definitive examination of clusters of galaxies to determine if any significant patterns are present is, therefore, one test of the dynamical model. Since the dynamical model is essentially the only model permitted within the framework of modern physics the search is, therefore, also a test of the extension of presently known physical principles to the scale of intergalactic distances, the assumption of which is fundamental to modern cosmology.

The dynamical model might not be subject to scrutiny if it fit observed data well and consistently. In fact, this is not the case and the concepts of large scale instability or large amounts of hidden mass with their associated problems of time scale consistency and forms which matter can take are well known.

With few exceptions, the redshift has never been assumed to represent anything other than the real systematic motion of a galaxy. There are, however, some notable cases where this interpretation encounters difficulty such as highly discordant redshifts for one galaxy in small groups like Stephans Quintet, VV172, and the IC3481 triplet. The situation is perhaps even more extreme in connected pairs of galaxies such as NGC7603 (Arp, 1971). A different form of the redshift discrepancy is seen in the Virgo Cluster where the spiral and lenticular galaxies have distinctly different mean redshifts from the elliptical galaxies (de Vaucouleurs, 1961). This has been interpreted to imply different distances for the clouds of spirals and ellipticals, however, the main group of ellipticals and spirals have the same center and Kowal (1970) finds no difference in distance modulus from supernovae. To these difficulties in interpretation of the redshift as a purely systematic motion one can add the problems of the local anisotropy

in the Hubble law and the well known controversy over interpretation of the redshifts of the QSS.

It was suggested by Tifft (1971a) that the bright galaxies in the Virgo Cluster showed a dependence of redshift upon nuclear region magnitude of a form which was at variance with the normal dynamical expectation. A subsequent investigation (Tifft, 1971b) appeared to confirm the presence of a related pattern among the brighter galaxies in the Coma Cluster. In this present paper the data on the Coma Cluster galaxies are considerably extended and the presence of significant non-dynamical patterns in redshift-magnitude and redshift-morphology is demonstrated.

OBSERVATIONAL DATA

Visual magnitudes for a large number of galaxies in the center of the Coma Cluster have been derived by Rood and Baum (1967, 1968) although detailed data has been published for only a few of the galaxies (Rood and Baum, 1968). Magnitudes used in this paper have been derived directly from the Rood and Baum material and are visual nuclear region magnitudes for a circular zone 4.8 arc seconds in diameter centered on the galaxy. This nuclear region magnitude will be denoted $V(4.8)$.

Redshifts for 22 galaxies on the Rood and Baum list, henceforth called RB galaxies, are contained in the Reference Catalogue (de Vaucouleurs and de Vaucouleurs, 1964). An additional 14 have been published by Kintner (1971). All 53 remaining RB galaxies with $V(4.8) < 16.98$ have new redshift determinations from image tube spectra taken at the Steward Observatory 90-inch telescope. Four of the 18 remaining RB galaxies, $16.98 \geq V(4.8) \geq 17.50$, have also been observed. Table I contains a listing of $V(4.8)$, type, and redshift when available for the 107 RB galaxies brighter than $V(4.8) = 17.50$. Details on the Steward Observatory redshifts along with additional detailed Coma galaxy photometry will be published separately. Internal consistency between lines and cases where two or more spectra are available indicate a mean error in the final redshift of ± 100 km/sec or better. NGC4889 was measured at a redshift of 6523 compared to the Reference Catalogue value of 6456. Three spectra of RB40 gave individual redshifts of 7977, 7842, and 7967.

THE CORRELATION OF REDSHIFT AND MAGNITUDE

The center of the Coma Cluster has been assumed to lie at the faint

TABLE I -- Coma Cluster Galaxies

Coma α				Coma α			
OBJECT	REDSHIFT	V(4.8)	TYPE	OBJECT	REDSHIFT	V(4.8)	TYPE
N4850	5995	15.53	SO	RB 31		17.37	SO
N4858	9398	16.97	SBb	RB 38		17.18	SO
N4864	6831	15.46	E	RB 40	7920	16.50	SO
N4865	4655	15.07	E	RB 41	3690	16.81	E
N4867	4827	15.49	E	RB 42	7663	16.74	SO
N4869	6715	15.41	E	RB 43	6812	16.07	E
N4871	7100	15.72	SO	RB 45	7001	16.27	E
N4872	7022	15.78	SBO	RB 46	6771	16.66	SO
N4873	5649	15.94	SO	RB 49	7916	16.07	SO
N4874	7148	15.62	SO	RB 55		17.19	SO
N4875	7870	15.77	SO	RB 64		17.02	SBO
N4876	6979	15.61	E	RB 74	5931	17.06	SO
N4881	6705	15.51	E	RB 77	7816	16.94: ⁴	SO
N4883	7949	15.75	SBO	RB 82	5136	16.70	SBa
N4886	6227	15.82	E	RB 83	9878	17.33	SO
N4889	6456	14.54	E	RB 87	7394	16.27	SBO
N4894	4560	16.13	SO	RB 91	6179	16.34	SBO
N4895	8420	15.23	SOp	RB 94	5146	17.24	SBO
N4898W	6768	15.22: ¹	E	RB 99	6936	16.36	SBO
N4898E	6513	16.08: ¹	E	RB100	7753	16.56	SO
N4906	7478	15.92	E	RB110	7587	16.43	SBO
N4908	8851	15.48	E	RB113	8056	16.23	SBO
I3955	7868	15.88	SO	RB116	6621	16.52	SO
I3963	6648	16.02	SO	RB119	8692	16.62	SO
I3973	4732	15.37	SBO	RB122	7215	17.08	SO
I3976	6937	15.40	E	RB128:		17.10	E
I3998	9358	15.90	SBO	RB136		16.98	SO
I4011	7115	16.24	E	RB139		16.99	SO
I4012	7348	15.68	E	RB140		17.37	E
I4021	5802	15.95	E	RB144		17.46	E
I4026	8162	16.14	SBO	RB155	7453	16.32	SO
I4040	7258	16.66: ²	I/Sc	RB160		17.27	SO
I4041	7052	16.22	E	RB167	6771	16.05	E
I4042	6243	15.72	SBO	RB234	7841	16.76	E
I4045	6541	15.40	E	RB241	7254	15.61	E
I4051	4945	15.76	E	RB243	5905	16.39	E
RB 6	6526	16.58	E	RB252	5940	16.19	SO
RB 7	6429	17.38	SO	RB257	5676	16.16	SO
RB 8	5100	16.35	SBO	RB260	8320	16.92	SO
RB 13	7671	16.68	SO	RB261	6905	16.89	E
RB 14	6091	16.38	E	RB262	6451	16.42	SO
RB 18	6665	16.85	SBO	RB268	7811	16.59	SO
RB 21		17.20	SO	RB271		17.42	SO
RB 22	5588	16.61	E				
RB 26	6850: ⁵	15.79: ³	SO				

TABLE I -- Coma Cluster Galaxies (Continued)

Coma β

OBJECT	REDSHIFT	V(4.8)	TYPE
N4854	8062	15.99	SBO
I3946	6112	15.29	SO
I3947	5703	15.72	SO
I3949	7537	15.84: ²	SO _p
I3957	6290: ⁵	15.91	E
I3959	7227	15.43	E
I3960	6682	15.76	SBO
RB183	5401	16.97	SO
RB188	6928	16.47	E
RB209:		17.04	SO
RB214:		17.17	SO
RB219	5366	16.07	SBa
RB223:	6879	17.06	E
RB224	5606	16.43	E
RB230	5989	16.01	SO

Coma γ

OBJECT	REDSHIFT	V(4.8)	TYPE
N4921	5472	15.65	SBb
RB124	6894	15.95	SO
RB129	6040	16.78	E
RB133	7473	16.27	E

¹Double galaxy, overlapping images.²Highly eccentric isophotes, conversion to circular aperture magnitude is uncertain.³Within halation pattern of bright star.⁴Projected onto the outer envelope of NGC4889.⁵Internally discordant redshifts, uncertainty ± 300 km/sec.

galaxy RB61 essentially midway between the two supergiant galaxies NGC4874 and NGC4889. A circle of radius 11.3 minutes of arc about the center contains 58 RB galaxies with known redshifts. Five of these galaxies cannot be utilized because of uncertainties in their magnitudes as indicated in Table I. The remaining 53 galaxies define the basic redshift magnitude diagram for the core of the Coma Cluster and is shown in Figure 1a. Two characteristics of the diagram are apparent; the galaxies appear to group about a series of essentially parallel bands sloping fainter with increasing redshifts and the higher redshift galaxies are nonellipticals. Figure 1a includes a notation assigned to features based upon the banded structure and earlier papers (Tifft, 1971a, 1971b).

In order to test the reality of the linear structure, the sample was increased by adding galaxies from the circular zone between radii 11'.3 and 15'.1 about the center. The addition of the 14 galaxies in this zone produces the result shown in Figure 1b. Twelve of the 14 galaxies fall very close to the banded structure defined by the core galaxies to produce a distinctly nonrandom appearance which will be considered in detail later in this paper. Two of the galaxies are more discordant, tending to fall in the gaps between the band structure and are circled in Figure 1b. These two galaxies, RB223 and IC3960, lie close together southwest of the Coma core. Figure 2 shows the distribution of all Coma galaxies available indicating the core and ring regions discussed above. RB223 and IC3960 are the two galaxies in the southwest part of the ring zone shown with open circle symbols. Extending outward toward the southwest from the Coma core there is a distinct secondary clumping of galaxies centered near IC3947. When the ten galaxies in this area with reliable redshifts and magnitudes are plotted on the Coma core redshift magnitude pattern, they are all found to be discordant from the core pattern in the same way as RB223 and IC3960. Figure 3a shows the nature of the deviation from the core pattern and further shows that a constant shift in redshift will bring the entire sample into accord with the core pattern. Thus, the IC3947 concentration of galaxies shows a banded pattern in the magnitude redshift diagram which is shifted by a constant from the Coma core pattern. On the basis of the physical clumping of galaxies around IC3947 and the constant relationship to the core pattern, the IC3947 group is suggested to be a separate entity, either a foreground cluster or more likely a subclumping in a large complex region making up the larger scale

FIGURE 1

Redshift-magnitude diagram for the central part of the Coma Cluster. Symbols refer to morphological types: E = filled circles, SO = open circles, SBO = X, and spirals = small S. The two objects with special symbols in the lower figure are associated with the Coma β subgroup. Notation assigned to features for reference purposes is indicated by letters T, N, R2-R6, and large S.

FIGURE 2

The distribution on the sky of the Coma galaxies with redshift determinations. The galaxies in the main central grouping, Coma α , are shown with filled circles. Outlying groups which show both spatial clumping and a systematic shift in the redshift-magnitude pattern are shown with open circles and designated Coma β and γ .

FIGURE 3

Redshift-magnitude diagrams for Coma β and γ showing the constant relationship to the Coma α pattern. Symbols have the same meaning as in Figure 1. The short vertical line shows the natural position of each point while the symbol is shown shifted by +525 or +750 km/sec for Coma β and γ .

Coma Cluster. The primary Coma core cluster will subsequently be denoted as Coma α while the IC3947 group will be denoted Coma β .

The five outlying galaxies north and west of Coma α show no deviation from the Coma α redshift magnitude pattern. This is also true of RB122 southeast of the core region. However, NGC4921 and its three closest companions east of the core region show a deviation from the core pattern as shown in Figure 3b. Again, a constant shift will bring the entire set of galaxies into accord with the core pattern. Examination of photographs of the Coma Cluster indicates that near NGC4921 there are several other relatively bright galaxies which lie outside the RB region, thus, as with Coma β a subgroup can be defined near NGC4921 and will be denoted Coma γ . NGC4921 is a rather large face-on spiral which is also rather atypical of the normal Coma Cluster galaxies.

Figure 4a as the complete redshift magnitude diagram for Coma α and contains 71 data points. In Figure 5 the same data is given without interpretive lines. Figure 4b includes Coma β and Coma γ adjusted by the systematic addition of 525 and 750 km/sec to the redshifts of the member galaxies. No attempt has been made to fit the different diagrams together precisely which would require simultaneous shifts in both magnitude and redshifts. The redshift differences involved are roughly a tenth of the Hubble velocity of the Coma Cluster and, therefore, implies magnitude corrections due to distance of only a tenth of a magnitude which will not affect the appearance on the diagrams. Most of the magnitude correction due to distance would, in fact, be cancelled by the change in aperture required to correspond to the new distance. Assuming the normal Hubble law applies, the spatial separations of the subgroups in the Coma Cluster will be on the order of 10Mpc, quite consistent with the idea that they represent individual centers within a larger cluster complex.

SIGNIFICANCE TESTING

The question now arises as to whether the observed pattern in redshifts and magnitude could be a chance occurrence between two noncorrelated variables. To answer this question, only the Coma α data sample will be considered to avoid the question of assignment of arbitrary constants. A special form of χ^2 test will be used. The hypothesis being tested is that no correlation exists between magnitude and redshift and we ignore the possibility that velocity

FIGURE 4

Redshift-magnitude diagram for the complete Coma α sample (upper) and for Coma α combined with Coma β and Coma γ (lower) after shifting as indicated in Figure 3. Symbols have the same meaning as in Figure 1.

FIGURE 5

Redshift-magnitude diagram for the complete Coma α sample without interpretive features indicated.

Symbols have the same meaning as in Figure 1.

dispersion might depend slightly on magnitude. The 71 point Coma α sample was first examined to determine the nature of the distribution function in redshift and magnitude separately. Both appeared to be good approximations to normal distributions. Although the true luminosity function is not a normal distribution, the effect of incompleteness on the faint end of the list provides the normal distribution for this sample. The normal distribution was divided into seven cells of equal area by placing boundaries at ± 0.18 , ± 0.57 , and ± 1.07 in the unity dispersion error function. The expected value in each cell is $71/7$ which was compared with the observed numbers for both the magnitudes and redshift distributions. Since the means and dispersions were derived from the data, the seven cell χ^2 test has four degrees of freedom in this case. The value of χ^2 for the fit of magnitudes to the normal distribution is 1.9 and for redshift 3.6. Both distributions are, therefore, well represented by the assumption of a normal distribution. Table II summarizes the results of the magnitude and redshift distribution analysis.

To analyze the redshift magnitude diagram for significant linear cross correlation, the redshift and magnitude distributions were first normalized to zero mean and unit dispersion by definition of new variables

$$m^* = (m - \bar{m})/\sigma_m, \quad V^* = (V - \bar{V})/\sigma_V. \quad (1)$$

If no correlation exists between two normalized normal distributions plotted against one another, then the distribution projected at any angle must have the same normal distribution. The process of pattern testing used consisted of projection of the normalized redshift magnitude diagram at some angle, θ , and testing against the standard normal function. The equation used for the projection is

$$T = m^* \cos \theta - V^* \sin \theta. \quad (2)$$

To avoid bias on choice of angle, all angles were considered by generating a computer program which stepped through any range of angle desired, testing the projection at each step and generating a χ^2 index as a function of angle. In this way it was shown that in only one narrow range of angle is the redshift magnitude diagram nonrandom and that angle corresponds very closely to a slope of 0.6 magnitudes per 1000 km/sec.

TABLE II -- The Distribution of Magnitudes and Redshifts Compared to the Normal Distribution.

BOUNDARIES	MAGNITUDE DISTRIBUTION	REDSHIFT DISTRIBUTION
-		
- ∞	10	8
-1.068	12	12
-0.566	10	9
-0.180	9	15
+0.180	7	9
+0.566	12	9
+1.068	11	9
+ ∞		
χ^2	1.9	3.6
P	0.8	0.5

The χ^2 test itself was carried out with a fixed cell width of 0.3 dispersion units in order to test for clumping on a particular scale. The width was set from the consideration that even if a precise linear relationship existed between the variables the observational errors in the variables which are roughly ± 0.1 dispersion units, would blur the lines so that the apparent width could not be less than about 0.3 units. On the larger scale, to detect a modulation of a given wavelength, the analyzing cell should be roughly half the wavelength or less. Since the apparent structure we wish to test for significance has a spacing of about 0.7 dispersion units, 0.3 is the natural cell choice.

With a cell width of 0.3 and a sample total of 71, the expected cell population value will drop below five close to the one sigma point in the distribution. The χ^2 test becomes unstable when the expected values fall below five (Hoel, 1954) consequently the tests were performed only over the range ± 1.05 dispersion units from the mean which corresponds to a 7-cell width interval. Since there is no unbiased way to group the cells in the wings of the distribution to retain a high expected value the wings were ignored. If nonrandomness cannot be shown in the central part of the distribution, the wings will probably add nothing important.

The choice of cell boundaries in the χ^2 test can considerably effect the result. In order to avoid any bias of this type the cell boundaries were not fixed at all. χ^2 was calculated as an essentially continuous variable across the interval and integrated. The resulting χ^2 index is, therefore, the value which would be derived as an average over a large number of 7-cell trials with all possible cell boundaries within the interval tested. In addition to the integrated χ^2 index as a function of projection angle, the analyzing program provides a tabulation of χ^2 as a function of position within the distribution function being tested at each angle considered.

Figure 6 shows the result of application of the testing procedure to the Coma α redshift-magnitude diagram. The probability that the apparent banded correlation in the diagram is accidental is less than 10^{-3} at the peak value of $\chi^2=22$ which occurs at $\theta=51^\circ$. The second part of Figure 6 indicates the fraction of the total interval tested over which χ^2 exceeded four which is roughly a measure of the fraction of the interval over which deviations exceeded two sigma. The 51° peak value of 0.3 appreciably exceeds

FIGURE 6

Chi square as a function of projection angle for the Coma α redshift-magnitude diagram (top) and 70 point random samples (bottom). The probability of accidental occurrence from a normal distribution is given at the right. The Coma α test has five degrees of freedom since the mean value was constrained. The random sample data has six degrees of freedom since the mean and dispersion are set from the random generating function but not the data itself. The random test data shows no significant clumping, however, the Coma α sample shows highly significant clumping at a 51° projection angle. The middle part of the figure indicates the fraction of the test interval over which $\chi^2 > 4$ which is a measure of the fraction of the interval over which deviations from the expected values exceeded two sigma. The random expected value of this quantity is less than 0.05. At the 51° Coma α peak some deviations in excess of four sigma are observed.

the value of 0.05 expected from the normal error function.

In Figure 7 the individual values of χ^2 across the distribution being tested are shown. Figure 7a shows χ^2 for the projection along the bands ($\theta=51^\circ$) while 7b is approximately perpendicular to them ($\theta=140^\circ$). Figures 7c and 7d show the analysis for the magnitudes and redshifts themselves ($\theta=0^\circ$ and 90°). The bands and gaps in the 51° projection are clearly seen.

In order to verify the test procedure a computer program was developed to generate random normally distributed sets of points which were then correlated with one another. The third part of Figure 6 shows χ^2 for three random sample tests. In no case does the χ^2 index indicate a significant probability of any clumping in the 70 point samples. The final conclusion is, therefore, that to a high degree of confidence there is a real fine structure correlation between nuclear region magnitude and redshift for galaxies in the Coma Cluster

THE CORRELATION OF REDSHIFT AND MORPHOLOGY

In Table II and Figure 7 it was shown that the distribution of redshifts in the Coma Cluster sample is a good approximation to the normal distribution. The mean redshift for the 71 galaxy sample is 6849 km/sec, while the dispersion is 1198 km/sec. Examination of Figure 5 suggests, however, that there is a morphological dependence upon redshift in the sense that very few of the higher redshift galaxies are ellipticals. The morphological sorting appears to be most distinct perpendicular to the banded pattern discussed in the previous section. To test the significance of the morphological sorting the normalized distribution function previously discussed was projected at 140° essentially perpendicular to the band structure and tested against the normal function. Table III contains the results of the testing. A 7-cell χ^2 test of the total population indicates a nearly perfect normal distribution as does the detailed test shown in Figure 7. To test the distribution of elliptical and nonelliptical galaxies separately, the cell number was reduced to five to maintain a sufficient expected number of galaxies per cell. The 5-cell χ^2 test on the elliptical galaxy distribution yields an index of 13 corresponding to only a one percent probability of accidental occurrence. The nonelliptical galaxies or S0 galaxies alone show no significant deviation from the normal distribution, thus, the morphological pattern arises from a deficiency of high redshift ellipticals rather than an excess of high redshift nonellipticals

FIGURE 7

The distribution of χ^2 across distributions being tested. χ^2 generated by excess or deficiency from the expected normal function values is distinguished by deviations above or below the zero line. The overall χ^2 index given at the right is the integral over the distribution shown which has a width of seven test cells. At intermediate angles the test has five degrees of freedom since only the mean value is constrained. At 0° and 90° the dispersion is also constrained, hence, the test near these angles has four degrees of freedom. The 51° projection shows the R2-R4 clumping and intervening gaps clearly. The test is not extended into the distribution wings beyond 1.05 sigma since the expected values in the test cell become too small.

TABLE III -- The Distribution of Galaxies in the 140° Projection Compared to the Normal Distribution

BOUNDARIES	TOTAL DISTRIB	BOUNDARIES	TOTAL DISTRIB	E DISTRIB	non-E DISTRIB	SO DISTRIB
- ∞	10	- ∞	14	2	12	10
-1.068	10	-0.841	13	1	12	5
-0.566	10	-0.253	16	10	6	3
-0.180	10	+0.253	13	5	8	6
+0.180	11	+0.841	15	10	5	3
+0.566	11	+ ∞				
+1.068	9					
+ ∞						
χ^2	0.3			13.1	5.0	6.1
P	0.99			0.01	0.25	0.15

It is of considerable interest to note that the morphological sorting is in the same sense as the redshift-morphology discrepancy in the Virgo Cluster (de Vaucouleurs, 1961). Figure 8 illustrates the different frequency distributions of E and non-E galaxies in the 140° projection. The mean coordinate of the E galaxies is 0.53 in the unit dispersion system with a mean error of ± 0.17 . For the nonellipticals the corresponding figures are -0.35 ± 0.16 . The two mean values, therefore, differ by more than five times their uncertainty. A t-test applied to the mean values indicates only a one to two percent chance that the morphological subgroups are randomly selected from the total population.

If the E and non-E samples are compared directly in the redshift coordinate rather than at the 140° projection, the respective mean values are $+0.30$ and -0.19 for a difference of three times their uncertainty or close to 600 km/sec. Some separation of the E sample from the S0 group at 140° is to be expected from the luminosity function alone since Rood (1969) has shown that the S0 sample peaks in frequency below the brighter E sample, and this contributes to the separation of the E and non-E groups in the 140° projection. The separation appears to be quite likely real in the redshift coordinate alone, however, and in both the sense and amount is similar to the Virgo Cluster difference (de Vaucouleurs, 1961).

Possible effects of field galaxies have not yet been considered. The Coma α investigation is complete to $V(4.8)=17.0$ in an area of about $1/5$ square degrees and cuts off very rapidly at fainter magnitudes. $V(4.8)=17.0$ is equivalent to total magnitude $V=16.2$ as will be discussed later in this paper. Adopting a figure of 48.5 field galaxies per square degree brighter than $V=17.8$ (Omer, et. al., 1965) the predicted number brighter than $V=16.2$ in $1/5$ square degree is one. Therefore, field galaxy effects cannot significantly alter any of the results of this study.

COMPARISON WITH FIELD GALAXIES

Final verification of reality of a general redshift-magnitude correlation must depend upon finding similar or related patterns in other clusters and upon satisfactorily predicting the observed redshift-magnitude relationships for field galaxies and pairs or small systems of galaxies. Detailed studies of other clusters are in process but results have not yet been derived. The fact that the spatially associated Coma β and Coma γ groups of galaxies are

FIGURE 8

The distribution of the total Coma α population and the E and non-E galaxies separately in the 140° projection of the redshift-magnitude diagram. Higher redshift and fainter magnitude is toward the right. Whereas the total sample is normally distributed the morphological types show distinct differences.

related to the Coma α pattern by a simple constant displacement in redshift is suggestive of the reality of the pattern, however, one can argue that these clusters are not actually independent.

A more independent test is possible using field galaxies. If there is a real intrinsic redshift component in all ordinary galaxies as suggested in this paper, then at any given distance galaxies will map into the standard m - $\log z$ plot in a specific way. By superimposing a series of patterns at various distances and weighting them according to spatial volume and observational selection one can predict what the observed m - $\log z$ plot for field galaxies would look like. One can make the same calculation for the standard model of redshift as a true index of distance with a simple velocity dispersion superimposed.

As a first step in predicting the field galaxy m - $\log z$ pattern, the Coma α nuclear region magnitudes were related to total magnitudes by plotting $V(4.8)$ against total visual magnitudes for Coma galaxies as given by Rood (1969). The relationship is shown in Figure 9 and is well defined except for a few isolated points. Using the relationship the nuclear region redshift-magnitude diagram for Coma α was transformed to redshift vs total visual magnitude. The result is tabulated in Table IV. In an actual plot of total magnitude vs redshift, the band pattern is largely unrecognizable since the dispersion in magnitudes is now on the same scale as the pattern details. The pattern still, however, determines the overall distribution of galaxies in the diagram.

The basic distance related Hubble velocity of the Coma α Cluster will here be taken to be 6000 km/sec. This is significantly less than the actual mean redshift of the group, however, if our contention that part of the redshift is non-Doppler is correct, the mean redshift need not be the best estimate of the group Hubble velocity. Tifft (1971b) has indicated that for the Coma Cluster the actual Hubble velocity may be at least 500 km/sec less than the mean redshift.

Given the Coma α pattern corresponding to a Hubble velocity of 6,000 km/sec, the pattern for 12,000, 3,000, 1,500, and 750 was found by shifting the Coma pattern by the appropriate constants in redshift and magnitude. The superimposition of the patterns for the five distance groups in an m - $\log z$ diagram is shown in Figure 10. In the upper part of the figure the individual band structure is shown, while the lower figure shows how individual bands

FIGURE 9

The relationship between total visual magnitude to the 26 magnitude per square second isophote and the nuclear region magnitude defined by a 4.8 arc second aperture.

TABLE IV -- Coma α Redshift-Magnitude Relationship For Total Visual Magnitudes.

REDSHIFT	S BAND	R2 BAND	R3 BAND	R4 BAND	R5 BAND	T BAND	N BAND
4500					15.1	(13.4)	
5000					15.1	(14.9)	
5500				14.9	15.9		
6000			14.4	15.3	16.2		
6500		13.9	14.9	15.7	16.6		(11.8)
7000		14.4	15.2	16.0	(16.9)		
7500		14.7	15.7	16.4			
8000		15.2	16.0				
8500	(13.9)	15.6	16.3				
9000	(14.4)	(16.0)					
9500	(14.9)	(16.3)					
10000		(16.7)					

FIGURE 10

The predicted $m\text{-}\log(cz)$ pattern for field galaxies based upon the Coma α pattern. In the upper figure the Coma pattern is superimposed at five different Hubble velocities. Dashed lines indicate the bands of low population; solid lines indicate dominant populations. The lower figure shows how the S, R3, and R5 bands individually map into the $m\text{-}\log(cz)$ diagram. The mean slope 5 line fit to real field E and SO galaxies is also shown. The key features in the predicted pattern are a steeper than slope 5 cutoff in the dominant populations in near space, a distinct upward bulge or curvature in the distribution centered between magnitude 12 and 13, and a kink in the upper envelope at faint magnitudes where the band pattern now runs out below rather than above the Hubble line slope 5.

map into the m - $\log z$ diagram. In Figure 11 the alternative model representing galaxies in a pure dynamical model is shown. The Coma Cluster has again been taken as the model by representing it at its mean magnitude and redshift with noncorrelated dispersion in both coordinates. This pattern has then been shifted by successive factors of two in distance as for the detailed Coma α pattern.

The two patterns show distinct differences. The dynamical model, as expected, shows a simple smooth expanding envelope. The Coma α pattern on the other hand has several distinct irregular features caused by the shift of the Hubble velocity away from the mean redshift and the apparent slope of the band pattern when mapped into the m - $\log z$ diagram. At very nearby distances the band pattern slopes upward in the m - $\log z$ plot much more steeply than the Hubble relationship. This produces two distinct effects: the bright cutoff of galaxies as volumes become vanishingly small in near space occurs along a slope distinctly steeper than the normal slope 5 and a distinct bulge above the slope 5 line is produced by the high redshift runout along the band pattern above the Hubble velocity.

At greater redshifts the band pattern rotates to become parallel to the standard slope of 5. This eliminates the bulge lying above the Hubble line at bright magnitudes and introduces a decided kink into the m - $\log z$ relationship. At still greater distances the band pattern slopes downward across the Hubble line. The range in the logarithm of the redshift is now too small, however, to produce marked effects. A slight bulge below the Hubble line should occur but selection against faint galaxies should mask most of this effect. At very large distances there are no differences between the band pattern and dispersion model.

In the lower part of Figure 11 the dispersion model envelope, defined by the Coma Cluster fit, is shown superimposed upon the observed m - $\log z$ diagram for all field E and SO galaxies for which both redshifts and magnitudes are given in the Humason, Mayall and Sandage (1956) redshift catalog. The magnitudes given by HMS are P values and have been related to the visual magnitudes in this paper by assuming a uniform color index of 1.0. No K corrections have been applied since they are small at low redshifts and will not significantly change the observed pattern. The fit of the dispersion model to the observations is relatively poor. The dispersion model does not account for either the concentration of points above the predicted

FIGURE 11

The predicted $m\text{-}\log(cz)$ pattern for field galaxies based upon a normal velocity dispersion model. In the lower figure the model is compared with observed field E and SO galaxies. The model fails to fit both the shape or the location of the field pattern.

region or the shape of the observed upper envelope. Incompleteness prevents any comparison of the lower part of the diagram. To fit a dispersion model one must introduce anisotropy in motion with distance or nonuniformity in the luminosity function with distance.

Figure 12 shows the comparison with the Coma α band pattern model. In the upper part the observed data on field galaxies is shown with just the Coma α pattern and shows that the Coma data smoothly extends the field galaxy diagram and that the slope of the field galaxy m -log z diagram matches the Coma band slope where they come together. The lower part of Figure 12 shows the observed m -log z diagram for field galaxies with the band pattern envelope for various distances. The match between the predicted and observed pattern is good in the form of the upper envelope, including the slope of the bright cutoff which is due to the characteristic band slope, the location of the bulge above the standard Hubble line produced by the high redshift runout above the low Hubble velocity, and the kink between magnitude 14-16 where the band slopes cross over the mean Hubble line with less than slope 5. The comparison of field galaxies with the Coma pattern is, therefore, consistent without the introduction of variation in the Hubble law or luminosity functions with distance.

One other observational consequence of the observed redshift-magnitude band pattern relates to observed differences in physical pairs. If the magnitude difference between two associated galaxies is relatively large, then the fainter one should statistically show a systematically higher redshift and perhaps a tendency away from elliptical morphology. This follows from the fact that for associated objects the band pattern slopes to higher redshifts as one moves fainter and the elliptical types appear to avoid the higher redshifts. This observation is consistent with the investigations of such galaxies as NGC7603 by Arp (1971). The dispersion model, with or without anisotropy, cannot produce such an effect.

DISCUSSION

There are no known physical mechanisms which could produce a correlation of redshift and magnitude or redshift and morphology of the multiple valued nature suggested in this paper. The approach to the study of such a relationship is, therefore, completely empirical and consists first of establishing statistical confidence in the pattern, second of making predictions of

FIGURE 12

The observed $m\text{-log}(cz)$ pattern for field E and SO galaxies compared to the Coma band pattern model as shown in Figure 10. In the upper figure the placement of the Coma band pattern is shown to form a direct extension of the field galaxy pattern. The lower figure shows that the dominant R2-R4 Coma bands map directly into the region of the diagram occupied by most field galaxies. The bright but uncommon S band galaxies are important only at larger volumes.

observable tests such as the field galaxy comparison in the previous section, and thirdly considering the effect of the pattern model on some of the major theoretical problems encountered by the standard dynamical models for formation and interaction of galaxies. In this final section some of the problems of the third type will be briefly considered.

The gravitational stability of clusters or groups of galaxies will be considered first. Figure 13 is a projection of the Coma patterns along the band slope direction and shows the basic clumping which was tested for significance previously. The existence of the separate bands is here ascribed to some intrinsic effect which is not understood. If this intrinsic effect does not have significant internal scatter or width of its own then the apparent width of the bands must be due to observational scatter in the magnitudes and redshifts and residual true Doppler motion of the mass centers and should show a normal distribution of points about the band clusters. In the lower part of Figure 13 the four major individual bands are superimposed about their means. The result is a remarkably good normal distribution with dispersion 0.14 in the units of the unity dispersion function for the total distribution. A 7-cell χ^2 test given in Table V shows that the residuals are normally distributed.

The mean error in magnitudes or redshift for the individual data points is not known precisely but is estimated to be close to ± 100 km/sec in redshift and optimistically ± 0.05 in magnitude. The magnitude dispersion is greater for barred galaxies where the Rood and Baum photometry is a composite of bar and envelope which complicates the derivation of the final magnitudes and produces greater uncertainty. The barred objects include eight galaxies with deviations greater than 1σ and only six less than 1σ in the distributions shown in Figure 13 as would be expected from the less certain photometry. If we consider only the E and SO galaxies in the four well defined bands R2-R5, the composite Coma α pattern has an observed dispersion of only 0.12 units and a predicted dispersion from the redshift and magnitude uncertainty of 0.09. Addition of more than 75 to the redshift dispersion will exceed the observed dispersion. Thus, 140 is an optimistic upper limit to the true Doppler velocity dispersion in the Coma Cluster. Any increase in the magnitude or redshift uncertainties will decrease the limit as will any scatter in the underlying "intrinsic" redshift and uncertainties arising from combining the several bands.

FIGURE 13

The projection of the Coma α banded pattern at 51° . In the upper figure the bands are shown individually while in the lower figure the four dominant bands are superimposed about their mean values to show that within the bands the points are normally distributed with a dispersion of less than one quarter of the band spacing. Symbols have the same meaning for galaxy morphology as in Figure 1.

TABLE V -- The Distribution of Galaxies Within the R2-R5 Band Structure
Compared to the Normal Distribution

BOUNDARIES	DISTRIBUTION
- ∞	10
-1.068	10
-0.566	8
-0.180	9
+0.180	5
+0.566	15
+1.068	8
+ ∞	
χ^2	6.0
P	0.2

If the Virial Theorem is applied using the residual dispersion just calculated, the Coma Cluster is not unstable. The residual dispersion is at most $1/9$ of the total dispersion, thus, the Virial mass of Coma is reduced by a factor of at least 80 yielding mean M/L values of 10 or less for the Coma galaxies. If anything, this figure is lower than expected. Since the observed total "intrinsic" dispersion is much larger than the Doppler "residual" dispersion, apparent mass defects calculated for a set of clusters or groups by comparing the Virial Theorem mass based upon total dispersion with galaxy counts should vary nearly directly as the square of the total dispersion, a result which is consistent with observations (Rood, et. al., 1970).

As a second dynamical problem we consider the uniformity of the Hubble law as perturbed by systematic and random motions of entire groups or clusters of galaxies. If a large component of the internal scatter in redshift within a cluster is not due to real center-of-mass motion but to some other intrinsic phenomenon, then the mean redshift of a group can differ appreciably from the true mean Hubble motion of the group. The most direct evidence for this is found in the mean redshift differences between the Virgo E and S clouds and between the Coma E and non-E types. Detailed matching of redshift-magnitude diagrams between the Virgo and Coma Clusters (Tifft, 1971b) also supports the concept that mean redshift is not the same as the Hubble velocity. The Coma Hubble velocity is tentatively considerably less than the mean redshift. It was further noted that when this assumption is made the field galaxy $m\text{-log}z$ diagram prediction matches the observed diagram as discussed in the previous section.

There is some evidence that whereas the mean redshift of clusters like Coma exceeds the Hubble velocity the mean redshift of clusters like Virgo may be closer to the Hubble velocity (Tifft, 1971b) and for nearby sparse groups such as Sculptor the Hubble velocity may exceed the mean redshift (Tifft, in preparation). Since there is a distinct selection effect with distance, a transition from local small groups to giant Coma-like clusters beyond 100 mpc, the assumption that mean redshift represents real Hubble velocity can introduce an apparent anisotropy with H appearing to increase with distance consistent with observations (de Vaucouleurs, 1970). Thus, whether for local or cosmological purposes the assumption that the Hubble velocity is equivalent to the mean redshift of a group is a questionable

assumption.

There are numerous other fundamental concepts to which the new concepts of the redshift interpretation relates, including the origin and evolution of galaxies by expansion from dense cores rather than collapse from a tenuous medium, the applicability of laboratory scale gravitational physics to the intergalactic scale, and the derivation of cosmological models. In most cases it is premature to discuss such subjects, however, the statistical significance of the Coma pattern and its apparent success in matching patterns of redshift and magnitude for field galaxies and double galaxies and offering alternatives to the instability and anisotropy problems suggest that the concept must be seriously considered.

ACKNOWLEDGEMENTS

The author wishes to acknowledge useful discussions on statistical testing with John Cocke and R. J. Weymann. Dr. Cocke also provided the random samples which were used to evaluate the statistical testing methods. Dr. H. J. Rood provided unpublished detailed photometric data on galaxies in the Coma Cluster.

REFERENCES

- Arp, H. 1971, *Astrophysical Lett.* 7, 221.
- de Vaucouleurs, G. 1961, *Ap.J. Supp.* 6, No. 56, 213.
- de Vaucouleurs, G. and de Vaucouleurs, A. 1964, Reference Catalog of Bright Galaxies, Univ. of Texas Press, Austin, Texas.
- de Vaucouleurs, G. 1970, University of Texas, McDonald Obs., Preprint No. 9.
- Hoel, P. G. 1954, Introduction to Mathematical Statistics, John Wiley and Sons, Inc., New York, 167.
- Humason, M. L., Mayall, N. U., and Sandage, A. R. 1956, *A. J.* 61, 97.
- Kintner, E. C. 1971, *A. J.* 76, 409.
- Kowal, C. T. 1969, *P. A. S. P.* 81, 608.
- Omer, G. C., Page, T. L., and Wilson, A. G. 1965, *A. J.* 70, 440.
- Rood, H. J. and Baum, W. A. 1967, *A. J.* 72, 398.
- Rood, H. J. and Baum, W. A. 1968, *A. J.* 73, 442.
- Rood, H. J. 1969, *Ap. J.* 158, 657.
- Rood, H. J., Rothman, V. C. A., and Turnrose, B. E. 1970, *Ap. J.* 162, 411.
- Tifft, W. G. 1971a, External Galaxies and Quasi Stellar Objects, I. A. U. Symposium 44, D. S. Evans ed., 369.
- Tifft, W. G. 1971b, University of Arizona, Steward Obs., Preprint No. 37.