

THE COMA CLUSTER OF GALAXIES

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General remarks.—The following study is a part of a long series of investigations which the author has carried out with the 18-inch and the 48-inch schmidt telescopes to analyze the geometrical distribution of the member galaxies in large regular and irregular clusters of galaxies. The strict definition of a galaxy as a physical object presents considerable difficulties. The whole of the astronomical literature has actually never produced such a definition. This neglect has resulted in some widely held erroneous views on the luminosity function of galaxies. The principal problem originates in the uncertainty regarding the objects which should be counted as separate entities. There is, for instance, the question of whether Messier 31 and its two companions should be counted as one system or as three. This uncertainty is greatly enhanced through the recent discovery by the author of the existence of intergalactic matter. Vast and often very irregular swarms of stars and other matter exist in the spaces between the conventional spiral, elliptical, and irregular galaxies. It is not at all clear how such swarms should be incorporated into any distribution function of galaxies. All of these questions must be cleared up in a comprehensive theory of the luminosity function of galaxies.

In the present analysis we shall largely disregard the problems just mentioned. We shall simply count galaxies more or less naïvely, as has been done in the past. This procedure is quite sufficient to demonstrate that most of the counts of galaxies made with the large reflectors are subject to grave doubts. In particular the luminosity function of galaxies as derived from these counts is erroneous. For instance, the luminosity function given by Hubble¹ has a sharp maximum at the absolute photographic magnitude $M_p \cong -14.2$. The present writer has shown pre-

¹ *The Realm of the Nebulae* (New Haven: Yale University Press, 1936), and *Ap. J.*, **84**, 158, 270, 1936.

viously that no such maximum exists in the range $M_p < -12$. Simple theory indicates that no maximum can exist.² Independent galaxies, stellar systems, and aggregations of matter in general become more frequent the smaller their material content. The results presented here strongly support these conclusions.

As we have stated, we shall simply count as individual galaxies those clearly discernible luminous patches which are totally surrounded by far less luminous areas (general uniform background, or individual stars of our own galaxy). We shall assume these patches to be extragalactic objects except in those cases where specific characteristics betray them to be members of our galaxy such as planetary nebulae, local star clusters, and so on. This procedure, although theoretically not entirely satisfactory, will enable us to show that the large clusters of galaxies "grow" not only in population but also in geometrical dimensions as one maps the distribution of ever fainter member galaxies. Also, the previously reported result³ is confirmed—that the tendency toward clustering becomes the more pronounced the brighter the objects. Galaxies of different absolute brightness are therefore partly segregated. This is the principal reason why, with the limited field of the large reflectors, completely erroneous luminosity functions were derived.

Counts of galaxies in the Coma cluster with the 48-inch schmidt telescope.—The Coma cluster of galaxies is located at $\alpha = 12^h 55^m$, $\delta = +28^\circ 20'$ (1950). Its two brightest members, according to Stebbins and Whitford, have the apparent photographic magnitudes $m_p = 13.2$ and 13.5 . Originally it was thought to be about 1.7° in diameter. The counts with the 18-inch schmidt telescope revealed it to be at least 5° across while the apparent diameter derived from the counts presented here is of the order of 12° . Assuming the distance of the cluster to be 13.8×10^6 parsecs, as derived by Hubble and Humason,⁴ the actual diameter of the Coma cluster is of the order of at least 2.8×10^6 parsecs, or about nine million light-years.

The results presented here must be regarded as preliminary.

² *Phys. Rev.*, **61**, 489, 1942; *Observatory*, **68**, 845, 1948.

³ F. Zwicky, *Ap. J.*, **95**, 555, 1942.

⁴ *Ap. J.*, **74**, 43, 1931.

There exists probably no possibility of improving these results for a few years to come, since the 48-inch schmidt telescope is not available for investigations of this character until the general sky survey has been completed. As has been pointed out before and as has become clear again in the course of this investigation, a truly satisfactory coverage of the Coma cluster with the 48-inch schmidt telescope will require at least five independent fields (one centered on the cluster and one in each of the four quadrants). Furthermore, counts of this character become much more reliable when each field is covered by several plates of excellent quality. It is therefore estimated that at least thirty plates taken under conditions of good seeing and darkness of the sky will be needed for a final analysis. For the reasons stated, such an ultimate analysis cannot be carried through for a long time to come. However, with the plates available, results of considerable interest have been obtained.

The 14×14 -inch plates of the 48-inch schmidt telescope cover about 36 square degrees. The fields available were :

1. Center : one fairly good plate
2. Southeast quadrant : one good plate
3. Southwest quadrant : one good plate
4. Northwest quadrant : one fairly good plate
5. Northeast quadrant : no plate except that part of the quadrant covered by the central plate

The average number of galaxies per square degree in the regions which are beyond 6° from the center of the cluster and which are covered by our plates are respectively 165, 183, and 190 in the NW, SE, and SW quadrants. We adopt the average of these three values as the number of galaxies N_f per square degree in the general field, that is :

$$N_f = 179 \text{ galaxies/square degree.}$$

The quantity $N_r - N_f$ listed in the last column thus is the average number of cluster galaxies per square degree in the rings between the indicated limits.

Since our central plate covers the NE quadrant to a distance of only three degrees of arc from the center, no actual counts of

TABLE I
 COUNTS OF GALAXIES IN THE COMA CLUSTER WITH THE 48-INCH SCHMIDT
 TELESCOPE. LIMITING PHOTOGRAPHIC MAGNITUDE
 ABOUT 19.0

Ring Limits	Quadrants				n_r^*	N_r^\dagger	$N_r - N_f^\ddagger$
	NW	NE	SE	SW			
0' - 5'	17	16	14	15	62	2843	2664
5 - 10	29	27	27	42	125	1911	1732
10 - 15	33	42	37	45	157	1440	1261
15 - 20	39	32	34	57	162	1061	882
20 - 25	40	29	33	50	152	775	596
25 - 30	30	51	41	55	177	738	559
30 - 35	47	39	43	52	181	639	460
35 - 40	34	61	33	61	189	578	399
40 - 45	46	40	32	62	180	486	307
45 - 50	37	61	54	72	224	541	362
50 - 55	36	60	40	73	209	456	277
55 - 60	34	46	91	84	255	508	329
60 - 70	83	89	136	150	458	404	225
70 - 80	98	105	146	130	479	366	187
80 - 90	88	122	118	115	443	299	120
90 - 100	105	120	143	145	513	309	130
100 - 110	122	156	134	98	510	278	99
110 - 120	130	134	170	145	579	289	110
120 - 130	167	159	170	155	651	299	120
130 - 140	132	176	170	190	668	284	105
140 - 150	149	166	153	173	641	253	74
150 - 160	153	207	134	224	718	265	86
160 - 170	195	220	161	185	761	264	85
170 - 180	250	197	190	210	847	277	98
180 - 190	296	(233)	209	195	933	289	110
190 - 200	327	(245)	200	207	979	288	109
200 - 210	356	(290)	268	246	1160	324	145
210 - 220	252	(249)	259	235	995	265	86
220 - 230	254	(256)	240	274	1024	261	82
230 - 240	326	(264)	250	315	1055	234	55
240 - 270	736	(850)	798	1017	3401	255	76
270 - 300	809	(825)	824	843	3301	221	42
300 - 330	866	(844)	863	804	3377	205	26
330 - 360	966	(914)	936	850	3666	203	24
Total	7182	7325	7151	7574	29,232		

* n_r = total number of galaxies in ring between indicated limits.

† N_r = average number of galaxies per square degree in each ring.

‡ $N_r - N_f$ = number of cluster galaxies per square degree.

galaxies beyond this limit in the NE quadrant are available. The numbers of galaxies listed in the NE column in parentheses are the average numbers of galaxies per indicated ring and quadrant derived from the counts in the NW, SE, and SW quadrants.

It is seen from the small quadrant fluctuations of the numbers of galaxies that the Coma cluster possesses high spherical symmetry. The numbers $N_r - N_f$ of cluster galaxies as a function of the distance from the center likewise present a smooth sequence which supports the view that the Coma cluster possesses great regularity.

The total number of galaxies counted within a circle of 6° radius is 29,232. From these, $6^2 \pi \times N_f = 20,244$ field galaxies must be subtracted in order to arrive at the total number N_{ce} of cluster galaxies within the said circle of 6° radius.

Thus

$$N_{ce} = 8988 \text{ cluster galaxies.}$$

Not too much meaning should be attached to our statement that N_{ce} represents the count of cluster galaxies to the limiting photographic magnitude $m_p = 19.0$. This limit refers to nebulae of adequate size and surface brightness. Very compact galaxies at great distances will be mistaken for individual stars even if they are brighter than $m_p = 19.0$. Likewise, very extended nebulae of low surface brightness will be missed entirely even if their brightness is very much greater than $m_p = 19.0$. For these reasons, all of the cosmological interpretations given by Hubble⁵ and others to counts of faint galaxies are subject to drastic revisions.

Comparison of the numbers of bright and of faint cluster galaxies.—In Table II we list the numbers per square degree of bright cluster galaxies as obtained with the 18-inch schmidt telescope and the numbers of faint nebulae obtained with the 48-inch telescope which are not recorded by the 18-inch schmidt. Roughly, therefore, the bright galaxies in the Coma cluster lie in the range of photographic magnitude $+13 < m_p < +16.5$, and the faint galaxies are in the range $+16.5 < m_p < +19$.

The decrease of R with the distance from the center of the cluster drastically demonstrates the increasing segregation of faint

⁵ *Ap. J.*, 82, 302, 1935.

from bright cluster galaxies. This is of course precisely what one expects for the distribution of heavy and light individual masses in a statistically stable assembly to which the general (Boltzmann-Gibbs) laws of statistical mechanics can be applied.

TABLE II

RATIO R OF THE NUMBERS OF GALAXIES PER SQUARE DEGREE IN RESPECTIVE RANGES OF PHOTOGRAPHIC MAGNITUDES $13 \leq m_p \leq 16.5$ (BRIGHT) AND $16.5 \leq m_p \leq 19$ (FAINT)

Ring Limits	Cluster Galaxies per Square Degree		Ratio R
	Bright	Faint	
0' - 5'	1431	1233	1.16
5 - 10	643	1089	0.59
10 - 15	485	776	0.62
15 - 20	285	597	0.47
20 - 25	193	403	0.48
25 - 30	193	366	0.53
30 - 35	81	379	0.21
35 - 40	120	279	0.43
40 - 45	77	230	0.33
45 - 50	95	267	0.35
50 - 55	75	202	0.37
55 - 60	66	263	0.25
60 - 70	55	170	0.32
70 - 80	19	168	0.11
80 - 90	15	105	0.14
90 - 100	18	112	0.16
100 - 110	6	93	0.06
110 - 120	12	98	0.12
120 - 130	8	112	0.07
130 - 140	1	104	0.01
140 - 150	6	68	0.09
150 - 160	2	84	0.02
160 - 170	0	85	0.00
170 - 180	0	98	0.00
180 - 360	0	—*	0.00

* For individual 10'-ring values see the last column of Table I.

The ratio of the total numbers of galaxies in the Coma cluster in the bright and faint ranges tabulated in Table II is

$$670/8318 = 0.085.$$

This clearly shows that the maximum in the distribution func-

tion which Hubble⁴ found at $m_p = 17.0$ is nonexistent and had its origin in selective counting near the center of the cluster.

The distance modulus of the Coma cluster is

$$\mu = m - M = 30.7.$$

Our results therefore show that in the range of absolute photographic magnitudes M_p

$$-11.8 < M_p < -17.7$$

the luminosity function of the member galaxies of the Coma cluster possesses no maximum. This conclusion has been differentially checked through repeated counting of galaxies on the same plates with optical magnifications three, five, and eight. Higher powers are dangerous since stars may then be mistaken for galaxies. Also objects of faint surface brightness will be missed. The use of several of the indicated magnifications, however, is very advisable inasmuch as it is equivalent to counting to different limiting magnitudes. This procedure clearly reveals that the luminosity function of the Coma cluster galaxies is monotonely increasing with decreasing brightness in the range of magnitudes discussed in this study.

One of the most interesting discoveries made in the course of this investigation is the observation of an extended mass of luminous intergalactic matter of very low surface brightness. The objects which constitute this matter must be considered as the faintest individual members of the cluster. They indicate that the luminosity function, at the faint end, assumes very great values, as expected. The isophotal contours of the intergalactic matter spread throughout the cluster are now being analyzed in various color ranges. It appears, however, that even on medium-good plates the extension of the luminous matter which is concentrated near the center of the cluster and which can easily be seen is of the order of 500,000 light-years. The problem of the effects on the apparent distribution of galaxies of both dark interstellar and intergalactic matter will require a special and thorough examination, which we shall not discuss here.

Field contour lines.—For a bird's-eye view of the distribution of galaxies in the field of the Coma cluster the topological repre-

over-all fluctuations in the general background and the superposed random fluctuations of a stationary globular cluster.

There is a slight tendency for the counts in the outlying quadrant plates to be the largest along the diagonals, especially the one from SE to NW. This may be accidental or it may indicate the existence of rotation of the cluster as a whole. This can be decided only when many more good plates will be available.

As to the general field around the cluster, the following three possibilities may be visualized:

First case: The general central field seems surrounded by a "groove" comprising 24 square degrees with an average of 165 galaxies each. The five indicated rises to over 200 galaxies/square degree may be caused by random "hills" or "mesas" in the general field. This assumption results in the largest possible number of galaxies per square degree around the Coma cluster and corresponds to the value $N_f = 179$ per square degree for the number of field galaxies.

Second case: It may be that the hills mentioned in case one are humps on a general radial slope. The cluster will be even greater in diameter than the twelve degrees we have arrived at in this study. Also its population may be considerably increased, essentially because the actual number of field galaxies to be subtracted from the total counts will be less than $N_f = 179$ /square degree, and the area involved will be larger.

Third case: The local increases in the specific numbers of galaxies at the edges of our fields may indicate the presence of actual clusters of galaxies neighboring to the Coma cluster. Instead of $N_f = 179$ we then should choose $N_f = 165$ galaxies/square degree for the average number of field galaxies, and the total population of the Coma cluster in the range $13 < m_p < 19$ would become

$$N_{ce} + 14 \times 6^2 \pi = 10,571 \text{ galaxies.}$$

Which one of the three cases actually prevails can be decided only after one dozen fields adjacent and outside of the square of 12° on edge which we have discussed will be available. It thus becomes clear that a final analysis of the Coma cluster with the 48-inch schmidt telescope is an undertaking of considerable pro-

portions. However, the essential conclusions arrived at in this preliminary analysis will remain unaltered, since we have adopted for our quantitative discussion the most conservative of the three possible alternatives concerning the qualitative and quantitative character of the general field of galaxies surrounding the Coma cluster.

Conclusions.—The conclusions arrived at in the present investigation support in a very pointed way the results obtained by the author previously in a long series of observational and theoretical studies.⁶ Some of the essential points are as follows.

As one analyzes the distribution of ever fainter cluster galaxies, the clusters grow. The Coma cluster in the light of galaxies of the 19th apparent photographic magnitude is at least nine million light-years in diameter and contains to this limiting magnitude at least nine thousand galaxies.

The Coma cluster represents a grouping of galaxies of great spherical regularity. The radial distribution function of the brighter nebulae is closely approximated by the theoretical distribution of mass in an Emden isothermal sphere. The fainter nebulae are relatively more and more frequent as the distance from the center of the cluster increases.

Because of the latter fact, the luminosity function of the Coma cluster nebulae monotonely increases in the range of apparent photographic magnitudes $+13.0 < m_p < +19.0$. This clearly is in contradiction with the luminosity functions derived originally from the work with the large Mount Wilson reflectors.¹ This contradiction is brought to a particularly sharp focus through the discovery of luminous intergalactic matter concentrated generally and differentially around the center of the cluster and the brightest (most massive) galaxies, respectively.

To round out this investigation, the 48-inch schmidt telescope will have to be used extensively to study a more extended region around the center of the Coma cluster and the 200-inch telescope will be necessary to check up on individual features and before all

⁶ *Ap. J.*, **86**, 217, 1937; *Pub. A.S.P.*, **50**, 218, 1938; *Proc. Nat. Acad. Sc.*, **25**, 604, 1939; **28**, 150, 1942; **28**, 317, 1942; **28**, 355, 1942; *ASP Leaflet* No. 163, 1942; *Pub. A.S.P.*, **54**, 185, 1942.

to allow the mapping on a sufficiently large scale of the isophotal contours of the intergalactic matter in the cluster. Unfortunately for some time to come neither of the two telescopes will be available for the solution of these problems, other tasks having been given precedence. The 100-inch reflector on Mount Wilson, with a very dark sky, may achieve some preliminary results on the isophotal contours of intergalactic matter in clusters or elsewhere. Under the present conditions of a brightly lit sky due to the lights of Los Angeles, however, the chances for such observations to succeed are practically nil, even if co-operation among all observers could be established.

I am indebted to Dr. A. G. Wilson for the loan of some plates which he obtained with the 48-inch schmidt telescope. Both Eastman 103A-O and 103A-E emulsions were used, the latter in combination with a red plexiglas filter.