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SPECTRA AND OTHER CHARACTERISTICS OF INTERCONNECTED GALAXIES AND OF GALAXIES IN GROUPS AND IN CLUSTERS. III

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ABSTRACT

An observational and theoretical analysis of the medium compact cluster of galaxies around NGC 541 has been initiated. The cluster, in an area of four square degrees, contains about five hundred galaxies whose apparent photographic magnitudes lie in the range $13.4 < m_p < 19.0$. The positions and magnitudes of eighty-five cluster members have been determined. Their distribution confirms the exponential luminosity function which was previously established from the study of the populations of 704 rich clusters of galaxies. The surface brightness of the above-mentioned cluster galaxies is plotted in dependence upon their magnitudes, indicating both decreasing and increasing surface brightness with increasing magnitude. This is related to the discovery, recently made, of a relatively great number of very compact and absolutely faint galaxies. Structural and spectral types of the galaxies of the cluster studied are remarkably uniform, pointing to a very old age and a stationary character of the cluster. The average symbolic velocity of recession of forty-one cluster galaxies is $\langle V_s \rangle = 5321$ km/sec and the dispersion $\langle (\Delta V_s)^2 \rangle^{1/2}$ is 406 km/sec. From the analysis of the spatial distribution of the values of V_s it follows that the cluster is not sensibly rotating, although it is elliptical in shape. From the spatial distribution of the values of the velocity dispersion it may be concluded that the cluster is not expanding. The fact that the fainter galaxies have a greater velocity dispersion than the brighter galaxies indicates a tendency toward the establishment of equipartition of energy among at least the brighter cluster galaxies.

The indicative distance of the cluster, the indicative absolute photographic magnitude of its brightest member galaxy and the relative indicative mass-luminsity ratio, as determined from the Virial theorem, are respectively, $D^* = 53.2$ million pc, $M^* = -20.2$ and $\mathfrak{R} \sim 100$. This value of $\mathfrak{R}$ lies midway between those found for individual bright galaxies and those of very richly populated compact clusters of galaxies. Suggestions are discussed of how $\mathfrak{R}$ might be found to be drastically reduced because of the presence of various types of as yet undetected types of intergalactic matter.

For the past four years the cluster around NGC 541 has been searched for supernovae with the 48-inch Schmidt telescope. As a result of this search one supernova of Type I has been found in the member galaxy IC 1703 of the cluster on January 22, 1963.

I. THE MEDIUM COMPACT CLUSTER AROUND NGC 541

As stated in Papers I and II (Zwicky and Humason 1960, 1961) of this series, one of the purposes of our investigations is to establish the values of $h\mathfrak{M}_t = \mathfrak{M}_t^*$ for ever larger groups and clusters of galaxies, where $\mathfrak{M}_t$ is the total mass of the group or cluster and h is the scale factor in the universal red-shift relation as defined by equations (1) and (2). If a spectral line of wavelength λ is shifted to $\lambda + \Delta\lambda$, we call $V_s = c\,\Delta\lambda/\lambda$ the symbolic velocity of recession of the light emitting galaxy. We assume that for the range 2000 km/sec $< V_s <$ 60000 km/sec the distance D of a galaxy is given by

$$D = V_s/H\,, \tag{1}$$

where H is the redshift constant; and we write

$$H = h\,H_0\,, \tag{2}$$

where h is a number of the order of unity and H_0 is equal to 100 km/sec per million parsecs. Therefore,

$$D = 10^4 \frac{V_s}{h}\,, \tag{3}$$

where the distance D is obtained in parsecs if V_s is expressed in units of kilometers per second. The indicative distance is

$$D^* = 10^4 V_s . \tag{3a}$$

The cluster around NGC 541 was chosen for our investigation because it is fairly isolated. Our expectation that its fifty brightest member galaxies could be pinpointed with fair certainy by direct inspection of plates photographed with the 48-inch Schmidt telescope was borne out by the results achieved. Structurally the cluster around NGC 541 has the following characteristics.

1. In the terminology used in the Volume I of *Catalogue of Galaxies and of Clusters of Galaxies* (Zwicky, Herzog, and Wild 1961) the cluster around NGC 541 is a medium compact cluster, that is, it contains one central condensation of about two dozen galaxies which are separated by two or three diameters. In the center of a compact cluster a dozen galaxies or so are in actual "contact" with one another. The cluster also contains some lesser peripheral condensations, a common feature of medium compact clusters.
2. The cluster is roughly centered at the elliptical galaxy NGC 541. This object lies in the middle of a long arrow-shaped luminous intergalactic cloud whose base is near the double galaxy NGC 545/547 and whose point lies at the single galaxy NGC 535 (see Fig. 1).
3. The cluster-member galaxies are rather uniformly of the elliptical type and their spectra of the average class G5.
4. The radio source 3C40 appears to be associated either with the double galaxy NGC 545/547, or with the luminous intergalactic cloud which envelops the whole center of the cluster. The radio source has two main concentrations, as indicated in Figures 1 and 2 by dotted circles (Maltby, Matthews, and Moffet 1963).

II. DISTRIBUTION OF GALAXIES IN THE FIELD OF THE CLUSTER OF GALAXIES AROUND NGC 541

Figure 2 shows the distribution of eighty-five of the brighter galaxies under investigation. Although the investigation of the spectra of these galaxies is still in progress, it may be stated that they possess symbolic velocities of recession which indicate that most of them are members of the cluster under discussion.

III. DISTRIBUTION IN LUMINOSITY OF 85 OF THE BRIGHTER GALAXIES IN THE FIELD OF THE CLUSTER AROUND NGC 541

In Table 1 the positions and photographic magnitudes of eighty-five of the brighter galaxies in a field which covers about twelve square degrees around NGC 541 are listed. The magnitudes were determined by Dr. E. Herzog from "Schraffur" films obtained with the 18-inch Schmidt telescope on Palomar Mountain on the same system as the magnitudes of galaxies in the *Catalogue of Galaxies and Clusters of Galaxies* by F. Zwicky, E. Herzog, and P. Wild (1961). Whenever possible the identification of the galaxies that have NGC and IC numbers is also given. For many of the numbers in the NGC and IC catalogues, however, no counterparts can be found on our plates.

In Figure 3 we have plotted the distribution in apparent photographic magnitudes of the eighty-five galaxies listed in Table 1. An average luminosity function for rich clusters of galaxies was derived some years ago from a study of 704 clusters located at distances for which the symbolic velocity of recession lies in the range $0 < V_s < 100000$ km/sec. If $m_{\max}$ is the apparent photographic magnitude of the brightest galaxy in the cluster, then the average number of galaxies in the said rich clusters in the range from $m_{\max}$ to m is (Zwicky 1957)

$$\langle n_{\rm cl} \rangle (\Delta m) = k[10^{\Delta m/5} - 1] , \tag{4}$$

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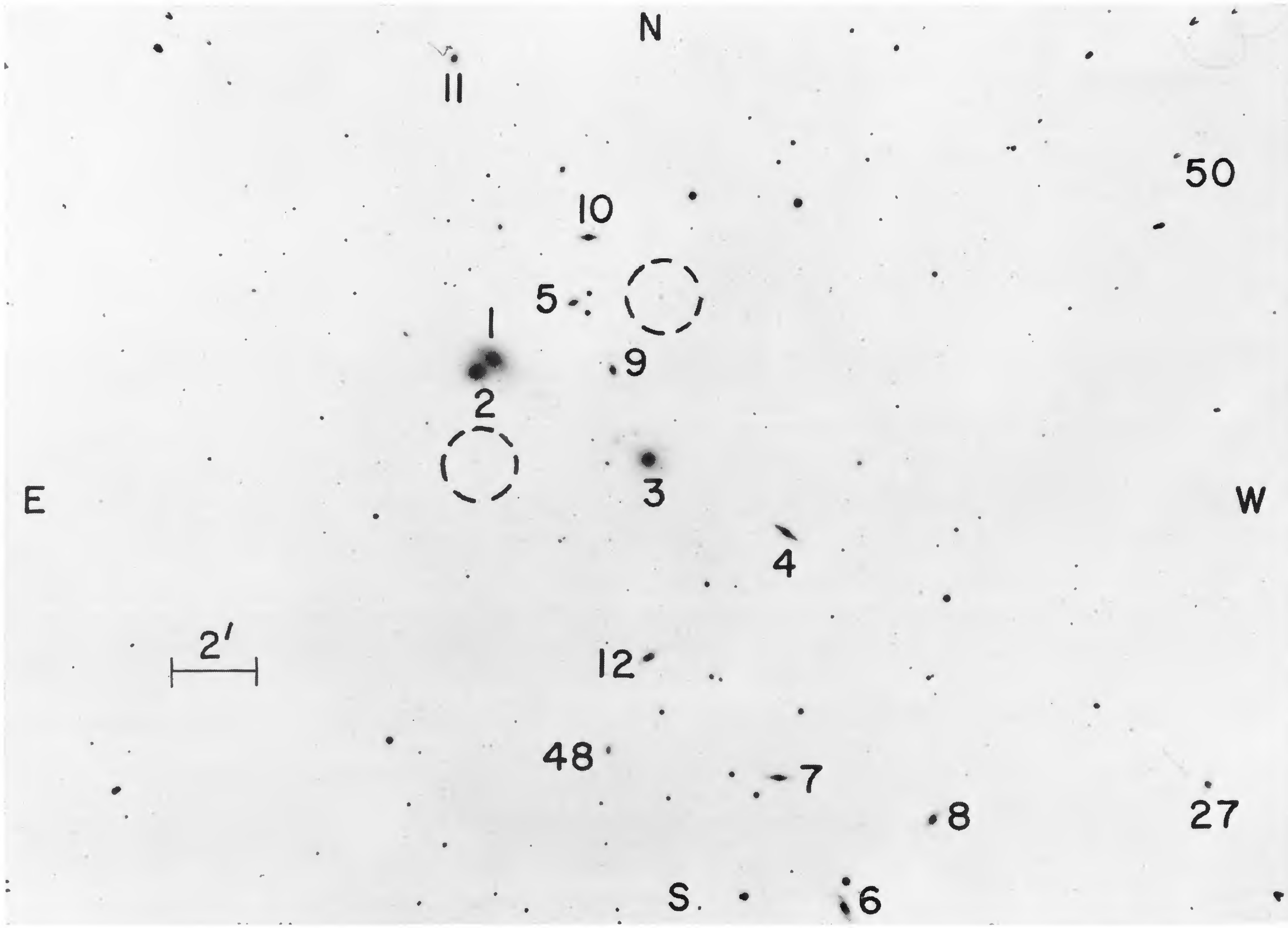

FIG. 1.—Central part of the cluster of galaxies around NGC 541. Photograph obtained with the 200-inch telescope on emulsion 103a-O, exposure 45 min. Scale is as indicated. The two main concentrations of the radio source 3C40 are indicated by dashed circles.

where $\Delta m = m - m_{\max}$ and $k \cong 16.0$. For less-populated clusters we may expect k to be smaller than 16.0. Indeed the dashed theoretical curve corresponds to a value $k = 6.0$. For all galaxies whose photographic magnitudes are in the range $13.0 < m <$ 15 0 the luminosity function (4) well represents the data. For $m > 15.0$ only a minor fraction of the cluster galaxies has been considered for spectral investigations. A statistical investigation of all galaxies to the limit of the plates obtained with the 48-inch Schmidt telescope, however, shows that a relation of the type (4) well represents the luminosity function in the range $13.0 < m < 18.0$ of the galaxies in our cluster. The luminosity function can therefore neither be represented by a Gaussian error function, as E. P. Hubble originally stated, nor are there any reproducible secondary maxima or any change of slope at the bright end, as it has recently been claimed by G. Abell (1961).

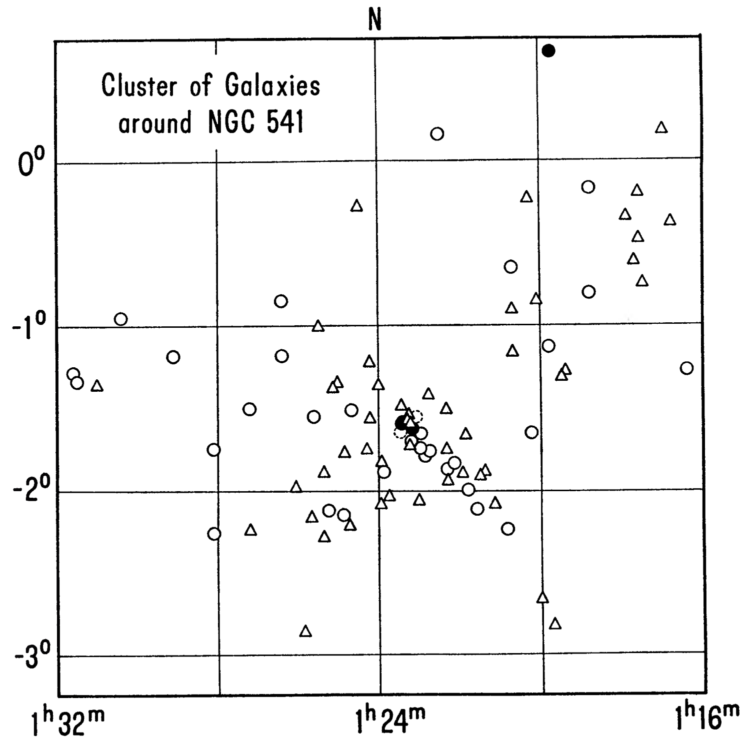

FIG. 2.—Plot of eighty-five of the brighter galaxies in the field of the cluster around NGC 541. Abscissae and ordinates indicate right ascension and declination for the epoch 1950.0. The photographic magnitudes are indicated by the symbols: full circle $13.0 < m_p \leq 14.0$; open circle $14.0 < m_p \leq 15.0$; triangle $15.0 < m_p$. The two broken circles, north preceding and south following the double galaxy NGC 545/547, represent the two lobes of concentration of the cosmic radio source 3C40.

An ultimate decision on the character of the luminosity function of the galaxies in clusters will only be possible when hundreds of symbolic velocities of recession of galaxies in each of a few representative clusters will be available. To this end we have been striving to photograph the spectra of galaxies in the cluster discussed here as well as in the classical Fornax I, Cancer, Hydra I, and Coma clusters and in two clusters located at (epoch 1950.0) $\alpha = 11^h8^m12^s$, $\delta = +28°57'$ and $\alpha = 11^h13^m48^s$, $\delta = +29°32'$, respectively. We have also discovered in the meantime that there exist exceedingly compact spherical and elliptical galaxies whose images, even on plates obtained with the 48-inch Schmidt telescope, have until recently been mistaken for images of stars. Just how much such ultracompact stellar systems contribute to the fainter end of the luminosity function remains to be investigated.

TABLE 1

RIGHT ASCENSIONS, DECLINATIONS (EPOCH 1950 0), AND APPARENT PHOTOGRAPHIC MAGNITUDES m_p OF EIGHTY-FIVE OF THE BRIGHTER GALAXIES IN THE CLUSTER AROUND NGC 541

Galaxy	NGC	Right Ascension	Declination	m_p
1	545	$01^h 23^m 4$	−01° 35′	13 7
2	547	01 23 4	−01 35	13 4
3	541	01 23 2	−01 37	14 0
4	535	01 23 0	−01 39	14 9
5	. . .	01 23 3	−01 34	15 2
6	538	01 22 9	−01 48	14 7
7		01 23 0	−01 45	14 8
8		01 22 8	−01 46	14 8
9		01 23 2	−01 35	15 2
10	. . .	01 23 3	−01 32	15 0
11	598	01 23 5	−01 29	15 1
12	. . . .	01 23 2	−01 42	14 9
13	IC 106	01 22 1	−01 50	14 5
14		01 21 8	−02 00	14 9
15		01 21 6	−02 07	14 7
16	. . . . . .	01 20 8	−02 14	14 8
17	IC 1703	01 23 9	−01 53	14 9
18	565	01 25 6	−01 32	14 6
19	. .	01 25 0	−01 20	14 8
20	560	01 24 9	−02 09	14 2
21	564	01 25 3	−02 07	14 1
22	497	01 19 8	−01 08	14 1
23	. . . .	01 20 2	−01 39	14 6
24	IC 1696	01 22 3	−01 52	14 7
25	570	01 26 4	−01 11	14 3
26	IC 119	01 25 4	−02 17	15 0
27		01 22 3	−01 45	15 4
28		01 21 9	−01 39	15 7
29		01 22 3	−01 56	15 5
30		01 21 9	−01 53	15 3
31		01 21 4	−01 53	15 5
32		01 21 5	−01 54	15 3
33		01 23 0	−02 03	15 8
34		01 23 7	−02 02	15 6
35		01 24 0	−02 05	15 4
36		01 20 7	−01 09	15 5
37		01 24 2	−01 13	15 2*
38		01 24 0	−01 21	15 6
39		01 24 7	−01 31	14 9
40		01 24 1	−01 33	15 6
41		01 25 1	−01 22	15 1
42		01 24 3	−01 45	16 3
43		01 24 9	−01 46	16 7
44		01 25 4	−01 53	15 7
45	. . . .	01 26 1	−01 58	15 0
46	IC 120	01 25 7	−02 09	15 3
47		01 22 8	−01 26	15 6
48		01 23 2	−01 44	15 8
49		01 24 0	−01 49	15 9
50	. . .	01 22 3	−01 30	16 4
51	558	01 24 7	−02 16	15 1
52		01 21 1	−02 05	15 4
53		01 25 5	−01 00	15 2
54		01 26 4	−00 49	14.5
55		01 24 5	−00 16	15 6
56		01 20 7	−00 54	15 3
57		01 18 8	−00 48	14 6

* Uncertain

TABLE 1—*Continued*

Galaxy	NGC	Right Ascension	Declination	m_p
58		01h16m.4	−01°16′	15 0
59		01 20 0	−02 40	15 2
60		01 19 7	−02 49	15 3
61		01 25 9	−02 51	15 2
62		01 27 2	−02 14	15 4
63		01 28 1	−02 15	14 3
64		01 27 2	−01 30	14 9
65		01 28 6	−01 45	14 8
66		01 29 1	−01 11	14 4
67		01 31 0	−01 21	15 2
68		01 31 5	−01 20	15 0
69		01 31 6	−01 17	14 7
70		01 30 4	−00 57	14 9
71		01 20 7	−00 39	15 0
72	. .	01 22 5	+00 10	14 9
73	493	01 19 7	+00 40	13 8
74		01 20 3	−00 13	15 4
75		01 18 8	−00 10	15 0
76		01 17 6	−00 28	15 6
77		01 17 7	−00 36	15 3
78		01 17 9	−00 20	15 4
79		01 17 6	−00 11	15 3
80		01 20 1	−00 50	15 2
81		01 16 8	−00 22	15 5
82		01 17 5	−00 44	15 7
83		01 19 4	−01 16	15 5
84		01 19 5	−01 18	15 1
85		01 17 0	+00 12	15 6

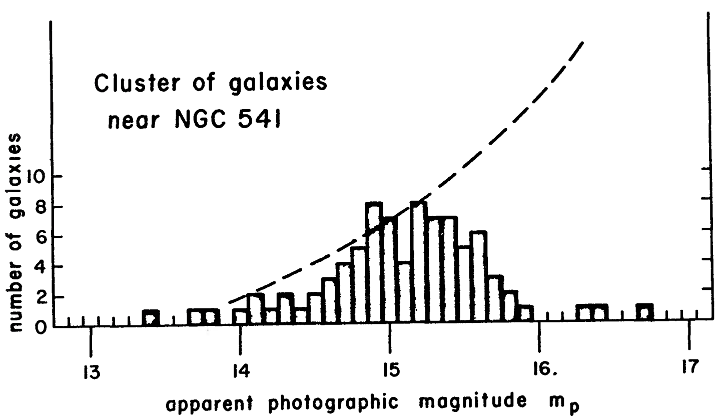

FIG. 3.—Distribution in apparent photographic magnitudes of the eighty-five galaxies listed in Table 1. The dashed curve represents the relation (4) with the constant $K = 6.0$.

IV. APPARENT DIMENSIONS AND SURFACE BRIGHTNESS OF THE BRIGHTER GALAXIES IN THE FIELD OF THE CLUSTER AROUND NGC 541

The largest and the smallest diameters d_1 and d_2 of the eighty-five galaxies listed in Table 1 have been measured on well-exposed plates obtained with the 48-inch Schmidt telescope. These diameters, which refer of course to the restricted boundaries of the images as they clearly delineate themselves from the general sky background, are listed in Table 2. Dimensions are given in units of 10 μ as measured on the original plates (1 mm = 67.2 seconds of arc). The fourth and fifth columns give $A = d_1 \times d_2$ and

$$S = m_p + 2.5 \log_{10} A \,, \tag{5}$$

that is, a quantity which is proportional to the average surface brightness of the galaxies in terms of photographic magnitudes per 100 μ^2 on the original plates taken with the 48-inch Schmidt telescope.

In Figure 4 the surface brightness of eighty-five galaxies in the field of the cluster of galaxies around NGC 541 is plotted in dependence upon their apparent brightness.

From Table 2 it is seen that the average surface brightness of the 85 galaxies listed lies in the range from about 20.50 to 24 69 photographic magnitudes per square second of arc. The latter value corresponds to a surface brightness which is about three magnitudes fainter than the brightness of the night sky on a clear and dark moonless night.

Commenting on the plot in Figure 4, we notice that for the majority of the fainter galaxies the average surface brightness is smaller than that of the brightest galaxies. This is as might be expected for stellar systems which loosen up as their mass becomes lower. It is therefore of interest that some of the fainter systems have higher surface brightness than even the brightest compact elliptical galaxies in our cluster. This finding may be related to the recent discovery (Zwicky 1963*a*, *b*) that there exist exceedingly compact stellar systems and isolated nuclei of galaxies in intergalactic space, which with any of the presently operating wide-angle telescopes, including the 48-inch Schmidt telescope on Palomar Mountain, cannot at all or at least not readily be distinguished from stars.

V. SPECTRA AND SYMBOLIC VELOCITIES OF RECESSION V_s OF FORTY-THREE GALAXIES IN THE CLUSTER AROUND NGC 541

Work is in progress to determine the values of V_s for all the eighty-five galaxies listed in Table 1. Although a greater number of spectra are available, only forty-three of them have been analyzed up to the present. The results obtained from this analysis are listed in Table 3.

If we omit the Galaxies Nos. 22 and 36, which almost certainly are not members of the cluster discussed, the mean velocity of recession of the remaining forty-one galaxies is

$$\langle V_s \rangle = 5321 \text{ km/sec} \,. \tag{6}$$

and the dispersion in symbolic velocities is

$$\langle (\Delta V_s)^2 \rangle^{1/2} = 406 \text{ km/sec} \,. \tag{7}$$

All the spectra were obtained with the prime focus spectrograph of the 200-inch telescope. The values with the associated low errors were derived from spectra with a dispersion of 190 Å/mm, the values with the large errors from spectra with a dispersion of 385 Å/mm.

The spectra of four galaxies in our cluster are reproduced in the Figure 5, *a*, *b*, *c*, and *d*. In Figure 6 the distribution of the symbolic velocities of recession is plotted.

The distribution of the symbolic velocities of recession of the forty-one cluster galaxies represented in Figure 6 is as closely Maxwellian as one might expect it for a cluster in *stationary* equilibrium. The two additional galaxies, Nos. 22 and 36, have values of V_s

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TABLE 2

DIMENSIONS AND SURFACE BRIGHTNESS OF EIGHTY-FIVE GALAXIES IN THE CLUSTER AROUND NGC 541

GALAXY	UNITS OF 10 μ		$A = d_1 \times d_2$	S*
	d_1	d_2		
1	130	60	7800	23 45
2	60	50	3000	22 09
3	100	70	7000	23 61
4	80	13	1040	22.44
5	40	20	800	22 46
6	100	22	2200	23 05
7	80	19	1520	22 75
8	100	21	2100	23.10
9	40	20	800	22 43
10	60	18	1080	22 58
11	42	22	924	22 51
12	50	20	1000	22 40
13	140	23	3220	23 27
14	70	21	1470	22 62
15	65	18	1170	22 22
16	80	22	1760	22 91
17	100	30	3000	23 59
18	80	25	2000	22.85
19	100	18	1800	22 94
20	160	21	3360	23.01
21	80	42	3360	22.91
22	200	60	12000	24 30
23	140	22	3080	23 32
24	40	22	880	22.06
25	65	30	1950	22 52
26	60	22	1320	22 80
27	80	20	1600	23 41
28	30	12	360	22.09
29	40	20	800	22 76
30	25	20	500	22 05
31	41	15	615	22 47
32	24	10	240	21 25
33	40	22	880	23.16
34	52	12	624	22 59
35	80	15	1200	23.10
36	60	12	720	22 64
37	40	20	800	22.46
38	35	25	875	22 95
39	60	30	1800	23 04
40	45	20	900	22 98
41	40	30	1200	22.80
42	30	10	300	22 49
43	60	13	680	23.78
44	35	25	875	23.15
45	100	20	2000	23 25
46	60	15	900	22 68
47	20	15	300	21.78
48	22	15	330	22 10
49	30	21	630	22.90
50	20	11	220	22.26
51	42	18	756	22 30
52	20	15	300	21.59
53	42	32	1344	23 02
54	106	44	4664	23 67

* S = Surface brightnesses, in terms of photographic magnitudes per 100 μ^2, or 0 45 square seconds of arc, of eighty-five of the brighter galaxies in the field of the cluster of galaxies around NGC 541.

TABLE 2—*Continued*

Galaxy	Units of 10 μ		$A = d_1 \times d_2$	S^*
	d_1	d_2		
55	60	42	2520	24 10
56	60	24	1440	23 20
57	132	126	16632	25 14
58	58	42	2436	23 44
59	120	28	3360	24 02
60	46	46	2116	23 61
61	140	32	4480	24 33
62	76	72	5472	24 74
63	136	124	16864	24 87
64	132	126	16632	25 44
65	114	48	5472	24 15
66	220	50	11000	24 50
67	118	12	1416	23 08
68	25	19	475	21 69
69	120	21	252	21 70
70	80	70	5600	24 27
71	104	76	7904	24 77
72	90	37	3330	23 71
73	380	90	34200	25 14
74	62	40	2480	23 89
75	100	46	4600	24 15
76	204	30	6120	25 07
77	73	65	4745	24 49
78	32	22	704	22 52
79	49	22	1078	23 13
80	48	46	2208	23 56
81	42	26	1092	23 35
82	34	27	918	23 11
83	64	29	1856	23 67
84	27	26	702	22 22
85	46	32	1472	23 52

equal to 8038 km/sec and 7077 km/sec, which depart so much from the average that we must assume them not to be members of the cluster. In passing we call attention to the remarkable fact that Galaxy No. 22 is one of the largest and brightest in the field, although it has the highest symbolic velocity of recession.

As to the material content of our cluster we note that, in contradistinction to most medium compact and open clusters of sparse population, the structural as well as the spectral characteristics of the galaxies in the cluster around NGC 541 are of remarkable uniformity. This fact, in addition to the Maxwellian character of the distribution of the symbolic velocities of recession points toward a very old age and a statistically stationary character. This conclusion finds additional support in the following discussion of the character of the velocity dispersion.

VI. THE DISPERSION IN SYMBOLIC RADIAL VELOCITIES OF GALAXIES OF DIFFERENT BRIGHTNESS AND OF GALAXIES IN DIFFERENT LOCATIONS RELATIVE TO THE CENTER OF THE CLUSTER

For the twenty-one brightest galaxies, for which the photographic magnitude is $m_p < 14.9$, the average symbolic velocity of recession is (always excluding No. 22)

$$\langle V_s \rangle = 5254 \text{ km/sec} \tag{8}$$

and the dispersion in V_s is

$$\langle (\Delta V_s)^2 \rangle^{1/2} = 360 \text{ km/sec}\,. \tag{9}$$

For the twenty-one faintest galaxies among the forty-one galaxies listed in Table 3 it is, if we exclude No. 36,

$$\langle V_s \rangle = 5392 \text{ km/sec} \tag{10}$$

and

$$\langle (\Delta V_s)^2 \rangle^{1/2} = 439 \text{ km/sec} . \tag{11}$$

It is seen that the velocity dispersion of the fainter and presumably less massive galaxies is greater than that of the brighter and presumably more massive galaxies. This indicates that among the forty-one galaxies discussed some sort of equipartition of kinetic energy has taken place, such as we should expect it for a stationary cluster in accordance with Boltzmann's principle. It will be of interest to investigate the velocity dispersion for still fainter galaxies and also to check whether or not the same result will be obtained for other stationary clusters. A preliminary analysis indicates that the brighter galaxies in the Coma cluster also have a smaller velocity dispersion than the fainter galaxies although their average symbolic velocities of recession are substantially the same.

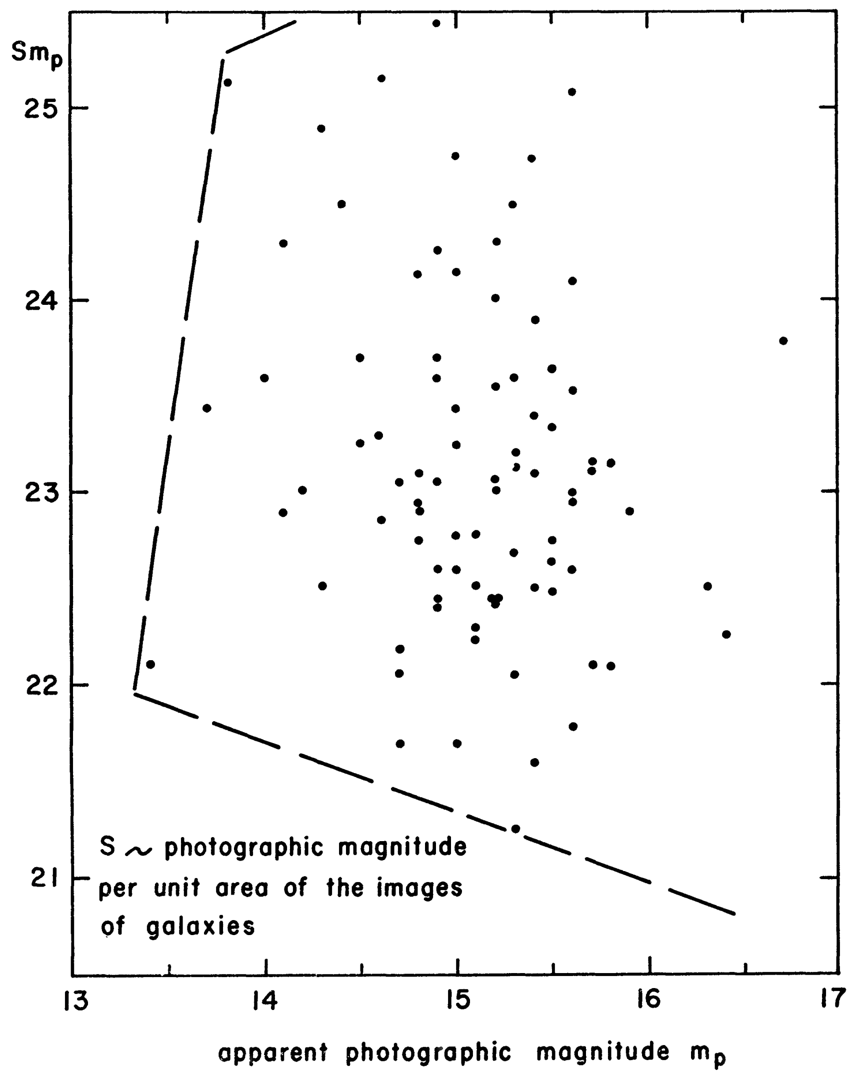

FIG. 4.—Average surface brightness S, as expressed in photographic magnitudes per 0.45 square seconds of arc in dependence upon the apparent photographic magnitudes m_p of the brighter galaxies in the field of the cluster of galaxies around NGC 541.

It must be stressed, however, in this connection, that no complete equipartition of energy can be expected for any cluster of galaxies, since galaxies are not permanent objects. The less massive galaxies in particular will suffer heavily during encounters and will be destroyed long before they could acquire the high velocities which would be expected for the components of low mass in any truly statistical equilibrium. If true equipartition were established between the two groups of the brighter and the fainter galaxies which we have discussed, we should expect for the ratio of their average masses a value of about 3:1 since their average luminosities are in this ratio. From the velocity

TABLE 3

SPECTRAL TYPES AND SYMBOLIC VELOCITIES OF RECESSION V_s OF FORTY-THREE GALAXIES IN THE CLUSTER AROUND NGC 541

Galaxy	Neb Type	Spectral Type	V_s (km/sec)	Standard Deviations
1	E3	K0	5316	± 30
2	E0	K0	5472	30
3	E0	G5	5392	30
4	E7	G5	4939	50
5	E5	G2	5374	30
6	Sb	G3	5398	30
7	E7	G5	6591	25
8	E7	G3	5118	50
9	S0	G5	5469	30
10	E7	G5	5238	30
11	E0	G5	5332	40
12	Sb	G5	5321	100
13	E7	G3	5016	40
14	Sa	G8	5275	30
15	E7	G8	5173	40
16	Sc	Em. only	4730	30
17	Sb:	G2	5688	50
18	Sa	G3	4464	40
19	E7	G3	4661	150
20	Sb	K0	5405	30
21	E2	G2	5556	50
22	Sc	G5	8030	100
23	Sc:	G5	5651	150
24	E0	G5	5768	30
25	SBb	G8	5502	30
26	Sc	G5	6203	300
27	Sb	G8	4788	100
28	Sb:	G8	4855	150
29	Sb	G5	5229	200
30	S0	G5	5332	150
31	E7	G5	5932	100
32	Sc	G5	5919	100
34	Sb	G5	5110	200
36	E7	G2	7707	200
37	Sa	G ?	5005	250
38	Sa	G8	5956	150
39	Sa	.	4794	100
41	S0	G5	5174	150
45	Sc:	G5	6271	150
46	E7	G2	4900	100
48	E2	G3	5078	150
51	E7	G5	5018	200
52	E5	K0	5648	±150
			Mean 5439	

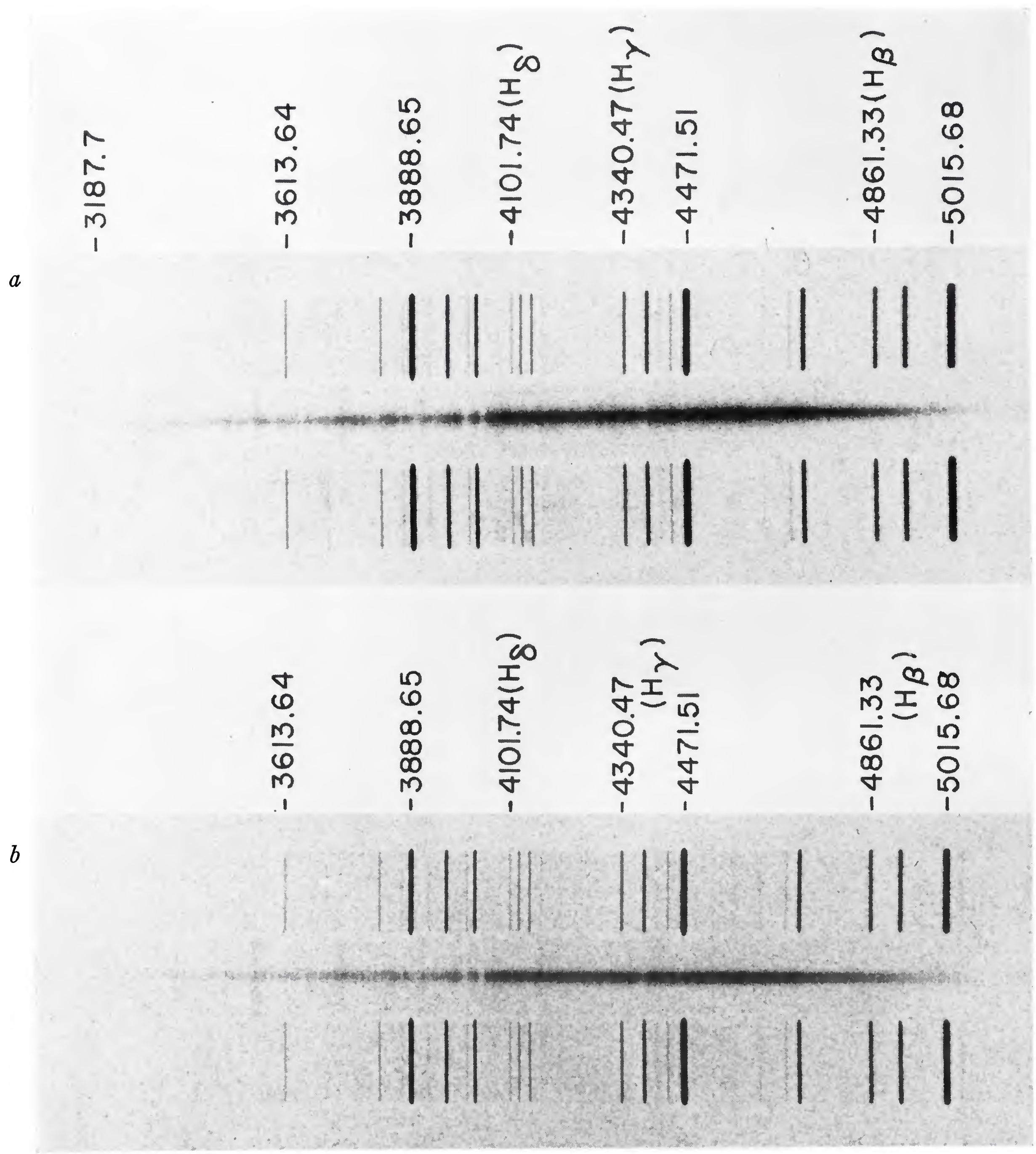

FIG. 5.—Spectra of four member galaxies of the cluster around NGC 541, obtained with the prime focus spectrograph of the 200-inch telescope at a dispersion of 185 Å/mm. *a:* Spectrum, Type K0, of Galaxy No. 1 = NGC 545, V_s = 5316 km/sec. *b:* Spectrum, Type G5, of Galaxy No. 9, V_s = 5469 km/sec.

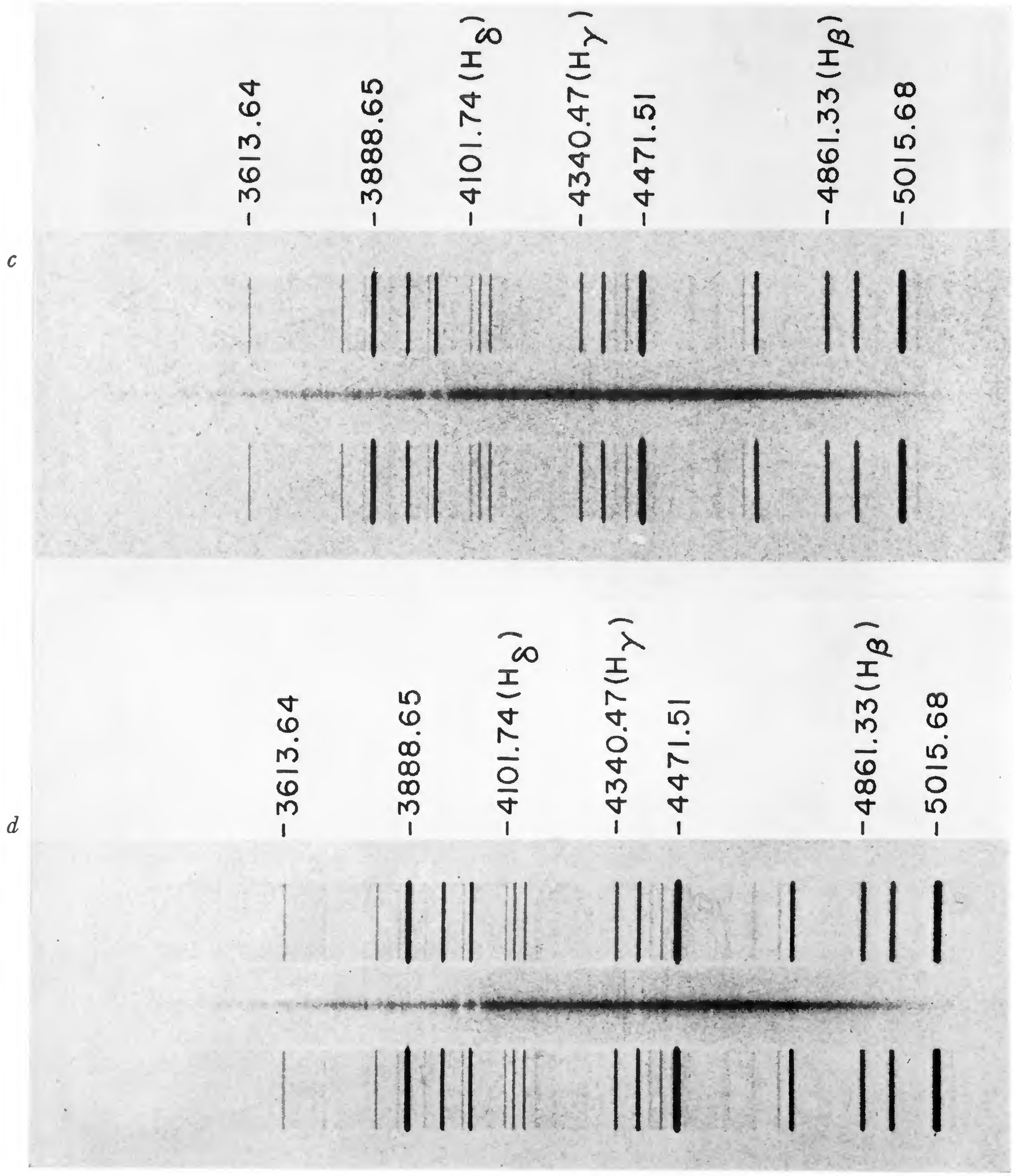

FIG. 5, *Continued*.—*c:* Spectrum, Type G5, of Galaxy No. 24 = IC 1696, V_s = 5768 km/sec. *d:* Spectrum, Type G8, of Galaxy No. 25 = NGC 570, V_s = 5502 km/sec.

dispersions (9) and (11) it appears however that the ratio would be only about 1.5:1, which means that the fainter galaxies have not been able to acquire their full share of kinetic energy as one would expect it in the case of full equipartition.

a) Rotation of the Cluster

Since the cluster has an elliptical appearance, it was thought worthwhile to test the distribution of the symbolic velocities of recession for any possible indication of rotation of the cluster as a whole. An axis running SE. to NW. was therefore chosen which cuts the cluster in half.

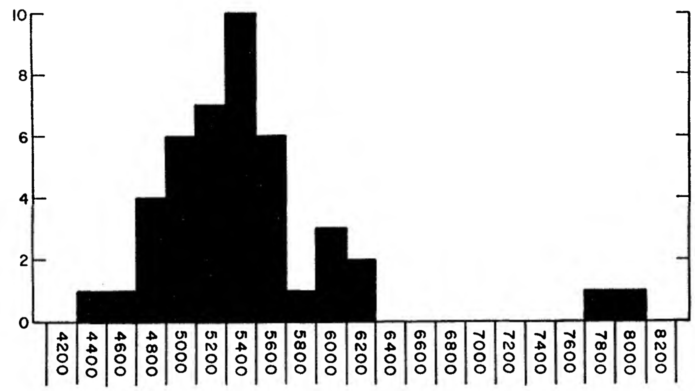

FIG. 6.—Distribution of the symbolic velocities of recession in km/sec of the forty-three galaxies listed in Table 3.

For the twenty galaxies Nos. 1–3, 5, 9–11, 17–21, 25, 26, 37–39, 41, 45, and 46, which form the southwest half, we find

$$\langle V_s \rangle = 5359 \text{ km/sec} \tag{12}$$

and

$$\langle (\Delta V_s)^2 \rangle^{1/2} = 448 \text{ km/sec} . \tag{13}$$

For the twenty-one galaxies Nos. 4, 6–8, 12–16, 23, 24, 27–32, 34, 48, 51, and 52, which form the northeast half of the cluster, it is

$$\langle V_s \rangle = 5285 \text{ km/sec} \tag{14}$$

and

$$\langle (\Delta V_s)^2 \rangle^{1/2} = 357 \text{ km/sec} . \tag{15}$$

According to the values (12) and (14) we do not, therefore, find any evidence for any rotation around the axis mentioned.

b) Test for Possible Expansion of the Cluster

In a cluster which has been expanding for a long time, that is, for at least several hundred million years, no central condensation would be expected. In any event, regardless of what the age of the cluster might be, the dispersion in the symbolic velocity of recession must decrease with distance from its center, if the cluster is expanding. For the member galaxies at the periphery of the cluster the dispersion in the symbolic velocities of recession must converge toward zero. In order to apply this test to our cluster, we have investigated the dispersion in the values of V_s for four groups of galaxies which are respectively located in the central circle A_0 and in the three ringlike areas A_1, A_2, and A_3 shown in Figure 7.

The average values $\langle V_s \rangle$ and the dispersions in V_s for the galaxies in the four regions shown in Figure 7, for which we have analyzed the spectra and determined the symbolic velocities of recession, are shown in Table 4.

Rather than decreasing, the values of the dispersion in the symbolic velocity of recession increase with the distance from the center of the cluster. This result supports our previous conclusion that the cluster of galaxies around NGC 541 has reached a stationary state, and is not expanding.

For completeness of the analysis, the distribution of the apparent photographic magnitudes of the galaxies lying in the four zones shown in Figure 7 is plotted in Figure 8. In Table 1 the apparent photographic magnitude of galaxy No. 37 is listed as being equal to 15.2. It has been found later on, however, that this magnitude may be in error

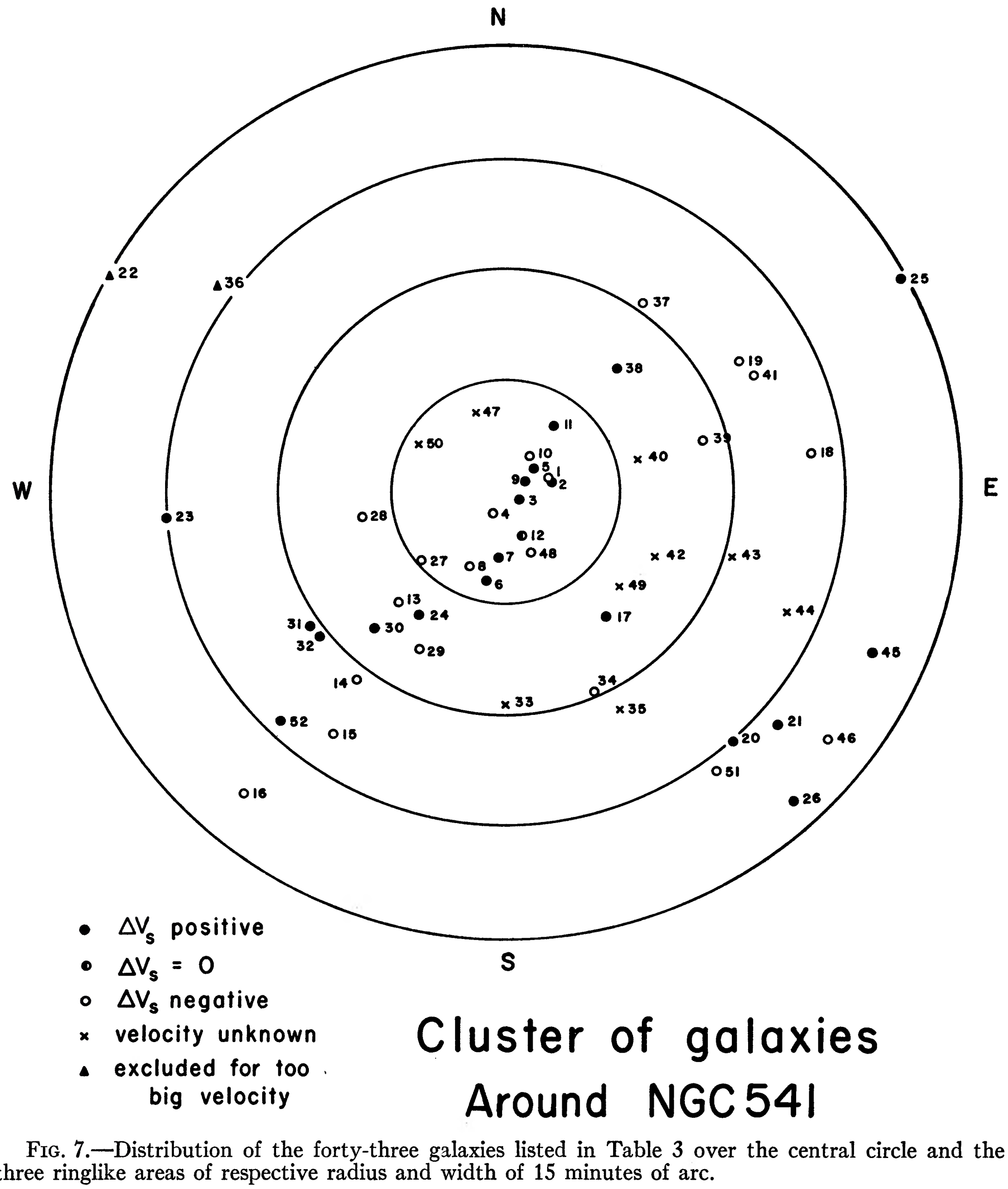

FIG. 7.—Distribution of the forty-three galaxies listed in Table 3 over the central circle and the three ringlike areas of respective radius and width of 15 minutes of arc.

TABLE 4

SYMBOLIC VELOCITIES OF RECESSION OF FORTY-ONE CLUSTER GALAXIES WHICH ARE DISTRIBUTED OVER THE FOUR AREAS A_0, A_1, A_2, AND A_3 STARTING FROM THE CENTER OUT* IN FIGURE 7

Regions	Nos of Galaxies	$\langle V_s \rangle$ (in km/sec)	$\langle (\Delta V_s)^2 \rangle^{1/2}$
A_0	14	5280	237
A_1	9	5305	396
A_2	10	5250	482
A_3	8	5448	533

* Shown in Figure 7

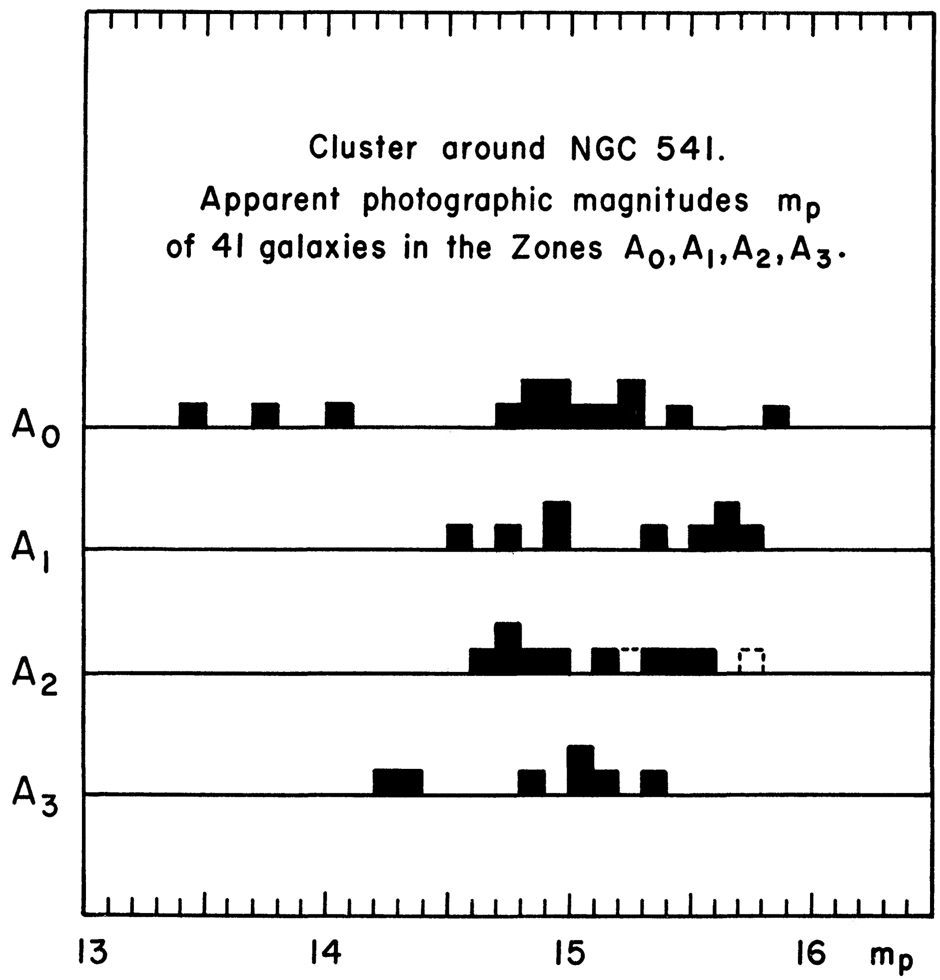

FIG. 8.—Distribution of the apparent photographic magnitudes of the galaxies which lie respectively in the circle and in the ringlike areas A_0, A_1, A_2, and A_3 shown in Fig. 7.

because of a foreground star projected onto the galaxy and that it is more probably that $m_p = 15.7$ (indicated by a *dashed square*).

From Figure 8 it is seen that there exists some slight tendency toward segregation of galaxies of different luminosities, the brightest being concentrated in the central circle. This segregation, in conjunction with the previously obtained result that the velocity dispersion is greater for the faint galaxies than for the bright ones, explains at least in part the increase in the values of $\langle(\Delta V_s)^2\rangle^{1/2}$ as we move from the center of the cluster outward.

VII. THE MASS-LUMINOSITY RATIO OF THE CLUSTER OF GALAXIES AROUND NGC 541

The indicative absolute photographic magnitude is defined (Zwicky and Humason 1960, 1961) as

$$M_p{}^* = m_p + 5 - 5 \log_{10} D^* , \tag{16}$$

where the indicative absolute distance, according to equations (3*a*) and (6) is

$$D^* = 53.2 \text{ million parsecs} \tag{17}$$

and

$$M_p{}^* = m_p - 33.6 . \tag{18}$$

The indicative absolute photographic magnitude of the brightest galaxy in the cluster, that is, of No. 2 = NGC 547, is therefore $M_{pi} = -20.2$.

The integrated apparent photographic magnitude of the first fifty-two galaxies in Table 1 is $m_p = 10.7$, so that the integrated absolute photographic magnitude of the whole cluster is

$$M_p{}^* \text{ (cluster)} < -22.9 , \tag{19}$$

or its indicative absolute photographic luminosity

$$\mathfrak{L}_p{}^* \text{ (cluster)} > 2.2 \times 10^{11} \, \mathfrak{L}_p (\odot) , \tag{20}$$

where $\mathfrak{L}_p (\odot)$ is the absolute photographic luminosity of the sun.

Assuming that our cluster is in statistical equilibrium the Virial theorem may be applied to determine its indicative mass $\mathfrak{M}^*$(cl) from the velocity dispersion. We thus obtain

$$\mathfrak{M}^* = \mu r^* \times 3\langle(V_s)^2\rangle/G , \tag{21}$$

where r^* is the indicative radius of the circle which contains the main concentration of galaxies and μ is a pure number of the order of unity. The apparent diameter of this circle is about 1°, therefore, $r^* = 0.0087\, D^* = 1.43 \times 10^{24}$ cm. G is the universal gravitational constant and μ a numerical factor of the order of unity. From this we obtain

$$\mathfrak{M}^* = 1.05 \times 10^{47} \times \mu \text{ gr} = 5.3 \times 10^{13} \, \mathfrak{M}_\odot . \tag{22}$$

The indicative mass-luminosity ratio of the cluster therefore is

$$(\mathfrak{M}^*/\mathfrak{L}^*)\text{(cluster)} = \mathfrak{R}^*(\mathfrak{M}/\mathfrak{L})_\odot \qquad \mathfrak{R}^* \leq 240 , \tag{23}$$

since the fifty-two galaxies used for the determination of the integrated luminosity of the cluster do not include all of its luminous members. If all of the fainter member galaxies were included, it is estimated that the value of $\mathfrak{L}^*$ would perhaps be doubled and we should arrive at a relative indicative mass-luminosity ratio of the order

$$\mathfrak{R}^* = 100 . \tag{24}$$

This result is in line with the general expectation that, as we proceed from individual galaxies to groups of galaxies (Zwicky and Humason 1960, 1961) and further to medium rich and very rich clusters of galaxies, the values of $\mathfrak{R}^*$ increase from 10 to 1000 in order of magnitude.

It is not clearly known at the present time what kind of as-yet undetectable matter contributes at the necessary increasing rate to the mass of associations of galaxies of increasing membership. Intergalactic obscuring matter, that is, dust is probably present but cannot account for the discrepancy between individual galaxies and clusters of increasing size, since we do not observe any sufficient dimming of distant galaxies which lie beyond the nearby compact clusters. Intergalactic monatomic hydrogen also seems to be ruled out on the basis of radio surveys of the intensities of the 21-cm emission line.

There thus remain, for the present, the possibilities that protons and electrons, neutral hydrogen molecules, dark bodies much more massive than dust particles, intergalactic stars, dwarf galaxies of faint surface brightness, and compact galaxies and isolated nuclei of galaxies of stellar appearance account for the missing mass. It is of interest to remark that if luminous bodies of the last-mentioned three categories were uniformly distributed over an area of 1 square degree throughout our cluster with surface brightness of the twenty-fifth photographic magnitude per square second of arc, not detectable with present means, the integrated magnitude of this intergalactic contribution to the luminosity of the cluster would amount to $\Delta m_p = 25 - 17.8 = 7.2$ photographic magnitudes or 3.5 magnitudes brighter than the integrated light from the fifty-two galaxies which we considered in deriving the relation (19). The indicative mass luminosity ratio (23), or (24), would thus be reduced by a factor 25, and the discrepancy which we have mentioned would be removed entirely since the resulting value of $\mathfrak{R}^*$ would be of the same order as those of the average individual galaxies.

Actually, luminous intergalactic matter is clearly visible in the center of the cluster. Luminous bands with a surface brightness estimated to be in places of the order of 23 photographic magnitudes per square second of arc connect the four bright galaxies NGC 535, 541, 545, and 547. The two lobes of the radio source 3C40 far removed from the bright pair of galaxies NGC 545/547 of course also indicates the presence of intergalactic matter, the more precise character of which remains to be investigated.

VII. SUPERNOVAE IN THE CLUSTER OF GALAXIES AROUND NGC 541

About three years ago our cluster was put on the list of objects to be searched for supernovae with the 48-inch Schmidt telescope. From its population and the fact that we can observe the cluster only for about 6 months every year, an average occurrence of about one supernova per six years was to be expected. In qualitative confirmation of this prediction one supernova has been found so far. It was of type I and was discovered in IC 1703 on January 22, 1963. Its apparent photographic magnitude at maximum was about m_p (max) $= 16.5$, corresponding to an indicative absolute photographic magnitude m_p^* (max) $= -17.1$, a value which is in good accord with the magnitudes of supernovae of Type I discovered in the clusters in Coma and Cancer.

REFERENCES

Abell, G. 1962, *Yearbook 1961–62 of the Carnegie Institution of Washington*, pp. 39–40.
Hubble, E. P. 1936, *The Realm of Nebulae* (New Haven, Conn.: Yale University Press).
Maltby, P., Matthews, T. A., and Moffet, A. T. 1963, *Ap. J.*, **137**, 153–163.
Zwicky, F. 1957, *Morphological Astronomy* (Berlin: Springer-Verlag).
———. 1963*a*, *A.S.P. Leaflet*, No. 403.
———. 1963*b*, Abstract (paper presented at AAS meeting, Tucson, April 18).
Zwicky, F., Herzog, E., and Wild, P. 1961, *Catalogue of Galaxies and Clusters of Galaxies*, Vol. I (Zurich: Published by the California Institute of Technology for L. Speich).
Zwicky, F., and Humason, M. L. 1960, *Ap. J.*, **132**, 627–639.
———. 1961, *ibid.*, **133**, 794–813.