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THE RADIAL DISTRIBUTION OF MORPHOLOGICAL TYPES OF GALAXIES IN X-RAY CLUSTERS

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ABSTRACT

Galaxies have been classified in six clusters which are known to emit X-rays. We find that in all cases the ratio of the surface density of spiral galaxies to that of S0's increases outward. Moreover, there is a correlation between the velocity dispersion of the galaxies in a cluster and the overall proportion of S0's among disk galaxies. These facts are interpreted as support for Gunn and Gott's hypothesis that S0's are produced from spirals by a process in which the interstellar gas in spirals is swept out as these galaxies move through the hot gas presumed to be responsible for the X-ray emission. A further test of this hypothesis is suggested.

In addition, new redshift measurements are presented for galaxies in several X-ray clusters.

Subject headings: galaxies: clusters of — galaxies: redshifts — X-rays: sources

I. INTRODUCTION

The predominance of S0 over spiral galaxies in the central regions of the great clusters, such as Coma and Coronae Borealis, was first discussed by Baade and Spitzer (1951). They referred to it as a "well known" fact, implying that they were not the first to notice the effect. In any case, Baade and Spitzer built around the observation a theory of the origin of S0 galaxies in which they supposed that these objects arise as a result of collisions between spiral galaxies. They showed that such collisions, occurring at the typical speeds encountered in rich clusters, would be sufficient to remove all of the interstellar gas from the colliding spirals. The resulting objects, containing disks of stars but not gas, would resemble S0's.

Revisions in the extragalactic distance scale and the consequent reduction in the estimated frequency of galaxy collisions led to the abandonment of Baade and Spitzer's theory as an explanation of the majority of S0's. Instead, Gunn and Gott (1972) proposed that the ram pressure exerted on the interstellar gas in a spiral, due to its virial motion through a tenuous gas in a cluster, would sweep out the gas and produce an S0. Using typical values for the appropriate parameters and speed of a spiral galaxy, they estimated that an intracluster gas density of 5×10^{-4} atoms cm^{-3} would be sufficient to strip such a galaxy of its interstellar material. Gunn and Gott pointed out that the X-ray observations indicate that large clusters contain a hot gas with $T \sim 10^8$ K and $n_e \sim 10^{-3}$, so that "we expect *no normal spirals* in the central regions of clusters like Coma."

The question of the origin of the X-ray emission observed from several clusters of galaxies has been controversial (see, for example, Brecher and Burbidge 1972), although recent measurements indicate that at least in the Perseus cluster there is a hot gas component (Scheepmaker *et al.* 1976; Mitchell *et al.* 1976; Malina *et al.* 1976). In any case, in view of Gunn and Gott's suggestion regarding the origin of S0's from spiral galaxies in clusters, we thought it important to investigate whether the effect described by Baade and Spitzer also obtains in the X-ray clusters. Accordingly, we have obtained high-scale plates and have classified the galaxies in six of these objects as a function of radius. Also as part of this work we obtained new redshifts for galaxies in several clusters. We find that the ratio of spiral to S0 galaxies increases outward in all of the X-ray clusters for which good data are available. We shall also show that it is possible to classify clusters according to the characteristic behavior of the radial distribution of morphological types. A more surprising result is that there is a good correlation between the velocity dispersion of a cluster and the overall proportion of S0 galaxies. Our improved data show that the correlation between the X-ray luminosity of a cluster and its velocity dispersion is poor and cannot be used to distinguish between the two principal theories of the X-ray emission.

Overall, our results are consistent with Gunn and Gott's explanation for the origin of S0's from spirals, although we have not thought of a convincing detailed explanation of the correlation between the proportion of S0's and the dispersion.

II. OBSERVATIONS AND DATA

a) *Direct Photography*

Morphological types of galaxies brighter than $m_{pg} \sim 16$ have been determined for six clusters possibly associated with *Uhuru* X-ray sources (Kellogg *et al.* 1973). Good scale plates obtained with the 60 inch (1.5 m), f/8.75 telescope at Palomar Observatory, covering an area of about 1.5 deg^2, were used for the clusters Abell 262, 376, 576, and 2666. The remaining two, Abell 426 and 1060, were classified on 48 inch (1.2 m) Schmidt plates. A summary of the plate material used is given in Table 1. Classification criteria were taken from the *Hubble Atlas of Galaxies* (Sandage 1961). The classification of the central galaxies of the Coma cluster by Rood and Baum (1967) was used as a secondary reference source by comparing galaxies whose classification was doubtful with galaxies in the Coma cluster on two plates taken with the 48 inch telescope and described in Table 1. The total number of galaxies classified ranged from 45 for Abell 262 to 175 for Abell 426, with close to 80 classified for the remaining three clusters.

b) *Image-Tube Spectroscopy*

As part of an ongoing program at the Hale telescope, low-dispersion spectrograms were obtained for galaxies in six X-ray clusters with the Cassegrain image-tube spectrograph. The spectra, recorded on IIa-D film, were measured for redshifts on the Caltech Grant Machine and reduced using a standard computer program. The radial velocities for the individual galaxies are presented in Table 2, and identification charts for the galaxies are given in Figure 1 (Plate 7). From these measurements it was possible to determine velocity dispersions for Abell 262 and 576. These, together with published velocity dispersions for other X-ray clusters, are listed in Table 3. Also included in Table 3 are the global population contents of clusters observed photographically and of those clusters observed by Oemler (1974) that have been associated by Kellogg *et al.* (1973) with X-ray sources.

III. DATA ANALYSIS

For each cluster, the total numbers of spirals, S0's, and ellipticals within a series of concentric rings were determined. The resulting radial distributions of morphological types for the clusters are presented in Figure 2 where the number of galaxies of each principal morphological type within a ring of radius R, $N(R)$, has been plotted against R. The corresponding distribution for the Virgo cluster, which we determined using the unpublished morphological classification of 181 galaxies in the cluster by Sandage and Tammann (1976), is shown in Figure 3.

According to the distributions in Figures 2 and 3, the clusters can be separated into three groups as follows:

1. *Abell 262, 1060, 2666, and Virgo.*—The common features of these clusters are a flat integral distribution

TABLE 1

PLATE MATERIAL

Cluster	Telescope	Emulsion	Filter	Exp. Time min	Notes
Abell 262	60-inch	103a-O	GG 13	120	1
376	60-inch	103a-D	...	90	...
576	60-inch	103a-D	...	134	...
426	48-inch	IIIa-J	Wr 2c	90	1,2
1060	48-inch	103a-O	...	10	3
2666	60-inch	103a-O	GG 13	120	1
Coma	48-inch	103a-J	Wr 4	30	4
Coma	48-inch	IIIa-J	Wr 4	120	1,5

1 - Baked at 65° in dry nitrogen
2 - Taken by John Kormendy
3 - Palomar Sky Survey Plates
4 - Taken by Charles Kowal
5 - Taken by James Gunn

TABLE 2

RADIAL VELOCITY DATA

Galaxy	Radial Velocity	Standard Error	Lines Measured
		Abell 262	
1[1]	4939	120	H, K, 3951, Na I 5892
2[2]	4663	140	H, K, Fe 4383
3[3]	4570	200	H, K
4[4]	4941	30	H, K
5	4085	167	H, K
7[5]	4280	44	H, K
8	2381	84	H, K
9	4984	173	H, K
10[6]	3419	38	H, K
		Abell 496	
1	9900	...	K
3	9826	...	K
4	9079	...	K
		Abell 576	
1	12743	89	H, K, 3951
2	11452	110	H, K
4	12027	312	H, K
5	13265	5	H, K
6	11940	243	H, K
7	11267	109	H, K
8	19871	149	H, K
9	9743	30	H, K
11	10200	111	H, K
12	12382	20	H, K
13	11327	134	H, K
14	9832	183	H, K
15	11170	78	H, K
16	13855	134	H, K
17	11506	146	H, K, 3951
18	12737	158	H, K
19	11433	104	H, K
20	11710	141	H, K
		Abell 2052	
1	10143	10	H, K
4	9488	60	H, K
5	10324	80	H, K
6	10870	15	H, K
7	10560	45	H, K
		Abell 2079	
1	19895	50	H, K
		Abell 2666	
1	7143	30	H, K
2	7483	40	H, K
3	7938	50	H, K

Notes:
1 - NGC 708
2 - NGC 703
3 - NGC 705
4 - NGC 704
5 - NGC 714
6 - NGC 709

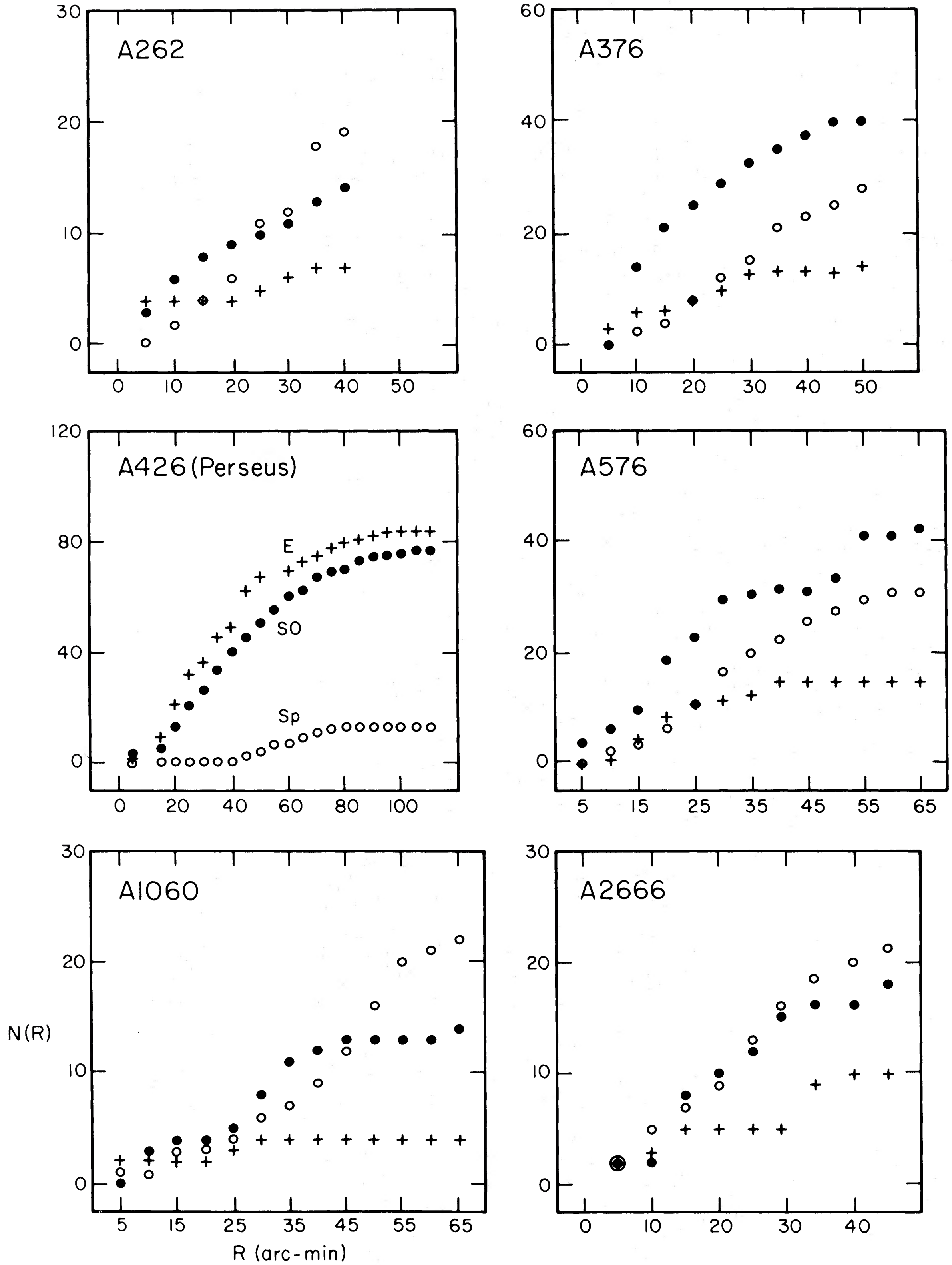

FIG. 2.—The radial distribution of morphological types for the six clusters observed. Different symbols are used for elliptical (E), spiral (Sp), and S0 galaxies, as indicated in the plot for Abell 426.

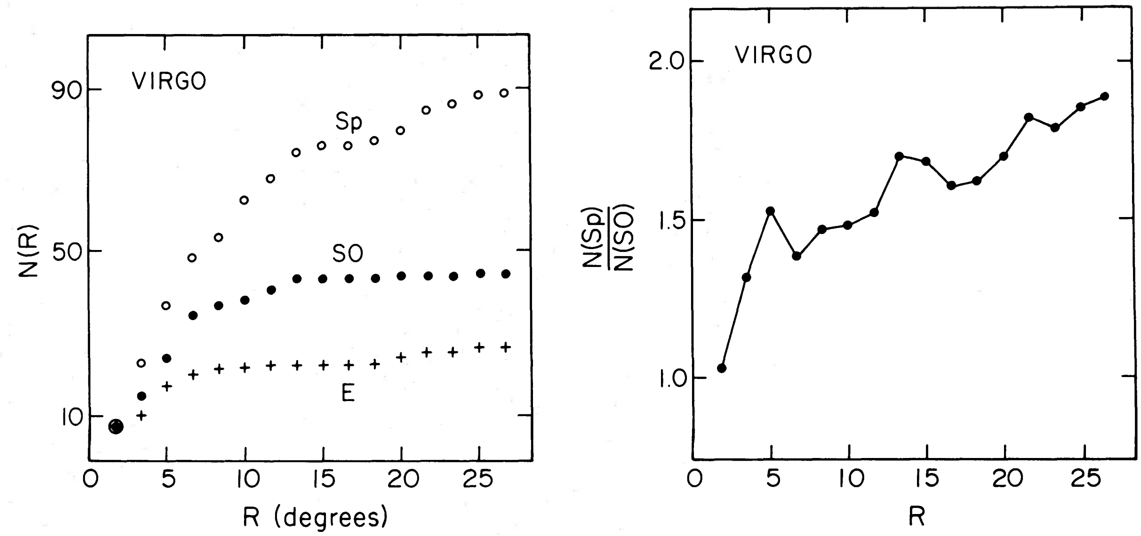

FIG. 3.—*Left*, the radial distribution of morphological types for the Virgo cluster. *Right*, plot of the ratio of the total numbers of spirals to S0's within a ring of radius *R* as a function of *R* for the Virgo cluster.

of ellipticals and a steep distribution of spirals and S0's; the S0's dominate in the central regions while spirals do so in the outsides, so that the distributions actually cross. We will refer to these clusters as "spiral" or "Sp" clusters.

2. *Abell 376 and 576*.—Again, the common features of these clusters are a flat distribution of ellipticals—although not as flat as that of spiral clusters—and a steep distribution of spirals and S0's. Here, however, the S0's dominate the population throughout the clusters, and the distributions of spirals and S0's do not cross. These clusters will be called "S0" clusters.

3. *Abell 426*.—The Perseus cluster shows a unique distribution. Here the few spirals have a flat integral distribution, whereas the S0's and the ellipticals show steep parallel distributions at all radii. The number of ellipticals remains larger than that of S0's throughout the cluster.

The common feature of all clusters studied appears to be that the relative number of spiral galaxies, nearly zero in the cluster centers, increases very rapidly outward. To better illustrate this point, the ratio between the numbers of spirals and S0's contained within a ring of radius *R*, *N*(Sp)/*N*(S0), has been plotted against *R* in Figure 3 for Virgo and in Figure 4 for the other clusters. The ratio is seen to increase steeply with radius in all clusters that were observed.

Oemler (1973) gives differential radial type distributions for eight clusters which he divides into three groups: spiral-rich, spiral-poor, and cD clusters. His results, converted into integrated plots to facilitate intercomparison with ours, are reproduced in Figure 5,

TABLE 3

X-RAY AND OPTICAL PROPERTIES

Cluster	Redshift	X-Ray Luminosity (10^{44} ergs s^{-1})	Velocity Dispersion (km s^{-1})	Percentage Sp	S0	E
Abell 262	0.0148[1]	0.3[10]	1387[1]	47[1]	36	17
376	0.0437[8]	3.8	...	43	48	19
426	0.0183[5]	9.0	2426[5]	7[1]	45	48
576	0.0394[1]	2.3	1871[1]	35[1]	48	17
1060	0.0114[6]	0.2	1380[6]	55[1]	35	10
1367	0.0218[7]	1.0	1230[7]	43[3]	40	17
1656	0.0230[4]	4.5	1440[4]	18[3]	47	35
2151	0.0360[5]	1.6	1100[5]	50[3]	36	14
2199	0.0312[5]	2.2	1460[5]	24[3]	41	35
2666	0.0258[1]	2.7	...	43[1]	37	20
Virgo	0.004 [2]	0.2	852[2]	57[2]	26	17
Centaurus	0.009 [9]	0.3	1650[9]	...	..	..

References: 1. This paper; 2. Sandage and Tammann (1976); 3. Oemler (1974); 4. Rood et al. (1972); 5. Noonan (1973); 6. Vidal and Peterson (1975); 7. Dickens and Moss (1976); 8. Peterson (1970); 9. Vidal and Wickramasinghe (1975); 10. Kellogg et al. (1973).

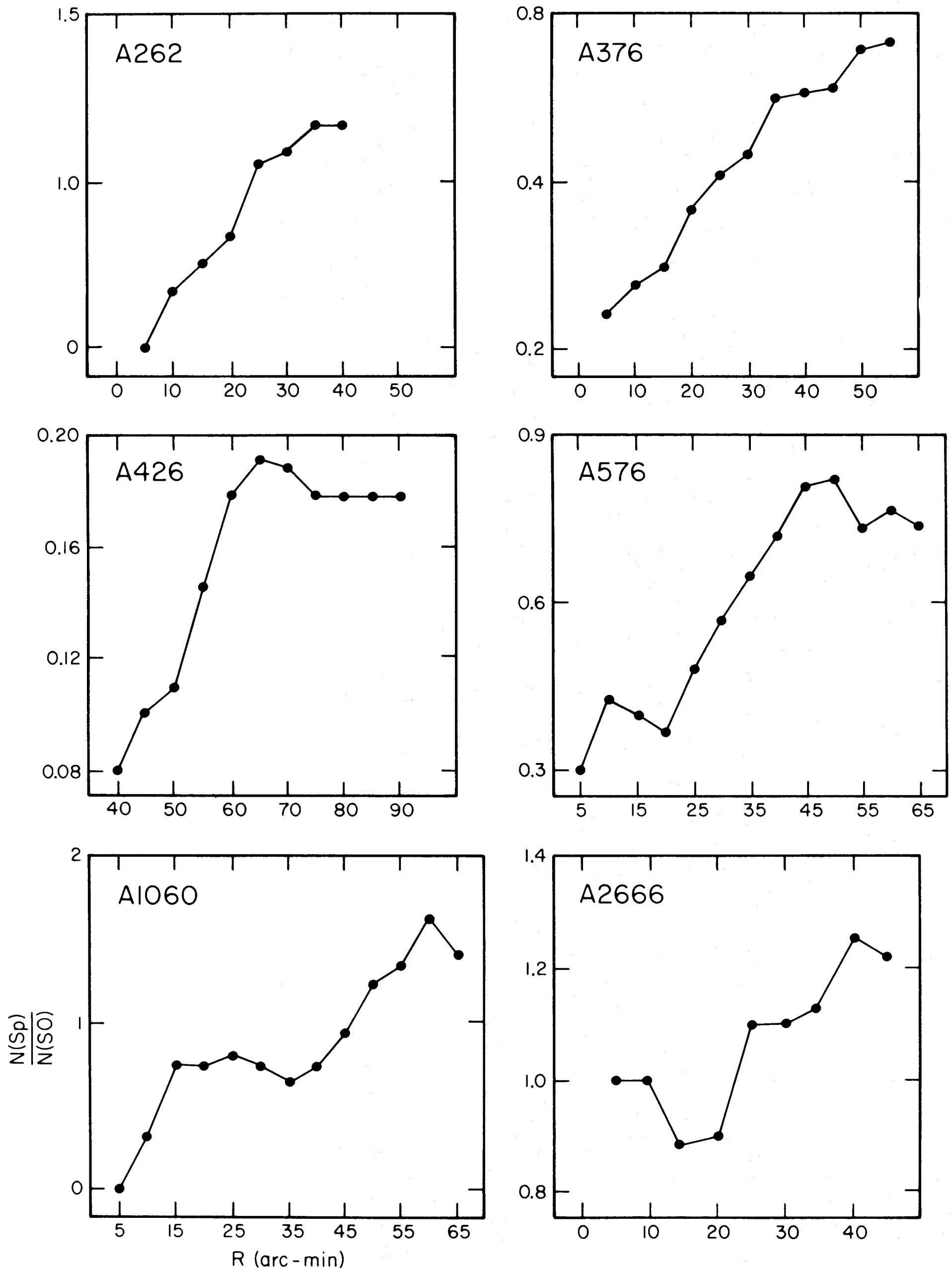

FIG. 4.—The integrated ratio of spirals to S0's plotted against radius for our six clusters

where $N(R)$ is in arbitrary units and R is in units of the gravitational radii R_G of the clusters. Inspection of Figures 2, 3, and 5 shows that Oemler's distributions for spiral-rich and spiral-poor clusters are similar to those of our Sp and S0 clusters. Moreover, the global population content of these clusters as presented in Table 3 corresponds closely to that of Oemler's spiral-rich and spiral-poor clusters. Oemler's distributions of spiral galaxies for these two classes appear to be somewhat steeper than those of our Sp and S0 clusters. However, these differences may not be significant: Morphological classification criteria are somewhat subjective, and systematic differences are expected from different observers using different plates on faint galaxies.[1] Our distribution in Figure 2 of the Perseus cluster resembles that of Oemler's cD clusters,

[1] We note that Abell 2666, which is clearly a cD cluster, is placed among the "spiral" clusters according to its radial type distribution; overall, it is dominated by spiral galaxies. Hickson (1976) in his study of the separations of galaxies in 14 cD clusters also noticed that Abell 2666 is not a normal cD cluster.

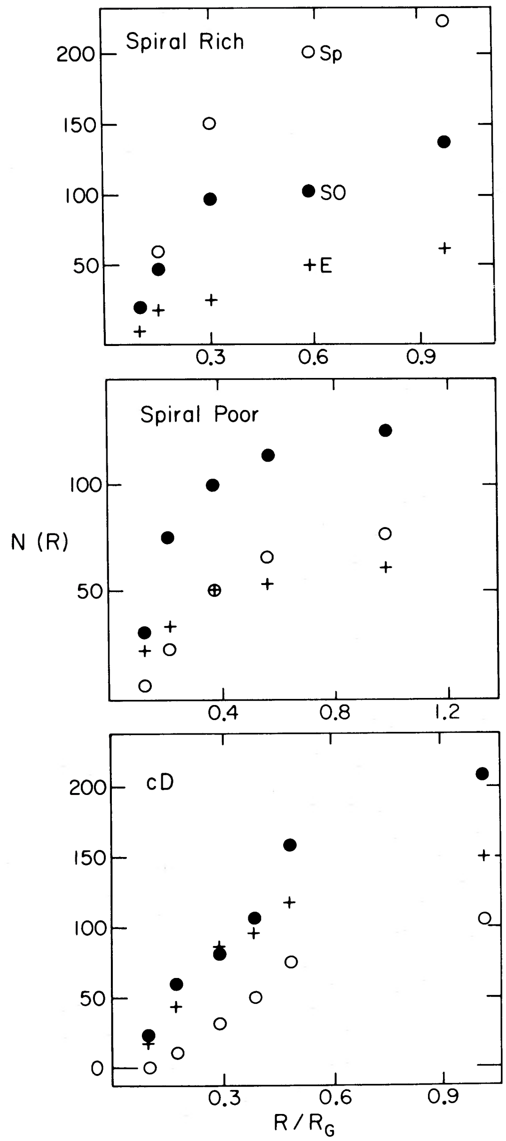

FIG. 5.—Integrated radial distributions of morphological types derived from Oemler's differential distributions for his three types of clusters. The radial coordinate has been normalized to the gravitational radii of the clusters determined by Oemler, and an arbitrary normalization has been used for the integrated numbers.

with almost no spiral galaxies and with a somewhat larger number of elliptical galaxies.

The overall proportion of S0 galaxies relative to spirals varies considerably from cluster to cluster, as may be seen from the last three columns of Table 3. The percentage of S0's relative to all galaxies is the least variable quantity, while the percentage of spirals is the most variable. We note that there is a correlation between the proportion of S0's as a fraction of all disk galaxies and the velocity dispersion of the cluster. This correlation is shown in Figure 6, where we plot $P = N(\mathrm{S0})/[N(\mathrm{S0}) + N(\mathrm{Sp})]$ versus the logarithm of the velocity dispersion.

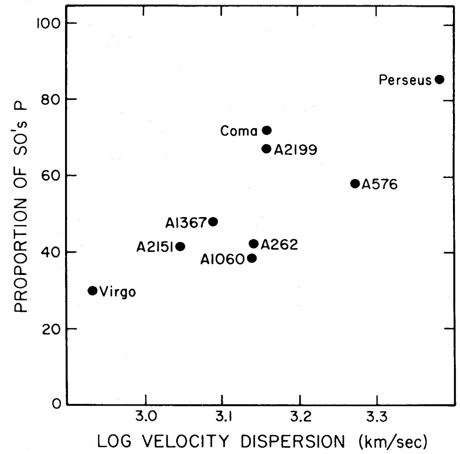

FIG. 6.—The correlation between velocity dispersion and proportion P of S0 galaxies (as defined in the text) for all X-ray emitting clusters for which both parameters are known.

The correlation in Figure 6 does not appear to have been recognized by earlier workers. If the "sweeping out" hypothesis for the origin of S0's from spirals is correct, then the correlation implies that in clusters with a higher velocity dispersion the sweeping process is more efficient. This seems reasonable.

Oemler (1974) has determined velocity dispersions and global population contents for four clusters not identified by Kellogg *et al.* (1973) with *Uhuru* sources. These clusters, Abell 194, 400, 1314, and 2197, have velocity dispersions too low even to be plotted in Figure 6. These values, ranging from 359 km s^{-1} for Abell 400 to 928 km s^{-1} for Abell 1314, are among the lowest known for clusters of galaxies and may be due to unfortunate selection of the redshifts used in their derivation. If real, with the possible exception of that found for Abell 1314, these values may be too small for the ram pressure to be high enough to remove the gas from the spirals, and a different origin for the S0's in these clusters would have to be postulated. If the heat input for the gas comes from the motions of the galaxies, these clusters would not be expected to be X-ray sources. Clearly, these important questions deserve further study, and better X-ray limits would be of significant value.

Solinger and Tucker (1972) proposed that if the X-ray emission from clusters is of thermal origin, the slope of the logarithmic relation between the X-ray luminosity L_x and the velocity dispersion ΔV in a cluster can be used to discriminate between possible origins and heating mechanisms for the gas. Figure 7 shows a plot of log (L_x) against log (ΔV) for the data given in Table 2. The expected correlation between L_x and ΔV, although present, is rather weak. A least-squares fit to the data, also shown in Figure 7, gives a slope of 2.8 $\pm$ 1.3. The correlation expected on the basis of Solinger and Tucker's very simple assumptions is $L_x \sim (\Delta V)^4$ if the temperature of the gas is independent of ΔV, and $L_x \sim (\Delta V)^5$ if $T \sim (\Delta V)^2$. Silk (1976) has rediscussed the assumptions leading to Solinger and Tucker's simple relations and has tested his

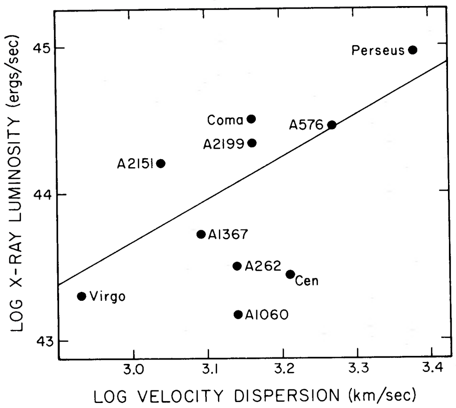

FIG. 7.—Plot of the X-ray luminosity of the clusters versus their velocity dispersion. A least-squares fit to the data with a slope of 2.8 ± 1.3 is also shown.

results on data for the same clusters used in Figure 7, with the exception of Abell 576. Silk concludes that if the size of the X-ray emitting volume is assumed to be independent of the velocity dispersion, then the empirical data are fitted equally well by two quite different models. One model assumes a primordial origin for the cluster gas through the infall mechanism discussed by Gunn and Gott (1972). The other model assumes a cluster gas to total mass ratio which is independent of the velocity dispersion; this assumption is satisfied, for example, by the ram-pressure-sweeping hypothesis for the origin and heating of the cluster gas, discussed in the present paper. The recent observations of a possible iron emission feature in the X-ray spectrum of the Perseus cluster (Mitchell *et al.* 1976) would rule out the primordial-infall hypothesis if it could be shown that the line arises from the overall cluster rather than from the central active galaxy, NGC 1275. The presence of iron in the intergalactic medium of the Perseus cluster is explained naturally, however, if the gas is assumed to have been stripped from the galaxies. If all the S0's in the Perseus cluster are assumed to be gasless spirals, about 10^9 $M_\odot$ of iron are predicted in the intracluster medium if solar abundances are assumed.

IV. CONCLUSIONS

In general, the fact that in all X-ray clusters the ratio of spirals to S0's increases outward and the observation that the overall proportion of S0's correlates with the velocity dispersion, both support the hypothesis that S0's are produced from spirals by their interaction with a tenuous intracluster gas. Moreover, the fact that the required density is comparable to that presumed necessary for the hypothetical hot gas to produce X-rays gives, in turn, confirmation to the hot-gas hypothesis. It is conceivable, of course, that some entirely different hypothesis not invoking a tenuous gas could account for the two empirical results that we have found; however, we have not been able to think of one. Thus, our observations support the thermal origin for the X-ray emission in clusters of galaxies.

As a further, independent test of the ram-pressure-sweeping hypothesis, an examination could be made of the radial distribution of the average colors of the S0 galaxies in clusters. A disk galaxy in which star formation ceased long ago would be expected to be redder than one in which the interstellar matter was swept out comparatively recently. Thus, it is a definite prediction of the sweeping hypothesis that the disks of the S0's near the centers of the great clusters should be on the average redder than those in the outer parts. There appears to be no empirical information on this point at the present time.

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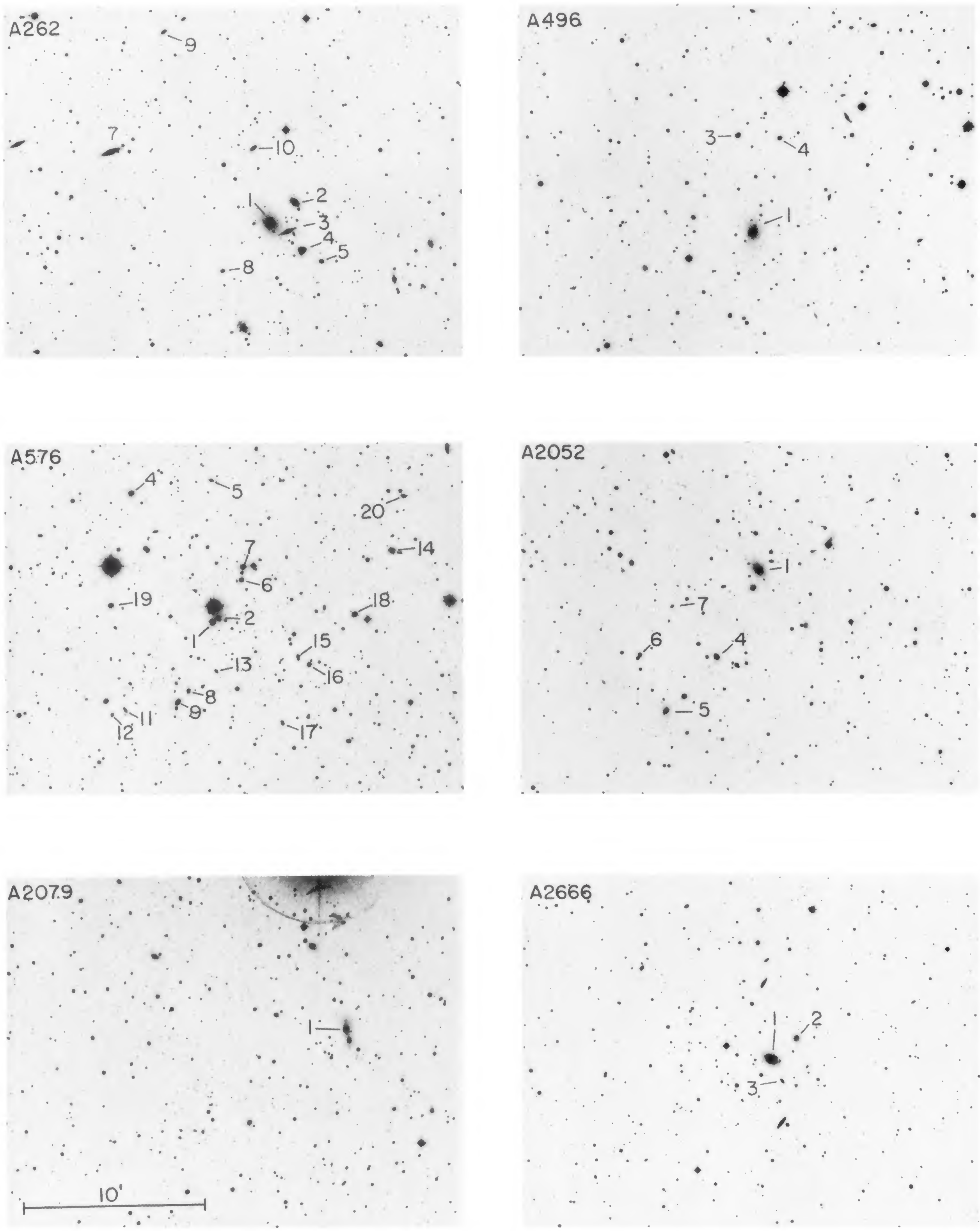

FIG. 1.—Identification charts for the galaxies listed in Table 2. All charts are reproductions of the National Geographic Society Palomar Sky Survey made to the same scale indicated on the lower left corner of the print. North is on top, east on the left.

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