THE ASTROPHYSICAL JOURNAL, 207:L1–L4, 1976 July 1

THE VIRGO CLUSTER. I. THE EQUALITY OF MEAN REDSHIFTS OF E AND S GALAXIES NEAR THE CLUSTER CENTER

ALLAN SANDAGE AND G. A. TAMMANN
Hale Observatories, Carnegie Institution of Washington, California Institute of Technology
Received 1976 February 27

ABSTRACT

The number of galaxies with known redshifts within 6° radius of the Virgo cluster core has increased from 77 galaxies in 1972 to 111 in 1975 December, of which two are certain background galaxies. The difference between the mean velocity of the E/S0 systems and the spirals is $\langle v_0\rangle_{E,S0} - \langle v_0\rangle_S = -26 \pm 114$ km s^{-1}, which is insignificant. The systemic velocity of the cluster, based on 102 galaxies in the 6° sample, is 1100 ± 68 km s^{-1} if the seven Sm and Im galaxies in the area are neglected. The total sample of 109 galaxies gives $\langle v_0\rangle = 1066 \pm 68$ km s^{-1}.

Subject headings: galaxies: clusters of — galaxies: redshifts

I. INTRODUCTION

The possibility that a significant difference exists in the mean velocities of spiral (S) and elliptical (E) galaxies in the Virgo cluster was raised by de Vaucouleurs (1961), and the problem has been discussed in the subsequent literature (cf. de Vaucouleurs and de Vaucouleurs 1963, 1972, 1973; Kowal 1969; Tammann 1972).

From early data, the velocity difference $\langle v_0\rangle_{E,S0} - \langle v_0\rangle_S$ was significant at about the 2–3 σ level and the effect has often been taken to be real, and cited as support for a new physics of nonvelocity redshifts (Arp 1968; Jaakkola 1971; Tifft 1972; de Vaucouleurs and de Vaucouleurs 1972). With enlarged material in subsequent years, the effect has decreased to less than 2 σ, yet sufficient agreement on the meaning of the data has not been reached to settle the question (cf. Tammann 1972; de Vaucouleurs and de Vaucouleurs 1973).

In view of the past emphasis on the problem, and the likely importance of a positive result, if real, a new effort has been made to obtain redshifts of all remaining Shapley-Ames galaxies in the Virgo cluster region. These are combined here with recent material from other sources for a new discussion.

II. THE DATA

To bypass debate on which regions of the Virgo complex should be included or excluded, we restrict attention in this *Letter* to a circle of radius 6° centered at 12^h25^m, $+13°06'$ (1950), which is near the core of the cluster. The difficult question of the relation of galaxies in the southern wing and the southern extension to the main body of the cluster is thereby conveniently avoided. Furthermore, the region is nearly the same as that treated by Tammann (1972, case III), and by G. and A. de Vaucouleurs (1973), a circumstance which should permit a straightforward comparison of the present work with the earlier studies.

The redshift material for Virgo cluster galaxies is considerably greater than was available in 1972. In the compilation by Tammann (1972, Table 1), 77 galaxies were available in the designated region, with 108 individual redshift values. These were also used by G. and A. de Vaucouleurs (1973). New redshifts, available to 1975 December, have expanded the material to 111 galaxies with 195 individual determinations. The new data are from six 21 cm studies (12 values from Davies and Lewis 1973; three by private communication from M. S. Roberts; six from Shostak 1975; three from Fisher and Tully 1975; 12 from Tully and Fisher 1976; and 13 from Huchtmeier, Tammann, and Wendker 1976). Optical redshifts for 32 galaxies with no previous values are from the redshift program in progress to complete the data for the Shapley-Ames catalog (Sandage 1976).

All 87 Shapley-Ames galaxies in the designated 6° circle (113 square degrees) now have available redshifts. Therefore, the present data constitute, in first approximation, a magnitude-limited sample, with a few fainter galaxies added. New galaxy types have been determined from large-scale Mount Wilson and Palomar plates for all galaxies in the sample to assure proper binning in the analysis. The new data will be published in a discussion of the kinematic and geometrical structure of the Virgo cluster as Paper II of the present series.

The surface distribution of most galaxies in the sample is shown in Figure 1, with separate coding for the E/S0's and the spirals. The most noteworthy feature is the well-known difference in the projected distribution of these types. The spirals are predominantly in the outer regions, generally avoiding the central core, while the E/S0's are more centrally concentrated.

This difference in spatial distribution, in conjunction with the known difference in shape of the velocity distribution between E and S galaxies (§ IV), is clearly a clue to cooperative evolutionary processes, as yet largely unknown, concerning galaxies of various types in the dense central regions of clusters. The problem, although fundamental, is not important for the restricted subject of this *Letter*, and is not pursued further here, but will be discussed in Paper III of the present series.

III. MEMBERSHIP

a) The Low- and High-Velocity Limits

The only individual galaxies that are *certain* members of the cluster are those with negative redshifts. There are seven such galaxies in the present sample, five of which are in the Shapley-Ames catalog. The galaxies are N4192 [Sb I–II, $v_0 = -186$], N4216 [Sb(s) II, $v_0 = -83$], N4406 [E2, $v_0 = -371$], N4413 [SBab, $v_0 = -140$], N4419 [Sab:, $v_0 = -342$], N4569 [Sab(s) I.8, $v_0 = -370$], and IC 3258 [Sm IV, $v_0 = -495$]. The velocities are corrected to the centroid of the Local Group by applying $300 \sin l \cos b$ km s^{-1} to the heliocentric values.

All seven galaxies occur within 4°.5 of the cluster center. Excluding the Local Group and these seven galaxies, there is no certain case of any other Shapley-Ames galaxy with a negative velocity. There are also no further negative velocities in the extensive redshift catalog of nearby galaxies of Fisher and Tully (1975). It is then obvious that these seven galaxies in the Virgo region, situated in an area of but 64 square degrees, must be cluster members on the low-velocity tail of the virial velocity distribution. (Compare 64 square degrees with 40,000 square degrees of the whole sky, or perhaps 10^4 square degrees as the "effective" Shapley-Ames area due to subtraction of the zone of avoidance, and the nonuniform distribution of Shapley-Ames entries along the supergalactic plane.)

Knowledge that these seven galaxies are members fixes the low-velocity tail of the Virgo cluster distribution at about -500 km s^{-1}. This now permits a prediction of the high-velocity tail (assuming the distribution to be symmetrical) because the mean v_0 is $\sim$1100 km s^{-1} (certainly the bulk of the sample are cluster members) giving $v_0 \approx 2700$ km s^{-1} for the high-velocity limit. The highest value in the sample is $v_0 = 2438 \pm 10$ km s^{-1} (N4388). Therefore, all galaxies in Figure 1 are potential cluster members, and none can be excluded on the basis of redshift alone.

b) Exclusions for Foreground or Background

Reclassification of the galaxies for Hubble type and van den Bergh luminosity class eliminated N4152 (Sc I.4) and IC 769 (Sb I) as cluster members, and assigned them to the background. (DDO 135 may be a foreground object, but we have treated it as a cluster member). Therefore, 109 galaxies remain in the sample. How many of these are field galaxies?

The magnitude-count relation for galaxies in the South galactic polar cap, well away from the north galactic anomaly, is $\log N(m) = 0.6\, m - 9.30$ per square degree, from the counts by Holmberg (1958), and in the Zwicky catalogs summarized elsewhere [Sandage, Tammann, and Hardy 1972 (STH), correcting their equation (6) for an error in the counting area

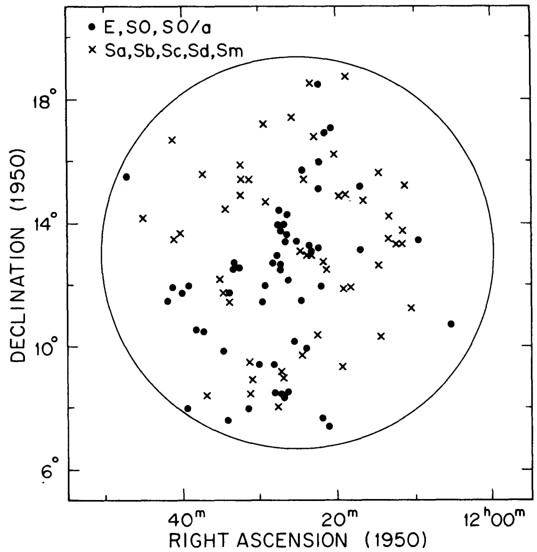

FIG. 1.—Distribution of E and S0 galaxies (*closed circles*) and spirals (*crosses*) in the central 6°, centered on the core of the Virgo cluster. Note the general central avoidance of the spirals, and the more central concentration of the E and S0 types.

of 36 square degrees rather than 42.25 assumed by them, and normalizing to $m = 13$ with a slope of 0.6]. Adopting $m = 13$ as the limit of our sample gives $N(13) \approx 3.6$ as the expected average contamination in 113 square degrees. But the average surface density in the north polar cap is $\sim$1.5 times that of the south polar cap (STH, Fig. 2) in the relevant magnitude range. If this reflects a higher density of field galaxies rather than an enhancement by only the Virgo complex and the Ursa Major cloud, then the maximum contamination of our sample could be as high as $n \approx 6$. We have identified one such galaxy (NGC 4152; IC 769 is fainter than $m = 13$) and have removed it from the sample. If the five possible additional contaminants are near the high velocity tail at $v_0 \approx 2000$ km s^{-1}, an error of only 50 km s^{-1} (too high) would be made in the overall mean velocity of the cluster. However, it is unlikely that the field galaxies would have this high a *mean* v_0, since there are only 13 galaxies with $v_0 \geq 2000$ km s^{-1} in the total sample, and many of these must be members because they are concentrated toward the center. Clearly, the effect on the mean velocity difference between E and S galaxies will be considerably less, because the contaminants will be of both types. In view of our ignorance of the correct statistics and the smallness of the effect, we ignore the contaminants in the remainder of this *Letter*.

IV. MEAN v_0 FOR E AND S GALAXIES

The distribution of radial velocities for the 50 E and S0 galaxies and for the 47 Sa–Sd galaxies is shown in Figure 2. (No Roberts [1972] correction has been applied to the optical data.) Although there is a marked

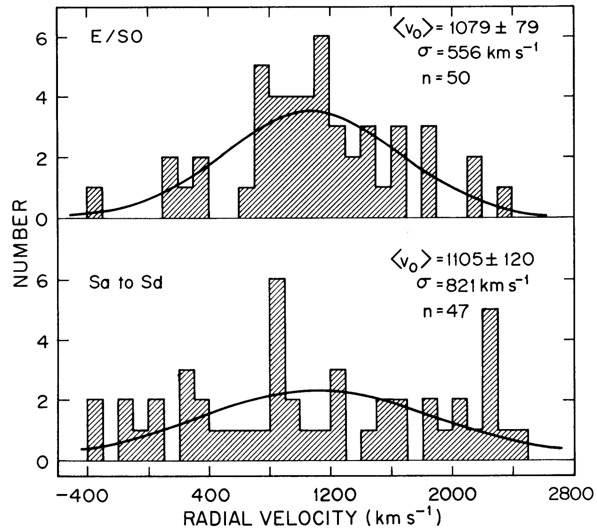

FIG. 2.—Distribution of radial velocities in our sample of E and S0 galaxies, and of spirals. Five galaxies of type S0/a, and seven galaxies of types Sm and Im are not plotted. Formal Gaussians with the same area, mean velocity, and dispersion as the histograms are shown, although the spiral distribution is distinctly nongaussian.

difference in the nature of the distribution,[1] the spirals are more uniformly spread throughout the range, somewhat like de Vaucouleurs's (1961) Figure 4, and the G. and A. de Vaucouleurs (1973) Figure 9, the *mean* values of 1070 ± 79 km s^{-1} for the E/S0 types, and 1105 ± 120 km s^{-1} for the spirals are the same to within 0.2σ of their combined errors.

Analysis of the material can be made with a finer binning of types. The values, listed in Table 1, summarize the main result of this discussion, and are plotted in Figure 3. There is no evidence here for a dependence of velocity on galaxy type, nor are any of the deviations from the mean line more significant than $\sim 1.8\ \sigma$.

V. COMPARISON WITH PREVIOUS CONCLUSIONS

The present analysis agrees with that of Tammann (1972), but differs from the conclusions of de Vaucouleurs (1961) and de Vaucouleurs and de Vaucouleurs (1972, 1973, 1974).

The chief effect of the new redshift data has been to increase the mean v_0 for E galaxies, and to decrease v_0 for the spirals. But even without the new material we

[1] There should be no concern about the difference in the character of the velocity distributions, for the reasons alluded to in § II.

TABLE 1

MEAN VELOCITIES OF VIRGO CLUSTER GALAXIES OF DIFFERENT TYPES

Type	$\langle v_0 \rangle$ (km s^{-1})	σ	n
E	1086±128	665	27
S0	1070±85	407	23
S0/a	1261±284	634	5
Sa, Sab	917±241	932	15
Sb, Sbc	945±349	986	8
Sc–Sd	1276±138	678	24
Sm, Im	572±307	811	7
E, S0	1079±79	556	50
S0/a	1261±284	634	5
Sa–Sd	1105±120	821	47
Sa–Im	1036±113	832	54
All	1066±68	705	109
All except Sm, Im	1100±68	689	102

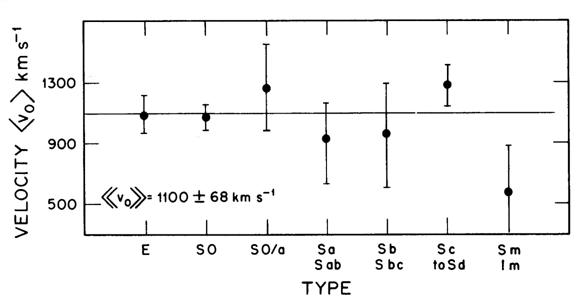

FIG. 3.—Variation of mean velocity $\langle v_0 \rangle$ with galaxy type in the 109 galaxy sample that is contained within a 6° radius of the Virgo cluster center. The systemic velocity for all galaxies, excluding types Sm and Im, is 1100 ± 68 km s^{-1}, shown by the solid line.

would have remained unconvinced that the rejection of certain high and low velocities by G. and A. de Vaucouleurs (1973) could be justified. With no rejection permitted by the argument of § III, the old material gives $\langle E \rangle - \langle S \rangle = 1012 \pm 71 - 1296 \pm 171 = -284 + 185$ km s^{-1}, for only a $1.5\ \sigma$ difference.

The new material has further reduced the mean difference to $\langle E \rangle - \langle S \rangle = 1079 \pm 79 - 1105 \pm 120 = -26 \pm 144$ km s^{-1}, which is a null result to within $0.2\ \sigma$ of the combined errors.

G. A. T. gratefully acknowledges financial support from the Swiss National Science Foundation, and wishes to thank the Director and Staff of the Hale Observatories for their hospitality during many visits to Pasadena.

REFERENCES

Arp, H. C. 1968, *Pub. A.S.P.*, **80**, 129.
Davies, R. D., and Lewis, B. M. 1973, *M.N.R.A.S.*, **165**, 231.
de Vaucouleurs, G. 1961, *Ap. J. Suppl.*, **6**, 213.
de Vaucouleurs, G., and de Vaucouleurs, A. 1963, *A.J.*, **68**, 96.
———. 1972, *Nature*, **236**, 166.
———. 1973, *Astr. and Ap.*, **28**, 109.
———. 1974, *ibid.*, **30**, 479.
Fisher, J. R., and Tully, R. B. 1975, *Astr. and Ap.*, **44**, 151.

Holmberg, E. 1950, *Medd. Lunds Obs.*, Ser. 2. No. 128.
———. 1958, *ibid.*, No. 136.
Huchtmeier, W. K., Tammann, G. A., and Wendker, H. J. 1976, *Astr. and Ap.*, **46**, 381.
Jaakkola, T. 1971, *Nature*, **234**, 534.
Kowal, C. T. 1969, *Pub. A.S.P.*, **81**, 608.
Roberts, M. S. 1972, *IAU Symposium No. 44, External Galaxies and Quasi-stellar Objects*, ed. D. S. Evans (Dordrecht: Reidel), p. 12.
Sandage, A. 1976, *Redshift Catalog*, in preparation.
Sandage, A., Tammann, G. A., and Hardy, E. 1972, *Ap. J.*, **172**, 253 (STH).
Shostak, G. S. 1975, *Ap. J.*, **198**, 527.
Tammann, G. A. 1972, *Astr. and Ap.*, **21**, 355.
Tifft, W. G. 1972, *IAU Symposium No. 44, External Galaxies and Quasi-stellar objects*, ed. D. S. Evans (Dordrecht: Reidel), p. 369.
Tully, R. B., and Fisher, J. R., 1976, *Astr. and Ap.*, in press.

ALLAN SANDAGE: Hale Observatories, 813 Santa Barbara Street, Pasadena, CA 91101

G. A. TAMMANN: Astronomisches Institut, Venusstrasse 7, CH-4201 Binnengen, Switzerland