PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Classification of Evolving Galaxies

S. Van Den Bergh

Phil. Trans. R. Soc. Lond. A 1980 **296**, 319-327
doi: 10.1098/rsta.1980.0176

Phil. Trans. R. Soc. Lond. A. **296**, 319–327 (1980) [319]
Printed in Great Britain

The classification of evolving galaxies

By S. van den Bergh
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics,
National Research Council of Canada, 5071 *West Saanich Road,*
*Victoria, B.C. V*8*X* 3*X*3, *Canada*

A review of available evidence favours the view that most lenticular galaxies are former spirals that have been stripped of gas rather than galaxies in which all gas was used up at the termination of proto-galactic collapse.

An analysis of new homogeneous colour observations of ellipticals by Sandage & Visvanathan suggests that E1 galaxies are slightly redder than are ellipticals of type E5. This situation might have arisen if (1) the mass spectrum of star formation, and hence the rate of heavy element enrichment, depended on turbulence and if (2) turbulence in proto- E1 galaxies was more violent than it was in proto- E5 galaxies.

Analysis of new data that have recently become available shows that the luminosity distribution of elliptical galaxies contains more luminous objects than does the luminosity distribution of lenticulars. This result suggests that the mass spectrum of lenticular galaxies is deficient in high mass objects when compared with that of ellipticals.

The frequency with which barred spirals occur is found to depend on both Hubble type and on galaxy luminosity but not on environmental factors such as membership in clusters or binary systems.

It is shown that statistically selected samples of 'binary' galaxies are heavily contaminated by cluster members. This result, and a selection effect described in the text, lower the credibility of galaxy mass:light ratios determined from studies of binary galaxies.

Finally, it is noted that the brightest galaxies in clusters of BM type I are much more likely to be binaries than is the case for first-ranked galaxies in clusters of BM type III.

1. The S0 controversy

The present morphology of galaxies is deeply rooted in their evolutionary history. Any classification scheme that provides a natural framework for the classification of the present diversity of galaxy types should therefore be capable of providing new insights into galactic evolution.

Present ideas on the evolution of galaxies are firmly embedded within the framework provided by Hubble's (1926) famous 'tuning fork' classification scheme. During the last few decades thinking on galactic evolution has proceeded along two divergent paths. Hubble (1936) and Sandage (1961) considered S0 galaxies as a class that was *intermediate* between spirals and ellipticals, whereas Baade (1963) and van den Bergh (1976*a*) regarded them as a sequence of increasing disk:bulge ratio that *parallels* that of normal spirals. According to the latter view, S0 galaxies were once spirals from which the gas was subsequently stripped (Spitzer & Baade 1951; Gunn & Gott 1972). A strong argument against Hubble's hypothesis, that S0 galaxies are a transitional type between elliptical and spiral galaxies, is provided by the sharp discontinuity in angular momentum per unit mass (*cf.* Illingworth 1977; Bertola & Capaccioli 1978) that appears to exist between ellipticals on the one hand and spirals and S0 galaxies on the other. A second argument against the idea that E and S0 galaxies form a continuous sequence is provided by observations which show (van den Bergh & McClure 1979) that major differences exist between the luminosity functions of these two classes of objects.

The view that the formation of S0 galaxies was due to initial conditions prevailing at the time of galaxy collapse rather than to environmental factors has recently been argued very eloquently by Sandage & Visvanathan (1978*b*). Their most telling points are that: (1) there are many S0 galaxies outside clusters where both the gas density and the random motions of field galaxies are too low for stripping to take place; and (2) the distribution of disk:bulge ratios of S0 galaxies differs from that of spirals in the sense that few if any S0 galaxies have as large disk:bulge ratios as do Sc spirals.

The first objection of Sandage & Visvanathan would lose much of its force if it could be shown that some mechanism other than stripping by ram pressure can remove gas from spirals. Specifically, van den Bergh (1963) has suggested that explosive events in the nuclei of spirals might turn them into S0s. Some support for this hypothesis is provided by observations of the classical S0 field galaxy NGC 5102 (van den Bergh 1976*b*; Pritchet 1979). The present morphology of this object appears to be due to a powerful explosion that triggered a burst of star formation in the nucleus of this galaxy *ca.* 2×10^8 years ago.

Sandage and Visvanathan's second point rests on at least two unproven assumptions: (*a*) the frequency function of disk:bulge ratios with which galaxies are created is independent of environment, and (*b*) this frequency function of disk:bulge ratios has not changed since the era when galaxies formed.

These two assumptions may be questioned on both observational and theoretical grounds. Observations by Oemler (1974) show that the ratio (number of ellipticals)/(number of S0 + number of spirals) is largest in dense clusters. This suggests that a high density environment favours the formation of galaxies with low disk:bulge ratios. According to White (1979), angular momentum considerations appear to rule out the alternate possibility that merging spirals in rich clusters might have turned into ellipticals. Finally, Biermann (1978) has suggested a plausible explanation for the almost complete absence of S0 galaxies with disk:bulge ratios as large as those observed in late Sc spirals. He points out that galaxies in which the gravitational potential is initially dominated by gas may self-destruct if that gas is suddenly removed.

If flattened galaxies form two parallel sequences comprising gas-rich (spiral) and gas-poor (S0) sequences, then objects with intermediate properties would also be expected to exist. On the basis of optical morphology, van den Bergh (1976*a*) suggested that galaxies such as NGC 4921 in the Coma cluster are gas-poor 'anaemic' spirals. Considerable support for this view is provided by recent 21 cm observations by Sullivan & Johnson (1978) which show that spiral galaxies in rich clusters are hydrogen deficient by factors of at least 3–5 compared with similar field spirals.

2. The luminosity distributions of E and S0 galaxies

Recently Sandage & Visvanathan (1978*a*, *b*) have published new photometry and morphological classifications for 405 early-type galaxies. Their sample is 83% complete for galaxies in the Shapley–Ames catalogue with types E, S0, SB0 or SB0/a. The distribution of absolute magnitudes of E and S0 galaxies drawn from the Shapley–Ames sample is shown in figure 1. These data show that the luminosity function of ellipticals contains more bright objects than does that of S0 galaxies. Inspection of figure 1 shows that the maximum in the observed luminosity distribution of ellipticals occurs almost a full magnitude brighter than does that for lenticulars. Application of the Kolmogorov–Smirnov two sample test to the data plotted in figure 1 shows that the observed differences between the E and S0 luminosity distributions are statistically significant at better than the 99.9% confidence level.

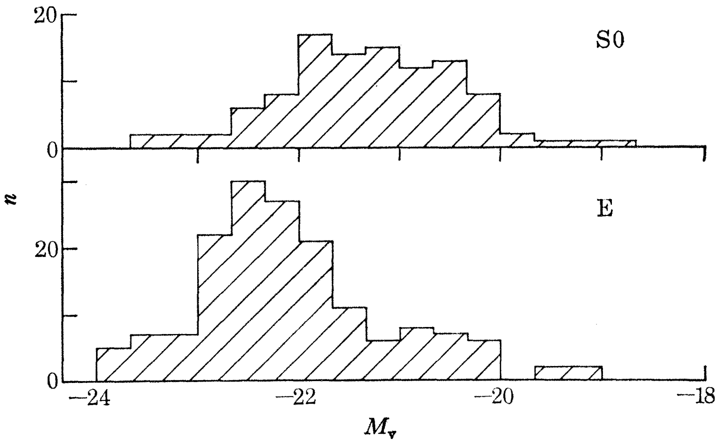

FIGURE 1. The observed luminosity distribution of elliptical galaxies is seen to contain a large fraction of bright objects than does that of lenticulars.

Both elliptical and lenticular galaxies exhibit a pronounced concentration in clusters. It therefore appears highly unlikely that the large differences that are observed between the luminosity distributions of E and S0 galaxies are due to effects produced by spatial inhomogeneities. An additional check on this point is provided by the observation that the differences between the luminosity distributions of E and S0 galaxies noted above occur for both field galaxies and for those E and S0 galaxies that are located in the great clusters. The case for a real dichotomy between ellipticals and lenticulars is further strengthened by the observation that the luminosity distribution of flattened ellipticals of types E4 to E7 does not differ significantly from that of more nearly circular objects of types E0 to E2.

Within the admittedly limited statistically accuracy of the currently available data, no significant difference is seen between the luminosity distributions of S0 and SB0 galaxies.

3. The colours of S0 galaxies

If S0 galaxies were formed at the termination of proto-galactic collapse then they should all have similar ages. In particular, no young relatively blue S0 galaxies should exist. Sandage & Visvanathan (1978*b*) use the absence of lenticular galaxies with 'fully corrected' colours $C_0 < 2.0$, corresponding to $U-V = 1.16$, as evidence against the idea that significant numbers of such young S0 galaxies exist. Recent numerical calculations on the colour evolution of galaxies in which star formation has been suddenly truncated (Biermann & Tinsley 1975; van den Bergh & Pritchet 1979) show that the severity of the age constraint imposed by the absence of S0 galaxies with $C_0 < 2.0$ depends quite critically on the rate at which star formation was declining before its sudden quenching. Our calculations indicate that an Sc galaxy, with a nearly constant rate of star formation, will reach $C_0 = 2.0$ at *ca.* 5×10^8 years after star formation was truncated. A galaxy of type Sb, in which the rate of star formation has declined by a factor of five, will take only *ca.* 2×10^8 years to reach this same colour.

Sandage & Visvanathan point out that few, if any, S0 galaxies exhibit the large disk: bulge

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

ratios that are observed in typical Sc spirals. It follows that most lenticulars must have been derived from early or intermediate type spirals for which $T < 2 \times 10^8$ years. Statistically, one would not expect a galaxy in which star formation has been truncated so recently to occur in the relatively small sample of only 88 S0 galaxies studied by Sandage & Visvanathan. Assuming a uniform rate of S0 production and a Hubble time of 1.5×10^{10} years, one would, on the average, expect one S0 galaxy in their sample to have been formed every 1.7×10^8 years. In the more likely event that the rate of formation of lenticulars is a declining function of time the present interval between the addition of new S0 galaxies would be more than 2×10^8 years. This is longer than the time interval during which an Sb galaxy that has been transformed to a lenticular remains bluer than $C_0 = 2.0$. It is therefore not surprising that the Sandage & Visvanathan sample appears to contain no S0 galaxies that are currently bluer than this value.

In summary, it is concluded that the presently available sample of homogeneous S0 colours is too small to exclude the possibility that lenticular galaxies are still being formed at present by the sudden quenching of star formation in spiral galaxies.

4. Colour and ellipticity of elliptical galaxies

Elliptical galaxies are, from a morphological point of view, the most homogeneous class of extragalactic objects. It therefore came as quite a surprise when a very extensive and uniform new survey of the colours of E galaxies by Sandage & Visvanathan (1978*a*, *b*) produced evidence for an intrinsic dispersion $\sigma \approx 0.10$ magnitude in C_0, the intrinsic $U-V$ colour of E galaxies reduced to the same absolute magnitude. Quite unexpectedly an analysis of the 168 pure ellipticals in the Sandage & Visvanathan sample shows a small but marginally significant difference in the mean C_0 colours of E galaxies with different apparent flattenings. From these colour data, which are collected in table 1, it is found that E0–E2 galaxies ('the E1 sample') are redder than the E4–E7 galaxies ('the E5 sample') by $\Delta C_0 = 0.064 \pm 0.021$ (m.e.). Intercomparison of the frequency distribution of ellipticities among red ($C_0 > 2.35$) and blue ($C_0 < 2.25$) ellipticals, which is shown in table 2 and figure 2, also suggests that red and blue ellipticals have different apparent flattenings. Application of the Kolmogorov–Smirnov two-sample test to these data shows that there is only about one chance in six that the red and blue ellipticity distributions were drawn from the same sample.

Table 1. Colour against flattening of E galaxies

type	n_{ga}	$\langle C_0 \rangle$ m.e.	σ
E0–E2	88	2.334 ± 0.012	0.11
E3	25	2.303 ± 0.020	0.10
E4–E7	55	2.270 ± 0.017	0.12

Table 2. Frequency distribution of ellipticities among red and blue ellipticals

C_0	E0	E1	E2	E3	E4	E5	E6	total
<2.25	8	6	7	8	11	7	3	50
>2.35	10	9	13	6	5	6	1	50

The following five possible explanations suggest themselves for the apparent differences between the E1 and E5 samples: (1) the effect is due to the perversity of small number statistics; (2) the effect results from some unsuspected problem with the aperture or luminosity correction procedures adopted by Sandage & Visvanathan; (3) the E5 sample has been contaminated by Sa galaxies; (4) the dominant stellar population in E5 galaxies is younger than that in objects of type E1; (5) the dominant population in E1 galaxies is, at a given absolute magnitude level, metal-richer than that in E5 galaxies.

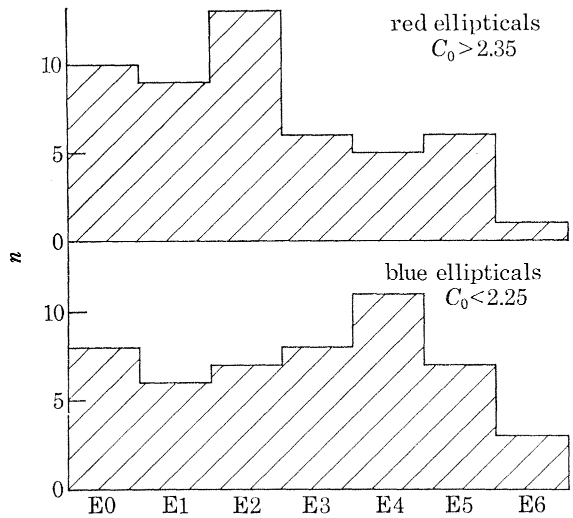

FIGURE 2. Comparison between the frequency distribution of ellipticities among red and blue ellipticals. The data suggest that the bluest ellipticals are more flattened than are the reddest E galaxies.

From the models of Larson & Tinsley (1978) it is found that the observed colour difference $\Delta C_0 = 0.064 \pm 0.021$ (m.e) could be accounted for if the dominant population in E1 galaxies were *ca.* 3×10^9 years older than that in E5 galaxies. Alternatively, the observed colour difference (Tinsley 1978; Frogel *et al.* 1978) might be explained by assuming that the average metallicity of the dominant population in E1 galaxies is about 40% greater than it is in E5 galaxies. The true difference in metallicity would, of course, have to be slightly higher than this because the E1 galaxy sample is contaminated by flattened objects seen almost pole-on. A speculative scenario for such metallicity differences is that the turbulent velocities in a collapsing E1 galaxy are higher than those in a collapsing E5 galaxy. This higher turbulence might lead to a mass spectrum of star formation that is more heavily weighted towards luminous stars, which produce the highest yield of heavy elements.

In view of the possible evolutionary significance of the suspected colour difference between the E1 and E5 samples it is very important that additional $U-V$ colours of elliptical galaxies be obtained.

5. Barred spirals in clusters

If the existence of barred spirals is in some way related to bar-like instabilities in cold disks (Ostriker & Peebles 1973), then SB galaxies might be more common among cluster objects than they are among field spirals. This is so because the massive halos of cluster spirals might be stripped off during tidal encounters (Gallagher & Ostriker 1972; Richstone 1975, 1976; White 1976; Strom & Strom 1978).

Some marginal support for the view that SB galaxies could perhaps be embedded in less massive halos than are normal spirals is provided by the recent work of Pişmiş & Maupomé (1978). Their data hint at the possibility that SB galaxies might have lower total masses than do normal spirals. To investigate any such systematic differences between normal and barred spiral galaxies in more detail we have studied their relative frequency inside and outside clusters (Zwicky *et al.* 1961–8) in the *Uppsala General Catalogue of Galaxies* (Nilson 1973). It should perhaps be emphasized that the boundaries of the Zwicky clusters enclose both the cluster core and its halo. Furthermore the sample of galaxies in Zwicky's clusters will be contaminated by foreground and background objects that appear projected on cluster areas. Since such superpositioning problems are most severe along the 'supergalactic equator' the present study was restricted to the zone 0h $< \alpha <$ 12h.

Table 3. Percentage of all galaxies that are barred spirals as a function of environment

	n	percentage SB (±m.e.)
field galaxies	1146	31±2
open clusters	440	27±3
moderately compact clusters	493	34±3
Abell clusters	293	33±4
entire sample	2087	31±1
binaries	264	26±4

Table 4. Fraction of barred spirals as a function of Hubble type

type	n	percentage SB (±m.e.)
S0	240	28±4
Sa	196	58±7
Sb	468	56±4
Sc	962	21±2

Only relatively large objects with 'information parameter' 3, 4 or 5, which have the most reliable morphological classification types, were included in the present analysis. Since the Hubble classification scheme is not strictly applicable to low luminosity galaxies (*cf.* van den Bergh 1977), subgiant and dwarf galaxies were excluded from the sample. In the subsequent analysis de Vaucouleurs's types SAB and SB and DDO types S(B) and SB will be lumped together under the barred spiral designation. Objects with intermediate Hubble types such as Sab were counted as half Sa and half Sb. All uncertain classifications were omitted.

Information on the relative frequency of SB galaxies in different environments is collected in table 3. The data in this table appear to indicate that the percentage of barred spirals is *ca.* 31 % in all environments. This conclusion should, however, be regarded with caution because (as is shown by table 4) the fraction of barred spirals in the *U.G.C.* differs by more than a factor of 2 between objects of differing Hubble type. Only *ca.* $\frac{1}{4}$ of the S0 and Sc galaxies are barred, whereas more than half of the Sa and Sb galaxies are barred spirals. The fact that early-type galaxies are more strongly concentrated in clusters than are late-type spirals might therefore affect the statistics. That this is not in fact so is shown by tables 5–8. The data in these tables show no statistically significant differences between the incidence of bars among field and cluster galaxies of a given Hubble type. Taken at face value this result suggests that the formation of bars in galaxies is determined by initial conditions prevailing at the time of galaxy formation rather than by environmental factors that subsequently affect the evolution of a galaxy. This conclusion should be checked by studying both the cores of rich clusters and field areas on large-scale reflector plates. Some support for the accuracy of Nilson's classifications is, however, provided by Rood & Baum (1967) who have studied the galaxies in the core of the Coma cluster on Hale 5 m plates. These authors find that 20 ± 4 % of the Coma S0 galaxies are barred. This result is consistent with the value 28 ± 4 % (*cf.* table 4) found from Nilson's data.

Table 5. Fraction of S0 galaxies that are barred as a function of environment

	n	percentage SB (±m.e.)
field	117	28 ± 6
open clusters	41	33 ± 10
moderately compact clusters	81	24 ± 7
Abell clusters	38	33 ± 11
binaries	53	25 ± 8

Table 6. Fraction of Sa galaxies that are barred as a function of environment

	n	percentage SB (±m.e.)
field	110.5	57 ± 9
open clusters	35.5	55 ± 15
moderately compact clusters	49.5	62 ± 14
Abell clusters	29.5	63 ± 19
binaries	43	37 ± 11

Table 7. Fraction of Sb galaxies that are barred as a function of environment

	n	percentage SB (±m.e.)
field galaxies	255	57 ± 6
open clusters	105	45 ± 8
moderately compact clusters	105.5	64 ± 10
Abell clusters	71.5	62 ± 12
binaries	59.5	45 ± 10

Table 8. Fraction of Sc galaxies that are barred as a function of environment

	n	percentage SB (±m.e.)
field galaxies	558.5	20 ± 2
open clusters	205.5	18 ± 3
moderately compact clusters	194	26 ± 4
Abell clusters	96	21 ± 5
binaries	50.5	25 ± 9

6. Barred spirals in binary systems

An additional check on the possible dependence of bar formation on environment is provided by the study of binary galaxies. A comparison between the frequency of bars in field objects and in a sample of binaries selected from Nilson's catalogue by Peterson (1978) is given in tables 3, 5–8. The data in these tables show no evidence for gross differences in the frequency with which bars occur among field and binary galaxies. (A possible small deficiency of barred objects among binary members of Hubble types Sa and Sb is only marginally significant.)

It is of some interest to note (*cf.* table 9 and figure 3) that the relative frequencies of E and S0 galaxies in Peterson's sample are about threefold and twofold greater, respectively, than they are in the entire Nilson catalogue. The conclusion that Peterson's sample is strongly biased in favour of early-type galaxies is significant at better than the 99.9 % confidence level. This result implies that either (1) Peterson's sample of binaries is heavily contaminated by cluster members, which tend to be of types E and S0, or (2) the evolution of binary systems favours the formation of early-type galaxies. The inclusion of objects such as Seyfert's Sextet in Peterson's sample of 'binary galaxies' shows that some contamination of his sample has in fact taken place. A similar bias in favour of early-types galaxies is found in the somewhat smaller binary sample studied by Turner (1976). The reason for this effect is that blind application of statistical selection techniques will frequently result in the two brightest galaxies in distant clusters being counted as 'binaries'. Since the velocity dispersion in dense clusters is larger than it is in typical binaries, such contamination of the sample by pseudo-binaries will result in an overestimate of the mass:light ratio. A bias that operates in the opposite direction might, however, be introduced by the fact that binary galaxies with massive halos will probably merge within a Hubble time (White & Sharp 1977; White 1978), whereas double systems without massive halos will survive to the present day. Since there is no observational evidence to link the invisible matter in massive halos with the luminous material in galaxies, it is quite conceivable that the total stellar mass in the cores of galaxies is only loosely correlated with the invisible mass in their halos. If this view is correct then only those binary systems that started out with below average halo:core mass ratios will have been able to survive to the present day.

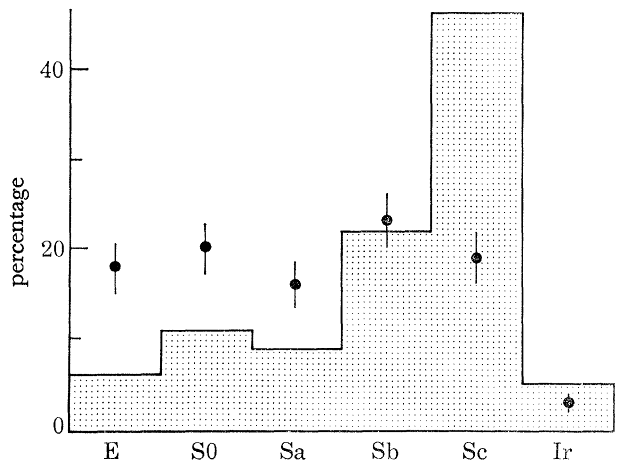

FIGURE 3. Nilson's catalogue (histogram) is seen to contain fewer early-type and more late-type objects than does Peterson's binary sample (error flags).

TABLE 9. FREQUENCY DISTRIBUTION OF HUBBLE TYPES†

Hubble type	Nilson galaxies number	Nilson galaxies percentage	Peterson binaries number	Peterson binaries percentage
E	123	6	48	18
S0	240	11	54	20
Sa	196	9	43	16
Sb	468	22	59.5	23
Sc	962	46	50.5	19
Ir	98	5	9	3

† Data refer to galaxies with Nilson's 'information parameters' 3, 4 and 5.

TABLE 10. MULTIPLICITY OF BRIGHTEST CLUSTER GALAXY AS A FUNCTION OF BAUTZ–MORGAN TYPE

type	single	multiple	percentage multiple
I	43	15	26
I–II	51	13	20
II	194	39	17
II–III	315	59	16
III	921	33	3

7. Binary first ranked cluster galaxies

Recently, Leir & van den Bergh (1977) have made a detailed study of 1889 rich clusters of galaxies in Abell's catalogue. As part of this investigation, Leir (1976) noted the multiplicity of each of the first-ranked galaxies in this sample. Subsequently Rood (*cf.* Rood & Leir (1979) and table 10) found that the frequency with which the brightest cluster galaxy is a binary is strongly dependent on the Bantz–Morgan type of its parent cluster. The data show that the fraction of first-ranked multiple galaxies decreases from 26% for BM type I to 3% for BM type III. The reason for this effect is not understood. In particular, it is difficult to see how the high frequency of binary systems in type I clusters could have been maintained against dynamical friction which destroys such systems on a time-scale that is much shorter than the Hubble time.

References (van den Bergh)

Abell, G. O. 1958 *Astrophys. J. Suppl.* **3**, 211.
Baade, W. 1963 *Evolution of stars and galaxies.* Cambridge, Mass.: Harvard University Press.
Bertola, F. & Capaccioli, M. 1978 *Astrophys. J.* **219**, L95.
Biermann, P. 1978 *Astron. Astrophys.* **62**, 255.
Biermann, P. & Tinsley, B. M. 1975 *Astron. Astrophys.* **41**, 441.
Frogel, J. A., Persson, S. E., Aaronson, M. & Matthews, K. 1978 *Astrophys. J.* **220**, 75.
Gallagher, J. S. & Ostriker, J. P. 1972 *Astr. J.* **77**, 288.
Gunn, J. E. & Gott, J. R. 1972 *Astrophys. J.* **176**, 1.
Hubble, E. 1926 *Astrophys. J.* **64**, 321.
Hubble, E. 1936 *The realm of the nebulae.* New Haven: Yale University Press.
Illingworth, G. 1977 *Astrophys. J.* **218**, L43.
Larson, R. B. & Tinsley, B. M. 1978 *Astrophys. J.* **219**, 46.
Leir, A. A. 1976 M.Sc. thesis, University of Toronto.
Leir, A. A. & van den Bergh, S. 1977 *Astrophys. J. Suppl.* **34**, 381.
Nilson, P. 1973 *Uppsala General Catalogue of Galaxies* (*Acta upsaliensis*, ser. 5A, vol. 1).
Oemler, A. 1974 *Astrophys. J.* **194**, 1.
Ostriker, J. P. & Peebles, P. J. E. 1973 *Astrophys. J.* **186**, 467.
Peterson, S. D. 1978 Ph.D. thesis, Cornell University.
Pişmiş, P. & Maupomé, L. 1978 *Revta mex. Astron. Astrophys.* **2**, 319.
Pritchet, C. J. 1979 *Astrophys. J.* **231**, 354.
Richstone, D. O. 1975 *Astrophys. J.* **200**, 535.
Richstone, D. O. 1976 *Astrophys. J.* **204**, 642.
Rood, H. J. & Baum, W. A. 1967 *Astr. J.* **72**, 398.
Rood, H. J. & Leir, A. A. 1979 *Astrophys. J.* **231**, L3.
Sandage, A. 1961 *The Hubble Atlas of Galaxies.* Washington: Carnegie Institution.
Sandage, A. & Visvanathan, N. 1978*a* *Astrophys. J.* **223**, 707.
Sandage, A. & Visvanathan, N. 1978*b* *Astrophys. J.* **225**, 742.
Spitzer, L. & Baade, W. 1951 *Astrophys. J.* **113**, 413.
Strom, S. E. & Strom, K. M. 1978 *Astr. J.* **83**, 732.
Sullivan, W. T. & Johnson, P. E. 1978 *Astrophys. J.* **225**, 751.
Tinsley, B. M. 1978 *Astrophys. J.* **222**, 14.
Turner, E. L. 1976 *Astrophys. J.* **208**, 20.
van den Bergh, S. 1963 *Publ astr. Soc. Pacif.* **75**, 498.
van den Bergh, S. 1976*a* *Astrophys. J.* **206**, 883.
van den Bergh, S. 1976*b* *Astr. J.* **81**, 795.
van den Bergh, S. 1977 In *The evolution of galaxies and stellar populations* (ed. B. M. Tinsley & R. B. Larson), p. 19. New Haven: Yale University Observatory.
van den Bergh, S. & McClure, R. D. 1979 *Astrophys. J.* **231**, 671.
van den Bergh, S. & Pritchet, C. J. 1979 In preparaion.
White, S. D. M. 1976 *Mon. Not. R. astr. Soc.* **174**, 19.
White, S. D. M. & Sharp, N. A. 1977 *Nature, Lond.* **269**, 395.
White, S. D. M. 1978 *Mon. Not. R. astr. Soc.* **184**, 185.
White, S. D. M. 1979 In preparation.
Zwicky, F. *et al.* 1961, 1963, 1965, 1966, 1968*a, b* *Catalogue of galaxies and clusters of galaxies*, vols. 1–6. Pasadena: California Institute of Technology.