W. A. BAUM
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington,
California Institute of Technology
Pasadena, California

Photoelectric Magnitudes and Red-Shifts

In a recent paper, Sandage [1] has reviewed four observational tests of world models, namely,

1. The relation between red-shifts and magnitudes of galaxies:
2. The relation between counts and magnitudes of galaxies:
3. The relation between red-shifts and angular diameters of galaxies:
4. The compatibility of age estimates.

Among optical observations, the red-shift-magnitude relation provides the most powerful test, and this paper is concerned with the present photoelectric attack on that problem.

There are two points that should be emphasized at the outset concerning the optical test described here and the radio test described by Ryle [2]. First, the radio test, which pertains to the count-magnitude relation, is unable to provide an unambiguous choice among the usual world models, whereas the red-shift-magnitude relation can lead to a single conclusion. The second point is that radiation from very distant galaxies started on its way when those galaxies were younger. We do not know how to cope with evolutionary changes in the radio magnitudes, but we do have some hope of estimating evolutionary corrections for optical magnitudes.

Apart from effects due to evolution or obscuration, the red-shift-magnitude relation depends upon world models as shown in Figure 1. Curve D represents the relation predicted by the steady-state

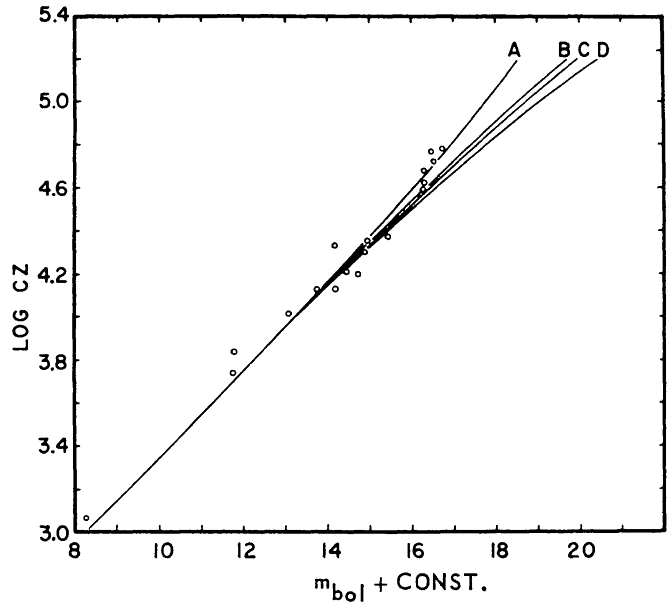

Figure 1. Theoretical curves for the red-shift-magnitude relations predicted by various world models. Adapted from Hoyle and Sandage [3].

model. Curve C is the limiting case for an exploding model with no significant gravitational deceleration; Curve B is the Euclidean case; and Curve A lies in the region of exploding universes which will collapse again. The points representing earlier photographic data [4] show the range of red-shifts ordinarily within the reach of the conventional spectographic method. The main reason for undertaking the photoelectric method [5] was to obtain points nearer the top of the diagram where the various world models are much more clearly distinguished. The photoelectric method is also less vulnerable to systematic errors in the bolometric magnitudes.

In the program described here, both the red-shift and the bolometric magnitude of a galaxy are measured photoelectrically. The light from each galaxy is measured in a number of colors. When the results are plotted on a true energy scale, they yield a spectral-energy distribution curve like that shown in Figure 2. This particular curve represents the mean of six bright elliptical galaxies in the Virgo Cluster. A curve for similar ellipticals in another cluster at a greater distance will have about the same shape, but will be displaced toward the right and will fall at fainter magnitudes. The horizontal displacement yields the difference in red-shift, while the vertical displacement, after a log $(1 + z)$ correction due to the logarithmic abscissa, yields the difference in bolometric magnitude.

This photoelectric program [5], which is still in progress, was undertaken at Palomar six years ago. At that time, it became possible to extend photoelectric observations of the infrared out to the

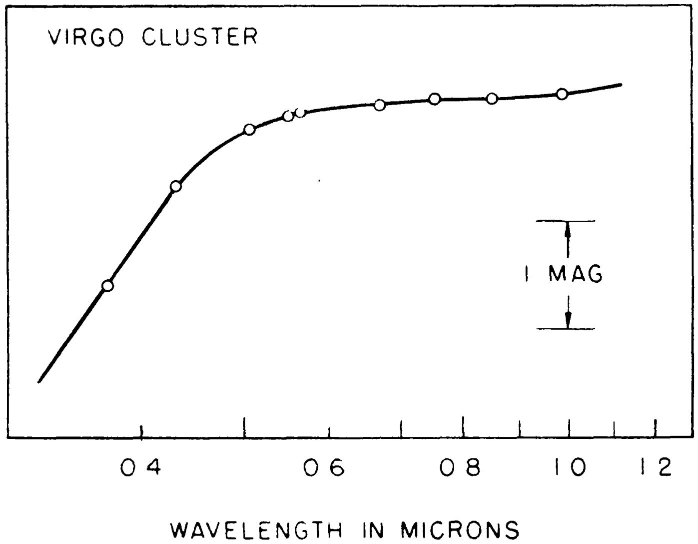

Figure 2. Mean spectral energy distribution curve for six bright elliptical galaxies in the Virgo Cluster. The ordinate represents relative energy per unit wave length expressed on a magnitude scale.

faintest objects which can be photographed. The possibility of measuring very faint objects photoelectrically in the infrared, as well as at shorter wave lengths, provided the opportunity of undertaking a completely photoelectric attack on the red-shift-magnitude problem. In addition to red-shifts and bolometric magnitudes, the photoelectric observations have also yielded a recipe for the stellar content of ellipticals [6] and some data on the intensity profiles of ellipticals.

After a cluster of galaxies has been chosen for study, plates in two or more colors are compared, and a few of the brighter elliptical galaxies in the cluster are selected for photoelectric measurement. In nearby clusters, ellipticals can be identified both by the appearance of the images and by their consistent color index. In distant clusters, one must depend mainly upon the color index to identify ellipticals and to exclude possible foreground galaxies. The photoelectric photometer is set onto faint galaxies by coordinate offsets and the data are obtained by the pulse-counting method. In the infrared, photocurrents as small as 20 electrons per minute must be measured against sky backgrounds which are many times larger.

Most of the photoelectric observations have been made in the nine colors identified in Table 1. In a few cases, two additional colors have been used to provide points in the yellow and orange regions. Effective wave lengths of the various colors in Table 1 were derived by multiplying together the transmission curves of the filters, the spectral sensitivity curves of the photocathodes, the

TABLE 1

Colors Observed

Color	*Photocathode*	*Filter*	*Effective λ for ellipticals (z=0)*	*Approximate band-width*
Ultraviolet *U*	Sb Cs	C9863(3) + C7740(2)	3730	500
Violet *V*	Sb Cs	BG12(3) + GG13(2)	4335	740
Blue *B*	Sb Cs	Wide-band interference	5065	430
Green *Ga*	Sb Cs	Wide-band interference	5525	470
Green *Gc*	$CsO_2(Ag)$	BG18(2) + OG1(2)	5645	700
Red *R*	$CsO_2(Ag)$	Wide-band interference	6705	850
Infrared *I*	$CsO_2(Ag)$	Wide-band interference	7525	600
Infrared *J*	$CsO_2(Ag)$	Wide-band interference + RG10(3)	8520	800
Infrared *K*	$CsO_2(Ag)$	Heimann No. 205	9875	1100

spectral transmission of the earth's atmosphere (for 1.2 air masses), and the approximate spectral energy distributions of the objects. Indeed, the effective wave lengths of some of the colors have a second-order dependence upon the red-shift of the galaxy being observed, and that effect has been taken into account.

There are two methods by which multicolor magnitudes with arbitrary zero points can be adjusted to a true energy scale. One method is to measure a reference object having a calibrated spectral energy distribution. Another method is a "bootstrap" process wherein data for two clusters of known red-shift, one nearby and the other far away, are compared with one another, and the problem is solved in reverse to derive the shape of the spectral energy curve which yields the correct difference in red-shift. Both methods have been investigated and they yield consistent results. The energy distribution curves in the present paper are based upon observations of the 7th magnitude AO star HD 182487, which has been calibrated against Vega by Oke [7].

Figure 3 shows the spectral energy distribution curve for a cluster of galaxies with a red-shift of $z = 0.19$ or $cz = 57{,}000$ km/sec. The points represent the mean results for three bright ellipticals in the cluster. Since these objects are brighter than 20th magnitude, the observational errors are relatively small. An unshifted energy curve is sketched at the left for comparison. This cluster lies approximately at the limit of the usual range of conventional spectrography, and the red-shifts estimated by the two methods agree within the errors of observation.

Beginning in 1955, I started observing clusters beyond the usual range of the spectrograph. Figure 4 shows the kind of results obtained for a faint, but populous, cluster visible in the October sky.

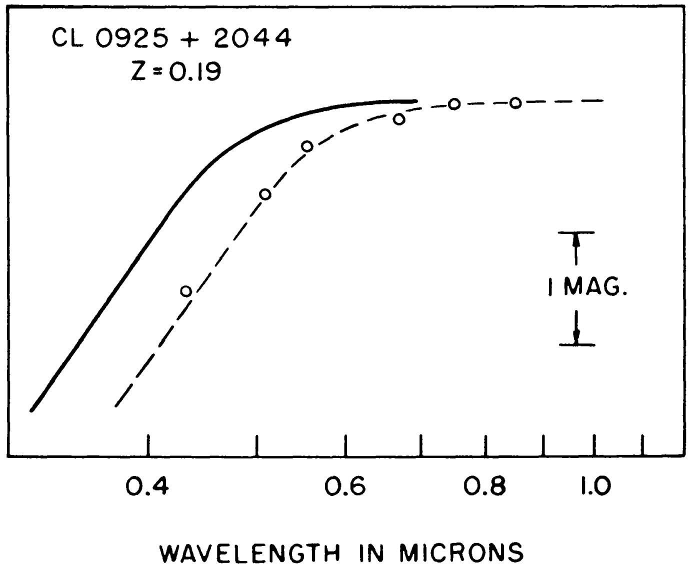

Figure 3. Mean spectral energy distribution for three elliptical galaxies in a cluster with a red-shift of $z = 0.19$. For comparison, the Virgo curve of Figure 2 is sketched here at the left of the points; the vertical displacement has been removed, and the horizontal displacement yields the difference in red-shifts.

The brightest members are around 20th magnitude, and the red-shift indicated here is $z = 0.29$ or $cz = 87{,}000$ km/sec. Each point is the mean for four galaxies. Some of the colors were also observed several times In each color, the process of pulse-counting was continued until enough statistical accuracy had been accumulated to reduce the probable error to the amount indicated by the short bar

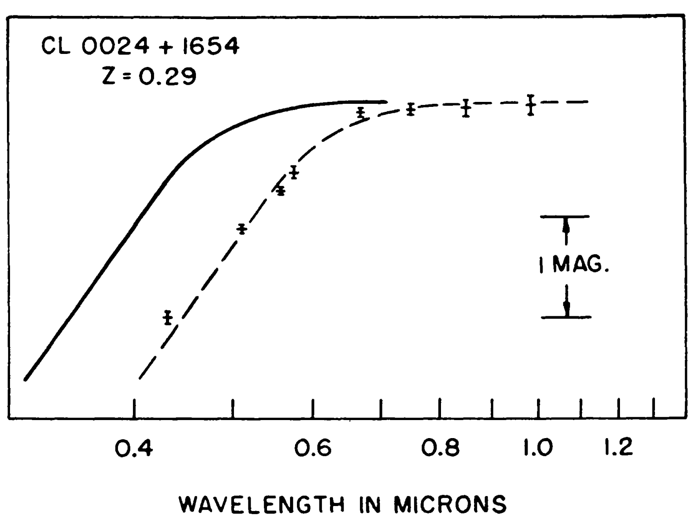

Figure 4. Mean spectral energy distribution for four elliptical galaxies in a cluster at $0^h\ 24^m$, $+16°\ 54'$. These results show the red-shift to be 0.29. The vertical bars through the observed points represent the individual probable errors.

in the diagram. One can obtain any accuracy desired simply by having the patience to continue the pulse-counting long enough; if twice the accuracy were desired, the duration of counting would need to be four times longer. Because of other sources of uncertainty, however, there is little reason to press for higher precision than is shown here.

Figure 5 shows my photoelectric observations for the cluster found by Minkowski [8] in the position of the radio source 3C 295. The points represent the mean results for two galaxies selected on the basis of some preliminary photographic photometry. Bluer-than-average objects which might be foreground galaxies or which might include the radio source itself were carefully avoided. The two galaxies selected for photoelectric observation were similar in color and appearance to the majority of the galaxies in the cluster and were located favorably for photometry. There can be no question that these data truly represent the cluster. The red-shift thus obtained was $z = 0.44 \pm 0.03$ or $cz = 132{,}000$ km/sec.

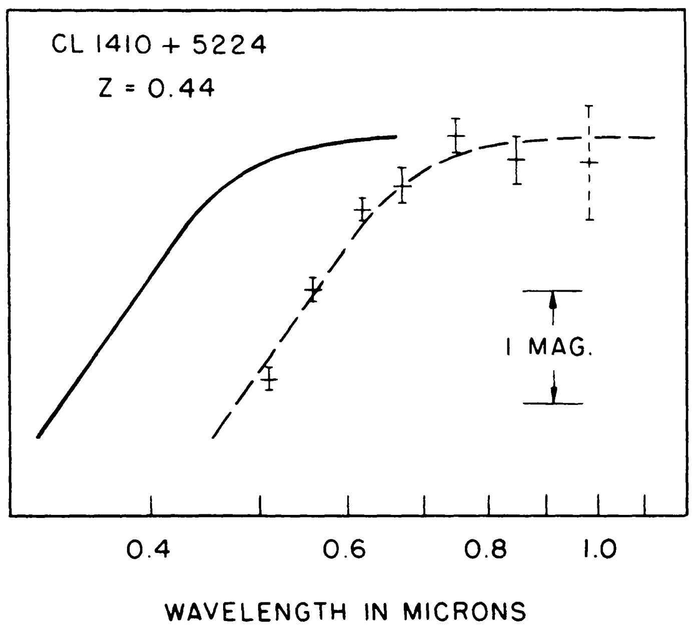

Figure 5. Mean spectral energy distribution for two elliptical galaxies in the cluster to which the Cambridge radio source 3C 295 evidently belongs. These results yield a red-shift of 0.44 ± 0.03.

One of the bluer galaxies, thought to be a likely candidate for the radio source, was found by Minkowski to have a single strong emission line at λ5448. On the reasonable assumption that the line is [O II] 3727, the inferred red-shift ($z = 0.46$) agrees closely with the photoelectric value. This agreement [9] means two things: 1) It strongly reduces any doubt about the membership of Minkowski's object in the cluster and about the identification of the emission line with [O II] 3727; 2) it provides a check, at a very large distance, on the photoelectric method of measuring red-shifts.

For a Hubble constant of 75 km/sec/Mpc, the corrected bolometric distance of this cluster is more than 10^3 Mpc.

TABLE 2
Clusters Observed Photoelectrically for the Red-shift-Magnitude Relation

Cluster	Galaxies Observed	Red-shift z	Probable Error in z
Virgo	6	0.0038	5.2%
Coma	3	0.022	1.6
Cor. Bor.	3	0.072	0.8
UMa 2	2	0.135	0.9
0925	3	0.192	0.9
0024	4	0.29	2.5
1448	2	0.36	4.0
1410	2	0.44	7.1

The red-shifts for eight clusters are listed in Table 2. The probable errors for the nearby clusters are based upon the intrinsic spread of velocities inside clusters, whereas the errors for the distant clusters are based upon the uncertainty in shifting the spectral energy distribution curves to fit the photoelectrically observed points.

The photoelectric red-shift-magnitude relation is plotted in Figure 6. As in Figure 1, the ordinate is the logarithm of the red-shift and the abscissa is a corrected bolometric magnitude. The zero-point of the abscissa scale, however, is not the same. Each cluster of galaxies is represented by a single point. The lowest point at the left represents the Virgo Cluster, and the highest point at the right represents Cluster 1410, which contains the radio source 3C 295. All except the Virgo Cluster are clusters of large membership.

Uncertainties in the magnitudes are greater than those in the red-shifts. The magnitudes require normalization to a standard intrinsic diameter; they require the matching of the luminosity functions of the various clusters to one another; and they are more vulnerable than the red-shift to any evolutionary effect. The normalization of magnitudes to a standard diameter, by means of an intensity profile, requires knowing the relationship between metric diameter and red-shift. This, in turn, depends upon the world model, but the problem can be handled by first assuming a simple $1/z$ relationship and by treating any difference as a correction. The matching of luminosity

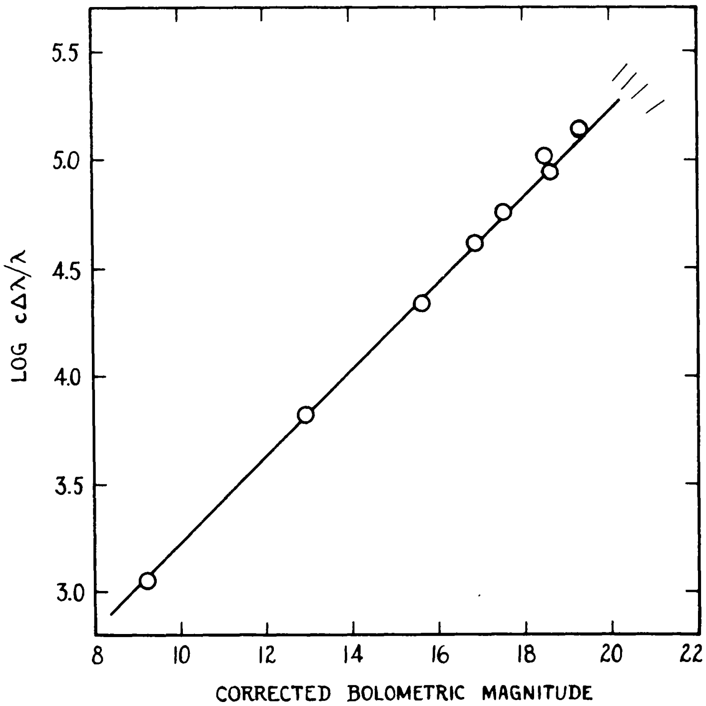

Figure 6. Red-shift-magnitude relation for the eight clusters investigated photoelectrically. Adjustments and corrections to the magnitudes are currently being reexamined. Pending those, the results continue to approximate a straight line, m(bol.) = *constant* + 5 log z.

functions is, by far, the weakest link in the chain. The previous procedure of extrapolating to a brightest magnitude is not adequate, but further photometry is needed before a more sophisticated adjustment can be made. The dependence upon evolution also remains to be introduced. This dependence can be estimated from a population model for elliptical galaxies which has been derived [6] in connection with the present program.

Pending the readjustment of magnitudes, a roughly linear relation (m, log z) is suggested by the eight clusters thus far investigated. The data fall in the range of exploding universes that collapse again after a long time. It is premature to quote a specific value of $R\ddot{R}/\dot{R}^2$, but it is, perhaps, of interest to note that the top end of the curve in Figure 6 must be bent to the right one whole magnitude if it is to approach compatibility with the steady-state universe, and that seems unlikely at present.

REFERENCES

[1] A. R. Sandage. *Ap. J.* **133**, 355 (1961).
[2] M. Ryle. This volume, p. 326.

[3] F. Hoyle and A. R. Sandage. *Pub. A.S.P.* 68, 301 (1956).
[4] M. L. Humason, N. U. Mayall, and A. R. Sandage. *A. J.* 61, 97 (1956).
[5] W. A. Baum. *A. J.* 62, 6 (1957).
[6] ——. *Pub. A.S.P.* 71, 106 (1959).
[7] J. B. Oke. *Ap. J.* 131, 358 (1960).
[8] R. Minkowski. *Ap. J.* 132, 908 (1960).
[9] W. A. Baum and R. Minkowski. *A. J.* 65, 483 (1960).

DISCUSSION

Hoyle: I would like to comment on two points. First, that we can say little about the evolutionary variation of the magnitudes of elliptical galaxies. It is not a question of the type of star involved, or of the evolutionary behaviors of individual stars, but of the number of evolving stars. This depends on the initial main-sequence luminosity function, particularly for the range +6 to +3. Since we do not know this for ellipticals, the evolutionary situation for such galaxies is quite uncertain (although one can be more hopeful about the evolutionary variation of *color*).

My second point concerns the difference between the integrated magnitude of a galaxy and its surface brightness. Surface brightness is quite independent of the cosmological theories, while the integrated magnitude does depend on the theory in question. This circumstance arises because angular diameter differs in different theories. Hence, any discussion of apparent magnitude versus red-shift in relation to different theories is really a discussion of angular diameter versus red-shift.

Baum: We do have a reasonable population model for an elliptical galaxy on which to base a first effort at estimating an evolutionary effect. I agree that the luminosity function can, at best, be only crudely estimated, but feel that a crude correction will be better than none.

Bondi: The agreement of the spectroscopic and the photometric measures of red-shift to $z = 0.46$ is an astounding achievement showing the absence of evolutionary effects to this range. How much effect should be expected on an evolutionary picture is in doubt, as stated before. However, the disproof of the Stebbins-Whitford effect is now remarkably complete.

Zwicky: I doubt the value of the red-shift-magnitude test because: *(a)* the identity of the two clusters has not been established; and *(b)* I doubt, unless spectra and spectral red-shifts are available, that it can be ascertained whether or not the galaxies are members of the clusters.

As an alternative, I suggest the use of structural indices of clusters which have proved to be identical by morphological criteria.

Spinrad: Do you think that the photometric synthesis of an elliptical galaxy is unique? There seems to be an equally acceptable model, using colors alone. That would be M 67 plus *many red dwarfs*. Such a synthesis fits the six-color Stebbins-Whitford colors quite well. The spectroscopic data in the visual region indicates that K and M dwarfs do contribute materially to the integrated luminosity—at least in the massive and luminous systems. M 32, however, has a spectrum indicating that giants probably give almost all of the light, even in the red.

Baum: Two synthetic models for the stellar population of elliptical galaxies were examined several years ago by means of six-color data. These two models can be described as Old Disk population and Halo population. To the extent permitted by each model, the luminosity function was left free to be varied. The results clearly favored the Old Disk population. When Tifft's eight-color data became available, they provided a better hold on this problem than the six-color data had, and a mixed model was examined. A model consisting of 20 per cent Halo population (referred to 6000 A) plus 80 per cent Old Disk population fits closer than 1 per cent in all colors from ultraviolet to infrared. I do not agree that a dwarf-enriched M 67 population is equally acceptable, nor can I agree with the analysis of Roberts, who compared no alternatives. There is a paper on this subject in the 1959 *P.A.S.P.*

Schücking: The source 3C 295 should show a variable Doppler shift of $(1+z)\cos b \times 30$ km/sec. With the mentioned precision, one could test the hypothesis that the red-shifts are caused by velocities.

Schmidt: Since angular diameters have been introduced in the discussion, I should like to note that the intrinsic diameter of a galaxy, defined in some way from the light distribution, is quite likely to be subject to evolution effects. These evolution effects would be due, not so much to the relaxation time, but mainly to a variation of distribution of bright stars as a function of time. Since in the case of 3C 295, we look back halfway in time, this could well be an important effect.

Baum: Since the dynamical relaxation time for stars in a galaxy is very long in comparison with most age estimates, an evolutionary change in the diameters or profiles of elliptical galaxies would have to arise, for instance, because the kind of stars near the center might evolve differently than the kind of stars farther out. A gradual trend of color index from the nucleus outward does exist, but it is not large.

Gold: How much error is introduced by a wrong selection of the size of the diaphragm? Can you give the actual change that would result from a different choice?

Baum: It is not the size of the actual diaphragm which matters so much as the diameter to which the data are subsequently adjusted. This adjustment is based upon an intensity profile, scaled in size to a function of the red-shift z. The uncertainty in this procedure ought not to exceed $0^{m}.1$. It is, therefore, a less difficult problem than, for instance, the matching of luminosity functions.

Neyman: The difference in the general appearance of Dr. Baum's and Dr. Sandage's diagrams showing the red-shift-magnitude relation is striking. Dr. Baum's diagram shows much less spread and indicates strict linearity. Presumably, the accuracy of the observations was improved. But was there any attempt made to avoid the effect of selection for brightness?

Oke: If one looks at Baum's energy distribution below $\lambda_0 = 6000$ A the slope is very steep. An intrinsic change of color with red-shift could be quite substantial but still not affect Baum's red-shift appreciably. In this spectral region, the question of the effective wave length which is applicable for each filter band is rather uncertain. This has been pointed out by Whitford already.

Vandererkhove: I want to congratulate Dr. Baum for his difficult and beautiful work which continues the measures of Stebbins and Whitford to the faintest galaxies. May I remind you that twenty-two years ago, I showed theoretically that the gradient of a galaxy should increase when the radial velocity was increasing and I proposed then the measure of the gradient of a galaxy in the spectral region of 5000 A as a criterion of the red-shift deduced from the spectral lines. This has been done, and well done. Now the time is coming for some refinements: effects of population, red giants, evolution, absorption. I think of the beautiful spectra of Dr. Oke. Personally, I can now measure gradients on spectra of galaxies obtained with the prism-objective of 84 cm. clear aperture of the Uccle Observatory.