THE EXTRAGALACTIC RELATIVE DISTANCE SCALE

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Abstract. Arguments are given to support the hypothesis that a characteristic point on a cluster luminosity function, m^*, corresponds to the same absolute magnitude in all clusters, and thus is an appropriate standard candle for determination of relative cluster distances. It is shown, however, that if m^* *is* a good standard candle, then the first and tenth brightest cluster galaxies, $m(1)$ and $m(10)$, respectively, are not, for $m^* - m(1)$ and $m^* - m(10)$ both differ significantly from cluster to cluster. Moreover, $m(1)$ and especially $m(10)$ depend on cluster richness. Distances derived from them for remote clusters chosen for analysis are thus subject to selection effects that depend on cluster richness and on Bautz-Morgan type. Finally, a procedure suggested by Bautz and Abell is described whereby m^* can be estimated from observed properties of distant clusters.

1. Introduction

It is well established (Sandage, 1968, 1972) that a useful criterion of distance for a cluster of galaxies is the apparent magnitude of its brightest member, its third or tenth brightest member, or some combination thereof. The possibility is ever-present, however, that selection effects which depend on distance may affect the observed magnitudes of the brightest cluster galaxies. Years ago, for example, Scott (1957) showed that, with various 'reasonable' assumptions about the luminosity functions of galaxies in clusters, the choice of apparent magnitudes of the first, third- or tenth-brightest cluster galaxies as distance indicators could lead to the derivation of values of the deceleration parameter, q_0, supporting almost any cosmological model. Essentially, the so-called *Scott effect* is that the very distant clusters of galaxies chosen for investigation are selected or discovered because they are richer in membership than average, and thus may have brighter than average brightest member galaxies.

That such selection effects are indeed possible has been shown by the writer (Abell, 1960) from a study of the luminosity functions of several clusters. In particular, Matthews *et al.* (1964), Morgan and Lesh (1965) and Bautz and Morgan (1970) have called attention to the existence of certain clusters (Bautz-Morgan type I and II clusters) which contain superluminous brightest galaxies – the Morgan class cD galaxies. Bautz and Abell (1973) have found evidence for a weak correlation between cluster richness and the presence or absence of a cD galaxy in a cluster. Sandage (1973), while not confirming the correlation between Bautz-Morgan class and cluster richness, nevertheless finds that the absolute magnitude of the brightest cluster galaxy is correlated with the cluster Bautz-Morgan class.

Thus there are several reasons why selection effects can play an important role. There may be a correlation between the presence of a cD galaxy and cluster richness; hence richer clusters, those most easily recognized at large distances, may have brighter than average first brightest members. In any case, a Bautz-Morgan type I

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or II cluster is more likely to be noticed at a very remote distance, simply because of the presence of the cD galaxy. If, in addition, clusters are selected because they contain radio sources, they are especially likely to be type I clusters with cD galaxies, for the latter are often radio sources. All of these considerations cast suspicion on the validity of the use of the first-brightest cluster galaxy as a criterion of distance. We shall present evidence below that the tenth-brightest cluster member is, in fact, very strongly correlated with cluster richness.

2. Cluster Luminosity Functions

Another approach to finding the relative distances of clusters is by comparison of their luminosity functions. The determination of a cluster luminosity function is a painstaking investigation, for it requires photometry of many individual galaxies in a cluster. Nevertheless, the data are rapidly accumulating. Elliptical galaxies, which comprise the dominant membership of most rich clusters, are found to display a very characteristic frequency distribution of magnitudes. The logarithmic integrated

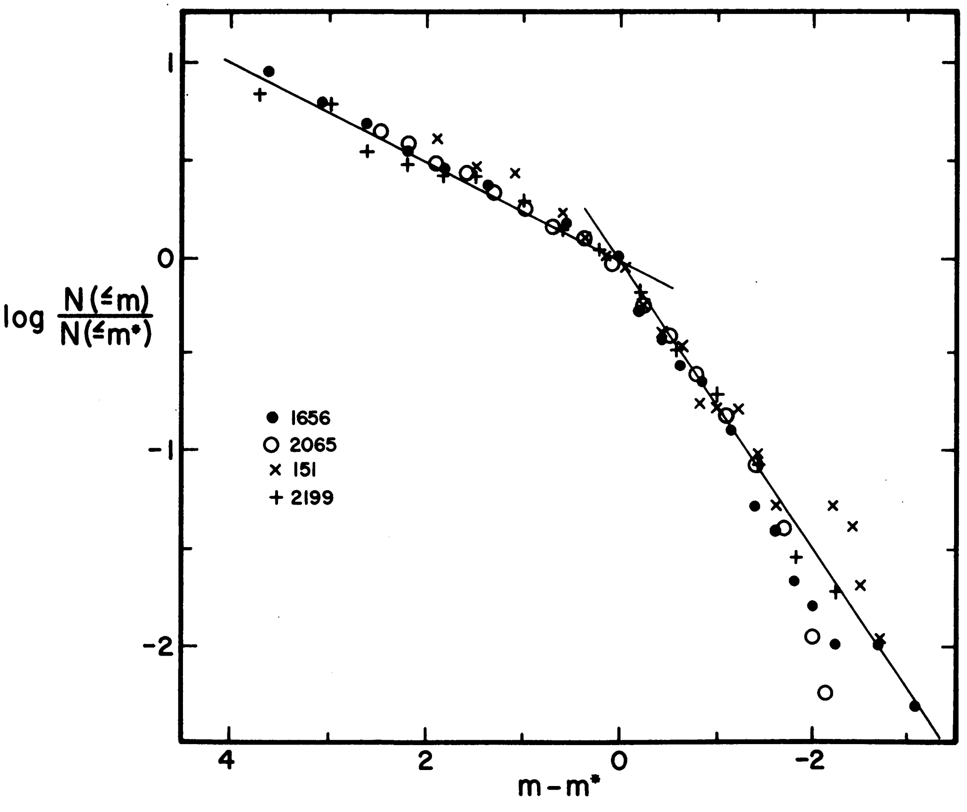

Fig. 1. Superimposed logarithmic integrated luminosity functions for four rich clusters of galaxies. Clusters are identified by their catalogue numbers in Abell (1958).

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luminosity function of elliptical galaxies in the Coma cluster (Abell, 1965), for example, is typical of that of elliptical galaxies in every other rich cluster so far investigated. Data for several clusters are shown in the composite plot of Figure 1. High quality photometry with zero-point calibration is available for only eight clusters at present, but less precise data for many other clusters show that they, too, have similar luminosity functions for their elliptical membership. Photometry by Oemler (1973), for example, while not yet on a standard photometric system, shows cluster luminosity functions like that in Figure 1. Also noteworthy are data by Krupp (1973), who has done crude 'flyspanker' photometry on Palomar Sky Survey prints of all galaxies brighter than $m_v = 16.75$ in Abell clusters of richness class 1 or greater and distance class 3 or less. The data for 27 of the 43 clusters studied by Krupp, for which the observations cover a great enough magnitude range to determine the form of the luminosity functions, are exhibited in Figure 2.

As can be seen from Figures 1 and 2, the integrated logarithmic luminosity functions of clusters can be made to coincide by vertical and horizontal shifts. The vertical shifts necessary for proper fits are measures of relative cluster richnesses, and the horizontal shifts indicate relative cluster distances if the magnitudes are all on the same system. A convenient point on the magnitude scale for the luminosity functions of the clusters can be defined as m^*, the intersection of straight lines fitted respective-

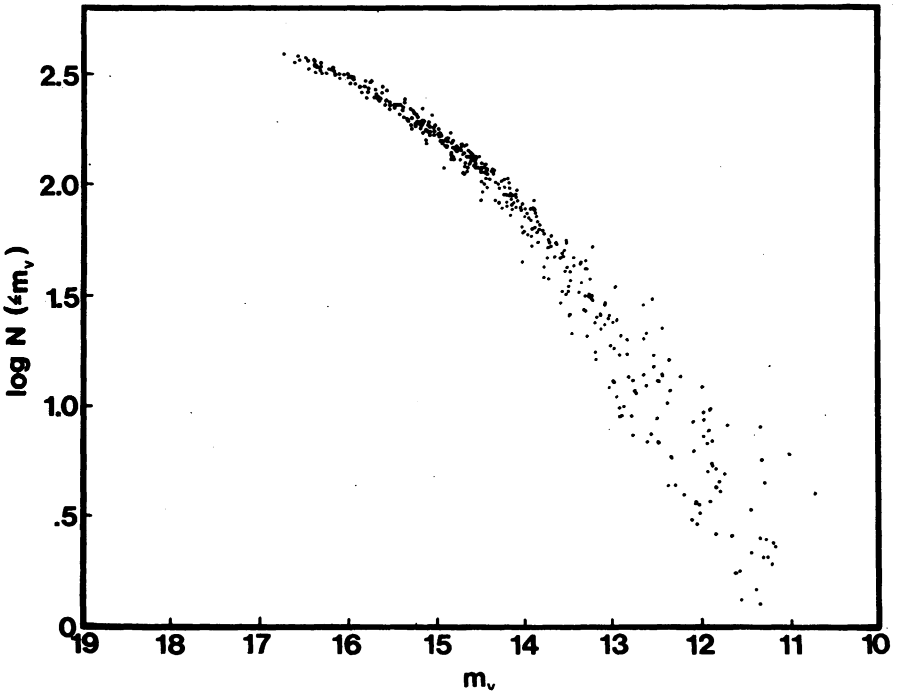

Fig. 2. Integrated logarithmic luminosity functions of the E-S0 galaxies in 27 rich clusters. Log N and m_v have been scaled to the values for the Coma cluster (from Krupp, 1973).

ly to the bright, steep, and to the fainter, less steep portions of plots such as those in Figure 1 or 2 (that is, m^* is the magnitude at which the luminosity function changes slope). If the magnitude determinations in a cluster are properly calibrated to a consistent zero point, a plot of log cz against m^* should provide a Hubble diagram, based not on the brightest cluster members, but on the form of the luminosity functions. Figure 3 is such a plot for 8 clusters for which appropriate photometric data exist (Bautz and Abell, 1973). The scatter, $\sigma \approx 0.1$ mag, is about that expected from the uncertainty of the interstellar absorption corrections alone (a plane-parallel absorbing model of half-thickness $m_{pv} = 0.16$ mag is assumed); thus there is no evidence for any intrinsic scatter at all in the $\log cz - m^*$ plot.

Krupp's step-scale photometry on Palomar Atlas prints can not be expected to have the same zero-point calibration for different clusters observed on different prints, because of the variations in quality of the original Sky Survey plates, and different sky background densities. These zero-point errors doubtless account for most, if not all, of the scatter ($\sigma \approx 0.5$ mag) in the similar plot of $\log cz$ vs m^* for the clusters observed by Krupp. Krupp (1973) has shown, however, that this scatter is nevertheless significantly less than those in plots of $\log cz$ vs $m_v(1)$ or $m_v(10)$, the magnitudes of

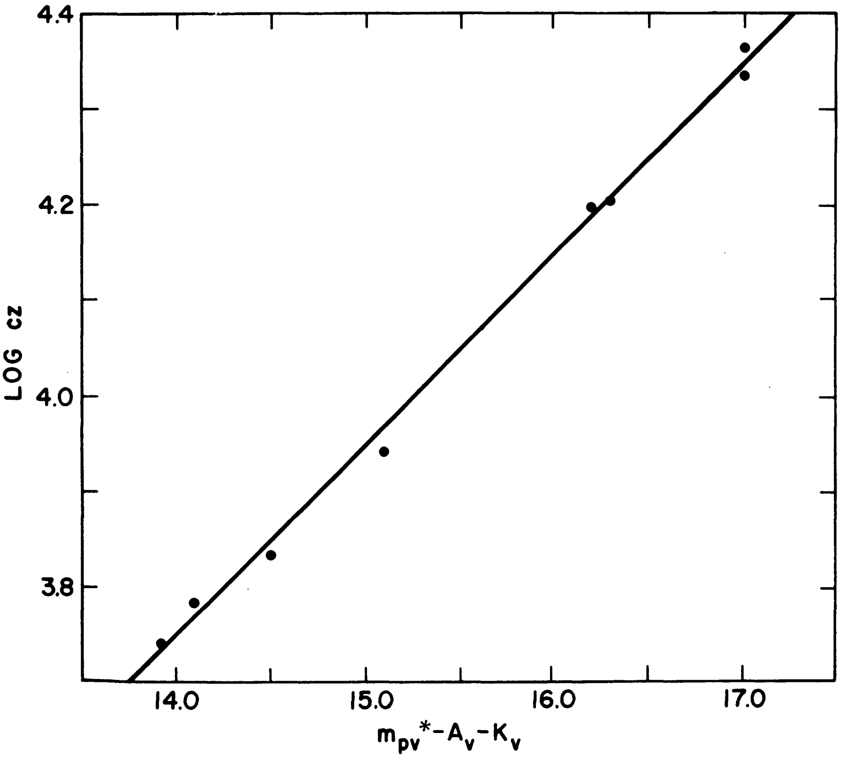

Fig. 3. Hubble diagram for m^* for eight clusters with well-determined luminosity functions. Ordinates are redshifts, corrected for galactic rotation. Abcissas are m^* corrected for K-dimming and galactic absorption.

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the first and tenth brightest cluster galaxies, respectively. The comparison of the scatters on the different plots does not depend on the zero-point differences referred to above, because all magnitude estimates in a single cluster are, of course, made on the same print.

The evidence suggests, therefore, that comparison of luminosity functions of clusters of galaxies can provide relative distances for the clusters that may be more reliable than comparison of the brightest cluster members. If the characteristic change of slope in the integrated logarithmic luminosity functions near m^* results from some fundamental property of cluster and galaxy formation, it may well be independent of cluster type and richness. At least available data indicate that m^* has a smaller intrinsic variation from cluster to cluster (indeed, perhaps none at all) than does $m(1)$ or $m(10)$. It may, of course, still depend on evolutionary effects.

3. Evidence for the Scott Effect in Clusters of Galaxies

If it is assumed that m^* does, indeed, correspond to the same absolute magnitude in every cluster, and also that $N(\leqslant m^*)$, the number of cluster elliptical galaxies brighter than m^*, is a measure of cluster richness, then Krupp's data provide an excellent test for the Scott effect. All clusters investigated by Krupp are relatively nearby, so evolutionary effects should not be present. In Figure 4, $\log N(\leqslant m^*)$ for each cluster is plotted against $m_v^* - m_v(10)$, the difference between the photovisual magnitudes m^* and of the tenth brightest cluster elliptical. Zero-point differences in the magnitude systems from print to print do not enter into Figure 4 because the magnitude differences plotted are always obtained from one print. Krupp's 'flyspanker' magnitude estimates on a single print are consistent to about $\frac{1}{4}$ mag; the differences in $m^* - m(10)$ between the different clusters are thus very large compared to expected errors in magnitude estimates.

Because m^* is assumed to correspond to the same absolute magnitude in all clusters, Figure 4 shows that the absolute magnitudes of the tenth brightest cluster members differ significantly from cluster to cluster, and moreover that the absolute magnitude of the tenth brightest elliptical cluster galaxy is strongly correlated with the cluster richness. This, of course, is just what is predicted by the Scott effect, and shows clearly that the tenth, or in general, the nth brightest cluster galaxy is suspect as a distance indicator.

A similar plot (Figure 5) of $\log N(\leqslant m^*)$ against $m_v^* - m_v(1)$, on the other hand, shows an entirely different situation. Whereas $m^* - m(1)$ varies from cluster to cluster even more widely than does $m^* - m(10)$, it is correlated, if at all, only very weakly with $N(\leqslant m^*)$. The data show (if m^* corresponds to a constant absolute magnitude) that the absolute magnitude of the brightest elliptical galaxy, $M(1)$, varies greatly from cluster to cluster, but evidently not in a manner that depends strongly on the cluster richness. In fact, both Bautz and Abell (1973) and Sandage and Hardy (1973) find $M(1)$ to be strongly correlated with the Bautz-Morgan (1970) form-type classification of the cluster. (The form-types of the clusters are shown as

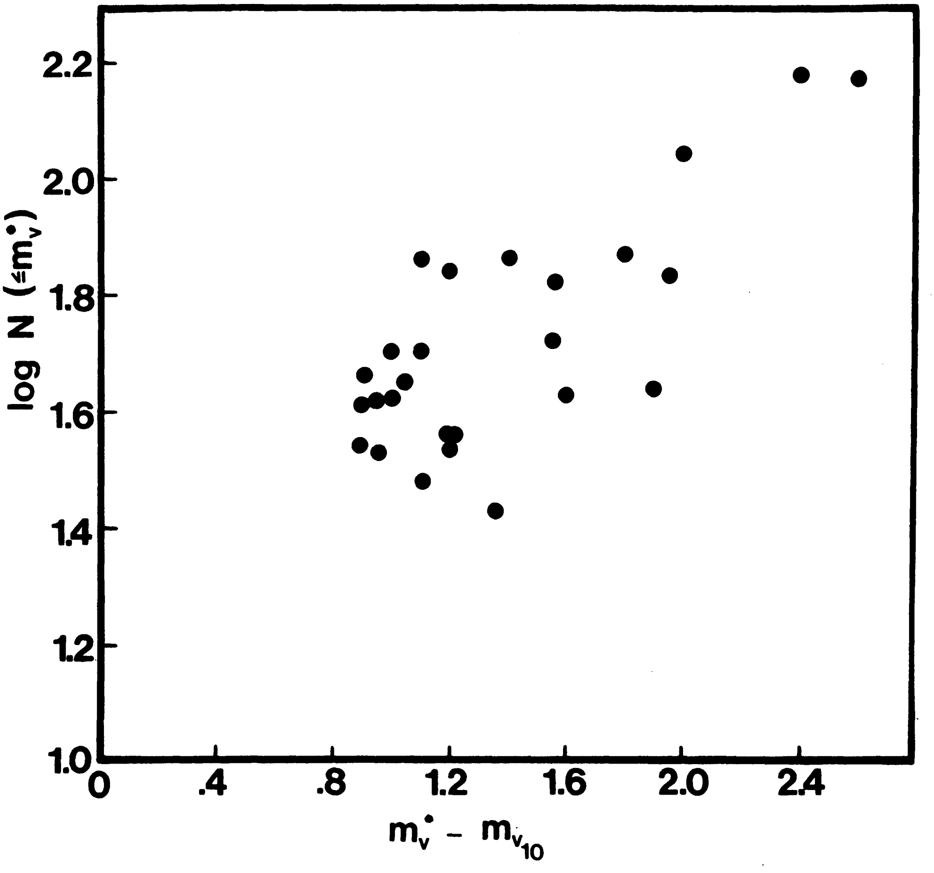

Fig. 4. Cluster richness, $\log N(\leqslant m_v{}^*)$, vs $m_v{}^* - m_v(10)$ (from Krupp, 1973).

Roman numerals beside the data points in Figure 5). Bautz and Abell find that there is also a weak correlation between $m^* - m(1)$ and cluster richness, and hence that both Bautz-Morgan type and cluster richness are needed to predict $m^* - m(1)$. This conclusion is consistent with the Krupp data in Figure 5, which suggest a possible weak correlation of $m^* - m(1)$ with richness, and is not inconsistent with data of Sandage and Hardy (1973), although they themselves express the opinion that there is no significant correlation between $M(1)$ and cluster richness. At any rate, the Sandage-Hardy, Krupp, and Bautz-Abell data are not inconsistent.

The principal conclusion to be drawn is that selection effects which can bias the determination of the relative distances of clusters are possible. If remote clusters are selected for study because they are preferentially richer than average, use of the tenth brightest cluster galaxy as a standard candle can result in an underestimate of the distances of those clusters, and an overestimate of the deceleration parameter, q_0. If remote clusters are selected because they contain radio sources (for example, the cluster containing 3C 295) or because they contain outstanding galaxies bright

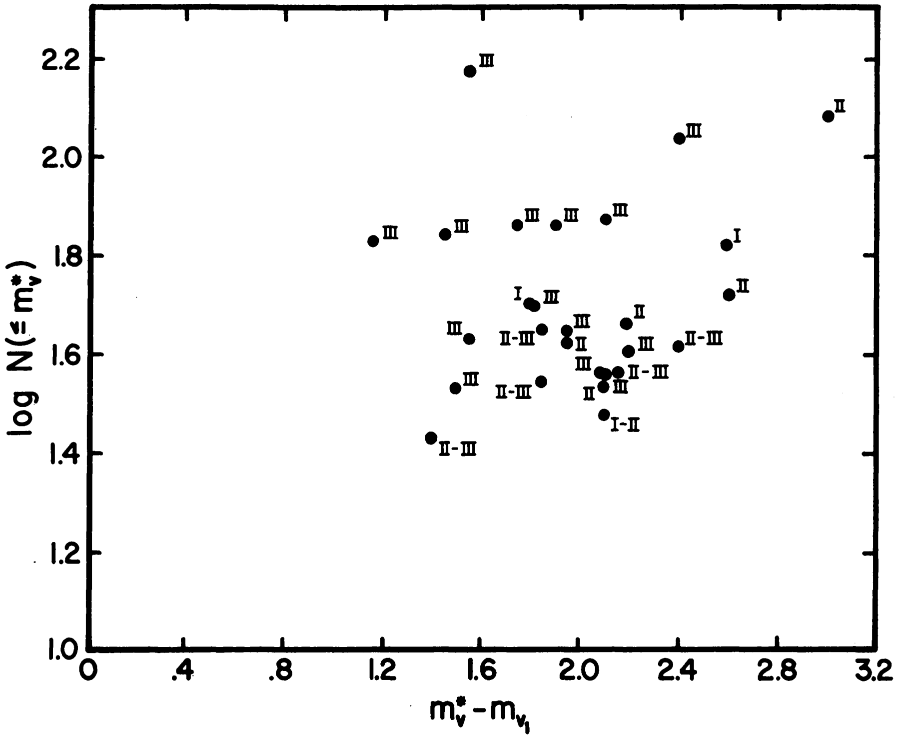

Fig. 5. Cluster richness, $\log N(\leq m_v{}^*)$, vs $m_v{}^* - m_v(1)$. The Bautz-Morgan form types for clusters are shown. (From Krupp 1973.)

enough for convenient redshift measurement (possibly cD galaxies), the use of $m(1)$ for a standard candle can produce the same bias.

4. A Procedure for Correcting for Selection Effects

In the writer's view, the evidence strongly suggests that some representative point on the luminosity function, such as m^*, is a better standard candle for determination of relative cluster distances than is the apparent magnitude of the first, tenth, or *n*th brightest galaxy. Unfortunately, luminosity functions are tedious to determine at best, and are difficult or even impossible to obtain for those clusters with cosmologically interesting distances. For the latter, in fact, photometry is sometimes reliable only for the brightest member galaxy. Even for these remote clusters, however, classifications can be made of the Bautz-Morgan form type, and rough estimates of cluster richness can be made. Bautz and Abell (1973) have published a provisional calibration of $m^* - m(1)$ in terms of form type and richness class (as defined in the Abell (1958) catalogue of rich clusters), based on those nearby clusters for which the most complete data are available. From this calibration, the form type and estimate of richness class for a remote cluster allow a prediction of how much fainter m^* would be than

$m(1)$, could m^* actually be observed. Estimates of richness classes of remote clusters are, admittedly, rather uncertain, but fortunately the quantity $m^* - m(1)$ is far less sensitive to cluster richness than it is to form type. The provisional calibration of Bautz and Abell is reproduced in Table I. Comparison of Table I with Figure 5 shows that the Krupp data are entirely compatible with the calibration and lend considerable support to its validity.

TABLE I

A provisional calibration of $m^* - m(1)$ in terms of Bautz-Morgan form type and richness classes for clusters of galaxies

Richness class	0	1 and 2	3
Form type			
I and II	>2	+2.9	+3.3
II–III and III	+1.5	+1.9	+2.3

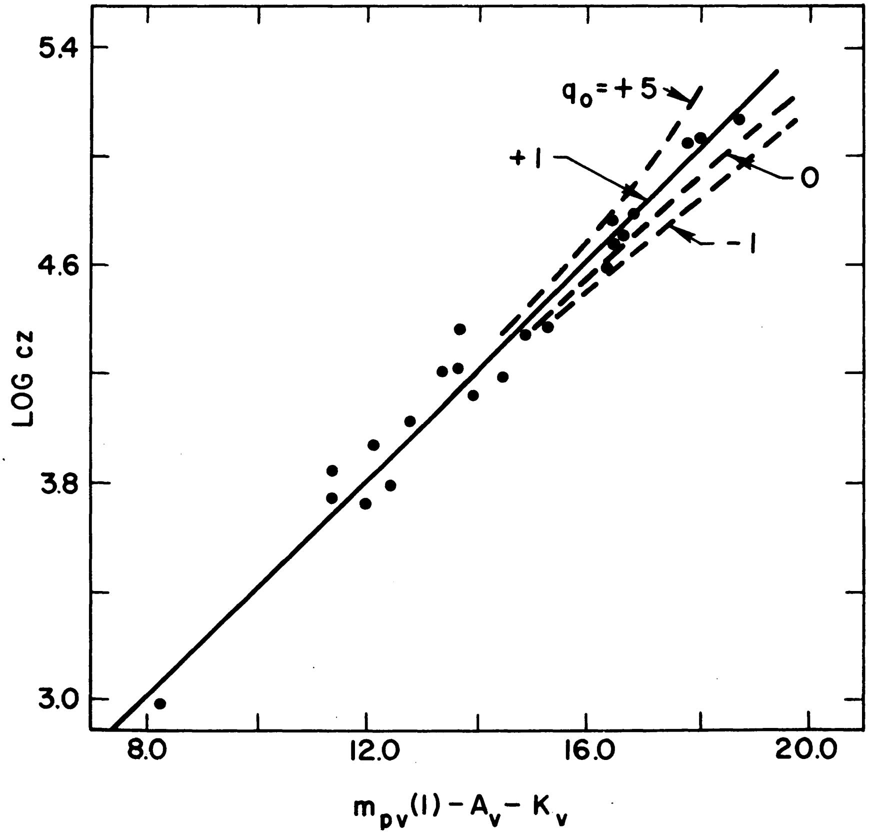

Fig. 6. Hubble diagram for first ranked cluster galaxies. Ordinates are redshifts, corrected for galactic rotation. Abcissas are $m_v(1)$, corrected for K-dimming and galactic absorption (from Bautz and Abell, 1973).

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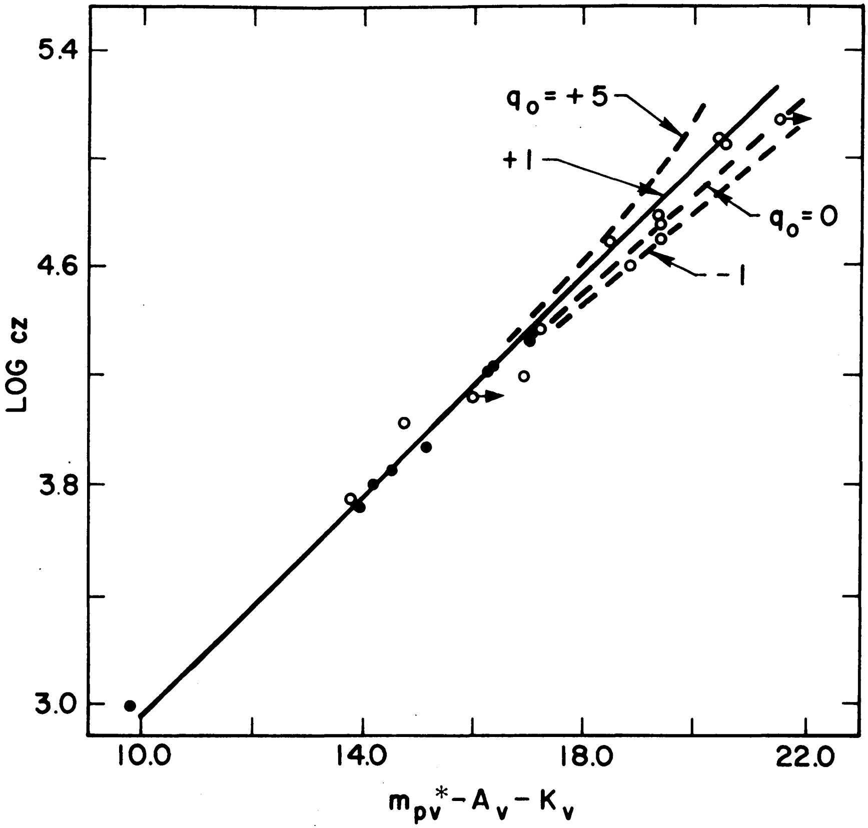

Fig. 7. Same as Figure 6, except abcissae are m_v*. *Filled circles*: clusters with known m_v* from observed luminosity functions. *Open circles*: clusters for which m_v* has been predicted from observed $m_v(1)$ and the calibration of Table I (from Bautz and Abell, 1973).

Figures 6 and 7, reproduced from Bautz and Abell (1973) show how a plot of $\log cz$ vs $m(1)$, in this case based on data from Humason *et al.* (1956), can be converted to a plot of $\log cz$ vs m^* with the use of the calibration of Table I.

5. Conclusions

Taken at face value, the use of $m(1)$ as a standard candle, as in Figure 6, leads to a Hubble diagram which is compatible with a value of $q_0 = +1$. When the $m(1)$ values are converted to m^*, however, the resulting Hubble diagram (Figure 7) is more compatible with $q_0 = 0$. Obviously, the calibration in Table I is too provisional, and the data are too crude (as seen from the significant scatter) to attribute any significance to a determination of q_0 by this procedure at present. Moreover, it must be emphasized that evolutionary effects have not been considered, and they almost certainly also affect the determination of q_0 from the Hubble diagram (e.g., Tinsley, 1972). The purpose here is to demonstrate the probable existence of selection effects that must be understood and taken into account in interpreting observations in terms of cosmological models, and also to review a suggested procedure by which such effects might be reduced.

References

Abell, G. O.: 1958, *Astrophys. J. Suppl.* **3**, 211.
Abell, G. O.: 1960, *Publ. Astron. Soc. Pacific* **72**, 459.
Abell, G. O.: 1965, *Ann. Rev. Astron. Astrophys.* **3**, 1.
Bautz, L. P. and Abell, G. O.: 1973, *Astrophys. J.* **184**, 709.
Bautz, L. P. and Morgan, W. W.: 1970, *Astrophys. J. Letters* **162**, L149.
Humason, M. L., Mayall, N. U., and Sandage, A. R.: 1956, *Astron. J.* **61**, 97.
Krupp, E. C.: 1973, *Thesis*, University of California, Los Angeles.
Matthews, T. A., Morgan, W. W., and Schmidt, M.: 1964, *Astrophys. J.* **140**, 35.
Morgan, W. W. and Lesh, J. R.: 1965, *Astrophys. J.* **142**, 1364.
Oemler, A.: 1973, *Astrophys. J.* **180**, 11.
Sandage, A. R.: 1968, *Astrophys. J. Letters* **152**, L149.
Sandage, A. R.: 1972, *Astrophys. J.* **173**, 485.
Sandage, A. R. and Hardy, E.: 1973, *Astrophys. J.* **183**, 743.
Scott, E. L.: 1957, *Astron. J.* **62**, 248.
Tinsley, B. M.: 1972, *Astrophys. J. Letters* **173**, L93.

DISCUSSION

Nandy: Is there any possibility that the members of the fainter clusters of galaxies could be reddened? Put another way, can intergalactic absorption affect the curvature of the redshift-distance relation?

Abell: Some years ago, Zwicky (Herzog, E., Wild, P., and Zwicky, F.: *Publ. Astron. Soc. Pacific* **69**, 409, 1957) suggested that intergalactic absorption caused by dust associated with nearby galaxies hides remote galaxies, accounting for an apparent anti-correlation between positions of nearby and remote galaxies. The absorption required, however, is far greater than what is allowed by the observed slope of the redshift-magnitude relation, and I suspect that Zwicky's results were due to a confusion factor, i.e. the difficulty of recognizing distant galaxies through nearby groups.

Otherwise, I know of no evidence for any intergalactic absorption. The $\log cz$ vs m relation (Hubble diagram) is linear for all cosmological models out to about $z=0.1$. The data to $z=0.1$ are good enough for us to place an upper limit on the total absorption to that distance. There could not, for example, be as much as 0.3 to 0.5 mag absorption to $z=0.1$.

On the other hand, I think we could not rule out a small amount of dust producing, say, absorption of as much as 0.1 mag. Now because of the expansion of the Universe, a given mass of dust would produce greater optical depth per unit redshift at greater redshift. Thus, we could not rule out absorption that may amount to significantly more than 1.0 mag at $z=1.0$. It would be very hard to detect this amount of absorption – and separate effects it would produce from cosmological effects – especially if, say, the dust were something like hydrogen snow which might be gray and produce no reddening.

Thus, intergalactic absorption could conceivably be present and is another uncertainty in the interpretation of the Hubble diagram. I think that this is an important point, one well taken.

Irwin: Has Sandage changed his mind? Originally he believed that the small scatter in the redshift diagram indicated essentially identical absolute magnitudes of all the *first* brightest galaxies in clusters of galaxies.

Abell: Yes, he now recognizes (Sandage, A. R. and Hardy, E.: *Astrophys. J.* **183**, 734, 1973) that at least part of the scatter in the Hubble diagram of first brightest members of clusters is due to the presence of cD galaxies in some (Bautz-Morgan type I and II) clusters and not in others (type III clusters).

Irwin: Do your results on the Virgo cluster suggest a change in the Hubble constant?

Abell: The effects I have discussed today do not depend on the Hubble constant. Nevertheless, if we do tentatively accept the fit of the luminosity function of the Virgo cluster to those of more remote clusters, we can find the relative distances of the Virgo and these other clusters, the redshifts of the latter being certainly cosmological. Then if we have a modulus for the Virgo cluster from independent methods (say photometry of globular clusters in M87), we can find the Hubble constant. Present estimates of the modulus of the Virgo cluster lead to a value of H of at most about 50 km s^{-1} Mpc^{-1}. This value is in reasonable agreement with the recent estimates of H from other methods.