THE REDSHIFT-MAGNITUDE RELATION FOR RADIO GALAXIES

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ABSTRACT

We examine the Hubble diagram for radio galaxies and compare radio galaxies and first-ranked cluster galaxies as cosmological test objects. Radio source identification programs are now producing reliable identifications with galaxies as faint as $\underline{V} \approx 23$ and spectroscopy of these objects has already resulted in the discovery of galaxies with redshifts as high as 0.75, thus there are great expectations for progress in the near future. As in the past, indeterminate corrections, notably luminosity evolution and a possible correlation between radio power and optical luminosity, preclude the determination of q_o.

1. RADIO GALAXIES AS STANDARD CANDLES

Current interest in observational cosmology has centered around the determination of the deceleration parameter q_o by means of the redshift-magnitude diagram. Most workers have restricted themselves to the use of first-ranked cluster galaxies as test objects since they exhibit uniformity of optical luminosity and are intrinsically bright objects thus detectable at cosmologically interesting distances. Gunn and Oke (1975) and Sandage, Kristian and Westphal (1976a) have both recently analyzed the Hubble diagram for first-ranked cluster galaxies, coming to substantially different conclusions about the interpretation of the diagram in terms of q_o.

After the identification of Cygnus A as the first extragalactic radio source, it was soon recognized that powerful radio sources are generally associated with optically luminous galaxies (c.f. Bolton 1960), often the first-ranked galaxy in a rich cluster. Sandage (1972b) has subsequently shown that radio galaxies have similar absolute magnitudes, $\langle M_V \rangle = -23.0$ ($H_o = 50$ km s^{-1} Mpc^{-1}) with a dispersion

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about the mean of 0.5 mag. Radio galaxies appear to differ from first-ranked cluster galaxies in this instance in that the distribution of absolute magnitudes has a slow tail off to fainter magnitudes rather than a gaussian about the mean (Sandage 1972b).

Radio galaxies offer several advantages over first-ranked cluster galaxies for use as standard candles:

i) The presence of radio emission allows us to identify candidate objects very efficiently. About 3/4 of identified 3C radio sources are galaxies. By selecting radio sources which show no optical counterpart to the limit of the Palomar Sky Survey, we have a high probability of selecting galaxies at high redshift ($z \gtrsim 0.4$), thus candidates of interest for the Hubble diagram.

ii) Because one need not identify other galaxies which may be 0.5-1.0 mag fainter than the candidate to establish the existence of a cluster, we can identify fainter, thus potentially more distant, radio galaxies than first-ranked cluster galaxies. Figure 1 shows a direct red, photograph of 3C 330, a distant radio galaxy ($z = 0.549$) in a rich cluster of galaxies obtained with the 4-m telescope at Kitt Peak National Observatory (Spinrad, Liebert, Smith and Hunstead 1976). Other cluster galaxies are easily detected and the cluster can be classified Bautz-Morgan II-III. This may be compared with Figure 2 showing 3C 427.1 identified by Smith, Burbidge and Spinrad (1976) from comparable plate material obtained during the same observing run.

Our experience indicates that the limiting magnitude for galaxies in direct photographic studies with fine-grain emulsions is on the order of $\underline{V} \approx 22$ or under the best possible conditions $\underline{V} \approx 23$. Even to $V = 23$, the surface density of background galaxies is approximately 1 per square minute of arc, thus for sources with accurate positions and without large structural peculiarities, unambiguous identifications may be made to the limits available to the largest optical telescopes. Kristian has already reviewed the excellent progress in identifying radio sources with faint optical objects earlier in this symposium.

The Scott effect (bias in the Hubble diagram due to correlation of brightness of the first-ranked cluster galaxy with cluster richness) does not operate on the sample of galaxies selected by their radio properties. There is, however, a corollary effect which may be even more serious. If optical luminosity is correlated with radio power, then in any sample limited to a given radio flux density, the more distant sources will have greater radio and optical brightnesses,

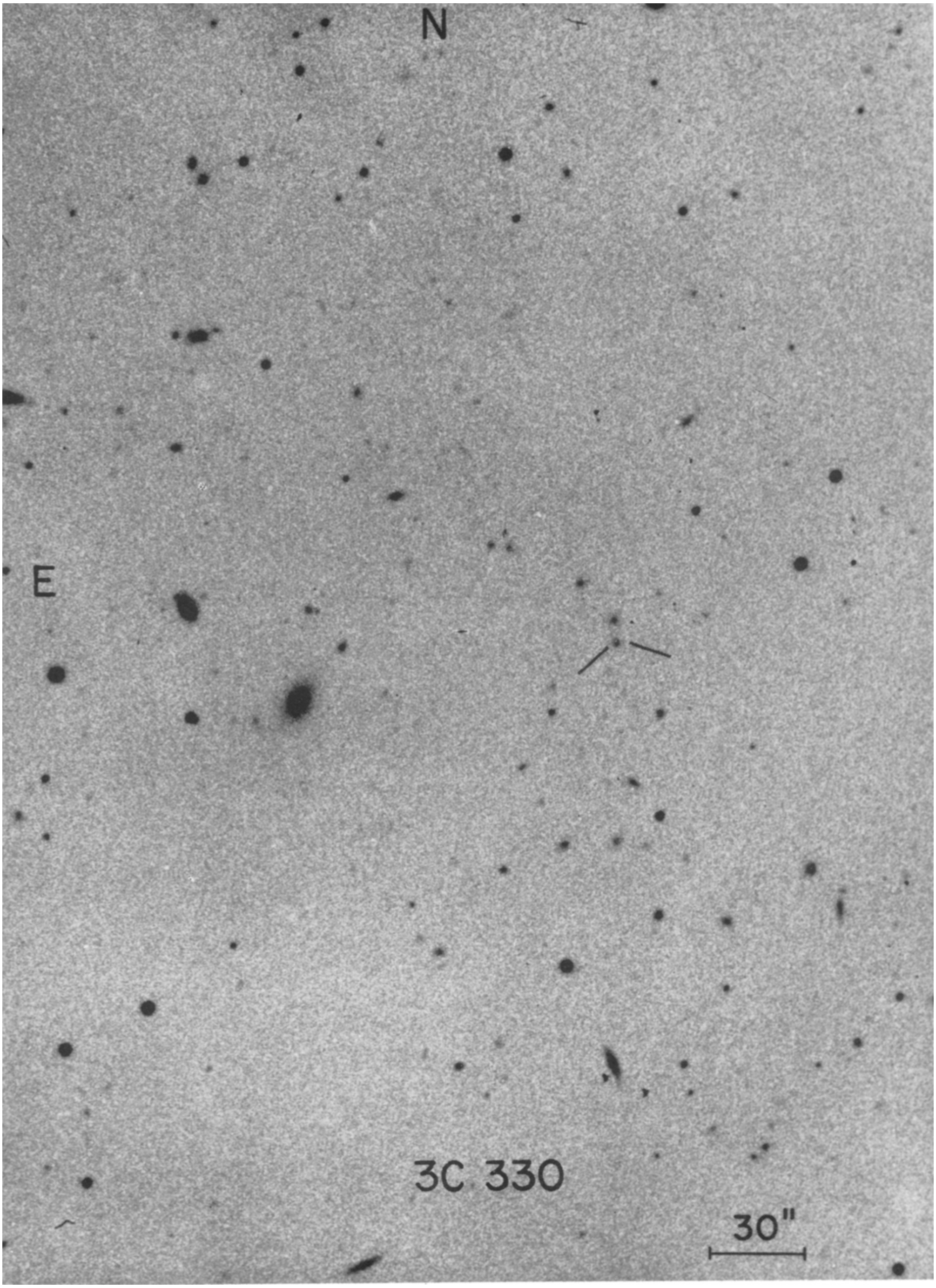

Figure 1. The radio galaxy 3C 330 (z = 0.549) in a rich cluster of galaxies.

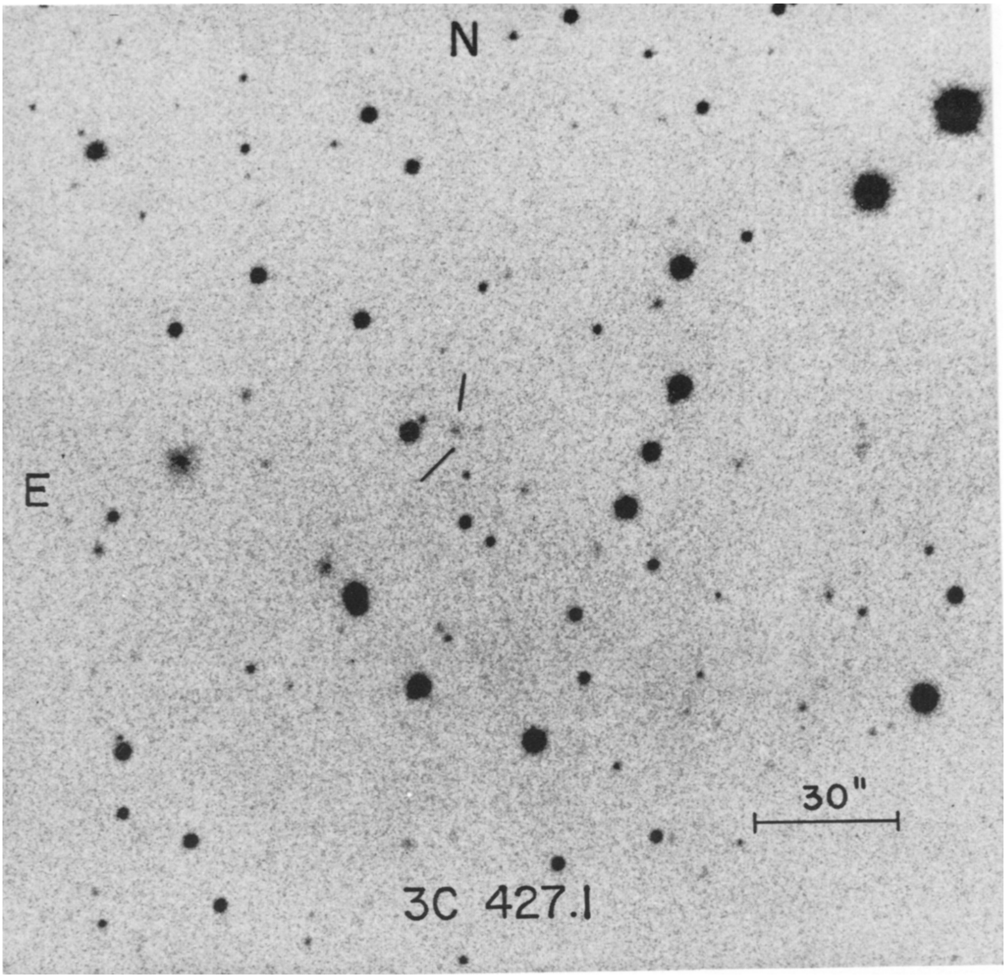

Figure 2. The galaxy identified with 3C 427.1.

biasing the redshift-magnitude relation toward larger values of q_o. It is this effect that has caused Gunn and Oke (1975) to question the use of 3C 295 in their Hubble diagram for first-ranked cluster galaxies since it was selected by its radio properties rather than the presence of a cluster. In a study of the radio/optical bivariate luminosity function of a complete sample of less powerful Bologna radio sources ($m_{pg} \leq 15.7$, $S_{408} > 0.25$ Jy) Colla et al. (1975) conclude that

$$\langle M \rangle \propto 1.25 \log P_{408}$$

This strong correlation does not, however, continue into the sample of more powerful 3C radio galaxies. For the radio galaxies in the

Revised 3C Catalog with $m \lesssim 19$, where the sample has some measure of completeness, the mean absolute magnitude is relatively constant at $M_V = -23$ over more than four decades in radio power at 178 MHz. Nonetheless, until this question is resolved, the "radio Scott effect" poses the most serious challenge to the use of radio galaxies in the Hubble diagram.

2. SPECTROSCOPY OF FAINT RADIO GALAXIES

There is other justification for obtaining spectroscopic observations of radio galaxies besides simply placing them on the redshift-magnitude plot. Redshifts and spectrophotometric line and continuum measures are necessary to understanding the physics of the non-thermal processes producing the radio emission and the emission-line spectrum. Observations of galaxies at high redshift, where the look-back time is a significant fraction of the "age of the Universe" are important to understanding the evolution of radio sources (and galaxies) and of course it is these that we wish to observe for the Hubble diagram. One must go to a redshift $z \approx 0.5$ before the separation between the $q_o = 1$ and $q_o = 0$ solutions for the redshift-magnitude relation is comparable to the dispersion in absolute magnitude for powerful radio galaxies. Obviously the higher the redshift the better since the separation increases with z. We have estimated that current identification programs can reach down to $\underline{V} \approx 23.0$ under the best possible conditions. For a normal galaxy with $M_V = -23$ this corresponds to a redshift $z \approx 0.75$ where the separation between the two solutions is more than 3/4 of a magnitude.

Spectroscopy to such faint optical magnitudes is another matter. With an aperture that subtends only 5 square seconds of arc (appropriate to many modern spectroscopic detector systems), a galaxy at $\underline{V} = 23$ contributes less than 1/10 the signal contributed by the background night sky at even the darkest northern hemisphere sites. Thus high quantum efficiency, sky subtraction detector systems are essential to programs for obtaining spectroscopic information from galaxies at high redshift. Even with such devices integration times may be very long and observations from several nights must be summed to reduce the noise to a level such that spectral features may be detected. Figure 3 shows a section of the average of four nights observations of 3C 123 with the Lick Observatory image-dissector scanner (Spinrad 1975). In some cases obtaining the redshift is easier due to the presence of strong emission features. However the presence of emission lines presents its own set of problems. Apart from the difficulty of obtaining emission free, continuum magnitudes, the presence of strong emission lines is highly correlated with the

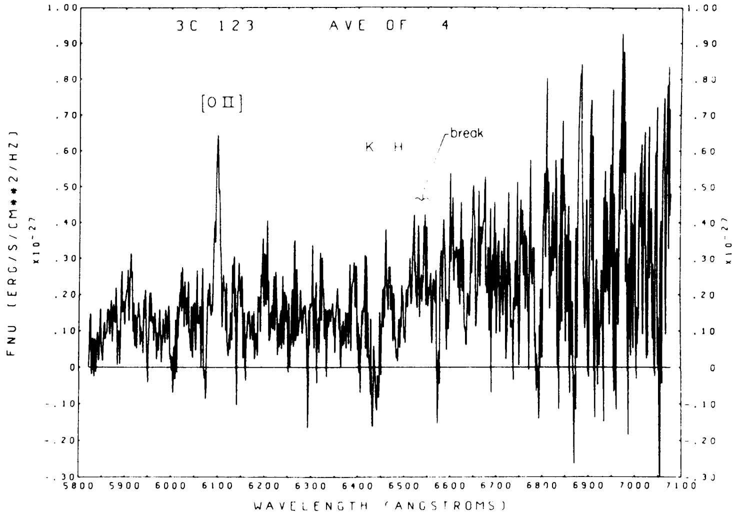

Figure 3. The spectrum of 3C 123, z = 0.637.

presence of optical non-thermal radiation. Unless the non-thermal component can be separated from the stellar galaxy, these systems must be discarded for use as "standard candles." An excellent example is the powerful radio galaxy Cygnus A which was the prototype of the class. Cygnus A has a very strong emission-line spectrum and, although it is not classified as an N galaxy, the optical spectrum is dominated by a non-thermal power law with spectral index α = 1.6 (Osterbrock and Miller 1975). No trace of absorption features due to starlight has yet been discovered. Attempts have been made (Sandage 1973a; Smith, Spinrad and Hunstead 1976) to subtract a non-thermal power law from the optical spectra of N galaxies in order to isolate the stellar component. However it is highly questionable whether this practice is applicable to the spectra of faint galaxies at high redshift. Certainly it must increase the scatter in the Hubble diagram. More importantly, the subtraction process depends upon reproducing the observed energy distribution of nearby low-redshift galaxies; if there has been significant color evolution over look-back times of several billion years, then the subtraction process will produce systematic errors in the magnitude of the galaxy as a function of z. It is alarming to note that even galaxies without strong emission lines may show optical non-thermal continua. Ulrich _et al._ (1975) have reported non-thermal emission from three galaxies identified with Bologna radio sources, which do not show line emission. It is unlikely that this non-thermal radiation would be recognized in the noisy spectrophotometric observations of galaxies at high redshift.

Another possible difficulty is van den Bergh's (1975) suggestion that star formation may be triggered by the event that produces the radio emission in radio galaxies. This speculation is based on the relatively blue colors of the stellar population near the absorption band of Centaurus A and by the presence of emission knots which appear to be H II regions in the radio lobes of Cen A (Blanco et al. 1975). The presence of young stars could be very troublesome since at high redshift we are observing the emitted UV where the contribution by young hotter stars would be most significant.

Certainly some high-redshift radio galaxies do show clear evidence for the presence of stars. Both 3C 295 ($z = 0.461$) and 3C 123 ($z = 0.637$) show the expected stellar absorption features as well as a single moderate strength emission line identified with [O II] λ3727. In fact our experience shows that the faint galaxies identified with radio sources more often show weak emission lines or a faint red stellar continuum without detectable emission lines than a rich Cygnus A type emission-line spectrum. The oft-quoted misconception that "all radio galaxies show strong emission lines" has been caused in large measure by the relative ease of measuring a redshift for an emission-line object and also by the possible ambiguity in identifying a very extended or asymmetric radio source with a faint galaxy showing no spectroscopic peculiarity.

Another difficulty for galaxies without a strong emission-line spectrum is presented by our unfamiliarity with the ultraviolet spectra of galaxies. The classical landmarks Ca II K and H, the 4000 Å discontinuity in the continuum associated with ultraviolet blanketing by metals, the G-band at λ4300 begin to be shifted into the region of the spectrum longward of 6900 Å at $z \approx 0.7$. Here the night-sky spectrum is dominated by strong OH emission which varies on very short timescales thus making detection of absorption features very difficult. Morton, Spinrad, Bruzual and Kurucz (1976) have obtained observations of the 2100-3200 Å spectra of α Agl and α C Mi from Copernicus from which they have selected absorption features likely to be strong in the emitted UV spectra of galaxies. A list of absorption/continuum features is given in Table 1 along with the redshift for which that feature is shifted into the atmospheric OH bands.

Despite the difficulties great progress has been made in recent years in obtaining redshifts of radio galaxies at high redshift. Minkowski's (1960) redshift $z = 0.461$ for 3C 295 stood for nearly

TABLE 1

Galaxy Absorption Features for Redshift Determination

λ_o	Description	z_{6900}
2640	Fe Continuum Discontinuity	1.61
2799	Mg II Resonance Doublet	1.47
3933,68	K, H Ca II	0.75
4000	Continuity Discontinuity	0.725
4303	G-band	0.603
5175	Mg-b	0.333
5895	D Lines Na I	0.170

fifteen years as the largest radio galaxy redshift. Following Spinrad's (1975) result for 3C 123 a number of radio galaxies have now been found with $z > 0.461$ by the groups at Lick Observatory and at Hale Observatories. Those available as of July 1976 are listed in Table 2.

TABLE 2

New High-Redshift Radio Galaxies

Object	z	V	Remarks
3C 318	0.752[1]	21	N-galaxy, strong non-thermal continuum, weak emission lines
3C 343.1	0.750:[2]	21	1 emission line = [O II] λ3727?
3C 123	0.637[3]	20.5	[O II] λ3727 emission, stellar absorption features
3C 467	0.631[4]	19.5	N-galaxy, strong non-thermal
PKS 0353+027	0.602[4]	18.5	continuum, strong emission lines
PKS 0116+082	0.594[5]	21	Strong emission, cluster
3C 330	0.549[5]	21.5	Strong emission, cluster
3C 19	0.482[6]	20.5	Strong emission, cluster
3C 411	0.467[7]	19.5	N-galaxy, strong non-thermal continuum, strong emission lines.

References to Table 2:

[1] Spinrad and Smith (1976); [2] Spinrad unpublished; emission line confirmed by Sandage, Kristian and Westphal (1976b); [3] Spinrad (1975); [4] Smith, Spinrad and Hunstead (1976); [5] Spinrad, Liebert, Smith and Hunstead (1976); [6] Sandage, Kristian and Westphal (1976b); [7] Spinrad, Smith, Hunstead and Ryle (1975).

3. CONSTRUCTION AND INTERPRETATION OF THE HUBBLE DIAGRAM

Four of the galaxies in Table 2 are N galaxies with strong optical non-thermal radiation. Given the difficulties in interpreting the optical spectrum, we will not consider them further. The remainder are normal radio galaxies and thus are candidates for placement on our Hubble diagram. We will carry 3C 343.1 as tentative (although no more tentative than Minkowski's redshift for 3C 295). Photometry for 3C 343.1, 3C 123, and 3C 19 have been obtained by Sandage, Kristian and Westphal (1976b). For 3C 330, we have taken the spectrophotometric observations of the strong emission-line galaxy associated with the radio source and recent observations of the other bright cluster galaxy by Spinrad. These data have been added to the body of data previously available (largely from Sandage 1972b) to produce the redshift-magnitude diagram for 3CR radio galaxies shown in Figure 4. The following corrections have been applied to the photometric data:

i) The data have been corrected to a standard linear diameter (86 kpc, $q_o = 1$) according to the method described in Sandage (1972a). This correction depends on q_o, of course, but the difference between $q_o = 1$ and $q_o = 0$ is only 0.08 mag (smaller for $q_o = 0$) at $z = 0.5$. Sandage's correction is about 1/2 mag larger than that of Gunn and Oke (1975) who choose a smaller standard diameter.

ii) K-corrections have been applied from Oke (1971). His high-quality spectrophotometric observations of 3C 295 have allowed correction to $z \approx 0.72$. For redshifts greater than 0.5 this correction is large (> 1.5 mag) and somewhat uncertain, thus photometry at the redshifted emitted V continuum would be preferable, however this requires photometry in the near infrared where detectors are less sensitive and the sky background is brighter.

iii) We have adopted the interstellar extinction correction given in Sandage (1973b), however differing methods of estimating the extinction as a function of galactic latitude (e.g. $F_{(B-V)}$, galaxy

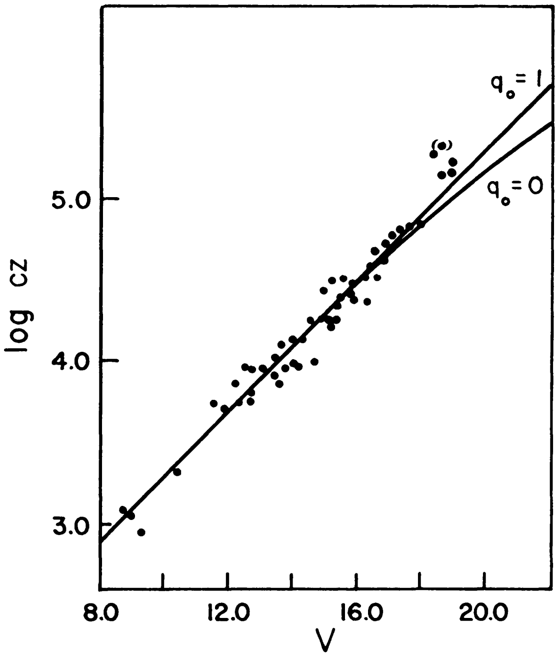

Figure 4. The Hubble diagram for 3CR radio galaxies.

counts, H I column density) disagree. Heiles (1975) has recently emphasized this point concluding that extinctions calculated for extragalactic objects must be uncertain by a few tenths of a magnitude. In a few cases for galaxies at low galactic latitudes where the extinction is most patchy and uncertain, other indicators (color, etc.) have been used to derive the extinction correction. Since we are not dealing specifically with cluster galaxies, and because we hope to press beyond the limits where clusters may be effectively classified, we have not applied corrections for either cluster richness or Bautz-Morgan type.

It is not the intention of this review to introduce yet another formal value for q_o into the literature. We believe that the difficulties discussed previously, the few galaxies yet available with $z > 0.4$, and the unknown correction for luminosity evolution make solution for q_o premature (let alone the consideration of Λ, the cosmological constant in Lemaitre models). A few comments may be made, however, The number of data points in Figure 4 is comparable to the number of first-ranked cluster galaxies considered by Gunn and Oke (1975) and Sandage, Kristian and Westphal (1976a). Neither of these studies have any galaxy with $z > 0.4$ save 3C 295 (which Gunn and Oke discard). There is a clear tendency in Figure 4 for the galaxies at high redshift to lie above the $q_o = 1$ line. If none of the selection effects we have discussed are operating (most of which would make a galaxy appear too bright), this would indicate an evolution-free solution for q_0 in excess of 1.

The correction for galaxy evolution currently presents the greatest uncertainty in the interpretation of the Hubble diagram. Tinsley and her co-workers have been most active in modeling the evolution of elliptical galaxies with a view toward providing corrections for the luminosity and colors of galaxies at previous epochs (c.f. Tinsley 1972; Tinsley and Gunn 1976). The calculated corrections range from a few tenths to over a magnitude at $z = 0.5$, all in the sense that galaxies were brighter in the past. Application of these corrections then revises the value of q_0 downward by as much as 1.5 from that derived without consideration of evolution. The necessity of applying this potentially large and uncertain correction precludes the determination of q_0 at this time. Observational detection of color evolution over the look-back times to distant galaxies would provide a valuable constraint on theories of galaxy evolution. It thus seems that spectrophotometry of galaxies at cosmological distances is necessary first as input for theories of galactic evolution which will then allow proper placement of these objects on the Hubble diagram.

We conclude with the obligatory call for more and better data before substantive conclusions may be drawn from the Hubble diagram. In this case, however, the prospects are excellent for obtaining this data in the near future. The barrier at $z = 0.461$ has been broken and programs of identification and spectroscopy of distant galaxies now going on at Lick and Hale Observatories and elsewhere have likely made this review outdated before it is presented, let alone published in the proceedings of this symposium.

It is a pleasure to acknowledge the contribution of Dr. Hyron Spinrad who initiated and collaborated with me on most of the research discussed here. I would also like to thank Drs. E. M. and G. R. Burbidge for their encouragement and helpful discussions and Drs. A. Sandage and J. Kristian for discussing their data with me before publication.

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DISCUSSION

Jaffe: You can use Dr. Perola's bivariate luminosity function to sort out the radio-optical selection process for radio galaxies even to the extent of constructing a probabilistic H-R diagram of radio/optical color to narrow the dispersion in M of the galaxies observed, whether "radio" galaxies or not.

It may be dangerous to assume a characteristic M of radio galaxies which does not change with z since the radio properties of the galaxies, as well as the optical, evolve with time.

H.E.Smith: Yes, the business of the radio optical luminosity function is very important to the question of using radio galaxies in the Hubble diagram. As I understand it, for powerful radio galaxies there is no correlation between radio and optical luminosity.

We hope to account for optical evolution. It is not clear to me how important the radio evolution will be to $z = 0.5 - 1.0$.

Lewis: You made no reference to the Ostriker & Tremaine correction to be expected from dynamical friction acting on close satellites. Perhaps this might be more severe for a sample of radio galaxies than for the first brightest cluster galaxy, as the radio activity may be a sign of the recent acquisition of a satellite galaxy, with the largest redshift galaxies being liable to have on average accreted more massive satellites.

H.E. Smith: I think that result is speculative and it can influence the diagram either way. Your suggestion seems to be a variation of the colliding galaxies hypothesis for production of radio sources, which has not proven very attractive.

Certainly there are a large number of radio galaxies which are not in clusters of galaxies and for which this effect cannot be important.

Tinsley: Ostriker and Tremaine noted that dynamical evolution (accretion of stars by the galaxy) can be important for any cluster galaxies. Several studies have shown that it will be very difficult to detect dynamical evolution even if it occurs at cosmologically important rates, so it cannot be eliminated as a correction. Moreover, its effect on the Hubble diagram could be of either sign.

It is worth noting that for any evolution (stellar evolution as discussed by Smith, or dynamical evolution), a luminosity change of only 3-5 percent per 10^9 years changes the apparent value of q_o by unity.

H.E. Smith: As I have said, I consider the Ostriker and Tremaine result rather speculative, and of course, unless the theory can make a specific prediction, it cannot be tested.

The corrections are large and the cosmological effects are small. If this work were easy it would have been done a long time ago. Hopefully careful spectrophotometric observations of galaxies at high redshifts will allow us to detect the stellar evolution over times that are a significant fraction of the Hubble time.

Grueff: Do you have any information about the (V-R) color for the new high redshift radio galaxies?

H.E. Smith: Our spectrophotometric observations show weak evidence for bluer colors than might be expected from redshifting a normal galaxy to 0.6 or 0.7. Perhaps Dr. Kristian who has obtained more accurate broad band observations would like to comment.

Schmidt: There is no need for the K-correction to be uncertain. All that is required is spectrophotometry at a given rest wavelength, say at Hδ, for each of the galaxies.

H.E. Smith: That's right. Unfortunately good spectrophotometry does not exist for this sample. I expect that to be done in the near future.

Ekers: I wonder if the Cambridge astronomers could provide a 'revised Revised 3C catalogue' - I mean especially the problem of the flux errors. I believe some 20 to 50 objects would be involved.

Shakeshaft: Unfortunately 178 MHz is now a television band - maybe 150 MHz would do.

Longair: It is really rather non-trivial. What we have been doing is using the revised Kellermann, Pauliny-Toth and Williams flux densities which are the best available. We at Cambridge use a complete sample of 166 sources brighter than 10 Jy on this scale. (Appendix I)

Pooley: The radio galaxy 3C123 has the highest known radio luminosity; it is therefore important to be certain that the galaxy is correctly associated with the radio source. The structure of 3C 123 is very asymmetrical and the galaxy does not lie at the radio centroid. When mapped with the 5 km telescope at 15 GHz at a resolution of 0".7 x 1".3, it becomes clear that the geometry of the source is that of a double with a flat spectrum nuclear component coincident with the galaxy, and both compact and diffuse components on either side. The ratio of the flux densities of the two compact components is very large (of the order of 50:1) and the faint features would be very difficult to detect in weaker sources. This emphasises the need for high sensitivity, high resolution radio telescopes to make sure of optical identifications in such cases.

Arp: Have you looked for any optical identifications of the components that are now resolved in 3C123?

Pooley: Yes, and there are none.