THE NATURE OF GALAXIES AND CLUSTERS OF GALAXIES AT VERY LARGE DISTANCES

J. B. Oke

Palomar Observatory, California Institute of Technology

1. Introduction.

The previous speaker, Marie-Helene Ulrich, discussed several problems in extragalactic research which require the use of a very large ground-based telescope. She emphasized studies of relatively nearby objects. In my talk I will discuss problems which have to do with observations of objects at very large distances.

Most studies of very distant objects involve studies of distant clusters of galaxies since this is one of the very few ways to pick a galaxy which is almost certainly very distant rather than a low-luminosity nearby object. Two exceptions are studies of radio and X-ray selected galaxies which very often are distant objects. Another exeption is the study of quasars which are almost all at very large distances. Even in these exceptions there is an interest in knowing whether these objects are associated with clusters or not.

I will begin therefore by discussing some of the problems associated with distant clusters of galaxies. Because galaxies are intrinsically red and because of cosmological effects and redshifts, distant galaxies are both extremely faint and very red. Furthermore, distant galaxies do not become extremely small; for values of the deceleration parameter q_o between 0 and 1 galaxies of a fixed size have almost the same angular size indpendent of redshift for redshifts above 0.5. Consequently, galaxies at large z remain distinguishable from stars even with only moderate seeing of 1 arcsec and they are distinguishable from nearby low-luminosity galaxies by virtue of their very red colors.

2. Surveys for Clusters of Galaxies.

Gunn, Hoessel, and Oke (1984) have completed a survey for distant clusters of galaxies. This survey has provided a catalog of about 425 clusters with redshifts ranging fromz = 0.2 to over 0.9. This catalog represents the limiting magnitude which can be reached using photographic techniques.

To find clusters with redshifts larger than 0.9 will require that the actual survey pictures be taken with high-performance CCD's on telescopes in the 3.5-5-m class. For example, the 5-m telescope imaging instrument 4 Shooter, which uses 4 TI 800x800 CCD's in a configuration similar to that of the Wide Field Planetary Camera of the Space Telescope, takes pictures which are 8'x8'. One could therefore survey a 1°x1° square in just a few good nights. We have already made a substantial number of such exposures and have a list of 8 to 10

Proceedings of the IAU Colloquium No. 79: "Very Large Telescopes, their Instrumentation and Programs", Garching, April 9–12, 1984.

possible very faint clusters with redshifts which one can only guess are between z = 1.5 and 2. To summarize, present sized telescopes with CCD cameras are adequate to search for very faint clusters out to redshifts of order 2 and to investigate superclustering at large z.

By using modern CCD technology (in the case of observations with the 5-m telescope this involves using the Prime Focus Universal Extragalactic Instrument (PFUEI) which has an 800x800 TI CCD, or 4-Shooter), it is relatively easy with 10-20 minute exposures in each color to measure accurate magnitudes and visual and red colors for clusters out to 0.9. Examples of faint cluster CCD pictures are shown by Gunn, Hoessel, and Oke (1984). Photometry of clusters in the blue and violet is much slower with exposure times of up to 2 hours needed. Surveys for clusters have always been done in the red since galaxies at moderate redshifts are indeed red. At large look-back times it may be important to look in the blue and violet since even Lα may be shifted into the visible spectrum. Such searches at redshifts of 1.5-2 will require very large telescopes.

3. Redshifts of Clusters. Cooled CCD's which have made the photometry of very faint clusters relatively straightforward can also be used very effectively for low-resolution spectroscopy to obtain redshifts, study metallicity, and to study peculiar galaxies in clusters. By combining multi-slit techniques with efficient CCD spectrographs one can obtain quite high quality spectra out to redshifts of about 0.7. An example of a spectrum of a first-rank galaxy at a redshift of 0.714 is shown in Figure 1. Spectroscopy at z = 0.90 becomes very

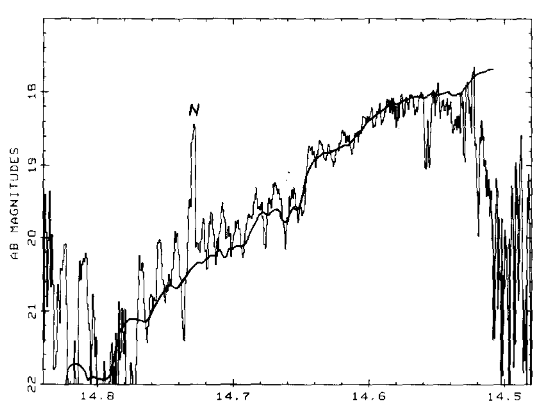

Figure 1. A 100 min PFUEI spectrum of 1322.5+3115. N makes a strong night sky line. The solid smooth curve is a standard galaxy energy distribution.

https://doi.org/10.1017/S0252921100108814 Published online by Cambridge University Press

much more difficult. The galaxies are fainter and most of the light has moved even further into the red. The dominant factors are exposure times available and subtraction of the very bright night sky in the red and near infrared. With a 5-m telescope and five or six hours of exposure spectra of galaxies at z = 0.9 are still of poor quality. It is possible to determine z, but there is very little additional information. It is very clear that at redshifts greater than 0.7 a VLT will be absolutely necessary to study extensively problems of evolution, metallicity, etc. Furthermore, it will be necessary to use multi-slits or fiber-optic feeds so that many galaxies in a cluster can be studied simultaneously.

4. Evolutionary Problems. There has been a considerable amount of recent theoretical work on galaxy synthesis and evolution particularly by Tinsley and Gunn (1976), Tinsley (1978, 1980), O'Connell (1980), Bruzual (1983) and Pickles (1983). The models are characterized by an initial mass function and a function to describe the way in which interstellar material is recycled through stars. The models, along with a family of energy distributions for stars of various types, can then be used to synthesize the energy distributions in real galaxies and then to see how real galaxies should evolve. For look-back times of several billion years, elliptical are slightly bluer in color above 4000 Å and considerably bluer between 3000 and 4000 Å. There is evidence for star formation as recently as 5 x 10^9 years ago in M32 (O'Connell 1980) and for star formation up to 10 x 10^9 years after the globular clusters formed (Pickles 1983). The possibility of star formation in giant ellipticals at these relatively late stages of evolution is important because one can actually study galaxies at this look-back time.

The observations by Gunn, Hoessel, and Oke (see Oke 1984) do not show any systematic change in either the visual or ultraviolet color out to z = 0.50. Kristian, Sandage, and Westphal (1978) found no evidence for evolution out to z = 0.30, the limit for which good K-corrections were available, but did find that galaxies became bluer at larger z. It is clear that much more work is needed on moderate band photometry of galaxies in very distant clusters to clearly detect evolutionary effects. A VLT is an ideal way to do such studies.

A further test of evolutionary effects is to look at the strong spectral features such as the H and K lines of Ca II, the Mg II λ2800 line, and the Mg b-band at 5200 Å in elliptical galaxies. The Mg b-band rapidly decreases in usefulness as z increases because it shifts too far into the red. The H and K break is an ideal probe between z = 0 and 1, while the Mg II λ2800 feature will be important for z = 0.4 to 1.8. Models for instance by Bruzual (1983) indicate a decrease in the H and K break as z increases. The observations of Spinrad, Stauffer, and Butcher (1981) and Bruzual (1983) confirm such a decrease although one must be cautious because some of their objects are radio galaxies with non-thermal contribution to the energy distribution. Other observations which may not be of as high quality (Oke 1984) do not show a change of the H and K break with z. A great deal more work is needed at large redshifts, Because high-quality spectra are essential, a VLT is required.

It has been found from IUE observations of nearby elliptical galaxies (see for example, Bertola, Capaccioli, and Oke 1982) that there is a hot component, corresponding to a blackbody or model atmosphere at a temperature of 30,000° K which contributes varying amounts of flux in the uv. If one makes models for the observed flux which are sums of a giant elliptical galaxy energy distribution plus a varying amount of 30,000° K radiation then one finds excellent fits to those energy distributions which we have obtained that are abnormally blue. It is still not clear whether this hot component is due to hot horizontal-branch stars or to young recently formed OB stars. The fact that star formation in ellipticals may have continued until 5 x 10^9 years ago, suggest that young stars may still exist in elliptical galaxies. The observation that the hot component appears to have the same spatial distribution as the cool stars favors a hot horizontal-branch explanation, since young stars might be expected to be more concentrated towards the nucleus. By studying a substantial sample of galaxies at large look-back times, one can hope to resolve this question and to learn more about star formation rates in ellipticals.

Only a beginning has been made on the study of fainter galaxies in clusters. Butcher and Oemler (1978) found large numbers of blue objects in the 3C 295 (z = 0.46) and 0024+1654 (z = 0.37) clusters. Dressler and Gunn (1983) have obtained spectra of 26 objects in the 3C 295 cluster of which 23 give redshifts. Six, including 3C 295 itself are normal galaxies, six other are blue, three have active galactic nuclei, while three show evidence for recent bursts of star formation. Nine galaxies are foreground objects. There are no normal spirals. Dressler and Gunn (1982) have also looked at six galaxies in 0024+1654. Four are normal ellipticals while two have strong emission lines. Their more recent unpublished data on this cluster show that 40 percent of the galaxies observed are blue and have spectra characteristic of normal spirals but with high-surface brightness. Bautz, Loh, and Wilkinson (1982) have done photometry of two clusters, Abell 370 (z = 0.37) and 2244-02 (z = 0.33). They find that the galaxies have colors consistent with those of normal ellipticals. The above results suggest that clusters may have very different populations of member galaxies. The population may consist of ellipticals, spirals, galaxies

https://doi.org/10.1017/S0252921100108814 Published online by Cambridge University Press

with recent bursts of star formation, active galactic nuclei galaxies, etc. How the population changes from cluster to cluster and as a function of look-back time must be pursued. This will require high-quality spectra of many galaxies in many clusters at all values of z.

5. Cluster Dynamics and Superclusters. Both theoretical and observational work suggests that cD galaxies in clusters have developed as a result of cannibalization whereby one galaxy swallows up another through dynamical friction. In nearby clusters, the cD galaxies often have multiple nuclei. Since this process requires time one would predict that at large look-back times cD galaxies will be much less prominent and perhaps even non-existent. At the same look-back times the process, however, is going on so that multiple-nuclei galaxies should still exist. One can look for cD galaxies at large z using photometry and moderate sized telescopes. Studying the dynamics of such galaxies is difficult and will require a VLT since one must obtain velocities of the various nuclei in the galaxy and also measure the velocity dispersion in the systems.

There are two limiting views concerning the formation of superclusters (see for example, Zeldovich, Einasto, and Shandarin 1982; Peebles 1983). In one view the galaxies themselves formed first and then through gravitational collapse the galaxies formed into clusters and superclusters. In the other view the masses characteristic of superclusters formed first, perhaps as pancake-like entities, and the galaxies formed after this. At redshifts of 1 to 1.5 we are looking at the Universe as it was 2 to 4 x 10^9 years after the beginning. In this length of time only very rich clusters can form (Gunn and Gott 1972). Therefore, in the first view, at redshifts of 1.5, we should not see superclusters but only the very richest clusters. In the second view clusters and superclusters will already exist. This is an extremely difficult observational problem which will require a VLT to solve. One must first of all survey an area of sky of at least 1°x1° to a faint enough limit so that both rich and poor clusters can be discovered. Spectra of several galaxies in every cluster in the large field will have to be obtained to provide the z coordinate. Only then can one see if superclusters exist. Such a program may involve 100 or more clusters and spectra of 1000 very faint galaxies.

A survey such as the above one may also be the ideal opportunity to study the association of quasars and clusters and superclusters. This same 1°x1° square probably contains 30 to 100 quasars for which redshifts will be required.

6. Supernovae. Apart from galaxies and quasars the only other objects which can be seen and studied at large distances are supernovae.

https://doi.org/10.1017/S0252921100108814 Published online by Cambridge University Press

The frequency of supernovae of different types at large redshifts give information about galaxy evolution. Type II SN, associated with young massive stars should be seen at all ages. However, the star formation rate in galaxies was much higher at large look-back times so the frequency of Type II's should be much higher at large z than near us. Type I's associated with low-mass stars, are found locally in galaxies where the stellar masses are significantly less than one solar mass. At large look-back times, the mass of the old population will increase to about 1 solar mass or more. Since it is still not clear what the progenitors of Type I's are, any knowledge about the possible masses is of importance.

The decay rate for supernovae light curves can also be measured for distant objects. This can provide a check that all time scales, including frequency of light, change in the same way with z, and that redshifts are not some peculiar property of light.

Supernovae have been used as standard candles both to determine H_o and to plot the Hubble diagram. The problem in the latter case is that evolutionary effects may come in so that the supernova maximum light may be a function of z. There is a way to correct for evolutionary effects. As first suggested by Searle, it is possible using a variation of the Baade-Wesselink method for determining absolute magnitudes of pulsating stars to determine the absolute magnitude of a supernova without reference to other distance measuring methods. This method has been discussed and applied by Branch and Patchett (1973), Kirshner and Kwan (1974), Branch (1977,1979), and Schurmann, Arnett, and Falk (1979). The basic idea is to use the P Cygni-like line profiles to measure the velocity of expansion of the atmosphere. This gives a difference in radius in km at two epochs. If one also measures the energy distribution to obtain an effective temperature and emergent flux, then for two epochs one can solve for the ratio of the radii. Using the difference and ratio gives an absolute radius and through the effective temperature the absolute magnitude and distance. The technique can be applied only while the atmosphere is optically thick, i.e., until about three weeks after maximum.

If one understood the expanding atmospheres of supernovae completely one could derive H_o accurately. At present lack of understanding limits the accuracy of H_o to perhaps a factor 2. One can also, however, apply the method in a differential manner only. That is, for two supernovae, one measures the ratio of the expansion rates from the spectra, and the ratio of the effective temperatures. Such ratios are much less sensitive to our limited knowledge about the atmospheres. The result is the difference in absolute magnitude of two

https://doi.org/10.1017/S0252921100108814 Published online by Cambridge University Press

supernovae. Applied to supernovae of different redshifts this yields the deceleration parameter q_o directly (Schurmann, Arnett, and Falk 1979; Wagoner 1979). Between redshifts 0 and 0.5 a change in q_o from 0 to 1 yields a difference in observed magnitude of a standard candle of 0.5 mag. Therefore, one should be able to derive q_o accurately by this method. With present day telescopes it should be possible to find and study supernovae out to about $z = 0.4$. A VLT would permit observations out to about $z = 1$ where the sensitivity to q_o is much greater.

7. Summary. I have outlined above a few of the crucial programs which can be effectively studied with a very large ground-based telescope. In addition to the telescopes one must have: (1) a high efficiency low- and moderate-resolution spectrograph; (2) a multi-slit or multi-fiber capability for spectroscopy; (3) a site with superb seeing; (4) a telescope designed for use for 3200 Å to a few microns.

REFERENCES

Bautz, M., Loh, E., and Wilkinson, D. T. 1982, Ap. J., **255**, 57.
Bertola, F., Capaccioli, M., and Oke, J. B. 1982, Ap. J., **254**, 494.
Branch, D. 1977, M.N.R.A.S., **179**, 401.
________. 1979, M.N.R.A.S., **186**, 609.
Branch, D., and Patchett, B. 1973, M.N.R.A.S., **161**, 71.
Bruzual, G. A. 1983, Ap. J., **273**, 105.
Butcher, H., and Oemler, A. 1978, Ap. J., **219**, 18.
Dressler, A., and Gunn, J. E. 1982, Ap. J., **263**, 533.
____________________________. 1983, Ap. J., **270**, 7.
Gunn, J. E., and Gott, J. R. 1972, Ap. J., **176**, 1.
Gunn, J. E., Hoessel, J. G., and Oke, J. B. 1984, in preparation.
Kirshner, R. P., and Kwan, J. 1974, Ap. J., **193**, 27.
Kristian, J., Sandage, A., and Westphal, J. A. 1978, Ap. J., **221**, 383.
O'Connell, R. W. 1980, Ap. J., **236**, 430.
Oke, J. B. 1984, Paper presented at the Meeting on Clusters and Groups of Galaxies, Trieste, September 1983. (To be published by Reidel).
Peebles, P. J. E. 1983, Ap. J., **274**, 1.
Pickles, A. J. 1983, Ph.D. Thesis, Australian National University, Mount Stromlo Observatory.
Schurmann, S. R., Arnett, W. D., and Falk, S. W. 1979, Ap. J., **230**, 11.
Spinrad, H., Stauffer, J., and Butcher, H. 1981, Ap. J., **244**, 382.
Tinsley, B. M. 1978, Ap. J., **222**, 14.
____________. 1980, Ap. J., **241**, 41.
Tinsley, B. M., and Gunn, J. E. 1976, Ap. J., **203**, 52.
Wagoner, R. V. 1979, Physical Cosmology, Les Houches Session XXXII, ed. R. Balian, J. Audouze, and D. N. Schramm (North-Holland), p. 179.
Zeldovich, Ya.B., Einasto, J., and Shandarin, S. F. 1982, Nature, **300**, 407.

https://doi.org/10.1017/S0252921100108814 Published online by Cambridge University Press

DISCUSSION

G. Chincarini: When centering a distant cluster on one CCD chip, how often did you detect another faint cluster in one of the other 3 CCD chips? In other words, have you any indication on clustering of clusters at large distances?

J.B. Oke: We have only qualitative impressions at present. It is very common to find a faint cluster on one of the other three CCD's, but this cluster will have a larger z than the one observed. Occasionally what we thought was a single simple cluster turns out to be a much more extended cluster or perhaps two close clusters.

R. Bingham: It has often been remarked that the angular size of galaxies at large redshifts means that the seeing with ground-based telescopes is not a serious disadvantage compared with Space Telescope. Could you comment on that?

J.B. Oke: This is indeed the case. The main consequence of the finite angular size of distant galaxies is that very large ground based telescopes have advantages over the much smaller Space Telescope. For very faint objects good or excellent seeing is an enormous advantage for ground-based observations. We simply do not work on very faint galaxies when the seeing is significantly worse than one arc second. (See also the answer to the question by Dr. Appenzeller.)

I. Appenzeller: Observations of very distant extragalactic objects have also been one of the main arguments for building the Space Telescope. Could you please comment on the relative advantages and disadvantages of doing such observations with the ST and with a ground-based VLT?

J.B. Oke: Unless distant galaxies have very compact bright nuclei the very much larger collecting area of the VLT as compared with ST more than offsets the brighter sky brightness from the ground. Also the VLT will be capable of obtaining spectra of many galaxies simultaneously whereas the ST will be able to observe at most two at a time. If distant galaxies are very luminous in the ultraviolet then ST observations might be more efficient than ground-based ones. The Space Telescope will have enough resolution to indicate whether distant galaxies are spirals or ellipticals.

B. Foing: There is a clear frontier between the capabilities of ground-based and space telescopes and we should use ground-based observations with big collectors

https://doi.org/10.1017/S0252921100108814 Published online by Cambridge University Press

in case of photon limitation and space in case of sky limitation (UV, sky fluctuation,...). Question: From the ground-based low resolution spectroscopy what is the limit due to the sky subtraction? Is there a need to enlarge the collecting area if this is the main limitation?

J.B. Oke: Spectroscopic observations of faint galaxies are indeed dominated by sky brightness. In this situation the limiting brightness which can be reached goes as the first power of the telescope diameter. For faint extended galaxies one is still better off with a VLT on the ground than with ST.