Prospects for Measuring the Evolution of the Luminosity Function and the Angular Correlation Function

Edwin D. Loh
Department of Physics and Astronomy
Michigan State University
East Lansing, MI, USA

Abstract

The angular correlation function has been measured at redshift 0.5 to 30 % precision and the characteristic luminosity to 20 % precision with a catalog of photometric redshifts of 1000 field galaxies. In the near future, the number of galaxies can be increased a hundredfold. Then 7 % precision in the characteristic luminosity for each of ten color classes and 5 % precision in the correlation function are attainable. If a nearby sample of 100 000 galaxy redshifts becomes available and if the same selection criteria are used for both samples, then one can measure the evolution of these statistical properties of galaxies over a period of a third the Hubble time to high accuracy.

1 Introduction

In 1981 we began a project to obtain a complete, magnitude-limited sample of galaxies with redshifts and magnitudes. The aims were to measure the volume element as a function of redshift and so the cosmology and to study evolution in a statistical fashion. We built a camera with a charge-coupled detector for the $f/2$ prime focus of the Wyoming 2.3 m telescope, and collected a sample of 1000 galaxies in 1983. The median redshift of the galaxies is 0.5. The cosmological density parameter Ω measured to a precision of 30 % (Loh and Spillar 1986b, Loh 1988b), the characteristic luminosity of galaxies at $z = 0.5$ (Spillar and Loh 1988), and the galaxy correlation function at $z = 0.5$ (Loh 1988a, Loh and Spillar 1988) — all these measurements have come from this rather small sample.

The aim of this paper is to discuss a planned experiment to increase the number of galaxies by a hundredfold. Both for studying cosmology and evolution of galaxies, one must compare a distant sample with a nearby one. The projects at Cambridge, Edinburgh/Durham and Münster, to collect large numbers of galaxies at $z \leq 0.2$, which were discussed at this meeting, are crucial for this project. Therefore I discuss in particular what is required of the low-redshift surveys.

2 Photometric redshifts

The technical advance that enables this experiment is the photometric method (Loh and Spillar 1986a) for measuring redshifts, which Baum (1962) invented 30 years ago. In approximate terms one determines the redshift of every galaxy in a field by finding the wavelength of the 400 nm break with six broad-band filters. More precisely, every object with a greater than minimum flux is photometered. The data for each object are compared with the colors, which are computed from spectra, of 100 types of stars and 11 types of galaxies at various redshifts. The object is identified as the star or the galaxy represented by the fiducial object that matches best. The 400 nm break (and therefore the redshift) is apparent even in the calibrated picture, as one can see for the cluster 0024+1654 at $z = 0.4$ as shown in *Fig. 1.* In 3 hours on the Wyoming 2.3 m telescope, we obtain the redshifts of 200 galaxies, for which the median redshift is 0.5 and the median distance is 0.4 of the Hubble distance. Spectroscopy yields redshifts with higher accuracy, but photometry is faster.

This technique for measuring redshifts has been tested (Loh and Spillar 1986a) by comparing the photometric redshifts of the cluster 0024+1654 at $z = 0.4$ with the spectroscopic redshifts of Dressler *et al.* (1985). Since the goal of the spectroscopy was to study the Butcher-Oemler effect, half of the spectroscopic redshifts were of blue galaxies. For 30 of 34 galaxies, the photometric and spectroscopic redshifts agree. (For the others, two photometric redshifts are probably wrong, and two spectroscopic redshifts are probably wrong.) From this test, one draws these conclusions: (a) The mean of $x = (z_{\rm photo} - z_{\rm spect})/\sigma_{\rm photo}$ is consistent with zero for both the red and the blue galaxies; *i.e.*, the photometric redshifts are not biased. (b) The mean of x^2 is consistent with 1; *i.e.*, the errors $\sigma_{\rm photo}$ in the photometric redshifts are estimated accurately. (c) Stars and galaxies are separated correctly.

3 The new experiment

A new experiment is planned to increase the detector area by a factor of 20. This, combined with a longer time at the telescope, enables a new sample of 10^5 galaxies. The new sample and the old are alike in other respects, namely the redshift range and the depth. The key to the new experiment is a new Tektronix charge-coupled detector, which is a square, 5.5 cm on a side, and contains 4×10^6 elements. Other essential items are a Wynne corrector to remove the coma of the mirror over a large field and an array processor to process the data. The new camera on the Wyoming telescope will have a 35 arcmin field.

4 Luminosity evolution

Using the correlation between color and the ratio of current to ancient star formation, Tinsley (1980) and Bruzual and Kron (1980) computed the evolution of the luminosity of galaxies. In these models the galaxies are $-0\overset{\rm m}{.}1$ to $1\overset{\rm m}{.}0$ brighter at $z = 0.5$ than at the present, the redder galaxies showing larger evolution. These must be considered first-order models, since one cannot account for the light in the U, B, and V bands of even the simplest galaxies, the ellipicals (Gunn *et al.* 1981).

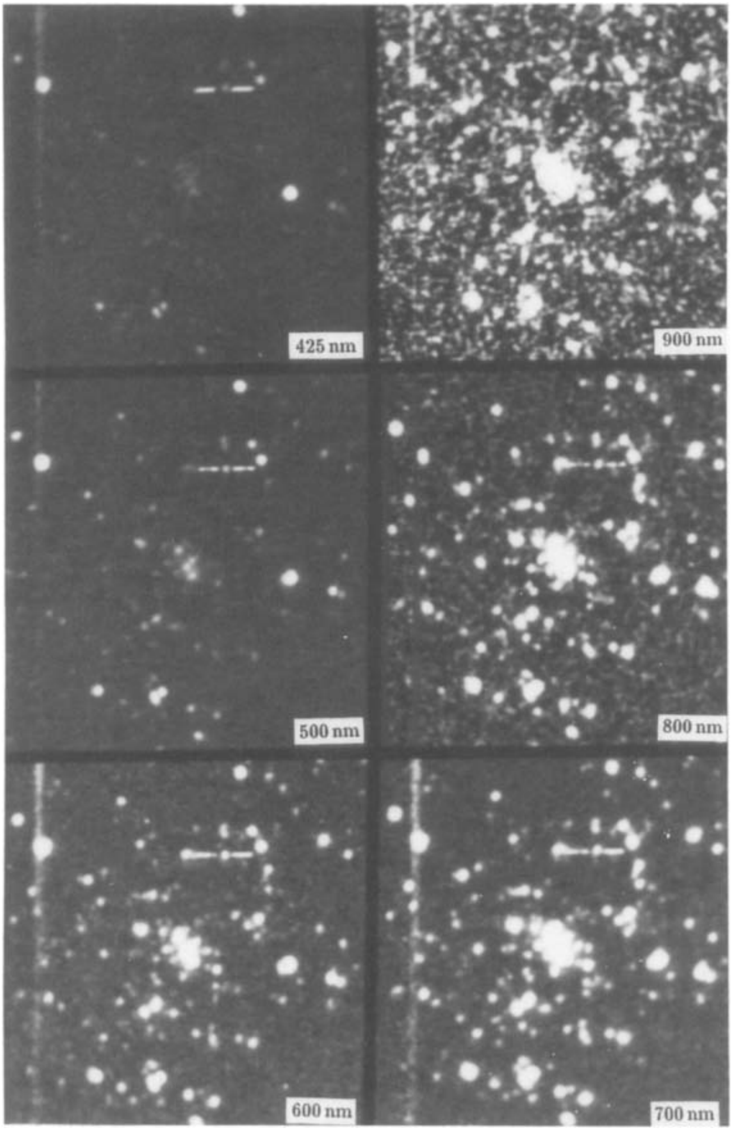

Fig. 1. The cluster 0024+1654 at $z = 0.4$ shown at 425 nm (upper left), 500 nm, 600 nm, 700 nm, 800 nm, and 900 nm (in counter clockwise sequence). The pictures are scaled so that an object with the same flux in ergs $\sec^{-1}$ cm^{-2} Hz^{-1} appears equally bright in all six pictures. The redshift of the cluster is readily apparent – the objects are much brighter in the 600 nm picture than in the 500 nm picture, and they brighten to a lesser extent at longer wavelengths, since the 400 nm break at $z = 0.4$ appears at 560 nm. A break is clear even for a blue galaxy (marked by a dash), which has colors of an Im galaxy. Each picture is a 3.3 arcmin square; north is to the right and east is down. The exposure time is 5 min for each filter on the Wyoming 2.3 m telescope.

Spillar and Loh (1988) find that the red galaxies, those with rest-frame $B - V > 0.7$ (the mean color of Sb galaxies), are brighter by $0\overset{\mathrm{m}}{.}7 \pm 0\overset{\mathrm{m}}{.}3$ and the blue galaxies are brighter by $0\overset{\mathrm{m}}{.}5 \pm 0\overset{\mathrm{m}}{.}4$ at $z = 0.5$, assuming an Einstein–deSitter universe. For an empty universe, the evolution is $0\overset{\mathrm{m}}{.}3$ greater. For this result, one measures the spatial density of galaxies with luminosity L, which is commonly assumed to have the Schechter form, $\phi^* e^{-x}, x^\alpha dx$, where $x = L/L^*$. One assumes α does not evolve and determines the characteristic luminosity L^*. The sample of Kirshner *et al.* (1983) is used to find L^* nearby, and half of the error is due to the nearby sample. This result is consistent with the models.

What can one learn with a hundredfold increase in the number of galaxies? The error in the luminosity scales as $N^{-1/2}$, where N is the number of galaxies. The ultimate error is probably limited by the systematic errors in matching photometric systems, which I take to be $0\overset{\mathrm{m}}{.}1$. One can learn more by using the color information. Assume the galaxies are split into 10 classes by color, with approximately the same number in each class. (The angular resolution is insufficient to classify the galaxies in this sample by morphology.) Then the error in measuring the characteristic luminosity of a single color class is $0\overset{\mathrm{m}}{.}07$. The fraction of the galaxies that belong to a particular class can be measured to about 3 %.

To discuss any question of evolution, one needs a sample of nearby galaxies with comparable characteristics, and these are: (1) magnitudes that are accurate to 10 %, (2) redshifts of the entire sample or at least of a sufficient subsample, and (3) classification of the galaxies by color. At the least, one must have enough redshifts to disentangle distant, intrinsically bright galaxies from nearby, intrinsically faint ones and to compute the mean shift in spectral band as a function of color class. To measure a 10 % evolutionary shift in the populations of 10 color classes requires enough redshifts to classify objects that make up only 1 % of the entire sample.

The J band of the nearby surveys, the median redshift of which is 0.15 (Schuecker 1987), measures the same rest-frame band as the sensitive 700 nm and 800 nm bands of the distant survey. Therefore, one need not invoke spectral models to compare the samples.

The shape of the luminosity function can be measured at $z = 0.5$ to 4^{m} fainter than L^*. Phillipps and Shanks (1987) measured the shape of the luminosity function of field galaxies at $z \ll 1$ with an ingenious scheme. The excess number of galaxies as a function of magnitude around a small sample of galaxies with known redshifts is determined from a larger and deeper sample without redshifts. The same method was developed and is used by Schuecker *et al.* (1988). The excess number is a direct and inexpensive (because it requires few redshifts) measurement of the luminosity function. This same idea can be used with the proposed experiment, if the redshift data are augmented with deeper pictures at 700 nm. The deeper pictures are easy to obtain compared with the redshift data because only one band, rather than six, is required and the 700 nm band is relatively efficient.

Having measured the joint evolution of luminosity and population frequency of the color classes, one can answer these questions in a statistically way. Are the first-order models confirmed? Are they deficient in certain color classes? If there is a rapid depletion of the gas in spiral galaxies (Larson *et al.* 1980), then spiral galaxies evolve from blue to red classes. Is this shift observed?

5 Correlation function

The form of the spatial correlation function is

$$\xi(r_\mathrm{p}) = (r_0/r_\mathrm{p})^\gamma (1+z)^{-3}$$

for $r_\mathrm{p} < r_0$, where r_p is the proper distance, r_0 is a parameter, and $\gamma = 1.8$ (Peebles 1980). At $r_\mathrm{p} \geq r_0$, ξ appears to fall faster than the power law (Groth and Peebles 1977); this is known as the 'break'.

Models of the evolution of the clustering have been constructed. In the BBGKY solution (Davis *et al.* 1977), small virialized groups, which dominate ξ for small r_p, neither contract nor expand, so that r_0 is a constant. Clustering does grow in the regions where $\xi \approx 1$, and the radius of the break changes as $(1+z)^{-1.67}$. In models in which galaxies have extended halos, dynamical friction changes the shape of the correlation function (Tremaine 1987).

The angular correlation function at $z = 0.5$ has been measured to 30 % accuracy (Loh 1988a, Loh and Spillar 1988). Extrapolating with the present data, one expects these errors for the angular correlation function $w(\vartheta)$ at $z = 0.5$ with angular bins of width $d\vartheta = \frac{1}{4}\vartheta$: at a projected distance of $100\,h^{-1}$ kpc, the relative error is 0.05. At a projected distance of $2.5\,h^{-1}$ Mpc, where the power law equals one, the relative error is 0.25. Therefore the data are sufficient to measure the amplitude of the angular correlation function for each of 10 color classes to 15 %, the shape of the correlation function, and the projected distance of the break if it exists.

Measurement of the evolution of the correlation function, also as a function of the color class, adds yet another dimension to the study of evolution. The evolution of luminosity and color involve the stellar evolution time scale and the gas evolution time scale, but the evolution of the correlation function is an entirely different process with a different timescale. Whether the two time scales are indeed different is an interesting question.

6 Test of object classifications

The classification of objects by color is likely not to be perfect. K stars and galaxies of all types at $z = 0.3$ may be confused, and M stars may be confused with early galaxies at $z = 0.8$. Furthermore, types of galaxies that are not among the fiducial objects, *e.g.* starburst galaxies and hitherto unknown extragalactic objects, will be misclassified.

The same technique of measuring the excess number around galaxies with known redshifts can be used to probe for misclassified objects in suspect samples. For example, one can find the correlation between galaxies and objects that are classified as K stars to determine the fraction of 'K stars' that are actually galaxies. Another group of objects, those that are classified as intrinsically faint galaxies at low redshift, appear anomolous because they are too numerous. The nature of these objects can be discovered by this technique. Extrapolating the measurement of the correlation function with the Loh-Spillar data, one can look for misclassified galaxies as rare as $0.02\sqrt{f}$ of all galaxies (or $0.02/\sqrt{f}$ of the sample), in a sample that is f times as numerous as galaxies. For example, suppose we wish to find the fraction of objects that are classified as M stars but are actually galaxies. M stars are about 25 % as numerous as galaxies. Then the galaxy contamination among the M stars can be measured to 4 %, and the fraction of the galaxies misclassified as M stars can be measured to 1 %.

7 Cosmology

The new experiment will measure the sum of the cosmological density parameter Ω and the dimensionless form λ of the cosmological constant to $\sigma(\Omega+\lambda)=0.4$ and the difference to $\sigma(\Omega-\lambda)=0.08$. I am assuming that the systematic error due to the evolution of the characteristic luminosity and the redshift errors are measured from the new data, and furthermore that the data from Cambridge, Edinburgh/Durham, and Münster are used to find the local density ϕ^*.

At the conclusion of this experiment when the data are at hand, will we know the geometry of the universe? I think that potentially the greatest problem is that the luminosity function may evolve in a way that prevents a reliable estimate of the evolution of ϕ^*. If galaxies of luminosity L at $z=0.5$ evolves to be L^γ, where $\gamma-1=-0.2$, then with the redshift-volume test, one finds $\Omega=1$ for an universe with $\Omega=0.1$ (Loh 1988b). A strong hint for this is the very short time for which the gas in a spiral galaxy, if not augmented, is converted into stars. The measurements of the luminosity function with the proposed experiment may settle this problem. Questions about the photometric redshifts are not fundamental. Photometric redshifts will have been tested against the spectroscopic redshifts of Koo and Kron, and the fraction of galaxies that are misclassified will be estimated accurately by the method of correlation. Therefore, if the measurements of the luminosity functions are easily interpreted, we will know the geometry of the universe.

Suppose these results show a substantial evolution that is difficult to model. Perhaps a substantial number of objects, not classified as galaxies, are found to be galaxies by their correlation with known galaxies. Perhaps the shape of the luminosity function has evolved substantially. Then this experiment will have failed to measure the geometry of the universe, but it will have contributed substantial data on the global properties of galaxies at $z \le 1$ — the luminosity function of galaxies of different color classes, the correlation function, the density of all objects that cluster as galaxies regardless of correct identifications by color, and limits to the spectral evolution of field galaxies.

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