analyzed independently, and hybrids that contained all the cat chromosomes or none (except the X chromosome) were not included in estimates of frequencies of discordancy. A computer program prepared by S. Knisley, Division of Computer Research Technology, NIH, was used for calculating the frequencies of discordancies between a marker and all the others tested. Feline enzyme phenotypes were entered into the program, which generated an output consisting of a list for each marker of the number and frequency of the four classes of hybrids (+/+, +/−, −/+, and −/−) with respect to each of the other markers. Putative linkage groups were established for each cross. The established feline cell lines (in contrast to fresh cells) each contained multiple chromosome rearrangements (W. G. Nash, unpublished observations). Therefore, these crosses were mainly used as independent confirmations of syntenies observed in crosses with fresh diploid tissues.
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$$\frac{(19-9)!}{8!2!}/(19)^9 = 1.4 \times 10^{-10}$$

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55. The data summarized in this article represent the combined efforts of several technical and student assistants over a 5-year period. Particularly important were the continued participation of Janice Simonson, Adam Greene, and Mary Eichelberger. Also contributing at various stages were Elizabeth Hubbel, M. Catherine Rice, and Eric Berman. We thank Drs. Peter Lalley and Richard Lemons for discussions, criticisms, and readings of early drafts of this article. Supported by the Virus Cancer Program of the National Cancer Institute.

The Most Distant Known Galaxies

Richard G. Kron

It is now possible to see astronomical objects at distances of many billions of light-years, with continuing gain in depth as new observational techniques are tried and old techniques are refined. Such distances are already appreciable fractions of the scale of the universe itself, which means that we may be able to see far enough to witness the formation of luminous objects (galaxies and quasars), the epoch that Sandage (*1*) has picturesquely called the edge of the world. In this article I review the situation at present, especially with regard to the discovery and spectroscopic study of distant galaxies.

The recessional velocities of galaxies derived from Doppler shifts are correlated with their distances, which can be estimated from their apparent brightnesses or angular sizes. This relationship is linear for small velocities and is more or less independent of direction in the sky: the hypothesis that we are not privileged in our vantage point leads to the concept of a uniformly expanding universe. These velocities, or redshifts, are measured by the dimensionless number $z = (\lambda_o - \lambda_e)/\lambda_e$, where λ_o is the observed wavelength of a spectral line and λ_e is the laboratory wavelength. In the following it will be assumed that the redshift is a strict function of distance and consequently of the travel time of light from the galaxy. The value of the proportionality factor between redshift and distance is controversial: a redshift of unity is believed to correspond to a distance somewhere between 5 billion and 9 billion light-years. This review will stress redshifts as the paramount method for determining relative distances. The enterprise of obtaining redshifts for distant galaxies is almost exclusively the story of optical techniques because of the concentration of strong spectral features in the optical band and the favorable signal-to-background ratio.

In the expanding universe picture sketched above, galaxies should evolve in various ways because, as time goes by, more and more gas is locked up in stars or stellar remnants (*2*) (unless there is counterbalancing replenishment by infalling gas). In addition, the abundance of heavy elements such as iron should be smaller in a young galaxy than in an older galaxy of the same total mass, since less time has elapsed for their synthesis in the cores of stars. The sup-

The author is an associate professor at the University of Chicago, Yerkes Observatory, Williams Bay, Wisconsin 53191.

ply of gas in a galaxy may change, through either star formation (which may result in a change in the optical appearance of the galaxy), rapid "stripping" of gas by an external agent (*3*), or infall of primordial gas. The internal stellar distribution may readjust on time scales of a rotation period or longer, due for instance to resonance in the field of a rotating nonaxisymmetric potential (*4*), such as the bar of a barred spiral galaxy. Another type of dynamical evolution is called galactic cannibalism, which refers to inelastic collisions and mergers between galaxies, occurring most favorably in places with a high density of slow-moving galaxies (*5*). Tidal forces during close encounters can lead to irreversible structural changes (*6*). One of the strongest motivations for finding the most remote possible objects is the expectation that such phenomena should be apparent from comparison of the properties of very distant galaxies (observed in a younger state because of the finite speed of light) with those of nearby galaxies.

Summary. Ever since the proposal of the idea of an expanding universe more than 50 years ago, each generation of investigators has found that some current theory could be (marginally) tested by the properties of the most distant known galaxies. There has consequently been a continuing effort to identify very remote objects, especially to confront theories of the evolution of galaxies (since galaxies are seen as they were at prior epochs) and to confront cosmological theories (which make predictions about the overall dynamics of the expansion of the universe). These theories have yet to be definitively tested, but a new generation of optical telescopes and detectors provides hope for significant progress during this decade.

Distant Galaxies and Cosmological Investigations

Historically, the most important motivation for studying faint galaxies was the task of mapping out the expansion of the universe by using galaxies to mark out the cosmological geometry. The idea is that by observing the detailed relationship between redshift and distance (deduced from the apparent brightness or angular size of a galaxy), it is possible to determine the deceleration of the expansion. Depending on the size of the deceleration, the universe may or may not continue to expand indefinitely, circumstances which correspond to an open, infinite geometry or a closed, finite geometry, respectively. In this fashion there is a straightforward theoretical connection between the large-scale dynamics and the large-scale geometry of the universe. But since galaxies can be expected to evolve in luminosity, the distance coordinate that one infers from the apparent brightness is accordingly uncertain. In practice it is extremely difficult to separate cosmological effects from evolutionary effects.

In any event, galaxies chosen to delineate the large-scale geometry should be luminous so that they can be seen to large distances. It was found early on that the brightest cluster galaxies have small dispersions in both luminosity and spectral characteristics. This latter property implies that these galaxies (called first-ranked galaxies, of either the giant elliptical, D, or the supergiant D class) are likely to evolve in similar ways. One disadvantage is that they have relatively little flux in the ultraviolet, which means that with redshift their optical apparent brightness becomes especially faint. If, say, the fourth-ranked galaxy in a cluster were a spiral with more ultraviolet light (due to a population of young, hot stars), it could appear at high redshift to be the first-ranked member (*7*). Near infrared broadband measurements are potentially very valuable in this regard, since such data are supposedly relatively insensitive to the young stellar population and are not as badly affected by the redshift dimming (*8*). Anyway, great care has to be taken to guarantee that the high-redshift galaxies in a sample are indeed of the same type as the low-redshift comparison galaxies. This is perhaps most efficiently done by "tuning" the bandpass in which the survey for clusters is done to longer wavelengths for higher expected redshifts, so that the same emitted wavelengths are sampled (*9*). Another problem is that of interloping field galaxies seen in projection against a cluster. These difficulties notwithstanding, the use of first-ranked cluster galaxies for testing cosmological models has continued to be very popular (*10*).

Limitations Imposed by Surface Brightness

Even the most distant galaxies usually have angular sizes somewhat larger than the blur circle imposed by the earth's atmosphere and the telescope optics. Extended images by definition have a sensible angular size, which means that the surface brightness for such images is another measurable quantity. The significance of this is that the observed surface brightness depends only on the intrinsic surface brightness and on the redshift, not on the cosmological model. Tolman (*11*) showed that the surface brightness, integrated over all wavelengths, is proportional to $(1 + z)^{-4}$, due to relativistic effects. The aberration of light increases angles by a factor of $(1 + z)$, thus accounting for two factors of $(1 + z)$ for the area of a receding disk. Also, the photon stream (rate of arrival) is diluted by the expansion by one factor of $(1 + z)$, and finally each photon appears with energy lower by $(1 + z)$ by virtue of the redshift.

To illustrate the observational limitations imposed by this strong dependence of surface brightness on redshift, consider that the net surface brightness of our galaxy at the position of the sun, as seen from the outside, would be about the same as the natural surface brightness of the night sky. Only the very brightest part of the nearest giant galaxy, the Andromeda Nebula, can be seen by eye. At redshift $z = 1$ the surface brightness would be lower by a factor of 16—actually more, since for almost all galaxies there is less energy at a wavelength of 250 nanometers than there is at 500 nanometers. This is the most important reason why galaxies have not been seen much beyond $z = 1$. For such galaxies to be detectable, there must have been a compensating increase at early epochs of the intrinsic surface brightness, as might be expected if the initial stellar population were formed rapidly (*12*). This idea has inspired a number of attempts to detect extended objects with very large redshifts (*13*), so far without success.

Remarks on Quasars

Quasar emission line redshifts are conventionally, but not universally, ascribed to the same cause as that of galaxy redshifts, namely the cosmological expansion. This view will be adopted here for the sake of the argument. Quasars can be seen to much greater redshifts because they are typically ~ 100 times more luminous than giant galaxies, and they are effectively point sources and so do not suffer any large decrease in surface brightness. Therefore, if quasars cluster with galaxies, they could be used as pointers to galaxies in their vicinity (*14*). Also, their high intensity compared with galaxies makes quasars practical background sources against which absorption lines in intervening gas clouds (in or outside galaxies) can be observed (*15*), although there is evidence that some of the absorption lines seen in quasar spectra are due to material physically associated with the quasar (*15*). In the former event, quasars can be used to study distant matter arguably associated with galaxies.

It has sometimes been suggested that very distant galaxies seen in an early phase might bear a superficial resemblance to the optical appearance of quasars (*16*); that is, they might be compact, blue, have strong emission lines from highly excited gas, and be sources of x-rays (*17*). The implication is that such "primeval galaxies" might already have been discovered, appearing in catalogs of quasars. The main difficulty with this line of thought is that quasars have spectra that do not look like an ensemble of stellar photospheres. Rather, the continuum spectra observed in the optical are consistent with radiation from a compact nonthermal source. Furthermore, since a large fraction of quasars vary in light with large amplitude on short time scales (*18*), in these cases the light cannot be dominated by starlight and the energy must be produced within a small volume.

Radio and X-ray Pointers to Distant Galaxies

Since about 1960, another popular way to find potential high-redshift galaxies has been the optical identification of powerful radio sources (*19*). Many of these sources are first-ranked cluster galaxies that have ordinary optical properties. Since there is a correlation between optical luminosity and the probability of being a strong radio source, it is not surprising that there is some evidence that radio galaxies are somewhat more luminous (*20*) than radio-quiet counterparts. Another feature of radio galaxies is their higher probability of displaying emission lines (the most important of which are due to O^+ and O^{2+}) in their spectra, which allows a redshift to be determined much more easily than from spectra containing only absorption lines. While there is no doubt that radio identifications do produce samples of distant galaxies, they also tend to uncover peculiar galaxies, especially galaxies whose optical radiation is derived partially from nonthermal processes, as in quasars and N galaxies.

An analogous technique for finding distant objects is identification of extragalactic x-ray sources, which tend to be either quasars and N galaxies or clusters,

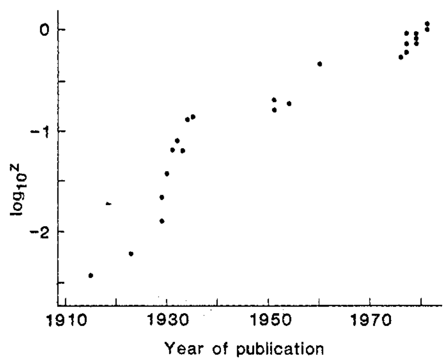

Fig. 1. Published highest spectroscopic redshifts for galaxies, illustrating the relative gains in observational sophistication. See text for sources of points plotted.

much like radio sources. Scaling arguments indicated that the Einstein satellite would be able to detect clusters at $z = 1$ if their x-ray luminosities were similar to those of low-redshift clusters (*21*). Published results (*22*) have rather been detections of nearer clusters already known from other types of surveys, and the discovery rate of new, extremely distant clusters has been disappointing. This may be telling us something about the evolution of cluster x-ray luminosity (*23*), or it may be no more than a reflection of the extent of optical follow-up data.

Redshifts from Colors

Although redshifts are normally determined by measuring the shift in wavelength of individual spectral features, another technique involves measuring the slope of the spectral energy distribution for a galaxy between several fixed bands, as pioneered by Baum (*24*). These ratios of fluxes seen through two or more wave bands are called spectral indices, or color indices, or just colors. The idea is that since giant elliptical galaxies in clusters have integrated energy distributions that look quite similar, a plot of apparent spectral index against redshift should show small scatter (*25*). Empirically, this expected correlation is not only tight but also very steep (for suitably chosen bands), so that a rather accurate redshift ($\Delta z = \pm 0.02$) can be derived from reasonably good data. This technique is useful because obtaining broad- or medium-band fluxes is, in most circumstances, easier than obtaining a spectrum. Baum (*24*) was able to measure redshifts almost twice as large as those achieved with conventional spectroscopy. A modern example is a tentative and approximate redshift of $z = 1.5$ for 3C 65 (*26*), based on optical and near infrared colors. The main uncertainty in this procedure stems from the fact that there is naturally less information in the broadband fluxes than there is in a spectrum. Thus an object with a peculiar spectrum could well have spectral indices that are very misleading for redshift determination: Lebofsky (*27*) has illustrated this point with the strong emission line galaxies 3C 405 and 3C 133. Even so, redshifts derived from optical (*24, 28*) or infrared (*8, 26, 27, 29*) colors are likely to become a very powerful tool, at least in a statistical sense.

Practical Aspects of Faint Spectroscopy

The two principal motivations for studying distant galaxies are thus to test ideas concerning the evolution of galaxies and to use galaxies as tracers of the cosmological expansion. Both effects due to evolution and effects due to cosmology are amplified at higher redshifts, but the difficulty of obtaining high redshifts becomes accentuated because of the strong decrease of surface brightness discussed earlier. An observer is faced with the problem of detecting (and recognizing) spectral features seen together with the spectrum of all other sources that contribute to the light of the night sky in that direction. This "sky radiation" is partly due to zodiacal light (and so has the spectral features of the sun at zero redshift), partly due to airglow, which produces an emission line spectrum that is especially troublesome for wavelengths longer than 680 nm, and partly due to various sorts of scattered light, both within the earth's atmosphere and in interstellar space (*30*). If the sky spectrum is not subtracted from the galaxy spectrum, a redshift of 0.2 is the practical limit with photographic detectors for ordinary galaxies (*31*). Humason's (*32*) efforts in the 1930's often required several nights of successive exposures onto the same spectrogram. A brilliant exception to the limit $z = 0.2$ (established for the Hydra cluster in 1951, shortly after the completion of the Hale 5-meter telescope) was Minkowski's (*33*) redshift of 0.46 for 3C 295, based on a single emission line due to forbidden O^+. The line was identified by default: any other candidate identification for the observed line would have resulted in some contradiction, such as the prediction of another line at a position where none was observed. Also, Minkowski knew the radio flux density and the optical apparent brightness, plus some information about the surrounding cluster, which indicated that such a high redshift was not only plausible but likely.

Photographic plates used as spectro-

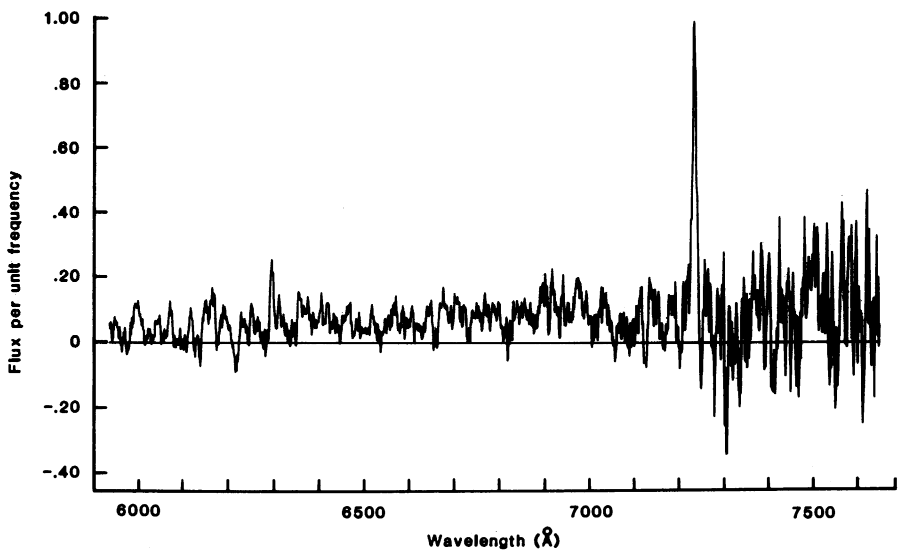

Fig. 2. Part of the spectrum of 1305+2952 G8, showing a strong emission line at an observed wavelength of 723 nm, identified as O^+ with a rest wavelength of 373 nm. This spectrum is the average of 11 separate scans by H. Spinrad with the Lick Observatory Shane 3-m telescope.

scopic detectors have two principal disadvantages with respect to modern electronic devices. In the first place, the quantum efficiency is very low, of the order of 1 percent. In the second place, there is a finite amount of information that can be impressed per unit area. This is a problem because this saturation can occur before sufficient statistics can be obtained at a given position on the photographic plate to allow sky subtraction to be effectively done from a very weak net signal. Electronic detectors, on the other hand, can be read out with sufficient frequency that saturation is not a problem. The detecting element itself is either a photoemissive surface or a solid-state diode array, such as a charge-coupled device (CCD). These devices have the important attributes of very high quantum efficiency (especially for red light), large dynamic range, linear response to light, and good stability. Spectrographs having CCD's as detectors can obtain redshifts in a fraction of the time formerly required (*34*); this is an important desideratum considering the high premium on large telescope time.

The highest redshift reported for any galaxy at a given time is, of course, partly a function of technological innovations, but it is also a function of persistence on the part of observers. Recent examples of the patience required are the redshifts for 3C 427.1 (z = 1.175) and 3C 13 (z = 1.050) reported by Spinrad *et al.* (*35*). Each of these galaxies required 30 to 40 hours of integration (with a photocathode as the detector) on 20 or so separate nights, all spectra being individually sky-subtracted and then added together. The observations were done in spite of the bright night sky above San Jose, California.

To give a rough idea of how the combination of persistence and technology has pushed the highest known redshift for galaxies to higher values, I have plotted in Fig. 1 the few highest known redshifts, derived from spectroscopic techniques, against the year of publication. The points come from (*9, 31, 33, 35–37*), with additional redshifts cited in (*27, 38*). The early points are the work of V. M. Slipher at Lowell Observatory, obtained at a time when the nature of galaxies was not well understood. Subsequently, the large reflectors at Mount Wilson produced results that dominated the field for three decades. The points from 1929 to 1954 are all due to Humason (*36*), who extended the observed depth by a factor that has not been matched since, in spite of the new detectors. The most recent redshifts shown in Fig. 1 are especially uncertain: few have been confirmed by independent groups, and some are keyed to a single feature or are otherwise based on spectra with a low signal-to-noise ratio. Also, the most recent redshifts are likely to be dominated by peculiar objects (for instance, having strong emission lines or higher than normal luminosity), due to selection effects intrinsic to the search techniques discussed earlier.

Anecdotal Examples

Redshifts of order unity can be obtained with current instrumentation and selection procedures (*34, 35*). The claim for a high redshift is still often difficult to establish. A good example of some types of ambiguities and problems that occur is the case of the cluster 1305+2952 (*37*), originally reported to have a redshift of 0.947 on the basis of one absorption feature in the spectrum of the first-ranked galaxy and additional arguments based on the shape of the continuous spectrum. (The cluster was originally selected for study because it appeared to be qualitatively too blue to be at the redshift of ~ 0.5 that might have been guessed from its apparent brightness.) Alternatively, the redshift would be 0.285 if the absorption feature were instead identified with the "400-nm spectrum break" commonly seen in nearby galaxies. One of the arguments against this identification was that from early data the spectrum appeared to turn up in the far red, which would not be explainable on the low-redshift hypothesis but would have a natural explanation on the high-redshift hypothesis. However, CCD

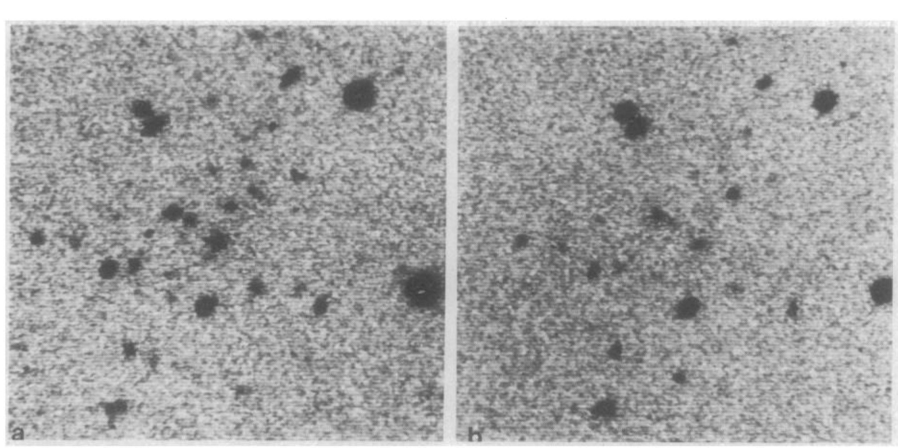

Fig. 3. The very faint, very blue cluster 0014.4+1551, depicting an area about 1.5 arc minutes on a side. (a) The digital sum of three photographic plates taken in ultraviolet (370-nm) light and two plates taken in blue light (obtained with the Kitt Peak Mayall 4-m telescope); (b) the sum of three plates taken in red light and three plates taken in far red (800-nm) light.

spectroscopy by Koo and Kron (*13*) failed to confirm this far-red upturn in any of the cluster members. In the meantime, Spinrad had been obtaining more data on the first-ranked cluster member, and at least one scan appeared to show an emission feature at the O^+ line position corresponding to $z = 0.28$. It thus seemed for a while that the case for the high redshift was weak, at best.

Subsequent events have, however, considerably strengthened the originally proposed high redshift. (i) As reported by Bruzual (*39*), a very red galaxy [cluster 8 (*40*)], presumed to be a true cluster member, shows a strong emission line (Fig. 2), which is most plausibly identified as O^+ at $z = 0.943$ by the same reasoning used by Minkowski to identify the single emission line in the spectrum of 3C 295. (ii) A very blue galaxy (cluster 3), also presumed to be a cluster member, does not show O^+ at $z = 0.285$, according to both Spinrad and Kron, although a galaxy as blue as this would be expected to show the line if the redshift were low. (iii) An infrared spectral index measured by Lebofsky (*27*) for the first-ranked galaxy indicates a color that would be normal for a redshift of 0.94 but would be too red for $z = 0.28$. According to Lebofsky, the apparent infrared flux of the galaxy is 2.6 sigma brighter than other first-ranked cluster galaxies, suitably scaled to a redshift of 0.94; this difference is not especially worrisome considering the large extrapolation. (iv) Another cluster in the same general direction, II Zw 1305.4+2941, has a redshift of 0.24 (measured by Spinrad) and appears to be much bigger, brighter, and redder than the 1305+2952 cluster, consistent with a large redshift difference between the two clusters. There are still some problems with the claim for the high redshift, namely the peculiar optical colors of the brighter galaxies of the cluster, as discussed by Bruzual (*39*); according to him, none of the galaxies has color indices that are expected for anything with redshift near 0.9. Also, the current version of the spectrum of the first-ranked galaxy (cluster 1) is just as plausibly at $z = 0.285$ as at $z = 0.94$; perhaps, ironically, this galaxy is not a member at all.

Another candidate for a very distant cluster is 0014.4+1551 (Fig. 3). This cluster is remarkable for its extreme blueness, quite unknown for low-redshift clusters but expected for very high redshifts (*39*). Unlike 1305+2952, there are no published spectroscopic data. The cluster is known not to be a radio source (*41*) or an x-ray source (*42*).

Conclusions

Recent progress in the identification and study of very distant galaxies has been rapid due to the development of new detectors and new techniques. In spite of this, no answers are yet available for the major motivating questions: what processes control the evolution of observable properties of galaxies, and what do observations of distant galaxies tell us about the large-scale structure of the universe? Regarding evolution, there are a number of examples of galaxies with colors that appear to be inconsistent with their redshifts, meaning that we do not understand the composition of these galaxies (assuming, of course, that the data are trustworthy). Regarding cosmology, different investigations (*10*) yield different values for the deceleration of the expansion, for reasons that are not at all clear. What is needed in both cases are strict selection criteria for the inclusion of any given galaxy in the statistical sample. There have been a number of noteworthy attempts to do this (*10*), but the very highest redshifts known are still those produced by some no-holds-barred technique, with inevitable biases.

It is likely that future efforts in this field will include the following developments. (i) Complete redshift surveys will be stressed, so that all visible galaxies in a patch of sky will be measured. Questions related to evolution and to cosmology would then address the distribution of observed redshifts, at a given apparent brightness. (ii) Spectroscopic techniques will exploit CCD's as detectors on a routine basis, especially for work in the range 600 to 1000 nm. (iii) Photometry in the near infrared will likely play a very important role, in particular with regard to measurements of color. (iv) The Space Telescope will allow spectroscopy of faint objects in the ultraviolet, as well as observations in the far red without interference from airglow. A combination of these and other techniques may reveal galaxies at $z \sim 2$, which may yield important insights into the origin of galaxies.

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