Exploring Distant Galaxy Evolution: Highlights with Keck

David C. Koo

UCO / Lick Observatory, Department of Astronomy and Astrophysics
University of California, Santa Cruz, CA 95064 USA
koo@ucolick.org, http://www.ucolick.org/~deep/

Abstract

The Keck 10-m Telescopes have revolutionized the study of distant galaxy evolution. Major advances have been made by Keck not only by reaching fainter limits or larger samples, but also by yielding qualitatively new information, such as kinematics. This brief review will touch on science highlights from each of the first generation of Keck instruments.

1 Introduction

The intent of this review is to provide non-specialists with an overview of the key science areas in distant galaxy observations with large telescopes, to highlight results from the Keck Telescopes, and to comment on the prospects for further advances in the near future on Keck and other 8–10 m class telescopes. For reference, a typical galaxy (L^*) at a redshift of $z \sim 1$ (roughly between one-half to two-thirds the age of the universe in lookback time) would have a brightness of $I \sim 22.5$.

The formation and evolution of faint galaxies is a major area of extragalactic research today. In part this is due to technological advances such as new telescopes on the ground and in space, large CCDs, multi-object spectrographs, and highly advanced computing capabilities that have enabled enormous progress in these fields. But the high scientific interest in faint galaxies is also due to the realization that the formation and subsequent evolution in the basic properties of galaxies are intimately linked to a number of fundamental unknowns. These include (i) the nature and amounts of dark matter, (ii) the geometry and age of the universe, (iii) the formation of structure and clustering, and (iv) the role of complex physical and environmental effects such as galaxy interactions, mergers, or interactions with the intergalactic medium.

Moreover, the high interest in faint galaxies has been fueled for years by long-term puzzles regarding the origin of the high counts of very blue galaxies at faint magnitudes (see reviews by Koo and Kron 1992, Ellis 1997). Explanations have ranged from cosmologies that yield larger volumes at higher redshifts, such as those with a relatively large cosmological constant (Fukugita et al. 1990, Totani, Yoshii, & Sato 1997), rapid merging of galaxies (Cowie, Songaila, & Hu 1991), and disappearance of new populations of galaxies at moderate redshift (Babul and Ferguson 1996) to rapid changes in the shape of the luminosity function (Broadhurst et al. 1988) or its characteristic luminosity (Lilly 1993). On the other hand, others show that milder amounts of merging or of luminosity evolution may still explain the bulk of the counts, colors, and redshift distributions of distant galaxies to $z \sim 1$ (Gronwall and Koo 1995, Pozzetti, Bruzual, & Zamorani 1996).

The landmark Canada France Redshift Survey (CFRS) by Lilly et al. (1995) is a noteworthy example of the enormous progress already achieved with 4-m class telescopes. The CFRS provides compelling evidence for evolution to median redshifts $z \sim 0.56$ at a depth of $I \sim 22$. The CFRS work (3 of the more recent include: Schade et al. 1999, LeFevre et al. 2000, Lilly et al. 1998) has concentrated on deriving a diverse set of diagnostics of distant galaxy evolution. These diagnostics include the global luminosity function, color, clustering, merger, star formation, spectral properties, disk sizes, and early-type galaxy evolution. Yet, although their results have been major strides of progress, much remains to be done. The physical mechanisms driving evolution and the nature of the high redshift galaxies (especially those at redshifts $z > 1$) largely remain unknown.

Given the importance and complexity of understanding distant galaxies, and given the large number of key problems that remain unsolved, a wide variety of observational approaches can be fruitful when the power of a 10-m telescope can be applied. Among the more popular areas for Keck users have been studies of:

Number Counts: These are classical diagnostics of galaxy evolution, since evolution in the number densities or luminosities of galaxies will change the slope and amplitude of their counts. Even cosmology is probed, since different geometries of the universe result in different volumes or luminosity dimming versus redshift. Keck has contributed to number count studies by pushing to the faintest limits in both optical and near-infrared (near-IR) regimes.

Redshifts and Source Identifications: Redshifts are critical to convert apparent observables, such as brightness, angular size, and apparent colors, to meaningful physical measurements of luminosities, linear size, and rest-frame colors. Such redshifts have been acquired by Keck for a variety of samples to depths almost unbelievable only a decade ago ($I \sim 24$ or fainter, depending on exposure and strengths of emission lines). Of particular importance are the discovery and surveys of "Lyman-break galaxies" at redshifts $z \sim 3$. Keck redshifts have also been the foundation for calibrating multicolor photometry to yield "photometric redshifts" (see workshop on this subject: Weymann et al. 1999), especially in the Hubble Deep Field (HDF).

Line Strengths: By taking advantage of the higher S/N ratios of very faint galaxies now achievable with Keck, some observers have been able to extract moderately reliable estimates of line strengths and ratios. Such data can be used to extract the star formation rates (SFR), state of the gas ionization, chemical abundances (e.g., O/H), and even dust extinction.

Kinematics: Spectra of faint galaxies have generally been taken at low spectral resolution, but with 8–10 m class telescopes, resolutions are high enough to allow meaningful measurements of kinematics via line widths and even rotation curves. Such kinematics are a new dimension for studying distant galaxy evolution by providing a diagnostic of masses, gas flows, dynamical disturbances, and evolution in the M/L ratios of galaxies.

HST Structure: The combination of Keck redshifts and kinematics with structural measurements from HST imaging has been particularly powerful. Programs include diverse studies of the HDF, the study of the Fundamental Plane (linear relationship of size, internal velocities, and luminosity) of early-type galaxies in clusters and the field, and studies of the bulges and disks of distant galaxies.

Unusual Galaxies: Keck spectra have also been taken of a wide range of more unusual distant galaxies, including very old galaxies that constrain the age of the universe, galaxies that host gamma ray bursts, and supernovae at high redshifts that are being used to constrain the geometry of the universe.

2 Keck Instruments

As listed in Table 1, the Keck I and II telescopes have a number of instruments that allow observers to study distant galaxies. Keck also has two mid-IR instruments in operation (Long Wavelength Spectrometer – LWS and Long Wavelength Infrared Camera – LWIRC), but, to the author's knowledge, neither have been used for distant galaxy work.

Although the most obvious gain of the Keck Telescopes has been the larger apertures (6$\times$ over a 4-m), the total gain can be significantly greater as the result of other factors. These include the site conditions (altitude, seeing, transparency, percentage of clear weather, water vapor density, etc.), the reliability and efficiency of the telescope system and its instruments, and especially the throughput and efficiency of the instruments themselves in detector size, areal coverage, and multiplexing capabilities.

3 Highlights from Keck

Distant galaxy observations were prime motivations for the construction of the Keck Telescopes and for the design and choice among many possible instruments. The following are representative scientific highlights related to distant galaxy research from Keck, starting with results from the first instrument available (NIRC) on Keck, followed by the next (HIRES), and ending with the workhorse for distant galaxy research (LRIS). NIRSPEC went into operation a month before the AG meeting and thus there has not yet been any results.

Table 1: Keck Instruments for Studies of High Redshift Galaxies

Instrument (a)	Gen (b)	FOV (c)	λ (d)	R (e)	No. (f)	Comments (g)
NIRC	1	$38''$	1–5	600	1	
HIRES	1	$10''$	0.3–0.7	3	1	7 % pk
LRIS	1	$7'$	0.4–1.0	30	$\sim$30	20 % pk
LRIS-B	2	$7'$	0.3–0.5	60	$\sim$30	
ESI	2	$20''$	0.4–1.1	11	1	20 %
DEIMOS	2	$16'$	0.4–1.0	25	150	25 %
NIRC-2	2	$40''$	1–5	25	1	
NIRSPEC	2	$30''$	1–5	5–60	1	

(a) Keck I or II Instrument
For more details and links on the Keck instruments, see URL:
`http://www2.keck.hawaii.edu:3636/realpublic/inst/index.html`

NIRC: Near InfraRed Camera
HIRES: HIgh Resolution Echelle Spectrograph
LRIS: Low Resolution Imaging Spectrograph
LRIS-B: LRIS-Blue
ESI: Echellete Spectrograph Imager
DEIMOS: Deep Imaging Multi-Object Spectrograph
NIRC-2: NIRC-second
NIRSPEC: NearInfraRed SPECtrograph
(b) First or second generation
(c) Field of view in arcsecs($''$) or arcmin($'$)
(d) Wavelength range in μ
(e) Spectral resolution σ in $\mathrm{km\,s^{-1}}$
(f) Number of targets per exposure
(g) Peak efficiency in %

3.1 NIRC

3.1.1 Near-Infrared Galaxy Counts

Among the first science results from Keck was the acquisition of near-IR images and counts to $K(2.2\mu) \sim 21.5$ (Soifer et al. 1994). Since optical counts and photometric corrections are very sensitive to star formation, such near-IR data are important as superior probes of older stellar populations and tracers of the global geometry of the universe. Due to the small areal coverage of NIRC, additional fields and deeper NIRC images were taken (Djorgovski et al. 1995, Moustakas et al. 1996, Bershady et al. 1998).

3.1.2 Narrow Band Searches for $z \sim 2$ Galaxies

NIRC also can be used in narrow-band (NB) imaging mode, and here the key goals have been to search for strong H_α at redshifts $z \sim 2$. Such searches are important surveys for primeval galaxies and for detecting star formation that may be difficult to detect in the optical due to high dust extinction in the rest-frame far UV. An early survey by Pahre & Djorgovski (1995) searched 4 fields with no detections. A later H_α survey by Teplitz et al. (1998) of twelve fields around QSO's with absorption near $z \sim 2$ was more successful; 11 candidates were found with typical star formation rates of $\sim 50 M_\odot/yr$. On the other hand, a search for O [III] yielded only one candidate in a 3 arcmin^2 field (Teplitz et al. 1999).

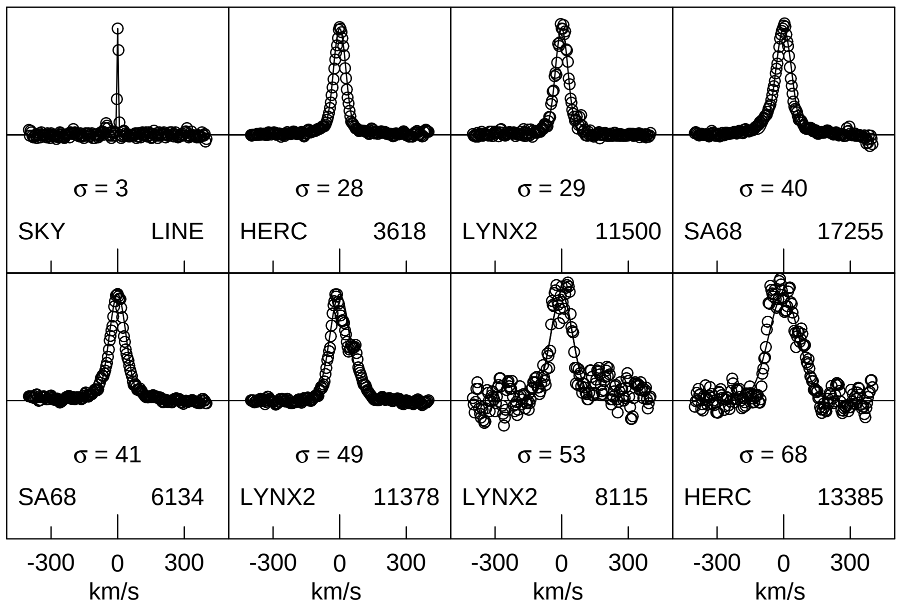

Figure 1: Panel of line profiles from HIRES showing the very narrow lines for a sample of very luminous (L^*) compact galaxies at redshifts $z \sim 0.1 - 0.7$. The σ are the FWHM/2.35 velocity widths in km s^{-1}. The dynamic range of M/L for these compact galaxies spans a factor of 45.

3.2 HIRES: Luminous Compact Galaxies

HIRES has 3 $\times$ lower efficiency than LRIS, so it has rarely been used for distant galaxy programs, except indirectly via absorption lines seen in bright ($\sim$ 16 mag) QSOs. This is an important area, but one which I will not be reviewing here. Moreover, HIRES has spectral resolutions of $\sim$ 8 km s^{-1} and thus greatly oversamples the kinematics of the vast majority of ordinary galaxies with velocities more typically at $\sim$ 500 km s^{-1}. But the velocity widths of the emission lines of some very luminous, blue, compact galaxies are unresolved, even with the moderate resolution of LRIS. Fortunately, the Keck collects enough light that some of these much fainter ($B \sim 22$) galaxies can be reached. As seen in Fig. 1, the HIRES results were impressive – some targets have Milky Way luminosities and yet have very small velocity widths (Koo et al. 1995). After adding measurements from HST that yield sizes of a few kpc or less, the implied masses are only a few $10^9 - 10^{10} M_\odot$ (Guzman et al. 1996). With resultant M/L $\sim$ 0.02 to 0.89, these results directly show that light can be poor tracers of mass in luminous galaxies; justifies the need to acquire kinematics to obtain a more reliable probe of the true nature of any given galaxy; and suggests that some of these galaxies may be the progenitors of local spheroidal galaxies.

Table 2: Very High Redshifts from Keck

Astro-PH Date	Redshift z	Method	Reference
Nov 94	4.25	Radio Galaxy	Spinrad et al. 1995
Apr 97	4.92*	Cluster-Lensed	Franx et al. 1997
Dec 97	4.04	Cluster Arcs	Frye & Broadhurst 1998
Mar 98	5.64	NB, blank sky	Hu et al. 1998
Mar 98	5.34*	B Drop-Out, Serendipity	Dey et al. 1998
Jul 98	5.60*	Red NICMOS-HDF	Weymann et al. 1998
Sep 98	5.33	Red in WFPC2-HDF	Spinrad et al. 1998
Jul 99	5.74*	NB, blank sky	Hu et al. 1999

3.3 LRIS:

3.3.1 Highest Redshifts

Besides the momentary glory of discovering the most distant object, the highest redshift galaxies are important in placing direct limits on the earliest epoch of galaxy formation and in providing vital clues to the primordial element abundances, source of ionization of the intergalactic medium, the origins and hosts of AGN's, and the power spectrum of density fluctations that has resulted in the formation of structure. As recently reviewed by Stern and Spinrad (1999), the search for distant galaxies is a major topic in itself, and has involved a range of techniques. Recently, the most successful have selected galaxies that had unusually red colors or strong emission lines detected in narrow band (NB) filters. The use of gravitational lensing from a foreground cluster has also been effective. Table 2 is a summary of the very high redshifts discovered or confirmed using Keck, with the (*) values indicating those that were the highest redshift at the time.

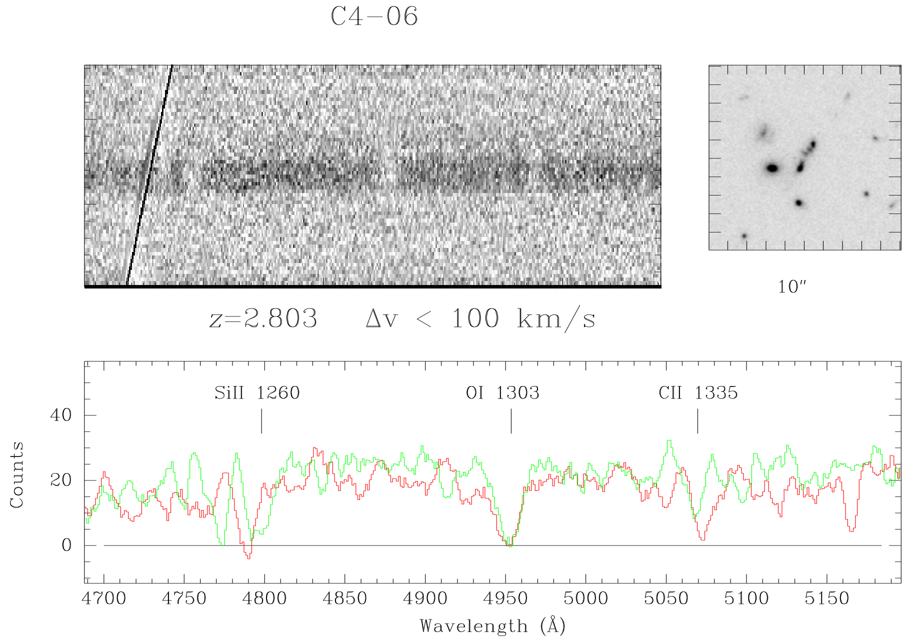

Figure 2: Upper left panel shows the 2-D sky-subtracted spectra for the very extended, or possibly two-component, Lyman-break galaxy shown in the center of the upper right panel. The bottom figure shows part of the spectrum of each component separately. A cross-correlation of the spectra yields no statistically detectable velocity shift. Adoption of an upper limit of 100 km s^{-1} for the differential velocity, no inclination corrections, and the apparent angular separation as a measure of the actual size of the system yields an upper limit to the mass of $10^{10} M_{\odot}$. This source, C4-06, was originally discovered in the HDF with Keck by Steidel et al. (1996b) and reobserved by us with longer exposures of several hours and at higher spectral resolution, so as to be able to derive the kinematics (Lowenthal et al. 1998). This figure was kindly provided by J. Lowenthal.

3.3.2 Lyman-Break Galaxies at Redshifts $z \sim 3$

One of the most important contributions from Keck is the sample of galaxies at $z \sim 3$ being studied by Steidel and his collaborators (an example is shown in Fig. 2). Candidates are selected as galaxies blue in their B and R bands, but showing a drop in the UV that suggests a high enough redshift ($z > 2.2$) that the lack of flux below the Lyman break at restframe 912Å in the spectra of galaxies has entered the U band. Although these galaxies do not break the redshift records, the large sample has been invaluable in probing the nature of $z \sim 3$ galaxies, their impact on the global star formation history of the universe, and their large scale structure and thus the bias of the clustering of luminous baryons to that of the dark matter.

To date, the sample has reached about 700 galaxies (Steidel & Adelberger 1999), but even the first small samples (including a sample of 10 that were observed using B as well as U band breaks, going somewhat fainter, and having higher spectral resolution by Lowenthal et al. 1997) were important in showing that these galaxies can be reached to $I \sim 26$ with only modest effort on a 10-m telescope (Steidel et al. 1996a, b). Moreover, although the exact decline or rise of star formation rate densities at high redshifts remain uncertain (Madau et al. 1998), largely because of uncertain corrections for dust extinction, these samples have played a pivotal role in this active area of observational cosmology.

Equally important, this large sample has revealed the presence of strong clustering at high redshifts, a result that supports a high bias and presumably due to the clustering of massive halos (Adelberger et al. 1998, Giavalisco et al. 1998, Steidel et al. 1998). This evidence strengthens the arguments that the Lyman-break galaxies are indeed the progenitors of massive spheroids and ellipticals as advocated by Steidel et al. (1996a, b). The kinematic data, however, currently favor an alternative view that some may instead be lower mass galaxies or sub-components (Pettini et al. 1998, Lowenthal et al. 1997, 1998).

3.3.3 Field Galaxy Evolution up to Redshifts $z \sim 1$

Although Keck has been exploring the $z \sim 3$ universe with relative ease, the universe at lower redshifts closer to $z \sim 1$ has not been neglected. At least three groups have undertaken intensive redshift surveys roughly comparable in sample size to the pioneering CFRS, but the Keck surveys have chosen to reach fainter limits or to use different filters in the selection of targets. The science has generally been in the same areas: luminosity functions (LF), star formation rates (SFR), structure and morphology via HST images, etc.

HDS: The Hawaii Deep Survey uses a multiband selection ($K < 20$, $I < 23$, $B < 24.5$) and has so far gathered 350 galaxies with an average of 85 % completeness to $B \sim 24.5$ (Cowie, Songaila, & Barger 1999). Some key conclusions from the HDS are that significant luminosity evolution of field galaxies to $z \sim 1$ is ruled out (Cowie et al. 1996); that the UV luminosity density has evolved less rapidly than formerly claimed by CFRS (Cowie et al. 1999); that galaxies with brighter K luminosities (and presumably higher mass) were actively forming stars at higher redshifts (Cowie et al. 1996); and that there exists a deficit of very red early type galaxies at redshifts $z > 1$ (Barger et al. 1999).

CFGRS: The Caltech Faint Galaxy Redshift Survey includes several programs. In one, the K band photometry is used for target selection and they have 140 galaxy redshifts with 80 % completeness to $K = 20$ with a median $z_m \sim 0.58$ (Cohen et al. 1999a). A major CFGRS contribution has been their spectroscopic survey to $R \sim 24$ of the HDF North region (Cohen et al. 1999b). Their main results include finding significant clustering at high redshifts as seen in the strong amplitude spikes in the redshift histograms; full consistency of their data with passive luminosity evolution; with no evidence for density evolution that would be expected if mergers play an important role at the depths of their survey.

DEEP: The Deep Extragalactic Evolutionary Probe program has also been collecting several different samples, including a major one to $R < 25$, and another to $I < 24$ and $B < 26$. Thus far, the first survey has yielded about 500 galaxies with 90 % completeness to $I \sim 23.5$ and a median redshift $z_m \sim 0.8$. This high median is inconsistent with the predictions of rapid merger models, but it can be reconciled with Cold Dark Matter (CDM) galaxy models if the cosmology is changed from Einstein-deSitter to an open one or one with a significant cosmological constant (Baugh, Cole, & Frenk 1996). Combined with HST images, the DEEP survey finds that most galaxies with Irr morphology are quite luminous and thus faint counts are not dominated by very dim nearby dwarfs (Koo et al. 1996). The lack of strong evolution as found by HDS and CFGRS is also supported in the DEEP surveys by evidence for mainly very red E/S0 and bulges up to $z \sim 1$ and no evidence for a dramatic drop of their number densities (Im et al. 2000).

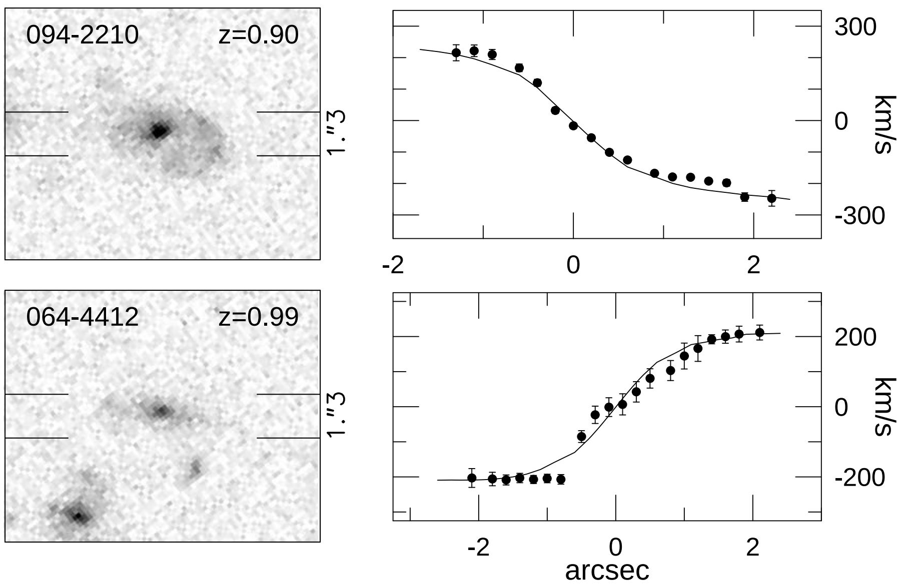

Figure 3: Examples of the rotation curves measured for two high redshift galaxies using two hour exposures with LRIS, the upper with total $I \sim 21.4$ and the lower with $I \sim 22.4$ (Vogt et al. 1997).

3.3.4 Kinematic Surveys

Besides redshifts, several gratings available on LRIS provide high enough spectral resolution to yield useful kinematics for galaxies, either through measurements of the velocity widths of emission or absorption lines or through

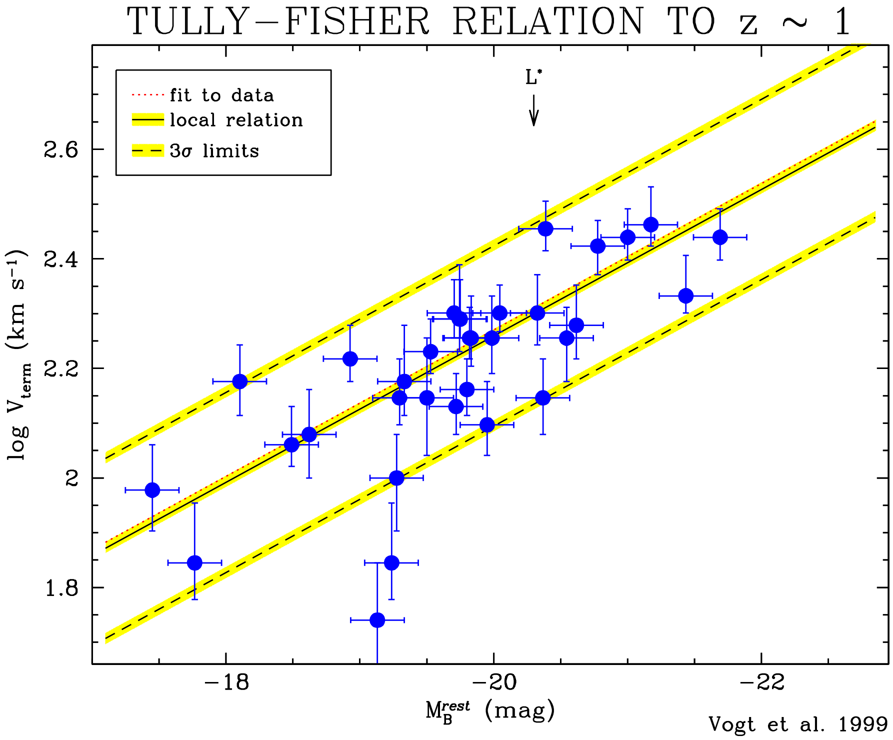

Figure 4: The Tully-Fisher relation from DEEP for faint, distant spiral galaxies up to redshifts $z \sim 1$ (Vogt et al. 2000). Note the consistency with the local TF relation. This figure and pre-publication data were kindly provided by N. Vogt.

extraction of rotation curves of objects large enough to provide spatial resolution as well. Such kinematics, when combined with size information (e. g., from HST), then provide dynamical masses (i. e., total masses including that from dark matter) for distant galaxies. Mass is a powerful new dimension to study distant galaxy evolution, since it is not necessarily tied to light and star formation. Mass is also more directly related to the outputs of theoretical simulations, since gas, dust, and star formation are all presently too poorly understood to model accurately.

An early Keck result using emission line widths was that the M/L evolution of spirals is not substantial up to $z \sim 0.5$ (Forbes et al. 1996). This finding was later confirmed with larger and more distant samples and with measurements of rotation curves. Indeed, deviations from the local Tully-Fisher relation of velocity vs. luminosity is found to be small (< 0.4 mag) even for spirals found at $z \sim 1$ (Vogt et al. 1996,1997). While spirals appear to be evolving quite slowly, another class of compact galaxies (similar to those observed with HIRES described above) exhibit much more evolution. Although luminous, many compact galaxies have very narrow velocity widths and small sizes that suggest their masses to be closer to that of dwarfs of a few $10^{10} M_\odot$ (Phillips et al. 1997). Moreover, these compacts are a major contibutor to the SFR density at high redshifts and have SFR/mass ratios shifting to larger masses at higher redshifts (Guzman et al. 1997).

Though more difficult, absorption velocity widths (σ) can also be measured. The bulk of this work has been among the early-type galaxies seen in rich clusters of galaxies as distant as $z \sim 0.83$ (Kelson et al. 1997, van Dokkum et al. 1998) though some field galaxies at similar redshifts have also recently been studied (Gebhardt et al. 2000). Both samples show a shift of the Fundamental Plane (luminosity, size, velocity width) of E/S0 by an amount corresponding to about 1 mag or more of luminosity evolution.

3.3.5 Miscellaneous Discoveries

Although QSO absorption lines themselves are not reviewed here, one important related discovery from LRIS is the identification of a redshift $z = 3.15$ damped Lyα system (Djorgovski et al. 1996), the first unambiguous identification and one where the young disk hypothesis is supported. Another important LRIS discovery is that the redshifts of gamma ray bursts are cosmological, with the highest ones $z = 1.6, 3.42$ (Kulkarni et al. 1998, 1999). Even a single very ordinary galaxy may have profound implications. For example, one weak radio galaxy at redshift $z \sim 1.55$ (53W091) has such red colors that the implied age is greater than 3.5 Gyr (Spinrad et al. 1997). This is so old at $z \sim 1.55$ that an open cosmology is preferred over an Einstein-deSitter. We close with an example that some might not include within the realm of distant galaxy work – distant supernovae and the discovery that the data are best fit by an accelerating universe (Perlmutter et al. 1999). These supernovae events are found from ground-based imaging programs using smaller telescopes, but Keck is essential to secure the redshift and refine the supernovae type.

4 Summary and Future

Advances on distant galaxy studies with Keck have been revolutionary and diverse. They range from continued redshift record breakers; more galaxies at $z \sim 3$ than the CFRS; the opening of new doors such as kinematics and masses of distant galaxies; to key observations of gamma ray bursts, supernovae, very red galaxies, and damped Lyα systems.

4.1 2nd Generation Keck Instruments by Y 2000

These advances have exploited only the first generation of Keck instruments. By end of Y2K, Keck is expecting to add five more powerful supplements:

DEIMOS: Due for commissioning by late 2000, DEIMOS will provide a $7\times$ gain over LRIS. Thus surveys of large scale structure at $z \sim 1$, requiring many 1000's of faint galaxies, will be pursued.

NIRSPEC: It is now operational and provides spectroscopic access to the near-IR, where H_α can be detected in the redshift region of $z \sim$1.2–2, which is likely to be one of the next frontiers of distant galaxy work. Very few redshifts of ordinary galaxies are known in this "desert", because of the lack of prominent spectral features visible in the observed optical.

LRIS-B: Due for operation by late 2000, LRIS-B enables access to UV imaging and spectra, and thus probes the restframe mid-UV of $z \sim 1$ galaxies. LRIS-B will also extend the Lyman-break spectral work done now with LRIS at $z \sim 3$ to lower redshifts in the frontier below $z \sim 2$.

ESI: It is now operational and provides about a 3× gain in QE over HIRES. Kinematics can be pushed for lower luminosity dwarfs to $z \sim 1$.

Adaptive Optics: With this capability, the near-IR structures, morphologies, and rotation curves can be measured (see Fig. 5 for an example of the gains over non-AO systems).

4.2 Prospects for Other 8–10-m Telescopes

Although Keck has had a headstart of 5 years or more over most other 8–10-m class telescopes, the potential science in the area of distant galaxies is so large that non-Keck astronomers should not be concerned that most or even many of the major advances have already been made. As one example of the need for much larger samples, note that after subdividing galaxy samples by luminosity, size, mass, star formation rate, morphology, etc., enormous samples of several 10,000's of galaxies will be needed to explore such fundamental relationships as their clustering properties. As another gauge of the need for very large samples, note that the baseline or local comparison sample will be the Sloan Digital Sky Survey, which is aiming for nearly one million galaxies. Finally, a suite of 8–10-m telescopes will be essential to provide followup observations of the flood of data from the next generation of major instruments in space or at other wavebands, including Chandra, SIRTF, NGST, LMT, FIRST, etc. The key to the success of any 8–10-m is not having just the aperture gain, but instead having the most advanced instruments. Unfortunately, they can be very expensive, with some costing up to US $ 8–10 M or roughly 10 % of the cost of an entire Keck telescope. By aperture alone, the expected gain of a 10-m over a 4-m should be roughly 1 mag and yet the gains have in some cases been 2 or 3 magnitudes. Thus the key to continued advances will in large part be controlled by future instruments, upgrades, and capabilities. Aspects of high value include having the largest and best detectors, large field of views, high resolutions in space or wavelength, and ability to increase the multiplex advantage by using slitlets, fibers, integral field units, etc. But the most important factor of all in making more advances in our study of distant galaxies will be having a sufficient pool of excellent scientists working in the area, especially bright, young astronomers. I hope this review has inspired some to join us in this grand adventure of the 21st century.

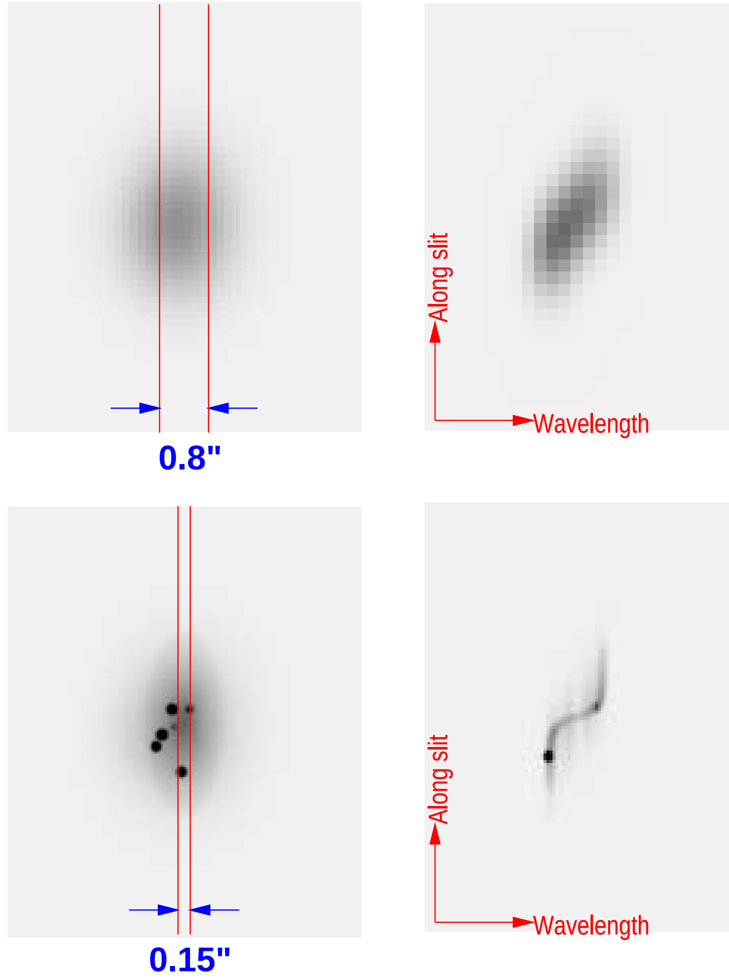

Figure 5: Simulations of an emission line rotation curve with and without using adaptive optics on the Keck 10-m Telescope. The target has an exponential disk with a scale length of $0.2''$, inclination of 45°, and a maximum velocity in the rotation curve of 40 km s^{-1}. The upper left panel shows the assumed placement of a $0.8''$ slit over the image under seeing of $0.6''$. The upper right panel shows the expected emission line using the DEIMOS instrument with $0.12''$ pixels in the vertical direction and 0.32 Å pixels in wavelength. The lower two panels, using about $4\times$ longer exposures, show the vast improvement in both imaging and spectroscopy when the adaptive optics system is assumed to have a Strehl of 0.33 with a $0.05''$ core and a much narrower slit of $0.15''$ is used with a hypothetical spectrograph having $0.03''$ pixels in the vertical direction and a spectral resolution of 0.08 Å per pixel. This simulation was produced and generously provided by A. C. Phillips, as part of efforts associated with the newly formed US National Science Foundation Science and Technology Center for Adaptive Optics (URL: `http://www.ucolick.org/~cfao`).

Acknowledgements

I wish to thank the organizers for their kind invitation to speak at the AG, giving me an opportunity to share the exciting results from the Keck community. I also want to thank J. Lowenthal, A. Phillips, and N. Vogt for their help in providing the figures. The DEEP program has been supported by NSF Grants AST 91-20005 and AST95-29098 and NASA grant AR-07532.01-96A.

References

Adelberger, K. L. et al., 1998, ApJ 505, 18

Babul, A. & Ferguson, H. C., 1996, ApJ 458, 100

Barger, A. J. et al., 1999, AJ 117, 102

Baugh, C. M., Cole, S., & Frenk, C. S., 1996, MNRAS 282, 27

Bershady, M. A., Lowenthal, J. D., & Koo, D. C., 1998, ApJ 505, 50

Broadhurst, T. J., Ellis, R. S., & Shanks, T., 1988, MNRAS 235, 827

Cohen, J. G. et al., 1999a, ApJS 120, 171

Cohen, J. G. et al., 1999b, Astro-ph/9912048

Cowie, L. L., Songaila, A., & Hu, E. M., 1991, Nature 354, 460

Cowie, L. L. et al., 1996, AJ 112, 839

Cowie, L. L., Singaila, A., & Barger, A. J., 1999, AJ 118, 603

Dey, A. et al., 1998, ApJ 498, L93

Djorgovski, S. G. et al., 1995, ApJ 438, L13

Djorgovski, S. G. et al., 1996, Nature 382, 234

Ellis, R. S., 1997, ARAA 35, 389

Forbes, D. et al., 1996, ApJ 462, 89

Franx, M. et al., 1997, ApJ 486, L75

Frye, B. & Broadhurst, T. J., 1998, ApJ 499, L115

Fukugita, M. et al., 1990, ApJ 361, L1

Gebhardt, K. et al., 2000, ApJ in preparation

Giavalisco, M. et al., 1998, ApJ 503, 543

Gronwall, C. & Koo, D. C., 1995, ApJ 440, L1

Guzman, R. et al., 1996, ApJ 460, L5

Guzman, R. et al., 1997, ApJ 489, 559

Hu, E. M., Cowie, L. L., & McMahon, R. G., 1998, ApJ 502, L99

Hu, E. M., McMahon, R. G., & Cowie, L. L., 1999, ApJ 522, L9

Im, M. et al., 2000, ApJ in preparation

Kelson, D. D. et al., 1997, ApJ 478, L13

Koo, D. C. & Kron, R. G., 1992, ARAA 30, 613

Koo, D. C. et al., 1995, ApJ 440, L49

Koo, D. C. et al., 1996, ApJ 469, 535

Kulkarni, S. R. et al., 1998, Nature 393, 35

Kulkarni, S. R. et al., 1999, Nature 398, 389

LeFevre, O. et al., 2000, MNRAS 311, 565

Lilly, S. J., 1993, ApJ 411, 501

Lilly, S. J. et al., 1995, ApJ 455, 50

Lilly, S. J. et al., 1998, ApJ 500, 75

Lowenthal, J. D. et al., 1997, ApJ 481, 673

Lowenthal, J. D., Simard, L., & Koo, D. C., 1998, ASP Conf. Ser. 146, 110

Madau, P., Pozzetti, L., & Dickinson, M., 1998, ApJ 498, 106

Moustakas, L. A. et al., 1997, ApJ 475, 445

Pahre, M. A. Djorgovski, S. G., 1995, ApJ 449, L1

Perlmutter, S. et al., 1999, ApJ 517, 565

Pettini, M. et al., 1998, ApJ 508, 539

Phillips, A. C. et al., 1997, ApJ 489, 543

Pozzetti, L., Bruzual A. G., & Zamorani, Z., 1996, MNRAS 281, 953

Schade, D. et al., 1999, ApJ 525, 31

Soifer, B. T. et al., 1994, ApJ 420, L1

Spinrad, H., Dey, A., & Graham, J. R., 1995, ApJ 438, L51

Spinrad, H. et al., 1997, ApJ 484, 581

Spinrad, H. et al., 1998, AJ 116, 2617

Steidel, C. C. et al., 1996a, ApJ 462, L17

Steidel, C. C. et al., 1996b, AJ 112,352

Steidel, C. C. et al., 1998, ApJ 492, 428

Steidel, C. C. & Adelberger, K. L., 1999, ASP Conf. Ser. 191, 119

Stern, D. & Spinrad, H., 1999, PASP 111, 1475

Teplitz, H. I., Malkan, M. A., & McLean, I. S., 1998, ApJ 506, 519

Teplitz, H. I., Malkan, M. A., & McLean, I. S., 1999, ApJ 513, 33

Totani, T., Yoshii, Y., & Sato, K., 1997, ApJ 483, L75

van Dokkum, P. G. et al., 1998, ApJ 504, L17

Vogt, N. P. et al., 1996, ApJ 465, L15

Vogt, N. P. et al., 1997, ApJ 479, L121

Vogt, N. P. et al., 2000, ApJ in preparation

Weymann, R. J. et al., 1998, ApJ 505, L95

Weymann, R. J. et al., 1999, ASP Conf. Ser. 191