# Keck Spectroscopy of Redshift $z \sim 1$ Field Galaxies

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**Abstract.** The first of the two 10m Keck Telescopes has been operational for over two years and is providing realistic previews of how well field galaxies at very high redshifts $z \sim 1$ or greater can be directly studied. Although detection and recognition of such galaxies are not difficult, gathering the wealth of information needed to decipher the physical mechanisms and their role in evolution will remain a challenge for future observers. To illustrate the value of adding such information as well as the potential of the VLT, we present highlights from three pilot projects from the DEEP program: redshifts of faint field galaxies; line widths and masses of some field galaxies with strong emission lines; and rotation curves of several high redshift spirals. The scientific results from all three surveys have relied on combining spectroscopy from Keck with high spatial resolution imaging from the Hubble Space Telescope.

## 1 Introduction

As the title of this workshop emphasizes, one of the major motivations for constructing large optical telescopes is to understand the early universe, especially in the context of the formation and evolution of galaxies. The emphasis of this review will be to use actual observations of field galaxies from the Keck I telescope to illustrate empirically the capabilities of VLT.

### 1.1 Overview of Keck Instruments for Studies of High Redshift Galaxies

As listed in Table 1, the Keck I and II (due for operation in fall 1996) telescopes have a number of instruments that allow observers to tackle high redshift field galaxies. Keck also has two mid-IR instruments (Long Wavelength Spectrometer and Long Wavelength Infrared Camera) that might also be used, but their potential for studying galaxies at high redshift has yet to be tested.

Among the first generation instruments, the workhorse for gathering the redshifts of the faintest galaxies is LRIS (Oke et al. 1995). This instrument has already yielded results that range from very faint number counts based on deep images (e.g., Smail et al 1995); redshifts of clusters of galaxies beyond $z \sim 1$ (see Dickinson in these proceedings); various redshift surveys of distant field galaxies by, e.g., Cowie et al. 1996, Cohen et al. 1996, and Koo et al. 1996; to the spectacular set of redshifts $z \sim 3$ of very faint galaxies selected by their UV-faint colors (Steidel et al. 1996; also see Giavalisco in these proceedings). This

**Table 1.** Keck Instruments for Studies of High Redshift Galaxies

| Instrument (a) | | Gen (b) | FOV (c) | $\lambda$ (d) | R (e) | No. (f) | Eff. (g) |
|---|---|---|---|---|---|---|---|
| NIRC | Near InfraRed Camera | 1 | 38″ | 1-5 | 600 | 1 | |
| HIRES | HIgh Resolution Echelle Spectrograph | 1 | 10″ | 0.3-0.7 | 3 | 1 | 7% |
| LRIS | Low Resolution Imaging Spectrograph | 1 | 7′ | 0.4-1.0 | 30 | 30 | 20% |
| LRIS-B | LRIS-Blue | 2 | 7′ | 0.3-0.5 | 60 | 30 | |
| ESI | Echellete Spectrograph Imager | 2 | 20″ | 0.4-1.1 | 11 | 1 | 20% |
| DEIMOS | Deep Imaging Multi-Object Spectrograph | 2 | 16′ | 0.4-1.0 | 25 | 150 | 25% |
| NIRC-2 | NIRC-two | 2 | 40″ | 1-5 | 25 | 1 | |
| NIRSPEC | NearInfraRed SPECtrograph | 2 | 30″ | 1-5 | 5-60 | 1 | |

a Keck I or II Instrument
b First or second generation
c Field of view in arcsecs(″) or arcmin(′)
d Wavelength range in $\mu$
e Spectral resolution in km-s$^{-1}$
f Number of targets per exposure
g Peak efficiency in %

work by Steidel et al. (1996) is a major breakthrough for high redshift observers, because the Keck demonstrates that such high redshifts can be recognized via *absorption lines* at rest-frame UV but redshifted to the optical, bypassing the need for strong Lyman $\alpha$ or other emission lines to secure the redshift. Prior to these observations, the next generation of near-infrared spectrographs (such as NIRSPEC on Keck – see Table 1; or ISAAC on VLT as described by Moorwood in these proceedings) appeared to be the most promising instruments with which to detect the usual set of strong optical emission lines in faint galaxies (e.g., OII(3727) or $H_\alpha$) after they redshift to the near-infrared.

The other two first-generation Keck instruments have also been used for high redshift galaxy observations, but somewhat more indirectly. For example, extragalactic HIRES targets are almost exclusively bright QSO's, which do yield information about distant galaxies, but via their gas that produce absorption lines. As shown later, however, Keck gathers enough photons to allow direct and powerful observations of the gas kinematics of very low mass galaxies. NIRC, on the other hand, with its access to the near-IR, has been extensively used to study various classes of high redshift galaxies. In imaging mode, for example, Soifer et al. (1994) used broadband filters to study a QSO at redshift $z \sim 4.9$ and deep K band counts, while Pahre and Djorgovski (1995) used the narrow-band mode

to search for primeval galaxies.

The second-generation Keck instruments will be even more powerful for the study of high redshift galaxies. The benefits of accessing the near-IR for spectroscopy (NIRSPEC) and of having higher spatial resolution imaging (NIRC-2) are clear. LRIS-B, with its access to the UV, will allow the commonly strong emission lines of either OII[3727] or Ly$\alpha$ to be observable over the full redshift range of redshifts $z \lesssim 7$, with no gaps. ESI, with its high throughput, will enable high spectral resolution work to be routine for very faint galaxies, but only through one slit. DEIMOS, in contrast, will allow $\sim 150$ slitlets, and thus provide a practical means to undertake massive surveys of 1000's of distant galaxies, but with only moderate spectral resolution (see discussion below).

### 1.2 Detection, Recognition, and Understanding of High Redshift Galaxies

What types of high redshift galaxy work is feasible with large telescopes? Detection of $z \sim 1$ galaxies is easy! A typical (L*) galaxy is visible on CCD images ($I \sim 22.6$) or infrared images ($K \sim 20$) taken with 4-m class telescopes. Recognizing that a particular object is indeed at high redshift takes more work, but is also not difficult. For example, astronomers have been working on samples of high redshift galaxies for several years via clusterings of objects found around distant radio galaxies (see Dickinson in these proceedings) or QSOs or via the study of the host galaxies around high-redshift QSOs (Heckman et al 1991). Another technique that is relatively efficient is to use multicolors to estimate redshifts (e.g., Connolly et al 1995); the UV drop method that has been adopted by Steidel et al (1996) or Guhathakurta et al (1990) are examples of using multicolor photometry to search for candidates at $z \sim 3$. Spectroscopic redshifts of any *candidates* remain, of course, the most trusted confirmation. Finally, note that many galaxies with $z \sim 1$ have already been acquired with 4-m class telescopes (e.g., Lilly et al 1995, or see contribution by F. Hammer in these proceedings). These examples show that detection or recognition of $z \sim 1$ field galaxies is not the exclusive domain of 8-10m telescopes.

The true challenge for astronomers is to gather the wealth of data needed to unravel the nature of high redshift galaxies. Knowing just the redshift, and presumably luminosity and perhaps colors from the photometry, is not enough. For interpreting the variety of physical processes likely to be affecting the wide diversity of galaxies that exist in a wide range of enviroments, astronomers also benefit from morphologies and spatial structure (from HST, lensing events, excellent ground-based seeing, or adaptive optics); the kinematics (velocity widths of spectral lines or rotation curves) and mass (when galaxy sizes and disk inclinations are also available); the age and metallicity of the underlying populations (from spectral indices measured from high S/N spectra); and the ionization, dust content, temperature, density, etc. of the gas (requiring observations in the IR, radio HI and CO, X-ray, sub-mm, etc.). Moreover, given the probable need to divide samples into related subclasses (e.g., by luminosity, mass, size, environment, redshift, etc.), large samples are generally needed for comprehensive

surveys. Despite Keck's early entry into the large telescope area, there will remain an enormous need for new VLT observations of high redshift galaxies to unravel what is really happening.

## 2 Examples of Keck Surveys that Combine HST with Keck

DEEP is a multi-institution collaboration now underway to exploit the Keck 10-m Telescope for a spectroscopic survey of faint field galaxies (Mould 1993, Koo 1995). The scientific goals are broad and include explorations of evolution in the spectral, dynamical, and spatial distribution of distant galaxies. These results will be used to probe dark matter on the scale of galaxies and clusters of galaxies in the past and to provide new estimates of the geometry of the universe via tests of correlations among galaxy properties (e.g, fundamental plane) as well as classical tests such as the volume density versus redshift. The ultimate goal is to acquire spectra for 10,000 galaxies or more to B $\sim$ 25. Such spectra will be used not only to measure redshifts for the full sample but also to measure kinematics (via rotation curves or velocity dispersions) as well as age and chemical abundances for a brighter subset of galaxies. A new imaging spectrograph for Keck called DEIMOS (see Table 1) is being constructed to complete such a massive survey. By exploiting the higher reflectivity of the silver-coated Keck II mirrors, 8Kx8K CCD mosaics in *each* of the two cameras, and a substantial field of view of 16'x5' for each of two multi-slit masks, DEIMOS will achieve a throughput gain of over 10x that of the current Keck I and LRIS system, at similar spectral resolution. Until DEIMOS is operational, the interim DEEP science programs will be limited in scope and will rely on LRIS and HIRES that are currently operational. The following three examples highlight some pilot DEEP programs that show the potential of combining HST with VLT to study distant galaxies.

### 2.1 Redshift Survey of $z \sim 1$ Field Galaxies

A strong rationale for large telescopes is to push redshifts to fainter limits. This was the goal of our first DEEP pilot program in which we combined these redshifts from the Keck Telescope with photometry, colors, and morphologies from refurbished HST images (Koo et al. 1996). Though this early Keck redshift sample has only 33 galaxies (due to the loss of 80% of the run to weather), the magnitudes are so faint (22 galaxies with $22 \lesssim I \lesssim 24$) and the redshifts so high (median $z \sim 0.8$), that this survey provides a unique probe of the nature of faint, distant field galaxies of *typical luminosities ($L^*$)* at an epoch beyond half the Hubble age.

Some examples of the spectra are shown in Fig. 1. Figure 2 summarizes our results in a V-I color versus redshift diagram for the Keck sample, including 18 galaxies from Forbes et al. (1996). The curves provide guides to the intrinsic colors of the galaxies. Figure 2 shows how well the galaxies fall within the bounds seen in the colors of normal, local galaxies. We find neither unusually blue nor

unusually red galaxies. Of perhaps more interest, we have detected the presence of several bulges in spiral-like galaxies which appear much redder, and thus presumably older, than their surrounding disks. Similarly, we have confirmed that at high redshifts $z \geq 0.7$, some *field* galaxies do exist with intrinsic colors comparable to that found for local ellipticals. Furthermore, although HST images show strong and frequent hints of mergers, interactions, other peculiar patterns, and infall of minor galaxies into larger hosts, galaxies with normal morphologies are also visible. The morphologies of $z \sim 1$ galaxies are thus not confined to late-type, peculiar systems and, conversely, the late-type galaxies seen in deep HST images are not predominantly at low redshifts (i.e., of low-luminosity).

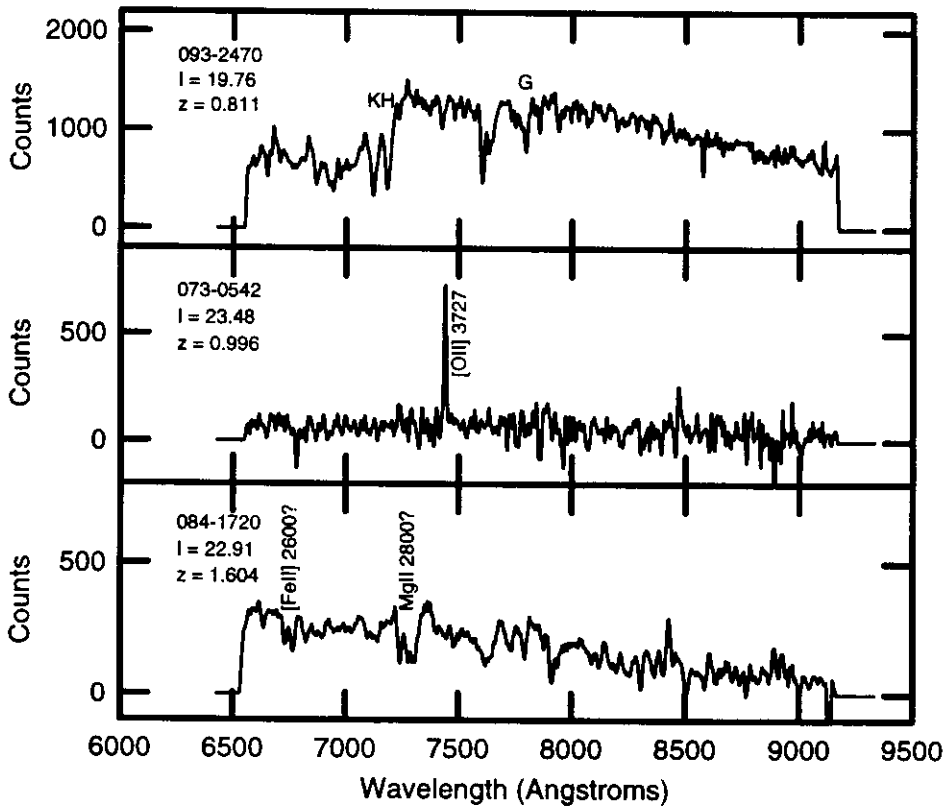


**Fig. 1.** Counts vs. wavelength for a sample of Keck spectra, each labeled with the source name, total $I$ mag, and redshift. The redshift is uncertain for the bottom object.

This glimpse of very faint $z \sim 1$ field galaxies strongly suggests that we need to invoke an unknown, possibly complex, mixture of physical processes to account for the faint blue field galaxies, rather than to rely on a single dominant mechanism, such as mergers or bursting dwarfs.

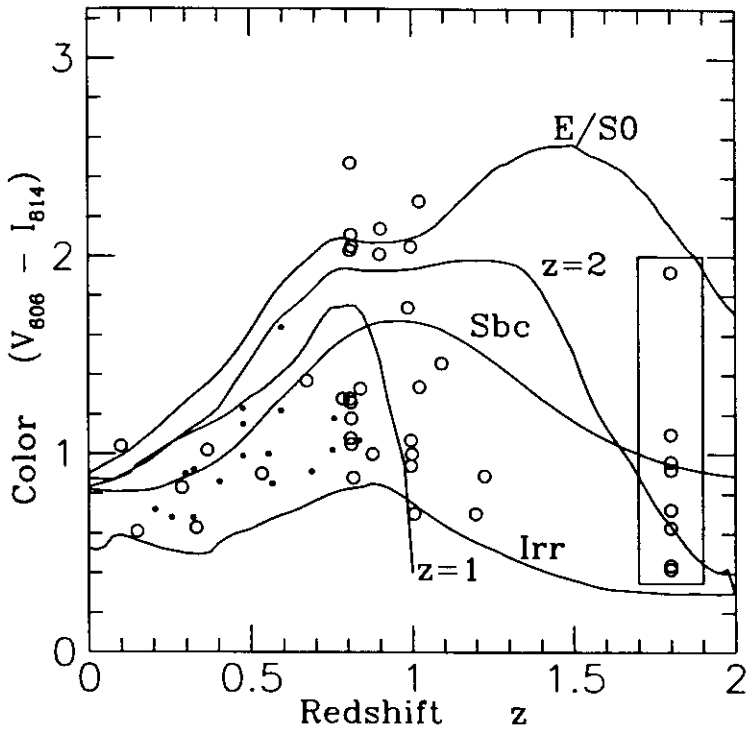


**Fig. 2.** $V - I$ color vs redshift plot of Keck targets from Koo et al. (1996 – open circles) and Forbes et al. (1996 – points). Objects without redshifts are placed in the separate box to the right. Several labeled lines show the expected colors for various spectral energy distributions, including one resulting from an instantaneous burst of star formation at redshift $z = 2$ that becomes almost as red as a non-evolving local elliptical or S0 (E/S0) by $z < 1$; another resulting from a model burst at $z = 1$ that might be compared to the bursting dwarfs in the model of Babul and Ferguson (1996); another to the colors of a local Sbc galaxy; and the bluest one for N4449, a very actively star-forming Irr galaxy.

### 2.2 Low Mass Progenitors of Dwarf Spheroidals

One of our more pleasant surprises in the early phase of Keck I operations was the serendipitous discovery that HIRES is able to yield important new information about faint field galaxies. Due to the failure of LRIS a few days before our run, HIRES was instead used to study a sample of $B \sim 22$ galaxies. Based on prior KPNO 4m spectra of the HIRES targets, these galaxies had measured redshifts z from 0.1 to 0.7, and thus inferred luminosities close to typical ($L^*$) galaxies. These galaxies were considered good HIRES targets because they were also known to possess unusually strong emission lines and very small sizes. The resulting line profiles were found to be well fit by Gaussians, with velocity widths ranging from 28-157 km-s$^{-1}$ (see Fig. 3 for some examples). Though such narrow

widths were easily resolved given the HIRES resolution of $\sim 3$ km-s$^{-1}$, these observations emphasize the importance of high spectral resolution for faint galaxy work.

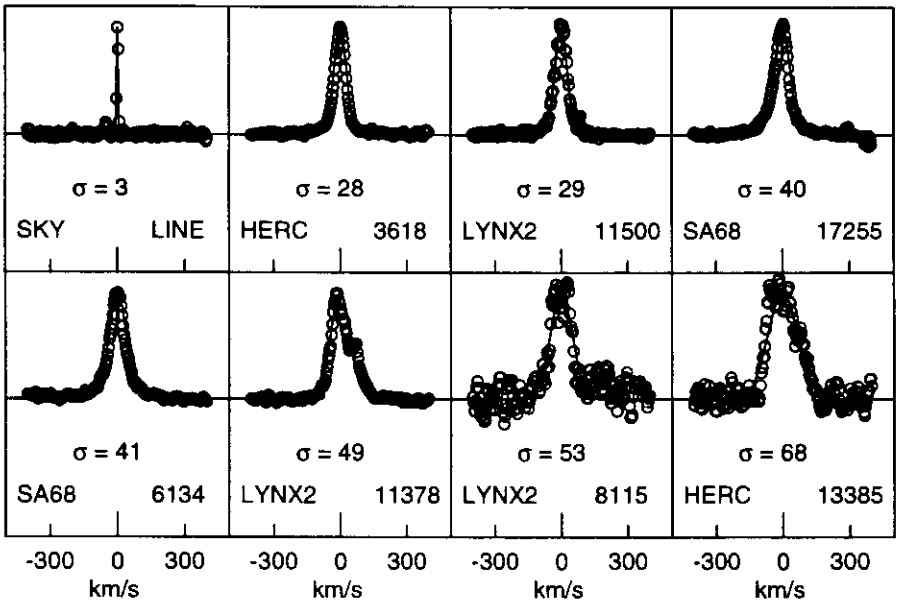


**Fig. 3.** Panel of HIRES emission line profiles from a sample of CNELG's that also have HST images (see Guzman et al. 1996 for more details). The HIRES instrumental profile is shown in the upper-left panel.

Furthermore, we have been able to obtain HST images for a subsample of our HIRES targets. The addition of an accurate size enables us to then make mass estimates (see Fig. 4) and we find CNELG's to have masses between $10^9$ to $10^{10} M_{\odot}$. Such low masses are much more typical of dwarfs than that of typical ($L^*$) galaxies. As discussed by Koo et al. (1995) and Guzman et al. (1996), the properties of these these compact, narrow-emission line galaxies (CNELGs) are all consistent with the view that we might be watching a sample of dwarf galaxies undergoing their final burst of star formation, strong enough to expel their remaining gas and to fade in luminosity to become some of today's brighter dwarf spheroidals (e.g., NGC 205).

### 2.3 Rotation Curves and Optical Tully-Fisher Studies of Distant Spirals

Instead of velocity widths, another DEEP program that probes masses of distant galaxies uses the rotation curves from optical emission lines, similar to

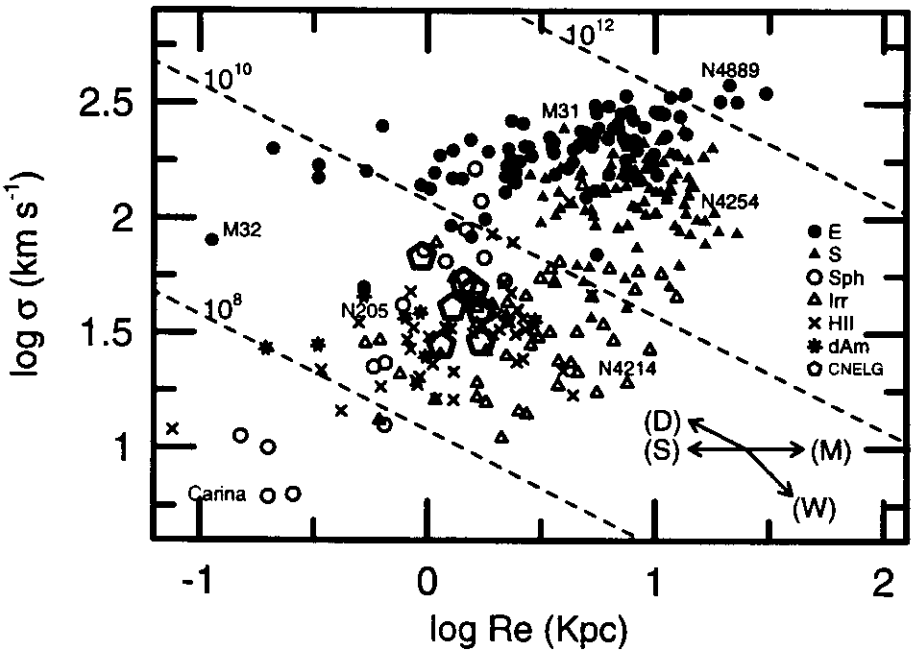


**Fig. 4.** Half-light size versus velocity-width relation that compares the CNELGs against local samples of galaxies. The dashed lines indicate the masses of $10^8$, $10^9$, and $10^{10} M_{\odot}$ . As discussed in more detail in Guzman et al. (1996), the arrows show the direction of change due to a variety of physical processes: dissipation (D), tidal stripping (S), merging (M), and galactic winds (W).

the measurements undertaken for nearby galaxies (e.g., Rubin et al. 1985). The feasibility of this approach was tested in a pilot study of 9 faint field galaxies with redshifts $0.1 \lesssim z \lesssim 1$ (see Fig. 5) as discussed in more detail by Vogt et al. (1996). HST images provided the complementary photometry, colors, galaxy morphology, and, most importantly, the orientation and inclination. In contrast to local measurements in which the slit-width is small compared to the galaxy, significant corrections are needed to derive a maximum circular velocity for distant galaxies, observed even under good seeing conditions. Except for one very elongated galaxy (with an unusually low-amplitude rotation curve that might suggest a merger seen perpendicular to the collision path), the remaining rotation curves appear similar to those of local galaxies in both form and amplitude. When the equivalent of a Tully-Fisher relation is plotted and compared to that of local galaxies, the high redshift sample reveals an upper-limit of 0.6 mag to the brightening in the past of spiral galaxies (see Fig. 6). Though this result is tentative due to the small sample size, these observations, nevertheless, demonstrate that optical rotation curves can be measured to high redshifts.

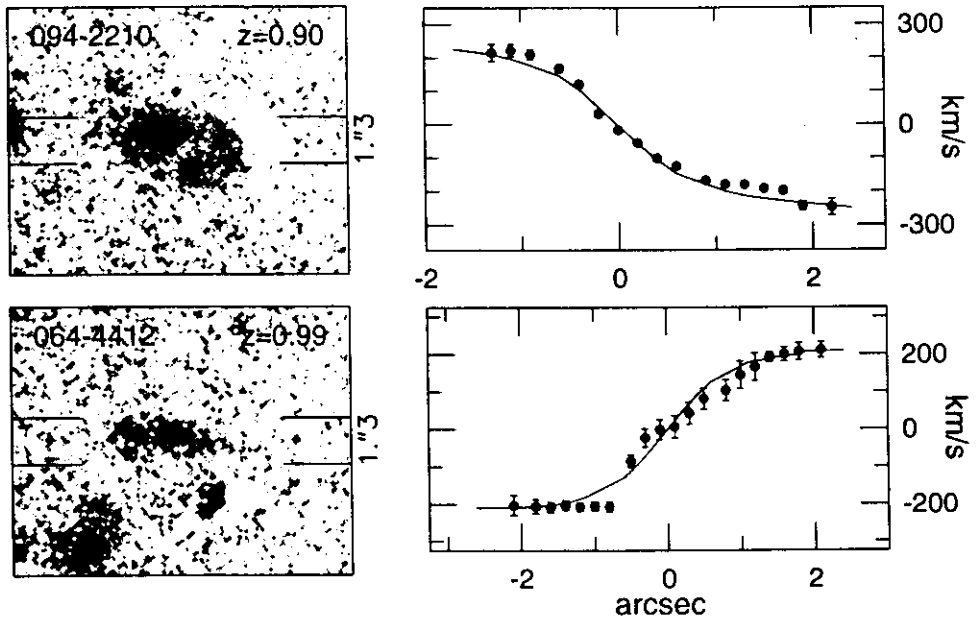


**Fig. 5.** Panel showing the HST image and Keck rotation curve of two high-redshift galaxies. Besides the ID and redshift at the top, the images show the orientation and width of the slit.

I would like to thank the Keck Telescope staff for the success of our DEEP projects. These results are contributions from a team effort of DEEP and especially its many younger astronomers who do most of the work: R. Brunner, A. Connolly, D. Forbes, C. Gronwall, R. Guzman, A. Phillips, N. Vogt, and K. Wu. DEEP is a project sponsored by the Center for Particle Astrophysics at UC Berkeley. Funding for this work was provided by NSF grants AST91-20005 and AST-8858203 and NASA grants AR-5801.01-94A and GO-2684.04-87A.

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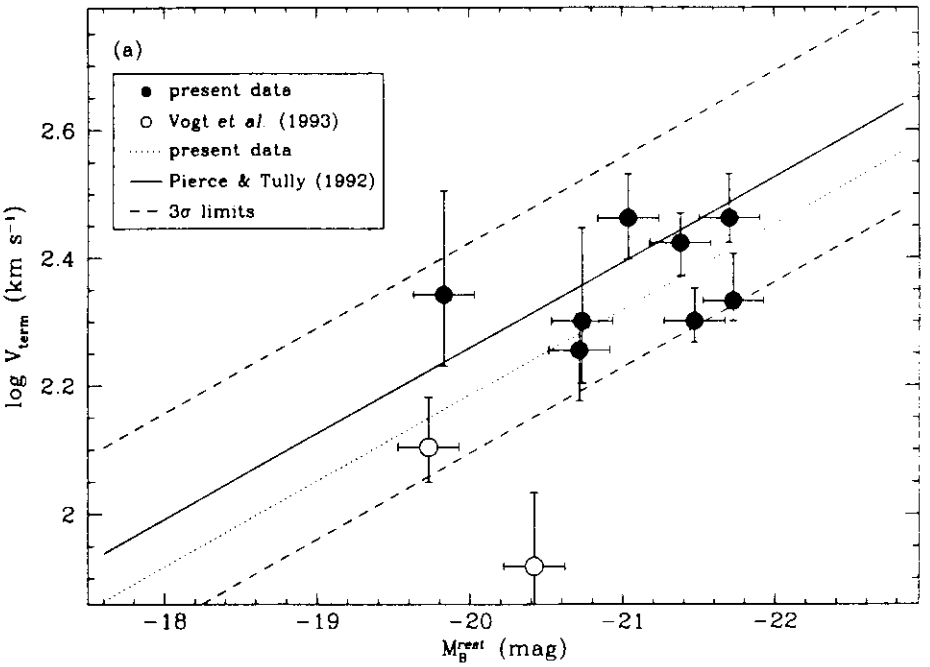


**Fig. 6.** Terminal velocity versus absolute magnitude in rest-frame blue (Tully-Fisher diagram) of the Keck and Vogt et al. (1993) sample compared to the best-fit $B$ band relation (solid line) and $3\sigma$ limits (dashed lines) from Pierce and Tully (1992). The best fit to the Keck data (dotted line) has an offset of 0.55 mag.

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