DEEP: A New Major Redshift Survey of Distant Galaxies

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Abstract

DEEP2 is a major new Keck spectroscopic survey of 50,000 field galaxies which aims to provide a detailed census and map of the cosmos at redshift $z \sim 1$. We present an overview of the status and science goals of DEEP2 after relating DEEP2 to its parent (DEEP), its predecessor (DEEP1), and the instrument which makes the survey feasible (DEIMOS). Early science results and advantages of DEEP2 for multiwavelength surveys are highlighted.

1. What is DEEP, DEEP1, DEEP2, & DEIMOS ?

DEEP (Deep Extragalactic Evolutionary Probe) was initiated over 10 years ago to use the Keck 10 m Telescopes for a major spectral survey of faint field galaxies. The use of DEIMOS (DEep Imaging Multi-Object Spectrograph) divides DEEP into two phases (see Table 1). The first (DEEP1) is comprised of several pilot programs that used pre-DEIMOS spectrographs on Keck as well as information from Hubble Space Telescope (HST) images. DEEP1 was designed to establish the technical feasibility and scientific scope of the second phase (DEEP2).

DEEP2 is distinguished from prior redshift surveys by its large sample of 50,000 galaxies that reach faint enough, $R_{AB} \sim 24$ mag, to access ordinary luminosities at redshifts $z \sim 1$. The survey uses BRI two-color diagrams to preselect galaxies at redshifts $z > 0.7$ for three of its four fields. The exception is the Extended Groth Strip (EGS) for which no redshift preselection is made. An upper limit of $z \sim 1.45$ is set by the accessibility of [OII] 3727Å up to the red limit of our spectral range (~9100Å).

DEEP2 is also distinguished by using spectral resolution high enough ($R \sim 5000$) to measure galaxy rotation curves and kinematic linewidths (see Fig. 1). Such internal kinematics of galaxies provide a powerful new dimension related to the dynamical masses of galaxies. These are intimately tied to dark matter halo masses, which in turn are the fundamental components of galaxies best understood from theoretical simulations.

The key to DEEP2's success is DEIMOS. This spectrograph has been designed to undertake the DEEP program by aiming for maximal efficiency to tackle a large density of very-faint, high-redshift galaxies. DEIMOS uses a huge (8K x 8K) CCD mosaic that is red sensitive to push the upper limit of the redshifts for detection of [OII]3727Å. The large format also allows high spectral resolution with a good spectral range. The advanced optics provide a field of view which is $16'$ in length, long enough to target 120 galaxies per mask. Together with improved throughput, faster setups, and a flexure compensation system, DEIMOS achieves roughly a 7 fold increase in efficiency compared to the first generation faint object spectrograph (LRIS). The reader can check papers [3] and [4] for more details on the reduction of data from and performance of DEIMOS, as well as to URL: http://www.ucolick.org/ ∼loen/Deimos/deimos.html. For more information about the DEEP, DEEP1, and DEEP2 projects, the reader is referred to URL: http://deep.ucolick.org/ and http://deep.berkeley.edu.

2. DEEP Science Goals

The main theme revealed by our DEEP1 pilot projects is that galaxy evolution is a complicated problem. Distant field galaxies are diverse – in size, luminosity, structure; are composed of subcomponents (e.g., bulges and disks) which appear to have experienced different star formation and dynamical histories and evolution; and reside in a wide range of environments (pairs, groups, clusters, voids) that are likely to engage different physical mechanisms that affect their evolution.

Results from our DEEP1 programs have established that kinematics are feasible with 10 m class telescopes for distant galaxies. More important, DEEP1 results show that kinematics provide information and science not possible to extract from luminosity and colors alone. Examples include the study of the Tully-Fisher relation for high redshift spirals, the study of the fundamental plane for early-type galaxies in the field, the establishment of very low dynamical masses in luminous compact galaxies, and estimates of dynamical masses for Lyman-drop galaxies found at redshifts $z \sim 3$. Moreover, even though DEEP1 was state-of-the-art for Keck and produced over 500 redshifts, the sample was clearly still too small to address important questions related to volume densities and clustering – samples at least 10 times larger would be needed. Besides showing that Keck spectra of distant galaxies can yield chemical abundances, star formation rates, ages of old stars, and gas conditions, DEEP1 also clearly demonstrated the essential role of HST imaging to explore the mass, morphology, structure, color gradients, etc. of distant galaxies (see summary and references in [5]).

While the scientific returns from DEEP1 have been high, DEEP2 will be pushing entirely new ground. DEEP2 will itself be comprised of two parts. The main part is the 1HS (One Hour Survey) which aims to collect 50,000 redshifts using one-hour exposures with DEIMOS and will use roughly 80 nights of Keck. The second part (3HS - 3 Hour Survey) has yet to be fully defined but aims to gather complementary Keck observations in subregions of the 1HS and in regions where deep HST imaging is available, such as in the GOODS fields. At present, the 3HS part of DEEP2 includes two projects. One led by R. Ellis and T. Treu includes 5-10 hour exposures with DEIMOS of a sample of 250 early-type galaxies seen in the GOODS-N region. The other led by C. Steidel uses the UV-sensitive side of LRIS to study galaxies from the 1HS that failed to yield reliable redshifts with DEIMOS and to explore the important "desert" redshift range, $z = 1.4$ to 2.5, where galaxies are believed to be undergoing major growth.

The 1HS will tackle several of the key scientific puzzles in cosmology today: the nature of dark matter; the nature of dark energy; and the formation and evolution of structure (from the few kpc scale of dwarf galaxies to clustering and voids on 100 Mpc scales). DEEP's internal kinematics provide estimates of dynamical masses and thus dark as well as ordinary matter. Dark energy is traced through the classical volume test, which in turn measures the equation of state (w) of the Universe. By good fortune, the comoving volume density of halo masses of a given circular velocity appears to be virtually independent of cosmology at our redshifts near $z = 1$. Thus, like a standard candle in the supernovae experiments, DEEP is able to use galaxies of given internal kinematics as standard volume tracers [9]. For structure formation, again, internal kinematics will play an important role. Derived dynamical masses can be related to other galaxy properties such as stellar masses, luminosities, colors, metallicity, age, star formation rate, etc.

From its inception, DEEP has been designed to be a magnet for surveys at other wavelengths and for followup imaging by HST. DEEP2 is particularly attractive for such intensive coverage because:

1) **Depth:** the DEEP2 survey reaches to $R \sim 24$ mag and thus beyond redshifts $z \sim 1$ when extensive star formation and AGN activity is expected. DEEP2's limit will reach a large fraction of the sources expected from deep X-ray, far-UV, mid-IR, far-IR, and radio surveys using present telescopes.

2) **Size:** DEEP2 will have 50,000 spectra. Such large numbers are especially valuable to yield targets (such as AGN's and ultra-luminous infrared

galaxies -ULIRGs) that are rare in the optical but relatively common in surveys at other wavelengths. A large sample also enables studies of galaxy properties as a function of environment and is less susceptible to cosmic variance for deriving volume densities.

3) **Spectral Resolution:** the survey resolution is 30 km/s. DEEP2 will thus enable measures of internal kinematics (i.e., dynamical masses if inclinations and sizes are known) that can then be compared to stellar mass estimates (using restframe K photometry of galaxies at $z \sim 1$) from the IRAC instrument aboard Spitzer. This resolution also enables measurements of merger signatures (via kinematic distortions and asymmetries) and detection of low-mass groups (via small velocity dispersions). Both are relevant for studying the merger scenario as the trigger of starbursts and AGN's and their environments.

4) **Good Quality Spectra:** The large CCD used by DEIMOS also allows a spectral range wide enough to capture a rich set of spectral features that complement key measures from other wavelength surveys. Important examples include star formation rates, metallicity, extinction, and ages of stellar populations, all of which have important links to science from Spitzer, GALEX, VLA, and CHANDRA.

While all four of our DEEP2 fields will have some near-IR imaging to complement the optical data from DEEP, one field (EGS) will receive the lion's share of very deep coverage over a wide range in wavelengths. The heart of this field will be a $16'$ x $120'$ area to be covered to $R \sim 24$ mag with DEEP2 spectra. No photometric redshift selection will be made so as to ensure good overlap with lower-redshift sources detected in the deep surveys at other wavelengths. DEEP2 is expecting to complete the EGS by mid-2005, weather permitting (for more details, see [6]).

3. Early Science Results from DEEP2

The DEEP2 1HS program is now 40% complete. Figure 2 shows how DEEP2 compares to three previous faint field-galaxy redshift surveys. With only 10% of the DEEP2 program, over 1600 galaxies with luminosities brighter than L^* and redshifts $z > 1$ have secure redshifts. This is well over 10 times larger than the number of such galaxies from the other three surveys *combined*. Figure 2 also shows how well we are able to select high redshift galaxies by using our *BRI* photometry. The vast fraction are at the desired redshifts $z > 0.7$. We do, however, find a small pool of extremely blue galaxies at redshifts less than 0.7; these contaminants are difficult to eliminate because they overlap very blue galaxies at higher redshifts $z > 1$ in the *BRI* two color plots.

This same 10% sample is now being actively worked on for a diverse range of science. These data have already yielded new measures of the clustering of distant galaxies [2] and shows that the differences found in local samples of red and blue galaxies appear to remain at redshifts $z \sim 1$. This work also discuss estimates of bias, the redshift distribution, and the velocity dispersion versus projected-separation distributions. Interpretation of such data is probably best done through mock catalogs, such as the one developed specifically for DEEP2 1HS [10].

Work is also well underway on the luminosity functions of distant galaxies subdivided by color and spectral type (using principal component analysis - PCA [8]); on close pairs, groups, and environments of galaxies; on the star formation rate as measured from [OII] lines; on O/H abundances in the emission gas seen in distant galaxies; and on studies of the ages and metallicities of red galaxies.

4. Summary and Future

DEEP1 is complete. DEIMOS has been fully commissioned and is performing superbly. The 1HS part of DEEP2, with 40% of the data already in hand, aims for completion of 50,000 galaxies by 2005. The 3HS part of DEEP2 has also been initiated, with 5-10 hour exposures gathered with DEIMOS for about 250 early-type galaxies in the GOODS-N region, and with highly successful acquisition using LRIS-B of redshifts of galaxies in the redshift desert from $z \sim 1.4$ to 2.5. The range of science enabled by DEEP, especially with measurements of internal kinematics of galaxies, is enormous, and includes tackling questions related to dark matter, dark energy, the formation and evolution of galaxies, and large-scale structure. With the recent successful launch of GALEX and Spitzer, and a suite of other complementary data, DEEP promises to provide exciting new results for years to come.

5. Acknowledgments

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Table 1. DEEP Survey Characteristics

-	DEEP1	DEEP2
Telescopes	Keck I & II	Keck I & II
Instruments [a]	LRIS, ESI, HIRES, NIRSPEC	DEIMOS, LRIS-B
Survey Period	1995-2001 (30 Nights)	2002-2005 (80^+ Nights)
Fields [b] (FOV)	HDF-N & FF ($8' \times 8'$)	0230+00 ($30' \times 120'$)
-	GSS 1417+52 ($4' \times 42'$)	1417+52 ($16' \times 120'$) EGS
-	SA68 0017+15 (five $4' \times 7'$)	1652+35 ($30' \times 120'$)
-	-	2330+00 ($30' \times 120'$)
-	-	GOODS-N & S
No. Galaxies	1000 to $I \sim 23.5$ (1-4h)	1HS: 50,000 to $R_{AB} \sim 24$ (1h)
& Depth (exp)	-	3HS: few 1000 to $I \sim 24$ (3-10h)
Photometry	KPNO ($UBRI$); HST(VI)	UH (BRI); HST(TBD)
Science	Spheroid/Bulge Evol.	1HS: non-HST DEEP1 Science &
-	Disk Surface Brightness Evol.	Clustering Evol. at z ∼ 1
-	Compact & High z Galaxy Evol.	Lum. Fct. (z, color, kinematics)
-	Tully Fisher & Fund. Plane Evol.	Volume Test (Dark Energy)
-	Red & Blue Galaxy Evol.	3HS: HST DEEP1 Science &
-	AGN/Variability/Lum. Funct.	“desert $z \sim 1.4 - 2.5$” galaxy Evol.
-	Star Form. & Metallicity Evol.	Red Galaxy Age & Metallicity
[a] ESI:	Echelle Spectrograph Imager	
LRIS:	Low Resolution Imaging Spectrog.	B - Blue side (UV sensitive)
HIRES:	High Resolution Echelle Spectrog.	
NIRSPEC:	Near Infrared Spectrog.	
DEIMOS:	DEep Imag. Multi-Obj. Spectrog.	
[b] HDF:	Hubble Deep Field;	N-North & FF-Flanking Fields
GOODS:	Great Obs. Origins Deep Surveys	N-North & S-South
GSS & EGS :	Groth Strip Survey	Extended Groth Strip
SA68:	Selected Area 68	-

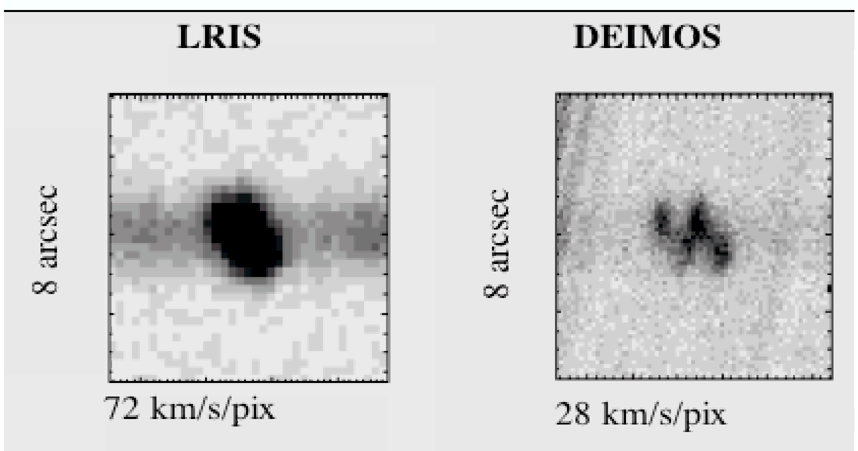

Fig. 1. Example of the improved measurements of internal kinematics of galaxies using the higher spectral resolution of the second generation Keck spectrograph, DEIMOS, as compared to that from the first generation faint object spectrograph, LRIS. The large 8Kx8K CCD detector of DEIMOS allows the use of such high resolutions for a given spectral range. The DEIMOS spectrum shows a well-defined rotation curve as seen via the [OII] 3727Å doublet, which has an intrinsic separation of its two lines of 220 km/s.

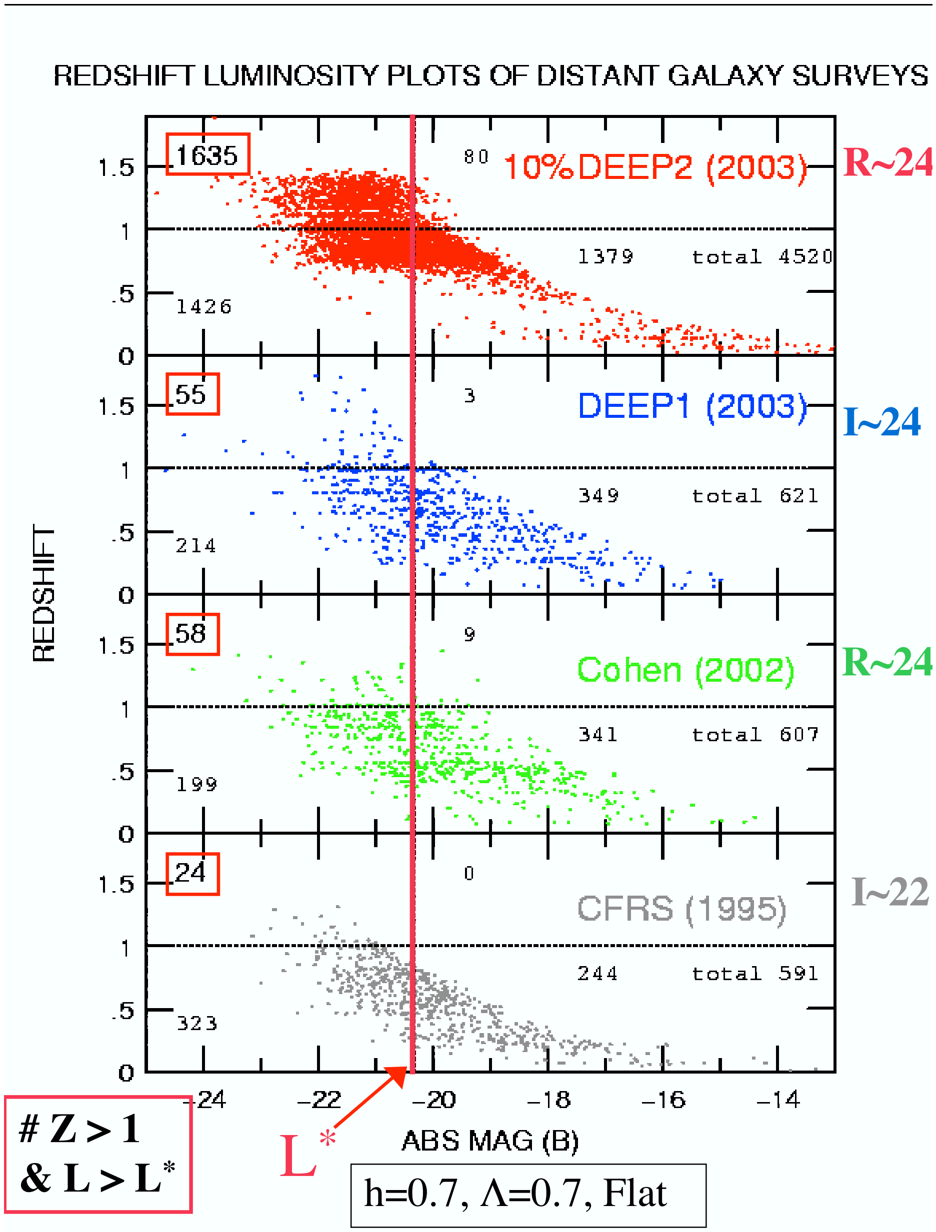

Fig. 2. Redshift vs luminosity (M_B assuming indicated cosmology) for four distant field galaxy surveys as indicated (CFRS: Canada France Redshift Survey [7]; Cohen: Caltech Faint Galaxy Redshift Survey [1]). The numbers on the right-hand side are the magnitude limits in the indicated passbands. Each of the panels is divided into quadrants by a vertical line at L^* of the local luminosity function of field galaxies and a horizontal line at redshift $z = 1$; the number of galaxies from each survey in each quadrant is noted, with the luminous, $z > 1$ sample size specified in a box at the upper left of each panel. Note that DEEP2, with only 10% of the survey completed, already has 1635 such galaxies, more than 10× the sum of the other three prior surveys (137).