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First Science Results from the DEIMOS/DEEP2 Redshift Survey

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Abstract. DEEP2 is a major new Keck spectroscopic survey of 50,000 galaxies that aims to provide a detailed map of the cosmos at redshift $z \sim 1$. We present an overview of DEEP2 and its relation to DEEP and its predecessor (DEEP1) in terms of science goals, of the instrument DEIMOS that enables completion of this survey in only a few years, and of the current status of the project. First science projects that use the first 10% of the survey data and their early results are highlighted.

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

DEEP (Deep Extragalactic Evolutionary Probe) was initiated over 10 years ago to be a major spectral survey of faint field galaxies using the Keck 10-m Telescopes. The use of DEIMOS (DEep Imaging Multi-Object Spectrograph) naturally divides DEEP into two parts (see Table 1). The first (DEEP1) is comprised of a suite of pilot surveys of 10's to 100's of galaxies using pre-DEIMOS spectrographs on Keck I and II. DEEP1 was designed to determine the technical feasibility and scientific scope of the second phase (DEEP2) of the DEEP program that will rely on using DEIMOS. DEEP1 covered fields with HST WFPC2 images, which provide not only morphology and photometry but also structure, size, and inclination data needed to convert kinematics from Keck spectra into direct measures of dynamical mass.

DEEP2 with DEIMOS is distinguished from prior redshift surveys, including DEEP1, by its large sample size of over 50,000 galaxies, depth to $R_{AB} \sim 24$, and high quality of the spectral data (see Table 1). To increase the efficiency of gathering redshifts at $z \sim 1$, three of the four 1HS fields will have a photometric pre-selection of galaxies, using BRI two-color diagrams, to isolate those most likely to have redshifts in the range of $z > 0.7$. The EGS field, with only half the area of the other three, will not have such a pre-selection, so that lower redshifts will be included to better support the large suite of complementary, deep surveys at other wavelengths. The only competitive survey currently underway is the VMOS-VLT Deep Survey (see article on VVDS by Le Fèvre in these proceedings), which is aiming for a larger but generally brighter sample, has no redshift pre-selection, and is generally of lower spectral resolution.

Large numbers for faint galaxy surveys are critical because galaxy evolution involves a complex interplay of diverse galaxy classes, galaxy properties, environments, and physical mechanisms. Another reason is that cosmological constraints via the volume test (e.g., Newman & Davis 2002) or velocity func-

Table 1. DEEP Survey Characteristics

	DEEP1	DEEP2
Telescopes	Keck I & II; HST	Keck I & II
Instruments[1]	LRIS, ESI, HIRES, NIRSPEC	DEIMOS, LRIS-B
Survey Period	1995-2001 (30 Nights)	2002-2005 (120 Nights)
Fields[2] (FOV)	HDF-N & FF (8′× 8′) GSS 1417+52 (4′× 42′) SA68 0017+15 (five 4′× 7′)	0230+00 (30′× 120′) 1417+52 (16′× 120′) EGS 1652+35 (30′× 120′) 2330+00 (30′× 120′) GOODS-N & S
No. Galx. & Depth (exp)	1000 to $I \sim 23.5$ (1-4h)	1HS: 50,000 to R_{AB} ~24 (1h) 3HS: few 1000 to I ~24 (3-10h)
Photometry	KPNO ($UBRI$); HST(VI)	UH (BRI); HST(TBD)
Science	Spheroid/Bulge Evol. Disk Surface Brightness Evol. Compact & High z Galaxy Evol. Tully Fisher & Fund. Plane Evolution Red & Blue Galaxy Evol. AGN/Variability/Lum. Funct. Star Formation & Chemical Abundance Evolution	1HS: non-HST DEEP1 Science & Clustering Evol. at z ~ 1 Lum. Funct. (color, z, vel.) Volume Test (Dark Energy) 3HS: HST DEEP1 Science & “desert $z \sim 1.4 - 2.5$” Galaxy Evol., Red Galaxy Age & Metallicity

ESI: Echelle Spectrograph Imager

LRIS: Low Resolution Imaging Spectrograph, B - Blue side (UV sensitive)

HIRES: High Resolution Echelle Spectrograph

NIRSPEC: Near Infrared Spectrograph

DEIMOS: DEep Imaging Multi-Object Spectrograph HDF: Hubble Deep Field; N-North, FF-Flanking Fields

GOODS: Great Observatories Origins Deep Surveys; N-North, S-South

GSS, EGS : Groth Strip Survey, Extended Groth Strip

SA68: Selected Area 68

tions require averaging over the expected fluctuations due to cosmic variance on large scales. The depth of $R \sim 24$ is needed to reach typical galaxies at redshifts $z \sim 1$ and beyond with high efficiency. The spectral quality in DEEP2 is high enough in resolution to yield rotation curves and linewidths (see Figure 1). Such internal kinematics of galaxies provide a powerful new dimension related to masses of galaxies, which in turn is presumably intimately tied to the dark matter dominated halo masses that are the fundamental parameters to have clear and direct links to current theoretical simulations of galaxy formation. Moreover, the spectral signal-to-noise (S/N) for a significant fraction of the DEEP2 1HS sample will be high enough to yield line strengths and line ratios that would be sensitive to star formation rates, gas conditions, stellar-population ages, and metallicity. Supplementing counts, colors, luminosities, and clustering properties of distant galaxies that have been the mainstay measurements of prior surveys of faint field galaxies, these new measures provide independent probes of galaxy properties at $z \sim 1$.

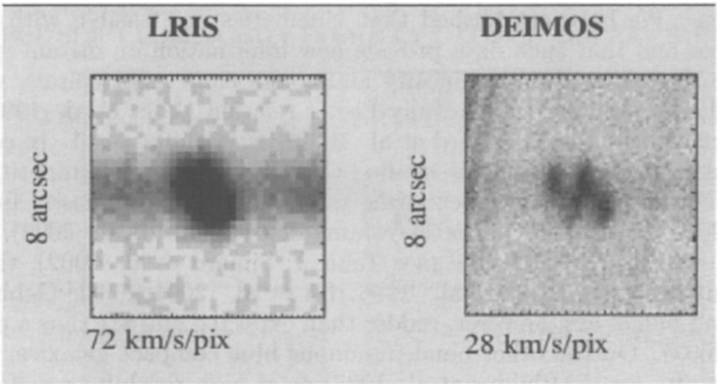

Figure 1. Example of the improved measurements of internal kinematics of galaxies using the higher spectral resolution of the second generation Keck spectrograph, DEIMOS, as compared to that from the first generation faint object spectrograph, LRIS. The large 8Kx8K CCD detector of DEIMOS allows the use of such high resolutions without losing spectral range. The DEIMOS spectrum shows a well-defined rotation curve as seen via the [OII] 3728Å doublet, which has an intrinsic separation of its two lines of 220 km/s.

The key to the success of DEEP is the completion of DEIMOS. This faint object spectrograph has a number of design features well suited for surveys of large samples of very faint galaxies. With credit to the advanced (aspheric) optics of the camera, the field of view is relatively large, spanning nearly 17 arcmin in available slit length. With this length and typical slitlets of 8 to 10 arcsecs, the DEEP program can easily achieve 120 targets per mask. To complement the large field, the CCD detector mosaic is not only huge (8K x 8K) so that high spectral resolution can be used while retaining reasonable spectral range (see Figure 1) but also sensitive to nearly 1 micron, thus allowing the detection of [OII] 3728Å to beyond redshift $z \sim 1.5$. Finally, DEIMOS has a built-in flexure compensation system that ensures high repeatability and stability of the spectral images so that excellent sky-line subtraction can be attained. Together, these gains translate to roughly a 7-fold increase in efficiency compared to LRIS. The reader is referred to papers by Faber et al. (2003) and Davis et al. (2003) 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. What did we learn from DEEP1? What new science will come from DEEP2?

The main theme that arises from our DEEP1 studies is that galaxy evolution is a complicated problem. Distant field galaxies are diverse in size, luminosity, and structure; are composed of subcomponents which experience different star formation and dynamical histories and evolution; and reside in a wide range of environments that are likely to engage different physical mechanisms for their evolution. We have established that kinematics are feasible with 10-m class telescopes and that such data provide new information on distant galaxies not possible to extract from luminosity and colors alone. For spirals, we find relatively little evolution in the Tully-Fisher relation (Vogt et al. 1996, 1997) or disk surface brightness (Simard et al. 1999) to redshifts $z \sim 1$. In contrast, for spheroidals at the same epoch, we find strong evidence for luminosity evolution in the fundamental plane (Gebhardt et al. 2003) and luminosity function (Im et al. 2002), but little change in volume density (Im et al. 2002). Using the DEEP1 data in the GSS field (see Table 1; Simard et al. 2002), the colors of spheroidal galaxies (Koo et al. 1996; Im et al. 2001, 2002; Gebhardt et al. 2003) and bulges are, however, redder than expected and are thus a puzzle (Koo et al. 2003). On the other hand, luminous blue compact galaxies, whether at low redshifts $z < 1$ (Phillips et al. 1997) or at high redshifts $z \sim 3$ (Lowenthal et al. 1997), appear to have low dynamical masses and thus are suggested to be possible progenitors of quiescent low-mass spheroidals today (Koo et al. 1995; Guzmán et al. 1996, 1997), or the building blocks of larger galaxies, rather than massive ellipticals undergoing formation via monolithic collapse (Steidel et al. 1996). Additional studies of the chemical evolution (Kobulnicky et al. 2003), ages of distant red galaxies (Schiavon et al. 2004, in prep.), AGN activity (Sarajedini et al. 2004, in prep.), general luminosity functions (Willmer et al. 2004, in prep.), and velocity widths (Weiner et al. 2004, in prep.) are being completed and should provide a broader view of the evolution of field galaxies at redshifts $z \sim 1$.

While the scientific returns for DEEP1 have been high, DEEP2 will be pushing entirely new ground. DEEP2 will itself be comprised of two major parts. The 1HS (One Hour Survey) aims to collect 50,000 redshifts using one-hour exposures of DEIMOS per target and roughly 80-90 nights of Keck. The second part (3HS - 3 Hour Survey) has yet to be fully defined but is aimed to gather a complementary set of Keck observations (40 nights worth) in subregions of the 1HS and in regions where deep HST imaging is available. At present, the 3HS part of DEEP2 includes two programs. One is being led by R. Ellis and includes 5-10 hour exposures with DEIMOS of a sample of 300 early-type galaxies seen in the GOODS-N region. The other, led by C. Steidel, uses the UV-sensitive side of LRIS-B to check the redshifts of galaxies from the 1HS that failed to yield reliable redshifts and to explore the important "desert" redshift range, $z = 1.4$ to 2.5, where galaxies are believed to be undergoing major growth and changes.

With DEEP2, the team aims to tackle several of the major scientific puzzles in cosmology today: the nature of dark matter; the nature of dark energy; and the nature and formation of structure, on scales ranging from small galaxies to groups and clusters of galaxies to super-cluster scales. As previously emphasized, DEEP is collecting spectra that yield data on the internal kinematics of galaxies. Such kinematics allow a measurement related to dynamical masses and thus dark as well as ordinary matter. The basic approach to probing dark energy is through a measure of the changes in volume per unit redshift, 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

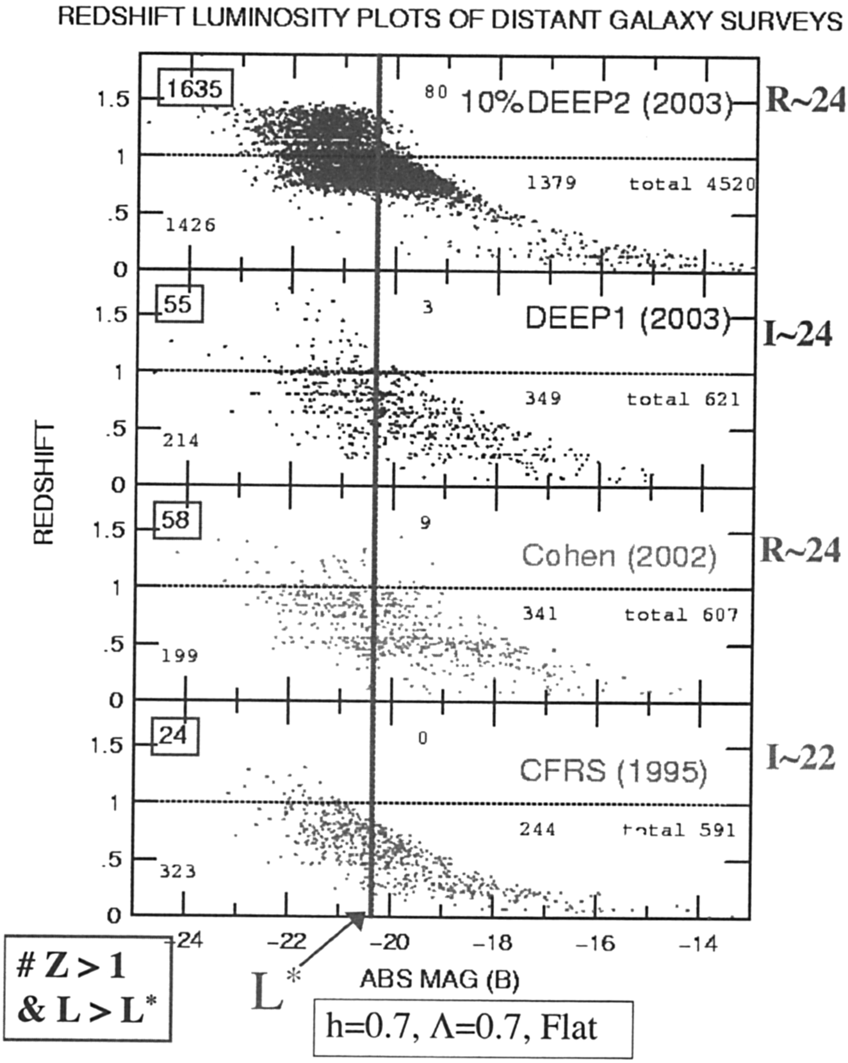

Figure 2. Redshift vs luminosity (M_B assuming indicated cosmology) for four distant field galaxy surveys as indicated (CFRS: Canada France Redshift Survey; Cohen: Caltech Faint Galaxy Redshift Survey). The numbers on the right-hand side are the magnitude limits in the indicated passbands. Each of the 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 subpanel. 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).

standard candle in the supernovae experiments, DEEP is able to use galaxies of given internal kinematics as standard volume tracers (Newman & Davis 2002).

Another challenge for DEEP is to understand how galaxies formed and evolved. Here again, internal kinematics will play an important role, largely by providing the fundamental galaxy property of mass, which can then be correlated and related to many other galaxy properties (luminosity, color, metallicity, age, star formation rate, etc.). Our theories are today far more secure in tracking the evolution of masses in galaxies than in estimating the luminosities, colors, structure, etc. of young galaxies.

Besides improved kinematics, the three other gains of DEEP2 over DEEP1 are the vast increase in sample size to over 50,000 galaxies, the use of four separate regions of sky, and the addition of several other deep surveys at other wavelengths, including X-ray from Chandra, near-UV from GALEX, near-IR to far-IR data from SIRTF, submm from Large Millimeter Telescope (LMT), and radio from the VLA. The major loss relative to DEEP1 is that only a tiny fraction of the DEEP2 will have HST imaging. With these gains, DEEP2 will be able to dramatically improve all the DEEP1 science programs by using vastly larger sample sizes, as well as to undertake new programs possible only with the large sample. Such programs include studies of large scale clustering, studies of how galaxy properties vary in environments of different densities, studies of rare objects (AGN's and close galaxy pairs), and studies requiring high S/N spectra achievable only by stacking 100's if not 1000's of spectra.

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 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 (see Coil et al. 2004; and Figure 3) and show that the differences found in local samples of red and blue galaxies appear to remain at redshifts $z \sim 1$. The Coil et al. (2004) work also discusses 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 recently especially for DEEP2 1HS by Yan, White, & Coil (2004). As they emphasize, both the redshift distribution and correlation functions such as from DEEP2 are non-trivial to reproduce. Thus they serve as important constraints on the halo occupation distribution (HOD) and the conditional luminosity function (CLF) that are critical inputs to the mock catalogs and serve as the link between theories of cosmology and galaxy formation. There

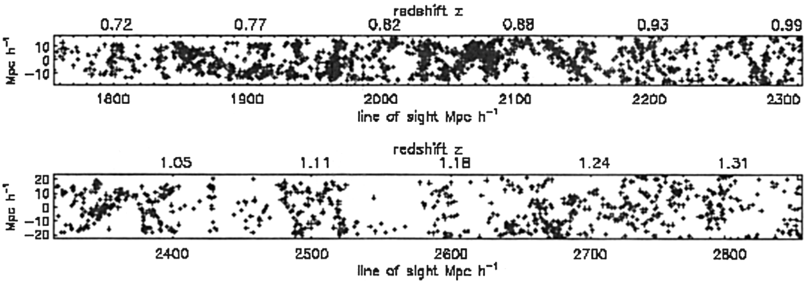

Figure 3. Redshift-space distribution of galaxies in early DEEP2 data in our most complete field (identical to Figure 3 from Coil et al. 2004). The galaxies are shown as a function of redshift and comoving distance both along and across the line of sight, assuming the cosmology of Figure 2. The sample has been split by using PCA classification (Madgwick et al. 2003), with the plus symbols (darker) corresponding to galaxies with strong emission-lines and the diamond symbols (lighter) corresponding to those with absorption-line dominated spectra. The stronger clustering of the red galaxies is quantified and shown in the next figure.

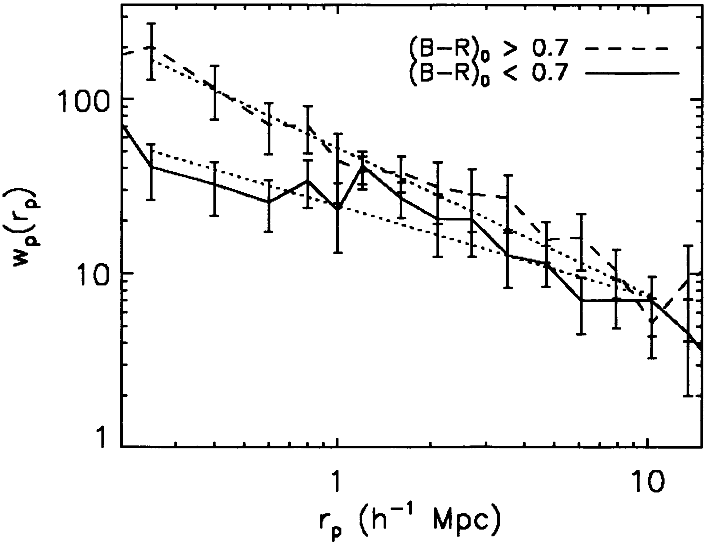

Figure 4. Projected correlation function amplitude ($w_p(r_p)$) vs the projected distance, r_p measured for blue (solid line) and red (dashed line) galaxies divided by $B - R$ color. The power-law fits are shown as dotted lines, while the one-sigma error bars shown are estimated from the variance found across mock galaxy catalogs. Note the steeper and larger amplitude of the clustering for the red sample. See Coil et al. (2004) for details.

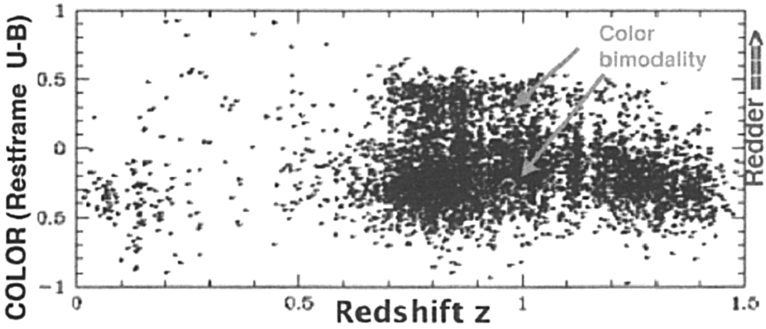

Figure 5. Restframe $U - B$ color versus redshift for a subsample of DEEP2 galaxies. Note the strong bimodality in the color distribution, a property of more local galaxies reported by the SDSS team (Strateva et al. 2001) and at higher redshifts (photometric redshifts) by the COMBO-17 group (Bell et al. 2004). This natural division, which appears to be relatively stable over a large range in redshift, allows comparison of galaxy samples divided by color.

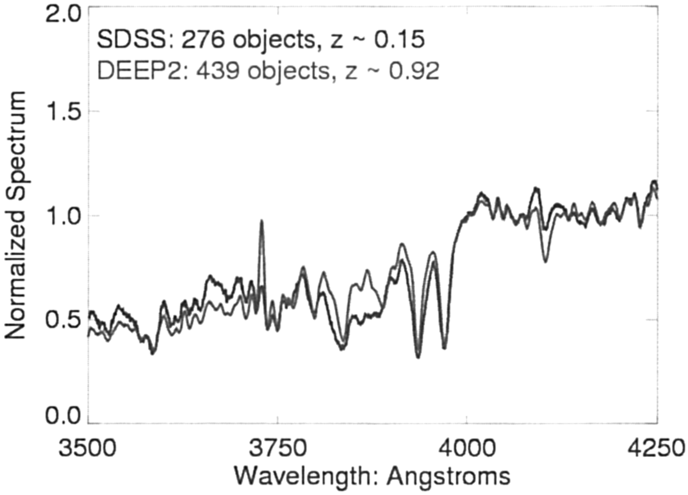

Figure 6. Comparison of stacked spectra from 276 of the SDSS luminous red galaxies (darker line) at the lowest redshift range $z = 0.15 - 0.25$ (Eisenstein et al. 2001) and from 439 DEEP2 galaxies (lighter line) chosen to match closely the SDSS sample in color and luminosity but selected at redshifts centered near $z \sim 0.92$. Note the stronger [OII] 3728Å line of the DEEP2 stack, the comparable $H\&K$ lines near 4000Å, and the stronger Balmer Hδ in absorption at 4101Å. The [OII] line is a measure of active star formation while the Balmer absorption line is measure of age (for a given metallicity).

are already hints of differences between the DEEP2 clustering results and the predictions of the mock catalog, which has inputs that are locked to match local galaxy properties. If confirmed with a larger fraction of the DEEP2 1HS data, these differences may be the first hints that an evolving HOD is needed, instead of the assumed constant HOD, and then the required evolutionary changes will provide important and valuable constraints on the formation and evolution of galaxies. These mock catalogs will undoubtably become more valuable as they advance in the future to include other observed properties of the galaxies, such as colors, ages, metallicities, and especially *observed* internal kinematics.

Work is also well underway on the luminosity functions of distant galaxies subdivided by color (see Figure 5) and spectral type (using principal component analysis - PCA ; see Madgwick et al. 2003); on close pairs, groups, and environments of galaxies; on the star formation rate as measured from [OII] lines (see Figure 6); on O/H abundances in the emission gas seen in distant galaxies; and on studies of the ages and metallicities of red galaxies (see Figure 6). This last project is an excellent example of the science that is possible with large samples. In this case, we have achieved an incredibly high S/N average spectrum of red galaxies at redshifts $z \sim 1$ that can be studied in exquisite detail (e.g., note the almost exact match of even the smallest features between the spectrum from SDSS and DEEP2).

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, is on target 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 300 early-type galaxies in the GOODS-N region, and with successful acquisition using LRIS-B of redshifts of galaxies in the redshift desert from $z \sim 1.5$ 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, and the formation and evolution of galaxies and large-scale structure. With the recent successful launch of GALEX and SIRTF, and a suite of other complementary data, some of the DEEP fields promise to provide exciting new results for years to come.

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