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DEEP AFTER 15 YEARS: LESSONS FOR GTC

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RESUMEN

DEEP2 es la mayor exploración espectroscópica del nuevo Keck de aproximadamente 35,000 galaxias de campo cuyo fin es el de proporcionar el censo y mapa detallados del cosmos en el corrimiento al rojo $z \sim 1$. Presentamos revisión general de DEEP2 y de su predecesor, DEEP1. Varios resultados científicos y las ventajas de DEEP2 aseguran que el GTC será científicamente poderoso a pesar de su llegada tardía entre los telescopios de clase de 8-10 m.

ABSTRACT

DEEP2 is a major new Keck spectroscopic survey of about 35,000 field galaxies and aims to provide a detailed census and map of the cosmos at redshift $z \sim 1$. We present an overview of DEEP2 and its predecessor, DEEP1. A few science results and advantages of DEEP2 for multiwavelength surveys are highlighted. We close with lessons that may help ensure that the GTC will be scientifically powerful, though it is a latecomer among 8-10 m class telescopes.

Key Words: **GALAXIES: EVOLUTION — GALAXIES: HIGH REDSHIFT — GALAXIES: KINEMATICS AND DYNAMICS — SURVEYS**

1. WHAT ARE DEEP, DEEP1, DEEP2, DEEP3, DEIMOS, & AEGIS ?

DEEP (Deep Extragalactic Evolutionary Probe) was initiated 15 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), commissioned in 2002, divides DEEP into two phases. 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, with only about 600 spectra, was designed to establish the technical feasibility and scientific scope of the main survey (DEEP2) in the second phase.

DEEP2 is distinguished from prior redshift surveys by its large sample of about 35,000 galaxies that reach faint enough ($R_{AB} \sim 24$ mag) to access ordinary galaxies 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. Each of these three cover about one square degree. The 4th field is the Extended Groth Strip (EGS) covering half the area (0.5 square degrees) for which no redshift preselection is made. This was done to better support the surveys under the aegis of the All-wavelength Extended Groth International Survey (AEGIS). An upper limit of $z \sim 1.45$ for all fields 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 Figure 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 main DEEP2 program by aiming for maximal efficiency to tackle a large density of very-faint, high-redshift galaxies. DEIMOS uses an 8K x 8K CCD mosaic that is sensitive in the red 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 by Davis et al. (2003) and Faber et al. (2003) for more details on the reduction of data from and performance of DEIMOS,

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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.

DEEP3 is presently still in the planning stages but aims to be an observational follow-up of DEEP2. Among many possible projects, one will be to reach both fainter galaxies and higher S/N for existing limits than achieved with DEEP2. Another under consideration will be to extend the spectra towards the blue and ultraviolet using the upgraded blue-sensitive spectrograph (LRIS). In the future, DEEP3 will want to complement the optical DEIMOS spectra with data from the forthcoming multiobject near-infrared spectrograph (MOSFIRE). Finally, for very tiny samples, efforts are already underway to obtain Keck near-infrared spectra with OSIRIS (Larkin et al. 2006), an integral field unit spectrograph, using adaptive optics to achieve much higher spatial resolution ($\sim$ 0.1 arcsec or better).

AEGIS is an outgrowth of our success in having several other teams conduct very deep surveys that overlap the EGS. These range in energy from the X-ray to the radio and are some of the deepest in the sky (see Davis et al. 2006 for details of the depth and coverage of the various surveys). While all four of our DEEP2 fields will have some near-IR imaging as well as several optical bands, EGS will receive the lion's share of very deep multiwavelength coverage. The heart of this field will be a 16' x 120' area to be covered by DEEP2. Due to loss of all nights in 2006 to weather, only about 75% of the DEEP2 survey is complete in EGS.

2. LESSONS FROM DEEP1 FOR DEEP2

DEEP1 was a success in serving its main purpose of demonstrating the feasibility of DEEP2 and in paving a clearer scientific path when much larger samples were to be gathered. Of high importance, we demonstrated to a previously skeptical community that internal kinematics (dynamical masses) are practical for distant galaxies (Vogt et al. 1996, 1997; Guzman et al. 1997; Gebhardt et al. 2003). More importantly, kinematics provide new clues to their nature and evolution. Examples include finding that 1) spirals to $z \sim 1$ show a rotation velocity versus luminosity relation (Tully-Fisher) that suggests only mild luminosity evolution relative to local samples (Vogt et al. 1996, 1997); 2) early-type galaxies to $z \sim 1$ show a fundamental plane relation among velocity dispersion, luminosity, and size that suggests such galaxies are roughly 5× brighter in the past (Gebhardt et al. 2003); 3) luminous compact galaxies with low velocity dispersions that imply low dynamical masses of a few % to 10% of more typical, comparably luminous galaxies (Phillips et al. 1997; Guzman et al. 1997); and Lyman-drop galaxies (more commonly referred to as Lyman Break Galaxies or LBG's) at redshifts of $z \sim 3$ have internal velocities indicating a wide range of masses (Lowenthal et al. 1999) rather than being uniformly massive.

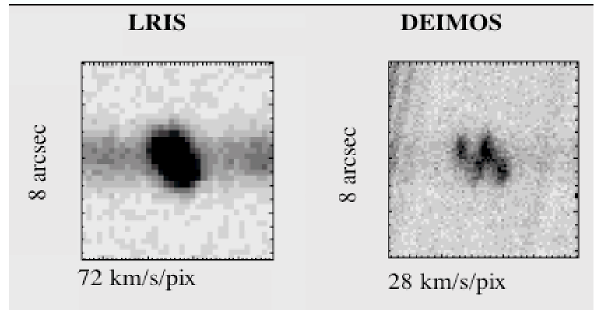

Fig. 1. Example of the improved measurements of internal kinematics of galaxies using the higher spectral resolution of the second generation Keck spectrograph, DEIMOS, as compared to that from the first generation faint object spectrograph, LRIS. The large 8Kx8K CCD detector of DEIMOS allows the use 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.

The next major lesson was that indeed very large samples (10,000 or more) are critical in several key areas of distant galaxy science that involve exploring large scale structure, cosmic variance, and environment. Such large samples are appreciated when science questions require subdividing the sample by luminosity, size, mass/light (M/L), morphology, redshift, etc. Unless other data are available to filter for rare objects such as high luminosity galaxies, kinematic pairs, or AGN, large samples are essential.

DEEP1 also confirmed that *HST* images are an important, if not critical, component of any comprehensive study of galaxy evolution, preferably using two or more filters. Such data are essential for reliable measures of dynamical mass through t he need of sizes, morphology, structure, and color analysis of galaxy bulges, disks, bars, and other subcomponents (Im et al. 2001; Simard et al. 2002; Koo et al. 2005).

Finally, DEEP1 showed the importance of gathering spectra rather than relying on crude photometric redshifts. Besides revealing kinematic structures such as groups or genuine close pairs of galaxies, spectra also provide data for chemical abundance evolution (Kobulnicky et al. 2003), star formation rate evolution (Guzman et al. 1997), ages of old stars, gas ionization, non-thermal radiation (Sarajedini et al. 2006), etc.

3. DEEP2 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.

While the scientific returns from DEEP1 have been high, DEEP2 will be pushing entirely new ground and 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). DEEP2'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, DEEP2 is able to use galaxies and groups of galaxies of given velocity dispersions as standard volume tracers (Newman & Davis 2002). For structure formation, internal kinematics play an important role by providing estimates of dynamical masses that can then be related to other galaxy properties, such as stellar masses, luminosities, colors, metallicity, age, star formation rate, etc.

From its inception, DEEP2 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:** DEEP2 is faint enough to reach beyond redshifts $z \sim 1$, when intense star formation and AGN activity are expected. DEEP2 yields spectra for a significant number of the sources from the full range of deep X-ray through radio surveys.

2) **Sample Size:** The 15,000 spectra planned for EGS are especially valuable to yield AGN's and ultra-luminous infrared galaxies (ULIRGs) that are rare in the optical, but relatively common in surveys at other wavelengths. Besides being less susceptible to cosmic variance for deriving volume densities, large samples with relatively high density of spectra also enables studies of galaxy properties as a function of environment.

3) **Spectral Resolution:** The survey resolution is about $\sigma \sim 30\,\mathrm{km/s}$. 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. Relatively low-mass groups can also be detected. Both are relevant for studying the merger scenario as the trigger of starbursts and AGN's and their environments.

4) **Spectra Range:** The large format of the CCD used by DEIMOS allows capture of a rich set of spectral features that complement key measures from other wavelength surveys. 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*.

4. SCIENCE HIGHLIGHTS FROM DEEP2

DEEP2 is over 90% complete and is already producing science results. DEEP2's large pool of redshifts provides the foundation of various basic studies of distant galaxies, including luminosity function evolution (Willmer et al. 2006; Faber et al. 2006), stellar mass evolution by adding near-infrared photometry (Bundy et al. 2006), and clustering and correlation evolution (Coil et al. 2004, 2006). Here I will highlight the science programs which take advantage of DEEP2's high spectral resolution. Such resolution enables several useful measurements:

1) the internal kinematics of galaxies: The evolution of the rotation velocity versus luminosity (Tully-Fisher - TF) relation with redshift remains confusing, in part because of sample differences and of the large scatter seen. By adding the velocity dispersion to the rotation component, we derive a new single global measure of the internal kinematics of emission line galaxies. Interestingly, we have discovered that by using this new measure, galaxies exhibit a much tighter TF relationship; moreover, the tight relation appears stable since redshift $z \sim 1$ (Weiner et al. 2006a, 2006b; Kassin et al. 2006). These results have yet to be understood theoretically.

2) the small relative velocities between kinematic close pairs or among member galaxies of groups: While most other researchers have found evidence for a rapid increase in the rate of mergers back in time, we find, instead, that the fraction of genuine close pairs, which are confirmed by DEEP2 to be kinematically associated, show little change with redshift

(Lin et al. 2004). This has only recently been accommodated in the standard hierarchical galaxy formation picture (Berrier et al. 2006). Since the velocity dispersions of groups are relatively low, only a few 100 km/s, and the few members of distant groups would be easily swamped by foreground and background galaxies, such groups cannot be easily identified without a survey like DEEP2. We have discovered that, while groups as far back as redshift $z \sim 1$ appear to be similar to groups today in hosting a larger fraction of red galaxies than the field, this color-density relation (presumably similar to the morphology-density relation) breaks down at higher redshifts (Gerke et al. 2005, 2006).

3) the narrow velocity window needed to define local densities that would serve as a measure of environment: Using similar measures for environment as those adopted in the local (SDSS) surveys, which requires fairly precise redshifts to weed out foreground and background galaxies, Cooper et al. (2006) has found that distant galaxies exhibit a color-environment/density relation similar to that seen in SDSS. Beyond a redshift of $z \sim 1$, Cooper et al. (2007) find results similar to that seen in groups, namely that the correlations decrease significantly.

4) the detection of weak spectral features: By searching for the weak, but valuable temperature sensitive, emission line of [OIII] 4363Å, we have discovered a sample of very luminous galaxies at $z \sim 0.7$ that fall off of the metallicity - luminosity relation that fit most galaxies (Hoyos et al. 2005). These galaxies have O/H values as low as 1/3 to 1/10 solar and thus serve as a caution against the common adoption of high metallicities for distant galaxies. Their relationship to local, but less luminous, counterparts or to higher redshift LBG's (Lyman Break Galaxies) is not yet understood. For absorption lines, single spectra tend to have insufficient S/N. Schiavon et al. (2006) show that stacking of spectra of distant red galaxies is able to yield information from weak lines, and they indicate that passive evolution from a single epoch is inconsistent with the combined SDSS and DEEP2 data.

A number of DEEP2 science results have also been possible through AEGIS. These can be found in a special issue of ApJ Letters (Nov. 2006).

5. LESSONS FROM DEEP FOR GTC

5.1. *Scientific and Technical Landscape Continually Evolves*

When DEEP was conceived 15 years ago, the scientific and technical landscape was very different from that when DEIMOS was finished and DEEP2 could be launched in 2002. Such changes will continue, perhaps at an even faster pace when GTC will begin scientific operation. This is especially true as another generation of new instruments are commissioned on the existing 8-10 m telescopes and even the *HST*; as the worldwide Virtual Observatory and adaptive optics become a reality; as entirely new and very powerful telescopes begin operation, such as the Large Millimeter Telescope, ALMA, *JWST*, and even the next generation of 20-30 m telescopes. These advances will challenge the users of GTC to undertake scientifically efficient and productive programs.

TABLE 1

DEEP TRIALS AND TRIBULATIONS

Dream	Reality	Result
Finish by 1996	DEIMOS late	90% by 2006
120 nights	lost Caltech	85 nights
50K spectra	bad weather	about 35K
1H & 3H prgm.	lost Caltech	only 1H
$I < 24$ galx.	I too shallow	$R < 24.1$
8 Fields	Images Incompl.	4 Fields
Get cosmology	SN & *WMAP*	Dark Energy?
Clusters too	CfPA says no	do only field
HST for 10%	GEMS/COSMOS	got only 5%
X-ray in EGS	failed 6 years	lucky 7th
SF/AGN Evol.	Dusty SF/AGN	need AEGIS
Get kinematics	emisson stronger	over 50%

Based on our experience, we strongly recommend that any competitive program aims for completion within two to three years. Gone are the days when programs can extend over many years and still be competitive. Thus the GTC TAC must have policies in place that can support key/large/multi-semester projects at a pace to ensure completion quickly. At the same time, the demands for continual productivity require that such programs are staged. Thus some *scientific milestones* should be achieved on short timescales along with publications of feasibility and pilot programs. Others should be on intermediate timescales that may include publication of preliminary scientific results, i.e. before the final conclusion phase.

This staging of projects ensures that progress can be assessed against the continually changing landscape, and if need, the program may need to be changed. Table 1 shows some of the many trials that

DEEP had to endure during its planning and implementation. For example, fundamental aspects of the project had to be changed, from its sample definition to sample size. Both were victims of weather. The reduced sample size was largely due to our Caltech partners being unable to get their TAC to grant time for DEEP. Even major changes in our scientific direction were forced upon us. For example, while the whole project was initiated and supported in large part because of its potential for constraining the basic geometry of the universe, this goal was no longer relevant after the supernovae (SN) and microwave observations from *WMAP* yielded the now widely accepted standard cosmology by year 2000. Particularly tough for the DEEP team were the many years needed before we were awarded complementary data from other telescopes. For example, we failed for 6 years to get our EGS field observed with *XMM-Newton* or *Chandra*. As an old adage goes, if you cannot beat them, join them. Thus we joined forces with our competition and finally had our field observed exceptionally well by *Chandra*; P. Nandra (PI) was awarded 200Ks coverage for seven separate pointings that covered the entire EGS region (1.4Ms total). Similarly, DEEP's proposals for additional *HST* coverage was turned down for more than five years, during which GOODS, GEMS, and COSMOS were awarded time. We finally got a major proposal through, in large part, we suspect, because of the strong multiwavelength teams that joined us.

Both the *Chandra* and *HST* proposal histories emphasize another lesson, the importance of collaborations to be successful in the modern era. Such collaborations improve the science value, whether by adding access to another hemisphere, adding wavelengths, shortening the time for completion, or generally adding resources (money, people, expertise - especially theorists) for timely and scientifically useful results. But such collaborations come with the challenge of defining leads and responsibilities among a wider pool of people, papers, subprojects, PhD theses, institutions, and observatories.

5.2. *Large Samples (1000s or more) are Needed*

This trend of working with large samples is pervading many areas of astronomy, whether studying stars, our Milky Way, galaxies near and far, or even traditionally rare classes such as AGN's. In part, this reflects the maturation in our research as we better understand and appreciate the *complexity* of multiple physical processes involved, e.g., in galaxy formation and evolution. To tackle the complexity, many more divisions of the sample are essential for discriminating the important factors, and this may mean, in the case of galaxies, selection of subsamples by redshift, mass, morphology, environment, different components (SMBH, bulges, disks, bars), etc.

Moreover, the trend is now towards "precision" cosmology and astrophysics, where measurements need to be numerous to yield small and well-understood random errors, to overcome cosmic variance, and to track down systematics. Also, galaxy observations and theory are both heading more towards understanding the distributions of parameters and volume functions instead of mere correlations among a set of parameters. Distributions require much larger samples than that needed for correlations. Besides being an efficient way to provide separate projects for large collaborations, these large samples are also becoming essential in the GTC era when so many competing telescopes and teams have been in operation in the community for years.

5.3. *Rich Data are Needed*

Since richness by having multiwavelength or high resolution data is now possible for so many astronomers, it is expected for the most competitive science programs. Moreover, if the dimensions are few, such data would have already been done by others or can be completed in relatively short time by others when GTC begins operation. Most importantly, such richness is essential to address many of the currently most popular targets and science issues: dusty star formation, AGN, high redshifts, galaxy bulges vs disks vs halo, dark matter, age versus metallicity in stellar populations, etc.

The richness is critical for cross checks of physical consistency by placing much tighter constraints on ever-improving theoretical models and simulations. Just as complexity of multiple physical processes imply the need for more measurements of any particular kind, the richness is essential to cover much larger dynamic range in energies, sizes, time, spatial environments, kinematics, metallicity, and fractions of subcomponents (SMBH, gas, dust, stars, bulges, disks, bars, etc.)

6. SUMMARY

DEEP2 is 90% finished with about 35,000 spectra of faint galaxies in hand. DEEP is a particularly powerful survey because of its solid access to redshifts beyond $z \sim 1$, its large sample size and surface density, and its rich spectral information on star formation, metallicities, ages, and dynamical masses. Science highlights near $z \sim 1$ include those needing large samples, such as measures of environments; those that involve rare subsamples such as kinematic close pairs, luminous distant galaxies with very low metallicities, or AGN's; or those needing detailed spectral information such as kinematics or metallicity. With AEGIS, we now have one DEEP2 field covered very deeply and panchromatically from the X-ray to radio. DEEP2 is now ready to embark on a new phase, DEEP3, when follow-up spectral studies will be added that reach fainter, bluer, to the near-infrared, or at higher spatial resolution.

DEEP provides many useful lessons for getting science from the GTC: data sets should be large, rich, and done quickly after a pilot program phase; collaborations provide essential leverage of resources; projects need to be continually monitored and responsive to a rapidly changing scientific and technical landscape; and the funding agencies and telescope TACs must provide explicit policies and support for large projects.

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