

THE HST COSMOS PROJECT: CONTRIBUTION FROM THE SUBARU TELESCOPE

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ABSTRACT

The Cosmic Evolution Survey (COSMOS) is a Hubble Space Telescope (HST) treasury project. The COSMOS aims to perform a 2 square degree imaging survey of an equatorial field in $I(F814W)$ band, using the Advanced Camera for Surveys (ACS). Such a wide field survey, combined with ground-based photometric and spectroscopic data, is essential to understand the interplay between large scale structure, evolution and formation of galaxies and dark matter. In 2004, we have obtained high-quality, broad band images of the COSMOS field (B , V , r' , i' , and z') using Suprime-Cam on the Subaru Telescope, and we have started our new optical multi-band program, COSMOS-21 in 2005. Here, we present a brief summary of the current status of the COSMOS project together with contributions from the Subaru Telescope. Our future Subaru program, COSMOS-21, is also discussed briefly.

Key words : observational cosmology — large scale structure —galaxies: evolution

I. INTRODUCTION

(a) Background

The Cosmic Evolution Survey (COSMOS) is an HST treasury project, awarded a total of 640 HST orbits, to be carried out in two cycles (320 orbits in cycles 12 and 13 each). This is the largest amount of HST time ever, allocated to a single project. COSMOS is a 2 square degree imaging survey of an equatorial field in $I(F814W)$ band, using the Advanced Camera for Surveys (ACS). These observations provide high resolution imaging to map the morphology of galaxies as a function of environment (overdensity) and epoch, all the way from high redshift ($z > 3$) to the nearby ($z < 0.5$) universe (detecting over 2 million galaxies) and covering a volume in the high redshift universe similar to the Sloan survey in the low redshift universe. It is known that substantial Large Scale Structure (LSS) occurs on scales up to 100 Mpc (comoving), including voids, filaments, groups

and clusters. Therefore, adequately mapping galaxy evolution over the full range of environments requires multi-waveband data with high spatial resolution, covering wide areas.

The COSMOS project is fundamental to virtually all areas of galaxy evolution, identification of different classes of objects, large scale structure and dark matter evolution, including:

- [1] the evolution of LSS, galaxies, clusters and CDM on scales up to $> 10^{14} M_{\odot}$ as a function of redshift,
- [2] the formation, assembly and evolution of galaxies and star formation as a function of LSS environment, morphology and redshift, and
- [3] detailed study of the nature, morphology and clustering properties of different populations of galaxies [AGN, extremely red objects, Ly α emitters (LAEs), Lyman Break Galaxies(LBGs), star forming galaxies] and their evolution with redshift, using enormous statistically complete samples.

The large area covered and the depth of the COSMOS, makes it complementary to other large HST surveys (UDF, GOODS, GEMS, and HDFs); see Fig. 1.

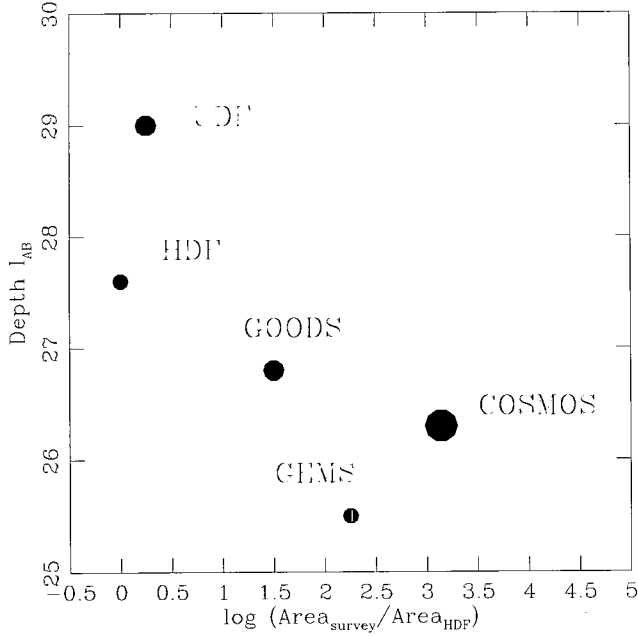


Fig. 1.— Comparison of the survey depth at I band vs. the survey area among the deep surveys made with HST; UDF, GOODS, GEMS, HDFs, and COSMOS.

The HST observations of the COSMOS are rapidly progressing, with a total of over 600 orbits completed so far. Over the last year, we successfully developed and partly completed an extensive multi-wavelength follow-up program for the COSMOS (Table 1). As shown in Table 1, the COSMOS project involves major commitments by non-HST facilities (XMM, CXO, GALEX, and Spitzer), but central elements are deep multi-color ($BVr'iz'$) imaging with Subaru ($\sim 2 \times 10^6$ objects – ~ 20 nights) and VLT/VIMOS and Magellan/IMACS spectroscopy ($\sim 5 \times 10^4$ objects – 540 hrs). Suprime-Cam on Subaru is an essential element of COSMOS, uniquely providing superb multi-color imaging data, well-matched to the depth of the HST 814 I band imaging.

(b) HST Observations

The HST-ACS observations of the COSMOS field are tailored to cover a contiguous area around its center. We perform one orbit per pointing with 10% overlap to avoid gaps between different pointings. Using the ACS pipeline developed by the Great Observatories Origins Deep Survey (GOODS) team, these data are immediately reduced and are ready for scientific use. The HST-ACS observations reach a depth of $I_{AB} = 27.8$ (5σ) over the entire COSMOS area. We expect to complete all our ACS observations by the end of Cycle 13.

While the ACS is used as the primary instrument, we

exploit NICMOS (H -band/ NIC3) and WFPC2 (UV filter) as parallel instruments. Therefore, high spatial resolution UV and near-infrared images also exist for parts of the COSMOS field. These data are also run through the pipeline and reduced.

TABLE 1.
MULTI- λ COSMOS DATA

Data	Bands, λ , Res.	AB mag 5σ pt. src
HST-ACS	814I	27.8
HST-ACS	475g	27.8
HST-ACS	475g(1)	27.8
HST-NIC3	160W	22.9(5% area)
HST-NIC3	110W	23.2(5% area)
HST-WFPC2	450W	26.4
Subaru-SCam	B, r' , z'	27.4, 27.4, 25.6
Subaru-SCam	NB816	25
CFHT-Megacam	u*	27.4
CFHT-Megacam	u, i*	26
CFHT-LS	u-z	
NOAO	K_s	22
CFHT	K	23 ($9' \times 9'$)
UH-88	J	23.5
GALEX	FUV, NUV	26.1, 25.8
XMM-EPIC	0.5 – 10 keV	10^{-15} cgs
CXO	0.5 – 7 keV	pointed
VLT-VIMOS sp.	(R=200,600)	$\#=3000$ ($I_{AB} < 23$)
VLT-VIMOS sp.	(R=600)	$\#=25000$ ($I_{AB} < 22.5$)
VLT-VIMOS sp.	(R=200)	$\#=12500$
		($B_{AB} < 25.5, 1.4 \leq z < 2.5$)
Mag.-IMAX sp.	(R=3000)	$\#=2000$
Keck/GEMINI sp.	(R=5,000)	$\#=4000$ ($I < 24$)
Spitzer-MIPS	160, 70, 24 μ m	30, 6, 0.08 mJy (5σ)
Spitzer-IRAC	8, 6, 4.5, 3 μ m	12.7, 10.3, 1.5, 0.8 μ Jy (5σ)
IRAM-30m	1.2 mm	1 mJy ($20' \times 20'$)
CSO-Bolocam	1.1 mm	3 mJy
VLA-A	20cm	24 μ Jy (1σ)
VLA-A/C	20cm	8 μ Jy (1σ)
SZA(full field)	9 mm	S-Z to $2 \times 10^{14} M_{\odot}$

(c) Multi-Wavelength Observations

We have been involved in an extensive observational campaign to use ground-based and space borne facilities to complement the HST-ACS dataset by performing multi-wavelength photometric and spectroscopic surveys of the COSMOS field. The present state of ground-based ancillary observations for the COSMOS are summarized in Table 1. All the ground-based data obtained so far are reduced, data quality tests completed and the multi-wavelength catalogs generated. Detailed description and up-dated progress on the ancillary observations are summarized on the COSMOS web page (<http://www.astro.caltech.edu/~cosmos/>). Early results of the COSMOS project were presented in the COSMOS special session of the AAS meeting in January 2005 (Scoville et al. 2004; Koekemoer et al. 2004; Lehmann et al. 2004; Mobasher et al. 2004; Rhodes et al. 2004; Shopbell et al. 2004; Schinnerer et al. 2004).

II. CONTRIBUTIONS FROM THE SUBARU TELESCOPE

(a) Five-color, Broad-band Imaging

The Subaru optical ($BVr'i'z'$) observations, obtained through 8 clear nights in January/February 2004, are completely reduced and cataloged. These images, taken in an average seeing of 0.7 arcsec, provide multi-waveband optical data for over 2×10^6 galaxies to $i' = 26.5$ mag (5σ). Although the HST-ACS observations of the COSMOS field are not yet completed, using the currently available multi-waveband COSMOS data, we have started to address the scientific questions which led to the formulation of the COSMOS project. In the following, we present a brief progress report.

Photometric Redshifts: Using the Supreme-Cam optical photometric data, we estimated photometric redshifts for $\sim 10^6$ galaxies detected in the COSMOS field. We also provided the spectral types for all the galaxies in the Subaru catalog. The photometric redshifts and spectral types are used to select galaxies for follow-up spectroscopic observations and to identify clusters.

Extremely Red Objects: Combining the near-infrared and optical data, we identified the Extremely Red Objects (EROs) in the COSMOS field. Study of the HST/ACS morphology of the EROs shows that they form a heterogeneous population, consisting of both bulge and disk dominated systems. Moreover, their photometric redshift distribution shows that the majority of the EROs are located around $z \sim 1$. Study of the clustering and luminosity function of the EROs is currently in progress.

Gravitational Lensing: For the first time, a comparison is performed between the gravitational lens candidates on the I814-band HST/ACS and i' -band ground-based Subaru images (see bottom panel of Fig. 2; Miyazaki et al. 2005, in preparation). We are investigating the efficiency of finding gravitationally lensed systems with HST, as compared to ground-based Subaru data taken under 0.4 arcsec seeing conditions.

r' and i' -band drop-outs: Samples of r' and i' -band drop-out candidates are identified from the COSMOS Subaru data. Also, combining the COSMOS z' -band and deep J -band data over the 9×9 arcmin central area of the COSMOS, we have identified a sample of z' -band drop-out galaxies, expected to be at $z \sim 8$. We are planning spectroscopic observations to confirm the redshift of these galaxies. This provides an unprecedented sample for statistical studies of galaxies at $4 < z < 8$.

A cluster of galaxies at $z=0.7$: Optical identification of X-ray sources found in our XMM-Newton survey has led to the discovery of a cluster of galaxies at $z \sim 0.7$ (Fig. 2). Follow-up optical spectroscopy has confirmed this cluster.

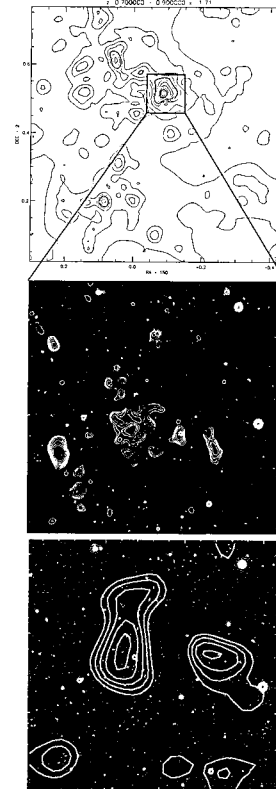


Fig. 2.— [top] A cluster of galaxies at $z \sim 0.7$ found from our photo- z catalog around one of XMM sources; X-ray contours are overlaid on Suprime-Cam i' band image. This cluster is spectroscopically confirmed as a real cluster by VLT/FORS1 spectroscopy. Large green circles are galaxies around $z = 0.73$. FOV is 6.7×6.7 arcmin. [middle] This cluster is also clearly detected in our weak lensing analysis by Satoshi Miyazaki [bottom]. The contour shows a weak lensing S/N map reconstructed from Suprime-Cam i' -band image whose smoothing scale (θ_G) is 30 arcsec. Here 1500 faint galaxies with $23 < i' < 25.5$ are used for the reconstruction. The contour starts from S/N = 1 with the interval of 0.5. FOV is the same as that of left panel.

(b) COSMOS-21

The COSMOS-21 program aims to extend and complete the ground-based optical observations of the COSMOS field with deep intermediate and narrow-band optical imaging of the entire 2 sq. deg field. The filters used in the COSMOS-21 project are summarized in Table 2. As for the intermediate-band filters, see Taniguchi (2004), Fujita et al. (2003), Ajiki et al. (2004), Shioya et al. (2005), and Yamada et al. (2005).

This COSMOS-21 project

specifically addresses two major goals:

[1] The first major COSMIC survey of emission line ($H\alpha$, $Ly\alpha$ & [OII]) galaxies with available HST/ACS morphologies, covering different local environments and sampling the critical range of redshift for galaxy formation and activity. This allows a wide range of studies

from properties of local ($z < 1$) star forming objects to proto-galaxies at the re-ionization epoch ($z \sim 7$).

[2] Major improvement in the accuracy of photometric redshifts (typically $\delta z/(1+z) < 0.1$) for over a million galaxies at high redshift ($z \sim 7$) down to $i_{AB} \sim 25.5$ (see Figure 3). The value of intermediate and narrow-band data in improving photometric redshifts is demonstrated by COMBO-17 survey (Wolf et al. 2003).

The result will be a survey with spectral coverage similar to COMBO-17 but 4 magnitudes deeper, over a larger area and a much more extensive ancillary (photometric/spectroscopic) dataset. The COSMOS will be a legacy survey for the world astronomical community for many years to come. With the possible shortened lifetime of HST, this may be the last and largest survey with the highest quality imaging for the next 2 decades.

TABLE 2.
A LIST OF FILTERS USED IN OUR PROJECT

Filter	λ_{center} (nm)	$\Delta\lambda$ (nm)	$z_{\text{Ly}\alpha}$	$z_{\text{[OII]}}$	$z_{\text{H}\alpha}$
NB921	920	13	6.6	1.4	0.41
NB816	815	12	5.7	1.2	0.24
IA797	797	34	5.6	1.1	0.21
IA738	738	34	5.1	0.98	0.12
IA709	709	34	4.8	0.90	0.08
IA651	651	33	4.4	0.75	...
IA624	624	31	4.1	0.67	...
IA598	598	30	3.9	0.60	...
IA574	574	28	3.7	0.54	...
IA550	550	27	3.5	0.48	...
IA527	527	26	3.3	0.41	...
IA505	505	25	3.2	0.35	...
IA484	484	24	3.0	0.30	...
IA464	464	23	2.8	0.24	...
IA445	445	22	2.7	0.19	...
IA427	427	21	2.5	0.15	...

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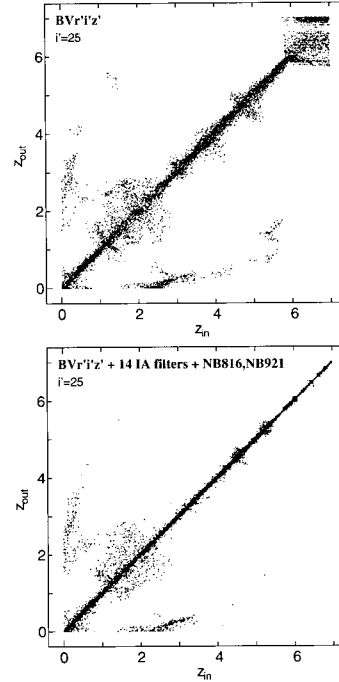


Fig. 3.— Photo- z simulations. [upper] Case for only broad-band ($BVr'i'z'$) data; limiting magnitudes are 28 for B and V , 27.5 for r' , 27.0 for i' , and 26.0 for z' . [lower] Case for the proposed filter set ($BVr'i'z' + 14$ IA filters + 2 NB ones: COSMOS-21); limiting magnitudes are 27.5 for B , 27.0 for V , 27.0 for r' , 26.6 for i' , 25.6 for z' (our current data obtained with Suprime-Cam), 26.0 for the 14 IA filters and 25.5 for the two NB ones.

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