Hubble Space Telescope

Cycle 14 GO Proposal

Searching for galaxies at z>7 in the Hubble Ultra Deep Field

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Instruments: ACS, NICMOS

Proprietary Period: 0

	3 Gyro Mode Orbit Request		2 Gyro Mode Orbit Request	
	Prime	Parallel	Prime	Parallel
Cycle 14	204	204	204	204

Abstract

We propose to obtain deep ACS (F606W, F775W, F850LP) and NICMOS (F110W, F160W) images of the NICMOS parallel and ACS Hubble Ultra Deep Field areas, respectively, so as to match their depth in the optical and near-IR bands. These observations will image seven fields with ACS and NICMOS producing data deep enough to detect the expected typical galaxies at z=7 and 8. Presently no such a field exist. If reionization is a process extending over a large redshift interval and the luminosity function doesn't evolve strongly beyond z=6, these data will allow us to identify of the order of a dozen galaxies at 6.5<z<8.5 and to place a first constrain on the luminosity function at z>7. Conversely, finding fewer objects would be an indication that the bulk of reionization is done by galaxies at z=6. By spending 204 orbits of prime HST time we will capitalize on the investment of 544 prime orbits already made on the Hubble Ultra Deep Field (UDF). NICMOS and ACS data will be obtained in parallel. We have verified that the program as proposed is schedulable and that it will remain so even if forced to execute in the 2-gyro mode. The data will be non-proprietary and the reduced images will be made public within 2 months from the completion of the observations.

Investigators:

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Number of investigators: 13

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Target Summary:

Target	RA	Dec	Magnitude
UDFNICP12	03 33 3.6000	-27 41 1.80	V = 18.0 +/- 0.1
UDFNICP34	03 33 8.2000	-27 52 56.80	V = 18.0 +/- 0.1

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
UDFNICP12	ACS/WFC Imaging F606W		9
UDFNICP12	ACS/WFC Imaging F775W		23
UDFNICP12	ACS/WFC Imaging F850LP		70
UDFNICP34	ACS/WFC Imaging F606W		9
UDFNICP34	ACS/WFC Imaging F775W		23

Target	Config Mode and Spectral Elements	Flags	Orbits
UDFNICP34	ACS/WFC Imaging F850LP		70
UDFNICP12	NIC3 Imaging F110W	CPAR	51
UDFNICP12	NIC3 Imaging F160W	CPAR	51
UDFNICP34	NIC3 Imaging F160W	CPAR	51
UDFNICP34	NIC3 Imaging F110W	CPAR	51
		Total orbit request:	408

- **Scientific Justification**

The Early Evolution of Stars and Galaxies
To understand how the stars, galaxies, and black holes we see today emerged from the primordial perturbations left over from the Big Bang, we need to study populations of objects at all epochs from the re-ionization era ($6 < z < 20$) until today. The most difficult task has been to find samples of objects at very high redshifts, when the evolution of structure, heavy element abundance, and luminosity was most rapid. A series of surveys with the Hubble Space Telescope (HST), including the Hubble Deep Field in 1996 (HDF), the Great Observatories Origins Deep Survey in 2003 (GOODS), and the Hubble Ultra Deep Field (UDF) in 2004, gave us the first extensive samples of Lyman-break selected objects out to redshifts of ~7 with enough resolution and sensitivity to study the morphology, color, and luminosity of young galaxies. The formation of galaxies and QSOs, and possibly the interplay between black hole and galaxy growth, originated at redshifts of 6 or greater, when hydrogen in the intergalactic medium was completely re-ionized for the first time since the era of recombination at $z\sim1000$. Studying objects at $z\sim6$ and higher is essential for understanding the first steps of galaxy formation.

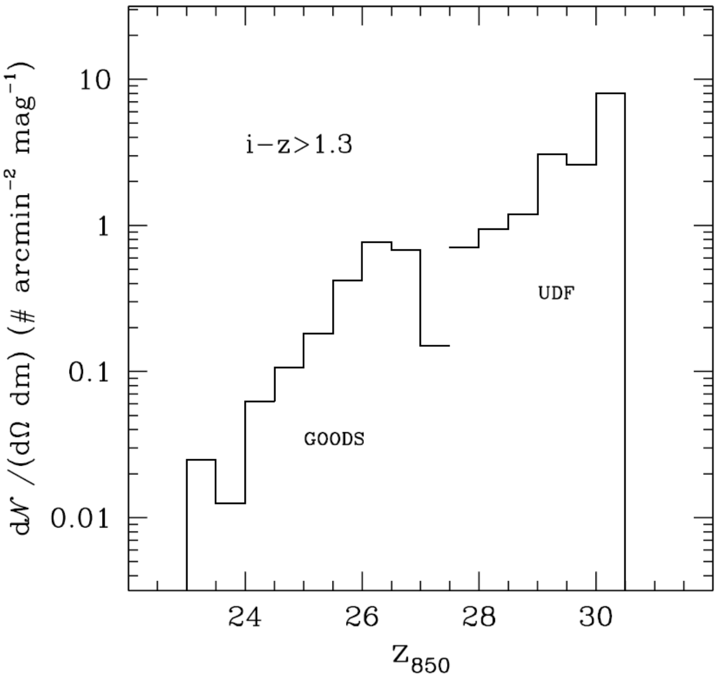

Figure 1. Observed counts of z=6 galaxy candidates from the UDF and GOODS. The objects are selected as *i*-*z*>1.3 and no completeness correction has been applied. The spectroscopically confirmed fraction at *z*<27 is about 80% per cent.

The early samples of high redshift galaxies were modest. The HDF contained only 69 *U*-dropout ($2<z<3.5$) and 14 *B*-dropout objects ($3.5<z<4.5$, Madau et al. 1996). The Advanced Camera for Surveys (ACS) improved HST's sensitivity at red optical wavelengths, allowing GOODS (Giavalisco et al. 2004) and especially the UDF (Beckwith et al. 2005, Fig. 1) to select galaxies as *V* and *i*-dropouts, with redshifts up to ~6.7. Here *V* denotes the F606W filter and *i* denotes the F775W one. These surveys uncovered several hundred *V*-dropouts and at least 70 well-detected *i*-dropout objects ($z>5.5$, Dickinson et al. 2004, Beckwith et al. 2005). Thus, for redshifts out to about 6, we now have adequate samples of galaxies to address the issues of early evolution (Fig. 1.).

When did reionization occur and what objects provided the ionizing radiation?

Determining when and how the universe was reionized has been an important question in cosmology for at least four decades (e.g. Gunn & Peterson 1965, Sunyaev 1977). The observational advances of the last few years have finally produced adequate data to begin addressing this question. The spectra of z>6 QSOs from the Sloan Digital Sky Survey (SDSS, Becker et al. 2001) and particularly that of SDSS J1030+0524 at z=6.28 show evidence for a Gunn-Peterson (1965) trough (Fan et al. 2001), meaning that the intergalactic medium (IGM) was not fully ionized at this redshift along this line of sight. Unfortunately, the samples are still small, while the differences between lines of sight are likely to be large. Moreover, searches for Lyman α emitting galaxies at z=5.7 and 6.5 (Rhoads & Malhotra 2004, Ajiki et al. 2004, Taniguchi et al. 2004) have not shown the major change in the luminosity function (LF) of these objects expected if these two redshifts were bracketing reionization.

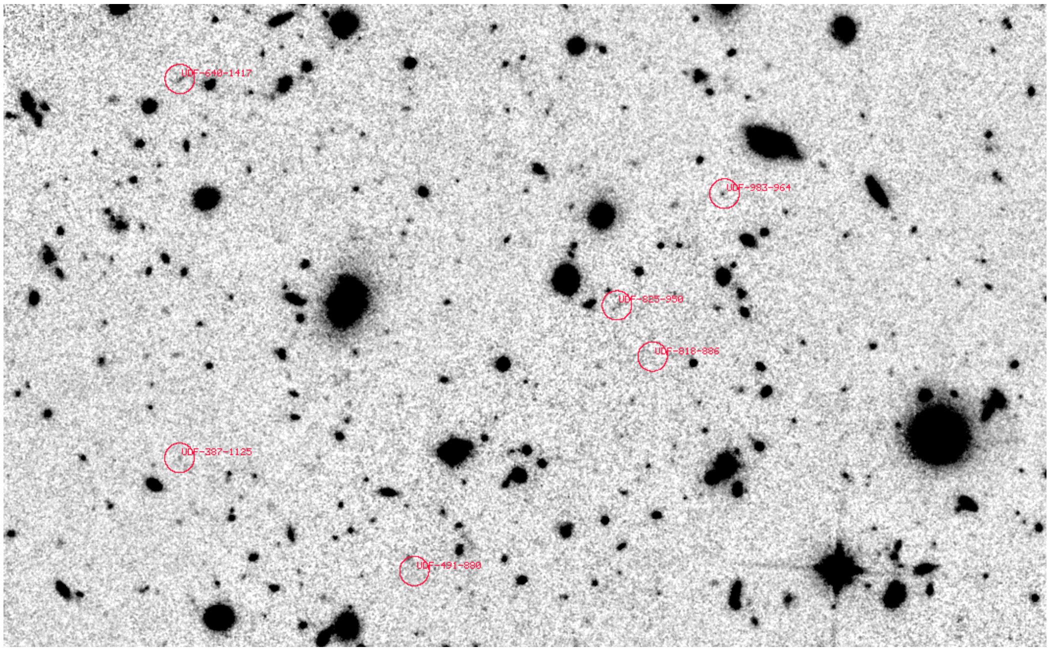

Figure 2. Redshift 7 and 8 candidates from Bouwens et al. (2004) as they appear on our independent reduction of the F160W data. Various NICMOS artifacts have been removed and we confirm four of the six candidates even though two are very faint. The image size is 95" by 60".

Preliminary evidence from WMAP indicates that a significant fraction of hydrogen was ionized at much higher redshifts (Kogut et al. 2003), suggesting a significant ionized fraction may have been in place at z~15-20. Even assuming the QSO and Lyman α results are not dominated by cosmic scatter, the extant results might still be compatible with a relatively simple reionization history, because the different indicators are sensitive to quite different neutral hydrogen fractions, e.g. a Gunn-Peterson trough can arise already for very low neutral hydrogen fractions that would not cause a major change in the observed LF of Lyman α sources. Alternatively, the universe might have had a complex reionization history (Cen 2003, Haiman & Holder 2003, Gnedin 2004) starting at z>15 but completed only at z~6, with a neutral fraction of ~10% at z=6.5.

We still don’t know even the tail end of the reionization history or which objects were responsible for it. The z=6 galaxies found so far may have an ionizing photon output that is tantalizingly close to what is needed to complete reionization and/or to keep the IGM ionized if the bulk of reionization had occurred earlier. Adopting a normal LF, normal stellar populations of solar metallicity and escape fractions of ionizing radiation similar to what estimated at z=3 (Steidel et al. 2001), the observed objects fail to produce what is needed for reionization (Bunker et al. 2004). They could be responsible for reionization if their LF is particularly steep (Yan & Windhorst 2004) or their stellar populations have low metallicity and a top-heavy initial mass function (Stiavelli et al. 2004). However, what is observed might fulfill the requirements to complete reionization even with a normal luminosity function (LF) and stellar population if the bulk of hydrogen was ionized at an even higher redshift.

The way to resolve this important open problem of cosmology is to study galaxy populations at z>6. If the number density of galaxies drops markedly beyond z~6, then it would suggest that either the population already observed at z~6 has the ionizing properties required to re-ionize the universe (whatever this implies for the LF, metallicity, escape fraction of ionizing photons) or objects other than galaxies provide the bulk of the luminosity at high redshifts. Conversely, significant numbers of galaxies at z>6 would corroborate a scenario of complex and extended reionization history.

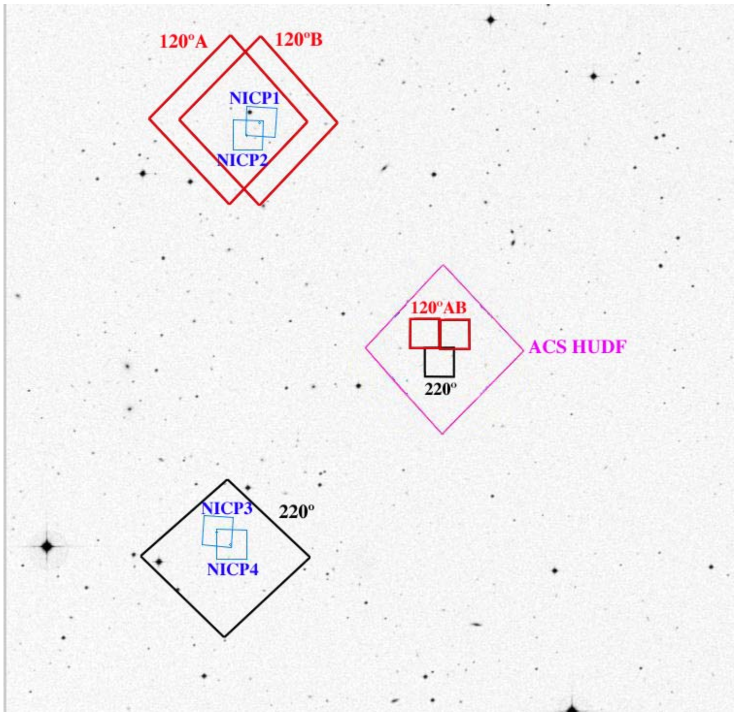

Figure 3. The main ACS UDF field (magenta) and the 4 existing NICMOS parallel fields (NICPx, light blue) are shown. Each NICMOS parallel field is deeper by 0.5-1.1 mag. than the NICMOS UDF Treasury exposures on the main field. The red and black fields sketch the footprint of ACS & NICMOS for the two orientations in this proposal. The details will depend on the number of gyros available.

Finding high redshift objects

There are indications that the LF at z=6 is at least as steep as that at z=3, $\alpha=1.6$, if not steeper (Bunker et al. 2004, Yan & Windhorst 2004), but the faint end slope is not well known because of the uncertainties in the completeness corrections. Moreover, if reionization really occurs between redshift 6 and 7, we expect the slope to become significantly steeper between redshifts 6 and 7, because the formation of dwarf galaxies should be favored by a less intense UV background before reionization (e.g. Quinn et al. 1996, Barkana & Loeb 1999, Shapiro et al. 2004).

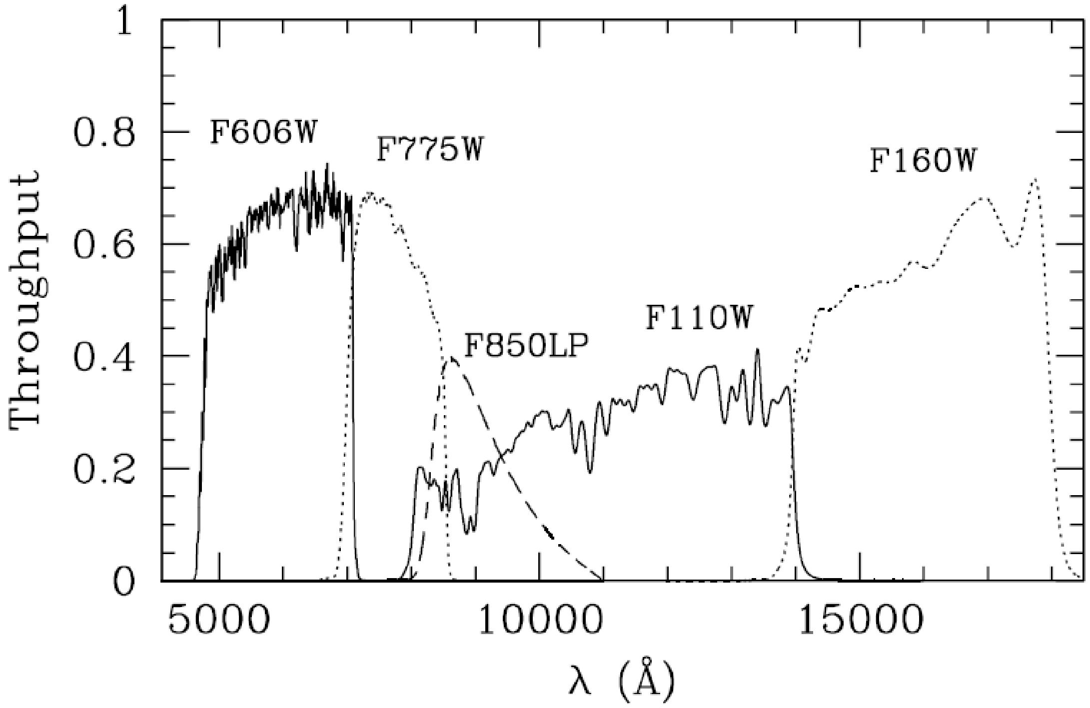

Figure 4. Total throughput curves for the ACS filters F606W, F775W, and F850LP and the NICMOS filters F110W and F160W. The NICMOS throughput has been rescaled for plotting purposes.

The sample of high redshift galaxies should increase quickly with additional depth. Bouwens et al. (2004) searched for z~7-8 galaxies in the combined NICMOS Treasury follow-up and main ACS-UDF data set and found 6 possible *z*-band dropout objects (*z*=F850LP) close to the faint limit of the current NICMOS data (see Fig. 2), four of which are credible candidates for high redshift galaxies. Extrapolating the number of observed objects at z=6 to redshifts 7 and 8 (distance modulus increments of 0.25 and 0.45 mag, respectively) and assuming the same luminosity function (Fig. 1), we expect 0.7 objects arcmin^{-2} or 4-5 objects in the whole Treasury UDF NICMOS field (~6.5 arcmin^{2}) down to AB=27.7 in the near-IR. These objects should lie very close to the faint limit of the survey in agreement with the results of Bouwens et al. (2004). By going just 1 magnitude deeper in the near-IR, the predicted number of objects increases to ~2.5 arcmin^{-2} at z=7 and ~2 arcmin^{-2} at z=8, an increase of more than a factor of three. Therefore, a sample of >10 high redshift galaxies could be obtained by searching a few arcmin^{2} to this depth.

Of the existing deep NICMOS/ACS fields, only the UDF has adequate depth to justify deeper observations. The deepest existing NICMOS fields are in the HDFN, HDFS, and the UDF parallel fields. The HDFN NICMOS field lacks the *z*-band exposure that is essential to discriminate between z=6 or z=7-8. The HDFS NICMOS field only has a wide band STIS image that is not useful for dropout searches. The main UDF ACS and the UDF NICMOS parallel fields will be covered by this proposal, as discussed below.

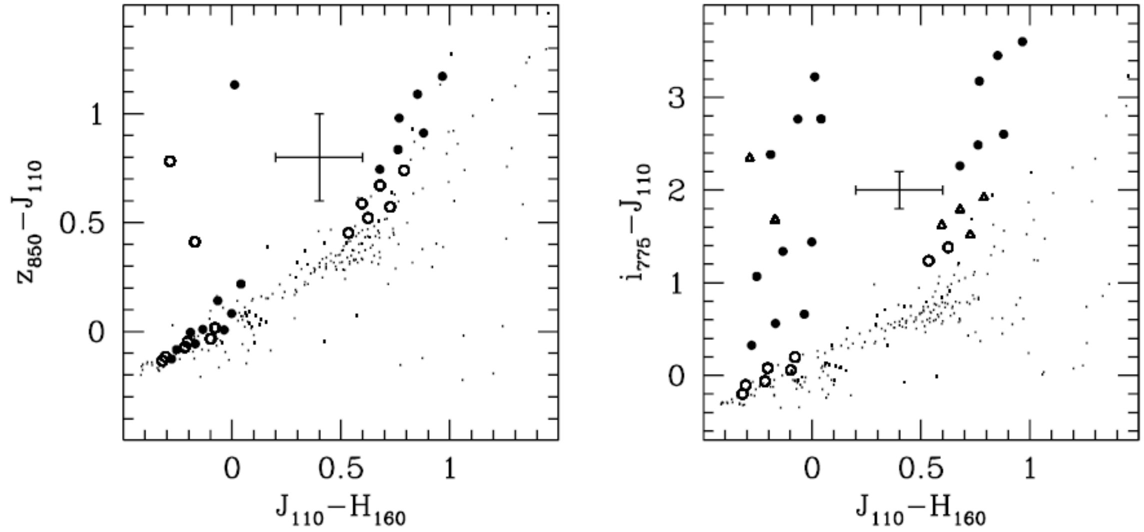

Figure 5. Color-color selection criteria in *z-J* vs *J-H* (left) and *i-J* vs *J-H* (right). The model SEDs represent a combination of age, metallicity, dust content, and star formation history. The small dots are objects at z<=5.5, the open symbols are objects at 5.5<z<7 and the filled circles are galaxies at z>7. The error bars correspond to colors measured to 0.2 mag. Selecting galaxies using simultaneously *i–J* and *i-z* provides for a wider color range (less sensitive to photometric errors) and allows for a better separation of z=6 galaxies from the z>=7 ones. Notice how many objects with red *i-J* in the right panel are compressed onto the sequence of foreground objects in the left panel. Objects at 5.5<z<7 that are red in *i–J* can be identified by *i-z* > 0.9 (triangles in the right panel).

This proposal

We propose to dramatically increase the sample of galaxies at redshifts greater than ~6.5 by increasing the area covered simultaneously by deep NICMOS and ACS data. We do so by increasing the depth of fields already available from the main UDF survey: a deep ACS field and 4 deep (partly overlapping) NICMOS fields that were originally obtained in parallel (Fig. 3). The depth of even the shallower of these fields (see Table 1) exceeds that of the NICMOS UDF Treasury program used in the Bouwens et al. (2004) study (25 to 75 orbits per filters instead of 9 orbits per filter). The NICMOS parallel fields need deep observations with ACS, whereas the UDF ACS field needs deeper J and H-band observations with NICMOS. Thus, we can simultaneously increase the depth in all fields by using coordinated parallel observations with an appropriate HST orientation on the sky as illustrated in Fig. 3.

Our proposed observations obtain data on several fields separated by several arcmin, i.e. ~10 comoving Mpc at z=7. From the point of view of cosmic variance this configuration is superior to a single field.

The primary observations will be 102 orbits (see Description of the observations) for each of two ACS fields centered on the current NICMOS parallel fields. Simultaneously, we will increase with parallel observations the depth of J and H data in three areas of the UDF ACS field (Fig. 3, see below the Required Depth section). One of the primary fields, NICP3+NICP4, will produce parallel NICMOS observations in the main ACS UDF field to a depth of 51 orbits/filter. The other two parallel fields will produce NICMOS observations to a depth of 25 orbits/filter each in separate portions of the main ACS UDF field. Our strategy is to obtain two “shallower” fields instead of a deeper single one because scheduling constraints force us to change both roll angle and pointing to achieve the primary exposure time. These observations will allow us to detect approximately 7 galaxies at $6.5<z\leq 7.5$ and 5 galaxies at $7.5<z\leq 8.5$ unless the LF strongly evolves beyond z=6. By placing one of our NICMOS parallel fields on top of the two faintest of the Bouwens et al. candidates, we will be able to confirm their nature and, more importantly, obtain a first constraint on the slope of the z=7-8 luminosity function. The LF of these objects would be very hard to obtain with other techniques as, e.g., lensing amplification probes only a small effective area and provides results that are affected by small number statistics and depend on the lens model. *For 204 primary orbits, i.e. only 38% of the investment already made in the UDF, we will image 7 fields with combined NICMOS and ACS exposures deeper than any available.*

High-redshift selection.

We will select objects using a *z*-dropout criterion. The *i-z* color has been proven effective in selecting objects at z=6; Malhotra et al. (2004) have shown that the fraction of interlopers is less than 20% for *i-z*>1.3. The same technique needs one additional step to be extended to the *z*-dropout objects. The NICMOS F110W filter entirely encompasses the F850LP filter and has a sensitivity increasing toward its red end (Fig. 4). Thus, an object with a red SED and no break could appear red in *z-J* (*J*=F110W), mimicking a high-redshift galaxy. Moreover, the color range in *z-J* spanned by typical objects is not very large, so that photometric errors can be very important. In contrast, the *i-J* color provides better separation between classes of objects (see Fig. 5) as the F775W filter has essentially no overlap with F110W. Objects at $5.5 < z < 7$ will also be selected by an *i-J* selection criterion, but can be identified from their red *i-z* color. Thus, we plan to select z>7 candidates using the color-color-color cube *i-z* vs *i-J* vs *J-H*. The F606W filter will be used for an additional rejection of low-redshift interlopers (z~1.5-2).

Depth and Sensitivity.

The UDF NICMOS parallel fields have exposures of 25 (“shallow”) or 75 (deep) orbits/filter with a small ultradeep overlap region reaching 100 orbits/filter. Each ACS image will cover a pair with “shallow” and deep NICMOS fields. Thus, our ACS observations must have a depth sufficient to identify *z*-dropouts in the deep fields. Since the deep fields have a limiting magnitudes of AB=28.7 (5σ) for an extended source (0.6 arcsec diameter), we need to reach AB=30.1 at 1 sigma in the F606W, F775W, F850LP bands to detect sources with the required colors. This depth allows us to place a 2σ limit to the *i-z* and *i-J* colors if redder than 1.3 for any source detected at 10-sigma in F110W.

Urgency of this investigation

The uncertainties in the servicing of HST and the fact that the ACS CCDs degrade because of radiation damage add urgency to this investigation. Passing on the opportunity of studying now galaxies at z=7 and 8 might force us to wait until the launch of JWST. In contrast, studying these objects now might even allow us to influence design aspects of JWST instruments such as filter choices in NIRCam or wavelength coverage of the tunable filters.

- **Description of the Observations**

Imaging data and exposure time.

Our goal is to detect galaxies at $z>6$. To do so, we need to detect them in the NICMOS F110W and F160W bands and establish firm upper limits in the visible. Because of the nature of the F110W filter, we believe that the best way of doing so is to require upper limits in both F775W and F850LP. We are also proposing to add an F606W exposure, because for a modest cost of 9 orbits per field it provides an additional data point to rule out lower redshift interlopers. We are not planning to obtain a F435W exposure, because the lower sensitivity makes imaging in this filter not useful for the primary goal of this proposal. For the two primary ACS fields, the required depth is AB=30.1 (1σ) for galaxies 0.6 arcsec in diameter. This depth requires 9 orbits in F606W, 23 orbits in F775W, and 70 orbits in F850LP. On the parallel fields, we will have 51 orbits in F110W and 51 orbits in F160W. These data will allow us to reach AB=28.4 at 5σ for galaxies 0.6 arcsec in diameter. The depth of the main ACS UDF field is perfectly adequate to search for *z*-dropouts down to the limit of our NICMOS parallel observations.

Following the UDF experience the observations will be done in two orbit visits of four half-orbit integrations and well dithered using individual, non overlapping, 4-point dither patterns. They will be combined with the multi-drizzle software with a final pixel size of 30mas. By carefully crafting the parallel exposures we were able to reach a scheduling efficiency for the NICMOS parallels of about 85% (in exposure time). We plan to use the same technique for the parallel NICMOS exposures requested here.

Proprietary rights.

We expect these data to be of general interest for the observational cosmology community therefore the data will be non-proprietary and immediately available from the HST archive. The reduced images and source catalogs will be made public within 2 months from completion of the observations.

Orientations and NICMOS Parallel.

By selecting the appropriate roll angles for HST, we can increase the combined optical-near IR depth simultaneously over both the UDF-NICMOS parallel fields and the UDF-ACS main field, generating in the process optical/near-IR seven ultra deep fields where none existed before. Indeed, the NICMOS fields 1-2 can be observed at ORIENT ~120 degrees, so that NICMOS will image the main ACS UDF. The NICMOS parallel exposures will be two fields with 25+26 orbits per filter because of scheduling constraints (see below). The NICMOS fields 3-4 can be observed at ORIENT around 220 degrees so that NICMOS will image one field in the main ACS UDF with 51+51 orbits per filter.

Achieving the required orientations requires some fine-tuning even with 3-gyros. Indeed, the orientation of the main UDF field was chosen to maximize visibility, and orientations at 180 degrees from those used for that field are less favorable. In the UDF, we found that we could utilize 6 orbits/day without stressing the schedule. We will use this as our criterion for a sanity check on the schedulability of this proposal. We will consider the observation as schedulable if we can have a visibility of at least 18 days at the required orientation. For orientation 120, thanks to the size of the ACS WFC FOV, we can cover fields 1 and 2 for a range of orientations between 116 and 145 degrees by changing the pointing. However, as the orientation approaches 145 degrees we get close to Sun avoidance and enhanced zodiacal background. A safe range is between 116 and 125 and could still be observed for about 19 days. We find that for orientation 220 degrees we can observe for 24 days if we allow orientations between 210 and 224 degrees. The visibility would be only about 10-14 days at any fixed orientation in this range. Thanks to the FOV of ACS we can adopt two roll angles while still covering the NICMOS parallel fields 3 and 4 and having a single NICMOS parallel field on the main ACS UDF. We have tested these ideas with the available orientation tools on the web and also by implementing a trial phase II.

Team expertise and work plan

Our team is very experienced with obtaining and analizing ACS and NICMOS data, in particular:

Scheduling and phase II. Stiavelli and Lucas developed the phase II for the UDF and its parallel observations and helped develop the phase II of GOODS. Ferguson and Lucas developed the phase II for HDF and HDFS.

Technical knowledge. Stiavelli is the lead of the imaging branch at STScI and Koekemoer is an ACS instrument scientists. Bergeron is a member of the NICMOS group. Koekemoer and Hook developed the multidrizzle software which will be used for the image combination.

Experience with large surveys. The proponents include the core team that carried out the UDF survey (Beckwith, Stiavelli, Koekemoer, Ferguson, Robberto, Hook, Bergeron, Lucas, Panagia) as well as critical members of the GOODS (Ferguson, Hook, Koekemoer) project, COSMOS, HDFS and HDF. Rix (the GEMS PI) and Beckwith were members of GEMS. Lilly was the PI of CFRS.

Work Plan Highlights. The STScI-based part of the team will carry out the observations and release them to the public. The European-based part of the team will take the lead in attempting deep follow-up spectroscopy of the candidates using the VLT. It is unlikely that the VLT will be able to detect the continuum of these objects but emission lines with rest frame EW of 50 or so could be detected if favorably placed with respect to the atmospheric lines.

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- ## Strategy for Two-Gyro Observations

In 2-gyros we will be able to obtain NICMOS parallel exposures on the main ACS UDF only for the NICMOS fields 3-4 corresponding to ORIENT around 220. ORIENT 120 was the most constrained even with 3-gyros and it will be unavailable in 2-gyro operations. Thus, in 2-gyro operations the ACS observations of the NICMOS parallel fields 1 and 2 will not be constrained in orientation.

In practice, 2-gyro operations will leave unchanged the number of 100+ orbits NICMOS fields with matching ACS exposures and lower the number of 50 orbits NICMOS fields from 4 to 2. A summary of the various fields with their NICMOS exposure time and 2-gyros feasibility is given below.

Table 1: Existing and proposed NICMOS fields, their exposure time in orbits, origin of the data and feasibility in 2-gyro HST operations. Fields labelled NICPx are the UDF parallel fields. Those labeled NICUx will be obtained by this proposal.

Field	NICMOS orbits	Origin of NICMOS data	Origin of ACS data	2-gyro feasibility
NICP1	25+25	Existing (UDF par)	**This prop.(prime)**	yes
NICP2	75+75	Existing (UDF par)	**This prop.(prime)**	yes
NICU1	25+26	**This prop. (parall.)**	Existing (UDF ACS)	no
NICU2	25+26	**This prop. (parall.)**	Existing (UDF ACS)	no
NICP3	25+25	Existing (UDF par)	**This prop. (prime)**	yes
NICP4	75+75	Existing (UDF par)	**This prop. (prime)**	yes
NICU3	51+51	**This prop. (parall.)**	Existing (UDF ACS)	yes

Another impact of 2-gyro operations will be a reduction of orbital visibility going from the 3-gyro duration of 48-54 minutes to the 2-gyro duration of 41-46 minutes. This reduced duration of up to 15 per cent combined with the possibly slightly degraded PSF will reduce the depth of our observations by less than 0.2 mag. and have no major impact on the proposed science. For this reason we have chosen not to compensate for this small loss in depth by requiring more exposure time for the 2-gyros implementation of this proposal.

- ## Special Requirements

None.

- ## Coordinated Observations

None.

- ## Justify Duplications

This proposal doesn’t duplicate any existing data set. NICMOS images on the main ACS UDF field were obtained by the UDF NICMOS Treasury team and ACS images on the NICMOS parallel fields were obtained by the GEMS team. These data sets are now public and our observations will be much deeper.

- **Previous Related HST Programs**

Our team was responsible for obtaining, reducing, and making available to the public the UDF ACS and NICMOS parallel observations. In Beckwith et al. (submitted to AJ), we describe the ACS UDF data reduction and main results. Robberto et al. (in preparation) describes the NICMOS parallel fields reduction. Stiavelli et al. (2004, ApJL 610, L1) discusses how the observed z=6 galaxies could be responsible for reionization. Mobasher et al. (in preparation) discusses in detail one of the z=7 candidates in the UDF.

Stiavelli is PI of a study of the environment of five z=6 QSOs (GO 9777, 35 orbits). The data have been reduced and are currently being analyzed. A first paper reporting on evidence of clustering in the field of J1030+0524 has been submitted to ApJL.

Stiavelli, Gardner and Panagia are CoIs of the GRAPES project securing ACS GRISM observations in the UDF (PI Malhotra, GO 9793, 40 orbits). The data have been fully reduced and a number of papers are being published including one on the sample (Pirzkal et al. 2004, ApJS, 154, 501) and one on the spectroscopically confirmed objects at z>5.5 and their clustering properties (Malhotra et al. submitted) .

Stiavelli was CoI of GOODS and the HDFS and is author/coauthor of the following papers based on these data: Giavalisco et al. 2004 ApJL, 600, L93; Lucas et al. 2003, AJ, 125, 398; Casertano et al. 2000, AJ, 120, 2747; Williams et al., AJ, 120, 2735; Stiavelli et al. 1999, AA, 343, L25.