The formation and evolution of galaxies I: The deep imaging survey(s)

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Scientific category: DISTANT GALAXIES
Instruments: OPT/CAM, NIR/CAM, MIR/CAM
Days of observation: 112

Abstract

It is proposed to carry out a deep multi-band imaging survey aimed at understanding galaxy evolution. The survey will detect and identify the first star-forming systems at extremely high redshifts and will produce deep imaging data for a large number of galaxies in the $1 < z < 5$ redshift range that will also be studies spectrocopically. In order to fully sample the very broad range of redshift and range of evolutionary states and spectral energy distributions that will be encountered at faint levels, the survey will consist of deep exposures in 8 filters spanning a factor of 10 in wavelength (0.5 - 5 microns) will be used. The deepest images will detect low star-formation rates at redshifts as high a $z \sim 20 - 40$. These will be taken in a single field and will represent 7 days integation per filter and will reach AB=34 for point sources. In addition 16 other fields will be observed to a 1.5 mag shallower depth in order to ensure that representative volumes of the $1 < z < 5$ Universe are surveyed.

Observing Summary:

Target	RA	Dec	m_{AB}	Configuration/mode	Days
DEEP FIELD	TBD	TBD	34 at L	NIR/CAM (J,K,L,M) R3	28
DEEP FIELD	TBD	TBD	34.8 at V	OPT/CAM (V,I) R3	14
DEEP FIELD	TBD	TBD		MIR/CAM (10) R3	14
WIDE FIELD X 16	TBD	TBD	32.5 at L	NIR/CAM (J,K,L,M) R3	28
WIDE FIELD X 16	TBD	TBD	33.3 at V	OPT/CAM (V,I) R3	14
WIDE FIELD X 16	TBD	TBD		MIR/CAM (10) R3	14
				Grand total days	112

Scientific Objectives

1. OVERALL SCIENTIFIC OBJECTIVES

A imaging survey with the NGST in the 0.5-30 micron waveband will extend our view of the Universe to unprecedented depth. The proposed survey is aimed at addressing the following questions: **What were the origins of the galaxies and other objects we see around us in the Universe today? In particular, what physical processes drove their formation and subsequent evolution?** While ground-based and HST observations have given us our first clues as to the history of galaxies in the $0 < z < 5$ range, major questions remain which must be answered before we can claim to understand this aspect of our Origins.

- *What were the first sources of light in the Universe?* Were they stars, black holes, or something else? How and when was the Universe reionized?
- *How were galaxies assembled?* Did this proceed hierarchically by merging? What was the role of dark matter? What was the relative importance of gravity, dissipation, and energy injection on different scales?
- *How did the Hubble sequence form?* When and how did the stars in spheroids and disks form? How important was merging in determining the morphologies of galaxies?
- *How do galaxies interact with their environment?* How and when did galaxies exchange mass, metals, and radiation with the intergalactic medium? What was the origin of the metal-rich hot gas in clusters of galaxies?
- *Regarding the Universe as a single system, what are the global histories of star formation, metal enrichment, and gas consumption?*
- *What is the relationship between active galactic nuclei and their host galaxies?* Do AGN stimulate or inhibit star formation? When did massive black holes first appear?
- *How did the spatial distribution of galaxies evolve?* What are the connections between the formation of galaxies and the development of structures on larger scales? When did the cores of the great clusters form?

2. SPECIFIC SCIENTIFIC OBJECTIVES

The proposed imaging survey addresses the first three of the questions above by (a) detecting the first visible objects in the Universe, (b) by following the assembly of proto-galactic structures into galaxies and (c) by tracing the emergence of the present-day morphological classification of galaxies and producing an understanding of the morphology of star-formation at high redshifts. Moreover, by serving as a basis for other NGST programs, a deep imaging survey is a pre-requisite for addressing most of the remaining questions. The proposed survey is the NGST-analogue of the highly successful Hubble Deep Field observations carried out with the HST (Williams et al 1996).

2.1: The first stars and quasars in the Universe

One of the outstanding problems in cosmology is the nature of the first generation of stars and quasars which appeared when the universe first transformed from its initial smooth state to its current clumpy state. Current observations probe bright quasars and galaxies out to redshifts $z \sim 5$ (Schneider, Schmidt & Gunn 1991; Franx et al. 1997; Dey et al. 1998), and the amplitude of linear density fluctuations on large-scales at $z \sim 10^3$ (Bennett et al. 1996), but provide no direct evidence as to when and how the first objects had formed.

Current Cold Dark Matter (CDM) models for structure formation predict the appearance of the first baryonic objects with masses $M \sim 10^5 \mathrm{M}_\odot$ at redshifts as high as $z \sim 30$, and objects with progressively higher masses later. Following virialization, the gas in these objects continues to collapse and fragment if it can cool on a timescale shorter than the Hubble time. In the metal–poor primordial gas, the only coolants that satisfy this requirement are neutral atomic hydrogen (H) and molecular hydrogen (H_2). However, H_2 molecules are fragile and are easily photodissociated throughout the universe by trace amounts of starlight (Haiman, Rees, & Loeb 1997; Gnedin & Ostriker 1997). Hence, most of the first stars are expected to form inside objects with virial temperatures $T_{\mathrm{vir}} 10^4$K where atomic cooling operates. Depending on the details of their cooling and angular momentum transport, the gas in these objects is expected to fragment into stars or form a central black hole exhibiting quasar-like activity. Conversion of less than a percent of the cosmic gas into stars or quasars could reionize the universe and strongly affect the entropy of the intergalactic medium.

Although the above scenario has been the focus of many theoretical investigations in the past, it has never been tested directly by observations. The various cosmological models differ appreciably in their detailed predictions for the mass and collapse redshift of the first generation of objects, since those depend critically on the fundamental cosmological parameters $\Omega_{\mathrm{M}}, \Omega_\Lambda, \Omega_{\mathrm{b}}, H_0$ and $\sigma_{8h^{-1}}$. Direct observations of the first collapsed systems with NGST would open a new avenue for setting constraints on these parameters.

How many sources will NGST see? Figure 1 shows the predicted number of very high redshift quasars and star clusters expected per field of view of NGST. In this calculation, the star formation efficiency was calibrated based on the inferred metallicity range of the Lyα forest (Songaila & Cowie 1996; Tytler et al. 1995) while the characteristic quasar lightcurve was calibrated in Eddington units so as to fit the observed luminosity function of bright quasars at $z \sim 2$–4. Both populations of sources were extrapolated to high redshifts and low luminosities using the Press-Schechter formalism. Typically, there are expected to be of order tens of sources at redshifts $z > 10$ per field of view of NGST. The redshift of early sources can be easily identified photometrically, based on the Lyα absorption trough.

2.2 : How were galaxies assembled

Our present view of the high redshift Universe is based almost entirely on systems that are actively forming stars (and furthermore doing so in the presence of only modest amounts of dust obscuration). The sensitivity of NGST to 5μm will allow older stellar systems to be detected well after a burst of star-formation. The long wavelength brightness of these more quiescent systems provides a much better indicator of the stellar mass of the system than does the light emitted during the star-burst phase.

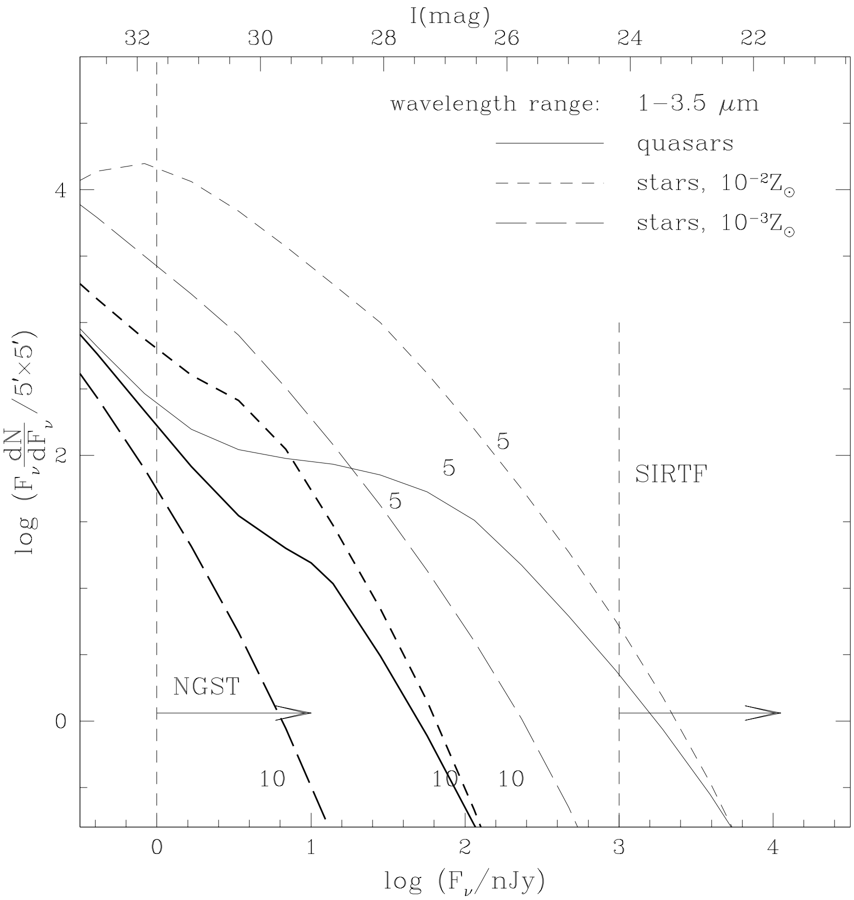

Figure 1: Predicted number counts per $5' \times 5'$ field of view per logarithmic flux interval in the NGST wavelength range of 1–3.5μm. The numbers of quasars and star clusters were calculated for a ΛCDM cosmology with $(\Omega_{\rm M}, \Omega_\Lambda, \Omega_{\rm b}, h, \sigma_{8h^{-1}}, n) = (0.35, 0.65, 0.04, 0.65, 0.87, 0.96)$. The lowest mass scale of virialized baryonic objects was chosen consistently with the photoionization feedback due to the UV background. The star formation efficiency was calibrated so as to bracket the possible values for the average metallicity of the Universe at $z \sim 3$, namely between $10^{-3} Z_\odot$ and $10^{-2} Z_\odot$. The thick lines, labeled "10", correspond to objects located at redshifts $z > 10$, and the thin lines, labeled "5", correspond to objects with $z > 5$. The upper labels on the horizontal axis correspond to Johnson I magnitude (from Haiman & Loeb 1998).

Thus, the ability to detect small and quiescent galaxies at very high redshifts will allow us to follow the assembly of previously-formed stellar mass into galaxies. This will enable us to address the key question of what fraction of the stars in massive galaxies were formed *in situ* and what fraction were brought together by merger activity.

Basic redshift information can be obtained from from broad-band (R $\sim$ 5) photometry, making use of the strong spectral breaks at Lyman α/Lyman limit (Steidel et al 1996), at the Balmer limit and/or 4000 Å region and the strong spectral change of slope at 1.6 μm. The 1.6 μm feature is of particular importance as it appears in even very young stellar systems (ages of as young as 10^7 years) and is almost unaffected by dust obscuration.

Diagnostic information on metallicities, masses, and stellar populations for galaxies and pre-galactic fragments would enable a more detailed picture to be constructed - the mass function could be computed over a wide range of redshifts, the evolution of which would trace the assembly of mass into galaxies. This information can only come from spectroscopy, which is also the only way of determining velocity dispersions of galaxies relative to each other and thus of following the likelihood of mergers of galaxies. The acquisition of such spectroscopy is a primary focus of the Deep Spectroscopy DRM of the "Galaxy Formation and Evolution" theme. The imaging survey will furnish deep multi-color images of large numbers of faint galaxies which will be studied in detail spectroscopically.

2.3: How did the Hubble sequence form?

It has been demonstratd that the kpc-scale resolution of the HST at optical wavelengths is sufficient to morphologically classify galaxies at high redshifts (Abraham et al 1996, van den Bergh et al 1996, Smail et al 1997, Brinchmann et al 1998 amongst many) in a scheme that is relatable to the classification of galaxies at the present epoch. Analysis of galaxies in the HDF has also shown the power of spatially resolved color information in understanding the star-formation process *within* individual galaxies - revealing the time sequence of successive bursts of star-formation across the face of morphologically complex galaxies (e.g. Abraham et al 1998).

The high quality spatially resolved colour and morphological information from the imaging survey, extending over a decade of wavelength, will enable a comprehensive physical picture of the evolutionary state of each galaxy to be built up over a very large range of redshifts. The high signal to noise of the imaging data on those galaxies that can be observed spectroscopically will allow us to trace the emergence of different morphological components (spheroids, disks etc.) in galaxies over cosmic time, determine the location and nature of star-formation activity relative to these components, and additionally identify unambiguous indicators of merging and interactions such as tidal tails.

3. SURVEY PROGRAM

We propose a two-part deep survey, the parameters of which are justified below. The first part pushes NGST to its limits and consists of seven-day integrations on a single field in each of seven filters. This provides sufficient depth to detect an unobscured point source forming stars at $2M_{solar}\mathrm{yr}^{-1}$ maintained for 10^6 years (i.e. a plausible forming globular cluster) to be seen by continuum emission to all redshifts up to $z \sim 20$, even under pessimistic

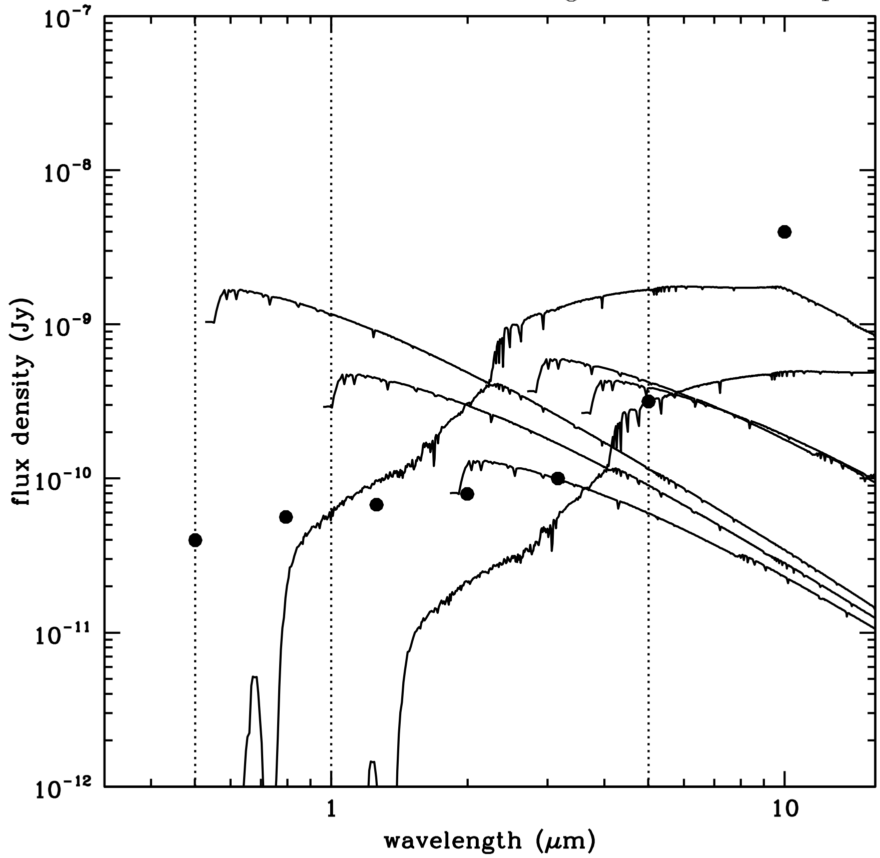

Figure 2: Spectral energy distributions of target objects compared with survey limits (5σ point source) for the ultra-deep survey. Sequence of blue objects represents a star-formation rate of 2 $M_\odot$ yr^{-1} for 10^6 years at z = 5, 10, 20 for an $H_0 = 50$ $\Omega = 0.2$, $\Lambda = 0$ Universe, and at z = 30,40 for brighter objects or a more favorable cosmology. The sequence of red spectral energy distributions represents a $10^8 M_\odot$ system seen 1 Gyr after star-formation ceases at z = 5, 10 (same cosmology as above).

cosmological assumptions ($H_0 = 65, \Omega_0 = 0.2, \Lambda = 0$). More favourable cosmologies, or higher star-formation rates, would allow such objects to be seen, if they exist, to $z = 30$ or greater (see Fig 2). This ambitious goal requires a 5σ point detection sensitivity of 0.1 nJy at 2-3 microns or 170 hours of integration in the yardstick design. An additional requirement is to detect a $10^8 M_{solar}$ system seen 10^9 years after star-formation ceased at redshifts up to $z = 10$ requires a 5σ point detection sensitivity of 0.3 nJy at 5 microns, which is also attained in the same integration time. For reference this "NSGT Ultra-deep Field" will represent a 5-fold increase in telescope time over the original Hubble Deep Field.

We also propose a less deep but wider field survey, consisting of 16 fields observed for 1/16 as long, or a factor of 4 less deep. This will ensure that a large and representative area of the sky of covered and will serve as the basis for follow-up spectroscopy. The total area covered will be about 50 times larger than that of the Hubble Deep Field.

APPENDIX: SURVEY PHILOSOPHY

The need for a deep imaging survey with NGST is fairly obvious and, as with the Hubble Deep Field and future images from HST, the deepest images of the Universe returned by NGST will provide a lasting legacy from the mission. As with the HDF, the success and value of the survey will depend on the detailed implementation of the survey. Therefore, in this section, we list the considerations that have led us to propose a particular set of parameters for the survey, and hence an estimated time budget for NGST, recognizing that the details of these will likely evolve with time.

3.1 Wavelength range

The wavelength range should be as broad as possible. A typical deep image of the sky reveals a very large number of galaxies (e.g. 9000 galaxies per nominal 16 arcmin^2 NGST FOV at the $I_{lim,AB} \sim 29$ depth of the HDF) spread out over a very broad range of redshifts ($0 < z < 6$ in the case of the HDF, and likely very much larger for the NGST) and cosmic epochs. At each redshift/epoch, the galaxies in the Universe sample a broad range of galaxian properties, including mass, luminosity and evolutionary/star-formation state. This broad range of properties and the broad range of redshifts combine to greatly affect the appearance of galaxies at any particular wavelength and it is therefore imperative to carry out deep imaging surveys of the same regions of sky over the fullest possible range of wavelengths accessible with the NGST. This will allow both optimal characterization of each object regardless of redshift and minimize the biasses against particular segments of the galaxy population. The scientific drivers for the different segments of the wavelength range are as follows:

(i) The 1-5 micron core range

The 1-5 micron images are central to the proposed survey. The Lyman break region of the spectrum between 912-1216 A (the key diagnostic for photometric estimation of redshifts in star-forming galaxies at high redshifts) is visible between 1-5 microns for $7 < z < 40$, precisely the redshift range where the first star-forming systems are expected to be located. the 3500-7000 Å spectral region where older stellar populations are most readily detected and studied lies in this spectral range for $1.8 < z < 6$. This is the redshift range where such populations are expected to appear and where the assembly of massive galaxies is likely to take place.

(ii) The 5000 Å - 1 micron visible extension

Extension of the survey down to 5000 Å is extremely important, for two reasons. Firstly, it allows the Lyman break spectral region to be identified down to redshifts $z \sim 4$. This provides some overlap with the redshift domain studied with HDF (it should be noted that at present there are no conformed galaxies known at $z > 6$!). Secondly, it provides information on the ultraviolet spectral region at $\lambda \sim 2000$ Å for galaxies in the $1.5 < z < 4$ redshift range. This is the redshift domain where we suspect the Hubble sequence is established and where there is evidence from ground-based and HDF studies that the luminosity density of the Universe at 2000 Å reaches a maximum. Including this wavelength in the NGST survey

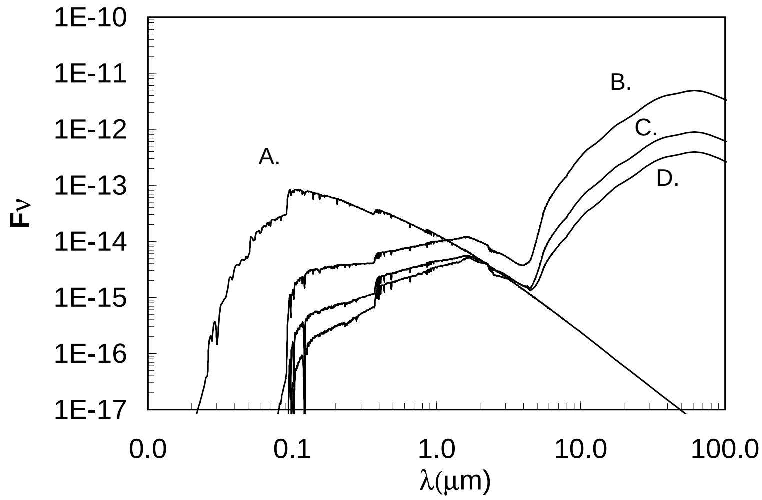

Figure 3: Spectral energy distributions of stellar populations as functions of age and dust obscuration: (A) A Bruzual-Charlot stellar population model at an age of t=3×10^6 yrs, with low (0.004 $Z_{\odot}$) metallicity, a single star-burst and no dust (and hence no thermal infrared emission); (B) Model as in (A) but at 1×10^7 yrs, with $A_V = 1$, and a mid-ir energy scaled to be equal to the energy absorbed assuming the Calzetti extinction law; (C) Same as (B) but for age of 5×10^7 yrs (D) Same but for 1.3×10^8 yrs. These show the prompt appearance of the pronounced spectral break at 1.6 μm (after only 10^7 years).

is thus extremely important. So much so that if visible cameras were not part of the NGST suite of instruments, then supporting observations with ACS, or the foreseen WFC3, on HST should be undertaken before the termination of the HST mission.

(iii) The 5-10 micron mid-IR extension

Beyond 5 microns the sensitivity of NGST is significantly diminished and the spatial resolution is becoming significantly poorer ($\geq$ 0.25 arcsec) that some morphological information is lost relative to the shorter wavelengths. The sensitivity gains relative top the ground are however increasing. In terms of high redshift galaxies, the main science driver for observations at 10 microns is the possibility of using the pronounced change of spectral slope that occurs at around 1.6 microns in stellar populations of almost all ages as a redshift indicator of stellar populations that is (a) relatively unaffected by dust obscuration (b) available for all galaxy types irrespective of age (see Fig 3). This would be usable out to $z = 4$ if the survey extended to 10 microns. The sensitivity of NGST allows us to detect enshrouded progenitors of L$\star$ galaxies up this redshift.

3.2 Filter separation

The proposed survey consists of deep images in a sequence of filters separated by about $\Delta\lambda \sim 0.20$ in wavelength - i.e. (as an example) at 6000 Å, 9300 Å, 1.6 μm, 2.5 μm 4.0 μm 6.3 μm and 10 μm. This separation is comparable to the wavelength separation (at shorter wavelengths) used in the HDF. Photometry at the 20% level in a set of such filters has been demonstrated to be adequate to yield photometric redshift estimates at the 5% level of accuracy (in (1+z)) (e.g. Brunner et al 1997, ApJ, 482, L21). In addition, for composite stellar systems, this separation is sufficient to yield significant morphological differences between adjacent filters (it is equivalent to the separation between U, V and I in the local Universe) that straddle strong spectral features such as the 4000 Åbreak.

3.3 Sensitivity

An optimal strategy is to carry out two or more surveys with different combinations of depth and areal coverage. We believe a reasonable approach is to spend equal amounts of observing time at two different depths separated by a factor of 16 in area and 1 mag in depth (see next section).

The depth of the deepest part of the survey is set so as to allow an unobscured system forming stars at a rate of $2M_{solar}\mathrm{yr}^{-1}$ maintained for 10^6 years (i.e. a plausible forming globular cluster) to be seen by continuum emission to all redshifts up to $z \sim 20$, even under the most pessimistic cosmological assumptions ($H_0 = 65, \Omega_0 = 0.2, \Lambda = 0$), although more favourable cosmologies would allow such objects to be seen, if they exist, to $z = 30$ or greater (see Fig 1). This ambitious goal requires a 5σ point detection sensitivity of 0.1 nJy at 2-3 microns (Fig 1). With the yardstick mission, this corresponds to 170 hours integration (7 days). An additional requirement is to detect a $10^8 M_{solar}$ system seen 10^9 years after star-formation ceased at redshifts up to $z = 10$. This requires a 5σ point detection sensitivity of 0.3 nJy at 5 microns, which is also attained in 170 hours integration (7 days).

The spectral energy distributions of the objects that are expected to be detected in such a survey will vary considerably, with some redder and some bluer than the natural sensitivity of the NGST. It is therefore proposed that equal exposure times be used for all filters.

3.4 Number of survey fields

The choice of area and number of fields is driven by three main considerations, namely (a) the need to sample representative volumes of the Universe (i.e. a large number of statistically independent volumes), (b) the need to observe adequate numbers of objects within those volumes so that statistically meaningful conclusions can be drawn, and (c) at a more detailed astrophysical level, the desire to that all of the fragments that will coallesce into a single object at some future epoch are represented within a given field.

Locations that are separated by more than 100 comoving Mpc along the radial line of sight may be regarded as statistically independent (since this is the separation of of the largest "picket fence" structures seen at lower redshifts) and so the relevant quantities are, as a function of redshift, the transverse comoving distance subtended by 4 arcmin, the volume contained within an interval of 100 Mpc increment in comoving radial distance, and the number of galaxies (or their progenitors contained therein), and the redshift interval corresponding to that radial increment of 100 Mpc (or equivalently the number of such increments along the line of sight). The NGST 4 arcmin FOV subtends a comoving distance of roughly 3 Mpc at $z = 1$ increasing to 10-30 Mpc at very high redshifts. This is large enough to ensure that all the fragments that will plausibly merge to form a single galaxy are present in each field (for comparison, the present day correlation length is 6 comoving Mpc). Each statistically independent volume as defined above represents about 1000 Mpc^3 at $z = 1$ (i.e. corresponding to about one L* galaxy or its progenitor fragments) increasing to $10^4 - 10^5$ Mpc^3 at very high redshifts (i.e. containing 10-100 L* galaxy progenitors). There are between 50 and 100 such independent volumes between $1 < z < 30$ (distributed approximately evenly in log z). In summary, a single NGST field will contain of order 25 independent L* galaxies/progenitors at $1 < z < 3$, of order 120 galaxies/progenitors in 25 independent volumes at $10 < z < 30$, and of order 600 galaxies/progenitors in 25 independent volumes at $10 < z < 30$. These galaxies may of course be in fragments and will be accompanied by a large number of lower mass galaxies.

Thus while a single fields will be likely adequate for the deepest aspects of the work, probing to the earliest stellar systems at $z > 5$, the lower redshift $1 < z < 5$ regime, where the focus is on the emergence of the Hubble sequence of massive galaxies, will require the larger 16 field survey to yield statistically useful samples of order 1000 L* galaxies/progenitors.

Within current models of galaxy formation, the depth of the proposed flanking fields is sufficient to detect objects 1-2 magnitudes fainter than the progenitors of typical $L\star$ galaxies at redshift 7.

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NGST Uniqueness/Relationship to Other Facilities

The NGST has unique sensitivity and spatial resolution in the whole 0.5 - 30 micron waveband. Even in the 1-2 micron waveband NGST has a sensitivity to compact sources which exceeds by about a factor 10 that of a ground based telescope (Gillett & Mountain 1998, in "Science with the NGST", p. 42) and the advantage of NGST grows to several order of magnitude beyond 2 microns. Moreover, NGST has the capability of offering high spatial resolution over a field of view larger than the adaptively corrected one of a ground based telescope by a factor 100.

Observing Strategy

Explained in detail in context of science above.

Special Requirements

Minimum Spatial Resolution:	0.1 mas at 2 μm
Minimum Spectral Resolution:	5 at 2 μm
Minimum FOV:	3 arcmin^2 at 2 μm

Precursor/Supporting Observations

The images at $\lambda < 1$ micron are so important that they should be obtained with ACS and/or WFC3 on HST before the NGST mission if they will not be (more optimally) obtainable with NGST.