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# The Next Generation Space Telescope

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**Abstract.** The Next Generation Space Telescope (NGST) will be an 8 m deployable telescope, radiatively cooled to 30 K and diffraction-limited at 2 $\mu$m, operating at the Sun-Earth Lagrangian point L2. It will be built by a partnership of NASA, ESA, and CSA (Canadian Space Agency). The camera sensitivity should be limited by the zodiacal light for wavelengths $< 10$ $\mu$m. The main scientific objectives are the study of the origin and evolution of galaxies, stars, and planets, beginning with the first luminous objects to form from the Big Bang. Other objectives include studies of dark matter, supernovae, the intergalactic medium, gamma ray bursts, star ages, and exobiology. The telescope will be operated like the Hubble Space Telescope (HST) by the Space Telescope Science Institute, with all observing programs openly solicited and selected by peer review.

The NGST scientific requirements originated with the report of the Dressler Committee *HST & Beyond*. The instruments recommended by the Ad Hoc Science Working Group (ASWG) include 1) a wide field near infrared (NIR) camera with an $8K^2$ detector array covering 0.6 - 5 $\mu$m, 2) a multi-object NIR spectrograph capable of simultaneously observing $> 100$ objects with a resolution of R $(\lambda/\delta\lambda) = 1000$, and 3) a combined mid-infrared (MIR) camera and spectrograph from 5-27 $\mu$m, with a resolution of R $> 1500$.

## 1. Introduction

In 1995, NASA began a feasibility study of a large aperture, passively cooled telescope, later to be known as the Next Generation Space Telescope (NGST, Stockman et al. 1997). Such a study had been recommended by a committee charged to consider the needs of the UV-Optical-IR astronomy community after the HST 15 year mission (Dressler et al. 1996). Using passive, radiation cooling concepts developed for the Edison mission (Thronson 1993) and SIRTF, such a mission could observe the infrared radiation from stars and galaxies at high redshift, without the high backgrounds and atmospheric absorption that limit ground-based observatories.

Many scientific breakthroughs have occurred in the intervening five years. The HST deep fields and larger ground-based surveys have discovered the rest-frame ultraviolet radiation from star forming galaxies at high redshift ($z = 2-5$). The DIRBE and FIRAS experiments have measured the far-infrared (FIR) extragalactic backgrounds, consistent with the reprocessing of more than half of that radiation by dust. Deep SCUBA fields reveal sub-mm sources with mm radio counterparts but only faint or unobserved visible sources, more evidence of dust-enshrouded star formation at high redshift. The improved calibration of the distance scale, observations of Type Ia supernovae and sub-mm observations of background anisotropy on sub-degree scales support a cosmology very different from the dark-matter dominated CDM paradigm of 1995: an accelerating universe with a large cosmological constant and more comparable contributions of dark and baryonic matter.

The discoveries of the last five years have encouraged astrophysical study of the conditions of the early universe. How did the first stars form? What is their legacy? Did structure growth and star formation increase monotonically or through discrete stages? When and how did massive black holes form? How and when did the intergalactic medium become reionized? Thus the interest in a telescope capable of reaching the distant past ($z > 5$) has dramatically increased. NGST is such a telescope.

## 2. NGST Project Status

The NGST is being studied by three space agencies: NASA (the lead agency), ESA, and the Canadian Space Agency (CSA). Formal agreements to identify the specific contributions of the three agencies and continue the collaboration to the beginning of construction are being developed. NASA, as the lead agency, is funding the Phase A studies of two major aerospace teams, Lockheed-Martin and TRW/Ball. These studies will form the basis for proposals to build and launch NGST in the 2004-2009 period. Selection of the prime aerospace contractor is planned to occur in Fall 2001, as well as the formal assignment of the STScI as the Science and Operations Center. The GFSC is the lead NASA center for managing the NGST Project and will also undertake the procurement and integration of the science instruments.

NASA, ESA, and CSA have funded feasibility studies of visible, NIR, and MIR instruments for NGST. Following detailed study of the technology readiness and scientific potential of these instruments, the Ad Hoc Science Working Group (ASWG) and the four Project Scientists (Mather, Stockman, Jakobsen, and Lilly) have recommended a three instrument complement:

- Wide Field Near Infrared Camera. The NIRCAM will have a wide field, $4' \times 4'$, and be critically sampled at 2 $\mu$m. Two different technologies (InSb and HgCdTe) are being developed to have low noise and high quantum efficiency between 0.6 - 5 $\mu$m.

- Multi-Object NIR Spectrograph. The NIRSPEC will be capable of obtaining moderate resolution, emission-line spectroscopy of more than 100 objects over a field of approximately $3' \times 3'$.

- Mid Infra-Red Camera-Spectrograph. The MIR instrument will have basic imaging and spectroscopic capabilities over a $2'$x $2'$ field. Its SiBIB detectors will be sensitive in the range 5 - 27 $\mu$m.

The three instruments will be developed by individual agencies or inter-agency teams and will be integrated into the instrument payload at GSFC. It is highly likely that all three instruments will have contributions from several agencies: NIRCAM (NASA & CSA); NIRSPEC (ESA & NASA), and MIR (ESA & NASA). In the latter case, a special committee of US and European scientists has been formed to recommend the two agency contributions and scientific management for the joint development.

## 3. NGST Science Goals

NGST capabilities in the NIR and MIR will be uniquely powerful for a wide range of scientific studies. The ASWG, in developing the 23 science programs in the Design Reference Mission (Stiavelli, Stockman, & Burg 1997), has delineated 5 major study areas. We list them below, along with the estimated fraction of the science program that they will represent.

- Cosmology and the Structure of the Universe (21%)
- The Origin and Evolution of Galaxies (33%)
- The History of the Milky Way and its Neighbors (15%)
- The Birth and Formation of Stars (16%)
- The Origins and Evolution of Planetary Systems (15%)

The principal science goal for NGST is the study of the formation and evolution of galaxies. As orginally conceived by the Dressler committee, this study would focus on the morphologies, luminosities, and derived masses of galaxies in the redshift range, $z = 1 - 5$. Using quantitative population studies, we should be able to develop a clear picture of the growth of structure, star formation, and the role of galaxy merging in this formative epoch. Since the Dressler report, this core goal has been extended to higher redshifts to detecting the first star clusters, the birth of quasars, and the reionization of the intergalactic medium. Reaching this goal requires exquisite sensitivity and angular resolution.

## 4. NGST Sensitivity

The combination of large aperture, low telescope temperature, and low background gives NGST an imaging sensitivity more than an order of magnitude greater than ground-based or previous space-based observatories. Figure 1 shows the point source, deep imaging sensitivity for the early NGST concept developed by NASA, the *Yardstick* mission. There are several features in the sensitivity curve that deserve noting. The most sensitive region, between 0.7 and 4 $\mu$m,

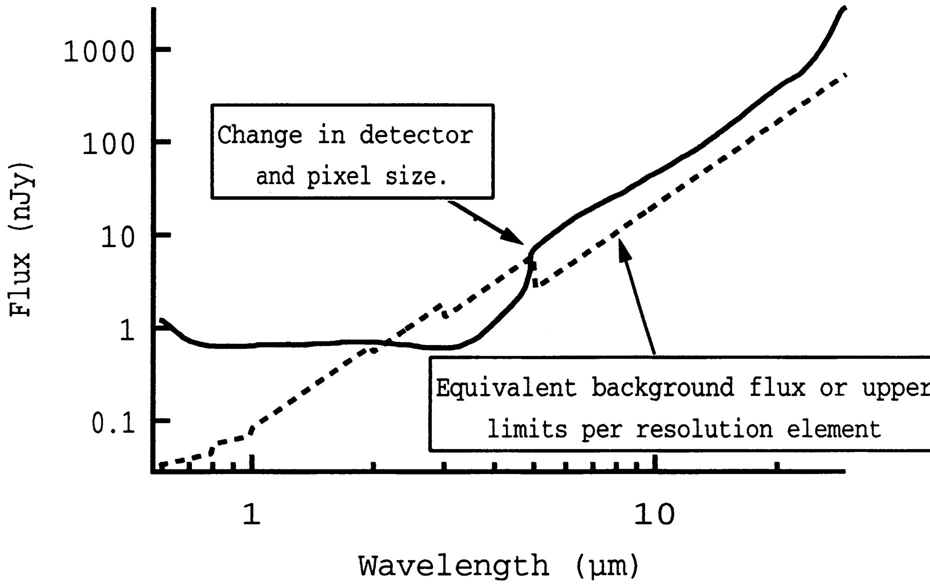


Figure 1. The NGST point source sensitivity for ultra-deep, wide-band imaging: 10 $\sigma$, $10^5$ s, $R$ = 3. The dashed line indicates the equivalent brightness of the CIB per resolution element.

is expected for a diffraction-limited telescope with a background caused by reflected sunlight at 1 AU. Shortward of 0.7 $\mu$m, gold coatings and mirror quality rapidly degrade the sensitivity of NGST, while longward of 4 $\mu$mthe background is increased due to thermal emission from the zodiacal dust cloud. In the wavelength region 0.7 $\mu$m – 4.0 $\mu$m, the NGST can detect source fluxes below 1 nJy, or an AB magnitude AB > 31.4. For galaxies with half-light radii $r = 0.1''$, comparable to the most distant and faintest observed in the HDF, imaging surveys will be complete to AB = 30 in the same band, a magnitude fainter than that obtained in the HDF. Figure 1 also indicates an inflection at 5 $\mu$m due to a slight change in detector characteristics assumed for the NIR detectors (either InSb or HgCdTe) and the MIR detector (SiBIB). Between 10-27 $\mu$m, the background may be dominated by MIR emission from the cold side of the sunshade that is scattered by dust and edges/gaps on the primary and secondary mirrors. The level of this background will be determined by the design selected for the sunshade. Low temperature sunshades (70 K) yield a background comparable to the zodiacal background, while high temperature sunshades (100 K) result in backgrounds several magnitudes higher.

The dashed line in Figure 1 indicates the equivalent brightness of the cosmic infrared background (CIB) per resolution element either as measured by COBE or the COBE upper-limit. The remarkable proximity of the background flux limits and the NGST sensitivity suggests that NGST may be capable of resolving the CIB over the wavelength range 1 $\mu$m – 27 $\mu$m. The key issue is that of source confusion, particularly at the longer wavelengths. At 20 $\mu$m, NGST can detect

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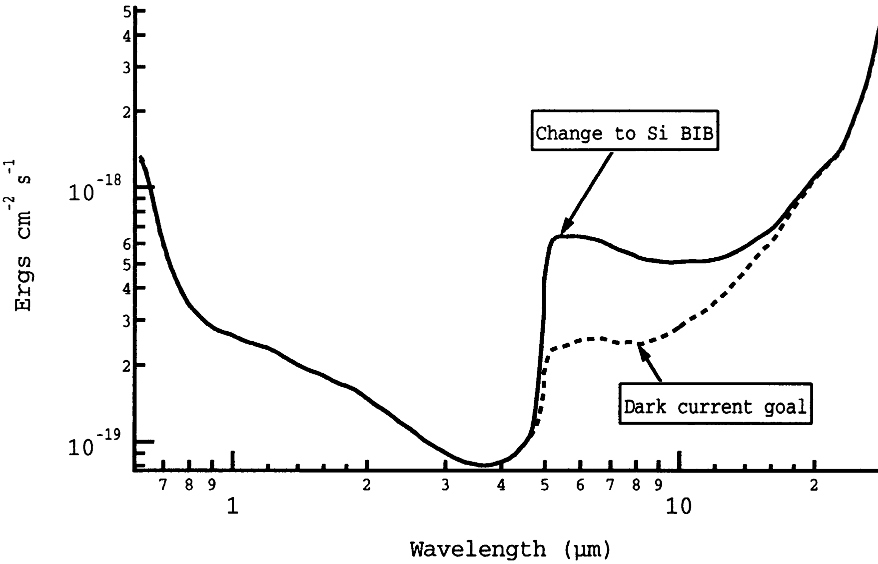


Figure 2. The NGST sensitivity to faint emission lines: 10 $\sigma$, $10^5$ s, $R = 1000 - 3000$. At wavelengths longer than 7–10 $\mu$m, the intrinsic width of the emission lines and the higher zodiacal and thermal backgrounds will limit the sensitivity to values greater than those shown here.

up to 800,000 sources per square degree before the canonical confusion limit of 1 source per 40 beams is reached. This areal density is comparable to that reached in the HDF (Williams et al. 1996) and is two orders of magnitude greater than the confusion density for SIRTF and SCUBA. While it is likely that the majority of the CIB will be contributed by relatively bright sources, the MIR equivalents of $L = L_*$ at $z = 1 - 2$, NGST will be uniquely capable of detecting the faint end of the luminosity function as well as detecting exciting new populations of objects at higher redshift, objects that may have special importance to the origin and evolution of galaxies.

The multi-object NIRSPEC will be capable of detecting faint emission lines in hundreds of faint galaxies per field. Figure 2 indicates the sensitivity of such a spectrograph, assuming that it is limited by the read noise and dark currents of the nominal NIR and MIR detectors. With that assumption, the most sensitive wavelength region is at $\lambda = 5$ $\mu$m, about $10^{-19}$ erg cm$^{-2}$ s$^{-1}$. At longer wavelengths, the sensitivity is limited by the dark currents of the MIR detectors in the MIR spectrograph, 1 e s$^{-1}$ (0.1 e s$^{-1}$ for the optimistic dashed line) and ultimately by the zodiacal light and intrinsic width of the emission lines (100–200 km s$^{-1}$). As a point of reference, the Ly$_\alpha$ sources found serendipitously with the Keck telescope have an average flux of 2 $10^{-17}$ erg cm$^{-2}$ s$^{-1}$, or two orders of magnitude brighter than the NGST limiting sensitivity for ultra-deep spectroscopy in the NIR.

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## 5. Detecting High Redshift Objects

One of the greatest challenges for NGST is the detection and characterization of high redshift objects, $z = 5 - 15$. These sources will be extremely faint and often unresolved. How will they be identified with confidence? In this section, we enumerate the potential sources and how they may be found.

### 5.1. The $Ly_\alpha$ Forest and the Epoch of Reionization

At redshifts greater than $z = 3$, absorption and scattering of $Ly_\alpha$ photons by residual neutral hydrogen in the intergalactic medium is sufficient to reduce the observed flux at rest wavelengths shorter than 1216 Å by more than one magnitude, with the absorption at the Lyman limit being complete (except for rare lines of sight). This signature, a sudden reduction in the flux at short wavelengths, is the primary indicator of high redshift for resolved, non-stellar, sources. However, the actual assignment of redshift is not automatic, since highly dust absorbed galaxies at $z = 1-2$ can be almost undetectable at visible wavelengths, with $V_{AB} - K_{AB} > 5$ (Stiavelli et al 1999). Astronomers can resolve this ambiguity with multi-band NGST photometry in the NIR and the use of various templates of the galaxy spectral energy distributions.

We know from observations of high redshift QSOs that the IGM is ionized at $z = 6$ (Fan et al. 2000), probably by star-forming galaxies. At much higher redshifts, the IGM will be predominantly neutral because of its increased density (higher recombination rate) and the presumed lack of active star forming regions and/or QSOs. The phase change from a neutral to predominantly ionized IGM will be relatively abrupt and will occur between $7 < z < 12$ (Haiman & Loeb 1998; Gnedin & Ostriker 1997). Low to moderate resolution spectroscopy of bright but rare high-redshift candidates should reveal either residual, patchy flux shortward of rest 1216 Å or the smooth damping wing due to the scattering of $Ly_\alpha$ photons (Gunn & Peterson 1965). The determination of the epoch of reionization is a major goal for NGST.

### 5.2. Line-Emission from Collapsing Halos

Haiman, Spaans, & Quataert (2000) have shown that the energy released from the collapse of proto-galactic dark matter halos and gas may result in $Ly_\alpha$ emission comparable to that from the resulting star formation. Since the energy release occurs on scales of 100–1000 pc, this emission should be resolved by NGST, without associated continuum emission. Unfortunately, the $Ly_\alpha$ emission from collapsing clouds at $z > z_{\rm reion}$ will be obliterated by the damping wing of neutral hydrogen. The epoch of reionization marks the boundary where $Ly_\alpha$ emission can be used as either a diagnostic or a method of discovery.

### 5.3. Line-Emission from Star-Forming Regions

One of the key science goals for NGST and the NIRSPEC is the study of high redshift, star-forming regions. Neglecting the effects of dust obscuration, regions with an average star-forming rate of 1 $M_\odot$ yr$^{-1}$ will produce detectable $H_\alpha$, $H_\beta$, N II, and O II, III out to redshifts $z > 7$. Using the strengths of these lines, we can estimate the reddening, star-formation rate, and metallicity of these early star-forming galaxies. Correlating the metal strengths with the observed supernova rates and dust obscuration, we will be able to test and improve our understanding of the creation of metals, the seeding of the IGM, and the subsequent growth of galaxies.

We also note that the detection of $H_\alpha$ is the best evidence that a faint, I-band or J-band dropout is at very high redshifts. For $z > 7$, $H_\alpha$ must be observed in the MIR spectrograph; for $z > 10$, $H_\beta$ can only be detected in the MIR.

### 5.4. Hot Massive Stars and Quasars

The first stars, born with primordial abundances, may be very massive, $M > 300\,M_\odot$, with hotter photospheres, $T > 100,000$ K, than typical of 80–100 $M_\odot$ stars with solar metallicities (Abel, Bryan, & Norman 2000). The existence of such stars may be directly observable, particularly in a large association. In addition to strong Balmer lines, the H II region surrounding such stars should emit strong permitted He II lines at 1640 and 4686 Å (Oh, Haiman, & Rees 2000). The latter line, though weaker than $H_\alpha$, would be observable in the NIR to $z = 10$. The He II 1640 line is weaker than He II 4686 but would be observable in the NIR to much higher redshifts, $z > 30$. It is also an excellent diagnostic of the strong ultraviolet emission expected from accretion onto the first $10^6 - 10^7\,M_\odot$ black holes. Candidates for such objects would be selected by their stellar appearance and sharp Gunn-Peterson break in the 1–3 $\mu$m region.

### 5.5. Conclusion

The Next Generation Space Telescope will address and answer many of the most important astronomical questions that we face today. Its extraordinary sensitivity and resolution will resolve or strongly bound the total CIB light and the contributions that such light implies: the amount of baryonic matter in stars, the production of the heavy elements, and the origins and roles of massive black holes within galaxies. Enabled by the contributions of its international partners, the NGST will be a powerful tool in advancing our understanding of star and galaxy formation.

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## Discussion

Toshio Matsumoto: Why do you not cool the sunshield to even lower temperatures?

H. S. (Peter) Stockman: The sunshield is made from metallized mylar or kaptan and is not amenable to active cooling. To enable active cooling, one would need a thicker and heavier sunshield which would create other problems for the mission.

Dietrich Lemke: What operational lifetime do you expect for NGST? (What determines the end of the mission?)

Stockman: NGST has a 5-year requirement for the mission lifetime and a 10-year goal. The shorter lifetime is set by the level of redundant elements of the spacecraft (gyros, star trackers, etc.). The expendables, mostly gas for station keeping and momentum management, will be sized for a 10-year mission.

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