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# Infrared Astronomy and NGST

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**Abstract.** The Next Generation Space Telescope (NGST), scheduled for launch in 2008, will be an infrared (0.6–10+ $\mu$m) optimized 8m telescope, passively cooled to 50K, located in an orbit about the second Lagrange point (L2). NGST is a successor to the Hubble Space Telescope (HST) and will be a key part of the NASA Origins Program. Like HST, it will be a general user observatory and will be capable of studying a wide variety of phenomena. For design purposes we are using a Design Reference Mission (DRM) which contains programs investigating; the light from the first stars and galaxies to form after the Big Bang, early supernovae and the chemical enrichment of the universe, protostellar environments within our own Galaxy, faint white dwarfs in Local Group galaxies, Kuiper Belt objects (KBOs) within the Solar system to name a few. The NGST will use many advanced technologies to realize its goals. Among these are advanced software and control systems for the telescope and its instruments. I give a brief update on the state of the NGST project and projected capabilities for this observatory.

## 1. Science Goals

Although there have been discussions about telescopes to succeed the Hubble Space Telescope (HST) since even before its launch, the vision for current science goals of NGST was first articulated the *HST and Beyond* report (Dressler 1996). This report outlines the enormous potential of a scientific successor to HST, optimized for the near infrared (NIR, 1-5 $\mu$m). The goals outlined in the report have been fleshed out and quantified by the NGST Ad Hoc Science Working Group (ASWG) and are currently represented by the Design Reference Mission (DRM). The DRM is comprised of a suite of observations that could be completed in 2.5 years. Below I highlight some facets of the DRM and the impact they would have on astronomy.

### 1.1. The Design Reference Mission

The goals of the DRM are to:

- Provide examples of NGST science to stimulate further inputs from the astronomy community,

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Table 1. NGST design reference mission components

| Theme Name | DRM fraction |
|---|---|
| Origin and Evolution of Galaxies | 33% |
| Cosmology and Structure of the Universe | 21% |
| History of the Local Universe | 16% |
| Birth of Stars | 15% |
| Origin and Evolution of Planetary Systems | 15% |

- Provide descriptions of science programs in sufficient detail to derive secondary requirements/capabilities of the observatory,
- Provide a semi-quantitative basis for trade studies (e.g., sensitivity versus field of view).

These science programs have been organized by the ASWG under five themes and can be accessed through the NGST science website[2]. During the Formulation phase (Phase A/B), we will continue to solicit programs for the DRM from our international partners and the astronomy community.

*The Origin and Evolution of Galaxies* The primary emphasis NGST science remains on detecting and characterizing the light from the first stars and galaxies to form after the Big Bang. In 2008, NGST will be poised complete our understanding of the formation and early evolution of galaxies such as the Milky Way by:

- Detecting the earliest phases of star and galaxy formation the end of the "dark ages" (Figure 1). This requires superb NIR sensitivity ($< 1$ nJy, 1-4 $\mu$m) in deep broadband imaging (in a $\sim 10^5$ second exposure);
- Resolving the first galactic substructures larger than individual star clusters ( 300 pc for $0.5 < z < 5.0$). This requires HST-like resolution in the NIR ( $0.060''$ at $2\mu$m);
- Quantitatively measuring the fundamental properties of individual galaxies. This will be enabled by emission-line and absorption-line spectroscopy, with broad spectral coverage and low-to-moderate spectral resolution ($R = \lambda/\Delta\lambda$):

  $R \sim 300$ ($0.6 - 5.0\mu$m) for redshift confirmation, cluster membership, and ages of stellar populations;

  $R \sim 1000$ ($0.6 - 5.0\mu$m or longer) for star formation rates, metallicity, and reddening;

  $R \sim 3000$ ($1.0 - 10\mu$m) for dynamics (mass).
- Detecting and diagnosing dust-enshrouded regions hiding massive star formation or active galactic nuclei during the epoch of greatest star formation to a minimum of $z \sim 2$.

*Cosmology, Structure and Chemical Enrichment of the Universe* The geometry and structure of the Universe, as well as its history of element formation, is intimately related to the formation of galaxies. The Microwave Anisotropy Probe

[2]http://www.ngst.nasa.gov/science/

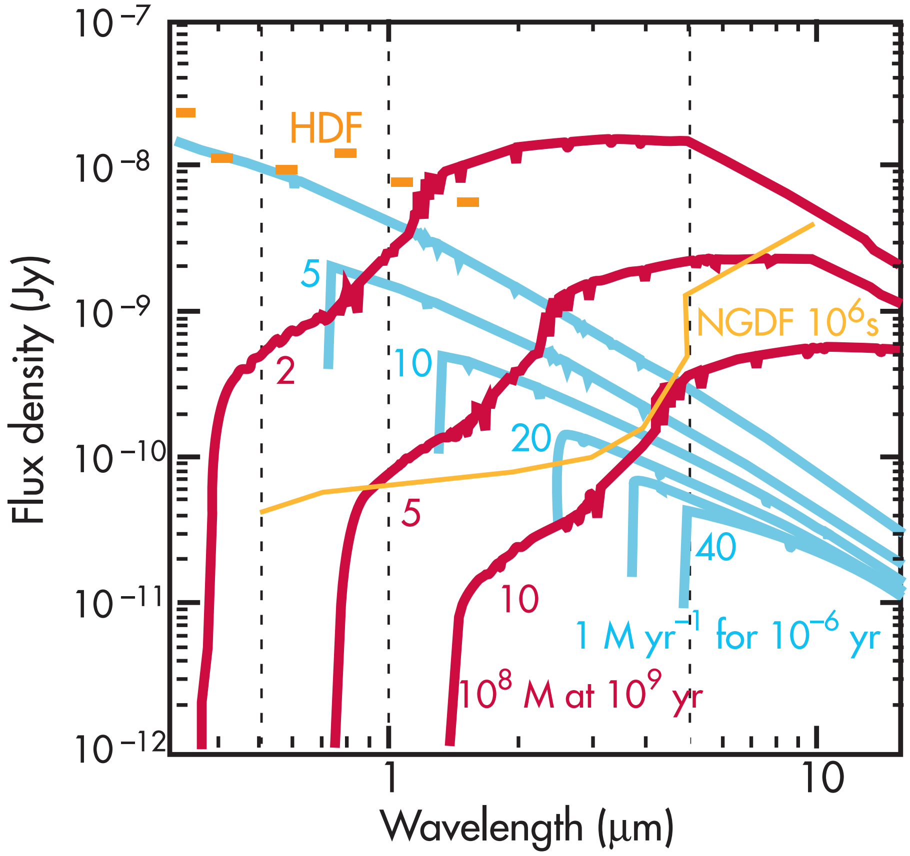


Figure 1. The sensitivity of an NGST deep field ($10^6$ s in 30% bandwidths, 10-$\sigma$ detection). Also indicated are the spectra of starburst regions ($10^6$ solar masses in $10^6$ years) and established populations ($10^8$ solar masses at 1 Gyr) at various redshifts ($\Omega_m = 0.2$). Comparable sensitivities also are shown for the Hubble Deep Field using NICMOS.

and Planck missions will measure the power spectrum of the Cosmic Microwave Background (CMB) at $z \sim 1300$ and, using standard models, will provide or constrain key cosmological constants. NGST will play a powerful complementary role in determining the distribution of mass and light on small scales. Large microlensing imaging surveys will use the wide field, superb angular resolution, and excellent $0.6 - 5.0\mu$m sensitivity of NGST to measure the mass structure of the Universe at $z = 1 - 5$ on scales smaller than those probed by CMB measurements from space or possible from the ground or HST. Anticipated science programs include:

- The dark matter halos of galaxies to redshifts of $z \sim 5$ will be weighed statistically by deep imaging of selected fields,
- The growth of galaxy clusters to redshifts of $z \sim 1 - 3$ will be measured using multi-color deep imaging of selected high-redshift clusters and proto-clusters discovered in other surveys,
- The statistical properties of the distribution of matter on scales of 1-10 Mpc can be found from wide-area, high-resolution NGST imaging surveys ($> 1$ deg$^2$).

These imaging programs are comparable in depth and required field of view to those used for the study of galaxy evolution. Such surveys also provide an excellent method for discovering Type 1a and Type 2 supernovae (SNe) at redshifts between $1 < z < 5$. Measuring the rates and galactic associations of Type 1a and Type 2 supernovae will provide an independent assessment of the history of element production. We expect that NGST will be crucial in extending the observations of Type 1a supernovae beyond $z \sim 0.9$ to$z \sim 5$. Only at the higher redshifts is it possible to distinguish between the behavior of Type 1a supernovae with cosmologies involving only $H_0$, $\Omega_m$ and $\Lambda$, and models with significant SNe evolution or smoothly distributed gray obscuration. Such data will provide measurements of the cosmological parameters, which are independent of and complementary to those derived from the CMB missions.

*The Processes of Star and Planet Formation* The potential studies in this arena are essentially limitless and depend crucially on the available spectral resolutions and MIR wavelength coverage. Examples include:

- Characterizing the infall and outflow processes through which stars are built and their final masses determined. MIR spectroscopy will diagnose the accretion shocks in protostellar systems, while NIR imaging will reveal outflow shocks and jets near their source, with a resolution of $\sim$2 AU;
- Tracing the structure and evolution of circumstellar material, from the massive envelopes of Class 0 protostars to the protoplanetary disks of pre-main sequence stars, and finally to the dissipation of these disks into mature debris disks of main sequence stars. NIR and MIR spectroscopy of gas and dust features, their excitation, and their radial variation within the circumstellar region will permit study of the growth of dust grains toward planetesimals, the chemical processing of disk gas, and the disk dissipation mechanisms that define the time available for planet formation;
- Detecting and characterizing substellar objects. Ground-based sky surveys and adaptive optics programs are now beginning to discover significant numbers of isolated and companion brown dwarf stars. However, these observations will be limited to the bright (high mass/low age) end of the

substellar luminosity function and to wide binary companions. NGST will have the needed combination of high-angular resolution, high sensitivity, and a stable PSF for high-contrast imaging of faint substellar companions in planetary orbits. Observations at 5 $\mu$m with a graded-mask coronograph will be able to directly detect planets with Jupiter's mass, age, and orbital semi-major axis in more than 90% of the single stars within 8pc of the Sun ($> 50$ systems). By detecting planetary photons directly, NGST will provide the first opportunity to spectrally characterize exoplanet atmospheres.

### 1.2. NGST Mission Concept

The science goals for NGST require a telescope with high sensitivity covering the wavelength range from 0.6 to 10 $\mu$m, with capability out to 28 $\mu$m, and with NIR angular resolution comparable to that of HST. Ball Aerospace, TRW, Industry, and NASA studied three several mission architectures during pre-Phase A (http://www.ngst.nasa.gov/Hardware/designs.html). For simplicity, the NASA architecture, referred to as the Reference Architecture, is presented here. The other concepts are similar, responding to the same high level requirements. The Reference Architecture established the technical and financial feasibility of the mission, and serves as a reference design to which proposed architectures and instruments can be compared. Figure 2 shows the observatory and its main components: the Optical Telescope Assembly (OTA), the Integrated Science Instruments Module (ISIM) and the Spacecraft Support Module(SSM).

*The Elements of the Reference Architecture Concept* The Reference Architecture optical configuration is a three-mirror anastigmat that provides a real, accessible pupil and permits a-relatively fast primary mirror to minimize telescope length. This design provides excellent imaging over a field of more than 20 arcminutes with achievable alignment tolerances. A real pupil permits the use of a deformable mirror (DM) for wavefront correction, and a-fast-steering mirror for fine pointing using image compensation. The primary mirror is a compact 8 m diameter segmented aperture. It is composed of a central mirror segment, with a diameter of 3.3 meters, surrounded by eight petals. The petals are folded alternately up and down and deployed after launch. The Reference Architecture mirror is made of beryllium, thermally controlled with very low power heaters (20 mW total) so that its figure remains insensitive to rapid or large positioning slews. The areal density of the primary mirror assembly (mirror, actuators and backup structure) is 13 kg m$^{-2}$. The DM provides a design margin for figure errors in the primary mirror,including those due to gravity release, thermal gradients, or edge effects. The DM will correct the wavefront so that the system will be diffraction limited below 2 $\mu$m. Unlike telescopes such as HST that are launched fully assembled, NGST must be able to compensate for errors in deployment position, long-term dimensional changes, and on-orbit thermal variations. Optics are aligned and phased by observing the image of a star and deriving mirror position corrections. Wavefront errors are determined by obtaining defocused star images and analyzing the image with a "phase retrieval" computer algorithm (Redding et al. 1998). Simulation of typical wavefront errors due to polishing, thermal gradients, etc., and diffraction effects due to

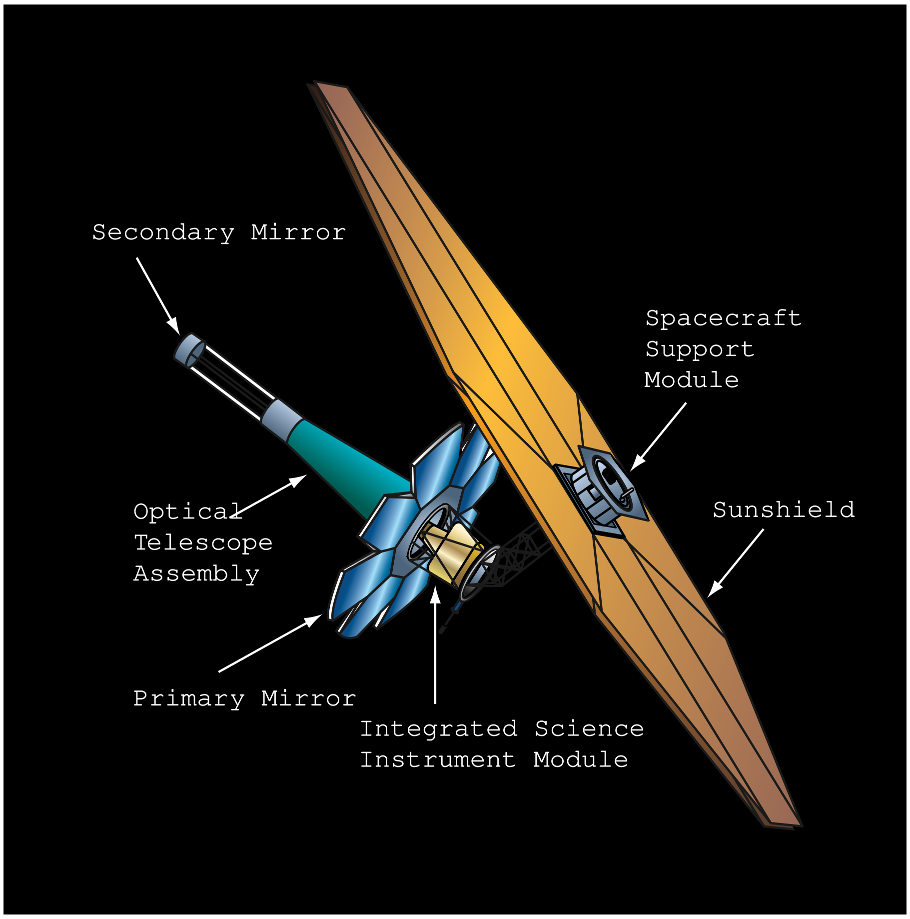


Figure 2. The reference architecture telescope design features.

aperture notches, gaps and obstruction of the secondary mirror support, indicate that the final image will have a Strehl ratio of about 81% at 2 $\mu$m, and 60% at 0.6 $\mu$m without additional DM correction.The Integrated Science Instrument Module (ISIM) consists of a cryogenic instrument module integrated with the OTA, and processors,software, and other electronics located in the Spacecraft Support Module. The ISIM provides the structure, environment, and data handling for several modular science instruments as well as components of the OTA system - the tertiary mirror, DM, and fast-steering mirror.The following ISIM design is illustrative and is not intended to define NGST's final complement of instruments. A wide range of pre-Formulation phase (pre-Phase A) studies of ISIM architecture and individual science instruments have been conducted by science community teams in the US, Europe, and Canada. Procurement responsibility for the science instruments will be allocated among NASA, ESA, and CSA during the Formulation phase (Phase A/B), and instrument proposals solicited by those agencies following selection of the flight NGST architecture. The Reference Architecture instrument suite includes:

- A NIR camera covering 0.6 to 5 $\mu$m, critically sampled at 2 $\mu$m. Efficient surveying capability, as well as guiding requirements, set the field at about $4'$x $4'$,apportioned over four sub cameras each covering a field of $2'$x$2'$. The NIR detectors (InSb or thinned HgCdTe) are radiatively cooled to 30 K;
- A NIR multi-object spectrometer, with spectral resolutions of 300 and 3000 and a spatial resolution of 100 mas, covering a field of $3'$x $3'$. Multi-object capability is enabled by an array of $2048^2$micro-mirrors used to form a reflective slit mask, directing light into or away from the spectrometer;
- A MIR camera/spectrometer covering a field of $2'$x $2'$ with a-spectral range of $5-28\mu$m using a 1K x 1K Si:As array as detector,and a long slit cross-dispersed grism. Its spectral resolution is$\sim 10^3$. The camera employs a selection of slits and a no-slit option to enable direct imaging with filters. The MIR detector is cooled to 6 Kby a miniaturized reverse turbo-Brayton cooler; open cycle solid hydrogen cooling has been identified as a viable alternative.

Following the 1996 NGST study, the NASA Project undertook a detailed design study of the ISIM to demonstrate engineering feasibility of the mission's science goals, assess the required technologies, and revisit the cost estimates. This study concluded that all engineering requirements of the baseline instrument complement including detector, thermal, and data system requirements are feasible with technology that is expected to be mature in 2003 at the beginning of the Implementation phase (Phase C/D).

## 2. Project Update

The NGST is being developed by a broad consortium of government laboratories, academic institutions and aerospace industry partners. Each of these groups bring unique strengths to the project. This past year saw the selection of the Phase A industry partners; Lockheed-Martin and a consortium of Ball Aerospace and TRW. Each of these two teams will develop independent architectures for the observatory working in conjunction with NASA, STScI and the international partners. Support for NGST is strong at NASA headquarters and the funding remains stable for the ensuing fiscal year. Twelve ISIM studies by US and international teams have been completed. These studies will be used to assist the project scientist in recommending a suite of capabilities that NGST requires. Once this suite is defined NASA, ESA and CSA will negotiate the allocation of responsibilities.

## 3. Operations Considerations

One distinct advantage we have in building NGST is that the operating organization, the Space Telescope Science Institute (STScI), was selected early on in the project's history. By having the operations institution participate in the early decisions about the configuration of the observatory and its instruments we can optimize the system trades and costs. From its conception NGST was envisioned as an observatory that would be simpler to operate than HST. The primary simplification comes from its distant orbit and corresponding lack of Earth occultations and the complications that these induce. Advances in computer hardware and software will also allow NGST to operate in a more "event–driven" mode rather than a strict time line manner like HST or other low Earth orbit missions. One could even imagine making use of the vast ground-based data archives that will exist by the launch of NGST to provide lists of alternate "interesting" targets near any given scheduled target which the observatory could slew to in the event that the primary acquisition fails. Such alternate targets could be autonomously selected when the next program in the event queue could not me started for engineering reasons (e.g., momentum management, sun angle constraints).Since the final instrument suite for NGST is not yet known we cannot determine just how the notion of operational simplicity will reflected in their design. STScI has begun to study a number of issues related to observatory operability and their associated impacts on the achievable science and mission costs. These include: proposed dithering strategy, observation overheads, sun shield imposed restrictions, guiding methodology, ground segment, on-board data processing.

## 4. Discovery Potential

NGST will be an observatory with enormous discovery potential both at 0.6-10 $\mu$m and at longer wavelengths. This is illustrated in Figure 3, which shows the time to achieve a broad-band, high-resolution wide field image with a variety of facilities: NGST, HST, Gemini (representing IR-optimized ground-based 8 m telescopes), and Space Infrared Telescope Facility (SIRTF). NGST enjoys a significant background advantage over the ground at all wavelengths, a larger field of view over which high-resolution images can be obtained ($4' \times 4'$ assumed) and a significant aperture advantage over SIRTF. The shorter times required to achieve a given threshold sensitivity can translate into larger fields observed (more targets) or greater sensitivities.

For wavelengths between 2.2 and 10 $\mu$m, NGST is many orders of magnitude faster than any other planned facility. In practice, it will have sensitivities several orders of magnitude better than even SIRTF because of source confusion in very deep observations. In this regard, SIRTF is a superb instrument for surveys of

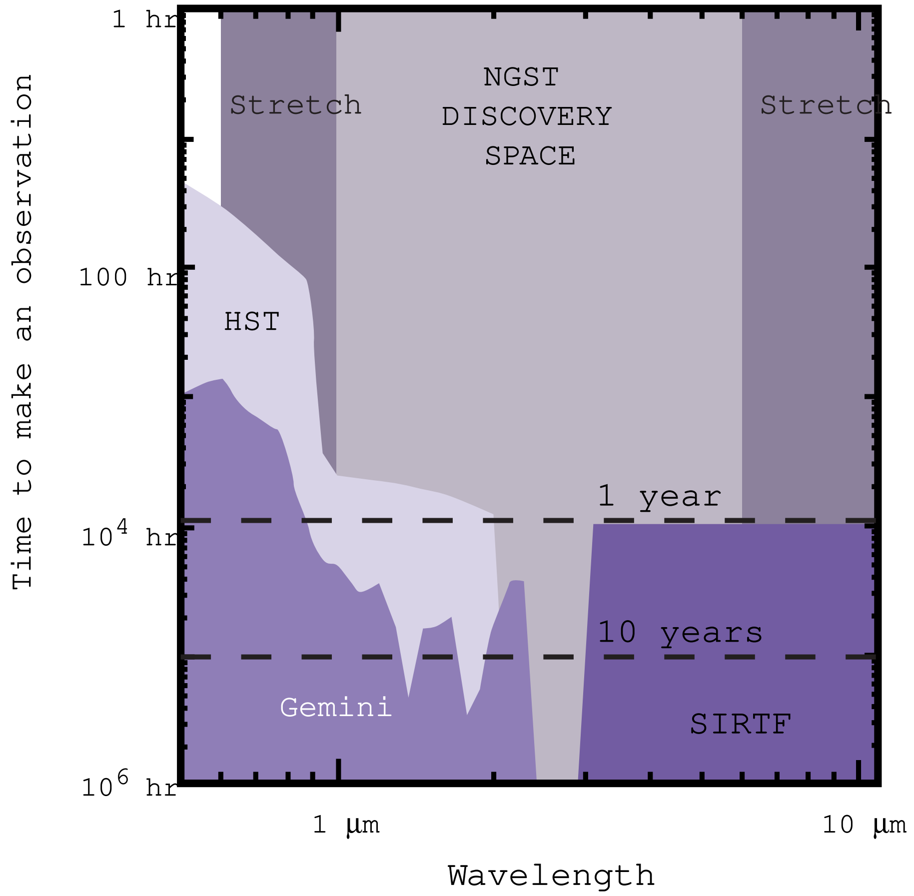


Figure 3. NGST Discovery Space: the relative speed of broadband NGST high resolution, wide field imaging compared with other observatories (HST, Gemini, and SIRTF).

10-100 square degrees. NGST is best used for deeper observations of smaller preselected fields. At wavelengths longer than 10 $\mu$m, NGST will surpass SIRTF by an order of magnitude in sensitivity despite a much higher MIR background. For NIR and MIR spectroscopy, it will be unsurpassed between 0.9 and 28 $\mu$m (28 $\mu$m is the cutoff for Si:As detectors) because NGST's thermal background is much reduced at high spatial resolution. The "uniqueness space" for NGST is defined relative to the many large ground-based telescopes that will be operating by 2008. The criterion is that NGST be at least 100 times faster than an optimally operated and equipped 8 m telescope with laser guide stars and adaptive optics. In the NIR, the NGST imaging uniqueness space is very large. For moderate spectral resolution 2-D spectroscopy the effects of detector noise significantly narrow the uniqueness space. At this resolution and detector dark current, $\sim$0.02 e$^-$ pixel$^{-1}$ s$^{-1}$, NGST is no longer background limited in the visible or NIR ($< 4\mu$m). For spectroscopy of single faint targets, for instance, NGST would be used primarily in the NIR ($> 0.9\mu$m). For high-resolution spectroscopy in the visible and J and K bands ($R > 5000$) or for visible imaging of large fields with 0.4$''$ resolution, large ground-based telescopes are competitive with NGST. This is where the large telescopes planned for the next decade will make major contributions.It is instructive to consider the relative power of NGST compared with that of HST. HST is currently unique in the windowed ultraviolet(0.1-0.3 $\mu$m, a factor of three in wavelength). It has comparable sensitivity but superior resolution over ground-based telescopes in the visible and NIR (0.3-1.8 $\mu$m, a factor of 6). NGST will have10 to 100 times more imaging sensitivity and superior resolution at 2.5 $\mu$m (a factor of 4, i.e. comparable to HST at 0.6 $\mu$m). It will be unique in imaging and spectroscopy from 2.5-28 $\mu$m (a factor of 10 in wavelength). It is clear from this simple analysis that NGST will have at least as great an impact on astronomy as HST.

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## References

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