The Institute of Space and Astronautical Science
Report SP No.14, December 2000

The Next Generation Space Telescope

By

John C. MATHER* and H. S. STOCKMAN†

(November 1, 2000)

Abstract: The NGST (Next Generation Space Telescope), scheduled for launch in 2009, will be a successor to the Hubble Space Telescope. It will cover the range from 0.6 to 28 μm with an 8 m radiatively cooled telescope, carrying cameras and spectrometers. It will study infrared light because the expanding universe redshifts the main stellar luminosity into the near IR, because many cool objects emit only infrared, and because infrared can penetrate opaque dust clouds to show the processes of star formation and obscured galactic nuclei. It will orbit around the Sun-Earth Lagrange point L2. It is a joint project of the NASA, ESA, and CSA, and scientific operations will be provided by the Space Telescope Science Institute.

1. INTRODUCTION

The Next Generation Space Telescope (NGST) is a key component of NASA's Origins Program, and responds directly to the questions:

• How did the Universe, galaxies, stars, and planets evolve? How can our exploration of the Universe and our Solar System revolutionize our understanding of physics, chemistry, and biology?

• Does life in any form - however simple or complex, carbon-based or other - exist elsewhere in the Universe? Are there Earth-like planets beyond our Solar System?

NGST has been under study since 1995 and is planned to be launched around 2009. NGST will be an 8 m class deployable, radiatively cooled telescope, optimized for the 1–5 μm band, with background limited sensitivity from 0.6 to 10 μm or longer, operating for 10 years near the Earth-Sun second Lagrange point (L2), 1.5 million km from Earth. It will be a general-purpose observatory, operated by the Space Telescope Science Institute (STScI) for competitively selected observers from the international astronomy community. NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA) will build NGST, with construction to start in 2003. The planned NASA part of the construction budget is \$500 M (FY96), but the combined total of NASA, ESA, and CSA contributions, including launch, operations, grants, technology development, and inflation, will be around \$2B (in real year dollars). This sum represents about one quarter of the amount invested in HST.

* NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; john.mather@gsfc.nasa.gov
† Space Telescope Science Institute, Baltimore, MD 21218, USA.

NGST will be a unique scientific tool, with excellent angular resolution over a large field of view, deep sensitivity and a low infrared (IR) background. As a cold space telescope, NGST will achieve far better sensitivities than ground-based telescopes. NGST will have diffraction limited resolution at 2 μm or better, and will achieve much higher Strehl ratios and wider fields of view than anticipated from ground-based telescopes using adaptive optics. NGST's aperture is an order of magnitude larger than SIRTF's, with a factor of 100 better sensitivity.

NGST will be able to observe the first generations of stars and galaxies, including individual starburst regions, protogalactic fragments, and supernovae out to redshifts of $z = 5-20$. NGST will resolve individual stars in nearby galaxies, penetrate dust clouds around local star-forming regions, and discover thousands of isolated sub-stellar and Kuiper Belt objects. In 2009, it will be NASA's premier general-purpose observatory.

The scientific and engineering studies of NGST are thoroughly documented at the NGST web site, `http://www.ngst.nasa.gov/science/`. Documents include images, design studies, scientific requirements, public presentations, and schedules.

2. SCIENCE GOALS

2.1 The Dressler "Core" Mission: The Origin and Evolution of Galaxies

The HST & Beyond Committee (Dressler et al. 1996) foresaw the enormous potential of a scientific successor to HST, optimized for the near infrared (1–5 μm), that would "...be an essential tool in an ambitious program of study in many areas of astronomy; it will be especially powerful in studying the origin and evolution of galaxies. By making detailed studies of these distant galaxies, whose light is shifted into the infrared portion of the spectrum, we will be able to look back in time to study the process of galaxy formation as it happened." Since 1996, when the report was written, many advances have occurred. Distant star-forming galaxies have been observed and studied down to magnitudes as faint as B $\sim$ 29 and $z \sim 5.6$ by HST and ground-based 8 and 10 m telescopes. The low but detectable metallicity of the Lyman-alpha forest and damped Lyman-alpha systems have provided evidence for the early formation of stars at $z > 4$. Observations of the ultraviolet luminosity density at high redshift by Keck and HST have placed a lower limit on the early chemical history of the Universe. The far-infrared (FIR, $\lambda > 100$ μm) extragalactic background has been found to be comparable in strength to that of the visible and NIR (1–5 μm). The Submillimeter Common User Bolometer Array (SCUBA) has unveiled a population of faint sub-mm sources that may be dust-covered regions of intense star formation or Active Galactic Nuclei (AGN) at $z \sim 1$. Observations with HST/NICMOS have established the importance of small and faint galaxies at high redshift and the early creation of galactic spheroids at $z > 2$. Collaborative and independent ground and HST observations of Type Ia supernovae suggest that the Universe is accelerating, $\Omega_\Lambda > \Omega_m$, and hence has an age consistent with the ages of the oldest stars.

NGST will enable such studies as:

• Detecting the earliest phases of star and galaxy formation - the end of the "dark ages." This requires superb NIR sensitivity (< 1 nJy, 1–4 μm) in deep broadband imaging ($\sim 10^5$ s).

• Resolving the first galactic substructures larger than individual star clusters ($\sim$ 300 pc for $0.5 < z < 5.0$). This requires HST-like resolution in the NIR ($\sim 0.060''$ at 2 μm)

• 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 ($R = \lambda/d\lambda$): $R \sim 300$ (0.6–5.0 μm) for redshift confirmation, cluster membership, and ages of stellar populations; $R \sim 1000$ (0.6–5.0 μm or longer) for star formation rates, metallicity, and reddening; $R \sim 3000$ (1.0–10 μm) for dynamics (mass).

• Statistically analyzing high-redshift galaxy properties, clustering, and rates of interaction. This will be accomplished with wide field ($\sim 4' \times 4'$) imaging and spectroscopic surveys. This angular size corresponds to restframe scales $\sim$ 1 Mpc $\times$ 1 Mpc (for $0.5 < z < 5.0$ and all reasonable cosmologies) and will include all likely progenitor substructures within galactic regions comparable to the Local Group, as well as the central regions of distant clusters of galaxies.

• 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 $z \sim 2$. Resolving the mid-infrared (MIR) and far-infrared (FIR) backgrounds would be enabled with the NGST stretch goal of MIR imaging and spectroscopy (5–28 μm).

2.2 The Structure and Chemical Enrichment of the Universe

The geometry and structure of the Universe, as well as its history of element formation, are intimately related to the formation of galaxies. In the coming decade, the MAP 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 μm 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 by AXAF, Planck, and ground-based 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 ($> 1\,\mathrm{deg}^2$). These scales are larger than those of galaxy clusters and smaller than those probed by the CMB satellites and ground-based surveys.

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 Ia and Type II supernovae (SNe) at redshifts between $1 < z < 5$. Supernovae at even higher redshifts could be confirmed by NGST and followed, using ground-based survey telescopes, to detect their brief but luminous ultraviolet precursor transients. Measuring the rates and galactic associations of Type Ia and Type II 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 Ia 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 Ia supernovae with cosmologies involving only $H_0, \Omega_\Lambda, \text{and}\, \Omega_m$, 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.

These science programs will require coordinated preparation and data analysis efforts by the community to optimize the science return:

• The weak lensing surveys will require well-characterized, high-resolution, point-spread functions over the entire wide field of view and wavelength range (0.6–5 μm). This can be accomplished either by special calibrations or some form of continuous figure sensing of the individual primary segments.

• To follow the light curves of supernovae, the NGST science operations must respond to new supernovae discovered in NGST fields within ~ 1 week. The time dilation at high redshift helps relax this requirement compared with that needed for nearby supernovae. NGST also must return to the same field, perhaps in a different orientation, over periods of two weeks to six months (for the highest redshift supernovae).

2.3 The Processes of Star and Planet Formation

NGST, with an extended MIR wavelength coverage (5–28 μm), will have a unique role in this area. We foresee the following examples:

• Characterizing the physical 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 ~ 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. High resolution NIR and MIR imaging with NGST will be a powerful probe of the distribution of cool material in dense circumstellar regions, allowing the resolution of AU-scale structures.

• 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. Only 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.

2.4 The Design Reference Mission

The NGST science described above is part of the Design Reference Mission (DRM), a set of science programs enabled by NGST (Stiavelli et al. 1997; and updates on the NGST web site). The goals of the DRM are to provide 1) examples of NGST science to stimulate further inputs from the astronomy community, 2) descriptions of science programs in sufficient detail to derive secondary requirements/capabilities of the observatory, and 3) a semi-quantitative basis for trade studies (e.g. sensitivity versus field of view). These science programs have been assembled by the NGST Ad Hoc Science Working Group under five themes and can be accessed through the NGST science website. During the Formulation phase (Phase A/B), we will continue to solicit programs for the DRM from our international partners and the astronomy community.

3. MISSION CONCEPT

The science goals for NGST require a telescope with high sensitivity covering the wavelength range from 0.6 to 10 μm with capability out to 28 μm, and with NIR angular resolution comparable to that of HST. Ball Aerospace, TRW, and NASA studied three mission architectures during pre-Phase A. For simplicity, the NASA architecture, referred to as the Yardstick, is presented here. The other concepts are similar, responding to the same high level requirements. The Yardstick 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.

3.1 The Yardstick Optical Telescope Assembly (OTA)

The Yardstick 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 $20'$ 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 m, surrounded by eight petals. The petals are folded alternately up and down and deployed after launch.

The Yardstick mirror is made of beryllium, thermally controlled with heaters (20 mW total) so that its figure remains insensitive to slews. The areal density of the primary mirror assembly (mirror, actuators and backup structure) is 13 kg/m^2. 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.

3.2 Integrated Science Instrument Module

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.

Following the 1996 NGST study, the NASA Project undertook a detailed design study of the ISIM to demonstrate the 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 systems requirements are feasible with technology that is expected to be mature in 2003 at the beginning of the Implementation phase (Phase C/D). In addition, this study suggested that a highly modular approach for the ISIM is possible, enabling procurement of individual instruments from science community teams.

3.3 Recommended Science Instrument Complement

The Ad Hoc Science Working Group met in late 1999 to recommended a suite of instruments that will meet the most important NGST science goals. According to the ASWG, the following three-instrument complement is necessary to achieve the minimum scientific program for the NGST mission. There is no acceptable two-instrument complement that will achieve NGST's highest priority science goals.

Visible/NIR Camera. This camera will have near-infrared (NIR) and visible filters, a 0.6–5 μm wavelength range, a $4' \times 4'$ FOV, and $0.03''$ pixels ($\lambda/2D$ at 2.4 μm) requiring an 8K^2 array detector. A basic spectroscopic capability with $R = \lambda/d\lambda \sim 100$ is essential and will be provided either in this camera (e.g. with a slit and grism) or in the spectrograph described below. Sub-arrays within this camera could possibly serve as a guide star and wavefront sensor. A low-cost coronagraphic capability could also be provided.

This camera is required for most of the mission's highest-ranked science programs, including the detection of light from the first stars, star clusters or galaxy cores; the study of high-redshift galaxies seen in the process of formation; investigation of dark matter through studies of weak gravitational lensing; the discovery of high-redshift supernova; and studies of the stellar populations in nearby galaxies, young stellar objects in our Galaxy, and Kuiper Belt Objects in our Solar System.

NIR Multi-object Dispersive Spectrograph. A multi-object dispersive spectrograph will have a wavelength range of 1–5 μm, $R \sim 1000$, pixels matched to the sizes of high-redshift galaxies ($\sim 0.1''$), a $3' \times 3'$ or larger FOV, and be capable of observing >100 objects simultaneously. Ideally, the spectral resolution will be selectable and will extend down to $R \sim 100$, unless this capability is provided in the Visible/NIR camera. The preferred technology for this instrument is micro-electro-mechanical systems (MEMS); (e.g. selectable micro-mirrors or micro-shutters). If this technology were unavailable, a multi-object spectrograph (MOS) with mechanically positioned slits (jaws or optical fibers) or a wide-field integral field spectrograph (IFS) would be acceptable alternatives at reduced observing efficiency.

The key scientific objectives of this instrument are studies of star formation and chemical abundances of young galaxies at high redshifts, measurement of the hierarchical development of large-scale structure at high redshifts, investigations of disk and gas structure in Active Galactic Nuclei (AGN), and the study of the initial mass function in young stellar clusters.

MIR Camera-spectrograph. This combined camera/slit spectrograph will be sensitive over the 5–28 μm mid-infrared (MIR) wavelength range with $R \sim 1500$ and a $2' \times 2'$ FOV sharing a single focal plane array. A low-cost coronagraphic capability could be provided.

The key scientific objectives for this instrument include the study of old, established, stellar populations at high redshift; mid-IR (MIR) diagnostic emission line features of obscured starbursts and AGN at $z < 5$; Hα emission to $z \sim 15$; local group AGB stars; the cool stellar mass function; the physics of protostars; circumstellar disk mineralogy; the sizes of Kuiper Belt Objects; and faint comets. This instrument will be ideal for the detailed follow-up study of new MIR sources that will be discovered by the Space Infrared Telescope Facility (SIRTF) and Infrared Space Observatory (ISO).

Additional Instruments. The three-instrument complement will not be able to address all of the high priority NGST science goals. Each of the following three instruments addresses important, unique scientific objectives of NGST: NIR Integral Field Spectrograph, High Resolution Camera, or MIR Integral Field Spectrograph.

3.4 Passive Cooling and Thermal Control

All NGST designs solve the problem of cooling to the cryogenic temperatures required for NIR and MIR operation passively by protecting the observatory from the Sun with a multi-layer shield; using a heliocentric orbit to decrease the Earth's thermal input; and configuring the telescope to have a large area exposed to space to improve radiative cooling. Baffles and stops prevent the science instrument detectors from directly seeing any surface other than the mirrors in the optical system. To make the thermal emissivity negligible compared with the zodiacal light, the back of the sunshield must be below 100 K. This is accomplished by adding five low-emissivity layers behind the surface of the shield facing the Sun. The main optics then reach very low temperatures (< 40 K) and do not contribute significantly to the overall emissivity of the observatory.

3.5 Attitude Control and Sky Coverage

An offset geometry characterizes many NGST designs: the warm spacecraft support system is several meters away from the telescope. The problem of rigid pointing of the OTA to the required milli-arcsecond stability is solved by using an image compensation system. The system is composed of a guiding sensor that monitors a star in the telescope's field of view coupled to a fast steering mirror to stabilize the line of sight. In the Yardstick concept, the NIR camera is used as a guiding sensor to eliminate the cost of a dedicated guiding system. The observatory can be pitched $\pm 25^\circ$ off the sunline and rolled 360° about the sunline. The portion of the sky accessible is a 50° wide spherical band centered 20° away from the perpendicular to the sunline. This represents 40% of the entire sky. Full sky coverage is achieved in slightly less than 6 months. At any time, any target in the accessible zone can be tracked for a minimum of 7 weeks.

3.6 Launch and Orbit

The overall mass of the Yardstick NGST is approximately 3300 kg, within the capability of an Atlas IIAS or the next generation of medium launchers (EELV Medium). Deployment of the OTA occurs soon after launch, before the sunshield is deployed, while all the mechanisms are still relatively warm. Optics alignment can then begin, followed by science calibration as the telescope cools. The halo orbit at L2 is reached about 3 months later.

ACKNOWLEDGMENT

The NGST project has enjoyed strong support from NASA Headquarters, including the NASA Administrator, Dan Goldin, and the Associate Administrator for Space Science, Ed Weiler. Our colleagues at ESA and CSA have also been very enthusiastic about this new project. The scientific content described above was developed by the HST & Beyond committee and expanded with detailed observing proposals by the Ad Hoc Science Working Group. A longer version of this manuscript was prepared by the Space Telescope Science Institute for presentation to the National Academy of Sciences Decade Survey committee.

REFERENCES

Dressler, A. et al. 1996, Exploration and the Search for Origins: A Vision for Ultraviolet-Optical-Infrared Space Astronomy, AURA, http://ngst.gsfc.nasa.gov/project/bin/HST_Beyond.PDF

Stiavelli, M. et al. 1997, ST-ECF Newsletter, 24, 4