James Webb Space Telescope
For the Review of the HST to JWST Transition Plan

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The James Webb Space Telescope is the planned successor for the Hubble Space Telescope, extending the discoveries made by HST into the infrared, where the highly redshifted early universe must be observed, where cool objects like protostars and protoplanetary disks emit strongly, and where dust obscures shorter wavelengths. Programmatically, it will be the next general observer facility for the international astronomy community.

JWST takes advantage of technical progress in large mirrors and infrared detectors to provide observing speeds ranging from 100 to 10^6 times greater than competing facilities over the 0.6 to 27 μm spectral range. It complements HST and ground-based facilities, which are superior at shorter wavelengths, and SIRTF, which also sees wavelengths longer than 30 μm. It is the only facility capable of observing the predicted first light objects (protogalaxies, supernovae, and black holes) at redshifts out to 20, when the universe was 180 Myr old.

The JWST will provide 2.5 times the HST aperture and 5.8 times the HST collecting area, covering wavelengths from 0.6 to 27 μm with comparable image quality. JWST will be deployed with a segmented primary mirror and actuators to adjust the optical system. It will carry three instruments and a fine guidance camera in the focal plane, which will be cooled to about 30 K. These instruments will provide imaging and coronagraphy over the entire wavelength range, multi-object spectroscopy from 0.6 to 5 μm, tunable filter spectroscopy from 1 to 5 μm, and integral field spectroscopy from 5 to 27 μm. All are optimized for ultimate sensitivity because of the faintness of the first light objects.

The JWST will be launched to orbit around the Sun-Earth Lagrange point L_2, about 1.5 x 10^6 km from the Earth in the opposite direction from the Sun (i.e., overhead at midnight). This point is a gravitational balance point in which the JWST moves around both Sun and Earth once per year, with only minor fuel consumption. At L_2, a multi-membrane shield protects the JWST from both Sun and Earth radiation.

JWST is being built by an international partnership, led by NASA/Goddard Space Flight Center. The observatory contractor is Northrop Grumman, teamed with Ball Aerospace, Eastman Kodak, and ATK. The Near IR camera is provided by the University of Arizona with Lockheed Martin, the Fine Guidance Camera comes from the Canadian Space Agency, the mid IR instrument comes from a partnership of a European Consortium and NASA/JPL, the near IR spectrometer comes from the European Space Agency, and the rocket will be an Ariane 5 purchased by ESA. The JWST will be operated by the Space Telescope Science Institute, using procedures and software derived from HST. All international commitments have been approved.

The JWST study was initiated in 1995, phase B (detailed design) will start in 2003, and launch is planned for 2011. While the schedule and budget follow NASA guidelines for slack and contingency, it is not unusual for large observatories to slip 1 or 2 years beyond such a planned date. For JWST to adhere to its launch date, it is critically important that it should have the planned budget.

JWST Science Program

The JWST Project has worked with NASA Headquarters to develop a mission with great scientific power and that is also financially and technically feasible. JWST will have a primary mirror of 25 m^2 area and low infrared background, and will provide imaging and spectroscopy from 0.6 to 27μm. The Science Working Group has described the JWST science program in four major themes that address two fundamental questions: How did we get here? Are we alone? The four themes are:

- **First Light (After the Big Bang)**
- **Assembly of Galaxies**
- **Origins of Stars and Planetary Systems**
- **Planetary Systems and the Origins of Life**

These themes are restatements of those in the HST and Beyond report. In 1995, the HST and Beyond committee, chaired by Alan Dressler, recommended that NASA build a Next Generation Space Telescope, with at least a 4 m aperture, optimized for the 1-5 μm region, with extensions to both shorter and longer wavelengths if the costs were reasonable. The report outlined many possible uses for such a mission but gave top priority to "(1) *the detailed study of the birth and evolution of normal galaxies such as the Milky Way*." [p. ix] A more detailed listing of the key questions of high redshift astrophysics is given on p. 44. This list is still current:

(1) *What was the sequence of mass accumulation (including dark matter) in the central*

regions of galaxies? Was this a sudden event or the result of steady accretion? Over what z range did this occur? Did very early mergers play a dominant role in shaping the masses of galaxies? Were there triggering events?

(2) *What was the sequence for disk formation?* Was this also a sudden event or was the accretion of matter into disks a prolonged process? How did this depend upon the type of (pre-existing?) central core in the galaxy?

(3) *When and where were the first heavy elements formed?* What was the mass spectrum of the first generation of stars, and how did the chemical enrichment process proceed through generations of type I and type II supernovae? What was the nature of the early interstellar medium?

(4) *What was the role of Active Galactic Nuclei (AGNs) in galaxy formation and early evolution?* What conditions in galaxies led to the dramatic peak in comoving density of AGNs at $2 < z < 3$ and what, if any, role did AGNs have in changing the evolution of their host galaxies?

(5) How do the answers to Questions #1 – #4 depend on environment, galaxian mass, state of the primordial gas, and dynamics?

(6) What were the conditions (e.g., temperature, density spectrum, elemental composition) in the universe between z » 1000 and z »5?

(7) *Were there any "precursor events" (e.g., supernovae) that preceded full-blown galaxy formation?*

The HST and Beyond report also discussed a very wide range of other topics:

(1) Our Solar System
(2) Extra-Solar Planetary Material and Circumstellar Gas
(3) Transition Objects: Brown Dwarfs
(4) The Interstellar Medium and the Birth of Stars
(5) Stellar Populations
(6) Stellar Death and Transfiguration
(7) Infrared Emission from Normal Galaxies
(8) Active Galaxies
(9) Chemical Evolution of the Interstellar Medium as a Function of Redshift
(10) Galaxy Dynamics in the Early Universe
(11) Cosmology

All of these research areas would benefit immensely from the capabilities of JWST, with sensitivity and angular and spectral resolution over its entire spectral range comparable to those of HST at shorter wavelengths.

> The science potential of such a telescope at near and mid-infrared wavelengths is formidable and led the 2000 Decade Committee of the National Research Council to recommend that the facility be the top priority for a major NASA facility. (The project submission to the UVOIR committee is available at http://www.ngst.nasa.gov/cgi-bin/pubdownload?Id=325, and the recommendation of the NRC is available at http://books.nap.edu/html/astronomy_and_astrophysics/index.html.)

To enable this scientific program, in 1999 the JWST Acting Science Working Group defined the package of three instruments that is now being developed. They also found that a telescope significantly larger than that recommended by the HST and Beyond report would be required. The precursors to the Milky Way were small and faint, according to the developing hierarchical picture of galaxy formation, and were formed at higher redshift than previously imagined. The early galaxies, although numerous enough for study, will be seen along with much larger numbers of foreground galaxies, so large fields of view will be required, and spectra will be needed for thousands of candidate objects.

In addition, the reionization of the primordial gas by luminous objects might have occurred at redshifts of 20 or 30. The search for very high redshift protogalaxies, supernovae, and active galactic nuclei is thus very important. The theory of the first stars suggests that many were in the mass range from 30 to 300 solar masses, that they could produce super-supernovae, and that the most massive of these might form black holes by direct collapse. The JWST might see these at redshifts out to 20 if they are significantly brighter than present Type II (core-collapse) supernovae. Similarly, primordial stellar aggregates of about 10^6 solar masses could also be discovered and studied with JWST up to z ~ 15-20, thus providing fundamental clues into the beginning of the epoch of star and galaxy formation.

The Wilkinson Microwave Anisotropy Probe (WMAP) showed evidence of this early reionization, with an estimated optical depth of electrons of 0.17 out to redshift ~20, when the universe was 180 Myr old. WMAP also confirmed the cosmic acceleration and distance scales and measured the baryon and dark matter content of the universe very precisely. For JWST the uncertainties in the cosmic distance and age scales are no longer significant limitations to our predictions.

Although the acceleration of the expansion of the universe has been measured by WMAP and the supernova distance scale, it is still essential to test whether the acceleration is due to a cosmological constant as envisioned by Einstein, or some new form of the stress-energy tensor with a different dependence on time. A more precise supernova distance scale measured by the Supernova Acceleration Probe (SNAP) could answer this question. JWST will be essential in understanding the evolution of supernova properties with time. For example, at a redshift of 4.2 the predicted supernova brightness is approximately independent of the value of the cosmological constant, so any deviations from the predictions must have other causes. Since JWST will be able to discover and study supernovae over a wide range of redshifts (spectroscopically up to z=5 and possibly beyond) it will be straightforward to disentangle possible systematic changes in the supernova properties with redshift from the evolution of a cosmological field.

The study of star and planet formation is one of the top objectives identified by the HST and Beyond report and by the above JWST SWGs. The JWST has the infrared coverage and high sensitivity needed to penetrate the dust clouds surrounding such interesting sites, and to measure the thermal emission from cool objects such as brown dwarfs, young Jupiters (especially if not too close to parent stars), and protoplanetary disks. Many low-mass objects will be found, particularly in regions where stars (and presumably planets) are being formed today. Kuiper Belt objects in the outer solar system, the most ancient observable relics of the formation of the Solar System, can be examined in both reflected sunlight and thermal emission, yielding their albedos (reflectances) and mineralogy for comparison with dust seen around other stars.

Simulations have shown that at least some nearby stars may have planets that can be observed directly by JWST. Vega is surrounded by a large disk of dust, with structure (observed at millimeter wavelengths) attributable to the gravitational effects of a Jupiter-like planet. The JWST is predicted to have the sensitivity and resolution to image both the disk and the planet and to obtain their spectra.

JWST was designed to take full advantage of the unique opportunity of the new spectral range opened up by new detectors, dark and cold L2 environment, and the large mirror made possible by deployable lightweight optics. No other mission offers this combination of new capabilities addressing key scientific questions from the First Light to the origins of stars, planets, and life.

JWST Project Status

Goddard Space Flight Center, in collaboration with the STScI, began the feasibility study of a 4-8m class telescope in the fall of 1995 and engaged the major aerospace contractors as well as over one hundred volunteer and selected scientists. At the urging of Dan Goldin, NASA administrator, the Next Generation Space Telescope Project concentrated on 8-m class deployable telescopes to be launched into an L_2 orbit with an intermediate class expendable launch vehicle.

The Project completed the feasibility phase in 2001 and prepared for selection of the prime contractor and US funded science instrument contributions. At that time, NASA elected to reduce the aperture requirement to 25 m^2 to reduce costs and development risk. During June 2002, NASA chose the University of Arizona, teamed with Lockheed Martin with contributions from the Canadian Space Agency to develop the Near Infrared Camera (NIRCam, Marcia Rieke PI) and the other members of the flight Science Working Group. During September 2002, NASA selected TRW to be the prime contractor and formally changed the name of the mission to the James Webb Space Telescope in honor of NASA's second administrator, who began the Apollo program and made science from space an important and critical element of the NASA charter. In turn, TRW was purchased by Northrop Grumman and became Northrop Grumman Space Technologies (NGST). Following the selection, NASA and NGST began a series of trade studies to synchronize schedules and responsibilities among NASA, NGST, the international partners (ESA and the Canadian Space Agency), the instrument teams, and the STScI. This phase was completed during June 2003 in time to prepare for a series of reviews required to begin detailed design and budgeting (Phase B). The important scientific outcomes are that the mirror area was set at 25 m^2; the original science instruments capabilities were maintained; and the planned launch date was moved to August 2011.

International Partner Contributions

The contributions of the JWST international partners have been firmly established. NASA will oversee the entire development and is responsible for the spacecraft, telescope, NIRCam, and operations development and overall integration and testing. NASA will also provide detectors, associated electronics and other important aspects of the two other instruments. The Science Program Committee of ESA has committed that organization to provide an Ariane 5 launch vehicle, the near infrared spectrograph (NIRSpec), and the optical portion of the mid-infrared instrument (MIRI).. The Canadian Space Agency has set aside funding for its responsibilities for the Fine Guidance System and the tunable filter imagers within that module. ESA and CSA will also provide staff support to the Science and Operation Center.

Observatory Architecture

The key elements are the deployable telescope mirrors, the multi-layer sunshield, the integrated science instrument module, and the spacecraft bus on the sunward side of the sunshield. The angle between the sunshield and the telescope axis is fixed. By rolling about the sun line (roughly perpendicular to the sunshield) and pitching the long axis of the observatory with respect to the sun, the telescope can observe any celestial object within a ~60 degree annulus that rotates about the ecliptic once per year. Small regions about the ecliptic poles are visible throughout the year; larger polar regions may be observed for more than half a year including large portions of the galactic poles – the regions of greatest transparency to galactic dust and most often used for deep galaxy surveys.

Deployable telescope mirrors

The current design of the JWST primary mirror incorporates 18 hexagonal segments attached to three lightweight composite backplanes. The backplanes are folded like a drop-leaf table during launch and are deployed and locked several days after launch. Each of the hexagonal segments is adjustable in six degrees of freedom and in radius of curvature. In late 2003, the Project and NGST will select the segment material (ultra-low expansion glass or beryllium) based upon the results of testing similarly sized advanced technology mirrors. The secondary mirror is mounted on a deployable secondary tower and has six degrees of adjustment. The finest adjustments of the optical train are made based on out-of-focus images in a fashion similar to that used in diagnosing the HST mirror aberrations.

Multilayer Sunshield

The deployed sunshield provides protection and solar insulation to the telescope optics and scientific instruments. In shadow, the heating of the telescope and instruments will be dominated by thermal conduction from the spacecraft avionics and low power instrument electronics. Radiation from the back surface of the sunshield (~90K) will scatter into the telescope beam but remain below the level of the zodiacal background at wavelengths $< 12\ \mu m$. TRW/NGST has extensive and highly successful experience in deploying such structures in space.

Second Lagrange Point

JWST will be launched directly into a wide halo orbit about L_2 (approximately 1.5 x 10^6 km from Earth). The primary advantages of this location are the lack of thermal and tidal forces on the observatory and only minor constraints due to scattered moonlight or Earthshine. Using the Deep Space Net, JWST can transmit over 400 Gbits per day of science and engineering data. JWST is not planned for retrieval from or servicing at L_2.

JWST Science Instruments

JWST will have three science instruments and a fine guidance camera with science capabilities. These instruments provide imaging, spectroscopy and coronagraphy over the full wavelength range of 0.6 to 27 μm.

Near-Infrared Camera (NIRCam)

NIRcam (PI: Marcia Rieke, University of Arizona) is JWST's imaging camera in the wavelength range of 0.6 to 5 μm. The current design of NIRCam consists of two identical broad- and intermediate-band imaging modules each with a 2.3 x 2.3 arcmin field of view. The modules will have a short and a long wavelength channel, taking images simultaneously with light split by a dichroic filter at about 2.35 μm. Each of the short wavelength channels will be Nyquist sampled at 2 μm with a 4096 x 4096 pixel mosaic of four 2048 x 2048 pixel detectors. The long wavelength channels are Nyquist sampled at 4 μm with single 2048 x 2048 detectors. Coronagraphs are present in all modules. NIRCam provides wavefront sensing to enable alignment of the primary mirror segments. The detectors will be HgCdTe arrays produced by Rockwell Scientific.

Near-Infrared Spectrograph (NIRSpec)

NIRSpec (Lead Scientist: Peter Jakobsen, ESA) will provide JWST with multi-object spectroscopic capability in the wavelength range of 0.6 to 5 μm. NIRSpec will obtain simultaneous spectra of more than 100 objects in a 9 square arcminute field of view with resolving powers of $R = \lambda/\Delta\lambda \sim 100$ and $R \sim 1000$. The baseline design uses an array of micro-electromechanical system (MEMS) micro-shutters to provide programmable aperture control that will enable users to select and observe hundreds of different objects in a single field of view. Selection of the NIRSpec detector technology will occur in late 2003. NASA/GSFC provides detectors and electronics to NIRSpec as well as the micro-shutter array system.

Mid-Infrared Instrument (MIRI)

MIRI (Science Team Leads: George Rieke, University of Arizona; Gillian Wright, UK ATC, Edinburgh) will provide imaging and integral field unit (IFU) spectroscopy at wavelengths from 5 to 27 μm. The MIRI detectors are Si:As photoconductor arrays with 1024 x 1024 pixels from Raytheon and will be cooled to ~ 6.9 K by a cryo-cooler or a cryostat. The MIRI imager will provide broad and narrow-band imaging, coronagraphy, and low-resolution ($R \sim 100$) slit spectroscopy. The imager will be diffraction limited at 6 μm with a pixel scale of 0.1 arcsec and a field of view of about 100 x 100 arcsec. The integral field spectrograph will obtain simultaneous spectral and spatial data on a relatively compact region of sky. Its design uses four image slicers to provide R ~ 3000 integral field spectroscopy over a λ = 5 to 27 μm wavelength range. The IFUs provide four simultaneous fields of view, ranging from 3.5 x 3.5 arcsec to 7.5 x 7.5 arcsec with increasing wavelength, with pixel sizes ranging from 0.127 to 0.631 arcsec. The spectrograph uses two detector arrays.

Fine Guidance System (FGS)

The FGS (PI: John Hutchings, Dominion Astrophysical Observatory, CSA) will provide high-precision pointing error signals to the observatory attitude control subsystem to enable stable pointing at the milli-arcsecond level, comparable to HST. The FGS will provide an appropriate guide star with 95% probability at any point in the sky. In the current design, the FGS consists of three modules, two providing the guidance signals and one providing tunable filter imaging. The tunable filter module has a short and a long-wavelength arm, with a dichroic splitting the light, and has a resolving power of about 100. The tunable filter module can function as a backup to the two main guider modules.

JWST Schedule

Detailed design and budgeting: 2003-2005
Development: 2006-2008
Integration and Testing: 2009-2011
Launch, commissioning, and first science: 2011-2012

JWST Budget and Schedule Confidence

The NASA portion of the JWST budget is estimated at $2.5 B US from pre-Phase A (studies and early technology development including full cost accounting charges) through launch and on-orbit commissioning, including contingency budget allocations in accordance with NASA policy. The Canadian contribution is estimated at $50 M in US FY96 units and has been allocated. The European contribution may cost approximately 270 M Euro from the European Space Agency and 40 M Euro from the national agencies funding the MIRI consortium, and has been approved by the Science Program Committee.

Experience with prior NASA projects of comparable size shows that there are many factors that can delay launch. These include lack of funding, late delivery from international partners, competition for test chambers, failure of technology developments to mature, failure of electronic parts in screening, launch vehicle failures, earthquakes and fires, and handling accidents. For background we show the experience with other missions in Fig. 1.

For HST, Chandra, and SIRTF, the average delay after C/D start was 1.8 years. (This assumes HST would have launched in fall 1986 except for Challenger.) The JWST is 3 years from C/D start, and the JWST schedule is aggressive in two of the other three categories. On the other hand, the JWST technology development program is funded at a higher fraction of total budget

(~15 percent) at an earlier point in time (pre-Phase A through Phase B) than for these missions, which significantly reduces the risk of cost overrun and schedule delay during development,

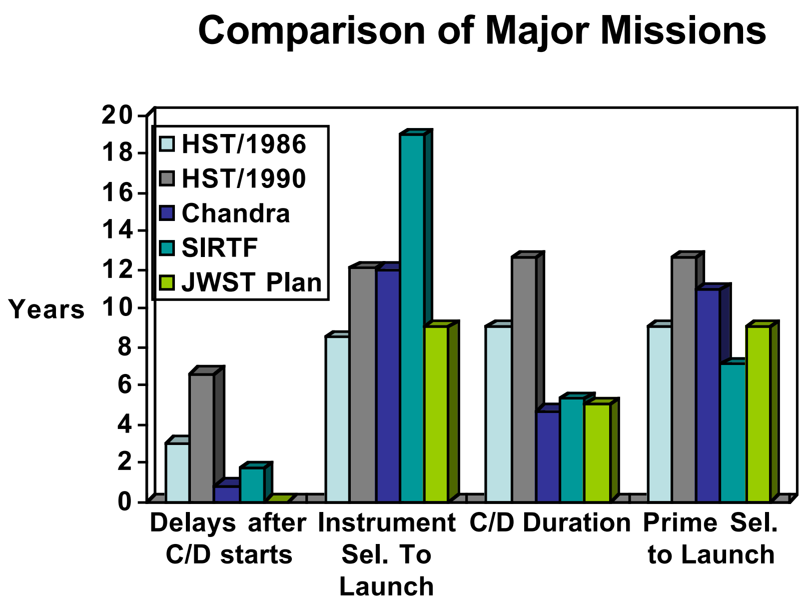

Fig. 1. Major mission schedule comparison.

integration and testing. From this history, one may guess that a 1-2 year delay in the JWST launch might occur relative to the current plan. JWST has been extremely carefully reviewed by NASA committees and is currently undergoing a detailed independent cost estimation process.

JWST complements other facilities

JWST will be launched at a time when many ground-based 8 and 10 m telescopes are mature and operating with advanced adaptive optics, HST will be more than 20 years old, SIRTF will have completed its mission, SOFIA (the Stratospheric Observatory For Infrared Astronomy) will be in regular use, ALMA (the Atacama Large Millimeter Array) will be in early operation in Chile, and the ground-based community will be constructing a 30-m class telescope (e.g. the Giant Segmented Mirror Telescope, GSMT).

The JWST is superior to all of these facilities in its own spectral range for four reasons. First, JWST is above the atmosphere, so the background light it sees is far lower than for ground-based equipment. The ratio ranges from a factor of a few at visible wavelengths, to millions in the thermal infrared. Moreover, there are no wavelengths blocked by atmospheric absorption. Image quality is not degraded by the atmosphere and is stable over a large field of view on time scales of weeks. Second, JWST is cold, to take advantage of this dark environment, and its imaging sensitivity will be limited by photon statistics of the zodiacal light background at all wavelengths less than 12 μm. Third, JWST is large, with a collecting area 46 times as large as SIRTF's, and 5.8 times as large as HST's. Fourth, JWST carries 67 Mpixels of greatly improved detector arrays (including the FGS guiders), compared with SIRTF's 0.30 Mpixels. On the other hand, JWST cannot be sufficiently superior to ground-based telescopes for very high spectral resolving power observations that can avoid telluric OH emission, and does not provide this capability. It is also not cold enough to compete well with SIRTF sensitivities at wavelengths > 30 μm. At short wavelengths, it cannot compete with HST's image quality and its new larger detector arrays. JWST will do only those things it can do best.

JWST provides approximately the same optical image quality as current adaptive optics systems on ground-based 8 m telescopes, with a Strehl ratio (on-axis intensity relative to a perfect system) of 0.8 at 2 μm. Hence, the primary JWST advantage at wavelengths less than 2 μm is in its relatively large field of view (2.3 x 4.6 arcmin with the near-IR camera, compared with ~ 30 arcsec for normal AO on the ground) with good, stable image quality (< 0.08 arcsec). For some problems, such as searching for faint primordial objects, this JWST advantage is critically important. JWST can find faint targets, and ground-based telescopes can provide spectroscopic follow-up observations.

The ALMA will provide cosmologically interesting sensitivity as well. As an interferometric millimeter telescope, it has a relatively small instantaneous field of view (around 30 arcsec at 1 mm). With baselines up to 10 km it can provide angular resolution of 0.01 arcsec for JWST sources with bright millimeter emissions.

Transition between HST and JWST

The JWST does not replace the HST, but complements it, extending its scientific programs to those areas where infrared capability is required for the next step. Example topics include both early universe science (highly redshifted or dust-obscured) and local science (cool objects, star and planet formation in dust-obscured regions and remnants of the early Solar System). The JWST science program was developed assuming that there would be no overlap in time with the HST observations, but that key observing programs could be coordinated in advance, and many needed HST observations have already been made.

Recommendation to the Committee

JWST is just as essential now as when it was endorsed by the National Academy of Sciences Decadal Survey in 2000. It takes the largest possible step in observing capabilities, and opens new wavelength ranges for study of fundamental topics ranging from the first light and the first galaxies in the Universe to star and planet formation and the origins of life. The JWST has been approved by the international partners and has been thoroughly reviewed by NASA. Its technology is mature, and all budgets and contracts are in place to meet its launch date of 2011. Considering the uncertainties of keeping the HST at the forefront of science, it is vital to continue with JWST at the maximum safe speed for launch in 2011.