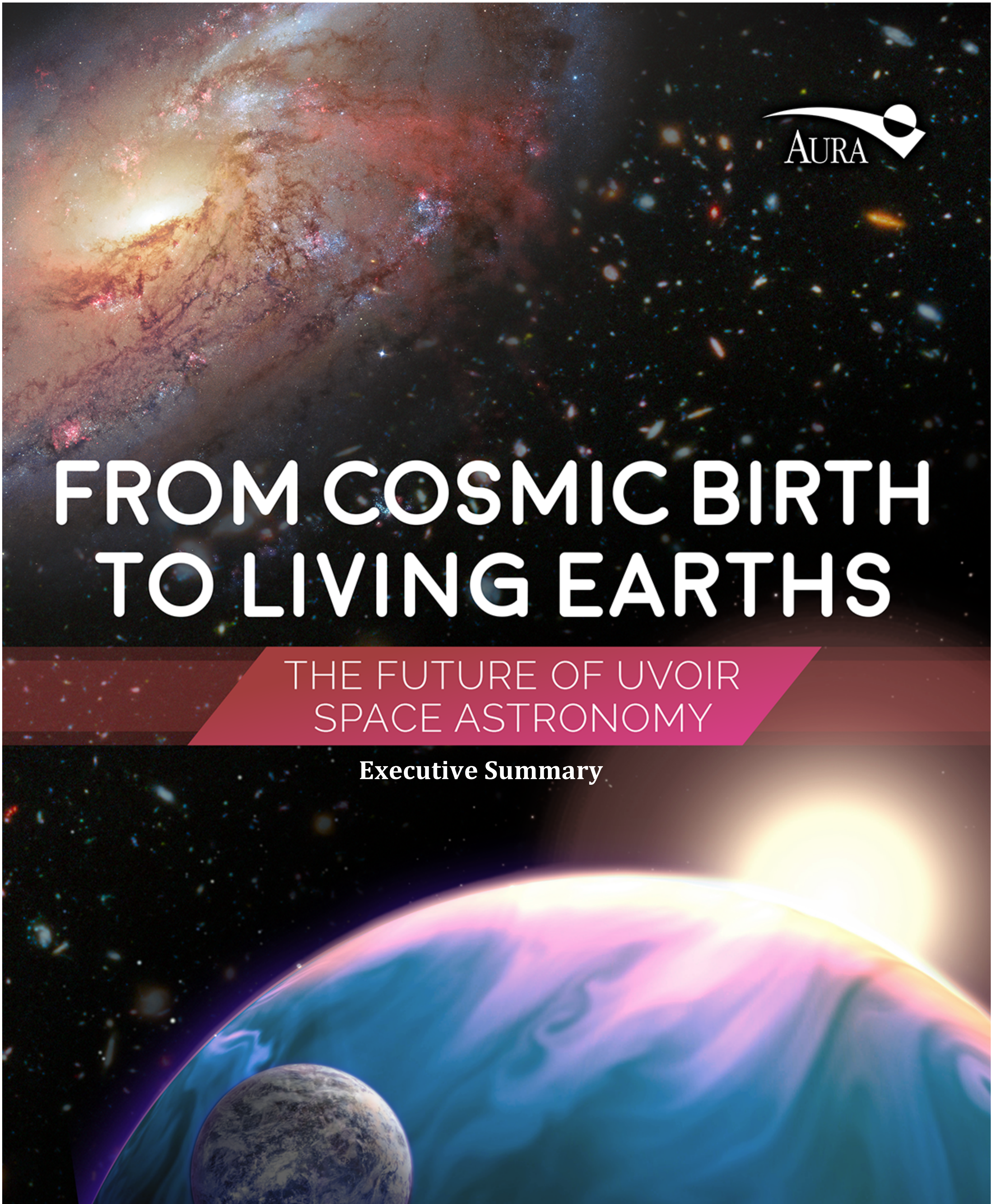


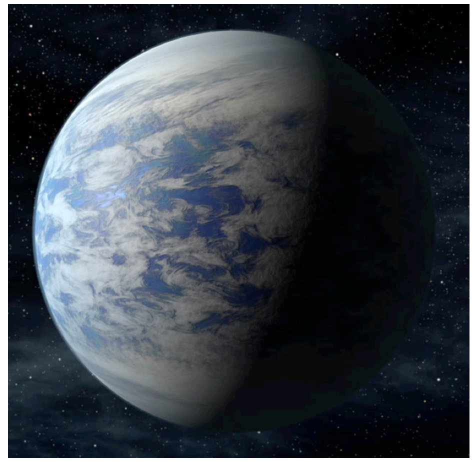
AURA

FROM COSMIC BIRTH TO LIVING EARTHS

THE FUTURE OF UVOIR SPACE ASTRONOMY

Executive Summary

The High Definition Space Telescope



An artist's rendition of the exoplanet Kepler-69c, which is 1.7 times larger than the Earth. Credit: NASA/Ames/JPL-Caltech.

Each time a new telescope has turned to the skies, unforeseen discoveries have opened windows onto revolutionary vistas. With only a primitive 2-inch diameter telescope, Galileo discovered Jupiter's moons and helped establish that Earth is not the center of the Universe. Four centuries later, the *Hubble Space Telescope* turned its 2.4-meter mirror towards a seemingly blank patch of the sky (the Hubble Deep field) and revealed a hidden universe of faint galaxies, proving that there must be upwards of a hundred billion galaxies in the visible Universe. And yet, with centuries of discoveries behind us, some of humanity's most compelling questions remain unanswered: Are we alone in the Universe? Are other Earth-like worlds common? Do any have signs of life? How did life emerge from a lifeless cosmic beginning? Curious humans have asked these questions for millennia, but for the first time we can foresee actually answering them. With the right technology, and the right telescope, we could soon search nearby exoplanets for signs of life, and tell the cosmic story of how this life came to be.

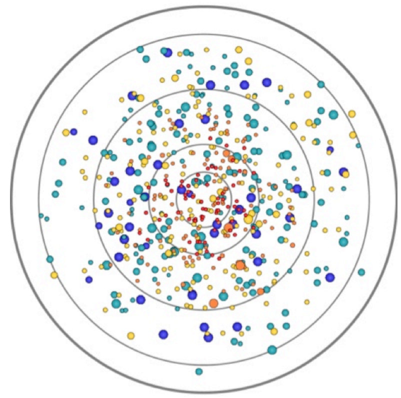
Ambitious goals require careful plans. The Association of Universities for Research in Astronomy (AURA) — charged with promoting excellence in astronomical research by providing community access to state-of-the-art facilities — therefore commissioned a study of how a new space telescope could revolutionize ultraviolet (UV) and optical astronomy in the era following the *James Webb Space Telescope*'s mission[1]. AURA tasked a team of scientists and technologists to "assess future space-based options … that can significantly advance our understanding of the origin and evolution of the cosmos and the life within it." The committee concludes that a space telescope equipped with a 12-meter primary mirror can find and characterize dozens of Earth-like planets and make transformational advances across nearly all fields of astrophysics. The concept is called the *High Definition Space Telescope*.

The High Definition Space Telescope (HDST) would be sensitive to light at UV through near-infrared wavelengths, viewing the universe from the second Earth-Sun Lagrange point (L2), one million miles from the Earth. Its segmented mirror would be folded into either a current or future heavy-lift rocket, before being launched and deployed at its final home. In its mission to discover and study Earth-like planets orbiting Sun-like stars, HDST will directly image exoplanets — including

[1] Plans for NASA's next major space telescope, *WFRST/AFTA*, do not include UV capability.

planets that may be as much as 10 billion times fainter than their host star — by carefully suppressing the star's light. *HDST's* exquisite image quality at visible wavelengths (with more than 25 times the resolving power of the *Hubble Space Telescope*) and high sensitivity all the way into the ultraviolet part of the spectrum (100 times more sensitive than *Hubble*), combined with a versatile set of imaging and spectroscopic instruments, will trigger profound breakthroughs in astrophysics. Like *Hubble* and *JWST*, *HDST* would operate as a general observatory, supporting a broad range of investigations beyond its core exoplanet mission.

HDST's primary goal is to find and characterize dozens of Earth-like exoplanets. A sample of dozens of exoEarths opens up the opportunity to identify truly Earth-like worlds with rocky surfaces and oceans, amidst a complex zoo of other varieties of terrestrial planets. With this large sample, observing telltale signs of life in the planets' atmospheres becomes possible. If life is rare, *HDST* will take us from our current complete ignorance of the occurrence rate of inhabited worlds to a first constraint, potentially showing how remarkable our own existence is. If life is common, a large sample of terrestrial worlds with highly unusual atmospheric chemistry will secure our belief that life of some kind exists beyond the Earth, regardless of possible false positives. Whatever the outcome, *HDST* will change how we see our place in the Universe.



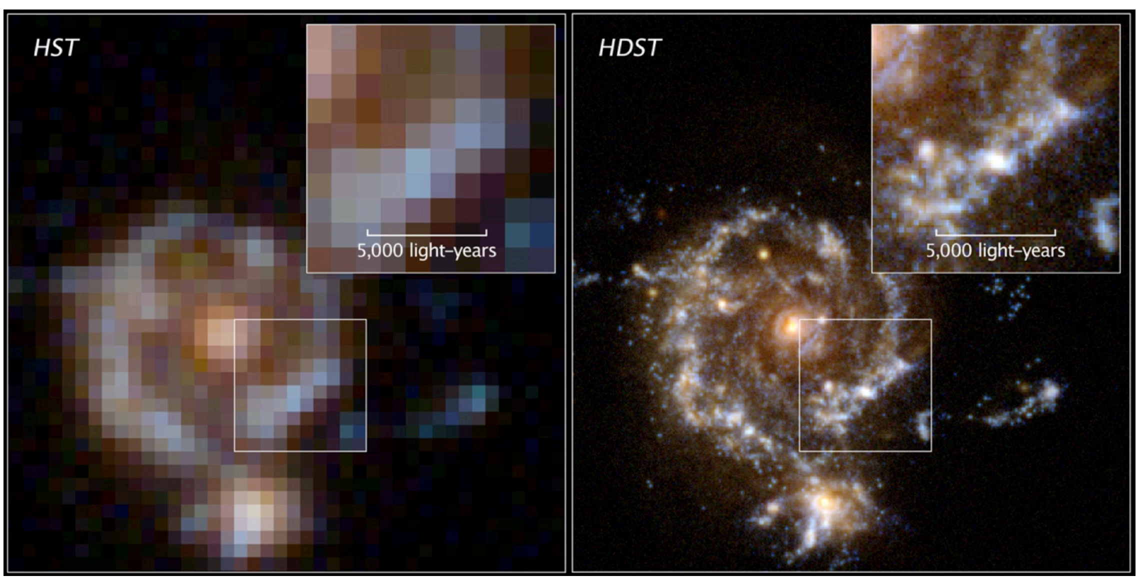
A map of the nearly 600 stars that would be surveyed with HDST to find dozens of exoEarths, given approximately two years of observing time. The stars are plotted on a projection of a sphere with radius 35 parsecs. Star colors and sizes correspond to star type and relative luminosity. Only a large 12-m telescope can survey hundreds of stars to find dozens of exoEarths.

While thousands of exoplanets are already known to exist, none are yet known to be truly Earth-like, even though some have radii similar to Earth's. Distinguishing habitable worlds like Earth (i.e., those with surface water oceans) from greenhouse planets like Venus, or barren worlds like Mars, requires understanding a planet's atmosphere. *HDST* will therefore not just image new worlds, but will also acquire spectra of their atmospheres at visible (and in some cases out to near-infrared) wavelengths to search for signs that indicate a potential planet like our own.

HDST will search for exoEarths around hundreds of stars, but during that quest will revolutionize the study of planetary systems in general. *HDST* will discover planets of all sizes, and any surrounding debris disks. Such discoveries will not only place detected exoEarths in context within their own planetary systems, but are also interesting in their own right.

While the search for the exoEarths that are waiting to be discovered is compelling, the search is not easy. Not only are these planets intrinsically faint, they also orbit very bright host stars. Viewed from another star, our Earth's reflected light would be 10 billion times fainter than the Sun itself, with an orbit that separates the Earth from the Sun by a tiny fraction of an arcsecond. These challenges can be overcome if *HDST* meets three significant goals. First, *HDST* must have a large primary mirror area both to gather enough photons (exoEarths are as faint as the faintest objects in the Hubble Deep Field) and to cleanly separate the planet and star for hundreds of star systems, many of which are tens of parsecs[2] away. Second, *HDST* must have exquisite starlight suppression that blocks out the starlight to 1 part in 10 billion for planet-star projected separations of about 35 milliarcseconds (equivalent to the width of a human thumb viewed from a distance of 130 km). Third, *HDST* must be thermally and dynamically stable for this starlight suppression to perform at the needed level.

***Major advances in all areas of astrophysics are possible with HDST*.** A telescope with *HDST's* degree of sensitivity, resolution, and stability will transform current understanding of how galaxies, stars, and planets form and evolve. With its high-definition resolving power, *HDST* has the amazing ability to take an optical image or spectrum at about 100-parsec spatial resolution or better, *for any observable object in the entire Universe*, no matter where a galaxy lies within the cosmic horizon. This 100-parsec threshold is the scale of individual star forming regions and dwarf satellites—the constituent building blocks of galaxies.



The 5× gain in angular resolution from *Hubble* (left) to *HDST (*right) is demonstrated in this simulated image of a galaxy 10 billion light-years away. *Hubble* detects the galaxy's bulge and disk but only *HDST* resolves the galaxy's star forming regions and its nearby dwarf satellite.

The fields of astrophysics that *HDST* will impact are too vast to list. But as a small sample, *HDST* will transform studies of the most distant bodies within our own Solar

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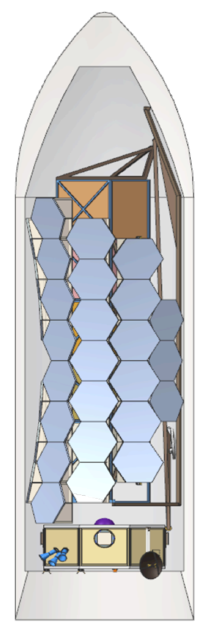
[2] One parsec is equal to 3.26 light-years or 3.08 x 10^{13} km.

System, elucidate complex chemistry within the nearest stellar populations, robustly measure of the masses of new stars, map panoramic high-resolution images of star formation in the vicinity of supermassive black holes, and trace detailed motions within the smallest, dark-matter-dominated galaxies. *HDST* will make the first maps of the nearly invisible material permeating the cosmic web and fueling the growth of galaxies, thanks to its unprecedented collecting area, its 100× gain in ultraviolet sensitivity over *Hubble*, and its novel multiplexed instrument modes. These same abilities will allow *HDST* to trace the recycling of heavy elements from stars to intergalactic space and back, to follow the origins of stellar masses, characterize the composition of planet-forming disks, and to monitor geysers on satellites of the outer planets. In many of these studies, *HDST* will operate in tandem with the next generation of 30-meter ground-based telescopes, in much the same way that *Hubble* and 10-meter telescopes operate cooperatively today.

In short, *HDST* promises dramatic gains in the survey volume, spatial resolution, and sensitivity of any astrophysical study, especially if it can operate its wide-field imaging cameras and spectrographs in parallel during long, staring exoplanet observations. In this mode, every observation of an exoEarth could be transformed into a new equivalent of the *Hubble* Ultra Deep Field, but one that takes hours instead of ten days to acquire. The information embedded in this data set would exceed any presently existing or contemplated survey.

***HDST* is poised to capitalize on a rich heritage in space telescope technology.** Although visionary in its goals, *HDST*'s technologies are well within reach. Starting with the *Hubble Space Telescope* (launch 1990) and including the *Spitzer Space Telescope* (2003), the *James Webb Space Telescope* (2018), and *WFIRST/AFTA* (a wide-area survey telescope to be launched in the 2020s), existing technologies provide a firm foundation to build on when scaling to the size and performance level required by *HDST*. These technologies include deployment of segmented apertures, thermal and dynamical stabilization, starlight suppression, precision pointing, wavefront control, and panoramic, high performance photon detectors. *HDST* will also benefit from technological developments in the commercial world, and from investments made by other countries and other government agencies, providing options for *HDST* in areas of detectors, electronics, structural materials, metrology systems, mechanisms, and large lightweight mirrors. The report carefully analyzes the needed technologies, and lays out a pathway that can bring them rapidly to the final state of maturity. By investing early in advancing starlight suppression for a telescope like *HDST*, and in broader supporting technologies, there is a path forward that can lead to a flight-ready *HDST* design within the near future.



HDST folded within an EELV or SLS-1 shroud.

HDST will operate at much warmer temperatures than *JWST*. This difference will allow *HDST* to utilize lower-cost optical materials, incur less thermal stress in the structures, simplify component and system design, manufacturing and qualification, and lower the costs of system integration and testing, much of which had to be done under cryogenic conditions for *JWST*.

The report lays out recommendations for meeting HDST's key engineering challenges. The first priority is to develop *high-contrast coronagraphs* for *HDST*. A coronagraph blocks the light from a star to enable direct detection of the planets orbiting the star. An onboard coronagraph will have the efficiency needed to search for exoEarths around hundreds of stars. *HDST's* science goals constrain the many performance requirements that such a coronagraph must meet. Another type of starlight suppression instrument is called a starshade – a free-flying specially-shaped occulter that casts its shadow on a telescope many thousands of km away. Although starshades are not part of the *HDST* baseline mission, they provide a vital alternative architecture, and could be employed in a second phase of the mission to enable more detailed characterization of interesting planetary systems.

The second-highest priority recommendation is to address *segmented-mirror system technologies*, including the mirrors, structure and mounts. The key issues are thermal and dynamic stability, but also important are: optical performance, mirror mass density, and efficiency of manufacture. Mirror substrate technologies are mature and in use now, but the other elements of the mirror systems—active thermal control, actuation, low vibration mounts and supports, etc.—are less so.

High observatory *throughput from the UV into the near-infrared* is also a top priority. This goal requires investment in instrument and detector technologies to optimize their efficiency, particularly for observations in the UV.

HDST in context. *HDST* has the potential to push back the frontiers of astrophysics with a single great observatory. Rather than small focused missions that have a shot at finding one to a few exoEarths (while relying on unusually good fortune to turn up signs of life on even one), or that specialize in a particular subfield of astrophysics, *HDST* pursues the more ambitious approach. *HDST's* sensitivity, resolution, and efficiency of exoplanet characterization make it a profoundly capable mission. It can deliver a high yield of exoEarths along with a rich database of information about all kinds of planetary systems. At the same time, and often while observing in tandem with exoEarth searches, *HDST* will fundamentally change our understanding of the Universe throughout cosmic time. Many fields of astronomy will be transformed by its capabilities; none will remain entirely untouched. *HDST* will transform how we all—scientists and public alike—see our place in the universe.