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ABSTRACT

The Habitable-Exoplanet Observatory (HabEx) is a candidate flagship mission being studied by NASA and the astrophysics community in preparation of the 2020 Decadal Survey. The first HabEx mission concept that has been studied is a large (~4m) diffraction-limited optical space telescope, providing unprecedented resolution and contrast in the optical, with extensions into the near ulttraviolet and near infrared domains. We report here on our team's efforts in defining a scientifically compelling HabEx mission that is technologically executable, affordable within NASA's expected budgetary envelope, and timely for the next decade. We also briefly discuss our plans to explore less ambitious, descoped missions relative to the primary mission architecture discussed here.

1. INTRODUCTION

NASA is funding four parallel flagship mission concept studies in preparation for the 2020 Decadal survey in Astronomy and Astrophysics: the Habitable Exoplanet Observatory (HabEx, discussed here), the Large UV-Optical-InfraRed Observatory (LUVOIR), Lynx, and the Origins Space Telescope (OST). The corresponding mission concept studies have been ongoing for over two years, and have been guided by community STDTs formed in March 2016. All four mission concepts have recently submitted their interim reports, which will be made public in the near future.

Keywords: decadal, exoplanets, biosignatures, high contrast imaging, galaxy formation and evolution, coronagraph, starshade

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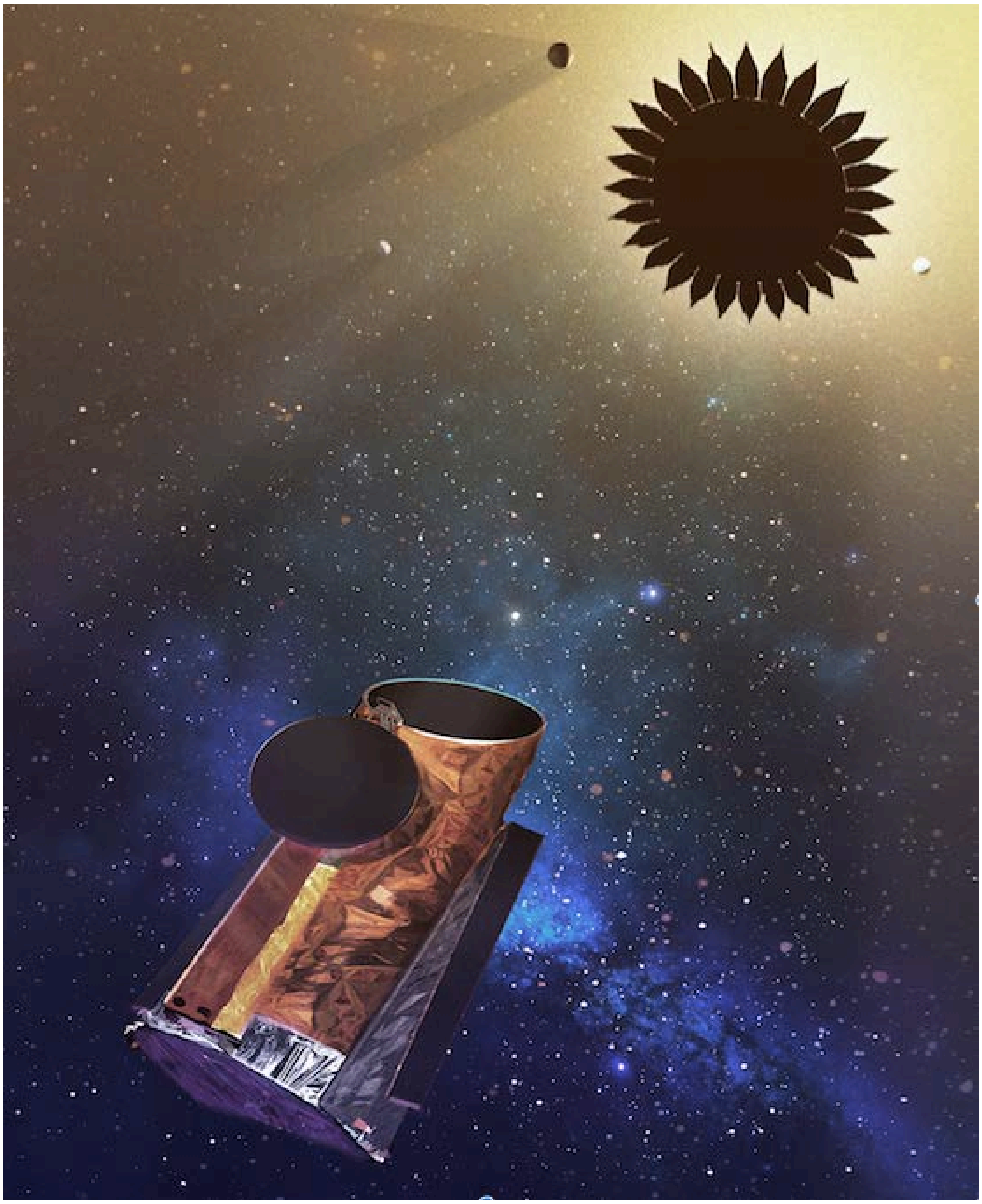

Figure 1 The Habitable Exoplanet Observatory mission concept, consisting of a telescope and starshade flying in formation, is a candidate for a Great Observatory of the 2030s. The telescope includes two instruments for direct imaging and spectroscopy of exoplanets: a starshade instrument and a coronagraph instrument. The telescope also includes two facility instruments: a UV spectrograph and a UV through near-IR camera and spectrograph.

The HabEx mission concept is optimized for the exploration planetary systems around nearby stars, using direct imaging and spectroscopy of reflected starlight in the visible region, with potential extensions to the UV and/or the near infrared parts of the spectrum. In particular, the mission would be designed to search for signs of habitability and biosignatures in the atmospheres of Earth-sized rocky planets located in the habitable zone of nearby solar type stars. We present in section 2 the preliminary science objectives envisioned for HabEx, discussing in particular the wavelength range required for such observations. In parallel to defining these exoplanet science goals, we define the capabilities of HabEx that will allow it to carry out high impact general observatory (GO) science – i.e, non exoplanet- investigations. In Section 3 we define the implementation of HabEx required to achieve these science goals. Section 4 argues how recent advances in our understanding of both the scientific and technological requirements needed to successfully design a mission such as HabEx, including our understanding of the frequency of small exoplanets orbiting other stars, as well as technological advances in starlight suppression techniques, make initiating missions like HabEx in the near future both practical and opportune. Future architecture trades that we have identified and will be studied for the remainder of the study are summarized in section 5.

2. PRIMARY SCIENCE GOALS

For the first time in human history, technologies have matured sufficiently to enable a mission capable of discovering and characterizing habitable planets like Earth orbiting sunlike stars other than the Sun. At the same time, such a platform would enable unique general observatory science not possible from ground-based facilities. This science is broad and exciting, ranging from new investigations of our own solar system to a full range of astrophysics disciplines.

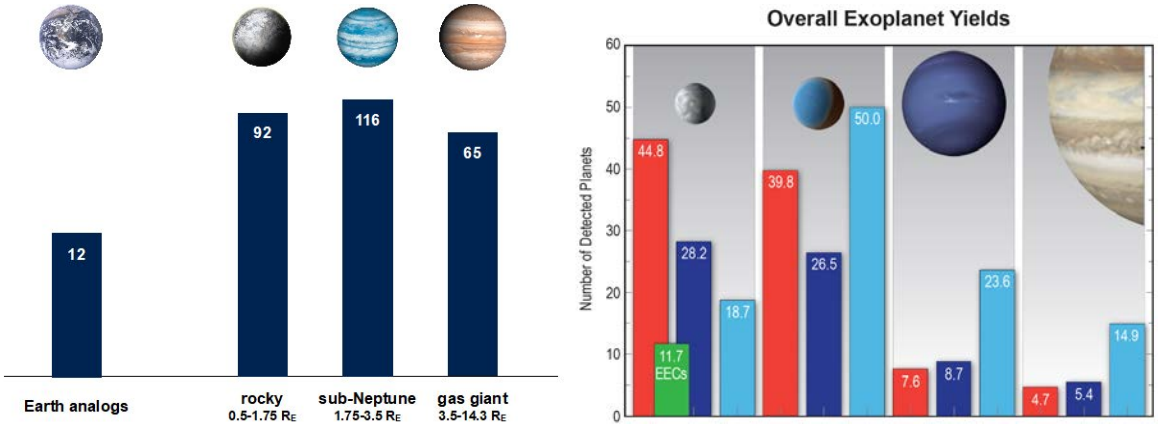

Figure 2: Left: predicted numbers of planets detected by HabEx using nominal Kopparapu et al. 2018[1] occurrence rates estimates for each planet type. Right: Same estimates but now subdivising each planet according to its stellar insolation level and temperature range (red: "hot", blue: "warm" and light blue: "cold", as defined by Kopparapu et al. 2018[1]) and splitting the detected planets between rocky planets, Neptune-size planets, and Saturn-to-Jupiter size planets. EECs (in green) are "exo-Earth candidates," i.e., Earth-analogs found in the HZ of their host stars with radii in the 0.6–1.4 Re range. All detected planets will have their orbits measured via multi-epoch imaging. All EECs and roughly half of the other planetary systems will have at least one 300–1,000 nm spectrum taken.

The Habitable Exoplanet Observatory, or HabEx, has been designed to be the Great Observatory of the 2030s, with community involvement through a competed and funded Guest Observer (GO) program. HabEx is a space-based 4-meter diameter telescope that, along with the capability to image and characterize habitable planets, also has ultraviolet (UV), optical, and near-infrared (near-IR) imaging and spectroscopy capabilities. HabEx has three driving science goals during its five-year primary mission:

1. **To seek out nearby worlds and explore their habitability.**
2. **To map out nearby planetary systems and understand the diversity of the worlds they contain.**
3. **To carry out observations that open up new windows on the Universe from the UV through near-IR.**

2.1 HabEx will seek out nearby worlds and explore their habitability.

A pervasive and fundamental human question is: Are we alone? Astronomy has recast this elemental inquiry into a series of questions: Are there other Earths? Are they common? Do any have signs of life? Space-based direct imaging missions that operate above the blurring effects of Earth's atmosphere are the only way to discover and study true exo-Earths—Earth-sized planets in Earth-like orbits about sunlike (F, G, and K-type) stars. With unparalleled high-contrast direct imaging and spectroscopy, HabEx will find dozens of rocky worlds, including a dozen exo-Earths, and hundreds of larger planets around mature stars (See Figure 2). HabEx will characterize exoplanets by determining orbital parameters and obtaining multi-epoch broadband spectra. Of particular interest for investigations of Earth-like exoplanets, HabEx will be sensitive to water vapor, molecular oxygen, ozone, and Rayleigh scattering, detecting these features if they have the same column density as modern Earth or greater. In addition, HabEx will detect other potential biosignature molecules, such as methane and carbon dioxide, if they have concentrations higher than modern Earth. The detection of these molecules may help with the interpretation of potential biosignature molecules such O_2 and O_3, by revealing whether they are biotic or abiotic in origin. For our nearest neighbors, HabEx will also search for evidence of surface liquid water oceans on exo-Earth candidates.

2.2 HabEx will map out nearby planetary systems and understand the diversity of the worlds they contain.

With high-contrast 12"x12" (equivalent to 90 AU x 90 AU at a distance of 7.5 pc) observations using the starshade, HabEx will be the first observatory capable of characterizing full planetary systems, including exoplanet analogs to Earth and Jupiter, and exodisk analogs to zodiacal dust and the Kuiper belt. HabEx is also expected to find and characterize a diversity of worlds that have no analogs in our solar system, including super-Earths and sub-Neptunes. These discoveries will provide detailed planetary system architectures, addressing open topics ranging from planetary system formation, to planetary migration, to the role of gas giants in the delivery of water to inner system rocky worlds. HabEx will test theories of planetary diversity, investigate planet-disk interactions, and place our solar system into detailed context for the first time.

2.3 HabEx will carry out observations that open up new windows on the universe from the ultraviolet (UV) through near-infrared (IR).

HabEx will be NASA's Great Observatory in the 2030s. Observing with a large aperture from above the Earth's atmosphere in an era when neither the Hubble Space Telescope (HST) nor the James Webb Space Telescope (JWST) will be operational, HabEx will provide the highest-resolution images yet obtained at UV and optical wavelengths. HabEx will also provide an ultra-stable platform and access to wavelengths inaccessible from the ground. These capabilities allow for a broad suite of unique, compelling science that cuts across the entire NASA astrophysics portfolio, as well as enabling new views of our own solar system. This "observatory-class" science, which will account for at least 25% of the HabEx primary mission and likely 100% of any extended mission, will be selected through a competed GO program, taking advantage of the community's imagination and priorities to maximize the science return of the mission.

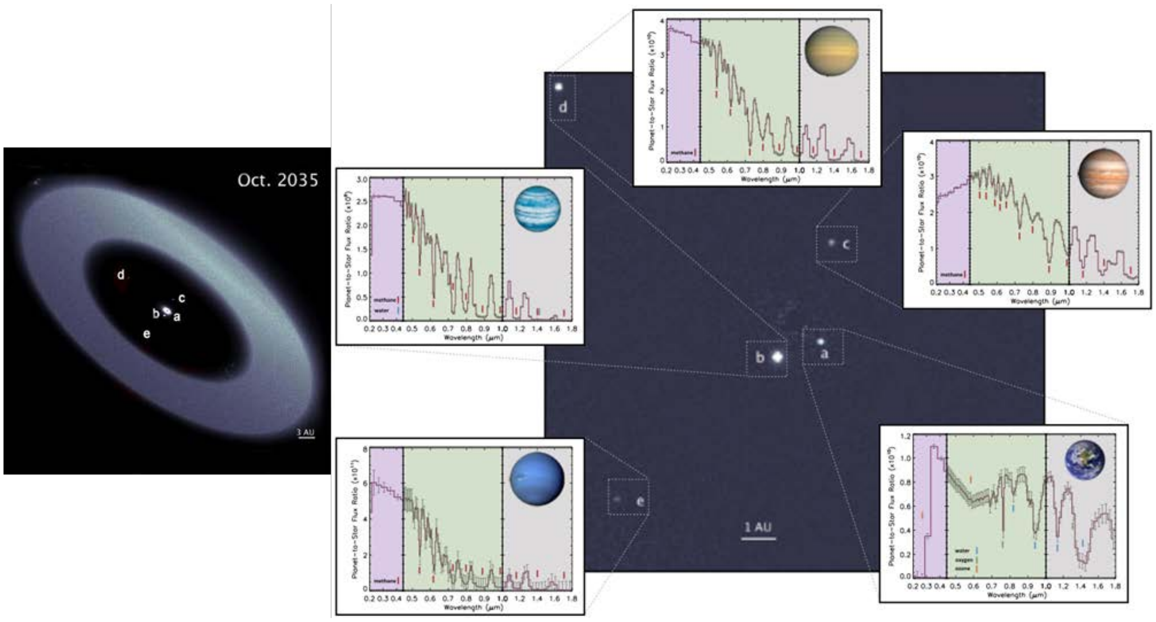

Figure 3: Simulations of an exo-system at 5 pc observed with the HabEx starshade. Left panel: the large field of view (12” x 12”) of the visible imager reveals exo-zodi and exo-Kuiper belt analogs—both 3× as dense as in the solar system—as well as an Earth analog at 1 AU, a sub-Neptune at 2 AU, Jupiter, Saturn and Neptune analogs at 5, 10, and 15 AU, respectively. The right image shows a zoom in the inner 3” x 3” region of the system and simulated spectra obtained for all 5 planets.

3. HABEX IMPLEMENTATION

The HabEx Observatory is an off-axis, monolithic 4 m diameter telescope, diffraction limited at 0.4 μm, in an Earth-Sun L2 orbit. HabEx has two starlight suppression methods described in more detail below: a coronagraph and a starshade, each with their own dedicated instruments for direct imaging and spectroscopy of exoplanets. HabEx also has two general-purpose instruments: a UV spectrograph, and a UV through near-IR imaging camera and spectrograph.

The HabEx prime mission is five years, with up to 75% of the time dedicated to two ambitious exoplanet surveys: a deep survey of nine of our nearest sunlike stars, and a broad survey of roughly 110 nearby mature stars. The primary distinguishing feature of the exoplanet surveys is that the deep survey will systematically search for fainter planets, integrating down to a planet-to-star flux ratio detection limit of 4×10^{-11} at the inner working angle (IWA, roughly the closest detectable angular separation of the planet from its host star), which corresponds to a Mars-sized planet around a sunlike star. In comparison, the individual exposure times for the broad survey are set to maximize the overall yield of Earth-like planets and the flux ratio detection limit will generally be higher than the deep survey ($\sim 10^{-10}$). The overall HabEx design has been optimized for high-contrast direct imaging and spectroscopy of Earth-sized and larger exoplanets. The off-axis monolithic primary mirror avoids the significant challenges faced by obscured and/or segmented mirrors in achieving both high contrast direct imaging and high planet light throughput with a coronagraph. The Earth-Sun L2 orbit provides a stable thermal and gravitational environment, ideal for high-contrast imaging.

The dual starlight suppression capabilities provide a flexible approach for optimized exoplanet searches and detailed studies of exoplanets and their planetary systems, and are therefore more resilient to uncertainties. Coronagraphs are nimble, as they reside inside the telescope, allowing for efficient multi-epoch surveying of multiple target stars to identify new exoplanet and exo-Earth candidates and also measure their orbits. However, coronagraphs generally have a narrow annular high-contrast field of view (FOV) with a bandpass limited to 20% or less[2-5]. By contrast, starshades are large, deployable, opaque occultors with a very specific shape (see Figure 1 and refs. 6-10). A starshade blocks the (on-axis) light from the host star before it enters the telescope, provides a wider FOV and broader instantaneous wavelength coverage than the coronagraph. However, it is fuel limited, rather than target limited, due to the relatively long slews needed to move the starshade between target stars. Importantly, this hybrid approach to direct exoplanet detection and characterization is a powerful combination, taking advantage of the strengths of each instrument and significantly increasing the resultant planetary yields over what is achievable by either instrument alone.

4.1 HabEx Instrumentation

The notional suite of four HabEx instruments is as follows.

4.1.1 The Starshade and Starshade Instrument. The HabEx 72 m diameter starshade will fly in formation with the telescope at a nominal separation of 124,000 km. The starshade advantages include a high throughput, small IWA, with an outer working angle (OWA) limited only by the instrument field of view (FOV). The HabEx starshade has a 60 milliarcsecond (mas) IWA at 1 μm and a 6 arcsec OWA (for broadband imaging), with deep starlight suppression over an instantaneous bandwidth of 0.3–1.0 μm. The starshade may also operate at two additional separations from the telescope, a larger separation of 186,000 km that covers bluer wavelengths and a smaller separation of 69,000 km that covers redder wavelengths. The former covers an instantaneous bandwidth of 0.2–0.67 μm with a constant IWA of 40 mas, while the latter covers an instantaneous bandwidth of 0.54–1.8 μm with an IWA of 108 mas at 1.8 μm. The starshade instrument has three channels: a near-UV/blue channel covering 0.2–0.45 μm with a grism, a visible channel covering 0.45–1.0 μm with an integral field spectrograph (IFS) and camera, and a near-IR channel covering 0.98–1.8 μm with an IFS and camera.

4.1.2 The Coronagraph Instrument. The coronagraph mask within the telescope suppresses starlight from within the telescope to reveal the light from the exoplanets. HabEx is adopting a vector vortex coronagraph[11] because of its high resilience to common low-order wavefront aberrations; this translates into significantly less stringent requirements on telescope thermal and mechanical stability than other coronagraph designs. The HabEx Observatory coronagraph has a

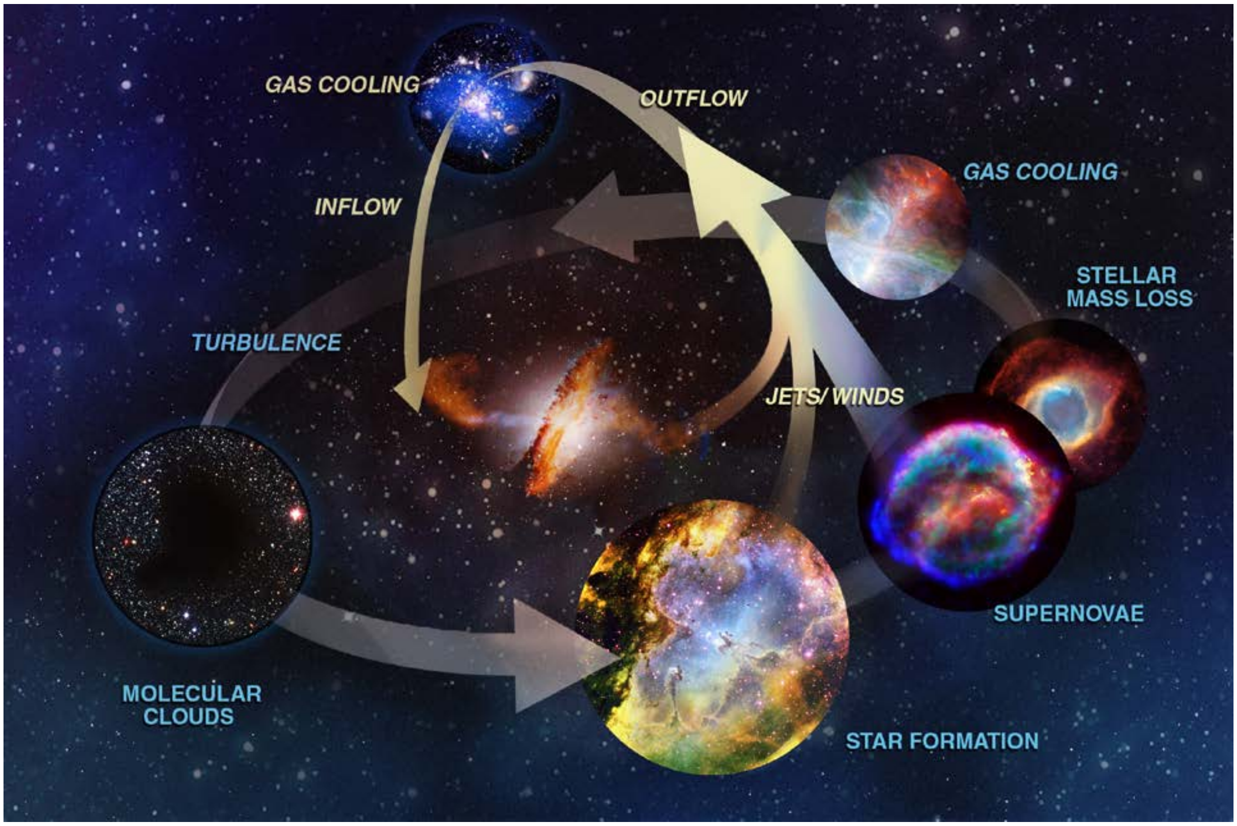

Figure 4: With its improved UV sensitivity and multiplexing capabilities, HabEx will be two orders of magnitude more efficient than previous missions at UV wavelengths, and will enable a broad array of general astrophysics studies, including the detailed investigation of the lifecycle of baryons.

62 mas IWA at 0.5 μm with a 20% bandpass. The coronagraph has a blue channel with a camera and IFS covering 0.45–0.67 μm, a red channel with a camera and IFS covering 0.67–1.0 μm, and an IR imaging spectrograph that covers 0.95–1.8 μm.

4.1.2 The UV Spectrograph (UVS). The UVS has more than 10 times the effective collecting area of HST's Cosmic Origins Spectrograph[12]. The UVS will be several orders of magnitude more sensitive than COS. Not only does the UVS provide improved angular resolution and throughput relative to HST, it also includes a microshutter array, allowing multiplexed UV slit spectroscopy for the first time in space. The UVS covers 0.115–0.3 μm with a FOV of 3' x 3' and multiple spectroscopic settings up to resolutions of 60,000.

4.1.3 The HabEx Workhorse Camera (HWC). The HWC is an imaging multi-object slit spectrograph with two channels covering wavelengths from the UV through near-IR and a spectral resolution of 2,000. The UV/optical channel covers 0.15–0.95 μm and the near-IR channel covers 0.95–1.8 μm. The HWC, with its larger 3' x 3' FOV and higher resolution, will provide capabilities similar to, but significantly more sensitive than, HST's Wide-Field Camera 3 (WFC3) or Advanced Camera for Surveys (ACS).

4.2 The HabEx Observational Strategy

The HabEx exoplanet observational strategy takes advantage of the dual starlight suppression instruments. A broad survey of roughly 110 stars will be undertaken primarily for discovery of small exoplanets. This survey utilizes the coronagraph's pointing agility to revisit the target stars over multiple epochs for discovery, confirmation of physical association with the host star, and measurement of orbits for all detected planets with periods shorter than 10 years. Spectra of these planetary systems are obtained by the starshade. A deep survey utilizing the starshade for multi-epoch broad bandwidth observations of nine of the nearest sunlike stars will provide even more detailed information about our nearest neighbors, with access to even smaller planets and star-planet separations than in the broad survey. Overall, HabEx's hybrid coronagraph/starshade architecture enables a nimble and optimized approach to exoplanet discovery and characterization.

The Guest Observer program will be community driven and competitively selected and will likely include solar system, exoplanet, Galactic, and extragalactic studies. One example of the kinds of transformative GO science that will be enabled by HabEx is illustrated in Figure 3. Both the UVS and HWC are designed for parallel observations of two separate detectors, each with 3' x 3' FOV during operations of the starshade and coronagraph, providing two HST-like ultra-deep fields in the vicinity of the exoplanet target stars and greatly improving the scientific productivity of the HabEx mission.

4. WHY NOW? SCIENTIFIC AND TECHNOLOGICAL READINESS

There have been tremendous achievements in the discovery of exoplanets over the last 20 years. In particular, astronomers have discovered that small rocky planets around main sequence stars are common. This key result implies that very large apertures of 10m or greater are not required to probe a sufficiently large volume to detect and characterize rocky planets; the relatively small aperture (4m) of HabEx is sufficient. Furthermore, the already planned near-term atmospheric characterization of rocky planets orbiting M dwarf stars by missions like NASA's Transiting Exoplanet Survey Satellite (TESS), points to the next logical step: the detailed characterization of Earth-like worlds and complete planetary systems around sunlike stars. HabEx will start this journey of exploration, providing the first detailed images and spectra of the full range of exoplanets orbiting nearby mature stars, and searching for signs of habitability and life on all of the small rocky worlds detected.

Over the last two decades, dramatic progress has also occurred in four key technological areas that make HabEx possible today: high-contrast imaging at small angular separations using broadband coronagraphs, starshade-specific modeling developments and technology demonstrations, manufacturing of large aperture monolithic mirrors, and vibration control using microthrusters for fine spacecraft pointing. In particular, steady progress in high contrast direct imaging technology has been very impressive, with the first direct detection of bright self-luminous exoplanets announced in 2008, and the characterization of closer-in self-luminous planets since then.

Through careful design choices, lessons learned from past studies (particularly the Exo-Starshade and Exo-Coronagraph probe studies[13,14]), and utilization of past and ongoing investments into these technologies, HabEx is able to present a design that minimizes cost and risk, while maximizing scientific return.

5. SUMMARY AND FUTURE DIRECTIONS.

HabEx is a cost-effective, low-risk, high-impact science mission. HabEx will leverage recent advancements in starlight suppression technologies to utilize both a coronagraph and starshade to seek new worlds and explore their habitability and map our nearest neighbor planetary systems to understand the diversity of the worlds they contain. While the HabEx mission architecture is optimized for direct imaging and spectral characterization of a broad range of exoplanets, HabEx also provides unique capabilities for UV through near-IR astrophysics and solar system science from the vantage of space, moving UV capabilities to the next level after HST retires. HabEx is a worthy UV/optical successor to HST in the 2030s with significantly improved sensitivity and spatial resolution stemming from HabEx's significantly larger 4 m diameter aperture, improved detector technology, exquisite wavefront control, and a more thermally stable orbit.

We have conducted a detailed analysis of the direct imaging and spectroscopic capabilities required to characterize the architectures, diversity, and habitability of nearby (<20 pc) mature planetary systems in detail. We found that a 4 m, off-axis, high throughput UV-optical telescope equipped with a dual (coronagraph + starshade) starlight suppression system provides exceptional performance. With nominally predict that HabEx will directly detect over 250 planets— *incuding 92 rocky planets*—around sunlike stars for the first time, most of them with orbits determined and spectra measured over a minimum wavelength range of 300-1,000 nm, the HabEx Observatory would revolutionize our knowledge of planetary systems in the mid 2030s. At the same time, it will provide a dozen spectra of possible Earth analogs, with the ability to search for signs of life in their atmosphere and confirm their biotic origin via near-UV to near-IR spectroscopy. We find that the hybrid (coronagraph + starshade) approach is very powerful, because it takes full advantage of the complementary strengths of each system. It also allows maximum flexibility to adapt the observing strategy to unavoidable astrophysical sources of uncertainties, and provides a more robust architecture overall. The nimble—easily repointed—coronagraph brings breadth to the HabEx exoplanet search and orbital determination phase, while the high throughput and inherently broadband starshade system provides in depth spectral characterization at small angular separations, all the way from the near-UV to the near-IR.

Our interim report describing the mission architecture outlined here is publically available on the HabEx website[1].

While we believe that the architecture presented here is likely the "sweet spot" with regards to balancing exolanet and general observatory science capabilities relative to cost and risk, we will nevertheless be studying the capabilities of less ambitious, descoped achitectures going forward. In particular, we will be studying smaller apertures, the full spectrum of starlight suppression technologies (hybrid, coronograph only, and starshade only), on-axis versus off-axis designs, and monolithic versus segmented apertures. All these key trades are not independent of each other, making the trade study very complex. We will therefore rely on extrapolations based on well studied designs, and concentrate on finding the "sweet spot", i.e., identifying a viable proof of concept design that is scientifically compelling, technologically executable, and timely for the next decade.

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