Astro2020 APC White Paper

Title: The Habitable Exoplanet Observatory (HabEx)

Type of Activity: Space Based Project

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HabEx: The Great Observatory of the 2030s.

For the first time in human history, technologies have matured sufficiently to enable an affordable space-based telescope mission capable of discovering and characterizing habitable planets like Earth orbiting nearby bright sunlike stars. Such an observatory can also be equipped with instruments that provide a broad range of capabilities, enabling unique science not possible from ground-based facilities. This science is broad and exciting, ranging from new investigations of our own solar system, to understanding the life cycle of baryons and its impact on the formation and evolution of galaxies, to addressing fundamental puzzles in cosmology.

The Habitable Exoplanet Observatory, or HabEx, has been designed to be the Great Observatory of the 2030s, a successor to the Hubble Space Telescope (HST) with enhanced capabilities and community involvement through a competed and funded Guest Observer (GO) program. This GO program—which shall represent 50% of HabEx prime 5-year mission—will include competed novel observations, parallel and serendipitous observations, and archival research. After HabEx's 5-year primary mission, HabEx is capable of undertaking an extended mission, during which the GO program would represent 100% of observing time.

HabEx is a space-based baseline 4m diameter telescope (see **Table 1**) with ultraviolet (UV), optical, and near-infrared (near-IR) imaging and spectroscopic capabilities, replacing and enhancing those lost at the end of HST's lifetime.

HabEx has three driving science goals during its 5-year primary mission (**Figure 1**):

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. Enable new explorations of astrophysical systems from our own solar system to galaxies and the universe by extending our reach in the UV through near-IR.

Figure 1. The HabEx Observatory has three science goals: 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, and 3. Enable new explorations of astrophysical systems from our own solar system to galaxies and the universe by extending our reach in the UV through near-IR.

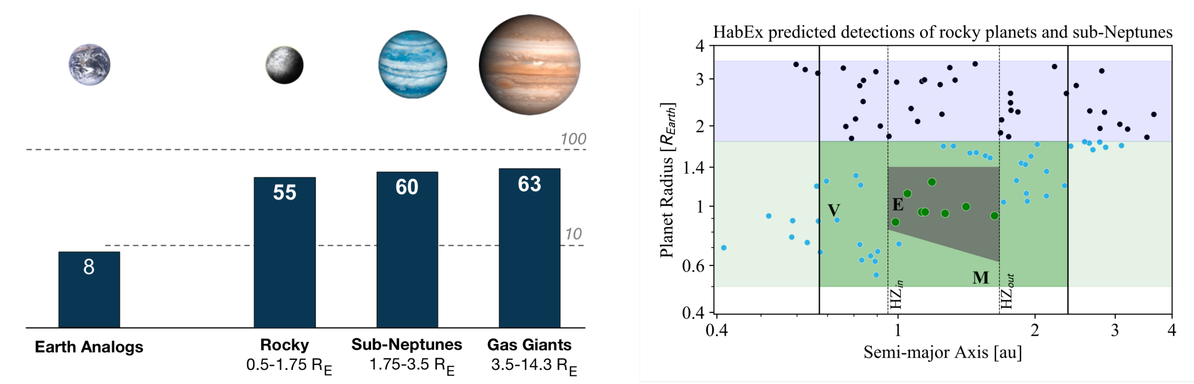

Figure 2. Assuming 2.5 years of observations, HabEx will detect over 150 exoplanets with a diversity of sizes and temperatures (*left*; note log scale). It will obtain broad spectra (at least from 0.3-1 µm) of the majority of these planets, including ~37 rocky planets proximate to the HZ (*right*, dark green region), and will get orbits and spectra of ~8 planets with radii and separations consistent with the adopted conservative definition of the habitable zone (*right*, grey region). Thus, HabEx will empirically constrain the habitable zone in terms of planet insolation and radii. Note on the right panel the semi-major axis boundaries are for a solar twin. For other host stars, they have been scaled to maintain a constant bolometric insolation.

HabEx Science

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 above the blurring effects of our atmosphere is the only way to discover and study exo-Earths—Earth-sized planets in Earth-like orbits in reflected light about sunlike (FGK) stars.

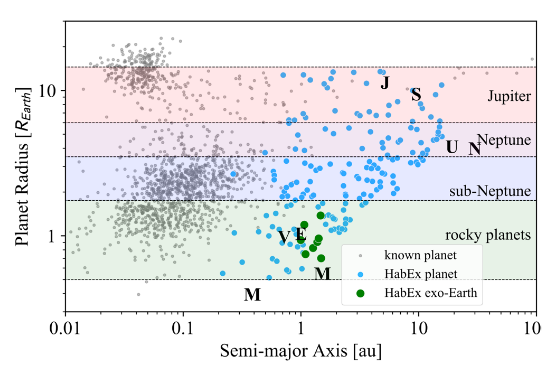

Figure 3. HabEx will discover and characterize over 150 new exoplanets (cyan points), from small exo-Earths candidates (green points) to gas giants, populating previously unexplored regions of parameter space.

With unparalleled high-contrast direct imaging capabilities, HabEx will spectrally characterize dozens of rocky worlds, including ~8 exo-Earth candidates (EECs), and over a hundred larger planets around mature stars (**Figure 2**). HabEx will characterize exoplanets by obtaining multi-epoch broadband spectra of most of the detected planets, including all EECs, and determining the orbital parameters of planets with orbital periods <15 years. Of particular interest for investigations of EECs, HabEx will be sensitive to Rayleigh scattering, water vapor (H_2O), molecular oxygen (O_2) and ozone (O_3). It will detect all three gases down to column densities as low as 1% of modern Earth levels. In addition, HabEx will detect other atmospheric gases for context, such as methane (CH_4) and carbon dioxide (CO_2), if they have concentrations higher than modern Earth. For our nearest neighbors, HabEx will also search for evidence of surface liquid water oceans on EECs via specular reflection or glint.

HabEx will map out nearby planetary systems and understand the diversity of the worlds they contain. With a high-contrast 12×12 $arcsec^2$ FOV (equivalent to 36×36 AU^2 at a distance of 3 pc) using the starshade, HabEx will be the first observatory capable of providing complete "family portraits" of our nearest neighbors. HabEx will characterize full individual planetary systems, including exoplanet analogs to Earth, Saturn and Jupiter (**Figure 3**), and analogs to the zodiacal and Kuiper dust belts. HabEx is also expected to find and spectrally characterize a diversity of worlds that have no analogs in our solar system, including super-Earths and sub-Neptunes.

Nearby star planet discoveries will provide detailed planetary system architectures, addressing open topics ranging from planetary system formation, planetary migration, and to the role of gas giants in the delivery of water to inner system rocky worlds. HabEx will place our solar system into detailed context for the first time.

Enable new explorations of astrophysical systems from our own solar system to galaxies and the universe by extending our reach in the UV through near-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) are operational, HabEx will provide the highest-resolution images yet obtained at UV and optical wavelengths (**Figure 4**). HabEx will also provide an ultra-stable platform and access to wavelengths inaccessible from the ground.

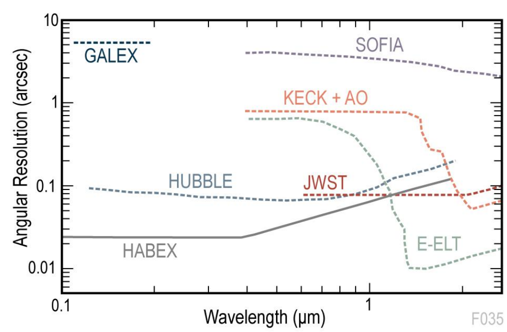

Figure 4. HabEx will provide the highest-resolution UV/optical images of any current or planned facility, enabling a broad range of studies from our solar system, to stellar populations and galaxies, to large-scale structure.

These capabilities allow for a broad suite of unique, compelling science that cuts across the entire NASA astrophysics portfolio including topics as diverse as the life cycle of baryons, metagalactic ionizing background sources, first generations of stars and supernovae, dark matter model constraints, cosmic expansion rates, protoplanetary disks, transiting exoplanet spectroscopy, and new views of our own solar system.

Of course, we cannot know which of the scientific questions that motivate HabEx's GO program as outlined here will still be relevant in the 2030s. However, by designing HabEx to have

	Category	Value	Description
	Mission	Duration	5 years primary, 10 years total consumables
		Orbit	Earth-Sun L2 Halo Orbit, 77,600 km nominal separation from the telescope
Telescope Flight	Mass	Total Wet Mass	17300 kg
		Capability	15.7 kW – BOL, 39 m^2 arrays, sized for 20 year lifetime
	Propulsion	Slew	Monoprop system
		Stationkeeping	Colloidal electrospray thrusters
	Payload	Optical Telescope Assembly	Off-axis, three-mirror anastigmat 4 m monolithic primary mirror
		Coronagraph	Imaging for discovering exoplanets and determining orbits; measures from 450-1800 nm
		Starshade Instrument	Characterize exoplanets, from 200-1800 nm
		UVS	High-resolution, UV imaging and spectroscopy, from 115-320 nm, 3x3 $arcmin^2$ field of view, microshutters
		Workhorse Camera	Multipurpose, imaging camera and spectrograph, from 370-1800 nm, 3x3 $arcmin^2$ field of view, microshutters
		Fine Guidance Sensor	Supports telescope pointing control to 1 mas
	Data	Volume generated	~210 GBytes per week uncompressed
		Comm. System	Ka-band ($\geq$6.5 Mbps) Data downlink X-band ($\geq$1 kbps) Command S-band ($\geq$100 bps) Starshade cross-link
Starshade	Mass	Dry	6800 kg
		Wet	15500 kg*
		Capability	800V Array: 38 kW 28V Array: 1kW
	Propulsion	Slew	Hall Effect Thrusters
		Stationkeeping	Bipropellant system
	Payload	Starshade	52 m tip-to-tip
	Data	Comm. System	X-band ($\geq$1 kbps) command S-band ($\geq$100 bps) telescope cross-link

Table 1: Basic mission, telescope, and starshade properties of the preferred HabEx design.

capabilities that significantly extend and enhance those of any current or planned mission, we can rely on the community's imagination and future priorities to maximize the science return of the mission.

Baseline HabEx Implementation

The HabEx Observatory design utilizes an off-axis, monolithic 4 m diameter telescope, diffraction-limited at 0.4 µm, launched on an SLS 1B launch vehicle to an Earth-Sun L2 orbit (**Table 1**). HabEx has two starlight suppression systems: 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 imaging spectrograph, and a UV through near-IR imaging spectrograph.

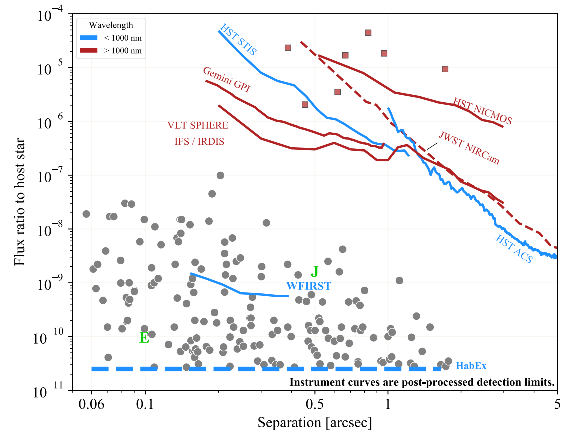

Figure 5. HabEx will detect and characterize exoplanets at low planet-star flux ratios (grey points), enabling the first detailed studies of Earth-like planets in the habitable zone.

The HabEx prime mission is five years (ten-year design life), with approximately 50% of the time dedicated to two ambitious exoplanet surveys, a *deep* survey of eight of our nearest sunlike stars, and a *broad* survey of 42 nearby, mature stars. The primary difference between the surveys is that the deep survey will systematically search for fainter planets around the very nearest stars, integrating down to a planet-to-star flux ratio detection limit of 2.5×10^{-11} (**Figure 5**), which corresponds to a Mars-like 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 thus the flux ratio detection limit will generally be higher than in the deep survey.

The overall HabEx design has been optimized for high-contrast direct imaging at small angular separations and broad 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 and formation flying. The dual starlight suppression capabilities provide a flexible approach for optimized exoplanet searches and detailed studies of exoplanets and their planetary systems, and is more resilient to uncertainties.

The coronagraph is nimble, residing inside the telescope, allowing for efficient multi-epoch surveying of multiple target stars to identify new exoplanets and EECs and also measure their orbits. However, the coronagraph has a narrow annular high-contrast field of view (FOV), and a bandpass limited to 20%. Compared to the coronagraph, the starshade provides a wider FOV and

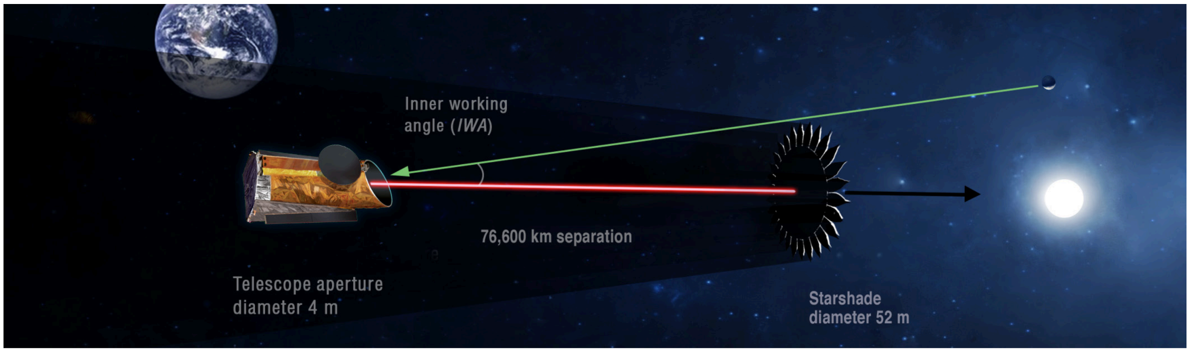

Figure 6. The HabEx telescope flying in formation with the starshade. HabEx is sensitive to exoplanets outside the shadow of the starshade, which defines the inner working angle.

broader instantaneous wavelength coverage. However, it is fuel limited rather than target limited due to the thrust required 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 complementary strengths of each instrument and significantly increasing the resultant yields of *well-characterized* planets that have both high-quality broadband spectra and orbits.

HabEx Instruments

Coronagraph. The coronagraph mask suppresses starlight from within the telescope to reveal the light from the exoplanets. HabEx uses a vector vortex coronagraph (VVC) because of its high resilience to common low-order wavefront aberrations, which translates into significantly less stringent requirements on telescope thermal and mechanical stability than other coronagraph designs. The HabEx Observatory coronagraph has a 62 mas inner working angle (IWA, representative of the closest detectable exoplanet separation) 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.

Starshade Occulter and Starshade Instrument (SSI). The starshade occulter blocks starlight before it enters the telescope, allowing light from the exoplanet to be observed. The HabEx 52 m diameter starshade will fly in formation with the telescope at a nominal separation of 76,600 km (**Figure 6**). The starshade advantages include a high throughput, small IWA, with an outer working angle (OWA) limited only by the instrument FOV and an ultra-broad bandwidth available for high contrast spectroscopy. The HabEx starshade has a 58 milliarcsecond (mas) IWA at 1 µm and, a 6 arcsec OWA for broadband imaging, and offers deep enough starlight suppression for spectroscopy over an instantaneous bandwidth of 0.3–1.0 µm. The starshade may also operate at two additional separations from the telescope. At a larger separation it covers bluer wavelengths at 0.2–0.67 µm, providing unique access to deep ozone features in Earth-like atmospheres. At a smaller separation, it covers redder wavelengths at 0.54–1.8 µm.

The SSI has three channels: a near-UV/blue channel covering 0.2–0.45 µm with a grism, a visible channel covering 0.45–0.98 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.

UV Spectrograph/Camera (UVS). The UVS covers 0.115–0.320 µm with a FOV of 3×3 arcmin^2 and multiple spectroscopic settings up to resolutions of 60k. Additionally, a grating set contains a mirror to provide imaging capability. The UVS has more than 10 times the effective area of HST's Cosmic Origins Spectrograph (COS) between 150-300 nm (**Figure 7**). Not only does the UVS provide improved angular resolution and effective area relative to HST, it also includes a microshutter array, allowing multiplexed UV spectroscopy for the first time in space.

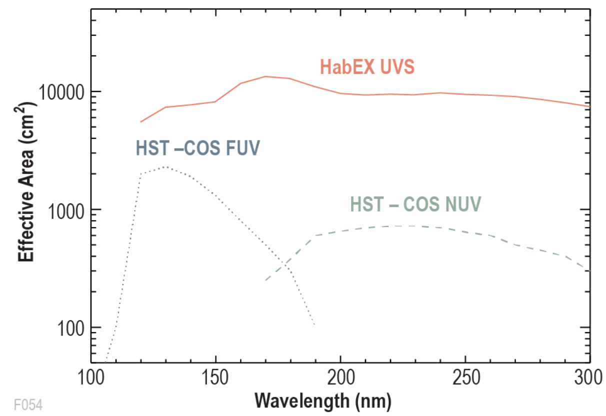

Figure 7. With more than ten times the effective area of HST-COS between 150-300 nm, combined with a microshutter array, the HabEx UVS provides several orders of magnitude improved efficiency for UV spectroscopic studies. This will enable the first multiplexed observations of multiple sightlines to a single galaxy, allowing a new probe of the baryon cycle in galaxies.

HabEx Workhorse Camera and Spectrograph (HWC). The HWC is an imaging multi-object slit spectrograph with two channels covering wavelengths from the near UV through near-IR and a spectral resolution of 1,000. The UV/optical channel covers 0.37–0.95 µm and the near-IR channel covers 0.95–1.8 µm. The HWC, with its larger 3×3 arcmin^2 FOV and higher resolution, will provide capabilities similar to, but significantly more sensitive than, e.g., HST's Wide-Field Camera 3 (WFC3) or Advanced Camera for Surveys (ACS).

More technical details on the preferred HabEx architecture and the four instruments can be found here https://www.jpl.nasa.gov/habex/documents/.

The HabEx Observational Strategy

The HabEx exoplanet observational strategy takes advantage of the dual starlight suppression instruments. The broad survey of 42 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 15 years. The HabEx strategy does not rely on any prior knowledge or contemporaneous independent observations.

Broadband spectra of these planetary systems are obtained by the starshade. A deep survey utilizing the starshade for multi-epoch broad bandwidth observations of eight 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 the broad survey.

Through joint scheduling of exoplanet and general astrophysics observations and engineering design, HabEx is capable of about 90% observational efficiency. The Guest Observer program will be community driven and competitively selected, and is intended to include solar system, exoplanet, Galactic, and extragalactic studies. Two opportunities will exist to guest observe with

HabEx. Standalone observations across the sky are scheduled during starshade retargeting. Parallel observations will be made with the UVS and HWC during starshade or coronagraph observations, providing two 3×3 $arcmin^2$ HST-like ultra-deep fields in the vicinity of each exoplanet target star.

The HabEx Philosophy

HabEx was designed to be a Great Observatory that can be realized in the 2030s. To achieve this, the guiding philosophy of this study was the recognition that any recommendation by the Astro2020 Decadal Survey (DS) must balance scientific ambition with programmatic and fiscal realities, while simultaneously considering the impact of its development schedule on the greater astronomy community and the need for a broad portfolio of science investigations. The HabEx study therefore aimed to develop a mission capable of the most compelling science possible, while still adhering to likely cost, technology, risk, and schedule constraints. The preferred HabEx architecture was thus chosen to be technically achievable within this time frame, leveraging the maturation of several enabling technologies over the last decade or more. HabEx adopted a conservative design with substantial margins, utilizing moderate to high technological maturity resulting in low development risk. HabEx also provides the community with imaging and spectroscopic capabilities an order of magnitude better than Hubble, which uniquely complement currently-planned space and ground based observatories. Finally, this study also considers eight other architectures, which offer greater flexibility in budgeting and phasing, such that HabEx may still be compatible with a balanced portfolio, even for the most pessimistic fiscal projections. Nevertheless, all nine architectures still enable groundbreaking science. Thus, this study provides the DS additional flexibility in its decision making.

HabEx is ambitious, offering humankind the first opportunity to glimpse into worlds like our own and uncover the signs of life, and provides a Hubble-like platform to support community science with deep, high resolution, multiwavelength observations. As one of four large strategic missions under consideration by the DS, HabEx recognizes that any recommendation by the DS will have to balance scientific ambition with the programmatic and fiscal constraints. HabEx also recognizes the impact of prolonged development programs to the greater astronomy community, as demonstrated by James Webb Space Telescope, that limit the ability of NASA to fund a broad portfolio of science investigations concurrent with mission development. From the beginning, the HabEx mission was guided by a philosophy to offer the most compelling science case as constrained by the realities each large strategic mission concept is subject to.

HabEx Alternate Designs and Architecture Trades

HabEx has evaluated the comparative science yield and cost for nine architectures in order to support the Decadal's assessment of HabEx. The primary HabEx architecture is a 4 m monolithic telescope employing both coronagraph and starshade high-contrast imaging technologies. This

# of Tech. / Category	TRL 4 or 5	TRL 4 (2019)	TRL 5 (2019)	TRL 4 (2023 exp.)	TRL 5 (2023, exp.)
Starshade	5	4	1	0	5
Large Mirror	2	2	0	2	0
Metrology	1	0	1	0	1
Coronagraph	3	3	0	0	3
Detectors	5	4	1	2	3
Microthrusters	1	0	1	0	1
Total	17	13	4	4	13

Table 2. HabEx enabling technologies, rolled up by category. As of 2019, HabEx currently carries no TRL 3 or lower technologies, 13 TRL 4 technologies, and 4 TRL 5 technologies. All other enabling technologies are higher than TRL 5. As we outline in detail in the supplemental webpage and our final report, we expect that by 2023, HabEx will carry no TRL 3 technologies, 4 TRL 4 technologies and 13 TRL 5 technologies; all other technologies will be at TRL 6 or higher. All other enabling technologies are expected to be TRL >5 by 2023. Detailed ("unrolled") breakdowns of the individual technologies, description of the current state of the art and capabilities needed, and the path to TRL 6 can be found here: https://www.jpl.nasa.gov/habex/mission/technology/

preferred HabEx architecture has been studied in depth to develop an accurate cost estimate and verify that it is responsive to all science objectives in the science traceability matrix.

The STDT also considered a trade of a total of eight additional options, three telescope mirror diameters (4 m, 3.2 m, and 2.4 m) and three different configurations of starlight suppression: hybrid starshade-coronagraph, starshade only, and coronagraph only. This trade was anchored by the baseline architecture, as well as detailed studies of a 4m off-axis coronagraph-only architecture, and a 3.5m segmented starshade-only option.

Why Now? Scientific and Technological Readiness

The time for HabEx is now. For the first time, decades of scientific and technological achievements now enable design of a relatively low-cost, low-risk mission that can take the first step in directly and characterize EECs to search for signs of habitability and possibly biosignatures, as well as image and characterize complete planetary systems around nearby sunlike stars.

There has been tremendous progress in the discovery of exoplanets over the last 20 years. It is now known that small rocky planets around main sequence stars are common, and that most sunlike stars likely do not host excessive amounts of dust in the terrestrial planet region which would preclude detection and characterization of EECs.

HabEx also leverages the technology investments made over the last two decades, including in particular those recommended in the 2010 Astrophysics Decadal Survey. As a result of these investments, dramatic progress has occurred in four key technology areas that make HabEx possible today: (1) High-contrast imaging at small angular separations using broadband coronagraphs. (2) Starshade development and specific modeling developments and technology demonstrations. (3) Manufacturing of large aperture monolithic mirrors, and (4) Vibration control using microthrusters for fine spacecraft pointing.

More specifically for high-contrast imaging, coronagraph lab-based demonstrations are within a factor of a few of requirements at the appropriate IWA. The starshade technology "S5" program at NASA's Exoplanet Program Office will close starshade implementation technology gaps in formation flying, starlight suppression, and mechanical shape stability and deployment accuracy to reach Technology Readiness Level (TRL) 5 by 2023.

The HabEx Observatory design is based on technologies that are at or near state of the art with clear paths of development. These technologies are being developed by existing teams with existing staffing. The design favors high TRL technologies as a strategy to minimize development risk and reduce potential cost. All enabling technologies are at TRL 4 or higher, with many expected to be at TRL 5 or higher by 2023 under currently funded development (**Table 2**).

Through careful design choices, lessons learned from past studies (particularly the Exo-S and Exo-C probe studies), and utilization of past and ongoing investments into enabling technologies, the preferred HabEx architecture minimizes cost and risk, while maximizing scientific return.

HabEx Cost and Schedule

Gantt chart mission development schedules for the preferred HabEx architecture are provided here https://www.jpl.nasa.gov/habex/mission/documents/. We present two schedules: one for a near-simultaneous launch of the telescope and starshade, and an alternative schedule where the starshade launch is delayed by just over four years.

The overall cost of the preferred HabEx architecture under either scenario described above is still being estimated in detail, but it is clear that both will exceed $1.5B in FY19 dollars. Thus, HabEx is firmly within the "Large Space Mission" category. The latter schedule option allows for both launches while still fitting in the annual NASA Astrophysics Division budget (extrapolated including inflation), while also allowing for ~2 probe-class (~$1B) missions during the 2030s.

Institutional, International, Industrial, and Philanthropic Partnerships

Numerous foreign observers and industry partners have both expressed interest and have supported the development of the HabEx concept. We fully anticipate that the development of HabEx, should it be selected, will involve contributions from multiple NASA centers, academic institutions, industry partners, and potentially philanthropic organizations.

Beginning a New Era for Astrophysics with HabEx

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 4m diameter aperture, improved detector technology, exquisite wavefront control, and a more thermally stable orbit. The preferred architecture is cost-effective, modest risk, and will result in high-impact science. HabEx will leverage recent advancements in both coronagraph and starshade starlight suppression technologies to detect and characterize potentially habitable worlds and map our nearest neighbor planetary systems. 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.

Non-exhaustive list of Astro2020 Science White Papers relevant to HabEx science cases and projected capabilities

1. Rahmani, H., "Quasar absorption lines as astrophysical probes of fundamental physics and cosmology"
2. Roederer, I. et al., "The Potential of Ultraviolet Spectroscopy to Open New Frontiers to Study the First Stars"
3. Bethan, J. et al, "Spatially Resolved UV Nebular Diagnostics in Star-Forming Galaxies"
4. Sahai, R. et al.,"Probing Strong Binary Interactions and Accretion in Asymptotic Giant Branch Stars"
5. Tripp, T. et al., "On The Unique Value of Spectroscopy in the Deep Ultraviolet for Galaxy Evolution Studies"
6. Peeples, M. et al.," Understanding the circumgalactic medium is critical for understanding galaxy evolution"
7. Tumlinson, J. et al., "The Baryon Cycle, Resolved: A New Discovery Space for UV Spectroscopy"
8. Lehner, N. et al., "Following the Metals in the Intergalactic and Circumgalactic Medium over Cosmic Time"
9. Ravindranath, S. et al., "Spatially-resolved studies of star-forming galaxies in the reionization epoch"
10. Martin, C. et al., "IGM and CGM Emission Mapping: A New Window on Galaxy and Structure Formation"
11. Thilker, D. et al., "The Nature of Low-Density Star Formation"
12. Burchett, J. et al., "Ultraviolet Perspectives on Diffuse Gas in the Largest Cosmic Structures"
13. McCandliss, S. et al., "Lyman continuum observations across cosmic time: recent developments, future requirements"
14. Scowen, P. et al., "Outline of Analysis Studies Conducted by NASA Cosmic Origins Program Analysis Group Members During the Past 10 Years"
15. Kopparapu, R. et al., "Exoplanet Diversity in the Era of Space-based Direct Imaging Missions"
16. Roser, J.-P. et al., "Solar System Science with Space Telescopes"
17. Ramirez, R. et al.," Habitable zone predictions and how to test them"
18. Chaufray, J.-Y. et al.," UV Exploration of the solar system"
19. Neveu, M. et al., "Investigating the Solar System's Ocean Worlds with Next-Generation Space Telescopes
20. Clarke, J. et al., "Solar System Science with a Space-based UV Telescope"
21. Arney, G. et al., "The Sun-like Stars Opportunity"
22. Lopez, E. et al., "Understanding Exoplanet Atmospheres with UV Observations II: The Far UV and Atmospheric Escape"

23. Currie, T. et al.," The Critical Strategic Importance of Adaptive Optics-Assisted Ground-Based Telescopes for the Success of Future NASA Exoplanet Direct Imaging Missions"
24. Krissansen-Totton, J. et al., "Atmospheric disequilibrium as an exoplanet biosignature: Opportunities for next generation telescopes"
25. Isella, A. et al., "Observing Planetary Systems in the Making"
26. Plavchan, P., "Community Endorsement of the National Academies Exoplanet Science Strategy and Astrobiology Strategy for the Search for Life in the Universe Reports"
27. Mennesson, B. et al., "Interplanetary dust around main sequence stars: origin, magnitude, and implications for exoplanet habitability searches"
28. Marley, M. et al.," Imaging Cool Giant Planets in Reflected Light: Science Investigations and Synergy with Habitable Planets"
29. Robinson, T. et al, " Characterizing Exoplanet Habitability"
30. Dreier, C. et al, "Thinking Big: How Large Aperture Space Telescopes Can Aid the Search for Life in Our Lifetimes"
31. Matra, L. et al., "Exocometary Science"
32. Apai, D. et al., "Planetary Habitability Informed by Planet Formation and Exoplanet Demographics"
33. Reinhard, C. et al, "The remote detectability of Earth's biosphere through time and the importance of UV capability for characterizing habitable exoplanets"
34. Domagal-Goldman, S. et al., "Life Beyond the Solar System: Remotely Detectable Biosignatures"
35. Sembach, K. et al., "The Search for Life Elsewhere as a Compelling Science Theme for Astro2020"
36. Debes, J. et al., "Cold Debris Disks as Strategic Targets for the 2020s"

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