

MIT Open Access Articles

*The Habitable Exoplanet (HabEx) Imaging Mission:
preliminary science drivers and technical requirements*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Mennesson, Bertrand et al. "The Habitable Exoplanet (HabEx) Imaging Mission: Preliminary Science Drivers and Technical Requirements ." Edited by Howard A. MacEwen, Giovanni G. Fazio, Makenzie Lystrup, Natalie Batalha, Nicholas Siegler, and Edward C. Tong. Proceedings of SPIE: Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave (August 2016): 99040L © 2016 SPIE

As Published: <http://dx.doi.org/10.1117/12.2240457>

Publisher: SPIE

Persistent URL: <http://hdl.handle.net/1721.1/116467>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of Use: Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.



PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

The Habitable Exoplanet (HabEx) Imaging Mission: preliminary science drivers and technical requirements

Bertrand Mennesson, Scott Gaudi, Sara Seager, Kerri Cahoy, Shawn Domagal-Goldman, et al.

Bertrand Mennesson, Scott Gaudi, Sara Seager, Kerri Cahoy, Shawn Domagal-Goldman, Lee Feinberg, Olivier Guyon, Jeremy Kasdin, Christian Marois, Dimitri Mawet, Motohide Tamura, David Mouillet, Timo Prusti, Andreas Quirrenbach, Tyler Robinson, Leslie Rogers, Paul Scowen, Rachel Somerville, Karl Stapelfeldt, Daniel Stern, Martin Still, Margaret Turnbull, Jeffrey Booth, Alina Kiessling, Gary Kuan, Keith Warfield, "The Habitable Exoplanet (HabEx) Imaging Mission: preliminary science drivers and technical requirements," Proc. SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, 99040L (24 August 2016); doi: 10.1117/12.2240457

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

The Habitable Exoplanet (HabEx) Imaging Mission: preliminary science drivers and technical requirements

Bertrand Mennesson^{*a}, Scott Gaudi^{a,b}, Sara Seager^c, Kerri Cahoy^b, Shawn Domagal-Goldman^d, Lee Feinberg^d, Olivier Guyon^e, Jeremy Kasdin^f, Christian Marois^g, Dimitri Mawet^h, Tamura Motohideⁱ, David Mouillet^j, Timo Prusti^k, Andreas Quirrenbach^l, Tyler Robinson^m, Leslie Rogersⁿ, Paul Scowen^o, Rachel Somerville^p, Karl Stapelfeldt^a, Daniel Stern^a, Martin Still^q, Margaret Turnbull^f, Jeffrey Booth^a, Alina Kiessling^a, Gary Kuan^a, Keith Warfield^a

^aJet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109;

^bDepartment of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210 USA;

^cDepartment of Earth, Atmospheric and Planetary Sciences, Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA ; ^dNASA Goddard Space Flight Center, Exoplanets & Stellar Astrophysics Laboratory, Code 667, Greenbelt, MD 20771, USA; ^eThe University of Arizona and Subaru Telescope, 933 North Cherry Avenue, P.O. Box 210065, Tucson, Arizona 85721, United States; ^fDept. of Mechanical and Aerospace Engineering Princeton University, Princeton, New Jersey 08544, USA; ^gNRC, Herzberg Institute of Astrophysics, Victoria, BC V9E 2E7, Canada; ^hDepartment of Astronomy, California Institute of Technology, 1200 E. California Boulevard, MC 249-17, Pasadena, CA 91125, USA ;

ⁱThe University of Tokyo and NAOJ, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan; ^jCNRS, IPAG (Institut de Planétologie et d'Astrophysique de Grenoble), UMR 5274, BP 53, 38041, Grenoble Cedex 9, France; ^kESA Scientific Support Office, ESTEC, PO Box 299, 2200 AG Noordwijk, Netherlands; ^lZAH, Landessternwarte Königstuhl 12 D-69117 Heidelberg Germany; ^mAstronomy Department, University of Washington, Seattle, WA 98195, USA; ⁿDepartment of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave, Chicago, IL 60637, USA; ^oSchool of Earth and Space Exploration, Arizona State University, P.O. Box 876004, Tempe, AZ 85287- 6004, USA; ^pDepartment of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA; ^qAstrophysics Division, Science Mission Directorate Mail Suite 3U32, NASA Headquarters, 300 E St SW, Washington, DC 20546-0001, USA; ^rGlobal Science Institute, P.O. Box 252, Antigo, WI 54409, USA

^rGlobal Science Institute, P.O. Box 252, Antigo, WI 54409, USA

ABSTRACT

HabEx is one of four candidate flagship missions being studied in detail by NASA, to be submitted for consideration to the 2020 Decadal Survey in Astronomy and Astrophysics for possible launch in the 2030s. It will be optimized for direct imaging and spectroscopy of potentially habitable exoplanets, and will also enable a wide range of general astrophysics science. HabEx aims to fully characterize planetary systems around nearby solar-type stars for the first time, including rocky planets, possible water worlds, gas giants, ice giants, and faint circumstellar debris disks. In particular, it will explore our nearest neighbors and search for signs of habitability and biosignatures in the atmospheres of rocky planets in the habitable zones of their parent stars. Such high spatial resolution, high contrast observations require a large (roughly greater than 3.5m), stable, and diffraction-limited optical space telescope. Such a telescope also opens up unique capabilities for studying the formation and evolution of stars and galaxies. We present some preliminary science objectives identified for HabEx by our Science and Technology Definition Team (STDT), together with a first look at the key challenges and design trades ahead.

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

*Bertrand.Mennesson@jpl.nasa.gov; phone 1 818 354-0494

1. INTRODUCTION

NASA is funding four parallel flagship mission concept studies in preparation for the 2020 Decadal survey in Astronomy and Astrophysics: the X-ray Surveyor, the Far Infrared surveyor, the Large UV Optical Infrared surveyor (LUVOIR) and the Habitable Exoplanet Imaging mission (HabEx). The corresponding mission concept studies have just started, and will be guided by community STDTs formed in March 2016. The HabEx mission is optimized for the exploration of a broad diversity of worlds orbiting nearby stars, by 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 will 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 the exploration of exoplanetary systems with HabEx, discussing in particular the wavelength range required for such observations. In parallel to defining these exoplanet science goals, our STDT started to define potential high impact general astrophysics (GA) – i.e, non exoplanet - investigations and corresponding instrumental requirements (section 3). Section 4 summarizes the main technical requirements and challenges that apply to both types of envisioned observations. A number of high-level architecture trades have been identified for the exoplanet and GA sides of the mission, and are summarized in section 5.

2. DIRECT IMAGING AND SPECTROSCOPY OF EXOPLANETARY SYSTEMS

HabEx's prime science goal is the discovery and characterization of Earth-sized planets in the habitable zones of nearby main sequence stars, searching in particular for potential biosignatures in their atmospheres. This goal drives the high contrast imaging requirements of the mission, and the continuous spectral coverage needed (although the full mission wavelength range for other applications may be significantly wider). More generally, it is expected that HabEx will take complete "family portraits" of our nearest and brightest neighboring planetary systems for the first time, and characterize the full diversity of planets orbiting these mature stars, both in the habitable zone and beyond. Because of its direct imaging capability, HabEx will also study the structure and evolution of debris disks around these stars, and their dynamical interaction with such planets.

2.1 Rocky planets in the habitable zone and biosignatures

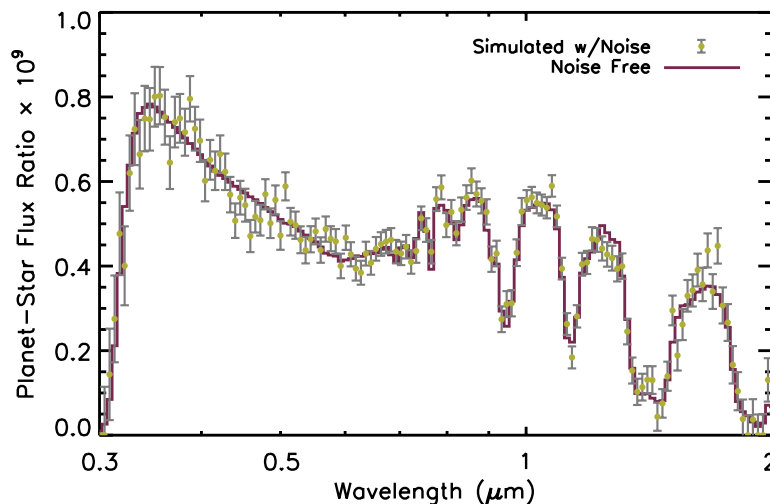


Figure 1 (based on models from Robinson et al. ⁴): Simulated spectrum of an Earth analog around Tau Ceti (a G8V star located at 3.6 pc), as observed with a 5m telescope providing a 10^{-9} raw contrast outside of a $2\lambda/D$ inner working angle. The exozodiacal emission is assumed to be 10x the solar level, the spectral resolution is constant at $R=70$ over the whole range shown and the integration time is set to 25 hours per each 20% bandpass. Realistic noise sources included.

As already established by many authors^{1,2,3}, numerous spectral features should be detectable in the atmospheres of rocky planets using low resolution ($R \sim 50-100$) spectroscopy from the near UV to the near infrared (IR). Figure 1 shows as an illustration the noise-free spectrum of an exo-Earth analog (red curve) between 0.3 and 2 μm sampled at a resolution of $R=70$, together with the simulated spectrum with realistic signal-to-noise ratio derived from high contrast imaging simulations⁴. In this case, a continuous spectral coverage from 0.4 to 1 μm would already reveal water vapor (0.94 μm absorption band), and potential bio-signature gases in the atmosphere such as O_2 (0.69 and 0.76 μm) and its photolytic product O_3 (via the Chappuis band centered on $\sim 0.6 \mu\text{m}$). Detecting both O_2 and H_2O is important to rule out some false positive scenarios⁵; thus the 0.4 to 1 μm spectral range is an absolute minimum for HabEx. Extending the observations down to 0.3 μm would allow one to detect the very deep Huggins band of O_3 , which starts to absorb at $\sim 0.34 \mu\text{m}$ and whose optical depth increases dramatically down to 0.3 μm and shorter wavelengths. Pushing even further in the UV may also allow one to distinguish a biotic, high- O_2 atmosphere from an abiotic, CO_2 -rich atmosphere based on the ozone absorption shortward of 0.3 μm ⁶. On the long wavelength side, extending the observations to 1.7 μm would make it possible to search for strong additional water bands (at 1.13 and 1.41 μm), and would also allow one to search for evidence that the detected O_2 and O_3 gases were created by abiotic processes (e.g., by looking for features from CO_2 , CO , O_4). A further infrared extension to $\sim 2.5 \mu\text{m}$ would allow to search for secondary features such as CH_4 , which may be inconsistent with abiotic processes.

In reality, whatever the instrumental spectral coverage selected, there will be a distribution of wavelengths accessible to high contrast measurements, depending on host star type and distance, planet brightness and separation. We retain for now that an absolute minimum continuous wavelength range is 0.4 to 1 μm , with possible short wavelength extensions down below 0.3 μm and near infrared extensions to 1.7 μm or even 2.5 μm . These possible near IR and near UV extensions of the nominal high contrast spectral coverage must be traded against technical cost and complexity, as discussed in section 5.

2.2 Characterizing the exoplanets zoo

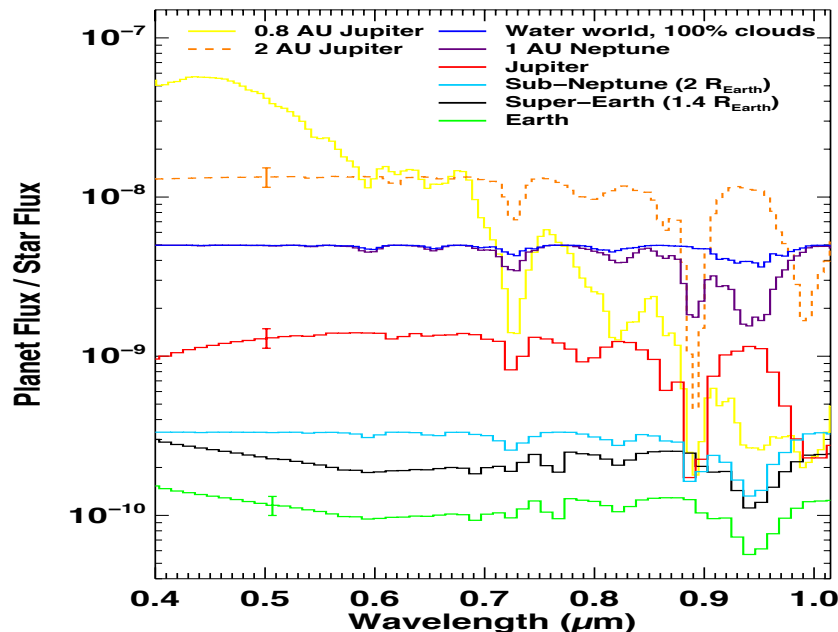


Figure 2 (adapted from Seager et al.⁷): Differences and similarities in brightness and spectral features for a variety of exoplanet types. Optical reflectance spectra of a diverse suite of exoplanets are shown without added noise. Features in the spectra of analogs to some of the planets in the Solar System, as well as planets that have no analogs in our solar system such as super Earths and sub-Neptunes, are readily distinguishable with a $R=70$ spectrum.

While the observation of Earth-sized planets in the habitable zone is of major interest and will drive HabEx high contrast imaging requirements, a whole suite of different exoplanets will also be characterized: super-Earths, possible ocean planets, sub-Neptune planets, Jovian planets, and possibly ice giants, if they are bright enough. Figure 2 shows as an illustration of the spectra that could be recovered for such a zoo of exoplanets, using the minimum spectral range defined previously.

In the case of giant planets, R=70 spectra will provide a wealth of further information over a simple measurement of the broadband flux. The shape of the spectrum would help determine the wavelength-dependent reflectivity of the planet, which is controlled by the atmospheric thickness and any cloud and haze layers. The overall spectral shape will therefore give an indication of the presence or absence of cloud or haze layers. Absorption features from CH₄, H₂O, NH₃, and CO, and emission features from Na and K, are all within the wavelength range of anticipated HabEx observations. The depths and widths of these features would be measured, from which the concentrations of these species could be determined or constrained.

Exoplanets are incredibly diverse and not limited to giant planets or Earth-size planets, but extend to the full range of sizes (and masses and densities) allowed by physics. While there are no solar system planets larger than Earth but smaller than Neptune, such planets appear to be the most common planets in our Galaxy, at least for orbits within a few hundred days. Being larger than Earth, these planets are favorable for detection and characterization with HabEx. Of particular interest is the possibility that super Earths or even some low-mass sub-Neptune planets exterior to the traditional habitable zone may have suitable surface temperatures to host life by a strong greenhouse gas atmosphere or envelope composed of H₂⁸.

2.3 Structure and evolution of circumstellar disks

With a contrast that is 1,000 times better than that achievable with the Hubble Space Telescope (HST), HabEx will resolve dust structures, tracing the gravitational effect of planets too small or remote to be detected by any other means, and measuring dust properties in a large sample of outer exo-Kuiper belts and inner exozodiacal belts at solar system emission levels or even lower. HabEx will indeed survey several hundred nearby solar type stars for exoplanets, and in doing so will directly image all types of dust structures around them, with the ability of resolving rings, gaps, warps and asymmetries driven by planetary perturbations in these disks. Such observational studies of dynamical disk/planet interactions would be similar to what has already been demonstrated on much brighter disks and self-luminous planets found around nearby young stars such as β Pic⁹, but with HabEx would be possible on much fainter disks orbiting mature stars. By imaging so many faint debris disks for the first time, HabEx will enable comparative studies of dust inventory and properties across a broad range of stellar ages and spectral types. This will put the solar system in perspective not only in terms of exoplanet populations, but also in terms of dust belts morphologies and other physical characteristics.

3. GENERAL ASTROPHYSICS OBSERVATIONS

A wide variety of investigations are currently being considered for HabEx general astrophysics program. They range from studies of galaxy leakiness and Inter-Galactic Medium (IGM) reionization through measurements of the escape fraction of ionizing (LyC) photons, to studies of the life cycle of baryons as they flow in and out of galaxies, to resolved stellar population studies, including the impact of massive stars and other local environment conditions on star formation rate and history. More exotic applications include astrometric observations of local dwarf galaxies to help constrain the nature of dark matter, or further improvements in the determination of the local value of the Hubble constant, using precision near infrared Cepheid-based measurements in scores of galaxies that have hosted SNe Ia events. All themes would take advantage of what would be the largest diffraction limited optical telescope in space, with likely extensions to the UV and/or near infrared regimes. As an illustration, we concentrate hereafter on three of these potential general astrophysics topics.

3.1 Measuring the star formation histories of nearby galaxies with stellar archaeology

One of the primary goals of studies of galaxy formation and evolution is to map how galaxies formed their stars and produced heavy elements over cosmic time. We can probe the formation history of stars in galaxies in a statistical way by studying galaxies at different redshifts, corresponding to “snapshots” of different cosmic epochs. However, a

complementary and very powerful technique uses measurements of the luminosities and colors of individual stars within a galaxy, along with our knowledge of how stars evolve in this diagram as they age, to determine the ages and chemical abundances of these stars. This allows us to extract a “fossil record” of when stars formed. The Hubble Space Telescope can resolve individual stars down to stars like our Sun only for very nearby galaxies (within our own Local Group). Hubble can reach only one other large galaxy with this technique, the Andromeda spiral galaxy.

With a >3.5-m diffraction-limited UV-optical telescope, we could map star formation histories out to much larger distances. By pushing to larger distances, we will be able to study the diversity of galaxy formation histories as a function of mass, environment, and other properties. Moreover, this information will be synergistic with several of the other science drivers discussed in this document and science that will be possible with other facilities by the time HabEx flies. For example, if we can map the circumgalactic medium (CGM) using UV spectroscopy, we can attempt to make links between the amount of energy and momentum that was deposited into the ISM over a galaxy’s history (using resolved stellar populations) and the conditions in the CGM. Although some of this science will be done with JWST in the infrared, UV and optical photometry are critical for obtaining deeper, more robust constraints on star formation histories and disentangling degeneracies between age, metallicity and dust. This work is very unlikely to be possible from the ground even with ELTs.

3.2 Tracing the Life cycle of Baryons – a candidate grand challenge for HabEx

One of the candidate general astrophysics grand challenges that HabEx could substantially address is to track and understand the life cycle of baryonic matter in the Universe. The goal would be to understand the nature of material in the IGM, and what can we learn about the cycle of material between star formation in galaxies and how the resulting material is ejected from those galaxies and subsequently returned via other mechanisms. There are a series of observational approaches that can be used to address this goal. One is to use QSOs or fainter AGNs as backlights to allow FUV absorption line studies of the intervening IGM. The idea is to use this methodology to trace invisible baryons and conduct a census of baryonic matter in the low redshift universe in the various phases of the IGM. In parallel to this we can also map the IGM/CGM emission to probe baryonic structure formation across cosmic time. This idea detects and characterizes the IGM in emission (rather than absorption) to determine the physical properties of the IGM and trace baryonic structure formation using that same emission. Another component would map and track the metallic evolution of the IGM, and through that data the physics and contents of galactic haloes, the evolution of UV irradiated environments and ultimately the emergence of life using a large number of spectroscopic lines of sight, coupled with narrow band UV imaging and spectroscopy.

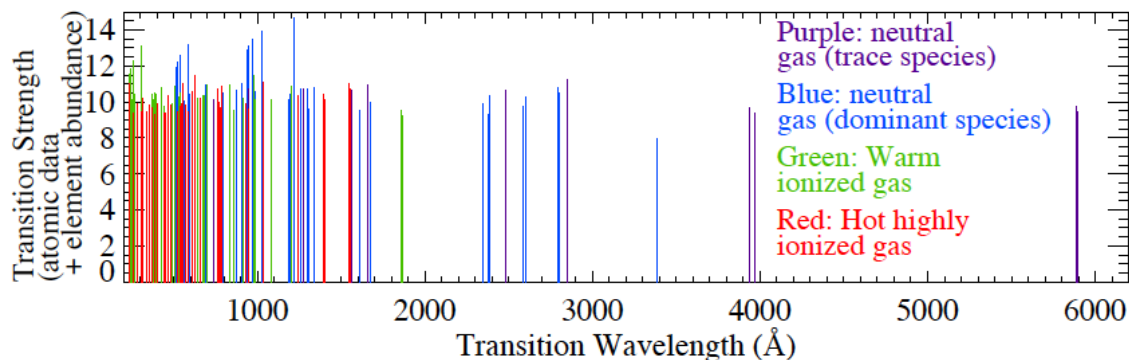


Figure 3 (adapted from Tripp 2013¹⁰): resonance absorption lines detectable with a HabEx class telescope. Using intermediate-redshift QSOs and fainter AGNs as backlights allows absorption line studies of the intervening IGM/CGM, with transitions from a tremendous suite of elements and ions redshifted into the UV band. Such observations provide a very effective tool to probe the flow of matter in and out of the CGM and constrain the cosmic baryon cycle over the past ~10 Gyr.

In addition, we can gain an understanding of how material, and in particular the chemical elements, are distributed and dispersed into the CGM and the IGM, and how baryonic matter subsequently flows from the IGM into galaxies and from there into stars and planets. Such a study is rooted in a high-resolution multiband UVOIR survey imaging of the Magellanic Clouds (MCs), together with a narrowband survey of HII regions and the diffuse warm Interstellar Medium (ISM) in the Clouds. A complementary FUV spectroscopic survey of 1300 early-type stars would provide direct tracers of both the ISM conditions as well as providing insight into the nature of these stellar atmospheres to provide checks for

atmospheric codes. A critical component of this work is to focus on massive stars as a tool to measure the range of properties that stars can be formed with: mass, composition, convection, mass-loss rate, rotation rate, binarity, magnetic fields, and ultimately birth cluster mass. Such a wide-ranging survey of a large sample of local star forming galaxies would allow one to study the escape rate of Ly α photons, which is critical since these have a direct impact on the ecology of the CGM and have implications for fundamental cosmological questions such as the source of the photons that drove cosmic reionization.

3.3 Precision Measurement of the local value of the Hubble Constant

The latest measurements of the local value of the Hubble constant, based on an extensive Hubble Space Telescope program, including significant optical and near-IR observations with the Wide Field Camera 3 (WFC3), find a local value that is 3.4 sigma higher¹¹ than the latest value measured by Planck. Importantly, the Hubble program measures the local value of the Hubble constant, while Planck observes the surface of last scattering of the cosmic microwave background at high redshift and infers the local value of the Hubble constant based on an assumed cosmology. In this case, the discrepancy arises for a vanilla Λ CDM cosmology. Thus despite having entered the era of precision cosmology where fundamental parameters have uncertainties less than 2.5%, significant tension remains, potentially indicating exotic new physics. One plausible explanation for this discrepancy could involve an additional source of dark radiation in the early universe.

Riess et al.¹¹ reduced the uncertainty in the local value of the Hubble constant from 3.3% to 2.4%, with the bulk of the improvement coming from near-IR observations of Cepheid variables in 11 host galaxies that have recently hosted type Ia supernovae (SNe Ia). This work more than doubled the sample of reliable SNe Ia with Cepheid-calibrated distances, to a total of 19. WFIRST, with the same aperture as Hubble, will only be able to incrementally improve upon Hubble because SNe Ia explosions are relatively infrequent within the small volume of the local universe in which Cepheid variables are accessible to a 2.4-m class telescope. A near-IR channel on HabEx would vastly increase the volume accessible to such measurements, thereby allowing precision Cepheid-based measurements to scores of galaxies that have hosted recent SNe Ia, and thus significantly reducing the uncertainty in the local value of the Hubble constant. The required precision photometry is not achievable from the ground.

4. TECHNICAL REQUIREMENTS AND CHALLENGES

4.1 High Contrast Imaging of Exoplanetary systems

Before considering contrast and spatial resolution, an obvious requirement for HabEx is to provide enough sensitivity for high signal-to-noise ratio spectroscopic measurements of $V \sim 30$ planets in reasonable exposure times. In terms of signal, taking the case an Earthlike planet seen at quadrature around a Sun-like star located at 10 pc, the *incoming* visible photon flux per $R=70$ spectral resolution element is only 10^{-3} photons/m²/s. Even with a 5m-class telescope, and assuming a 50% overall transmission, it will take about 100s to detect a single planetary photon during spectroscopic observations. This points to extremely low noise and very stable detectors, with dark current lower than ~ 0.001 count/pix/s, and read noise smaller than ~ 0.1 count rms¹². Energy-resolving detectors are an attractive solution that will be examined for the different wavelengths considered.

Whether an internal coronagraph or an external starshade is used (or both), the detection of a meaningful number of Earth-sized planets in the habitable zone of nearby stars requires starlight suppression levels of $\sim 10^{10}$ at physical separations smaller than 100 mas over large ($>20\%$) optical bandwidths. This implies stringent control of residual starlight scattered from the edges of a distant starshade or from imperfect optics inside a telescope coronagraphic beam train.

In the case of internal coronagraphs, raw contrast levels of the order of 5×10^{-10} have already been demonstrated over the required optical bandwidth and range of planetary separations considered¹³. These vacuum experiments used unobscured telescope apertures and a stable laboratory bread-board; several other candidate coronagraphs architectures have come close to the required performance¹⁴. This suggests that under static wavefront conditions, the required 10^{-10} detectability levels should be accessible in the near future with current coronagraph designs, especially after applying post-processing techniques to further reduce residual starlight speckles. More challenging is to reach the same

performance under dynamical conditions, i.e., in the presence of fast line-of-sight jitter and slow wavefront drifts due to small changes in the telescope thermal load. Such effects have already been examined and modeled in some detail in the context of the WFIRST coronagraph, which will primarily focus on imaging and characterizing brighter giants planets previously detected by ground-based RV measurements. HabEx will basically require a tenfold contrast improvement over WFIRST. Assuming a primary aperture of ~ 3.5 m, and depending on the exact wavelength and coronagraph architecture considered, the HabEx telescope line of sight pointing jitter will have to be kept below to ~ 0.1 - 0.5 mas rms. Such low numbers will likely only be accessible after active correction of residual telescope pointing jitter using a fast stirring mirror. Similarly, very small low order wavefront drifts will be tolerable, down to the ~ 10 pm rms level. Such performance could in principle be reached passively through exquisite thermal design, and likely through additional active low order wavefront sensing and control using either natural starlight (WFIRST's approach) or laser metrology for faster control.

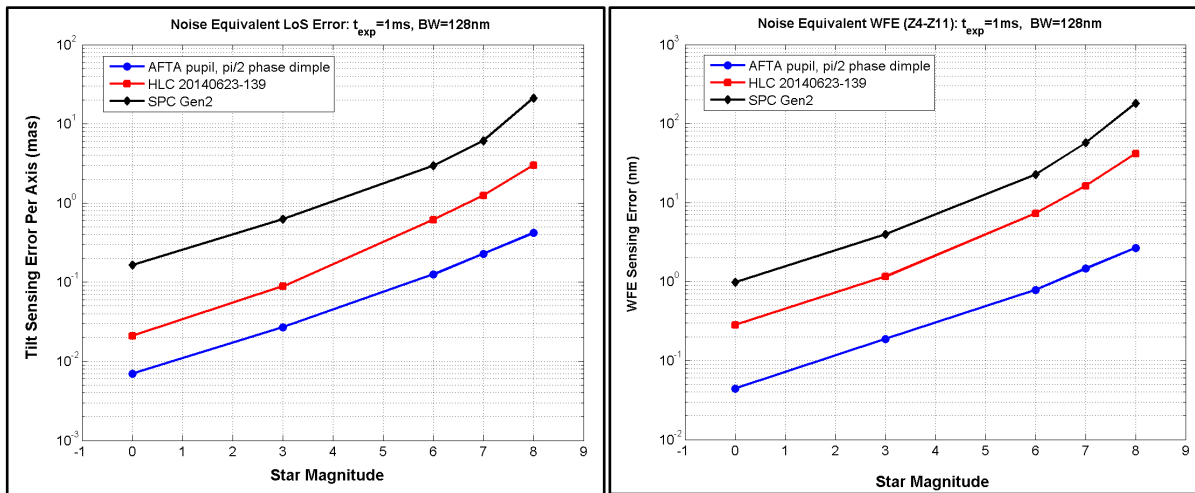


Figure 4 (adapted from Fang Shi 6): expected sensing capabilities for the WFIRST telescope using diverse low-order wavefront sensing schemes and 1 milli-second exposures on natural starlight. The blue lines are representative of the sensing performance expected with a larger (~ 3.5 m to 8m) HabEx telescope optimized for exoplanets direct imaging. Left: a pointing *sensing* error of 0.1 mas rms per axis is reachable in 1milli-second on a $V=6$ star. Right: a 10 pm rms *sensing* error is achievable on a $V=6$ star in ~ 10 s. Controlling the line-of-sight and wavefront jitters down to these theoretical levels requires however that the input drifts before any starlight based correction be lower and slower than these limits, or pre-reduced using vibration isolation and laser metrology.

In the case of an external starshade, the telescope will not require the ~ 10 pm level stability needed by the coronagraph. The major requirement is hence no longer set on the telescope stability, although it will still need to be diffraction limited down to ~ 400 nm for best performance, requiring some active control at the ~ 100 nm level. The challenge is instead on the control of the starshade petal shapes and positions to within ~ 100 μm , and precision formation flying of the telescope inside the shadow casted by the starshade (typically ± 1 m of tolerance) and on model validation, given difficulties in end-to-end testing of such a large system from the ground. All of these key aspects have been the objects of successful demonstrations over the last few years¹⁵ and recognized as high priorities for further verifications in the near future tests. The potential WFIRST starshade rendezvous mission currently being studied would strongly advance the technology readiness level of the starshade, bringing it on par with the coronagraph.

It is worth noting here that the starshade and the coronagraph represent at this point two viable options for the HabEx high contrast imaging system, and that they are not necessarily incompatible. In fact, while more work is needed to properly optimize possible synergies (section 5) and assess compatibility, it could be that the highest exoplanet science yield is obtained when using both systems in conjunction. For example, exoplanet observations may take advantage of the coronagraph agility to conduct multiple blind search visits around different stars, and use the intrinsic broad wavelength coverage and small inner working angle (IWA) of a starshade for subsequent spectroscopic characterization. As shown above, the coronagraph and starshade approaches present very different and quite “orthogonal” technical challenges, so that operating both may also increase the robustness of the mission.

4.2 General Astrophysics

General astrophysics observations may level requirements on the HabEx design (e.g in terms of wavelength range and field of view), if justified by a high science return while still being compatible with top exoplanet science goals and preferred architecture. Table 1 summarizes the investigations currently suggested for HabEx general astrophysics program (Section 3), together with some notional instrument requirements for each of them. A number of themes point toward spectroscopic observations in the far UV, and diffraction limited imaging over a significant field of view (at least 3x3 arcmin), none of which appear to be especially difficult. However, extending the spectral range into the UV would require aluminum-based primary and secondary mirrors and dedicated UV coatings, and while HST has observing capabilities in the far UV, they do not extend with high throughput below 120nm. The exact impact of a UV capability on high contrast imaging observations will have to be assessed, specifically in terms of throughput loss at longer wavelengths, expected polarization effects when using a coronagraph, and perhaps others. This will be part of the trades discussed hereafter.

Science Driver	Observation	Wavelength	Spatial R	Spectral R	Field of view
Local Hubble Constant	Image Cepheid in SN Ia host galaxies	Optical- NIR	Diffraction Limited	Low	3' x 3'
Galaxy Leakiness and Reionization	UV imaging of galaxies (LyC photons escape fraction)	UV, preferably down to LyC at 91 nm	10-20 mas	R ~ 1000-3000	few arcmin
Cosmic Baryon Cycle	UV imaging & spectroscopy of absorption lines in background QSOs	Imaging down to 115nm Spectroscopy down to 91nm	10-20 mas	R ~ 40000	3' x 3'
Massive Stars /Feedback	UV imaging & spectroscopy in the MW and nearby galaxies	110-1000nm imaging 120-160 nm spectroscopy	< 40 mas	R ~ 10000	3' x 3'
Stellar Archaeology	Resolved photometry of individual stars in nearby galaxies	Optical (500-1000nm)	Diffraction Limited	Low	3' x 3'
Dark Matter	Photometry and astrometric proper motion of stars in Local Group dwarf galaxies	Optical (500-1000nm)	Diffraction Limited	Low	TBD

Table 1: Possible General Astrophysics themes to be pursued by HabEx and corresponding instrumental requirements (all notional).

5. MAIN ARCHITECTURE TRADES AHEAD AND CONCLUSIONS

The HabEx mission *design* will be optimized for high contrast imaging and spectroscopy of Earth-sized planets in the habitable zone of nearby solar-type stars. HabEx will also enable a broad range of general astrophysics observations, with possible applications ranging from galaxy leakiness and reionization studies, to tracing the life cycle of baryons in and out of galaxies. To optimize HabEx science return with respect to cost and technical risk, the main trades ahead are clearly identified. We will explore during the concept study a range of possibilities for each of the following trades:

- **Telescope size and technology.** At this point, we are considering primary mirror sizes ranging from ~ 3.5 to 8m, both on-axis and off-axis. There is no real drive for considering segmented primaries below ~ 4 m in diameter, while 4m+ apertures may have to be segmented. In terms of control, both passive and active controls will be considered, and active correction may be based on laser metrology sensing and/or natural starlight. An important trade to conduct will be the choice of the telescope f-number: higher values may be favored when polarization is a concern (i.e., for a coronagraph), but lower values would provide better stability of the secondary mirror and more compact designs.
- **High contrast architecture (also see section 4.1).** Currently, all options for high contrast starlight suppression are being considered: a coronagraph system only, a starshade only, a hybrid coronagraph and starshade operation, or even multiple starshades. Clearly, the telescope and high contrast architecture trades are highly correlated. Operating a coronagraph will place significantly more stringent requirements on wavefront control and stability. It would also point to an unobscured aperture, i.e., an off-axis telescope design. Increasing the telescope diameter will cause a significant increase in starshade size, distance and repointing ability.
- **Wavelength range.** It is worth noting here that the wavelength range selected for high contrast observations may be different than that adopted for general astrophysics (or other type of exoplanet observations), and thus may level different requirements on the mission. On the exoplanet side, going to longer wavelengths would require a larger starshade and/or a larger telescope in order to reduce the amount of exozodiacal background collected per spatial resolution element, or to keep the coronagraphic IWA small. Characterizing exoplanets at wavelengths shorter than ~ 350 nm would require a fully UV-sensitive high contrast optical train to preserve throughput, and will make all wavefront requirements more stringent, whether for a starshade or a coronagraph architecture. The desired wavelength range for general astrophysics will have an impact on the telescope temperature if going above $\sim 2\mu\text{m}$, or will strongly impact telescope design if going below 200nm. In particular, far UV operation would require an aluminum based UV-coated primary, which will affect throughput at visible wavelengths and may cause additional polarization issues if a coronagraph is used. The choice of the HabEx wavelength range will also impact trades on the detector technology.
- **Nature and extent of target pre-screening.** The trade here consists in understanding the gain (both in terms of science yield and cost) provided by different types of precursor observations of exoplanetary systems, in particular measurements of exozodiacal emission levels and the detection of Earth mass planets in the habitable zone using precursor RV measurements and / or astrometric measurements. We will assess what type of precursor measurement is the most beneficial, and how to best obtain them, i.e., through separate observations or as part of the mission itself.

All these key trades are not independent of each other, and many iterations would be necessary to thoroughly search this multi-parameter space and find an absolute optimum. Given available resources, we will instead concentrate on finding the “sweet spot”, i.e., identify a viable proof of concept design that is scientifically compelling, technologically executable, and timely for the next decade.

ACKNOWLEDGEMENTS

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

- [1] Owen, T. "The search for early forms of life in other planetary systems: future possibilities afforded by spectroscopic techniques". In *Strategies for the Search for Life in the Universe*, edited by M. Papagianis, Reidel, Dordrecht, the Netherlands, pp. 177-185 (1980)
- [2] Kasting, J.F., "Habitable zones around low mass stars", and the search for extraterrestrial life. *Orig. Life* 27, 291 (1997)
- [3] Des Marais, D.J. et al, "Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets, *Astrobiology*, 2, 153 (2002)
- [4] Robinson T., Stapelfeldt, K. R., and Marley, M., "Characterizing rocky and gaseous exoplanets with 2m class space based coronagraphs", *PASP*, 128, 960 (2016)
- [5] Domagal-Goldman, S. et al., "Abiotic ozone and oxygen in atmospheres similar to prebiotic Earth", *ApJ*, 792, 90 (2014)
- [6] Harman, C.E., et al. "Abiotic O₂ levels on planets around F,G,K and M stars: possible false positives for life?", *ApJ*, 812, 137 (2015)
- [7] Seager, S. et al., *Exo-S Starshade Probe Class Exoplanet Direct Imaging Mission Concept report to NASA* (2015)
- [8] Pierrehumbert, R. & Gaidos, E., "Hydrogen greenhouse planets beyond the habitable zone", *ApJ*, 734, 13 (2011)
- [9] Lagrange, A.M., "The position of β Pic b relative to the debris disk", *A&A*, 524, 40L (2012)
- [10] Tripp, T., "Quasar absorption lines in the far UV: an untapped goldmine for galaxy evolution studies", eprint arVix:1303.0043 (2013)
- [11] Riess, A. G., et al., A 2.4% determination of the local value of the Hubble Constant, *ApJ*, 826, 56 (2016)
- [12] Stark, C. et al., "Lower limits on aperture size for an exoEarth detecting coronagraphic mission, *ApJ*, 808, 149 (2015)
- [13] Trauger, J. and Traub, W., "A demonstration of the capability to image an Earth-like extrasolar planet", *Nature*, 446, 771 (2007)
- [14] Technology Development for Exoplanet Missions: Coronagraph starlight suppression demonstrations white papers listed at <https://exoplanets.nasa.gov/exep/technology/TDEM-awards/>
- [15] Technology Development for Exoplanet Missions: Starshade technology white papers listed at <https://exoplanets.nasa.gov/exep/technology/TDEM-awards/>