The need for a multi-purpose, optical–NIR space facility after HST and JWST

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Experimental Astronomy
https://doi.org/10.1007/s10686-021-09732-w

ORIGINAL ARTICLE

The need for a multi-purpose, optical–NIR space facility after HST and JWST

The case for an ESA-led HabEx Workhorse Camera

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Received: 28 July 2020 / Accepted: 12 March 2021 / Published online: 18 April 2021

Abstract
In the early 2030s, after the end of operations for the epochal Hubble Space Telescope and the long-anticipated James Webb Space Telescope, astrophysics will lose access to a general purpose high-spatial resolution space observatory to cover the UV–optical–NIR wavelength range with a variety of imaging bandpasses and high-multiplexing mid-resolution spectroscopy. This will greatly impact astrophysical

This White Paper is in large part based on material provided by the HabEx study team, in particular the HabEx Interim Report (available from: https://www.jpl.nasa.gov/habex/pdf/HabEx_Interim_Report.pdf) and the HabEx "APC" whitepaper (available from https://assets.pubpub.org/tsbuk8m1/21598545206635.pdf) recently submitted to the US Decadal Survey on Astronomy and Astrophysics (Astro2020).

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"discovery space" at visible wavelengths, in stark contrast to progress at most other wavelengths enabled by groundbreaking new facilities between 2010 and 2030. This capability gap will foreseeably limit progress in a number of fundamental research directions anticipated to be pressing in the 2030's and beyond such as:

– What are the histories of star formation and cosmic element production in nearby galaxies?
– What can we learn about the nature of dark matter from dwarf galaxies?
– What is the local value of the Hubble Constant?

A multi-purpose optical–NIR imaging and multiplexed spectroscopy Workhorse Camera (HWC) onboard NASA's 4m-class Habitable Exoplanet Observatory (HabEx) space mission would provide access to these required data. HabEx is currently under study by NASA for the US Decadal Survey on Astronomy and Astrophysics 2020, and if selected would launch around 2035. Aside from its direct imaging of Earth-like exoplanets, it will have a general-observatory complement of instrumentation. The versatile Workhorse Camera will provide imaging and R$\sim$1000 spectroscopy from 370nm to 1800nm, diffraction-limited over the whole wavelength range, with simultaneous observations of the visible and NIR. Spectroscopic multiplexing will be achieved through microshutter arrays. All necessary HWC technology is already at Technology Readiness Level 5, hence technological risks are low. HWC has a rough-order-of-magnitude (ROM) cost of 300 M€, and could be European-funded within the cost envelope of an ESA S-class mission in the Voyage 2050 program, with matching funds by national funding agencies to construct HWC by a European instrument consortium. This White Paper is intended to put a European HabEx Workhorse Camera into ESA's considerations. If ESA shares the wide interest and if HabEx were to be selected by NASA, there would be ample time to identify interested institutes for a European instrument consortium, including MPIA, to design, finance, and build the HabEx Workhorse Camera.

Keywords Voyage2050 · Space Astronomy · Exoplanets · Observatory

1 Context: astrophysics 2030+

1.1 The astrophysics landscape in the 2030s

Between now and the 2030s, the astronomical community will commission an impressive array of new facilities and instruments. These include both survey facilities that will image large swaths of the sky with unprecedented sensitivity in the optical (e.g., the Rubin Observatory's Legacy Survey of Space and Time, LSST), near-IR (e.g., Euclid, Roman Space Telescope), or X-ray (eROSITA) part of the electromagnetic spectrum, as well as facilities with more limited fields of view, optimized for deep or detailed follow-up studies (e.g., ESO-ELT, GMT, TMT, JWST).

Up to now, in the ultraviolet and visible wavelength regime the Hubble Space Telescope (HST) has been, and continues to be, the state of the art when it comes to accessibility for the ultraviolet and spatial resolution for both the UV and visible wavelength range. The near-infrared benefits substantially from HST's low background environment compared to ground-based 10m-class facilities, and for many applications HST's field of view is, and will remain, larger than offered by ground-based instruments even when paired with "extreme Adaptive Optics" technology.

HST's partnership between NASA and ESA has led to a vast number of groundbreaking scientific results that would not have been possible in any other way than with HST's space-based location and renewed state-of-the-art instrumentation. The demand for HST's capabilities, the innovativeness of the proposals submitted, and the impact of the results has remained unabated for decades. Similarly, active partnerships are modeled on this for the soon to be launched James Webb Space Telescope (JWST; NASA/ESA/CSA, 2021) and Euclid (ESA/NASA, 2022) missions, both with similar expectations of new paradigm-changing knowledge.

While JWST and Euclid, together with NASA's Roman Space Telescope, will provide excellent access to data in the near-infrared, their capabilities in the visible wavelength range will be very limited in terms of wavelength coverage, spatial and spectral resolution, and bandpass diversity. As a result, after the end of HST, astronomy will effectively lose access to high-spatial resolution, versatile, spectrophotometric observatory capabilities. While the visible wavelength range will be observable by JWST, Euclid, and Roman, these facilities will not cover the full wavelength range, spectral resolution and bandpasses demanded by the science landscape in the 2030s. Specifically, none of these observatories extend *beyond* HST's capabilities as an observatory. Up to $\sim 1\mu$m, JWST will not have a better spatial resolution than HST, as it is only diffraction limited above roughly 1.2μm. Euclid and Roman will only provide a very limited variety of photometric bandpasses and low spectral resolution.

Beyond HST, astronomy will not have any high spatial resolution visible imaging capabilities available. Image quality will be limited by natural atmospheric seeing even for the next generation of 30–40m ground-based telescopes currently under construction and extreme adaptive optics in the visible is not in sight.

All of these arguments hold true even more dramatically in the near-UV spectral range, which is crucial for understanding resolved (and also unresolved) stellar populations and their implications on how galaxies formed and how chemical elements were produced in the cosmos.

Similarly to the great progress for high-resolution access to the NIR from the ground and in space, further progress in many areas of astronomy requires high spatial resolution access to the visible wavelength range, with improvements in angular resolution and effective area over HST. This will only be possible with a single new space mission that is on the horizon: NASA's HabEx and its Workhorse Camera.

The science that can be accomplished with a space-based optical-NIR Workhorse Camera is vast. Here we just touch on a few specific key questions in astrophysics, expected to be left partially or wholly unanswered in the 2030s, which could be propelled or answered by a high-spatial resolution, 4m-class, diffraction-limited 21–50mas spatial resolution, general space-based observatory for the UV–optical–near-IR wavelength range. This will be followed by a description of NASA's HabEx concept, its technical capabilities and layout, and how an ESA partnership stake through a European-funded optical-NIR Workhorse Camera would enable this.

1.1.1 Key science questions for the 2030s

Several billions of Euros are currently being spent on ground- and space-based facilities with a primary goal of mapping large swaths of the Universe in order to study the history of cosmic expansion and address fundamental questions of cosmology. As a byproduct of these studies, many classes of rare, exciting astronomical sources are expected to be found, from dwarf galaxies in the nearby Universe, to a hundred-fold increase in the census of strong gravitational lenses, to quasars at redshift $z \sim 10$ and beyond. These discoveries will demand a range of follow-up studies, some of which will be amenable to ground-based facilities available in that era, but many of which will require space-based follow-up. At the same time, a multitude of key science questions are expected to remain unanswered into the 2030s, including, but not limited to, the missing baryon problem, the nature of dark matter, the history of cosmic acceleration, the history of cosmic reionization, the nature of the seeds of supermassive black holes, the sources and physics of gravitational wave events, detailed understanding of Solar System analogs to exoplanets, and a detailed understanding of the formation and evolution of galaxies.

1.1.2 Discovery space for the 2030s

With no more servicing missions planned, HST is expected to degrade and be out of service sometime in the 2020s, thereby shutting off access to high-spatial-resolution data in the visible wavelength range. The discovery potential for a next-generation optical/near-IR satellite is large. First light is expected to occur for several 30 m-class, ground-based ELTs by the 2030s – specifically the European ELT (E-ELT), the Giant Magellan Telescope (GMT), and the Thirty Meter Telescope (TMT). Since it is widely recognized that adaptive optics (AO) will remain infeasible at optical wavelengths for the foreseeable future (i.e., well past the 2030s), the greatest gains for these facilities will occur at longer wavelengths, where diffraction-limited AO-assisted observations of unresolved sources provide gains that scale as aperture diameter, D, to the fourth power (i.e., D^4) rather than the simple seeing-limited D^2 gains provided by the larger aperture. Accordingly, significant effort is going into designing the AO systems for these telescopes, which will allow the full gains from these large apertures to be realized. Indeed, all the first-light instruments for the E-ELT are diffraction-limited, AO-fed infrared instruments, while GMT and TMT include first-light plans for both diffraction-limited, AO-fed infrared instruments and seeing-limited optical instruments. Therefore, the sharpest imaging at optical wavelengths will remain a domain best achieved from space for the foreseeable future.

Space-based observations provide a platform significantly more stable than ground-based observatories, which is essential for a range of science applications, from sensitive weak lensing studies, which require an exceptionally stable, well-characterized point spread function (PSF), to astrometric studies that require a stable, well-characterized focal plane, to studies that require extremely accurate and stable photometry or spectrophotometry.

Much of the extraordinary progress in astrophysics over the past 20 years has been enabled by combining HST's exquisite resolution and stability, with the light-gathering power of larger-aperture 10 m-class telescopes, such as the Very Large Telescopes (VLTs) and Keck. Often these resources were employed in tandem, with HST providing high-resolution imaging and the ground-based facilities providing spectroscopy (e.g., the Hubble Deep Field). We expect the 2030s to witness similar, but considerably more powerful synergies between HabEx and the ELTs.

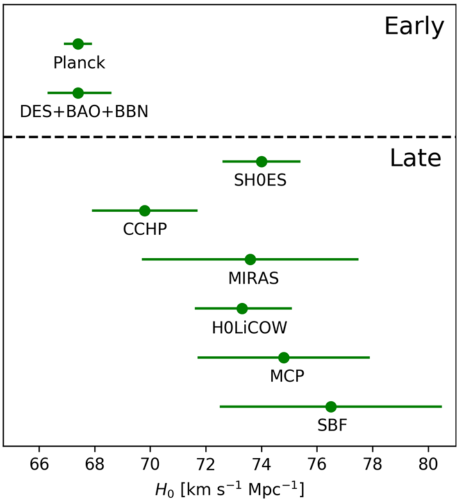
In the following sections, we detail a selection of science cases that take major advantage of a 4-meter UV-to-near-IR mirror in space to uniquely address pressing open questions in astrophysics. These science cases showcase the functional requirements of the HWC instrument on HabEx and demonstrate the immense value a HabEx mission and a Workhorse Camera would have for astrophysics.

1.2 Local value of the Hubble constant

Recent measurements of the local value of the Hubble constant, H_0 (i.e., the local expansion rate of the Universe), have been controversial, and hint at possible new physics. One set of observations is based on an extensive HST/WFC3 program of imaging nearby galaxies at optical and near-IR wavelengths [6]. This study finds a local value of the Hubble constant that is 3.4σ higher than the latest value measured by the Planck satellite [3], based on measurements of the cosmic microwave background (CMB). With the HST program reporting a value of $H_0 = 73.24 \pm 1.74$ km s^{-1} Mpc^{-1} and Planck reporting $H_0 = 66.93 \pm 0.62$ km s^{-1} Mpc^{-1}, the era of precision cosmology has certainly arrived, but, at first glance, perhaps not yet fully the era of accurate cosmology. Importantly, the HST program measures the local value of the Hubble constant, while Planck observes the surface of last scattering of the CMB at high redshift ($z \sim 1100$) and infers the local value of the Hubble constant based on an assumed cosmology. Potentially, the discrepancy arises from the assumption of a "vanilla" ΛCDM cosmology (i.e., the simplest dark energy equation of state, with a temporally invariant cosmological constant, Λ). One plausible explanation for the apparent discrepancy could involve an additional source of dark radiation in the early Universe.

This tension to CMB-based H_0 values also exists for other, independent measurements. [11, H0LiCOW collaboration] find a value of $H_0 = 73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1} from gravitationally lensed quasar time delays. These discrepancies seem to persist now at the 4–6σ-level, as summarized in Fig. 1 (values taken from the overview in [9]) , highlighting the tension. Recent work to reduce the uncertainties from supernovae saw the bulk of the improvement coming from near-IR observations of Cepheid variables in 11 galaxies that hosted recent type Ia supernovae (SNe Ia). Riess et al. [6] more than doubled the sample of reliable SNe Ia with Cepheid-calibrated distances to a total of 19 and improved the local measurement of the Hubble constant by improving calibrations for the lowest rungs on the cosmic distance ladder. The Roman Space Telescope, with the same aperture as HST, will only be able to improve upon HST if more SNe Ia occur within the small volume of the local Universe

Fig. 1 Compilation of recent H_0 value measured either from CMB ("early" Universe) or a variety of surveys using methods ranging from SN1a, quasar lensing, to megamasers around black holes, and other ways to determine a geometric distance ladder across the "late" Universe. There is a consistent discrepancy between early and late measurements on the 4–6σ level. Data from [9]



in which Cepheid variables are accessible to a 2.4 m class telescope. The near-IR channel on HabEx/HWC would vastly increase the volume accessible to such measurements, allowing precision Cepheid-based measurements to dozens of galaxies that have hosted SNe Ia identified between now and when HabEx launches, thereby significantly reducing the uncertainty in the local value of the Hubble constant. The required precision photometry is not achievable from the ground. JWST will be able to achieve some of this science, but fewer accessible SN Ia will have been identified when JWST launches, and JWST is highly inefficient for cadenced observations given its slow slew and settle times.

The time required for such a program is estimated based on [6], which used HST to identify and measure Cepheids in 20 nearby galaxies with a mean exposure time of $\sim$15 kiloseconds per galaxy. Assuming similar exposure times, but reaching to much greater volumes given the eight-fold improvement in HabEx sensitivity relative to HST (i.e., taking advantage of the D^4–scaling for unresolved sources), a survey of a few dozen galaxies could be accomplished in a few weeks of observations. This would increase the number of well-calibrated Cepheid distances to galaxies known to host type-Ia supernovae by a factor of several, thereby decreasing the uncertainties in the local value of the Hubble constant. Such data would also be valuable for a range of nearby galaxy science, such as resolved studies of their stellar populations. These observations would require a 4 m class telescope (or larger), with a field-of-view comparable to nearby galaxies (i.e., $\geq$ 2.5$\times$2.5 arcmin^2), and multiple filters options for imaging from the optical ($\geq$ 0.4μm) to the near-IR ($\leq$ 1.7μm). The same capabilities would immediately be usable for high-fidelity mass-models of a sizable number of quasar lenses and hence improvements in their usability for systematics-independent H_0 time-delay measurements.

1.3 Measuring the star formation histories of nearby galaxies from 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. This is essential for understanding the life cycle of baryons in a cosmological context, as well as how and when the conditions fertile for forming planets and life arise. However, the current picture of galactic star formation has many open questions. How does the distribution of stellar types formed out of gaseous clouds – i.e., the stellar initial mass function (IMF) – vary with the metallicity of these clouds? What role does environment play? For example, in denser regions, an important impact from UV photons emitted by nearby stars, stellar remnants, and potentially active galactic nuclei may be expected.

The formation history of stars can be probed in a statistical way by studying galaxies at different redshifts, providing snapshots at different cosmic epochs. However, a complementary and very powerful technique identifies individual stars within nearby galaxies. Applying knowledge of how stars evolve in color and brightness as they age, the ages and chemical abundances of these stars can be determined. This allows a "fossil record" of when the stars formed to be extracted. HST can resolve individual stars down to stars like our Sun only for the very nearest galaxies. This means that HST can directly detect sunlike stars in only one other large galaxy, the Andromeda spiral galaxy (M31). HabEx would enable the mapping of star formation histories for a much larger and more diverse sample of galaxies, probing galactic environments beyond the Local Group. By pushing out to larger distances, HabEx would enable studies of the diversity of galaxy formation histories as a function of mass, environment, and other properties.

This science goal requires high-resolution, wide-field precision photometry of crowded fields down to the stellar main sequence in multiple UV-optical bands. As shown in Fig. 2, HabEx Ultraviolet Spctrograph (UVS) plus HWC provide the

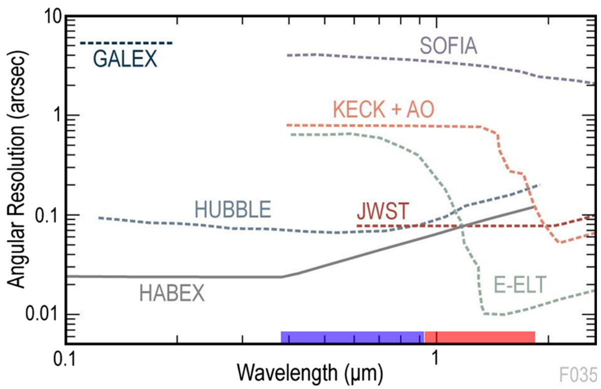


Fig. 2 Spatial resolution of HabEx compared to most-relevant ground- and space-based observatories. The HabEx HWC will have substantially better spatial resolution even compared to JWST up to $\sim 1.1\mu$m. The wavelength ranges for the visible and NIR channel of HWC are marked in blue/red on the X-axis

highest resolution UV and optical images of any facility currently in development. A resolution of 0.1 arcsec or better is required to minimize stellar blending, while a field of view of at least a few arcminutes on a side is required to obtain a sufficient source density to study the properties of the population (e.g., age, metallicity). Multiple bands are required to determine stellar colors. This work requires an extremely stable PSF over arcmin-scale fields, which will not be possible with ground-based telescopes, particularly at optical wavelengths. Stellar archaeology has been pioneered and demonstrated with HST for very nearby galaxies, mostly dwarf galaxies within the Local Group [8, 10]. Even if HST's lifetime were extended, few galaxies are sufficiently close to resolve their stellar populations in this way with a 2.4 m telescope – specifically, there are only two: M31 and M33. JWST will be able to push somewhat further, but UV-optical measurements are critical for breaking the well-known degeneracy between dust, metallicity, and age [1]. Similarly, although Roman will have a large FOV, roughly two orders of magnitude larger than what HST, JWST, or HabEx provide, it has an HST-class aperture, and so will have a similar angular resolution to HST, and thus will not be able to do these studies beyond the Local Group.

In terms of the time required to do such studies, exposure of hours to tens of hours per galaxy will be required, implying that this program could be implemented in a moderate, several day program, easily accommodated as a HabEx Guest Observer (GO) program. In terms of instrument requirements, the capabilities of the Workhorse Camera would suffice, with an addition of UVS multi-object slit spectroscopy ($\geq$ 0.25 μm) with a minimal multiplexing factor of 20.

1.4 Probing the nature of dark matter with dwarf galaxies

One of the most fundamental unanswered questions in physics regards the nature of dark matter. We know that dark matter comprises most ($\sim$85%) of the matter and about a third ($\sim$30%) of the total energy density in the Universe [3], but beyond that, little is known. Is dark matter a single particle, or is there a whole dark periodic table of particles? Standard or "vanilla" dark matter only interacts with itself and with normal matter (i.e., baryons) through gravity (and perhaps through the weak force). However, particle physics allows for many other possibilities. For example, it is possible that dark matter could be "self-interacting".

Dwarf galaxies in the Local Group (e.g., Fig. 3) provide promising laboratories for probing the nature of dark matter because, unlike larger galaxies, which are mostly comprised of "normal" matter (e.g., stars and gas) near their centers, dwarf galaxies are overwhelmingly dominated by dark matter all the way to the center. If galaxies formed out of pure standard dark matter (i.e., with no stars or gas, as well as no additional dark matter self-interactions), theory robustly predicts that their density profiles should monotonically increase all the way to their centers – i.e., that their density profiles should have "cusps" at their center. However, there has been much debate and consternation over the fact that many observed dwarf galaxies instead have "cores" – i.e., their density profiles plateau to a constant value at the center. Figure 4 illustrates how the density profiles of dwarf galaxies depend on the nature of dark matter.

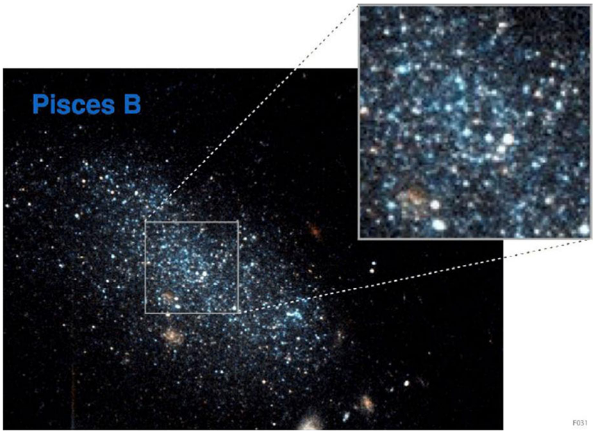


Fig. 3 With high-resolution images of dwarf galaxies in the local Universe, HabEx would measure the distances and star formation histories of local analogs of the first galaxies. Shown here is a Hubble image of the recently discovered nearby dwarf galaxy Pisces B at a distance of 8.9 Mpc (NASA, ESA, and [7]). Compared to HST, HabEx would resolve fainter stars in galaxies like Pisces B, and obtain images like the one shown here for galaxies over a $\sim 10\times$ larger volume

There are two main proposed solutions to explain these observations. Either (1) dark matter is not "vanilla", or (2) the large amounts of energy created by massive stars as they explode in supernovae remove the dark matter from the cusps, thus

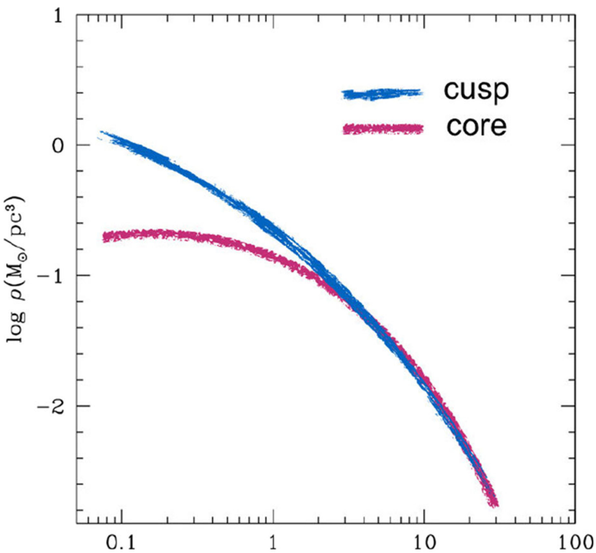


Fig. 4 By spatially resolving the inner kpc of a sample of dwarf galaxies with a range of star formation histories, HabEx would determine if the flattened "core" profiles seen in many galaxies are indicative of self-interacting dark matter, or simply due to supernovae feedback clearing out the inner baryons in galaxies with standard dark matter, which has a "cuspy" density profile

flattening them out into cores. There is a very large parameter space of "non-vanilla" dark matter models that are considered equally plausible, or natural, to particle physics theorists, and astrophysical observations are likely the most efficient way to narrow down this large parameter space. Theory groups largely agree on one clean prediction: if the flat density profile galaxy cores are created by non-vanilla dark matter, they should be seen universally in all galaxies. On the other hand, if the flat core profiles are created by stars and supernovae, then pristine "cusps" should be seen surviving in galaxies with truncated star formation histories [5], because they did not have vigorous enough star formation to produce the requisite energy to remove the dark matter and therefore destroy the cusps. It should also be possible to see correlations of the central galactic density profiles with galaxy properties, such as the ratio of the mass of stars to the mass of dark matter.

In order to test these predictions, high-resolution photometry is needed to probe galactic light profiles, as well as spectroscopy and proper motions to probe the stellar velocities, which act as tracers of the overall gravitational potential. Such data must be collected for a sample that spans a range of masses and star formation histories. Ultra-faint dwarf galaxies have total luminosities of 100–10^5 L_{sun}, while the more luminous "classical" dwarf galaxies have total luminosities of 10^5–10^7 L_{sun} (i.e., $M_V \sim -2$ to –15) and physical sizes ranging from 100 pc to 1 kpc (half-light radii). Roughly 100 dwarf galaxies are known currently within ~3 Mpc (e.g. [2]), and many more are expected to be discovered by Euclid, Rubin, and Roman.

HabEx is essential for multiple parts of this study. First, the high spatial resolution and photometric precision of HabEx is required to obtain accurate star formation histories using optical colors for individually resolved stars. Line-of-sight (LOS) velocity measurements are probably best obtained by ELTs from the ground. However, there is a well-known degeneracy between the velocity anisotropy of the stars and the density profile. Therefore, constraints of the velocity anisotropy can be obtained by measuring the proper motions of stars, requiring astrometric accuracy of better than 40 mas yr^{-1} assuming a fiducial distance of 60 kpc [4]. For the ultra-faint dwarfs that possess the largest dark-to-baryonic matter ratios, main sequence stars are needed to measure these proper motions. This is likely to be infeasible even with ground-based 30m telescopes.

In terms of the time required to do these HabEx dark matter investigations, exposure times of hours to tens of hours per galaxy would be required for the photometric studies, while the proper motion studies would require multiple observations, ideally with large temporal baselines. Assuming such studies are done on a few dozen galaxies, sampling a range of ages, masses, and morphologies, an ambitious version of this program should be executable within a few weeks of observatory time, while a more limited version observing a smaller sample of galaxies could be done more economically, in a few days of observing time. Either way, this unique and fundamental investigation into the nature of dark matter with HabEx could easily be accommodated as a GO program. The instrument requirements levied by the two previous sections would suffice for this program.

1.5 Beginning a new era for astrophysics with HabEx and its Workhorse Camera

Overall, HabEx is a worthy and extremely powerful UV/optical successor to HST in the 2030s with significantly improved sensitivity and spatial resolution stemming from HabEx' significantly larger 4m diameter aperture, improved detector technology, exquisite wavefront control, and a more thermally stable orbit. The preferred architecture for HabEx and its Workhorse Camera is cost-effective, modest risk, and will result in high-impact science. Aside from coronograph and starshade applications, HabEx will provide unique capabilities for UV, optical, and near-IR astrophysics and Solar System science from the vantage of space. HabEx and its Workhorse camera will move visible capabilities to the next level after HST retires.

2 HabEx and its Workhorse Camera

The Habitable Exoplanet Observatory, or HabEx, has been designed to be NASA's Great Observatory of the 2030s, a successor to the Hubble Space Telescope (HST) with enhanced capabilities and community involvement through a competitive Guest Observer (GO) program. This GO program – which shall represent 50% of the 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.

The HabEx baseline architecture is a space-based 4m-diameter telescope 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 (Fig. 5).

The mission will have two starlight suppression systems, each with a dedicated instrument – the Coronagraph (HCG) and the Starshade Instrument (SSI), for direct imaging and spectroscopy of exoplanets – the latter in conjunction with a free-flying starshade spacecraft for HabEx. In addition HabEx has two general purpose instruments: a UV Imaging Spectrograph (UVS), and a visible–near-IR imaging spectrograph, the Workhorse Camera (HWC).

HabEx has three driving science goals during its 5-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 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.

Observing with a large aperture from above the Earth's atmosphere in an era when neither HST norJWST are operational, HabEx will provide the highest-resolution images yet obtained at UV and optical wavelengths (Fig. 2). 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 including topics as diverse as the life cycle of baryons, metagalactic ionizing background sources, first generations of stars

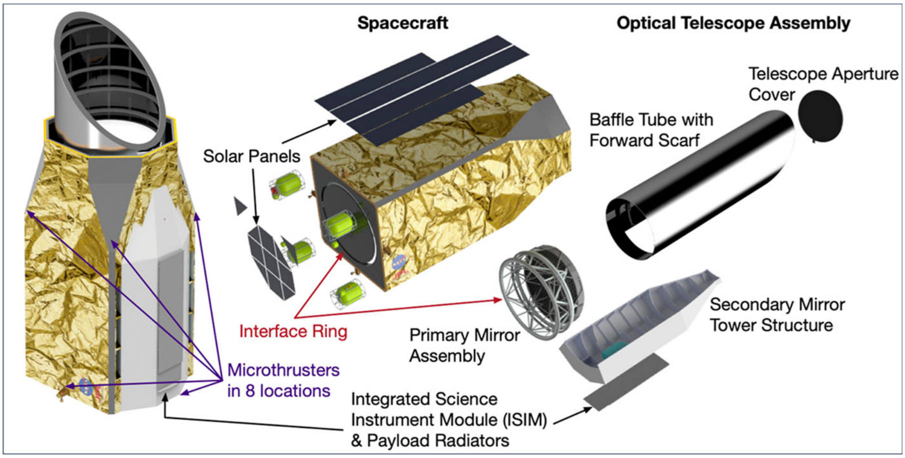


Fig. 5 Rendering of the HabEx baseline design. The off-axis telescope feeds light into the instruments located in the servicable instrument box to the side of the main baffle tube

and supernovae, dark matter model constraints, cosmic expansion rates, protoplanetary discs, 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 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.

The HabEx prime mission is five years (ten-year design life), with approximately 50% of the time dedicated to two ambitious exoplanet surveys, and 50% for Guest Observer (GO) science programmes. 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.

2.1 Baseline HabEx implementation

The HabEx Observatory baseline design utilizes an off-axis, monolithic 4m diameter telescope, diffraction-limited at 0.4μm, launched on an SLS 1B launch vehicle to an Earth-Sun L2 orbit.

HWC and UVS needs drive part of the telescope design. The wide fields of view required by the HWC and UVS instruments led to adoption of a three-mirror anastigmat (TMA) layout. HabEx is designed as an off-axis TMA with a scarfed straylight tube, a 4m-diameter 400mm thick Zerodur primary mirror at focal ratio f/2.5 (Fig. 5).

The telescope provides a collimated 500mm diameter beam at the output, facilitating on-axis instrumentation arranged near the tertiary mirror (Fig. 6). Science light for the HWC will be extracted by a plane folding mirror near the tertiary mirror, where the fields-of-view are spatially separated (Fig. 7). The instrument box is in a servicable location so future upgrades and exchanges will be possible.

2.2 The HabEx Workhorse Camera and spectrograph (HWC)

The HabEx Workhorse Camera (HWC) is a general purpose instrument providing visible through near-IR imaging and spectroscopy, with objectives ranging from Solar System science to detailed studies of galaxies and quasars at the epoch of reionization to cosmology. The HWC will enable detailed follow-up of interesting targets, such as those identified from the wide-field surveys of the 2020s, such as Euclid, LSST, and Roman. Specifically, the instrument is designed to provide unique scientific capabilities compared to the facilities expected in the 2030s. For example, nearly all of the first-generation instruments on the new 30m class telescopes (e.g., TMT, GMT, and ELT) are near-IR instruments because ground-based adaptive optics (AO) are not expected to be effective for wavelengths much shorter than about 1μm. The HWC will provide unique capabilities, including: (1) Visible wavelength range science, (2) high-spatial resolution imaging, (3) a stable platform for both photometry and morphology, and (4) access to spectral regions inaccessible on the ground due to telluric absorption.

The HWC is an imaging multi-object slit spectrograph with two channels, similar to the Wide-Field Camera 3 (WFC3) on the HST, that can simultaneously observe the same field of view: a optical channel using delta-doped CCD detectors providing good throughput from 0.37–0.95μm, and a near-IR channel using Hawaii-4RG HgCdTe arrays providing good throughput from 0.95–1.8μm, beyond which the thermal background of the telescope dominates over most celestial targets.

Both channels will have imaging and spectroscopic modes, and a microshutter array (MSA) as used on JWST provides for multi-object slit (MOS) spectroscopy of targeted sources at R$\sim$1000, significantly reducing the backgrounds and source confusion compared to the slit-less spectroscopic modes available on HST. The two modes of operation share the same optical path and cameras, with a 3$\times$3 arcmin^2 field-of-view. In the spectrographic mode, the MSA and grism sets are introduced

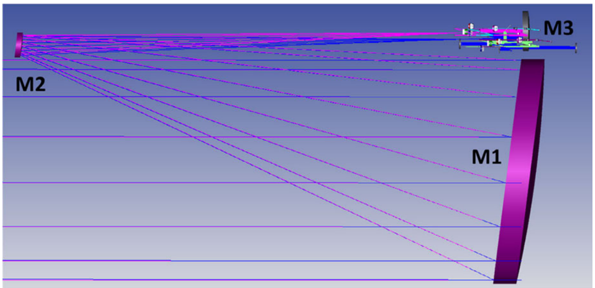


Fig. 6 HabEx principal off-axis TMA optics. The instruments are located near the tertiary mirror M3

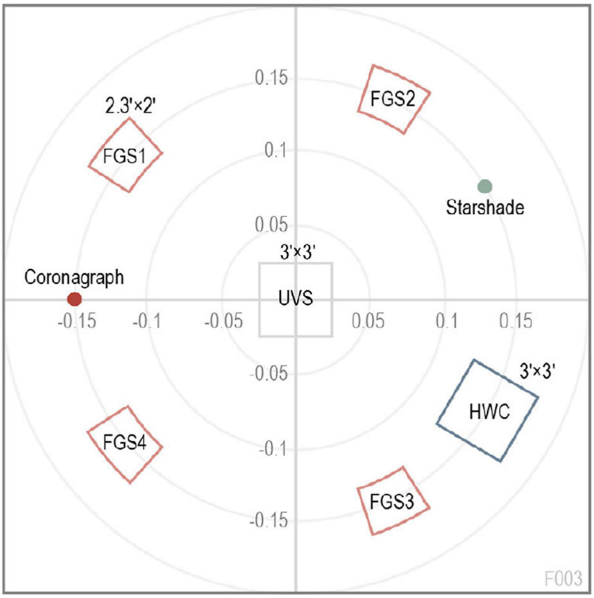


Fig. 7 The HabEx instrument fields of view on the sky. The fields are spatially separated near the tertiary mirror where they can be relayed into the separate instruments

into the beam paths. It is intended that the MSA be attached to a mechanism and thereby removable for the best imaging function. For good imaging, the pixel magnification is chosen to Nyquist sample the point spread function. To obtain sufficient field of view, the visible channel has a 3×3 array of 4k square CCD detectors, and the IR channel utilizes 2×2 H4RG10.

HWC requires a fairly large FOV and a microshutter array to conduct MOS. The minimum spectral resolution is set by the dark matter science. Hubble constant science sets the photometric precision. Like the HabEx starshade and the UVS instruments, pointing for the HWC is driven by the telescope's diffraction-limited point spread function.

Figure 8 shows the layout of the HWC instrument. After reflecting off M3 and the fold mirror, the input beam strikes a fine-steering mirror used for image dithering and small pointing adjustments and is normally fixed during an observation. The beam then passes through a relay formed by a pair of biconic paraboloidal mirrors, then on to a dichroic where the visible light is separated from the IR light. In spectroscopy mode, a microshutter aperture array is inserted into the focal plane of the relay, enabling selection of particular targets. This array is identical to the set of arrays installed in JWST's Near-Infrared Spectrograph (NIRSpec).

2.2.1 HWC visible channel

At the dichroic, visible light is reflected and passes through a filter wheel to a camera. The filter wheel is mounted at a pupil plane and enables selection of different wavelengths of interest in the image. A grism is also placed in the wheel to allow

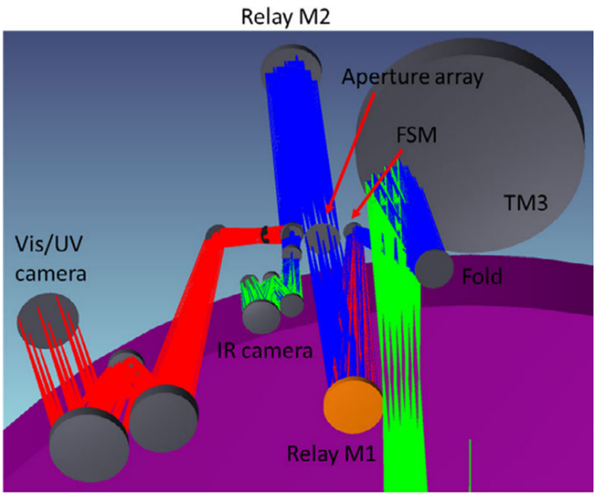


Fig. 8 Principle baseline layout of the HWC optics. Light is split into visible and NIR channels by means of a dichroic. Each channel can either contain its own MSA for spectroscopy or a common MSA can be used. Alternative designs with reflective prisms instead of grisms and different geometrical layouts are currently being studied

spectroscopy in conjunction with the MSA at R = 1000. The camera consists of a three-mirror relay and the focal plane itself. The performance is diffraction limited at 400nm. The focal plane is designed for Nyquist sampling of the $3' \times 3'$ field at the same wavelength. The selected array is CCD203, a conventional low-noise CCD with 12μm pixel size and 4k×4k format. A set of nine of these CCDs, cooled to 153K, forms the focal plane.

2.2.2 HWC infrared channel

At the dichroic, infrared light from 0.95μm to 1.8μm is transmitted and passes through a filter wheel to a camera. As in the visible channel, the filter wheel is mounted at a pupil plane and enables selection of different wavelengths of interest in the image. Again, a grism is placed in the wheel to allow spectroscopy in conjunction with the MSA at R = 1000. The camera consists of a three-mirror relay leading to the focal plane. Performance is diffraction limited at 0.95μm. The focal plane is designed for Nyquist sampling of the $3' \times 3'$ field at the same wavelength. The selected array is the Teledyne H4RG10, a low-noise hybrid HgCdTe/CMOS bump-bonded array with 10μm pixel size and 4k×4k format. These focal plane arrays (FPAs) are currently being developed by NASA for the Roman Space Telescope. A set of four FPAs cooled to 100K forms the focal plane.

2.2.3 A low risk–high return approach

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.

The HabEx Observatory design itself 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 for the Workhorse Camera are already at TRL 5. This includes the microshutter array (MSA), which is an improved version of the ones flying on JWST. Currently-investigated improvements in MSA technology would allow butting of several MSA units into a near seamless array to cover a larger field-of-view. These potential near-future advances can easily be incorporated into the existing designs and would improve HWC's capabilities at no extra risk.

2.2.4 A European HabEx Workhorse Camera as an ESA S-class mission with national consortium contributions

Europe and ESA have the option to participate in HabEx by providing the Workhorse Camera. In general NASA-JPL is interested in finding international partners to construct – and fund – the HWC as a contribution to the mission, shall it be selected as the top priority NASA mission for the Decadal Survey 2020.

The rough order of magnitude (ROM) costs for fully designing, building, and testing the HWC are estimated based on the experience with the NIRCam and NIRSpec instruments onboard JWST, which were of similar complexity. Given the low development risk due to already high TRL-levels, the estimate lies around 300 M€. If a European consortium of astrophysics and instrumentation institutes were to be formed, similar to e.g. the Euclid Consortium, national contributions of half the costs are realistic. In this case a European HWC would neatly fit into the ESA S-class cost envelope of 150 M€, with another 150 M€ required from national funding agencies.

Such a NASA–ESA–consortium partnership would promise both technological advancement in the European high-tech industry as well as high scientific return on investment – as in the cases of HST, JWST, and Euclid.

Funding Open Access funding enabled and organized by Projekt DEAL.

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