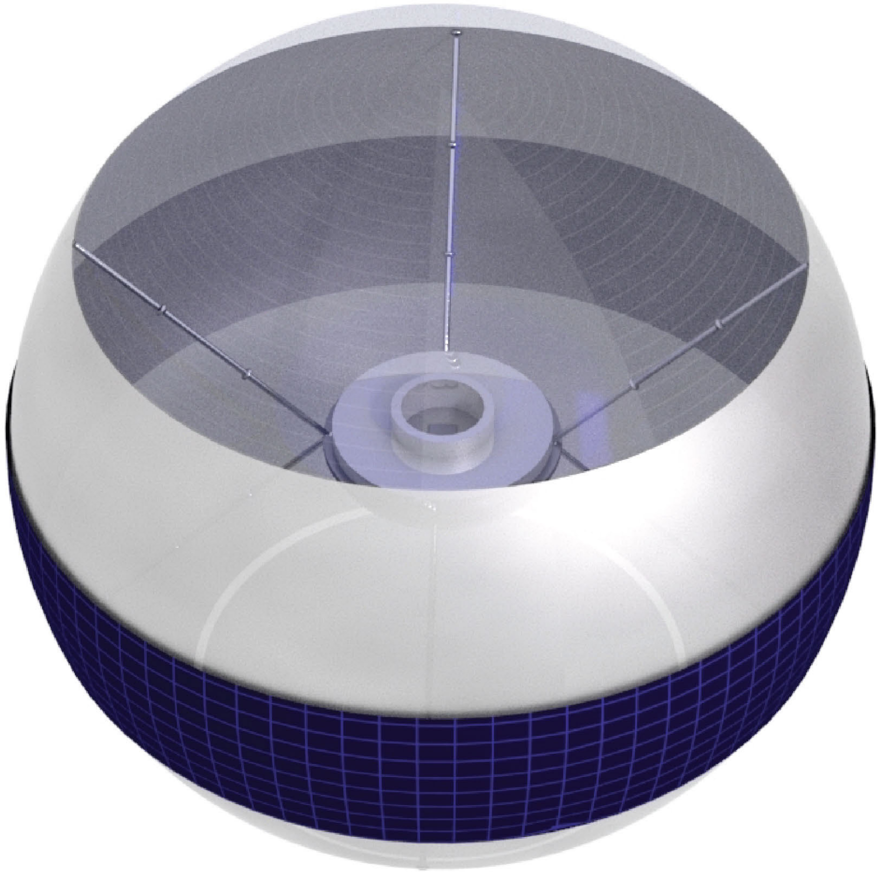
Nautilus

A Very Large Aperture, Ultralight Space Telescope for Exoplanet Exploration, Time-domain Astrophysics, and Faint Objects



A White Paper submitted to the
Astro2020 Decadal Survey

http://nautilus-array.space

Nautilus

A Very Large-Aperture, Ultralight Space Telescope for Exoplanet Exploration, Time-domain Astrophysics, and Faint Objects

Dániel Apai
Steward Observatory and Lunar and Planetary Laboratory
The University of Arizona
Email: apai@arizona.edu — Phone: +1-520-621-6534

Alex Bixel, Benjamin V. Rackham, and Glenn Schneider (Steward Observatory, The University of Arizona), Tom D. Milster, Dae Wook Kim, and Ronguang Liang (James C. Wyant College of Optical Sciences, The University of Arizona), Jonathan Arenberg (Northrop Grumman Aerospace Systems), John Grunsfeld (NASA Goddard Space Flight Center Emeritus).

[Project website: nautilus-array.space]

1 Nautilus Overview

Nautilus is a Probe-class mission concept that will explore the diversity of rocky exoplanets through transit spectroscopy, characterize habitable planets, and search for biosignatures in nearby transiting planets. By providing a larger collecting area than HST and JWST *combined*, Nautilus will obtain low-resolution spectra simultaneously in the visual (0.5–1 μm) and near-infrared (1–1.7 μm). It will observe $>$1,000 transits of 500 small (Earth- to Neptune-sized) planets discovered by TESS, PLATO, and other surveys. Nautilus will provide the largest and most sensitive library of atmospheric abundances of small exoplanets for decades. With an image quality on par with HST but with $\sim$12–15$\times$ greater sensitivity – due to its larger collecting area and simpler, higher-efficiency instrument – Nautilus will also revolutionize time-domain astrophysics and studies of faint astrophysical sources.

Nautilus achieves its uniquely high sensitivity by utilizing an 8.5m diameter, ultralight, achromatic, multi-order diffractive lens instead of a traditional primary mirror. The Nautilus architecture is simple and designed for robustness and low cost-to-collecting-area ratio. The Nautilus mission concept is expected to greatly reduce fabrication and launch costs, and mission risks compared to the current space telescope paradigm. This paradigm shift will also enable incoherent telescope arrays with collecting area equivalent to that of a 50m telescope [1], but at a very low cost and with a scalable design that distributes risks between many units.

2 Key Science Questions and Objectives

The Unexplored Diversity of Extrasolar Planets: Over the past two decades astrophysics has opened a window onto a rich new class of objects: extrasolar planets. Observations of the new worlds with telescopes *not optimized* for exoplanet characterization (e.g., HST, 8m-class telescopes) have revealed planets entirely different from anything seen in the solar system, including hot jupiters, hot neptunes, super-jupiters, and super-earths.

Although multiple space telescopes have been launched (CoRoT, Kepler, TESS), or are in development (CHEOPS, PLATO) to *discover* new planets, the lack of a powerful space telescope designed for exoplanet characterization means that the sample of worlds that can be studied with high signal-to-noise ratios – now with HST, soon with JWST, and in the future with ARIEL – remains mostly limited to planets significantly larger and hotter than Earth (gas giants down to neptune-sized planets). **The true diversity of small extrasolar planets remains unexplored and can only be addressed with a telescope more sensitive than anything in existence or in development.**

The great interest in detailed studies of extrasolar planet atmospheres, evolution, and habitability is demonstrated by the nearly twenty Astro2020 Science WPs submitted by different groups [2, 6, 8, 9, 14, 15, 20, 21, 22, 24, 25, 27, 28, 33, 35, 38]. We refer to those WPs for the scientific context and the broad variety of exciting science questions in the field of exoplanet atmospheric characterization. Here we only focus the Nautilus science objectives that are motivated by the WPs.

NAUTILUS SCIENCE OBJECTIVES

Objective 1) To understand the diversity of extrasolar planet atmospheres by building a large, uniform transmission library of the atmospheric spectra of small extrasolar planets, from sub-earths to neptune-sized worlds.

Objective 2) To determine the atmospheric composition of ~500 extrasolar planets.

Objective 3) To identify processes that shape planetary atmospheres by testing connections between atmospheric composition, orbital properties, stellar irradiation, planet mass, and planet density.

Objective 4) To identify and characterize habitable planets with atmospheric abundances that are unlikely to be consistent with abiotic processes.

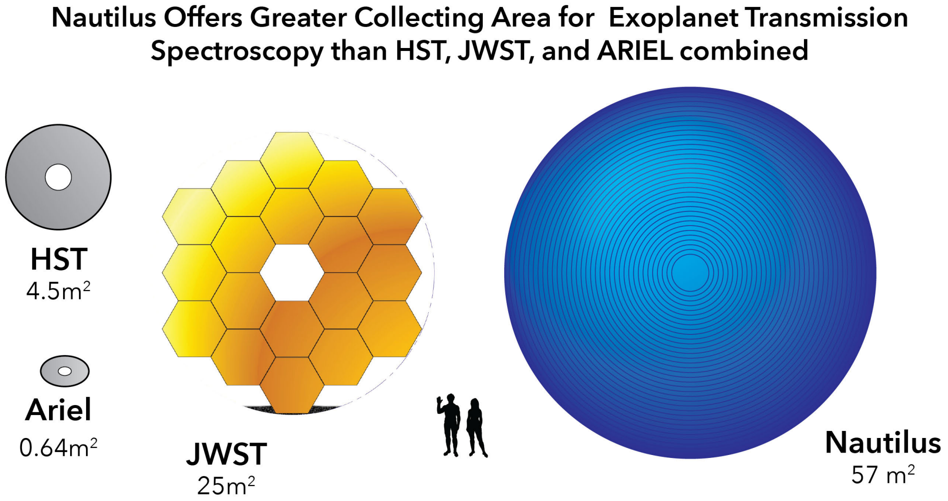


Figure 1: Comparison of the apertures of current (HST) and future (JWST, ARIEL) space telescopes capable of exoplanet transmission spectroscopy to that of Nautilus.

Timeliness: We have recently passed the mark of 4,000 known extrasolar planets. By the end of the 2020s, this number will be an order-of-magnitude higher. The vast majority of these planets will be *transiting exoplanets* discovered by NASA's Kepler (completed) and TESS (ongoing) missions and ESA's PLATO mission (scheduled to launch in 2028).

In its high-cadence (postage stamp) images TESS is projected to detect $1,250 \pm 70$ planets (at 90% confidence), including 250 with $R_p < 2R_\odot$ [5]. An additional 13,100 planets are expected from the analysis of the full-frame images (and similar number of additional planets from a potential extended mission). Focusing on early-to-mid M dwarfs ($3200 < T_{eff} < 4000\,\mathrm{K}$) and taking into account planet occurrence in compact multiple planetary systems, others estimate that TESS will detect $1,274 \pm 241$ planets in M-dwarf systems alone [4]. Additionally, more than 1000 planets are predicted to transit once during TESS observations, including an estimated 79 habitable-zone planets, and be suitable to discovery through ground-based follow-up efforts [37]. ESA's PLATO mission, which will include two 2–3 year pointings in addition to a step-and-stare survey covering 50% of the sky, will produce precise light curves for more than 10^6 stars. With this sample, PLATO is estimated to detect and characterize several thousands of planets, including hundreds of planets with $R_p < 2R_\odot$ [34].

In total, we estimate that by the end of the 2020s, between 25,000 and 45,000 extrasolar planets *will be known, including thousands of targets suitable for a large survey to assess the atmospheric diversity of planets – if a sensitive enough telescope is available!*

Although the study of extrasolar planets is one of the most rapidly developing fields of astrophysics, there are no NASA missions in development with the primary focus of exoplanet characterization. Both HST and JWST have relevant capabilities, but these facilities could not possibly characterize a meaningful fraction of the known exoplanets (even if they are fully functional in 2030). Kepler has demonstrated the power of exoplanet population statistics – but no mission is currently planned that is capable of similar systematic characterization of atmospheres of all types of transiting exoplanets. ESA's ARIEL plans to explore larger planets, but due to its $<$1m-diameter effective aperture it will have limited potential for obtaining high-quality spectra for the majority of smaller transiting planets.

The Nautilus mission will offer over *90× greater* light-collecting area than ESA's ARIEL mission (see Fig. 1). In its primary mission Nautilus will obtain a unique, high-quality 0.5–1.7 μm transmission spectral library for 500 transiting exoplanets. This library represents an orders-of-magnitude improvement over the state-of-the-art in exoplanet characterization in 2030. It will also enable the first comprehensive statistical study of exoplanet atmospheric properties and system parameters.

THE PHOTON HARVEST

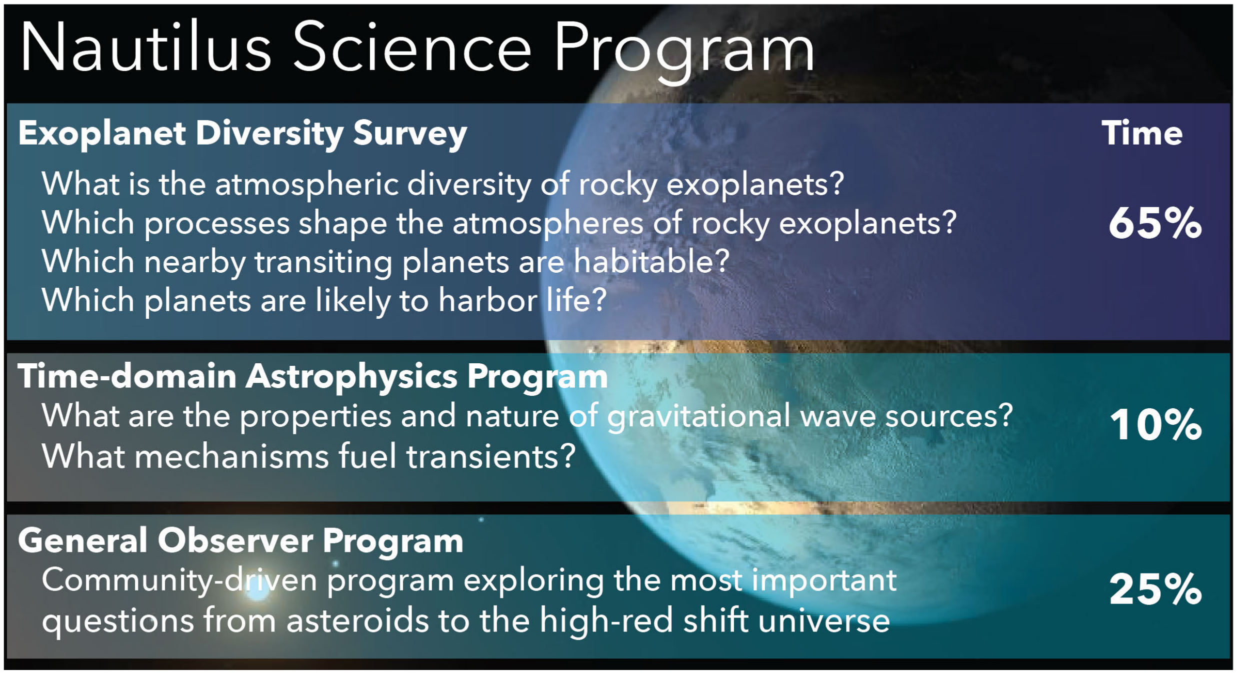
Nautilus will have a collecting area *twice that of HST and JWST combined.* The increase in sensitivity will revolutionize time-domain astrophysics and studies of faint astrophysical objects – from small Kuiper belt objects to very high redshift galaxies.

General Astrophysics: Because Nautilus will enable a dramatic increase in the sensitivity of space-based imaging and spectroscopy, it has the potential to impact and even transform many fields beyond the study of extrasolar planets (see Fig. 2). With a collecting area 12× greater than HST and more than twice that of JWST, it will also revolutionize studies of extremely faint objects and time-domain studies.

TIME-DOMAIN ASTROPHYSICS: Nautilus is designed for high sensitivity and high spectrophotometric precision and will be the ideal observatory for time-domain astrophysics. From studies ranging from rotational mapping of Kuiper-belt objects and brown dwarfs through the characterization RR Lyrae and Cepheids in the local group and beyond, to tidal disruption events, kilonovae, high-redshift supernovae, and reverberation mapping of AGNs, Nautilus will provide a uniquely powerful platform.

THE FAINTEST OBJECTS: Nautilus will exceed HST's light-collecting power by 12×, allowing the studies of objects about *3 magnitude fainter* than HST's limiting magnitude. Furthermore, with simultaneous spectrocopy over the 0.5–1.7 μm bandpass, it will be an order-of-magnitude more efficient instrument for the detection and photometric/spectroscopy characterization of the faintest astrophysical objects (e.g., high-red shift quasars, GW source optical counterparts).

Exoplanet Transit Observations: Figure 3 shows example, exploratory Nautilus spectra for three types of transiting planets, based on NASA's Planetary Spectrum Generator [36]. The simulations follow the methodology described in [1]. All modeled planets orbit a nearby (15 pc) mid-M dwarf (0.2 $M_\odot$), and analogous planets have already been discovered in systems such as GJ 1214 [7], LHS 1140 [10], and TRAPPIST-1 [13]. Model A [12] is an Earth twin in the middle of the habitable zone with no clouds and prominent absorption features due to H_2O and O_3 – a poten-



Nautilus Science Program

Exoplanet Diversity Survey **Time**

What is the atmospheric diversity of rocky exoplanets?
Which processes shape the atmospheres of rocky exoplanets?
Which nearby transiting planets are habitable?
Which planets are likely to harbor life?

65%

Time-domain Astrophysics Program

What are the properties and nature of gravitational wave sources?
What mechanisms fuel transients?

10%

General Observer Program

Community-driven program exploring the most important questions from asteroids to the high-red shift universe

25%

Figure 2: The Nautilus science program will revolutionize studies of extrasolar planets and time-domain astrophysics. Furthermore, quarter of the Nautilus mission will be open for GO programs.

tial biosignature. Model B [11] is a Venus analog which lies within the run-away greenhouse limit, but which lacks the high-altitude haze which obscures Venus' transmission spectrum, so that the prominent CO_2 absorption can be seen. Model C [29] is a warm sub-neptune analogous to GJ 1214 b, but with a clear, solar-composition atmosphere. For the Earth and Venus analogs, combining $\sim$10–30 transit observations will enable the confident detection of all of the aforementioned features, while the atmospheres of warm sub-neptunes and super-earths could be precisely characterized with as little as a single observation – enabling both in-depth characterizations of dozens of nearby potentially habitable planets and broad statistical analyses of the atmospheres of hundreds of larger planets.

These models are optimistic in that they do not include systematics and neglect effects of limb darkening and spectral contamination from the host star, but they demonstrate the potential of the Nautilus misson. In comparison, detailed modeling by [26] suggests that $\sim$20–100 transit observations with JWST would be required to detect the infrared signatures of H_2O and CO_2 in the atmospheres of planets in the TRAPPIST-1 system. In contrast, Nautilus will offer greater sensitivity in the 0.5–1.7μm wavelength range, significantly reducing the number of required transits.

3 Technical Overview

Nautilus will provide powerful light-collecting capabilities for high signal-to-noise visual/near-infrared spectroscopy and imaging. Nautilus will utilize a simple and robust telescope architecture with paradigm-changing light-collecting power at relatively low cost.

Simple, Low-cost Design: The driver of the design of the Nautilus is to maximize the ratio of sensitivity (light-collecting area and throughput) to cost. The Nautilus combines a simple, non-cryogenic instrument (imager and slitless spectrograph) with a new, lightweight, and low-cost

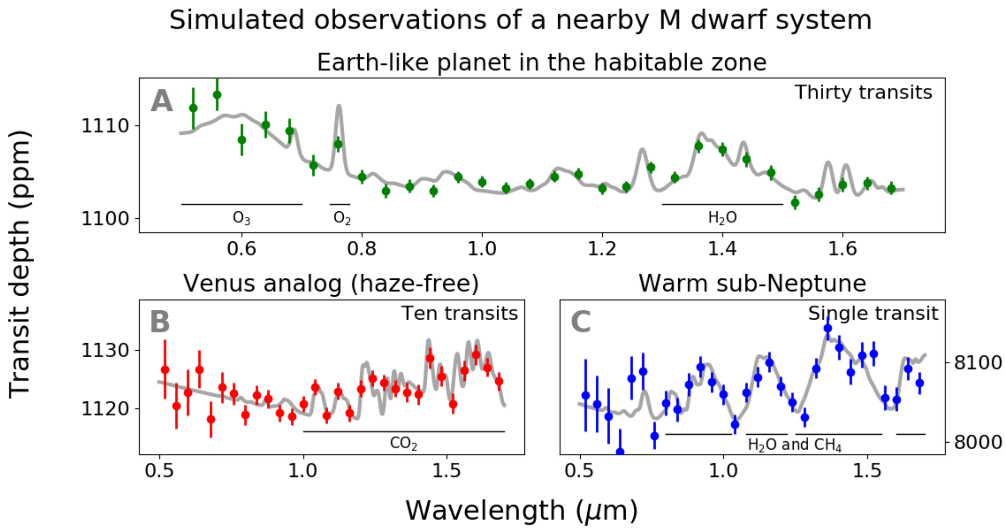


Figure 3: Nautilus will enable the study of exoplanet atmospheres with unprecedented detail, as demonstrated by these simulated transit spectra (binned for visibility). Through combined observations of several transit events, H_2O and O_3 absorption bands could be resolved in nearby potentially habitable planets, or CO_2 and H_2O in post-runaway atmospheres. With single transit observations, high signal-to-noise spectra could be achieved for several sub-neptunes and nearby super-earths.

optical element instead of primary mirrors.

Replacing Primary Mirrors with Ultralight Diffractive Lenses: Nautilus will use an 8.5m-diameter multi-order diffractive engineered material lens (MODE lens) instead of a primary mirror. These diffractive lenses have ∼100× lower areal density than traditional mirrors, are 100–1,000× less sensitive to misalignments (drastically reducing fabrication and integration costs), and can be cost-effectively replicated (via pressure molding). MODE lenses have been recently developed by our team: these lenses are enabled by revolutionary progress in optical free-form fabrication and high-fidelity pressure molding of low-temperature optical glasses.

Mission Architecture: Nautilus will be launched in a compact configuration to minimize launch volume. Once in orbit the telescope will use an inflatable balloon to deploy the MODE lens (see Figure 4) and lock-in struts will be used to stabilize the lens at its nominal position. Focusing and alignment of the instrument will be achieved through a tip-tilt and focusing mechanism in each arm (visual and near-infrared) of the instrument. Power will be provided by a flexible solar cell film with space heritage. High-precision pointing will be provided by reaction wheels. Thrusters will be used to offload the accumulated angular momentum. More details on the telescope design are provided in Apai et al. [1].

Nautilus Visual-Near-infrared Imager and Spectrograph (NAVIIS): Nautilus will use a single instrument, the Nautilus visual/near-infrared imaging spectrograph (NAVIIS). At this point no optical design exists yet for NAVIIS, but in the following we describe the preliminary concept for this instrument. NAVIIS will utilize a dichroic mirror to split the incoming light into the visible light (NAVIIS-VIS, 0.5–0.95 μm) and near-infrared (NAVIIS-NIR, 0.95–1.7 μm) channels. Each channel will include a diffractive color corrector optimized for the 8.5m MODE lens *and* for the bandpass of the channel (VIS or NIR). With the diffractive color corrector each channel will provide close to diffraction-limited imaging performance (1-3× diffraction limit, see Apai et al. [1]

for spot diagrams). In each channel two filter wheels will allow the use of narrow, intermediate, and broad-band filters, as well as grisms for low- and medium-resolution spectroscopy. The lightpath of each channel will also include a tip-tilt and a focus mechanism and an internal flat field and flux calibration source.

Due to its operational wavelength range ($<1.7~\mu$m) and the instrument's operating temperature, NAVIIS will not require cryogenic cooling. It will use a simpler thermoelectric cooling mechanism with a cold pupil and cold shroud to ensure low thermal backgrounds for the infrared observations.

The NAVIIS-VIS and NAVIIS-NIR channels will use 2K×2K detectors with matched fields of views of 15'×15', allowing simultaneous imaging of the same field in visual and near-infrared wavelengths, as well as continuous 0.5–1.7 μm spectral coverage for the time-resolved spectroscopy (e.g., transits).

Instrument and Spacecraft Requirements: See Table 1.

Table 1: Science requirements and design solutions.

SCIENCE OBJECTIVE	PERFORMANCE REQUIREMENT	DESIGN
Detect O_2, O_3, H_2O in M-dwarf exo-earth at 15pc		
	3 ppm-level photometric precision	D=8.5m Aperture High-efficiency instrument Earth-Sun L2 Orbit
	Pointing stability <0.2"/hr	Four reaction wheels
	Wavelength range: 0.5– 1.7 μm	VIS + NIR channels
	Spec. Resolving Power>100	VIS and NIR Grisms
	Continuous Obs. >24 h	Earth-Sun L2 Orbit
Observe 1,000 transits to establish exoplanet diversity		
	15,000 h of transit observations	Mission Lifetime > 5 yr
Search for and characterize optical counterparts of transients		
	FOV 15'×15'	VIS+NIR 2K×2K detectors
	Image resolution <100mas	Color-corrected optics
	Broadband filters	Two filter wheels

Technical Resources and Margins: Our UA team has significant resources at its disposal for the design, development and fabrication of MODE lenses (e.g., Moore Nanotech diamond-turning machine, precision pressure molding facility), metrology equipment used for 8m-class telescope optics, medium-sized thermal-vac facility, and additional payload integration and testing facility is under development.

Launch Requirements and Launch Vehicles: The science objectives of Nautilus require uninterrupted observing windows and high thermal stability, making the Sun-Earth L2 orbit the ideal orbit. The large diameter of the MODE lens (D=8.5m) restricts the choice of fairings and, correspondingly, it will require as launch vehicle either the SpaceX/BFR or NASA SLS B2. The dynamical envelopes of both planned fairings can accommodate payloads of up to 9m in diameter, enabling the launch of Nautilus. The launch could be shared with other payloads with compatible orbits. We note that a smaller diameter, less capable version of Nautilus (∼3.5m lens diameter) could be launched with New Glenn or Falcon-Heavy; these may also enable launching multiple Nautilus units simultaneously.

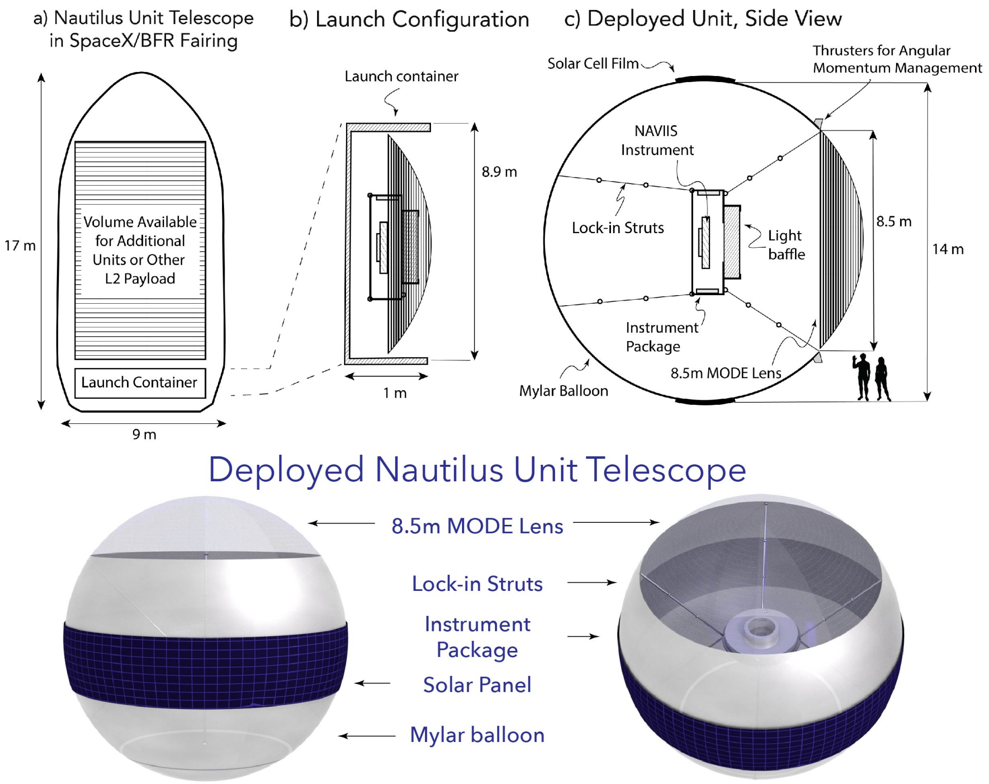


Figure 4: Nautilus is launched in a compact configuration and, once in orbit, it uses inflatable structure to deploy the MODE lenses. Volume and mass capacity in next-generation heavy launcher fairings will allow simultaneous launch of over a dozen Nautilus units, if desired [1].

LARGE TELESCOPE WITH A COST ADVANTAGE

MODE lenses have the potential to greatly reduce the cost of space telescopes because:
(a) As transmissive optics, MODE lenses are 100–1,000× less sensitive to misalignments and deformations than reflective optics, leading to greatly increased tolerances in the optical telescope assembly.
(b) MODE lenses have 100× lower areal density than traditional telescope mirrors, thus enabling lower-weight support structures and lower launch costs.
(c) Their greater tolerance to misalignments also greatly reduces the costs of testing and integration.
(d) MODE lenses can be fabricated quickly and cost-effectively via diamond turning and pressure-molding.

4 Setting the Stage for an Array of Replicated Telescopes

The Key Step toward the Nautilus Space Observatory: In [1] we described a concept in which multiple (~35) identical Nautilus Unit Telescopes are used as a non-coherent telescope array (i.e., digitally combining intensity measurements). We showed that such an array may reach the light-collecting power (i.e., sensitivity) of a *50m-diameter space telescope* – a true gamechanger for all branches of astrophysics. Such an array could, for example, survey 1,000 transiting exo-earth candidates for atmospheric biosignatures [1]. Built from identical, relatively simple units launched in just two launches, the Nautilus Space Observatory could provide an orders-of-magnitude increase in sensitivity at a cost comparable or lower than LUVOIR. The Nautilus Unit Telescope described here not only provides revolutionary capabilities for high-sensitivity spectroscopy and imaging, but also demonstrates a powerful feature of the Nautilus concept: once a Unit Telescope is operating, it can be replicated at lower cost, enabling the Nautilus Space Observatory.

5 Technical Drivers

The idea underpinning Nautilus is to build a very sensitive, but otherwise simple and low-cost space telescope, whose sensitivity can be further increased and its per-unit cost can be further decreased through replication. Nautilus could be thought of as a giant "light bucket", but one with an image quality on par with HST.

Large-scale Diffractive Optic: The potential of *diffractive* optics to provide ultralight, low-cost, and easy-to-replicate replacements of telescope primary mirrors has been recognized for over two decades [e.g., 18]. Multiple projects made progress toward this goal (e.g., LLNL's Eyeglass concept, [19], and Ball and DARPA's MOIRE project, [3], see Figure 5). However, these advanced yet optically simple designs had two important shortcomings for astrophysical applications: large chromatic dispersion and very long focal lengths.

Our team has invented MODE lenses, a new type of advanced multi-order diffractive lens and diffractive color corrector system that, for the first time, enables fast ($\sim$f2) diffractive lenses with excellent chromatic properties [31, 30, 1]. Nautilus utilizes optical free-form fabrication through ultra high-precision diamond turning [23, 17] that – in combination with precision glass compression molding [16, 32] – enables the *cost-effective fabrication and replication* of large-scale diffractive optical elements (see Figures 5 and 7).

Current Status: At the heart of the Nautilus concept is the MODE lens technology, which is currently at TRL2.5. Further development of MODE lenses to TRL4 (by Dec 2020) is funded by the Gordon and Betty Moore Foundation. The current focii of our work are: (a) maturation of the design and fabrication of the MODE lens technology (advancing small-scale MODE lenses toward TRL7); (b) scaling up the largest currently available optical pressure-molding equipment to diameters $>$1m.

Our Nautilus concept is currently at a low conceptual maturity level. We have demonstrated that multiple viable technical solutions exist for all challenges unique to MODE-lens-based telescopes [1], but no detailed trade studies have been carried out.

Technology Maturation Pathway: We envision the following steps for MODE lens technology maturation: (a) fabrication and on-sky demonstration of a 0.24m-diameter telescope built from replicated glass MODE lens segments (by Dec 2020, funded by the Moore Foundation). (b) Launch of two high-altitude balloon-borne MODE-telescope demonstrators (by 2024). (c) Scaling up current optical free-form fabrication and pressure-molding facilities to 8.5m diameter (by 2024). We have funding for step (a) and we are seeking funding for steps (b) and (c).

Figure 5: **(a)** 5m diameter Eyeglass prototype using 72 single-order diffractive optical elements [18]. **(b)** MOIRE test segment, using single-order diffractive optics lithographically replicated to membranes [3]. This DARPA-funded project aims to create low-cost, ultralight, 25m-diameter space telescopes. **(c)** MODE lens prototype developed by our team [1]. MODE lenses provide much broader wavelength coverage and enable faster optical systems than single-order diffractive lenses.

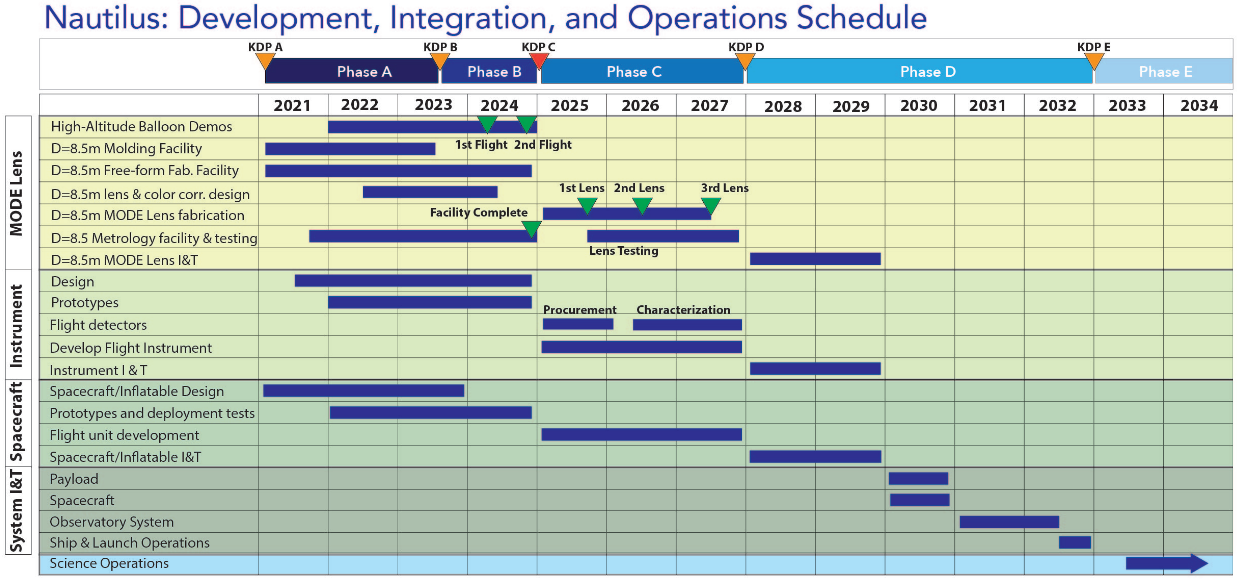


Figure 6: Project schedule for Nautilus.

6 Organizations, Partnership, Current Status

Participating Organizations: The lead institution is The University of Arizona (UA). UA's Steward Observatory (UA-SO) and Lunar and Planetary Laboratory (UA-LPL) have long heritage in the development of space telescope and space mission instrumentation (e.g., HST/NICMOS, Spitzer/IRAC, JWST/NIRCAM, JWST/MIRI, OSIRIS-REx). UA faculty will lead the Nautilus science team. UA's College of Optical Sciences (UA-COS) has extensive experience in design, fabrication, and testing of both diffractive optics as well as large-scale mirrors (UA Mirror Lab), and will lead the design, fabrication, and testing of the MODE lenses. Northrop-Grumman Aerospace Systems (NGAS) is a possible industrial partner. NGAS Chief Engineer Arenberg has been involved in Nautilus since its inception. We plan to partner with one or more NASA Centers.

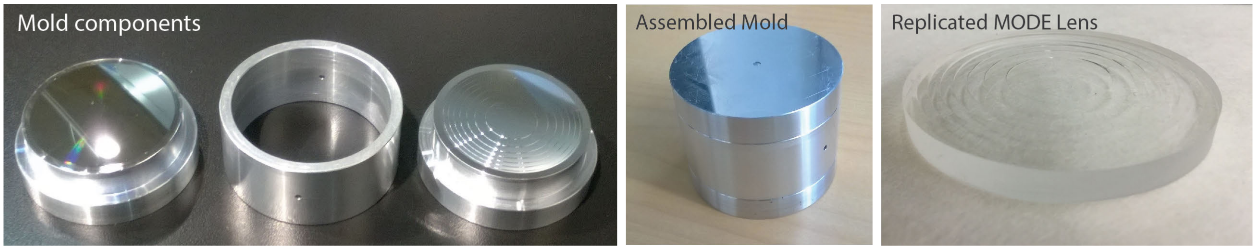


Figure 7: Mold-replicated diffractive lenses at the University of Arizona College of Optical Sciences, developed by our team. The mold is produced via diamond milling, the optical design of the MODE lenses provides nearly diffraction-limited image quality over a broad wavelength range with negligible chromatic aberration. The MODE lenses can be readily and very cost-effectively replicated. From [1].

Partnership: We are in the early formulation stage and the partnership is evolving. The management and science teams will be lead by UA-SO and UA-LPL. Project management will be provided by a NASA Center. The technology development and fabrication (including testing and integration) of the MODE lenses will be led by UA-COS.

Possible Partnership with DARPA: DARPA has a long-standing interest in ultralight and flat optics and has made major investments in this field. For example, their MOIRE project has demonstrated high-quality narrow-band imaging with meter-scale, membrane-based (ultralight) diffractive optics [3] (see Fig. 5). MOIRE aims for a 25m space telescope. DARPA's THEIA program aims to develop large (meter-scale) flat optics (width <1cm) to revolutionize ground- and space-based telescopes for a variety of uses. Several short-term goals of the THEIA program are close match to the technology development steps envisioned for Nautilus.

Current Status: Our core team at UA has technology development funding until Dec 2020 for optical design and maturation of MODE lenses.

7 Schedule and Cost Estimate

The tentative schedule for the Nautilus project is shown in Figure 6. Assuming funding can ramp up from 2021 for the mission design, facility development, and technology maturation, the launch is projected for 2032.

Cost Category: We believe that Nautilus will fit well in the medium ($500–$1.5B) category. Our team is developing a detailed cost model on the basis of design-to-cost approach. In short, our model allocates cost to each step as a probability distribution, and tracks our confidence level in these assessments. Confidence levels of costing relationships are increased through cost validation. Equipped with this cost model, the entire design process will be able to predict the probability distribution of the final total project cost. In the design-to-cost approach, project costs are a clear and paramount requirement, similar to any technical requirement. Our team is preparing a publication on this approach and examples of its implementation.

In summary, Nautilus will address one of the most important questions in modern astrophysics by providing the first extensive, high-quality spectral atlas of small exoplanet atmospheres. Importantly, Nautilus will also transform astrophysics through its paradigm-breaking, scalable, and ultralight technology.

Acknowledgements: We acknowledge support by the Gordon and Betty Moore Foundation.

References

[1] Apai, D., Milster, T. D., Kim, D. W., et al. 2019, Astronomical Journal, in press, arXiv:1906.05079

[2] Apai, D., Banzatti, A., Ballering, N. P., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 475

[3] Atcheson, P., Domber, J., Whiteaker, K., et al. 2014, in , Vol. 9143, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, 91431W

[4] Ballard, S. 2019, Astronomical J., 157, 113

[5] Barclay, T., Pepper, J., & Quintana, E. V. 2018, Astrophys. J. Suppl., 239, 2

[6] Barnes, R., Shahar, A., Unterborn, C., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 561

[7] Charbonneau, D., Berta, Z. K., Irwin, J., et al. 2009, Nature, 462, 891

[8] Checlair, J., Abbot, D. S., Webber, R. J., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 404

[9] Ciardi, D., Bean, J., Burt, J., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 322

[10] Dittmann, J. A., Irwin, J. M., Charbonneau, D., et al. 2017, Nature, 544, 333

[11] Ehrenreich, D., Vidal-Madjar, A., Widemann, T., et al. 2012, Astron. Astrophys., 537, L2

[12] Gelaro, R., McCarty, W., Suárez, M. J., et al. 2017, Journal of Climate, 30, 5419

[13] Gillon, M., Triaud, A. H. M. J., Demory, B.-O., et al. 2017, Nature, 542, 456

[14] Greene, T., Batalha, N., Bean, J., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 61

[15] Hu, R., Friedson, A. J., Sotin, C., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 559

[16] Huang, C.-Y., Chen, C.-C., Chou, H.-Y., & Chou, C.-P. 2013, Optical Review, 20, 202

[17] Huang, C.-Y., & Liang, R. 2015, Applied Optics, 54, 6979

[18] Hyde, R. A. 1999, Applied Optics, 38, 4198

[19] Hyde, R. A., Dixit, S. N., Weisberg, A. H., & Rushford, M. C. 2002, in , Vol. 4849, Highly Innovative Space Telescope Concepts, ed. H. A. MacEwen, 28

[20] Kataria, T., Zellem, R. T., Fortney, J. J., et al. 2019, Astro2020: Decadal Survey on Astronomy and Astrophysics, 2020, 462

[21] Kopparapu, R. K., Hebrard, E., Belikov, R., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 12

[22] Krissansen-Totton, J., Arney, G. N., Catling, D. C., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 158

[23] Lee, W. B., & Cheung, B. C. F. 2003, Surface generation in ultra-precision diamond turning: modelling and practices, 1st edn. (John Wiley & Sons)

[24] Lopez, E., Airapetian, V., Christiansen, J., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 522

[25] Lunine, J., Greene, T., Beichman, C., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 15

[26] Lustig-Yaeger, J., Meadows, V. S., & Lincowski, A. P. 2019, Astronomical J., 158, 27

[27] Marley, M., Lewis, N., Arney, G., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 345

[28] Mazin, B., Artigau, E., Bailey, V., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 128

[29] Miller-Ricci, E., & Fortney, J. J. 2010, Astrophys. J. Letters, 716, L74

[30] Milster, T. D., Apai, D., & Johnson, L. C. 2018, A multi-order diffractive Fresnel lens (MOD-DFL) and method for enhancing images that are captured using the MOD-DFL, U.S. Provisional Pat. Ser. No. 62/695,531

[31] —. 2018, A multi-order diffractive Fresnel lens (MOD-DFL) and systems that incorporate the MOD-DFL, U.S. Provisional Pat. Ser. No. 62/691,892

[32] Nelson, J., Scordato, M., Schwertz, K., & Bagwell, J. 2015, in , Vol. 9633, Optifab 2015, 96331L

[33] Ramirez, R., Abbot, D. S., Fujii, Y., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 31

[34] Rauer, H., Catala, C., Aerts, C., et al. 2014, Experimental Astronomy, 38, 249

[35] Robinson, T. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 356

[36] Villanueva, G. L., Smith, M. D., Protopapa, S., Faggi, S., & Mandell, A. M. 2018, J. of Quant. Spect. & Rad. Trans., 217, 86

[37] Villanueva, S. J., Dragomir, D., & Gaudi, B. S. 2019, Astronomical J., 157, 84

[38] Wang, J., Meyer, M., Boss, A., et al. 2019, in Bulletin of Astron. Astrophys., (Astro2020 White Paper),, Vol. 51, 200