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Very Large-diameter, Ultralight Space Telescopes to Enable Large-scale Survey of Candidate Earth-like Planets for Signatures of Life

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With the ongoing discovery of thousands of planets around other stars, the question of whether life exists on other worlds is not only compelling but is becoming answerable. However, due to the faintness of these distant worlds, a bold new generation of space telescopes, building on new technologies, is a must to search for signatures of life. We present a revolutionary space observatory concept, the Nautilus Space Observatory, designed to survey a thousand planets for atmospheric gases that are indicative of life. Nautilus is enabled by a new technology of hybrid (diffractive-refractive) lenses, which provides very large-aperture (8m-class) space telescopes that are ultralight and can be cost-effectively reproduced. We briefly describe here the new lens technology, the Nautilus Space Observatory concept, ongoing technology and concept development work, and also introduce the Nautilus Probe, a first, stand-alone science and demonstration unit proposed to the Astro2020 Decadal Survey.

I. Search for Atmospheric Signatures of Life

State-of-the-art observational techniques have enabled astronomers to detect extrasolar planets – planets orbiting other stars – in rapidly growing numbers (>4,000, *). There is now strong statistical evidence that Earth-sized planets that are potentially *habitable* (liquid water could exist on their surface) are likely common in the Galaxy. However, as extrasolar planets are intrinsically faint and difficult to study due to the extreme planet-to-star contrasts, very few of the planets discovered have been studied in detail. In particular, the smallest planets (similar in size to Earth or smaller) pose great observational challenges and their nature remains very poorly understood.

An efficient technique for analyzing the atmospheric composition of extrasolar planets is to observe systems in which the planet is seen passing in front of its host star due to the alignment of its orbital plane with the sightline to the system. During such *transit events* – as the planet passes in front of its host star – starlight filters through the planet's atmosphere, enabling the characterization of its atmosphere via transmission spectroscopy [e.g., 1]. However, as the projected size of the planet's atmosphere is small with respect to its host star, the typical spectral modulations in this configuration are small (ppm-level) and remain very challenging for terrestrial exoplanets[2].

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It is not just the detection itself that is challenging: Deducing the presence of life from atmospheric composition is very challenging and has never been done before. Confidently identifying atmospheric gases as signatures of life requires robustly excluding their abiotic nature [e.g., 3–5]. This is particularly difficult for systems potentially as complex as Earth, and with the limited information available from remote sensing [e.g., 6]. Thus, achieving confident identification of life will likely require comprehensive studies of a very large number of candidate Earth-like planets (exo-Earths), which will provide context for the interpretation of candidate life-bearing worlds [e.g., 6–9].

The upcoming James Webb Space Telescope is unlikely to be able to efficiently search for atmospheric signatures of life (such as O_2) in even a small set of transiting, potentially habitable planets [2]. Exploratory mission concept studies have been conducted – building on the architectural heritage of existing space telescopes – with the primary goal to explore and study habitable worlds [10, 11]. However, the yields of even the most ambitious of these missions is expected to be no more than about 30–60 habitable worlds – a far cry from the many hundreds we will likely need to develop a robust understanding of their nature and diversity. No extension of the current space telescope paradigm can conceivably deliver a sample size of a thousand worlds.

To understand the diversity of habitable worlds and to search for life on these planets, a much larger space telescope must be constructed than is possible with the current technological paradigm. Thus, we have been compelled to explore pathways toward a new paradigm in space telescope technology, with a focus upon one that will enable a fundamental change in the cost vs. diameter profile [e.g., 12] that past and current space observatories have followed. Here we present a new optical technology and a new telescope architecture which, in combination, are projected to greatly decrease mission costs and risks.

II. The MODE Lens Technology

Perhaps the most fundamental element of any space telescope is its primary mirror, which collects and focuses light. All else being equal, larger mirrors collect more light and provide higher spatial resolution (i.e., diffraction-limited resolution) images than smaller mirrors; yet, mirror diameter has been arguably the most slowly-increasing key performance indicator of telescopes (~ 2.5× increase over ~25 years). Mirrors are very expensive to fabricate (requiring complex grinding, polishing, testing, and coating cycles), challenging (and expensive) to align (e.g., co-phasing them), and keeping them in alignment is often a critical driver of optical telescope assembly's metrological tolerance requirements. Due to these factors, mirrors and their related requirements impact a large fraction of a modern observatory's mass, cost, and risk budgets and their fabrication, testing, and integration schedules.

We sought to find an alternative technology with more favorable properties for space telescope applications. We describe here a new technology invented [13, 14] and developed by our team with the specific goal to change the current paradigm of space telescope design, fabrication, and launch. The novel technology underpinning the telescope design described in this paper is a hybrid diffractive-refractive "multi-order diffractive engineered material" (MODE) lens (Figure 1). MODE lenses combine front and back optical surfaces that are themselves diffractive optical elements, and integrate these with the refractive nature of the lens' main body. Thus, a MODE lens is, in essence, a three-element-integrated lens. With chromatic dispersion varying in the opposite sense (i.e., self-compensating) between the diffractive and refractive components, it becomes advantageously possible to design such lenses with excellent image quality and very good achromatic properties [15]. In fact, the first prototype lenses already demonstrate nearly diffraction-limited performance over spectral bandwidths of ~20 percent. [15].

MODE lenses provide multiple key advantages over conventional telescope primary mirrors, including:

1) ~100× thinner than conventional refractive lenses,
2) ~100× lower mass to surface area ratios,
3) 100–1000 larger tolerances to misalignments/deformations,
4) shaping through controlled, direct & local process (i.e., single point diamond turning), not cycles of grinding/polishing,
5) cost-effective replication through a molding process, and
6) the enabling of simple dispersive instruments (e.g., a single-element spectrograph).

Thus, MODE lenses can provide very high optical quality images in an exceptionally flat (~1–5mm thick) envelope, and over very large diameters (~8m).

By reducing launch cost, simplifying the fabrication, testing, and integration phases, and relaxing requirements on the optical telescope assembly and the spacecraft itself, MODE lenses favorably impact many aspects of the cost, mass, and risk budgets of space telescopes. Therefore, MODE lenses provide a revolutionary alternative to conventional mirror-based large space telescopes. Furthermore, given the continuing decline in launch costs, it is plausible that small

(< 0.5m diameter) MODE-based space telescopes could be affordable to university consortia (or even to individual major universities) within the next ten years.

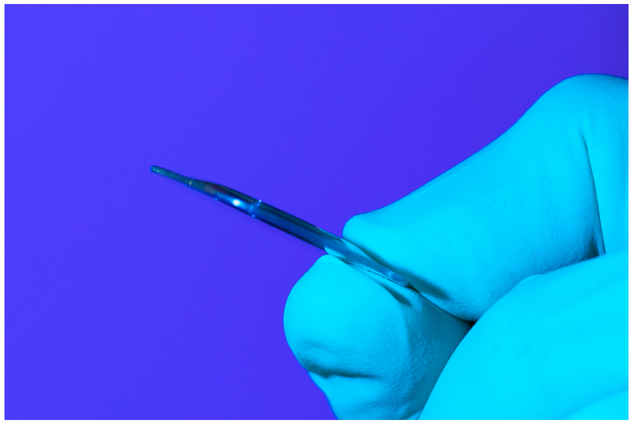

Fig. 1 Prototype MODE lens fabricated at The University of Arizona. Although only 2–5 mm thick, MODE lenses combine two diffractive and one refractive optical element. In essence, they are ultralight, high-performance, three-element-integrated lenses that can be cost-effectively replicated.

Technology Transfer: The MODE technology developed for the Nautilus Probe and Nautilus Space Observatory concepts has the potential to impact or revolutionize other space-based applications, primarily in the areas of remote sensing, laser communications, and compact imaging systems, where ultralight optics are important.

III. The Nautilus Space Observatory Concept

The MODE lens technology thus enables ultralight and very large aperture telescope optics. In the following, we describe the Nautilus Space Observatory concept (described in detail in [7] and [16], project website: `https://nautilus-array.space`), which utilizes an *array* of ultralight space telescopes to provide, in incoherent combination (i.e., digitally co-adding the measured light intensity), the light-collecting power equal to a 50m diameter aperture space telescope; i.e., two orders of magnitude larger than that of the upcoming James Webb Space Telescope. The increased sensitivity, in turn, can be used to survey hundreds – with the goal of up to a thousand – exo-Earth candidates.

Each Nautilus unit telescope will be equipped with an 8.5m-diameter primary MODE lens, compatible with the internal dimensions of the SpaceX/Starship cargo fairing. The light-gathering power of even a *single* Nautilus unit telescope will be significantly greater than the combined light-gathering power of ESA's ARIEL space telescope, the Hubble Space Telescope, *and* the James Webb Space Telescope (see Figure 2).

In order to greatly reduce costs and risks while building up the large collecting area of a space telescope with a minimum number of launches, the Nautilus unit telescope is designed to enable efficient replication. In other words, the spacecraft, instrument package, optical telescope assembly, etc. are kept simple and optimized for efficient light-collection and spectroscopy. All unit telescopes will likely be identical, providing resilience to the observatory through redundancy.

The Nautilus unit telescopes are launched in a compact configuration and, once in orbit, deployed via the use of inflatable elements (see Figures 3 and 5). (Inflatables are identified to provide low-cost and robust single-use deployment, but are not a critical part of the mission architecture.) Once deployed, each unit telescope can function independently but, during planetary transit events, all can turn toward the same targets to collect signal simultaneously. The relative locations of the unit telescopes are unimportant: no formation flying or special alignments are required, as long as most units can view the target. Each unit will be equipped with at least one science instrument, an imager/low-resolution spectrograph with a visible and near-infrared arm.

We estimate that building up the 50m-diameter-equivalent light-collecting power will require 2–4 launches with the SpaceX/Starship or NASA SLS B2 launch systems, allowing the deployment of all 35 replicated Nautilus units (see Figure 3), and, potentially, additional back-up units.

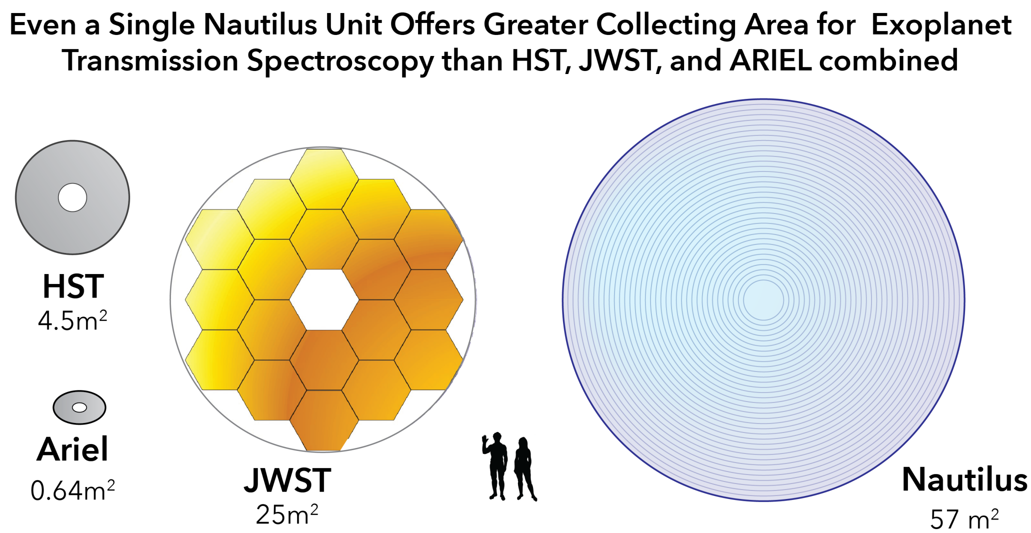

Fig. 2 Comparison of the relative aperture sizes of ESA's ARIEL mission, the Hubble Space Telescope, the James Webb Space Telescope, and a single Nautilus unit telescope. Even a single Nautilus unit telescope has more light-collecting power than that of ARIEL, HST, and JWST *combined*.

IV. The Nautilus Probe Concept

With its 35 units and vast light-collecting power, the Nautilus Space Observatory is a Flagship-class concept. As an intermediate step we proposed to the ongoing National Academy of Sciences' Astro2020 Decadal Survey the development of a *Nautilus Probe*, a Probe-class (~$800M) mission that can be developed in parallel with a Flagship mission. (For a detailed description of the Nautilus Probe, see Apai et al. [17].) The Nautilus Probe could be used as a full-scale and full-capacity verification of the unit telescopes that make up the Nautilus Space Observatory; but it would be primarily a science mission. Providing greater sensitivity in the visible–near-infrared regime than the Flagship-class James Webb Space Telescope, the Nautilus Probe would revolutionize the study of extrasolar planets, time-domain astronomy, and studies of faint objects (from small asteroids through Kuiper-belt Objects to the high redshift quasars in the distant universe).

Identical to the Nautilus Space Observatory units, the Nautilus Probe will be equipped with an 8.5m-diameter MODE lens. The Nautilus Probe's focus is to provide a platform for ultra-precise transmission spectroscopy of transiting extrasolar planets. The Nautilus Probe will be equipped with a single instrument, NAVIIS, a visible–near-infrared imager and low-resolution spectrograph. This will enable – for the first time – the exploration of the diversity of broadly Earth-sized worlds through the study of a very large number (~1,000) of small (1–2 Earth radii) planets. For example, the Nautilus Probe could determine how common Venus analogs with post-runaway atmospheres are, study the frequency and tidal migration of terrestrial moons, and begin to probe the atmospheres of the closest Earth-sized habitable zone planets (for strong signals such as Rayleigh scattering, ozone absorption, and potentially water vapor).

The Nautilus Probe concept is currently under consideration by the Astro2020 Decadal Survey; if technology and concept development are supported as proposed and remain on track, launch is foreseen within nine years from the project start date.

V. Ongoing Technology and Concept Development

Our team pursues progress simultaneously in technology and mission concept developments, and in supporting cost/risk/duration studies. Our ongoing work includes:

MODE Lens Optical Design: Over the past three years our team has made great leaps in developing the optical design of the novel MODE lenses. This work resulted in numerous patents and publications [e.g., 13–15]. Our team developed and validated a variety of design and performance simulation tools. Current focus is on the impact of optical fabrication tolerances and optical performance, and on further stretching the wavelength range in which MODE lenses can reach diffraction-limited performance.

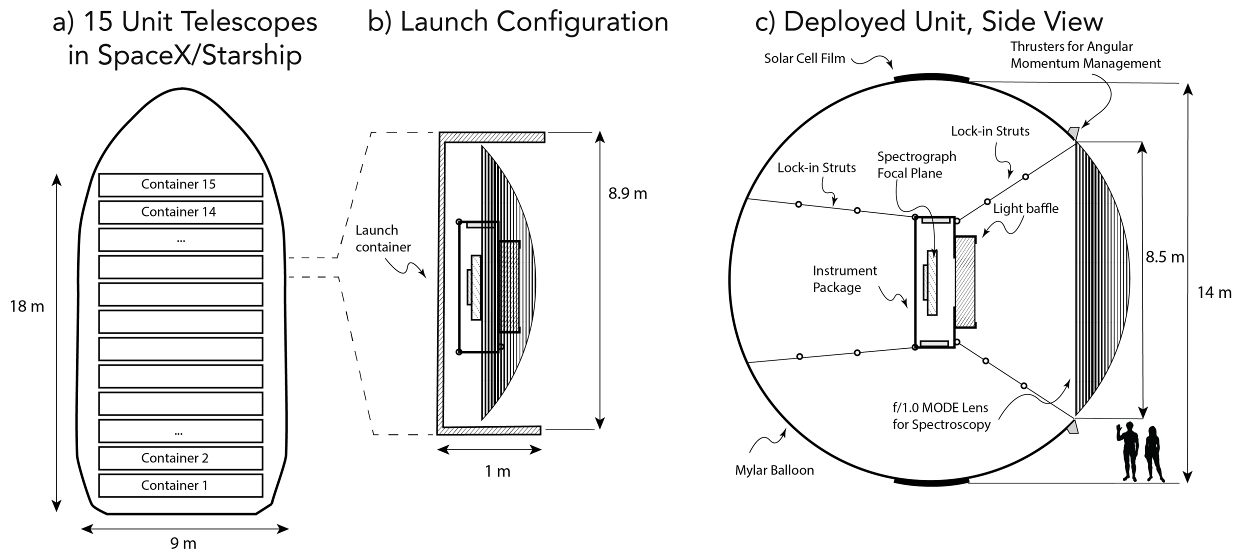

Fig. 3 A single SpaceX/Starship could launch up to 15 Nautilus units (a), which are launched in a compact configuration (b), and fully deploy (c) at the target orbit. As a cost-effective and robust deployment mechanism, an inflatable structure is envisioned but is not a critical part of the design. The units are identical and are not flying in formation, but are capable of observing the same target simultaneously.

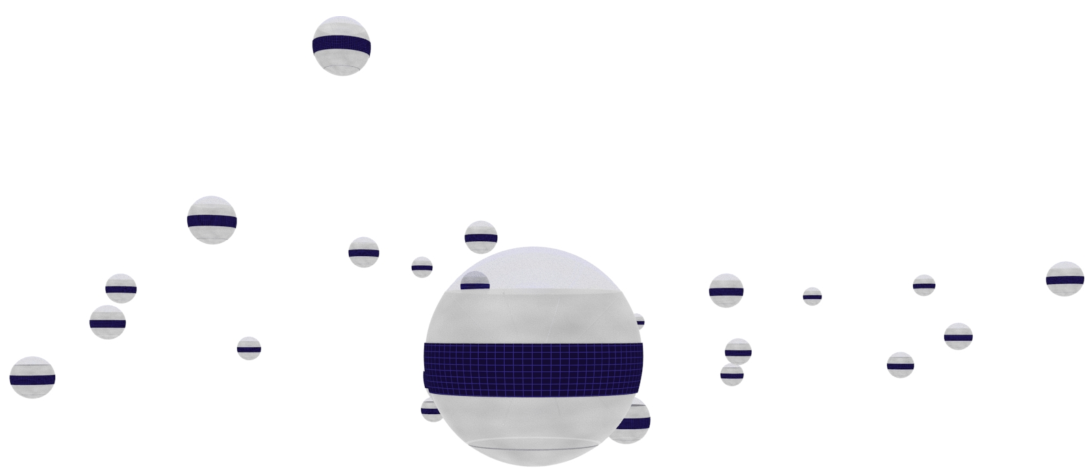

Fig. 4 An illustration of the Nautilus Space Observatory, which consists of identical telescope units (shared launch) that combine light incohorently, i.e., by digitally co-adding the measured intensity in the targeted astrophysical sources. The relative positions of the units is not important, as long as the target is visible to all units.

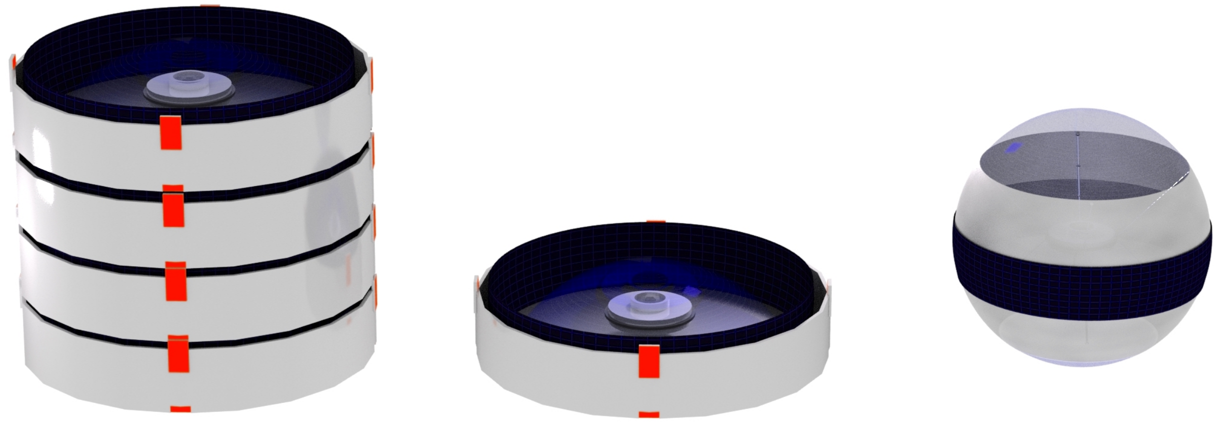

Fig. 5 Illustration of the stacked Nautilus launch containers (*left*), a single container with the telescope in compact launch configuration (*center*), and deployed flight configuration (*right*) The 8.5m MODE lens is visible at the upper end of the telescope units; the dark belt is a flexible, film-based solar cell unit.

MODE Lens Fabrication: Our team has fabricated and replicated multiple generations of MODE lenses, using PMMA (acrylic) and a number of low-temperature glasses. The fabrication combines optical freeform fabrication (via diamond turning) and optical glass molding. The current focus of our work is scaling up our 50mm diameter prototype lens to a segmented 240mm diameter lens. The completion of the 240mm diameter lens is expected for March 2021.

MODE Lens Alignment and Optical Performance Assessment: Our metrology team focuses on methodology and device development to align/co-phase and test MODE lenses and/or MODE lens segments. Multiple inventions and publications resulted from this work [e.g., 18, 19].

Laboratory Demonstration of MODE Lenses: We built up, carefully aligned, and tested a capable laboratory testbench, where the optical performance of the MODE lenses and prototype demonstration telescope can be measured within a known and well-characterized imaging system. This testbench is complete and in use.

On-sky Demonstration of MODE Prototype Telescope: We are close to completing a MODE observatory atop Mt. Lemmon at the UArizona's SkyCenter. At this site we plan to carry out a series of on-sky observations with a 0.24m-diameter MODE lens-based telescope, to demonstrate system-level performance under real-world conditions. Our observations will provide on-sky image quality and photometric stability characterization of the system. The telescope optical tube assembly, detector, and mount are ready and will be installed in a dome by December 2020, with the MODE lens installation expected for March 2021. On-sky tests are foreseen for April–May 2021.

VI. Conclusion

Undertaking one of the most ambitious steps in human history, probing Earth-size extrasolar planets for signatures of life, requires a bold new generation of space telescopes. The current space telescope paradigm does not scale favorably and we present here a paradigm-changing new-technology approach. We introduced a novel hybrid (diffractive-refractive) lens technology (MODE lenses) that enables the design, fabrication, and replication of ultralight and very large-aperture (8m-class) space optics. Adopting and exploiting this new technology we present a revolutionary new space observatory concept, the NASA Flagship-class Nautilus Space Observatory, and a precursor, the Probe-class Nautilus Probe.

The Nautilus Space Observatory, as an incoherent array of identical, replicated, ultralight, large-aperture space telescopes, represents a radical change in the way space telescopes are built. The Nautilus Space Observatory concept provides a resilient, scalable, and versatile observatory, where launch costs and risks are shared between many units in an array rather than concentrated in a single, unique unit. This concept makes use of the new generations of ultra-heavy launch systems (SpaceX, NASA SLS).

The Nautilus Space Observatory, as envisioned here, will provide light-collecting power equivalent to that of a 50m-diameter space telescope with an estimated cost within a Flagship-class mission, a feat that would be inconceivable with conventional space telescope technology.

In summary, the Nautilus Space Observatory concept is designed to search a thousand extrasolar Earth-candidates for atmospheric signatures of life, truly transforming our understanding and view of the nature of humanity and of the universe.

Acknowledgments

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