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Nautilus Observatory: a space telescope array based on very large aperture ultralight diffractive optical elements

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ABSTRACT

We describe a novel space observatory concept that is enabled by very large (8.5m-diameter), ultralight-weight multi-order diffractive lenses that can be cost-effectively replicated. The observatory utilizes an array of identical telescopes with a total combined light collecting area equivalent to that of a 50m-diameter telescope. Here we review the capabilities of a Nautilus unit telescope, the observatory concept, and the technology readiness of the key components. The Nautilus Observatory is capable of surveying a thousand transiting exo-earth candidates to 300 pc for biosignatures, enabling a rigorous statistical exploration of potentially life-bearing planets and the diversity of exo-earths.

Keywords: Diffractive Optics, Space Telescopes, Ultralight Telescopes, Extrasolar Planets, Nautilus Space Observatory, MODE Lens, Space Telescope Array, Atmospheric Biosignatures

1. INTRODUCTION

In this paper we present a novel space telescope concept that aims to provide a cost-effective solution for increasing the light-collecting area of telescopes by an order of magnitude compared to the state of the art. This jump is achieved by substituting primary mirrors – often one of the technically most challenging components of space telescopes – with very large-diameter diffractive lenses.

The single most important parameter of any visual-near-infrared space telescope is the diameter of its aperture (typically primary mirror). This parameter determines not only the telescope's diffraction-limited spatial resolution but – even more importantly – the amount of light it can collect. Yet, the increase in diameters of the largest astronomical telescope mirrors have been slow due to the challenges of the fabrication (grinding, polishing, structural support) and precision metrology of such large optical surfaces.

Large diffractive optics have been identified early as possible alternatives to primary mirrors for space telescopes. The Eyeglass project[1,2] aimed to develop technology to enable extremely large diameter (100m-class) space telescopes through a multi-element thin diffractive lens that is deployed in an origami-like fashion from its compact launch configuration. Ground-based tests of a 5m-diameter prototype have been successful.

Subsequently, the DARPA-funded MOIRE project[3] has developed diffractive lenses integrated on a membrane through lithography and UV-curing. The goal of the MOIRE project was to develop technology that enables 25m-diameter, ultralight space telescopes for observations of terrestrial targets.

These projects demonstrated the general feasibility of developing ultralight, flat optics. However, both designs suffered from strong chromatic dispersion and had impractically long focal lengths. The strong dispersion of these diffractive lenses is not necessarily a limiting factor for Earth observations, where shapes can be recognized in

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images taken with narrow-band filters. However, the exclusive use of narrow-band filters is inconsistent with most astrophysical applications, where sources tend to be very faint and wavelength-dependent information is often essential. Furthermore, the space lifetime of UV-cured polymers (used in the MOIRE project) is likely to be a limiting factor for astrophysical observatories.

Therefore, the question emerged whether the general principles that made the Eyeglass and MOIRE demonstrations successful could be extended to astrophysical applications – in other words, could an optical solution be found that can reduce chromatic aberrations and also lead to faster optical systems?

2. MODE LENSES

Our team has developed a new generation of diffractive lenses, which we call multi-order diffractive engineered-material (MODE) lenses.[4,5] With multiple diffractive surfaces, high harmonic orders (M=1000), and multiple zones, these diffractive-refractive lenses are able to suppress the chromatic error that is inherent to single-order diffractive lenses. The optical design and properties are detailed in an upcoming publication (Milster et al., in prep.), and we only focus here on simulated performance in the context of the Nautilus concept, also discussed in details in a separate publication.[6]

2.1 Advantages of MODE Lenses for Astrophysical Applications

MODE lenses offer multiple important advantages for astrophysical applications, although further technology development is required to fully realize these.

Low Areal Density: MODE lenses as thin as 1-4 mm can provide high-quality optical imaging performance. This flat format greatly reduces the weight of the lens and the supporting structure required – and, therefore, the net mass of the spacecraft, one of the cost drivers.

Tolerance to Misalignments: Our analysis shows that the quality of images formed by MODE lenses are 100-1,000× less affected by lens misalignments (tip-tilt, off-axis shifts, and rotation) than images formed by mirrors. This is not surprising, given that MODE lenses are transmissive rather than reflective optics. Importantly, the tolerance to misalignments translates to greatly relaxed requirements on the optical telescope assembly and, in some cases, to the entire spacecraft architecture. Thus, the greater tolerance to misalignments has the potential to greatly reduce the overall costs of the optical telescope assembly and the spacecraft itself.

Lighter and Lower-cost Telescope Structure: The lighter structure and the more relaxed tolerances not only benefit design, fabrication, and launch mass; they also have the potential to significantly reduce the integration and testing costs of the observatory. As integration and testing is a major (and expensive) project stage, this provides an additional important reduction in total project costs.

Fabrication through localized process and replication: MODE lenses are produced through optical free-form fabrication,[7,8] a process that is very different from the traditional multi-stage grinding-polishing approach large mirror fabrication requires.[9] Diamond-milling and diamond-turning allow highly precise, localized (∼18 nm typical spot size) fabrication of metals; direct cutting of PMMA is also possible. The combination of diamond turning/milling and high-precision optical glass molding[10,11] provides a powerful tool with the potential to fabricate – and replicate – large-scale precision optics, including those optimized for the infrared. Diffractive optical elements have, in fact, been replicated via precision molding.[12,13]

2.2 Current Status of the MODE Technology

Our University of Arizona-based MODE lens technology demonstration project has designed and fabricated multiple generations of prototype MODE lenses (see Figure 1). The lenses currently fabricated are small (25–50mm in diameter), but are ideal for understanding the details of the design and fabrication process. Our group has established an advanced optical testing and metrology environment in which the optical performance and surface quality of the MODE lenses are characterized.

Our team is currently working on creating a 0.24m-diameter MODE lens from low-temperature glass, suitable for optical high-precision molding. Our current approach calls for building the MODE lens from smaller segments, which are fabricated through replication (molding). Our design requires only three unique molds (center segment, first ring, second ring) to build up a 0.24m-diameter lens.

The free-form fabrication and the optical molding processes are both well-suited to also work at larger scales (1m-sized and above). However, at the moment – due to the lack of commercial interest in very large-scale optics – no diamond milling/turning and molding machines are available for such scales.

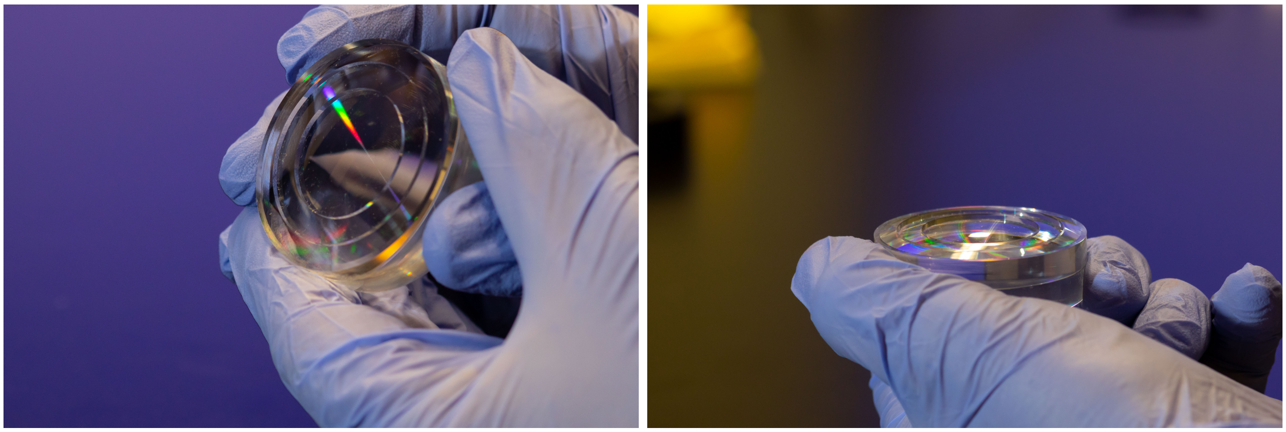

Figure 1. MODE lens prototype designed and fabricated by our University of Arizona team. This prototype has two diffractive surfaces (a front MODE surface and a traditional, single-order diffractive Frensel lens backsurface). The combination of the two diffractive surfaces and the refractive component results in a very favorable chromatic performance.

3. NAUTILUS UNIT TELESCOPE

We describe here the architecture of a novel telescope concept that builds on large-diameter (8.5m) MODE lenses. A cross-sectional view of the unit telescope in its launch and deployed configuration, and within the launch vehicle's fairing is shown in Figure 2.

The Nautilus unit telescope is optimized to provide very large collecting area at low-cost. Correspondingly, we prioritized simple and robust technical solutions over more complex (and therefore more risky and costly) solutions whenever the science requirements allowed it. The Nautilus unit telescope is launched in a compact configuration (Panel b of Figure 2). Upon reaching its target orbit the telescope (Sun-Earth L2 point), it uses a spherical inflatable structure (mylar balloon) to deploy the 8.5m-diameter MODE lens to its nominal position. Mechanical struts, which include dampers, extend and lock in as the lens reaches its final position. The MODE lens focuses light into the single science instrument of the telescope, NAVIIS (Nautilus Visual Infrared Imaging Spectrograph), which provides imaging and low-resolution spectroscopic capabilities in the 0.5-1.7μm band. The inflatable mylar balloon (with a 14m-diameter) is equipped with a flexible solar cell film band (with space heritage) that provides ample power for the unit's operation. High-precision telescope pointing and tracking is achieved through reaction wheels, and the accumulated angular momentum is periodically off-loaded through micro-thrusters positioned on the mount of the MODE lens.

The launch configuration of the Nautilus unit is vertically compact (flat): 8.9m in diameter and 1.0m in height. This compact packaging allows launching many Nautilus units with a single launch vehicle. For example, we estimate that the Space/BFR fairing may be able to launch over 15 units, while the NASA SLSB2 fairing may accommodate the launch of up to 25 units. Therefore, two launches of these vehicles would be sufficient to establish a 50m telescope-equivalent collecting area, a resource that will entirely transform astrophysics.

Even a single Nautilus Unit will lead to revolutionary progress in several fields of astrophysics, as we will review in Section 5.

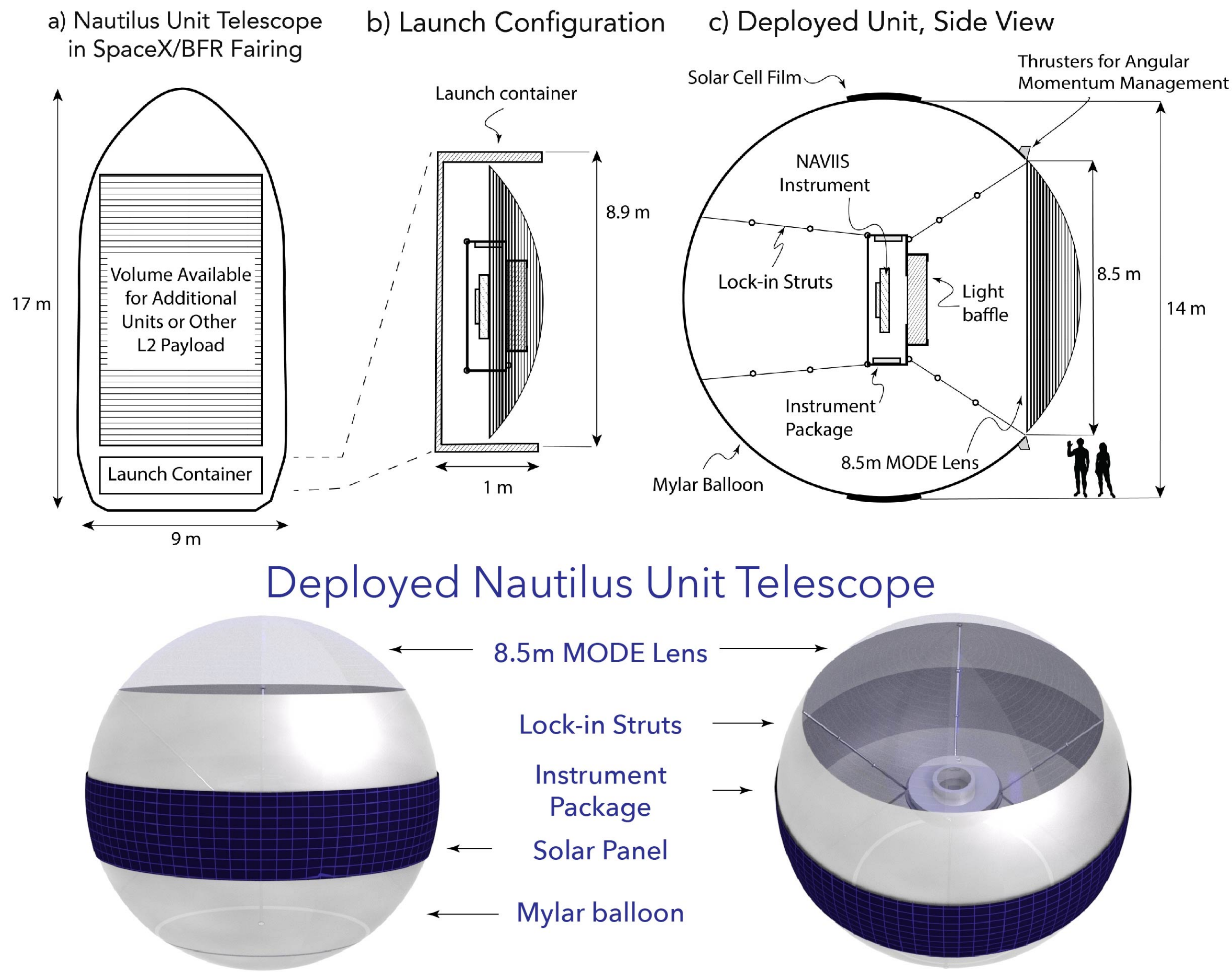

Figure 2. The Nautilus telescopes are launched in a compact configuration (b) and inflated in orbit (a). The inflation of the mylar balloon deploys the MODE lens (c). Due to the compact launch configuration, as many as 25 Nautilus units could be launched simultaneously in next-generation of fairings.

4. NAUTILUS SPACE OBSERVATORY

The unit telescope is very light-weight (for its size) and has a very compact launch configuration, which makes it possible to launch more than one unit. In fact, in the next generation of large fairings (SpaceX/BFR and NASA SLS B2) between 15–25 Nautilus units could be launched at the same time. This simultaneous launch and deployment capability, coupled with the Nautilus design in which the replicability is emphasized, makes it possible to envision a large, non-coherent array of space telescopes.

With just two launches of a SpaceX/BFR or NASA SLS B2, a telescope array with a combined collecting area equivalent to that of a 50m-diameter telescope could be built.[6] The array – which we call the Nautilus Space Observatory – will consist of fully self-contained telescopes that can be used for independent or coordinated observations. With an 8.5m-diameter collecting area, each of these units will have more light-gathering power than HST and JWST *combined* (see Section 5), allowing 35 different observations to proceed simultaneously. However, during an event of interest – such as an exoplanet transit – all units could point to the same target, carrying out simultaneous observations. These coordinated observations will allow combining the measured intensity (signal) from all units, ushering in a paradigm change in astrophysics: sensitivity that is 2-3 orders of magnitude larger than the current state-of-the-art.

Building multiple, identical units also represents a powerful strategy to *manage risks:* a telescope array with distributed functionality provides a resilient solution as a loss of any single unit telescope would not compromise the functionality of the entire array. This risk management approach, of course, impacts the tolerances and the cost profile of the observatory: it is fully expected that the resilience of the observatory will directly and indirectly translate into a greatly reduced total mission cost.

Finally, another fundamental advantage of the Nautilus Space Observatory is that it *allows for a much greater cost control*. Due to its natural scalability (expanding the array unit-by-unit), the costs are more predictable and can be better controlled than they can be for the traditional approach that aims to develop single unique units – essentially prototypes. A half-finished LUVOIR would be completely disfunctional but very expensive. In contrast, a half-finished Nautilus Observatory would still be a functional, revolutionary facilty.

5. SCIENCE WITH THE UNIT TELESCOPE

Even a single Nautilus unit telescope will provide a large improvement over the state–of–the–art sensitivity: more than twice the collecting area of JWST, the largest space telescope currently in development (see Figure 3). Correspondingly, the unit telescope has the potential to significantly advance multiple important branches of astrophysics.

The larger collecting area – and the corresponding increase in sensitivity – is particularly beneficial for two types of observations: time-domain astrophysics and the studies of the faintest objects. In the following we will briefly review the key questions in these topics without aiming for a complete description.

5.1 Faint Object Studies

The Nautilus unit telescope will significantly push the envelope on the detection and characterization of the faintest objects observable. With the same integration time, Nautilus will be able to study objects ∼3 stellar magnitudes fainter than HST. The ability to search for and characterize faint objects is desirable in multiple fields of astrophysics, including studies of minor bodies (e.g., asteroids, Kuiper belt objects), individual stars in local group galaxies, kilonovae and supernovae in intermediate-redshift galaxies, and active galactic nuclei at very high redshifts.

In addition to furthering existing fields of study, the greater sensitivity will likely open windows on new fields, too: for example, we envision that Nautilus will be able to study in detail the geysers of the Jovian moon Europa. While barely detectable currently with HST, Nautilus may be able to obtain low-resolution spectra of the ejecta and analyze those for absorbers, including organic molecules.

5.2 Time-domain astrophysics and Exoplanets

One of the most rapidly developing frontiers of observational astrophysics is time-domain astronomy. High-precision measurements of temporal intensity modulations in a broad variety of objects – rotational, expansive, and explosive – provide powerful and often-unique insights into physical processes that drive these temporal changes. The technical capabilities that enabled this revolution are greatly-improved detectors (often allowing intensity measurements at sub-percent-level precisions) and improved models of optical system thermo-mechanical temporal instabilities (essential for distinguishing systematics from genuine signals).

Very large apertures are *very* important for time-domain astrophysics: because the measurements characterize a signal that is *changing in time*, there is only a limited time window in which a high signal-to-noise ratio can be built up. Examples for time-domain astrophysics include studies of supernovae, cloud properties in rotating brown dwarfs and directly imaged exoplanets.[14–17]

Here we will highlight Nautilus's potential for characterizing extrasolar planets through the transit method, one of the most spectacular uses of time-domain astrophysical measurements. As planets pass in front of their host stars, the host stars' light filters through (and is partly blocked by) the planets' atmosphere. Through the temporal changes in the system's geometry (planet and star relative locations), the presence of different gas-phase absorbers in the planetary atmosphere will produce a spectrally-temporally modulated signal. High-precision observations of planetary transits (simultaneously at multiple wavelengths) have provided powerful tools to probe the compositions and properties of planetary atmospheres.[18–20]

The typical signals, however, are tiny as planets are much smaller than their host stars and the annulus of the planetary atmosphere that is semi-transparent (not optically thick and can thus be probed) is very small. Spectral modulations on the temporally modulated signal are typically are lower than 50ppm. Existing observations are usually only sensitive to the strongest features of the most observationally favorable exoplanet–star systems.

The Nautilus unit telescope will increase the sensitivity of transit observations (multiplied as unit telescopes are integrated into the Nautilus Space Observatory, Section 6) greatly expanding, greatly expanding the sample of planets that can be probed, as well as the the inventory of molecules that can be detected in them. A more rigorous exploration of the scientific yield must be done after the mission reaches a higher concept maturity level, but as an illustration of the type of observations a single unit telescope could provide we show simulated results in Figure 4.

We used the Planetary Spectrum Generator[21] to explore the transmission spectra a Nautilus unit telescope could provide on transiting small planets (from Earth-sized to sub-Neptune-sized). In Figure 4 we show representative models for three planets hosted by nearby ($d = 15$ pc) M-type stars: an Earth-like planet (panel A), a Venus analog (planel B, without hazes), and a warm sub-Neptune planet (panel C).

Our simulations should be seen as somewhat optimistic, as they only include photon noise as a noise source – future simulations will incorporate a detailed and complete error budget. However, the fact that high-precision, time-domain Hubble Space Telescope observations have consistently succeeded in reaching essentially photon-noise limited performance (typically within 10–25%[19,20,22]) suggests that our simplified noise model is an appropriate first approximation.

For the warm sub-Neptune, absorption features from water vapor and methane can be detected *in a single transit* (approx. 5 hours). For the smaller Earth-sized planets (panels A and B), multiple transits must be observed to build up the required signal. With ten transits of the Venus analog, we could identify the characteristic CO_2 absorption features. Excitingly, with thirty transits of the Earth-like planet, we could identify O_2, O_3, and H_2O absorption in its atmosphere.

The presence of these absorbers in the atmospheres provides, of course, a powerful tool to classify the planets – at least, based on our knowledge drawn from solar system planets. The presence of abundant molecular oxygen and ozone is a good indicator that the planet may have been transformed by oxygenic photosynthesis, i.e., may host life.[23,24]

6. SCIENCE WITH THE NAUTILUS SPACE OBSERVATORY

The unit telescope described Section 3 will demonstrate the functionality and cost of very large-scale MODE telescopes. Given that the telescope is designed to enable very cost-efficient replication, the natural next step is to replicate the unit telescopes and build up a telescope *array*. In[6] 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). Built from identical, relatively simple units deployed with just two launches, the Nautilus Space Observatory will provide an orders-of-magnitude increase in sensitivity at a cost potentially lower than NASA's LUVOIR concept.

In that study[6] we showed that such an array may reach the light-collecting power (i.e., sensitivity) of a *50m-diameter space telescope* – a true game-changer for all branches of astrophysics.

Such an array could, for example, survey 1,000 transiting exo-earth candidates to ∼300 pc for atmospheric biosignatures[6] (see Figure 5), vastly extending the study described for the Nautilus Unit Telescope in Section 5. The systemic search for atmospheric absorbers and biosignatures in a sample as large as 1,000 Earth-sized habitable zone planets would, without doubt, revolutionize the study of extrasolar planets and, possibly, even the studies of Earth paleoclimate. Such a study would provide a detailed, statistically meaningful context for Earth's evolution and will allow us to understand the diversity of Earth-sized planets[26] and their possible evolutionary pathways.

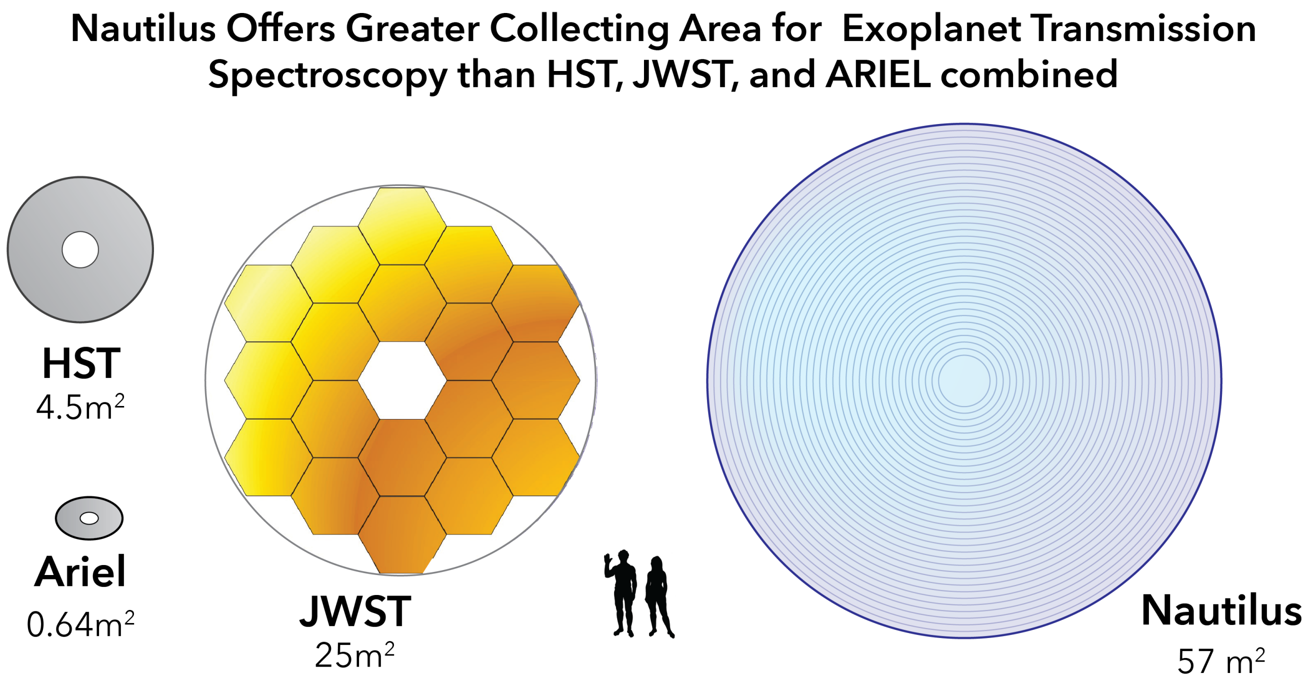

Figure 3. Comparison of the light-collecting area of space telescopes capable of exoplanet transmission spectroscopy. With its 8.5m diameter a Nautilus unit telescope's light-collecting area would exceed the combined light-collecting area of HST, Ariel (ESA's upcoming exoplanet characterization mission[25]), and JWST.

7. SUMMARY

We presented here an overview of Nautilus, a space observatory concept enabled by very large-diameter (8.5m), ultralight, multi-order diffractive engineered material lenses (MODE lenses). The key advantages of MODE lenses are threefold:
(1) They have low areal density, leading to 100× lower mass than typical to traditional telescope mirrors, and correspondingly to lower launch costs.
(2) They are 2–3 orders of magnitude less sensitive to misalignments, reducing costs of the optical telescope assembly and relaxing requirements on the entire observatory.
(3) They can be fabricated through replication, offering a potential for significantly reduced fabrication costs per telescope unit.

We show that a Nautilus unit telescope based on a single 8.5m-diameter MODE lens has the potential to survey hundreds of transiting planets in the solar neighborhood. Furthermore, for transiting Earth-sized planets within 15 pc, it has the potential to even allow the detection of biosignatures in the atmospheric transmission spectra.

We also show that an array of such unit telescopes – the Nautilus Space Observatory – could be used to build up a combined collecting area equivalent to that of a 50m-diameter space telescope. Such an array could be a true *game-changer for all branches of astrophysics.* We explored here one of the most compelling science cases for such a telescope: an atmospheric biosignature survey of 1,000 transiting, Earth-sized, habitable zone extrasolar planets. We show that it will be able to probe the atmospheric absorption of key absorbers in Earth-like atmospheres, including O_2, O_3, and H_2O.

In addition to its unprecedented light-collecting capability, the Nautilus Space Observatory also represents a paradigm shift in how space telescopes are designed, built, and launched: instead of unique prototype telescopes, Nautilus makes use of the economy of scale. Building up scientific capability by replicating relatively simple

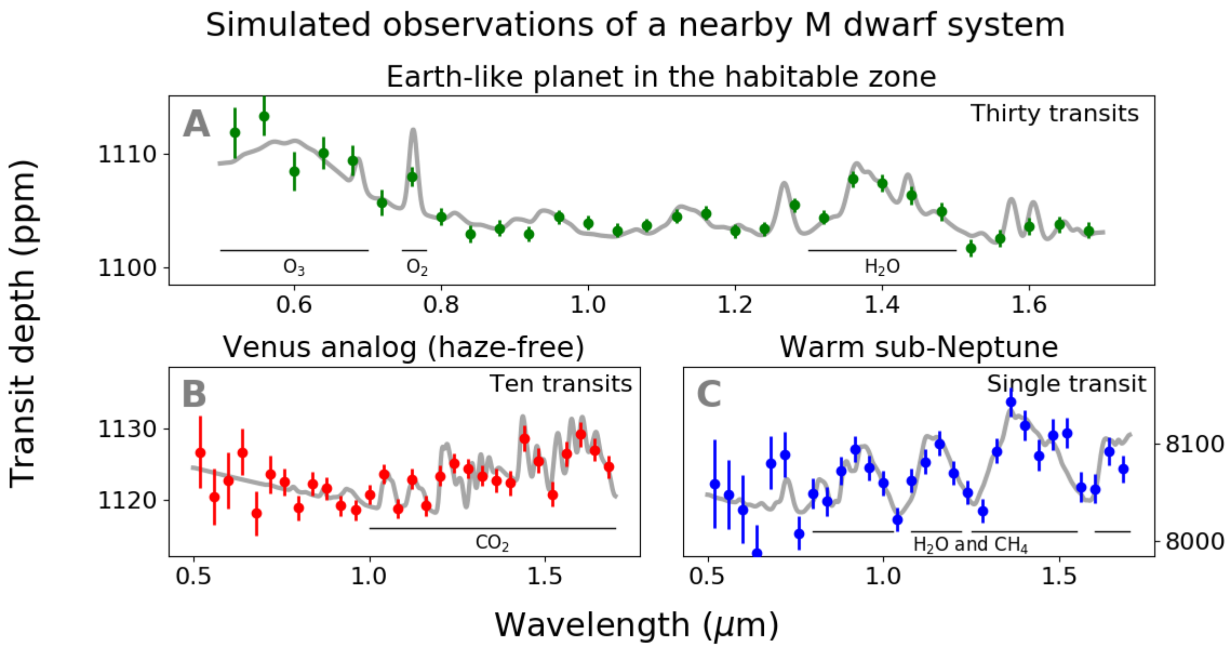

Figure 4. Due to its very large collecting area, even a single 8.5m-diameter Nautilus unit unit provides capabilities revolutionizing space-based astrophysics. Here, for example, are shown simulated transmission spectra of an Earth-like (A), a haze-free Venus-like (B), and a warm sub-Neptune exoplanet (C), orbiting a nearby M-dwarf star. While these simulations do not include a realistic instrument and systematic noise model, and thus should be considered optimistic, they show that a nearly-photon-noise limited Nautilus unit can provide revolutary data for exoplanet studies. In thirty transits of an Earth-like planet, for example, evidence for O_3, O_2 (produced by photosynthesis on Earth), and H_2O can be detected.

functional units represents a lower-risk, incremental, and more cost-effective approach than that followed over the past fifty years – in short, the Nautilus concept represents a paradigm-change in space telescope design.

ACKNOWLEDGMENTS

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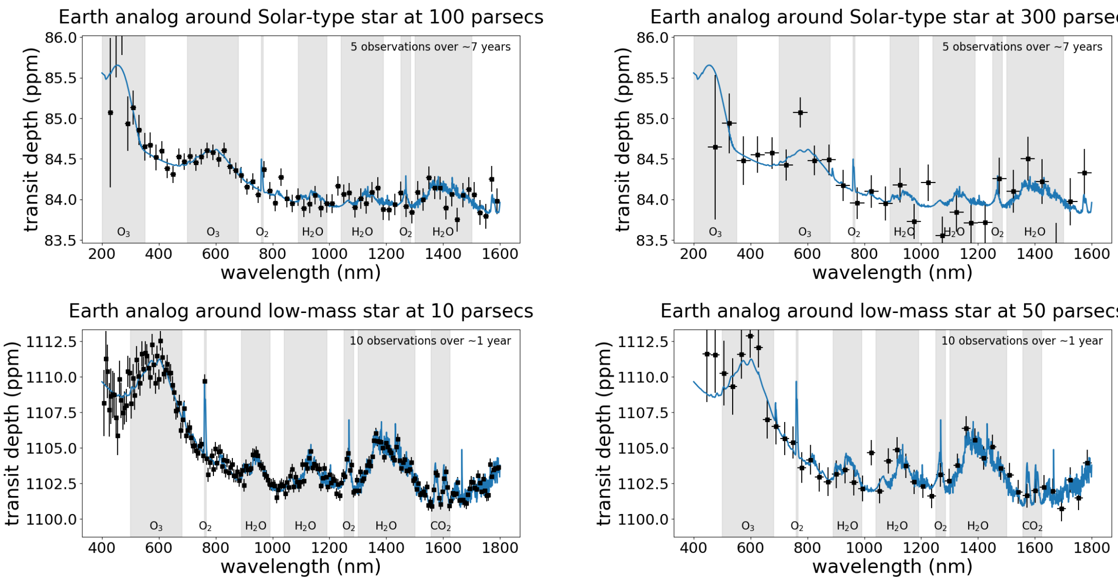

Figure 5. Simulated Nautilus Observatory spectra of nearby and far targets (Earth-sized habitable zone planets) around low-mass stars (M-dwarfs) and sun-like stars (G dwarfs), assuming 35 telescopes with 8.5m-diameter apertures. The light-collecting power equivalent to that of a $D \sim 50$m telescope enables the detection of H_2O and O_3 in ∼1,000 Earth analogs. The same configuration often also enables detection of O_2 and, in hundreds of simulated Earth-analogs around nearby low-mass stars, CO_2 absorption.

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