# Starshade Rendezvous Probe

JPL







NORTHROP GRUMMAN

# **Starshade Rendezvous Probe Study Report**

Imaging and Spectra of Exoplanets Orbiting our Nearest Sunlike Star Neighbors with a Starshade in the 2020s

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## **EXECUTIVE SUMMARY**

The past two decades have yielded tremendous exoplanet discoveries, with many planet-finding techniques including transit, radial velocity, microlensing, coming to fruition. Thousands of exoplanets are now known to exist, and as many as one in five stars like the Sun may host a rocky planet in the habitable zone (HZ). Space-based direct imaging is the next frontier of discovery for exoplanet science, and a space-based direct imaging mission to ultimately find and characterize other Earth-like planets (Figure ES-1) is a long-term priority for space astrophysics [1, 2].

The Wide Field Infrared Survey Telescope (WFIRST) space telescope mission with the Coronagraph Instrument (CGI) is scheduled to launch in late 2025. The work presented in this report demonstrates that a realizable, highly capable starshade launched and operated in formation with the WFIRST observatory can perform space-based direct imaging capable of discovering and characterizing exoplanets around our *nearest neighbor star systems*. This first-of-its-kind combined mission will enable a *deep-dive* exoplanet investigation around these neighbor star systems (Figure ES-1).

This report documents the quantified science WFIRST-CGI-Starshade objectives that the observing system will accomplish in this deep dive investigation. The Starshade Rendezvous Probe Mission presented herein is designed to accomplish these science objectives within the context of the opportunity provided by the WFIRST-CGI. This opportunity, realizable in the next decade, allows NASA to gain operational experience in space with a telescope-starshade observing system. The value of such experience focused on one of NASA's highest priority goals is difficult to overstate-it would inform the design and operation of all such future observatories. As this report demonstrates, the cost to achieve the science and obtain this experience fits within the proposed cap of a probeclass mission. Leveraging WFIRST as described is the only way to achieve such value at a cost of less than \$1B, and in less than 10 years.

With the WFIRST modest telescope aperture and existing instrumentation capabilities, the Starshade Rendezvous Probe bridges the gap between census missions like Kepler and a future



**FIGURE ES-1.** A 26-meter diameter starshade, also called an external occulter, flies in formation with the WFIRST telescope at a range of 20,000–30,000 km. The starshade blocks starlight to create a high-contrast shadow so that only planet light enters the telescope.

space-based flagship direct imaging exoplanet mission, such as the Habitable Exoplanet Observatory (HabEx).

This Starshade Rendezvous Probe Study was competitively selected by NASA to update the previously completed 2015 Starshade Rendezvous Mission concept study (Exo-S; [3]), for submission to the 2020 Decadal Survey. The Starshade Rendezvous Probe Study began in May 2017 and completed with delivery of this report in February 2019. The mission study presented herein incorporates significant updates since the Exo-S study, including:

- Increased breadth and depth of science models and simulations relevant to proposed science objectives;
- WFIRST mission progress;
- WFIRST accommodation to be "starshade ready";
- NASA's Exoplanet Exploration Program technology investments ("Starshade to Technology Readiness Level 5," or S5); and
- CGI instrument development.

#### **Summary of Science Goals and Objectives**

NASA's Strategic Plan 2018 [4] includes "Searching for Life Elsewhere" as one of three core contexts of NASA's first strategic objective, "Understand the Sun, Earth, solar system, and Universe." NASA's goal in Astrophysics [5] is to "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars," and leads to the broad scientific question, "Are we alone? Discover and study planets around other stars, and explore whether they could harbor life."

The Starshade Rendezvous Probe Mission aims to study the nearest 10 to 12 sunlike stars to explore any planetary systems found, and to find other Earth-like planets, if they exist around the target stars. An example of what the solar system would look like at 8.44 pc is shown in Figure ES-2 with the Starshade Rendezvous Probe imaging sensitivity plotted in Figure ES-3.

The science team formulated two overarching questions to guide the mission study:

- Is the Earth unique as compared to small planets orbiting our nearest neighboring sunlike stars?
- How does the solar system compare to the planetary systems orbiting our nearest neighboring sunlike stars?

In order to begin addressing these questions, the Starshade Rendezvous Probe Mission has three science objectives.

**Objective 1a: Habitability and Biosignature Gases.** Determine whether super-Earth size or smaller exoplanets exist in the habitable zone around the nearest sunlike stars and have signatures of oxygen and water vapor in their atmospheres.



**FIGURE ES-2.** Starshade simulated image of the Rendezvous Probe Mission's observation of a solar-system–like planetary system orbiting a nearby sunlike star.

# **Objective 1b: The Nearest Solar System Analogs.** Detect and characterize planets orbiting the nearest sunlike stars.

Objective 1a is focused on the possibility of discovering Earth-size exoplanets in the habitable zones of nearby sunlike stars, if they exist. If an Earthlike planet exists around one of the mission's target stars, Starshade Rendezvous Probe can obtain spectra. While searching for potential Earth-like planets, Objective 1b will be achieved. Other planets in the observed system that are larger and possibly at different orbital distances will be discovered. Starshade Rendezvous Probe will produce an imaging and spectroscopic portrait of the major components of the nearest equivalents of our solar system.

**Objective 2: Brightness of Zodiacal Dust Disks.** Establish if the zodiacal cloud of our inner solar system is representative of the population of our nearest neighbor stars.

Observations under Objective 2 will shed light on the dust-generating parent bodies (asteroids and comets), as well as assess exozodi levels for future missions.



**FIGURE ES-3.** Conceptual illustration of the solar system at 8.44 pc as observed with a starshade. Venus (V), Earth (E), Mars (M), Jupiter (J), and Saturn (S) shown at maximum separation from the star. The starshade inner working angle and field of view set the limits of which star-planet separations can be observed. The starshade contrast requirement of  $10^{-10}$  is shown in the red dashed line along with a simulated range of performances shown as the solid red curve. The diagonal purple line indicates the exozodiacal dust background of 1 zodi. The  $5\sigma$  imaging sensitivity with 24-hour integration times are shown in the purple dashed (based on requirements) and solid (current best estimate) lines. Planets above the  $5\sigma$  sensitivity line are observable.

**Objective 3: Giant Planet Atmosphere Metallicity.** Determine the atmospheric metallicity of known cool giant planets to examine trends with planetary mass and orbital semi-major axis, and to determine if these trends are consistent with our solar system.

With this third science objective, high science return of known exoplanet targets is achievable. The set of known giant planets are detectable by virtue of their positions in the late 2020s.

In addition to these objectives, several pressing astrophysical questions have come to the forefront, including:

- How much can be learned about planets with limited spectral and temporal information?
- How planets can be efficiently distinguished from background sources?
- How stray light from binary stars should be handled?
- How exozodiacal dust levels higher than the solar system's might impact the science harvest of a direct imaging mission?

Several ongoing and future space missions (Transiting Exoplanet Survey Satellite [TESS], PLAnetary Transits and Oscillations of stars [PLATO], Atmospheric Remote-sensing Infrared Exoplanet Large-survey [ARIEL]) will be concentrating on transit spectroscopy measurements of exoplanets, providing deep characterization of their atmospheres in the years to come. However, these observations will favor hot/warm planets on short orbits, and it is expected such observations will primarily reveal or study Earth-sized planets around M-type stars. On the ground, future extremely large telescopes (ELTs) will have the spatial resolution to directly image exoplanets around nearby stars. However, with projected instrumental contrast limited to  $10^{-8}$ – $10^{-7}$  at best in the near infrared, they may only be able to directly detect and characterize temperate habitable zone planets around nearby M-type stars. Direct imaging and characterization of exoplanets in reflected light around sunlike (FGK) stars requires 10<sup>-10</sup> contrast or better and is only accessible from the vantage of space.

To discover Earth-size planets in the habitable zones of nearby stars and to answer many other outstanding questions requires the large-scale dedicated effort of the Starshade Rendezvous Probe Mission.

#### The Deep Dive to Study Our Nearest Neighbors

The Starshade Rendezvous Probe provides the unique capability, within the next decade, to know our nearest sunlike stellar neighborhoods, with all the richness of exoplanetary diversity they may harbor. The deep dive strategy focuses observing time on the ten nearby targets. This maximizes the scientific discovery potential with a telescope the size of WFIRST. The requirements for the starshade are set by Objective 1, to probe to the sensitivity needed to discover Earth-like planets and measure oxygen or water vapor in their atmospheres. We cannot put constraints on the universe to guarantee that a suitable Earth-like planet will be there, but as this is the most challenging measurement to make, any other larger planets (i.e., super-Earths, sub-Neptunes) will also be discovered and studied in depth. Exoplanets continue to be more complex and diverse than expected. The deep dive strategy allows for the potential characterization of a habitable zone, Earth-like planet, but guarantees we'll be able to put our solar system in context with our stellar neighbors. This also allows the mission to identify specific investigations (Objectives 2 and 3) as part of the science program.

#### **Starshade Operations**

The Starshade Probe Rendezvous Mission includes a starshade with its own spacecraft, launched separately to rendezvous on orbit with WFIRST. The starshade spacecraft performs the retarget and formation control maneuvers. The science objectives are carried out by an observing program, created from a careful balance of the search for new exoplanets with the spectral characterization of known giant planets. Key factors in mission design are: end-to-end photon efficiency of the observing system, inner working angle (IWA), exoplanet-star flux ratio required, derived starshade design (petal shape, size, etc.), time, and the fuel it takes to align the starshade and telescope system to observe target stars. The mission design presented herein traded all these factors, and more, to arrive at a design of the probe spacecraft and starshade payload to achieve the science objectives.

The baseline spacecraft is based on the NASA Goddard Space Flight Center (GSFC) WFIRST spacecraft; with the WFIRST project, this will be a heritage bus by the time of the Starshade Rendezvous Probe launch.

The starshade payload design is directly derived from the technology currently being developed by NASA's Exoplanet Program Office as part of its activity to mature starshade technology to Technology Readiness Level (TRL) 5, "Starshade to TRL 5" or S5. The probe payload is a 26 m starshade (10-meter-diameter inner disk with twenty-four 8meter petals), along with equipment required for formation flying. The starshade design and deployment concepts are summarized in Section 3 of this report. Significant progress has been made on all technological fronts for the starshade payload; these accomplishments and planned development activity are summarized and referenced in Section 6. The development plan ensures the starshade technology is ready for the Starshade Rendezvous Probe to rendezvous with WFIRST less than a year after its launch.

The WFIRST 2.4 m telescope and its spacecraft, in development by NASA, includes starshade-ready requirements. These requirements ensure hardware needed to support the Starshade Rendezvous Probe is in place for the future mission. The requirements encompass formation flying equipment and a broadband instrument for planet detection and spectral characterization. The impact on WFIRST for starshade readiness is minimized with the lowest cost and lowest risk approach to meet requirements. Imaging and spectral characterization of any detected planets, as well as relative imaging for formation flying, is done with existing instruments within CGI.

The starshade spacecraft would launch on a Falcon 9 (Atlas 521 as alternate), following the WFIRST 2.4 m telescope launch to a halo orbit

about the Earth-Sun L2 point. The Starshade Rendezvous Probe Mission presented herein assumes a 2-year prime mission duration, with a 1-year extended mission.

The mission design was developed by a science team led by the Principal Investigators and mission and payload engineers at JPL, GSFC, and Northrop Grumman Corporation. The design demonstrates that NASA has a timely and high-value, relatively low-cost opportunity to fly the first operational starshade in space.

#### Summary

A combined WFIRST Mission and Starshade Rendezvous Probe Mission offers NASA and the scientific community an opportunity for breakthrough space-based exoplanet direct imaging in the next decade within a probe-class budget (<\$1B).

Compelling science can be returned at the same time that the scientific framework and operational experience are developed for future exoplanet discovery and characterization missions.

The Starshade Rendezvous Probe will be capable of discovering Earth-size planets in the habitable zones of nearby stars using the relatively moderate aperture WFIRST space telescope. This will be possible because the planet-star flux ratio and IWA achievable with starshade are nearly independent of the telescope aperture size. The Starshade Rendezvous Probe Mission provides an opportunity for unprecedented science return and can serve as the first step in-space for utilizing starshades in achieving NASA's grand goal of "Searching for Life Elsewhere."

### **1** INTRODUCTION

Exploration is part of what it means to be human. Our desire to explore the stars started by mapping them, tracking their motions, and finding that not all the bright points of light in the sky moved in the same way. We discovered our neighboring planets, and for the first time understood that we existed in a diverse solar system. We dreamed the other planets might also harbor life and imagined what it could look like.

As observing tools matured, the diversity further revealed itself as an intriguing mixture of large and small, hot and cold, wet and dry, giant and terrestrial planets with rings and moons, but none of them are like our own home. The Earth is unique in our solar system and our solar system architecture appears to be rare. While examining our neighboring planets has provided a wealth of information on how we might have formed and why our exceptional situation exists, we must now start a new stage of exploration, looking to other stars to improve our understanding.

In the last decade of exoplanet science, we have discovered and cataloged thousands of planets around other stars, finding many in the habitable zone where water could exist on the surface as liquid, and in the atmosphere of a terrestrial planet. Once again, we dream, imagine, and hope that even if our solar system architecture is rare, Earth-like planets around nearby sunlike stars exist and have the possibility of life. We wonder how diverse other star systems will be and what we will discover. To find out, we need to take the next step by continuing to improve our observation capability: imaging full planetary systems, including their habitable zones (HZs), and obtaining planetary spectra with the sensitivity to determine if a planet is Earth-like for the first time. A starshade operating with the Wide Field Infrared Survey Telescope (WFIRST) and its onboard Coronagraph Instrument (CGI) provides a singular opportunity within the next decade to explore our neighboring stars and discover their planetary systems.

Our nearest neighboring stars (Figure 1-1) provide intrinsic cases of planetary system formation, dust distributions, planet populations, and planetary compositions. Imagine a future when we can point to the nearby sunlike stars and describe their 'solar systems' with improved knowledge of their planets and orbits, including habitable zones, atmospheric compositions, and potential habitability. The starshade science case lays out specific science goals and focused investigations to image the dust disks and planets around at least 10 of our nearest sunlike stars and obtain spectra during "deep dives" (Section 2). The science case also includes imaging another 10 slightly more distant sunlike stars to obtain spectra of known giant planets. The goal of the Starshade Rendezvous Probe Mission is to place our Earth and solar system into context with the nearest planetary systems.



**FIGURE 1-1.** Moving outwards from our Sun by factors of ten (left). The Sun is followed by the terrestrial planets, asteroid belt, giant planets, and the Kuiper Belt. The Voyager spacecraft have recently crossed the outer edge of the Sun's influence. The Oort cloud, the final bound part of the solar system lurks beyond. Next are the nearest stars (right)—the next frontier for space exploration. This map was adapted from images by Richard Powell at atlasoftheuniverse.com. Credit: ESO, Richard Powell

#### 1.1 Starshade in Context: Why Starshade? Why Now?

To put the Starshade Rendezvous Probe science in context requires surveying the state of exoplanet science, both the tremendous past discoveries, current state of the art, and ambitious plans for the future.

Enormous advances in exoplanet science have been made over the past two decades, largely from discoveries using the radial velocity and transit techniques. The explosion of planets discovered by Kepler has taught us about the diversity of planetary systems, most very different from our own solar system [1, 2]. New planet types have been discovered that do not fit into existing planet formation models. The first Earth- and super-Earthsize planets have been found orbiting cool M dwarf stars [3-6], capturing the imagination of scientists and the public alike.

Yet some of the most significant questions in all of science remain unanswered: Do other Earth-like planets exist? Are they common? Are any habitable? How does our solar system compare to others? How does planetary system architecture (planets and dust distributions) influence habitability? For the first time, our technology is mature enough to begin to answer these ancient questions within the next decade.

The Starshade Rendezvous Probe Mission aims to find other Earths and planets in context with their entire planetary systems. The team has formulated two overarching questions to guide the mission study:

- Is the Earth unique as compared to small planets orbiting our nearest neighboring sunlike stars?
- How does the structure of our solar system compare to the planetary systems orbiting our nearest neighboring sunlike stars?

To begin addressing these questions, the Starshade Rendezvous Probe Mission will have, for the first time, the sensitivity to characterize Earth-like planets in the habitable zones of nearby, sunlike stars. This driving requirement enables the discovery and characterization of entire systems including Earth-sized to Jupiter-sized planets.

#### 1.1.1 Exoplanet Science Background

Transit spectroscopy from the ground and in space as well as direct imaging from the ground have given us a taste of the complexity of exoplanet [9] and planets in the process of formation [10].

Nevertheless, despite the tremendous progress in exoplanet discovery, there is still a large portion of parameter space unexplored. Figure 1-2 shows that very few (<10) planets <1.4  $R_{\oplus}$  (Earth-sized and super-Earth-sized) have been discovered beyond 0.5 AU, and none of them have been characterized spectroscopically. In fact, almost none of the planets beyond 0.1 AU and <10 R<sub>⊕</sub> including Earth-sized, super-Earth-sized, sub-Neptune-sized, and Neptune-sized planets have been characterized spectroscopically. The current methods shown in the plot cannot provide the sensitivity, as a starshade can, to explore this intriguing part of the exoplanet parameter space.

The path forward to discovery and characterization of potentially habitable worlds is along two tracks: transit spectroscopy and direct imaging. In the first track, NASA's new planetfinding mission, the Transiting Exoplanet Survey Satellite (TESS), and other ground-based surveys will find planets transiting bright nearby stars that are suitable for follow-up atmospheric measurements with the James Webb Space



**FIGURE 1-2.** Space-based direct imaging, as with a starshade, has the sensitivity (region inside black lines) to characterize the atmospheres of planets with 1–10 Earth radius from 0.5 to 20 AU for the first time, a major region of interest for putting our solar system into context with nearby sunlike stars.

Telescope (JWST). Transit transmission spectroscopy on small planets with JWST is limited to M dwarf host stars because, for a sunlike star, the atmospheric annulus imposed on the star is too diminutive [11]. In addition, it is extremely unlikely that planets with Earth-like orbits at 1 AU about nearby sunlike stars will in fact transit (the probability is roughly 1/200). The search for habitable planets and life with the TESS/JWST combination is therefore primarily limited to planets orbiting smaller stars that are more plentiful (nearby M dwarf stars).

The second path forward for small exoplanet atmosphere study is via direct imaging, which is itself divided into ground- and space-based categories. The extremely large ground-based telescopes (ELTs) now under construction, given the right instrumentation, will be capable of directly imaging and characterizing exoplanets using reflected light about M dwarf stars [12, 13]. Observations will include following up on TESS/JWST targets, reaching a new population that includes small, rocky planets. Large ground-based telescopes, however, are largely limited to planets orbiting M dwarf stars because of the limitations of adaptive optics and the attainable planet-star contrast (see Figure 1-3).

Space-based direct imaging is the only way to discover and spectroscopically study temperate, small exoplanets about sunlike stars. Space-based direct imaging is the natural and essential next step in NASA's continuing series of exoplanet missions—and is the next frontier of discovery for exoplanet science. The Starshade Rendezvous Probe



Mission is by far the most efficient, cost effective, and timely way to begin characterizing habitable zone exoplanets.

#### 1.1.2 Why a Starshade Along with a Coronagraph on WFIRST?

The Starshade Rendezvous Probe Mission relies on WFIRST and the CGI to provide imaging and spectroscopy of ten or more known radial velocity planets informing models of planetary formation, measurements of reflected light spectra of the enigmatic sub-Neptune–size planets, and potentially provide the first images and spectra of Earth or super-Earth-like planets around sunlike stars.

The CGI itself is already a large step forward on the path to dedicated direct imaging missions. The CGI will demonstrate key technologies necessary to produce a two to three order of magnitude improvement in contrast over past and current coronagraphs, including those on the Hubble Space Telescope (HST) and JWST, enabling future Earth-like planet imaging missions (see sidebar on next page); its success is thus critical to lowering the design and implementation risk of future coronagraphic missions. Figure 1-3 illustrates the powerful advances in achievable inner working angle (IWA) and detectable flux ratio with CGI. The CGI will also be the first exoplanet imager to operate in visible light and to approach the habitable zone of sunlike stars.

As part of the WFIRST mission, the CGI will observe a small number of large, Jupiter-size planets beyond the ice line and provide useful observations of zodiacal dust and disks. The CGI has an IWA of

FIGURE 1-3. Direct imaging capabilities of current and future instrumentation. Shown are the 5  $\sigma$ contrast limits after post-processing one hour's worth of data for various coronagraph instruments and 100 hr integration times for the WFIRST CGI and starshade. The state of the art is located in the upper-right section of the plot, including both ground- and space-based coronagraphs. The WFIRST CGI is expected to improve sensitivity by at least two orders of magnitude over the state of the art. During deep dives, starshade sensitivity is another order-of-magnitude better, enabling for the first-time discovery and characterization of Earthlike planets in the habitable zones of nearby sunlike stars. Figure and caption adapted from Refs. [14] and [15], and Stapelfeldt (private communication 2015). Image credit: T. Meshkat and V. Bailey.

200–300 milliarcseconds (mas) and a flux ratio sensitivity ranging from  $5 \times 10^{-9}$  to  $5 \times 10^{-8}$ , depending on wavelength. Adding a starshade expands the scientific reach significantly, with an IWA  $\geq 100$  mas, lower contrast (down to  $10^{-10}$ ) and ~10 times larger throughput. This capability enables observation of the habitable zones of our nearest sunlike stars (Figure 1-2).

For the probe mission, CGI will have operated during the first years of WFIRST, very likely allowing the starshade to start with a refined target star list based on exozodiacal dust disk observations and giant planet contextual measurements. The starshade would begin by imaging nearby target star systems, searching for any detectable planets and looking at dust disk distribution with higher sensitivity. If planets are observed in the first two visits, follow-up "deep-dive" observations would constrain their orbits and spectral observations would occur if the planet is bright enough (see observation decision tree in Section 2.2.3). In the future, the combination of coronagraphs and starshades will lead to the most efficient strategy for exploring exoplanet systems.

#### 1.1.3 Why Now for the Starshade Probe?

Flying a starshade with WFIRST and CGI provides the only opportunity to image and characterize the habitable zones of our nearest neighbors in the next decade. Leveraging the next NASA large telescope mission that is already being made starshade-ready and the capabilities of the onboard CGI opens up tremendous discovery potential at the cost of only building and flying a starshade. The technology will be ready and the mission has been studied thoroughly to allow meaningful overlap with the WFIRST baseline mission and exoplanet science goals. A starshade could operate during the last two years of WFIRST's prime mission if Phase A begins by the end of 2021 or as part of the extended WFIRST Mission with a later start.

WFIRST is currently being designed to accommodate a starshade. The CGI imager and integral field spectrograph (IFS) will be used as the starshade instrument. Filter alignment mechanisms will move the CGI's coronagraph masks and stops from the optical path, thus increasing throughput. To accommodate the starshade, CGI is providing available space in existing filter alignment The combination of the WFIRST CGI and a starshade provides an essential stepping stone to future NASA observatories designed for direct imaging of Earth-like planets, such as the Habitable Exoplanet Observatory (HabEx). The HabEx approach, in particular, incorporates both a coronagraph and a starshade as dual, complementary instruments, providing resiliency and efficiency. Such a design leverages the coronagraph's agility to search many systems and determine orbits and the starshade's wide field of view and large bandwidth for deep characterization. Taking advantage of the strengths of each maximizes the science yield.

The WFIRST CGI will demonstrate, in space, the key technologies needed for future coronagraphs designed to reach Earth-like planets in the habitable zone: high actuator count deformable mirrors; low noise, single photon-counting detectors in the visible; low-resolution integral field spectroscopy; advanced algorithms for wavefront sensing and control; high-fidelity integrated modeling; and advanced postprocessing approaches. At the same time, including a starshade with WFIRST will make available a suite of new science, including imaging and spectra of small rocky planets in the habitable zone, characterization of planets similar to the sub-Neptune class discovered by Kepler, deep spectroscopy on at least 10 known radial velocity planets, and perhaps the first glimpse of biosignatures on rocky planets orbiting our nearest neighbor stars. Flying both on WFIRST will also provide an essential demonstration of how the combination of a coronagraph and starshade is much more than the sum of its parts.

mechanisms to support additional and wider bands for spectroscopy and using the low-order wavefront sensor (LOWFS) as a tracking and guidance camera. WFIRST is also planning to have a starshade acquisition camera and radio for direct communication with the starshade (see Section 4.4). The WFIRST project plan already includes continuing starshade accommodation work until the Decadal Survey committee releases its recommendations.

The Starshade Rendezvous Probe Mission would also provide a crucial test of starshade technology and operations, informing future mission concepts, such as HabEx, that plan to employ much larger starshades. Such a future telescope would be able to find dozens of Earth-sized planets around sunlike stars and perform deeper and higher resolution spectroscopy in search of indications of life. In 2016, NASA began a dedicated technology development activity to prepare and demonstrate all the necessary technologies on the ground in time for a starshade rendezvous with WFIRST and for future missions such as HabEx. An additional in-space technology demonstration mission is not required (see Section 6) prior to the science-focused mission that is described in this report.

Within the next decade, a starshade mission could discover an Earth-sized exoplanet in an Earth-like orbit about a nearby sunlike star and obtain spectra of its atmosphere. This report provides a detailed description and analysis of the Starshade Rendezvous Mission performing a "deep dive" science-based exploration of our nearest sunlike neighbors, scouring the systems for their contents. The discovery of an Earth-like planet would reverberate far beyond astronomy and characterization of other planet types (i.e., cool sub-Neptunes) will also be a first-time event.

Space-based direct imaging is a natural and essential next step in a continuing series of NASA exoplanet missions—and is the next frontier of discovery for exoplanet science.

#### 1.2 Starshade Overview

The starshade is a powerful tool for space-based direct imaging of exoplanets, one that simplifies demands on the telescope compared to other starlight suppression techniques. A starshade is a large, precisely shaped screen, tens of meters in diameter, flying in formation with a distant telescope situated tens of thousands of kilometers

away (see Figure 1-4 and Ref. [16]). The starshade blocks unwanted starlight, creating a shadow where the telescope lies, thus allowing only (off-axis) planet light to enter the telescope. Built to tolerances better than ~100  $\mu$ m for petal shape and ~1 mm for petal positioning, with lateral position tolerances ±1 m at distances up to 37,700 km, the starshade can

reach IWAs of  $\leq 100$  mas and reduce the residual starlight by more than a factor of  $10^{-10}$  compared to the planet flux. First conceived of in the 1960s [17], and revisited nearly every decade since (see BOSS [18]

revisited nearly every decade since (see BOSS [18] and UMBRA [19], as well as Refs. [16, 20-22]), starshade technology builds upon heritage from large space-based radio antenna deployables [23]. The benefits of a starshade are:

- No new technologies for the space telescope are needed because the burden of starlight suppression is on the starshade;
- The contrast and IWA largely decouple from telescope aperture size;
- The outer working angle is limited only by the size of the detector;
- No complex wavefront control is necessary;
- High throughput and broad wavelength bandpass (400–1,000 nm);
- The modest number of nearby target stars available is well-matched to the number of starshade retargeting maneuvers, mitigating the main starshade challenge of repositioning for target stars; and
- Other telescope instruments can operate between starshade observations while the starshade is slewing to the next position.



**FIGURE 1-4.** Schematic of the starshade-telescope system (not to scale) and observing geometry with the inner working angle independent of telescope size.

#### 1.3 Progress Since Exo-S Study

In 2013, NASA commissioned the Exo-S study team to examine a probe-class mission using a starshade with a small telescope [16]. The Exo-S study team considered two concepts. First, the Starshade Dedicated Mission with a co-launched 1 m telescope and 30 m diameter starshade; and second, the Starshade Rendezvous Mission, with a 34 m diameter, separately launched starshade operating with an existing telescope, such as WFIRST.

A variety of options are available within the dedicated and rendezvous concepts. Larger starshades (for larger telescopes) improve inner working angle and habitable zone access. Longer mission durations allow more observations, enabling both longer integration times and more revisits to establish orbits and disentangle background objects and multiple planets.

In addition to the Exo-S study, a 2015 Extended Exo-S Study [24] reduced the rendezvous baseline to a 26 m starshade and also considered a smaller 20 m starshade but concluded that such a mission would not accomplish impactful science. A 2016 Starshade Readiness Working Group [25] recommended a plan to validate starshade technology and furthermore concluded that no space-based technology demonstration was needed prior to a starshade mission flying.

A directed effort to mature five different starshade technologies to Technology Readiness Level (TRL) 5 was created by NASA's Astrophysics Division in March 2016 (called the "Starshade Technology Development Activity" or S5), though shorter timescales are possible with additional funding. Progress on these key technologies is described in Ref. [26] and Section 6. A major mechanical architecture trade study has been completed and the Starshade Accommodations Interface Requirements Document with WFIRST is currently being finalized and is scheduled to be released in 2019. Major risks will be retired by mid-2019 and TRL 5 will be reached by June of 2023 with no additional new technologies needed beyond those matured by S5.

#### 1.4 Starshade Rendezvous Probe Study

In 2017, a new Starshade Rendezvous Probe Study, reported on here, began to update the earlier Exo-S work. This study entails: 1) detailed development of focused science objectives that drive measurement and starshade requirements (Section 2); 2) increased fidelity of model parameters based on more mature WFIRST CGI and S5 developments (Sections 3 and 4); and 3) higher-fidelity costing based on S5 and the mission concept development work presented here (Sections 4 and 5).

The objectives for this report are to:

- Update and provide traceable science mission requirements from a set of achievable, focused investigations;
- Update the Exo-S design reference mission driven by the science objectives;
- Justify and motivate a worthy probe-class mission;
- Show starshade technology is compatible with the mission requirements and the WFIRST opportunity; and
- Highlight the rare opportunity to take advantage of an existing telescope and instrument on WFIRST, which is being made starshade ready, provided the Decadal Survey recommends pursuing this concept.

The Starshade Rendezvous Probe fits within NASA's serial development approach to strategicclass missions by providing a foundation of technology and experience that will significantly reduce development risk while returning its own worthwhile, probe-class science. The larger exoplanet mission concepts looking to operate in the 2030s and beyond (currently under study by NASA for the 2020 survey) target a significantly greater number of stars than a first starshade mission is capable of and should build upon the technical and scientific heritage obtained by development and operation of a smaller starshade mission in the 2020s. The first and best opportunity to do so is the Starshade Rendezvous Probe Mission with WFIRST.

## 2 STARSHADE PROBE SCIENCE

Astronomers are poised to enter a new era of exoplanet science. The past decade has seen a revolutionary advance in our knowledge of other planetary systems, driven by discoveries of transiting planets, primarily from the Kepler mission. That revolution will continue in the next decade with detailed characterization through the powerful combination of the Transiting Exoplanet Survey Satellite (TESS) and the James Webb Space Telescope (JWST). These discovered systems are diverse but also extremely different from our own. This is a natural consequence of the methods used: the sample of planets accessible to transits is both incomplete and heavily biased towards planets close to low-mass stars.

The planetary systems of the nearest sunlike stars are essentially inaccessible either from ground telescopes or with current NASA missions. Starting the era of direct imaging for characterization of those systems and new ones to be discovered, hunting for true analogs of our solar system, and, possibly, finding another Earth, are the motivations for the Starshade Rendezvous Probe Mission, which begins to address the two overarching guiding questions:

- Is the Earth unique as compared to small planets orbiting our nearest neighboring sunlike stars?
- How does the solar system compare to the planetary systems orbiting our nearest neighboring sunlike stars?

These questions address NASA's strategic goals "Searching for Life Elsewhere" [1] as one of three core contexts of NASA's first strategic objective "Understand the Sun, Earth, solar system, and Universe." The 2010 Decadal Survey: New Worlds, New Horizons in Astronomy and Astrophysics includes the priority science objective for the decade 2012–2021 "seeking nearby habitable planets" [2]. NASA's Astrophysics Website NASA's goal in Astrophysics is to "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars," and leads to the broad scientific question "Are we alone? Discover and study planets around other stars, and explore whether they could harbor life" [3].

More recently, the National Academy of Sciences Exoplanet Science Strategy laid out two goals "to understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes" and "to learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside" [4].

To develop the science objectives that the Starshade Rendezvous Probe will accomplish, the two overarching science questions are further articulated through a traditional series of science investigations (Section 2.2.) that lead to a quantitative Science Traceability Matrix (STM; Section 2.2.3), both of which are discussed further below.

Seeking an answer to these questions motivates the "deep dive" approach of the Starshade Rendezvous Probe; that is, a detailed investigation of our nearest-neighbor sunlike stars. This approach targets a select set of 10 nearby sunlike stars where starshade observations have both high imaging sensitivity for exoplanet discovery and exozodiacal dust disk characterization and high spectral sensitivity to characterize their atmospheric composition (Figure 2-1) while also allowing multiple visits to constrain the orbits of any habitable zone (HZ) planets found (Figure 2-2).

Maintaining the sensitivity to discover and characterize potentially Earth-like exoplanet candidates around these stars drives the observatory requirements. Meeting challenging these requirements means the observatory will be capable of discovering and characterizing a wide range of planet types, including those like the giant planets in our solar systems and the previously unknown and never imaged recently discovered planet types (e.g., the sub-Neptune planets common in Kepler discoveries).

The net result of the deep dive will be a reconnaissance of 10 of our closest neighboring sunlike stars with ~60% completeness for Earth-like planets and more for larger planets. Planetary systems almost certainly exist around several of these stars, and we will discover those systems and spectroscopically characterize their members. If an Earth-like planet candidate is discovered in at least one of these stars, it will be spectroscopically observed to hunt for water vapor and oxygen. We will also study the non-planetary components of these

systems—the zodiacal dust disks produced by cometary or asteroidal bodies. The discovered set of planetary systems will help put our own planetary system into detailed context, provide information about pathways to planet formation potentially distinct from the transiting systems, and provide planetary and astrobiology scientists with data for new understanding and further investigations. These immediate neighbors, including any discovered Earth-like planet candidates, will be the most studied systems for decades to come; their discovery and characterization will provide a strong motivation for future missions.

In addition to discoveries around nearby stars, the mission will also carry out a high signal-to-noise ratio (SNR) spectroscopic study of at least 10 known giant exoplanets to explore how their composition varies with planetary or orbital parameters.

Starshade Rendezvous Probe will begin the scientific journey toward understanding our place in the universe, whether planets and solar systems like ours are common, and whether life is not unique to our Earth.

In the remainder of this section, we describe in more detail the science objectives of the Starshade Rendezvous Probe (Section 2.1), providing the rationale, physical parameters, scientific measurements, and the flow down to science requirements; describing implementation, including instrument requirements, predicted performance, mission requirements, and observation approach (Section 2.2); and concluding by discussing the scientific impact of Starshade Rendezvous Probe discoveries (Section 2.3).



**FIGURE 2-1.** Earth-like planets drive the sensitivity requirements that enable observation of a wide variety of exoplanet types. Simulated spectra with the CGI spectral resolution R=50 for various planet types are shown in relation to the spectroscopic bands available. The Starshade Rendezvous Probe (656–800 nm) spectroscopic band is shown as a green shaded region while the (800–975 nm) band is shown in orange. The presence of oxygen, water vapor, and methane is inferred from the spectral absorption lines. Credit: Aki Roberge



**FIGURE 2-2.** Multiple observations enable the tracking of habitable zone exoplanets. Image simulations of the solar system (inclination angle 60°) at a distance of 6 pc observed with a starshade and WFIRST CGI camera show the presence of Venus (V), Earth (E), and Mars (M) in a zodiacal dust cloud of 1 zodi. Jupiter (J) appears in the last two frames. Each image is obtained with 1 day of integration time. The color scale indicates the number of detector counts with the highest value being equivalent to signal to noise ratio of 25. Credit: Sergi Hildebrandt

#### 2.1 Science Objectives

**Objective 1a: Habitability and Biosignature Gases.** Determine whether super-Earth size or smaller exoplanets exist in the habitable zone around the nearest sunlike stars and have signatures of oxygen and water vapor in their atmospheres.

**Objective 1b: The Nearest Solar System Analogs.** Detect and characterize planets orbiting the nearest sunlike stars.

#### Rationale

An important point to emphasize is that while searching for potential Earths, other planets in the same system that are larger or at different orbital distances will be discovered. If the planetary occurrence rates measured in inner solar systems by Kepler continue at larger scales, such planets are certainly present. With the Wide Field Infrared Survey Telescope (WFIRST) Coronagraph Instrument (CGI) integral field spectrograph (IFS), spectra of all observable objects may be obtained, allowing for detailed study of their atmospheric composition. Starshade Rendezvous Probe will produce an imaging and spectroscopic portrait of the major components of the nearest equivalents of our solar system.

Should they be present, rocky planets like Earth would likely be detected by Starshade Rendezvous Probe (with a completeness of roughly 60%). Rocky planets with thin atmospheres are the most promising abodes for life. Giant planets are too hot beneath their atmospheres and have no solid surface as we know it. The habitable zone is the region around the star of most interest—the zone around a star where a rocky planet with a thin atmosphere, heated by its star, may have liquid water on its surface. Evidence suggests [5] that planets with radius below 1.4 R<sub>Earth</sub> are predominantly rocky, so this value serves as an upper limit for Earth-like planets in the simulation results presented here.

Water vapor is a sign of habitability as it can be indicative of the presence of liquid water oceans, needed for life as we know it. Without a liquid water reservoir, water vapor would be absent from a small rocky planet atmosphere, as water vapor should have been photodissociated with the hydrogen escaping to space and oxygen reacting away with the surface.

Oxygen is considered Earth's most robust biosignature gas and is present in Earth's atmosphere at 20% by volume; without vegetation and photosynthetic bacteria, there would be negligible amounts of atmospheric oxygen. Oxygen is a highly reactive gas and under most scenarios must be continually produced to be present in a small planet atmosphere.<sup>1</sup> Of course, a broad range of life-bearing planets could exist without oxygen (such as the early Earth), but its detection remains a sufficient condition to strongly indicate the possibility of life.

#### Physical Parameters, Scientific Measurements, and Science Requirements

The first part of this investigation is to search for planets in the habitable zone and beyond via direct imaging. For candidate planets detected, several visits will follow to constrain the orbit and confirm that they are indeed in the habitable zone. Finally, the most compelling candidate planets—particularly those in the habitable zone—will be spectroscopically characterized.

The exoplanet's semi-major axis is an important orbital parameter that indicates the amount of radiation from the star that is incident on the planet. For an exoplanet with a thin atmosphere like Earth's, the semi-major axis determines whether it is in the habitable zone. Determining the semi-major axis with sufficient accuracy requires at least three astrometric measurements of the planet's position spread out over two years.

An example of an orbit reconstruction simulation is shown in Figure 2-3. Earth-like exoplanets in the HZ are generated with randomly sampled Keplerian orbital parameters with the planet's phase-varying brightness and associated astrometric precision. The simulated observations are then reconstructed with a Markov Chain Monte Carlo (MCMC) that forward models the simulated data. An ensemble of these simulations for Starshade Rendezvous Probe target stars demonstrated that Earth-like planets can be constrained to the habitable zone with >80% confidence.

Habitable zone exoplanets with sufficient brightness (based on imaging observations) can be

<sup>&</sup>lt;sup>1</sup> Recent ongoing debates on a variety of false positive oxygen generation scenarios are mostly being settled in favor of oxygen attributed to life [6, 7].

Detection of an exoplanet with Earth's atmospheric abundances of oxygen and water vapor is accomplished through measurements of spectral features. Both water vapor and oxygen have strong spectral features at visible wavelengths in the regions accessible to the Starshade Rendezvous Probe Mission (Figure 2-4). Oxygen has a strong spectral feature at 760 nm. Water has several spectral features at visible wavelengths, including one at 720 nm, close to the oxygen feature.

Detailed modeling of spectral retrievals has or shown that meaningful detection of water vapor as and oxygen requires a spectral resolution R=50, Th an SNR of approximately 20 or greater, and a th wavelength range encompassing oxygen and sa water vapor spectral features ([8] and Figure 2-4) re and is practical even through cloudy re atmospheres. The WFIRST CGI IFS spectral band pass of 656–800 nm contains both the oxygen and water vapor spectral features desired.

Starshade Rendezvous Probe will perform reconnaissance observations of at least 10 stars. Depending on the warm dust disk brightness of the observation, targets will be revisited for orbit



**FIGURE 2-3.** Four well-spaced observations, as planned with Starshade Rendezvous Probe, are sufficient to constrain orbits to the HZ. This figure is an example from a MCMC simulation to reconstruct orbits. A simulation of an Earth-like planet with a circular orbit around a star (Epsilon Eridani in this instance) is shown on the left with true positions marked in red circles and astrometric estimates with error bars shown in black. The inner working angle (IWA) is shown in gray with the inner and outer HZ bounds shown in green. *Right:* sample orbits (gray lines) from the MCMC reconstructed posterior distribution demonstrating reconstructed posteriors are bound within the HZ.

determination and, for sufficiently bright habitable zone Earth-like planet candidates, spectroscopic measurements will be performed. For this objective, it is required that at least 4 targets can be fully characterized, but the number could be as high as 5, depending on the realization of dust disk brightness and planet populations observed.



**FIGURE 2-4.** Oxygen and water vapor are detectable with SNR $\geq 20$  based on a study of Feng et al. [8]. *Left:* the planet (F<sub>p</sub>) to starlight (F<sub>s</sub>) flux ratio spectrum at high resolution for a cloudy Earth model with molecular features indicated. *Right:* a simulation of the spectrum observed with the WFIRST IFS in the CGI. The IFS has spectral resolution R=50. The points with error bars shown a simulated instance with the increase in the size of the error bars at longer wavelengths is due to the roll-off in the CGI detector's efficiency. The green and orange shaded regions indicate the starshade bands of observation as described in Figure 2-1. The study of Feng et al. [8] used MCMC information retrieval methods to show that with an SNR $\geq 20$ , oxygen and water vapor are detectable. Note that the majority of the sensitivity is contained in the 656–800 nm region where the CGI detector performance is highest.

More massive planets, and those outside the habitable zone, can also be spectroscopically characterized. For higher-mass planets observation of oxygen would not be expected, of course, but the features of water vapor, methane, clouds/hazes, and other atmospheric constituents can be detected for atmospheres resembling the giant planets, Venus, Titan, or planets with no solar system equivalent. For the brightest such planets, high SNR measurements can determine not just the presence of compounds but their abundance (see Objective 3); for fainter planets, low SNR spectroscopy or photometry can be used to quickly classify them and determine the dominant components of their atmosphere [9].

#### Discussion

For Objective 1, up to 10 target stars can be studied while meeting the Starshade Rendezvous Probe Mission's observing constraints discussed in Section 2.2, with the assumption that not all stars will have detectable Earth-sized or super-Earthsized planets requiring full revisits and spectra. The limiting factor for the number of stars that can be visited is the finite amount of fuel available for retargeting maneuvers.

If an Earth-like planet exists and its orbit is such that Starshade Rendezvous Probe can detect and characterize it, then its habitability can be established by detection of water vapor. Oxygen will be a strong indicator for the presence of life, although more context to sort through false positive scenarios will have to await a future mission with more advanced capabilities, in particular near-infrared spectral capabilities.

#### **Objective 2: Brightness of Zodiacal Dust Disks.**

Establish if the zodiacal cloud of our inner solar system is representative of the population of our nearest neighbor stars.

#### Rationale

The solar system's zodiacal dust originates from ongoing asteroid collisions and the outgassing/disruption of comets. It is debated that asteroids delivered water and other volatiles to Earth early in the solar system's history. Detected around a nearby star, exozodi would indicate a reservoir of small bodies analogous to the solar system's asteroids and comets (Figure 2-2), again helping to answer the question of how the solar system compares to the planetary systems orbiting our nearest neighboring sunlike stars.

For some systems, exozodiacal dust might be a major impediment to Earth-like planet detection during the rendezvous mission because its brightness can exceed that of an Earth-like planet given the spatial resolution of WFIRST. The optical brightness of zodiacal dust disks around other stars has not been directly measured. The current best sensitivity to warm zodiacal dust disks is from infrared (12 µm) observations using the Large Binocular Telescope Interferometer (LBTI) [10] with a sensitivity of ~100 zodi for sunlike stars (1 zodi is the brightness of the solar system's zodiacal dust cloud if observed with inclination angle 60° at 550 nm wavelength). Above 10 zodi, the dust disk brightness has a significant impact on the sensitivity to Earth-like exoplanets [11]. For disks with 20 zodi brightness, local density fluctuations in the disk can be brighter than an Earthlike planet resulting in a source of confusion and false positives [12]. Assessing the levels, geometry, and structure of exozodiacal dust around the nearest star systems is critical for the design and target selection of future direct imaging missions.

# Physical Parameters, Scientific Measurements, and Science Requirements

The physical parameter for Objective 2 is the spatial distribution of the dust disk surface brightness. The scientific measurement is brightness in the imaged planetary system. The science requirements are sensitivity to 0.5 zodi (where zodi is the equivalent to Earth's zodiacal dust disk) with 20% uncertainty at Earth equivalent irradiation distance. A spatial resolution of 1 AU is sufficient to detect exozodi. The exozodiacal dust disk brightness of at least 10 stars will be measured as part of the deep dive strategy for Objectives 1 and 2.

#### Discussion

The zodiacal dust disks, also called "warm dust disks," like our asteroid belt are not detectable with any existing ground-based or projected space-based telescopes. While the LBTI Hunt for Observable Signatures of Terrestrial planetary Systems (HOSTS) survey [10] studied 38 stars with a sensitivity 5 to 10 times better than previous surveys for an individual star, the survey was not able to robustly inform on the presence of warm dust down to solar system levels. The study did assume a log-normal distribution anchored by new and already known zodi detections (ranging from 85 to 2,700 zodi). Based on 2 detections out of 23 stars without previously known cold dust excess and extrapolated down to a low-zodi tail, the study estimates a median of 4.5 zodi.

The Starshade Rendezvous Probe would be the first observatory with the capability to reach down to solar system zodi levels. The WFIRST CGI is the community's first instrument capable of detecting exozodiacal dust down to 5-10 solar zodi at the 3-5 sigma level [13], whereas LBTI was sensitive to ~100 zodi for sunlike stars and measured at longer wavelengths. Starshade Rendezvous Probe will be capable of directly imaging the dust in the habitable zone and will be able to detect dimmer zodi due to its one to two orders of magnitude improved contrast. More specifically, Starshade Rendezvous Probe has an improved inner working angle (IWA) (100 mas vs. CGI's 200 mas) and improved instrument contrast compared to WFIRST CGI (10<sup>-10</sup> requirement for Starshade Rendezvous Probe vs. 5×10<sup>-8</sup> requirement for WFIRST CGI).

Detecting solar system–level exozodiacal dust disks, only possible with the Starshade Rendezvous Probe Mission, will help answer the overarching guiding question, "How does the solar system compare to the planetary systems orbiting our nearest neighboring sunlike stars?" Even though this capability of measuring down to solar system levels will only be on 10 or so sunlike stars, the results will still be critically informative to future space-based imaging missions. The pool of 10 target stars helps to ensure that even if some stars are too contaminated with dust for an Earth-like planet detection, other target stars remain available to be searched.

In addition to the value of measuring the zodi levels, these measurements have intrinsic scientific value as they can be probed for indirect signs of planets, even if the dust brightness is so high it prevents an Earth-like planet from being discovered directly. For bright warm dust disks that are not too massive (with brightness between about 6 to 10 zodi), and have planets over about 4 Earth masses, the planet may sculpt the disk to create patterns such as disk azimuthal asymmetries and clumps [14] (Figure 2-5). In addition, planet collisions (if any) will generate clumps that, over time, may evolve into non-Keplerian orbits as they



**FIGURE 2-5.** The presence of a planet can strongly influence the brightness distribution of zodiacal dust disks. The image is produced with the Exozodi Simulation Catalogue [14] assuming a 5 Earth mass planet at 1 AU. From left to right, the product of the dust grain density  $\rho$ , in g cm<sup>-3</sup>, and size *s*, in mm, varies by an order of magnitude. The structure of surface brightness relative to the maximum shows clear morphological changes in its brightness distribution.

may be disturbed by both radiation pressure and stellar wind that can reveal the presence of exoplanets or planet collisions [15].

Without driving science requirements, a goal within Objective 2, therefore, is to follow up on any planetary systems with an excess of warm dust. Detection of dust disk brightness "bulges" or "clumps" on a spatial scale resolution of half the semi-major axis of the planet orbit will motivate future missions to further investigate the interaction between dust disks and planets.

One target star, epsilon Eridani, is already known to have an outer and inner massive dust disk [10], and a giant planet [16]. Another target star, tau Ceti, is known to have an outer cold dust disk [17] but lacks inner, warm dust, at least at the level detectable by LBTI. Radial velocity measurements have also found potential evidence for five exoplanets around tau Ceti [18], including at least one that is near Earth mass. Both stars are intriguing targets of searches for warm inner dust disks down to solar system levels, with the hope of perhaps revealing more definitive evidence of planets.

# **Objective 3: Giant Planet Atmosphere Metallicity.** Determine the atmospheric metallicity of known cool giant planets to examine trends with planetary mass and orbital semi-major axis, and to determine if these trends are consistent with our solar system.

#### Rationale

In our solar system, the atmospheric composition of the giant planets is a major clue to

their formation. The solar system giant planets, Jupiter, Saturn, Uranus, and Neptune, are located in progressively increasing distance from the Sun, but also progressively decrease in mass and increase in atmospheric metallicity (Figure 2-6). Here, metallicity is used to describe the abundance of elements heavier than hydrogen or helium; carbon is the most easily observed. Carbon abundances in the solar system giant planets are all higher than solar values at 3, 10, and 30 times, respectively, for Jupiter, Saturn, and Uranus/Neptune.

Planet formation models predict and explain these trends through a range of mechanisms. (e.g., Refs. [19-24])—an interplay between accretion of hydrogen-rich gas and "metal"-rich solid material. Observations of transiting planets show a tentative trend of increasing atmospheric metallicity with decreasing mass, but of course have almost no ability to probe a range of semi-major axes and thus may be observing planets that have migrated far from their formation sites. Probing how these trends continue in other solar systems will help test planet formation and migration theories.



**FIGURE 2-6.** The Starshade Rendezvous Probe will test the solar system giant planet atmosphere metallicity vs. mass and semi-major-axis correlation for giant exoplanets. In this plot adapted from Wakeford et al. [25], the correlation of solar system giant planet atmospheric metallicity to planet mass is shown in black bars and gray shaded region. The exoplanet data in shown in red bars with the solar system plus exoplanet results shown in the yellow shaded region. A randomly selected set of 10 known RV targets for Objective 3 is shown in green with 30% uncertainty in atmospheric metallicity assuming they follow the solar system trend.

# *Physical Parameters, Scientific Measurements, and Science Requirements*

The Objective 3 physical parameter is the giant planet atmosphere abundance of carbon (via methane) and oxygen (via water vapor), assuming the planet atmosphere is warm enough so that the water vapor is not frozen into clouds.

The scientific measurements are spectral features of methane and water vapor. Both methane and water vapor have a number of spectral features at visible wavelengths. Methane has spectral absorption features at 730 nm, 790 nm, and 890 nm (Figure 2-4).

The science requirement is a spectral resolution of R=50 and an SNR $\geq$ 15, for a robust detection of a spectral feature. The CGI IFS spectral bandpass 656–800 nm contains both the methane and water vapor spectral features. CGI also has a set of filters optimized for the study of giant exoplanet atmospheres that can be used in starshade observing mode.

To fully explore correlations would also require the giant exoplanet mass, through a combination of Doppler measurements and either WFIRST-CGI imaging or Gaia astrometry.

#### Discussion

The goal is to test whether the atmospheric metallicity vs. planet mass and semi-major axis shows any trend consistent with the solar system giant planet trend (Figure 2-6). Beyond our solar system planets, a handful of transiting hot giant planets have measured metallicities but this sample is highly irradiated (complicating measurements) and likely significantly migrated from their formation sites [25].

The baseline WFIRST CGI in coronagraph mode can obtain spectra for at most 2–3 such planets. Starshade Rendezvous Probe's improved contrast and throughput make it possible to obtain spectra of 10 targets in a modest amount of mission time. These spectra will be highly complementary to observations with JWST and Atmospheric Remotesensing Infrared Exoplanet Large-survey (ARIEL); around sunlike stars, JWST will likely be limited to giant planets with temperatures > 400 K, while the Starshade Rendezvous Probe can access outer solar system planets with temperatures similar to Jupiter (Figure 2-7).



**FIGURE 2-7.** Known and predicted giant planets spectroscopically characterizable with WFIRST starshade, JWST, and a hypothetical high-contrast coronagraph on an Extremely Large Telescope (ELT). Although JWST can characterize dozens of giant planets, the transit sample is necessarily biased to hotter planets and cooler stars; Starshade Rendezvous Probe can obtain spectra of cooler giant planets spanning distinct cloud chemistry (shown at top) and objects similar to our own solar system. Credit: Nikole Lewis and Bruce Macintosh.

#### 2.2 Implementation and Observations

#### 2.2.1 Observing System, Constraints, and Model Approach and Inputs

The Starshade Rendezvous Probe Mission is a first-of-a-kind exoplanet observing system composed of the WFIRST telescope, the CGI sensor integrated on the WFIRST spacecraft, and the Starshade Probe spacecraft. This section describes how the starshade system is designed to meet the science objectives presented in the previous section when combined with the WFIRST-CGI system.

The figure of merit for the driving investigation (Objective 1) is the probability of discovering, constraining the orbits to the HZ, and detecting the presence of water vapor and oxygen in the atmosphere of an Earth-like exoplanet, provided such a planet is present around a nearby sunlike star. The probability of success from requiring orbit constraints and spectral measurements is defined as the target HZ completeness.

The breakdown of the estimate target HZ completeness is shown in Figure 2-8. For each star considered, the orbits are constrained via multiple visits for astrometric observations over the life span of the mission and, if the planet is imaged with



**FIGURE 2-8.** Figure of merit for the habitability and biosignatures investigation is the target HZ completeness, which is broken down into the orbit determination completeness and spectral characterization completeness. Orbit determination depends on the single-visit completeness and the visit schedule, which includes both the number and timing of observations.

sufficient brightness, a spectral measurement will be performed. The orbit determination completeness breaks down to the number and cadence (schedule) of visits and the completeness of each visit. This study assumes that 3 detections with SNR>5 out of 4 visits is sufficient to determine whether a planet is in the HZ with >80% confidence (Figure 2-3). The spectral characterization completeness is the probability that water vapor and oxygen, assuming Earth-like atmospheric abundances, can be detected. This translates to requiring an observation with SNR>20 assuming a spectral resolution R=50 [8].

The single-visit completeness, which is the probability a planet is detected with SNR>5 in any given visit, and the spectral characterization completeness are based on a detailed model of the signal, background, and instrument (Figure 2-9).

**Signal.** The planet's reflected starlight flux density depends on its size, albedo, distance, and illumination phase angle. The range of values assumed for the habitability and biosignature gases investigation are shown in Table 2-1. For the completeness estimates presented here, Earth-like HZ planets are modeled with circular orbits of orbital radius *a* that conservatively spans 0.95– 1.67 AU [26] with planet radii of 1.4 R<sub> $\oplus$ </sub> down to 0.8 *a*<sup>-0.5</sup> R<sub> $\oplus$ </sub> [27]. The orbital radius scales by the square root of the bolometric luminosity of each star to keep the same insolation range as the solar system. Earth-like planets are modeled with Earth's geometric albedo of 0.2 [28] with a Lambertian illumination phase function. Simulations account for



**FIGURE 2-9.** The detailed observatory model used for the sensitivity estimates in this study. Single-visit completeness is determined by IWA, field of view (FOV), and SNR resulting from a planet observed with the Starshade-WFIRST-CGI system. Red boxes are parameters entirely determined by nature, purple boxes are parameters controlled by observatory design, and black boxes are a combination of both. The same model is used for spectral completeness by using the corresponding values for bandpass and end-to-end efficiency.

the observation windows (Section 2.2.2), Keplerian motion, and the associated changes in planet brightness.

**Background.** The main sources of natural backgrounds are the light scattered by zodiacal dust surrounding our own solar system and the starlight scattered by the exozodiacal dust surrounding the planet of interest. In addition to scattered starlight, solar glint results in an additional localized and predictable background. Solar glint has not been included in this study but it will be treated in future work. The solar system zodiacal dust model is based

**TABLE 2-1.** Overview of planet input assumptions. The geometric albedo adopted value is Earth's. Planet size and semi-major axis are drawn from a distribution given by the range shown. Both zodi and exozodi are in units of Earth's zodiacal brightness of 22 mag arcsec<sup>-2</sup>. Exozodi are scaled by the ratio of stellar flux to solar flux and correct for EEID.

Parameter	Value
$A_g$	0.2
Planet Radius	0.8–1.4 R <sub>Earth</sub>
Habitable Zone	(0.95–1.67) √L <sub>sun</sub>
Solar System Zodi	1
Exozodi	4.5

on Ref. [29], which accounts for variations with direction and wavelength. The exozodiacal dust brightness is modeled in units of zodi (22 mag/arcsec<sup>2</sup>) [30]. For exozodiacal dust brightness in this study, a fiducial value of 4.5 zodis [10] is used unless otherwise stated.

Instrument. The Starshade-WFIRST-CGI observatory serves to suppress the stellar background while maximizing the planet signal. The starshade IWA, which is the angular separation beyond which a source has 100% optical throughput, is tuned to observe the habitable zones of nearby sunlike stars. By using a starshade with WFIRST, the flux sensitivity for objects with a separation from the star beyond the IWA is entirely determined by the WFIRST collection area, the WFIRST telescope + CGI end-to-end efficiency with respect to the aperture (Table 2-2), the CGI bandpass, and the target integration time. The key instrument performance parameters are summarized in Table 2-3.

The flux of zodi and exozodi backgrounds are proportional to the solid angle subtended by the point spread function (PSF) core ( $\Delta\Omega_{PSF}$ ), which is inversely proportional to the telescope diameter. **TABLE 2-2.** Detailed account of the WFIRST telescope + CGI end-to-end efficiency with respect to the aperture in Starshade mode for the IFS and direct imaging (DI) channels. The values are given for both the instrument predicted performance based on requirements (Required) and current best estimates (CBE).

	Efficiency				
Contribution	Requ	uired	CBE		
Geometric obscuration of the WFIRST pupil	0.8	82	0.82		
Reflection losses in the telescope optics	0.8	81	0.	0.81	
Reflection & transmission losses inside CGI (exclusive of coronagraph masks)	0.29 0.48 (IFS) (DI)		0.43 (IFS)	0.60 (DI)	
Starshade dichroic beam splitter	0.9	90	0.	90	
Detector effective QE (at end of life)	0.:	0.25		).285	
Core throughput losses due to diffraction from WFIRST pupil	0.34		0.34		
Total	0.015 (IFS)	0.024 (DI)	0.025 (IFS)	0.035 (DI)	

The starshade instrument contrast, which is the fraction of starlight leaked at the IWA, has a predicted performance value of  $4 \times 10^{-11}$  ( $\leq 10^{-10}$  required). This results in a stellar background contribution below the expected zodi and exozodi background, enabling the sensitivity to detect Earth-like exoplanets. The total noise counts,  $n_{bkg}$ , is determined by the combination of background fluxes, the flux sensitivity, and the CGI detector noise contribution of ~10 counts/hour, including noise equivalent dark current (dominant term), clock

**TABLE 2-3.** Overview of Starshade Rendezvous Probe performance capabilities and WFIRST CGI modes used in this study.

Parameter	Predicted Performance
IWA	100 mas
FOV	5 as
Imaging Band	615–800 nm
Imaging End-to-End Efficiency	0.035
IFS Spectral Range	656–800 nm
IFS End-to-End Efficiency	0.025
Spectral Resolution	50
PSF	65 mas
Instrument Contrast	4×10 <sup>-11</sup>

induced charge, and read noise (negligible contribution).

The observation model described here also applies to Objectives 2 and 3. Exozodiacal observations are built into the model of Objective 1. For Objective 3, the planet parameters simply change from Earth-like values to giant exoplanet values.

#### 2.2.2 Implementation of Objectives

Given the model and inputs described in the previous section, implementation of each objective is described below.

#### **Objective 1 Implementation**

To quantitatively consider Objective 1, the imposed required conditions per target are:

Four separate observations (i.e., "visits") during the time a star is visible under starshade and telescope solar exclusion angle constraints (Figure 2-10);



**FIGURE 2-10.** Target star observability windows as constrained by telescope and starshade solar exclusion angles (54° and 83°, respectively). The black dots correspond to the times where the targets, if selected, will be tentatively observed. Each star typically has 2 observing windows ~30 days long each per year. Higher latitude stars have a single observing window per year that is longer in duration. For target list details see Table 2-6.

- Planet bright enough for SNR > 5 detection with ~1 day integration time assuming performance parameters;
- Three successful detections in four visits, to establish an approximate planet orbit; and
- One of the four visits enabling a spectrum of SNR>20 in less than 25 days to detect water vapor and oxygen.

The instrument functional requirements of the STM (Section 2.2.4) directly map to the criteria listed above. These requirements are separated into WFIRST-CGI requirements, which are taken as given, and starshade requirements, which have been designed to meet the objectives in Section 2.1. The paragraphs below describe how the requirements for Objective 1 translate to flux sensitivities via the model shown in Figure 2-9. The contributions to the SNR are illustrated with a concrete example. The target list is presented followed by target HZ completeness estimates to show closure on Objective 1a. Finally, yields by planet type are shown to close on Objective 1b.

The existing instrument functional requirements for the WFIRST-CGI (Table 2-8) result in a flux sensitivity (or noise-equivalent flux), at a central wavelength of  $\lambda = 700$  nm, shown in Table 2-4. The integration time of 1 day for imaging observations is the average time required per target, although it can be allowed to be as high as 4 days for some targets. For spectroscopy observations, up to 25 days can be allocated, based on typical observing availability windows, although the integration time can be shorter to reach an SNR>20, based on the imaging observations.

To illustrate the relative contributions of each background, a list of fluxes and detector counts are shown in Table 2-5, following the model in Figure 2-9. The leading background term is the exozodiacal dust with a 4.5 zodi fiducial value. The solar system zodiacal dust is typically equivalent to 1 zodi but, in general, it varies depending on the position in the sky of the star. Detector noise counts result in a smaller contribution.

**TABLE 2-4.** Flux sensitivities based on required values in the STM (Table 2-8) for imaging and spectroscopy mode observations.

Mode	Flux Sensitivity at 700 nm	Integration Time		
Direct Imaging (DI)	1.6×10 <sup>-25</sup> W m <sup>-2</sup> nm <sup>-1</sup>	1 day		
Spectroscopy (IFS)	1.4×10 <sup>-25</sup> W m <sup>-2</sup> nm <sup>-1</sup>	25 days		

**WFIRST-CGI Requirements.** The bandpass (615–800 nm for imaging and 656–800 nm for spectroscopy) is tuned to be sensitive to water vapor and oxygen absorption lines at 720 nm and 760 nm, respectively. The field of view of 5,000 mas (imaging) and 750 mas (spectroscopy) enables observations well beyond the habitable zones of the nearest sunlike stars, providing the potential for discovery and characterization of giant outer planets.

**Starshade Requirements.** The IWA of 100 mas corresponds to a separation of 1 AU at 10 pc, enabling observations of Earth-like planets in the habitable zones of the nearest sunlike stars (Table 2-6). The starshade bandpass requirement of 26% is compatible with the bandpass filters that are used in the CGI instrument in imaging mode. In the illustrative example in Table 2-5, required instrument contrast of  $10^{-10}$  results in a noise contribution comparable to the solar system' zodiacal dust. Instrument contrast values below the requirement result in small improvements to the sensitivity while values above the requirement can become the dominant noise contribution, depending on the exozodiacal dust brightness.

**Target Selection.** The selection of targets shown in Table 2-6 is based on completeness assuming a 24-hour integration time. Stars with nearby optical companions (such as binaries) resulting in additional light leakage comparable to the starshade instrument contrast are not included in the list. Note that all 16 stars in this list will not necessarily be visited. The 10 most promising stars will be given priority for at least one visit. The decision to revisit will be based on the exozodiacal dust disk brightness measured in the initial observation and whether or not planets are detected in follow-up observations (Section 2.2.3).

<b>TABLE 2-5.</b> Example detector count budget
assuming an Earth in tau Ceti resulting in an
imaging SNR=20.

Contribution	Flux Density at 700 nm	Counts (1 day integration)
Earth at 45° Illumination Phase	2.9×10 <sup>-22</sup> W m <sup>-2</sup> nm <sup>-1</sup>	1,830
Exozodiacal Dust (4.5 zodi)	7.1×10 <sup>-22</sup> W m <sup>-2</sup> nm <sup>-1</sup>	4,500
Solar System Zodiacal Dust	1.5×10 <sup>-22</sup> W m <sup>-2</sup> nm <sup>-1</sup>	990
Leaked Starlight	1.3×10 <sup>-22</sup> W m <sup>-2</sup> nm <sup>-1</sup>	820
Detector Counts	-	240

	HIP	Common Name	d(pc)	Vmag	Teff (K)	SpType	Completeness
1	16537	epsilon Eridani	3.7	0.35	5146	K2.0V	0.74
2	8102	tau Ceti	3.7	3.5	5283	G8.5V	0.71
3	37279	Procyon A	3.5	0.40	6543	F5IV-V	0.69
4	108870	epsilon Indi A	3.6	4.7	4683	K4V	0.66
5	32349	Sirius A	2.6	-1.4	9580	A1.0V	0.62
6	19849	omicron 2 Eridani	5.0	4.4	5151	K0.5V	0.67
7	97649	Altair	5.1	0.76	7800	A7IV-V	0.55
8	99240	delta Pavonis	6.1	3.5	5590	G8.0IV	0.64
9	15510	82 Eridani	6.0	4.3	5401	G8.0V	0.70
10	96100	sigma Draconis	5.8	4.7	5246	G9.0V	0.63
11	2021	beta Hyi	7.5	2.8	5873	G1IV	0.56
12	61317	beta CVn	8.4	4.2	5930	G0V	0.61
13	22449	1 Ori	8.1	3.2	6424	F6V	0.50
14	91262	Vega	7.7	0.030	9519	A0Vvar	0.60
15	86974	Mu Herculis	8.3	3.4	5641	G5IV	0.60
16	113368	Fomalhaut	7.7	1.2	8399	A3V	0.58

**TABLE 2-6.** Nearest neighbor single sunlike or larger stars. Completeness is single visit completeness.

The Starshade/WFIRST system is able to observe stars if they are between 54° and 83° degrees from the Sun. This results in observation availability to two windows per year that are typically 30 days long each. For higher ecliptic latitude stars, the window can be significantly longer. The observing windows for the targets in the list are shown in Figure 2-10.

Completeness Estimates. The completeness estimates are based on simulations that include propagation of Keplerian orbits and the observing time window constraints in Figure 2-10. For the exozodiacal dust at Earth equivalent insolation distance (EEID), a fiducial value of 4.5 zodi is assumed. For each target, the total HZ completeness

is listed encompassing a single visit detection, orbit determination (at least 3 detections (SNR>5) in 4 visits), and spectral characterization (at least one spectral measurement with SNR>20 in the 4 visits).

Figure 2-11 shows simulation results for singlevisit, orbit determination, spectral characterization, and the target HZ completeness (requiring both orbit determination and spectral characterization). The difference in completeness assuming the instrument function requirements compared to predicted performance (Table 2-8) is almost entirely due to the end-to-end efficiency of the WFIRST CGI. The main limitation is spectral characterization completeness. For the brightest targets, spectral characterization completeness is high (>20%) but as the expected



Requirements

FIGURE 2-11. Completeness estimates. The completeness of each target is estimated individually with the results sorted from best targets (top) to least sensitive targets (bottom). The right-hand plot uses the instrument functional requirements and the left-hand plot uses the instrument predicted performance (CBE) in Table 2-8. Single-visit, orbit determination, spectral characterization, and target HZ completeness are defined in the text.

Earth-like planet flux density decreases, 25 days is not sufficient to achieve a spectral SNR>20. Even for these targets, the probability of detection and orbit constraint of habitable exoplanets is high, and lower SNR spectra will be sensitive to some atmosphere types. This knowledge will feed forward to future observatories such as the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR).

This analysis assumes an average observation time of 1 day per imaging observation. For spectroscopy mode, up to 25 days of integration time are allowed but it can be shorter, based on the brightness measured by imaging. The spectroscopic observation is made in any one of the 4 visits where the imaging brightness of the Earth-like exoplanet candidate indicates an SNR>20 can be obtained. Other than the observing window limitations on integration time, the analysis presented so far is on a per-target basis and has not assumed any constraints on retargeting time or total mission duration.

The expected number of Earth-like exoplanets detected, assuming the value of  $\eta_{Earth} = 0.24$  adopted by the EXOPAG SAG-13 [32] is ~1.3. With the additional requirements that it be spectroscopically characterized with SNR  $\geq 20$  and that the orbit is constrained to the habitable zone, the expected yield is ~0.4. It is worth noting that the 1  $\sigma$  uncertainty interval estimated by SAG-13 is [0.08, 0.7], nearly spanning an order of magnitude.

Increasing the end-to-end efficiency of the CGI instrument results in significant improvements to Earth-like exoplanet sensitivity. This analysis shows that with CGI requirements and a starshade, it is possible to detect the oxygen and water vapor absorption lines (spectral SNR>20) for the ~4 nearest sunlike stars, provided an Earth-like exoplanet is present, with the assumption of an exozodiacal dust disk brightness of 4.5 zodi. With the predicted performance of CGI and starshade, the number doubles to ~8 targets. The integration time window is constrained due to the solar exclusion angles making the end-to-end efficiency of the WFIRST CGI the limiting factor for sensitivity to Earth-like exoplanets.

**Yields for Various Planet Types.** It is important to note that WFIRST observations with starshade will be sensitive to a wide variety of planets. Figure 2-12 shows the expected number of planets discovered by imaging (SNR>5) the stars in the target list with the possibility to obtain spectra with SNR>15. This threshold SNR value is relaxed compared to Earthlike planets because giant exoplanets tend to have more pronounced spectral features. The planet properties and frequency of occurrence are the same as the Exo-S report [31]. These results indicate that ~8 new planets will be discovered in the nearest sunlike stars providing additional information on their planetary system architectures.

#### **Objective 2 Implementation**

The observations for Objective 2 would be carried out alongside Objective 1 on the same set of target stars, without any additional integration time or required capabilities. Assuming a log-normal distribution with a median of 4.5 zodi and standard deviation of 2.5, based on an update to the HOSTS survey results [10], it is expected that nearly half of the targets will have exozodiacal disks with <10 zodi at EEID. Requiring  $\geq$ 10 targets for dust disk measurements for Objective 2 is compatible with the requirements of  $\geq$ 4 targets with revisits for the driving investigation (Objective 1).

Sampling the dust disk distribution does not require spectroscopic measurement, meaning that an integration time of 1 day (on average) or up to 4 days (maximum) is sufficient to obtain a flux sensitivity of 0.5 zodi with 20% uncertainty at EEID. This quality of measurement is sufficient to provide a



**FIGURE 2-12.** Planet yield as a function of planet type and approximate temperature. The yield was obtained based on the single-visit completeness assuming detection with an SNR  $\geq$  5. All observations assume a zodiacal dust disk brightness of 4.5 zodi. The bar chart assumes that the top 10 targets for the habitability and biosignature gases investigation are visited at least once. The planet parameters are taken from the Exo-S report [31]. Each detected planet is amenable to SNR=15 spectra.

direct constraint on the fraction of sunlike stars with exozodiacal dust disks dim enough for detecting and characterizing Earth-like exoplanets. These observations will provide the first sample of the distribution of exozodiacal dust disk brightness at optical wavelengths, which is critical to future direct imaging exoplanet observatories such as HabEx and LUVOIR.

For the aim (i.e., not driving requirement) of characterizing the influence of planets in the dust disk distribution, target stars with bright exozodi (6-10 zodi) that show clumps with  $\geq 10\%$  excess brightness may be revisited up to three more times. Objective 1 takes priority, but in the event that exozodiacal dust is too bright in most stars and systems with the characteristics described above exist, these observations could be executed. These observations will track the motion of dust disk clumps to test whether their orbits are Keplerian, indicative of an associated planet. Provided a target system with this exozodi range and a  $\gtrsim 4 \; M_\oplus$  is found, this measurement will provide a means to probe planetary systems in stars with high levels of exozodiacal dust in their habitable zones.

#### **Objective 3 Implementation**

The goal of Objective 3 is to study correlations between atmospheric metallicity and fundamental



**FIGURE 2-13.** Derivation of required number of targets and atmospheric metallicity fractional uncertainty for Objective 3. Black line: a set of 10 targets is randomly selected to test for correlation between metallicity and mass (assuming it follows the solar system trend) and the statistical significance of the Pearson correlation coefficient (y-axis) is estimated assuming a metallicity fractional uncertainty (x-axis). Purple lines show the results for different sets of 10 targets. The gray band is a range of uncertainties in the Pearson correlation significance.

planetary properties such as mass or semi-major axis. As a fiducial case, the requirements for Objective 3 are based on the quantitative objective of achieving a  $3\sigma$  uncertainty in correlation between mass and atmospheric metallicity. There are currently 17 exoplanets (Table 2-7) with known radial velocity measurements from the NASA Exoplanet Archive with orbital semi-major axes (translating to 170-1,050 mas separations) and radii that make them accessible to the Starshade Rendezvous Probe. Figure 2-13 shows the results of a study to determine the dependence of the Pearson Correlation Significance for various subsets of 10 targets from Table 2-7 and the fractional atmospheric metallicity uncertainty. This study determined that 30% metallicity uncertainty is sufficient to discern a statistically significant correlation. This uncertainty can be achieved with spectral SNR>15 measurements in one or two bands from ~600 to ~800 nm [33].

Starshade + CGI requirements based on the driving investigation (Objective 1) enable the measurement of known giant planet metallicities. Table 2-7 shows the integration times required to achieve SNR>15 for a range of illumination phase angles where a Jupiter-like albedo of 0.5 assumed with radius constrained by the mass-size relation of [34] but capped at 1 Jupiter radius. Integration times are on the order of several days for the majority of targets at favorable illumination angles. These results indicate that 10 spectral measurements can be achieved with a total of 50 days of integration time

# **TABLE 2-7.** Target list for Objective 3 and expected integration times for a range of illumination phase angles $\beta$ . Dashed entries indicate the integration time exceeds 25 days.

		Integration Time (days)				
#	Target	β=45°	β=90°	β=135°		
1	beta Gem b	≤0.1	≤0.1	≤0.1		
2	epsilon Eri b	≤0.1	0.25	4		
3	upsilon And d	≤0.1	0.25	4		
4	47 UMa b	≤0.1	0.4	6.3		
5	47 UMa c	0.4	1.6	-		
6	HD 114613 b	1.0	4.0	-		
7	mu Ara e	1.6	6.3	-		
8	HD 190360 b	1.6	6.3	-		
9	HD 39091 b	2.5	10	-		
10	14 Her b	2.5	10	-		
11	55 Cnc d	4.0	16	-		
12	HD 154345 b	6.3	25	-		
13	GJ 832 b	10	-	-		
14	HD 142 c	10	-	-		
15	HD 217107 c	16	-	-		
16	HD 134987 c	16	-	-		
17	HD 87883 b	25	-	-		

allocated among the most favorable targets. Note that by the time starshade begins operations, this target list is expected to grow providing even more flexibility in meeting the objective. It is assumed that the WFIRST-CGI observations, continued Doppler monitoring, and Gaia will constrain the brightness and orbital parameters prior to starshade operations, so these observations can be precisely planned for maximum planet visibility with no need for revisits. The observing windows for these targets are plotted in Figure 2-14 showing that a target is available for observation at any given time during operations. These measurements will test whether the planet-star atmospheric metallicity correlation is common between sunlike stars, as suggested by planetary formation models, or if there are significant deviations.

#### 2.2.3 Observations

The observation strategy for meeting the science objectives will be based on the decision tree illustrated in Figure 2-15. Prior to the beginning of starshade observations, the targets for Objectives 1– 2 and Objective 3 are prioritized based on best estimates of completeness and target observing windows. The best 10 targets for Objectives 1 and 2 are included in the initial schedule along with 10 targets for Objective 3. The plan is designed to start observations within a few days of the start of the window determined by solar exclusion angles (Figures 2-10 and 2-14).

For targets relevant to Objectives 1-2, it is assumed that the exozodiacal dust disk brightness at optical wavelengths will not be known, at least not to the  $\sim 10$  zodi level. For this reason, the observation plan is designed to remove targets from the list if the first observation finds that their exozodiacal dust disk brightness is  $\geq 10$  zodi, which is unusable for HZ exoplanet searches. If a target is removed, the observation plan will be updated with the next best target in Table 2-6. If the exozodiacal dust disk is ≤10 zodi but no planet consistent with HZ orbit is found, the target is kept on the list for a revisit as a planet could still appear in subsequent observations. The imaging data will be available for analysis within 7 days of the observation based on WFIRST policy. During that time, WFIRST can be used for other observation programs with the starshade standing by. If a planet consistent with a HZ orbit is found, then the imaging data will inform on the brightness of the planet, which determines whether a spectral measurement with SNR > 20 is achievable in the remainder of the observing time window. If that is the case, then, within 9 days of the original observation, the starshade will begin a longer observation in spectroscopy mode. The integration time will be determined by the brightness of the planet determined from the imaging observation limited by the observing window (Figure 2-14), which is typically 25 days.

On the second visit, if no planet consistent with an HZ orbit has been detected, then the target is removed and the observation plan is updated with



**FIGURE 2-14.** Star observability windows for Objective 3 constrained by telescope and starshade solar exclusion angles. The planet observation availability will be determined through a combination of Doppler measurements and either WFIRST-CGI imaging or Gaia astrometry.



**FIGURE 2-15.** The decision tree for Objectives 1 and 2, illustrated for one star (tau Ceti), enables Starshade Rendezvous Probe to adapt its observations as new information is gathered. The 2-year timeline on the bottom of the figure shows the windows available for observations. At each visit, the decision tree determines whether long spectroscopic integration times are executed, whether the target will be revisited, or whether the target will be removed from the Objective 1 target star list.

the next best target in the list. If the planet is detected either for the first or second time, a decision is made based on the data to take a spectroscopic measurement as described above. Spectroscopic measurements are only required to be performed once so if such a measurement was made in the first visit, it will not be repeated.

On the third visit, if the planet consistent with an HZ orbit has only been detected once, no further visits will be planned since at least 3 observations in 4 planned visits are required. However, there is some flexibility in this decision since the third visit will be made in the second year of observations and the science team will have additional information on the exozodiacal dust disk brightness and population of planet candidates in the ensemble of targets already observed. In the event that there are a small number of target systems relevant to Objectives 1–2 left, then this system could have more visits planned. If there are a large number of relevant target systems still available, this revisit priority may fall lower than the priority of these other systems, recognizing revisit priority may evolve as knowledge is gained about each system. Spectroscopic measurements can be triggered based on the criteria discussed above.

A fourth visit will be needed in the event that the planet has only been observed twice before and/or

no spectroscopic measurement has been made yet. At this point, the target observation requirements for Objectives 1-2 will have been met.

The total estimated time needed for carrying out the objectives, including overheads, is 136 days. This estimate is based on assumptions of the underlying Earth-like exoplanet population and exozodiacal dust disk brightness distribution. The estimate is broken down by objective in Figure 2-16.

Objective 1 is estimated to take 65 days, assuming 10 stars are searched and 5 have low enough zodi levels for planets to be discovered. Each star with planets has four visits requiring 1 day



**FIGURE 2-16.** Approximate budgeted time allocation by objective.

(on average) of imaging observations per visit, for a total of 20 days. Since each target is visited at least once for Objective 2, 5 days are subtracted from this estimate as they are already counted. Assuming  $\eta_{Earth}$  of 0.24, up to two Earth-like planets would require at most 25 days of integration time, reaching a total of 65 days for Objective 1.

Objective 2 assumes 1 day per target to reach sensitivity of 0.5 zodi at EEID. For 10 targets, this requires 10 days.

Objective 3 assumes integration times on average of 5 days (planets may not be at the most favorable illumination phase, and assuming planets have albedos ranging from 0.2 to 0.5), for 10 planets yields 50 days for Objective 3.

The overheads are estimated under the assumption that 8 hours of telescope time are needed for aligning the starshade with WFIRST.

Retargeting the starshade is not included in the 136 days since WFIRST can be used for non-starshade observations. However, the propulsion for the number of revisits needed satisfies the number of retargets, as described in Section 4.

The above numbers will be better estimated based on a Monte Carlo simulation using the decision tree presented in Figure 2-15. The reality of planetary systems means that decisions on which target star to observe for how long will be made as

the exozodiacal dust of systems is measured and as planets are discovered.

#### 2.2.4 Science and Traceability Matrix

The STM based on the discussion above is presented in Table 2-8.

#### 2.3 Perceived Scientific Impact

The Starshade Rendezvous Probe Mission has the capability to deliver first-of-a-kind exoplanet direct imaging and spectroscopy results in the next deep dive investigation, decade. А with requirements driven by Objectives 1 and 2, will provide the first examination of planetary systems around our nearest sunlike stars, including their habitable zones, giant exoplanets, and warm dust disks, opening a new frontier. A starshade with WFIRST is the only observatory in the next decade capable of characterizing Earth-like exoplanets orbiting stars similar to the Sun. Objective 3 will determine whether the atmospheric metallicity and mass of known giant exoplanets follows the correlation observed in our own solar system, testing whether there is a trend in planetary formation. Meeting these objectives will begin to answer the driving questions of whether Earth is unique and how the solar system compares to the planetary systems orbiting our nearest sunlike stars.

#### Starshade Probe Benefits from the Perspective of HabEx

The Habitable Exoplanet Observatory (HabEx) is one of four large strategic mission concepts studied by the community in preparation for the Astro2020 Decadal Survey [35]. HabEx baseline architecture relies on a dual coronagraph and starshade high-contrast direct imaging system. These systems operate in a complementary fashion to detect and spectrally characterize exoplanets orbiting nearby sunlike stars. While internal coronagraphs are well adapted to broadband exoplanet searches and detection, a starshade enables detailed spectroscopic studies of faint exoplanets (such as Earths). While coronagraphic observations can be readily obtained by simply retargeting the telescope, using a starshade provides the capabilities required to obtain spectra of faint exoplanets: high throughput, very broad instantaneous bandwidth, small IWA, large FOV, and relaxed optical constraints at shorter wavelengths. All of these are essential to HabEx predicted high sensitivity and ability to gather highquality broad exoplanet spectra with a 4 m aperture.

The HabEx starshade would be on the order of 52 meters in diameter, and provides the bulk of HabEx spectroscopic capabilities, with simultaneous observations from 0.3 to 1 micron at a constant IWA of 70 mas. Planetary spectra taken by HabEx starshade would also extend further in the ultraviolet (down to 0.2 micron) and in the near-infrared (up to 1.8 microns) for favorable targets.

Starshade Rendezvous Probe with WFIRST prior to a possible HabEx mission will be an invaluable demonstration of the type of scientific observations that can be achieved through the first use of starshade technology in space. Such a mission would inform the future development and use of a starshade by HabEx from technological, scientific, and operations perspectives.

#### Starshade Probe Benefits from the Perspective of HabEx (continued)

- **Technology:** At exactly half the size of the HabEx starshade and one-third of its nominal telescope separation, the Probe starshade would demonstrate in space all the starshade key technologies at a relevant scale: starshade petal deployment, petal shape and stability, starshade lateral formation sensing and control, starshade starlight suppression, and model validation at pertinent levels. While all of these technology items are already expected to reach Technology Readiness Level (TRL) 5 by June 2023 following the NASA-funded "S5" starshade technology development plan, the in-space demonstration would no doubt bring a considerable return of experience, helping to further optimize and expedite HabEx starshade design.
- Science: On the scientific side, a successful Starshade Rendezvous Probe mission will:
  - (i) Conduct deep searches for HZ Earths and super-Earths around our 10 nearest neighbors and reveal giant planets orbiting at larger separations. HabEx broad (starshade-based) exoplanet survey nominally includes these nearby systems, which it will observe with significantly increased spectral capabilities and completeness. Initial detections and characterization, including orbit determinations, with Starshade Rendezvous Probe will contribute to prioritizing these targets, a priori, thus increasing the efficiency of the observations and of the overall mission.
  - (ii) Measure exozodiacal dust brightness at unprecedented sensitivity levels in the visible, down to dust densities comparable to our own solar zodiacal cloud, revealing potential dust structures at sub-AU scales. Such information would increase HabEx observing efficiency and help concentrate its starshade slews on the most favorable planetary systems for the deepdive observations.

The 2018 "Exoplanet Science Strategy" (ESS) consensus study report [4], stated prominently that "the exoplanet community needs to develop the means to study potentially habitable planets orbiting more Sun-like stars," and that "a coronagraphic or starshade-based direct imaging mission is the only path currently identified to characterize Earth-size planets in the habitable zones of a large sample of nearby Sun-like stars in reflected light." As a key stepping stone in the perspective of a HabEx-like mission, Starshade Rendezvous Probe is perfectly aligned with these findings and with the ESS report #1 recommendation that "NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars."

#### **TABLE 2-8.** Science traceability matrix.

				Scientific Measurement	Instrument Fun	ctional Requirements	Instrument Pr	redicted Performance	Mission Functional	Mission Functional
			Scientific Measurement	Requirements:					Requirements Common to	Requirements Specific to Each
nvestigation	Goals	Objectives	Requirements: Physical Parameters		Starshade	WFIRST-CGI	Starshade		all Investigations	Investigation
he Nearest olar System nalogs	<ul> <li>NASA Science Plan 2014:</li> <li>Discover and study planets around other stars, and explore whether they could harbor life.</li> <li>New Worlds, New Horizons (2010 Decadal Survey):</li> <li>Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?</li> <li>Discovery area: Identification and characterization of nearby habitable exoplanets.</li> <li>Exoplanet Science Strategy (National Academies of Sciences 2018) Goal 2: to learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside.</li> </ul>	O1a: Determine whether super-Earth size or smaller exoplanets exist in the habitable zone around the nearest sunlike stars and have signatures of oxygen and water vapor in their atmospheres. O1b: Detect and	Exoplanet orbital properties: constrain planet's semi-major axis to the habitable zone of the star with >80% confidence. Abundance of atmospheric oxygen and water vapor: detect Earth-like abundances or greater.	Water vapor absorption line at 720 nm: detect current Earth's atmosphere (15 nm width, $\geq$ 12% depth) with SNR $\geq$ 20 with R=50. Oxygen absorption at 760 nm: detect current Earth's atmosphere (10 nm width, $\geq$ 65% depth) with SNR $\geq$ 20 with R=50. Astrometric planet position and time: capable of at least 3 detections with $\leq$ 13 mas uncertainty (1 $\sigma$ ) in 4 observations spread over 2 years. Number of targets: $\geq$ 4 stars		Telescope (WFIRST): PSF: 65 mas Collection area: 4.4 m <sup>2</sup>	Inner working angle::103 mas Instrument contrast: 4×10^-11 at angular distances greater than the inner working angle. Bandpass: ≥ 26% at	WFIRST-CGI         Telescope (WFIRST):         PSF: 65 mas         Collection area: 4.4 m <sup>2</sup> Instrument (WFIRST-CGI):         Imaging:	Field of regard: 54–83 degrees Sun angle Slew time: requires the ability to retarget within 8 days Launch window: within 2 years of WFIRST launch	Observation time: >120 days for sufficient integration time over a duration of 2 years to track exoplanet orbits. Number of targets: at least 4 targets with 1 spectral measurement for absorption lines and 4 revisits over 2 years to constrain the exoplanet orbit. Observation time for each target: capability of up to 6 contiguous days (1 day on average) for imaging with the ability to trigger a 25-day observation within 5 days from the image.
Brightness of Zodiacal Dust Disks	<ul> <li>New Worlds, New Horizons (2010 Decadal Survey):</li> <li>How do circumstellar disks evolve and form planetary systems?</li> <li>Exoplanet Science Strategy (National Academies of Sciences 2018) Goal 1: to understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes.</li> </ul>	O2: Establish if the zodiacal cloud of our inner solar system is representative of the population of our nearest neighbor stars.	Spatial distribution of dust disk surface brightness ≥0.5 zodi with 20% uncertainty with ≤0.5 AU resolution.	Flux sensitivity to <0.5 zodi with <20% uncertainty at Earth-equivalent insolation distance. Spatial resolution corresponding to 1 AU. Number of targets: ≥12 stars	Inner working angle: ≤103 mas Instrument contrast <=10 <sup>-10</sup> at angular distances greater than the inner working angle. Bandpass: ≥26% at 700 nm					Observation time: >10 days for sufficient integration time. (Note that this is in overlap with and not in addition to the habitability investigation). Number of targets: at least 10 visited at least once (note these targets are in overlap and not in addition to the habitability investigation). Observation time for each target: capability of up to 6 contiguous days for imaging (1 day average).
Metallicity	<ul> <li>by these processes.</li> <li>New Worlds, New Horizons (2010 Decadal Survey)</li> <li>How diverse are planetary systems?</li> <li>Exoplanet Science Strategy (National Academies of Sciences 2018) Goal 1: to understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes.</li> </ul>	known cool giant planets to examine trends with planetary mass and orbital semi-major axis, and to determine if these trends are consistent		Water vapor absorption line depth at 720 nm: measure (15 nm width, ≥30% depth) with SNR ≥15 with R=50. Methane absorption line depth at 730 nm and 790 nm (20 nm width, ≥20% depth) with SNR>=15 with R=50. Number of targets: ≥10 planets	Inner working angle: ≤103 mas. Instrument contrast ≤10 <sup>-10</sup> at angular distances greater than the inner working angle. Bandpass: ≥26% at 700 nm					Observation time: >50 days for sufficient integration time. Number of targets: at least 10 targets with the capability of up to 25 days of observation (5 average). Note: the 10 targets are in addition to the habitability investigation. Observation time for each target: capability of up to 10 days.

## **3 STARSHADE PAYLOAD**

The starshade payload is a large, optically precise deployable mask that when flown along the line of sight between the Wide Field Infrared Survey Telescope (WFIRST) and a target star, blocks the starlight, making exoplanet detection and characterization possible.

To perform the mission, the following are required: launch and deployment of the starshade, formation flying of the starshade spacecraft with the WFIRST spacecraft, and retargeting maneuvers of the starshade within associated propellant requirements. This section gives a summary of the starshade system including science drivers, concept of operations, and mechanical system, followed by a description of deployment. Section 4 provides more detail on formation flying and retargeting.

#### 3.1 Starshade/WFIRST System

The Starshade/WFIRST system includes two spacecraft: the starshade spacecraft and the WFIRST observatory (Figure 3-1). The starshade spacecraft itself is comprised of two major elements: the starshade bus and the starshade occulter payload. Section 3.4 discusses the three starshade mechanical subsystems: 1) petal, 2) inner disk, and 3) the Petal Launch Restraint Unfurl System (PLUS).

The starshade payload is designed to meet the science objectives described in Section 2 of this report. The payload design, a 26-meter deployable-in-space starshade, is enabled by and based upon the technology developed under NASA's Exoplanet Exploration Program [1].



The following subsections describe the key science requirements that drive the starshade payload design. Further detail on the requirement flow down is presented in Section 4, Design Reference Mission.

#### 3.2.1 Inner Working Angle and Contrast

The requirements from science drive specifications on inner working angle (IWA) and contrast at a specific wavelength. These in turn drive the engineering variables: starshade radius and starshade distance.

References [2] and [3] provide background material on scaling and sizing the starshade. This mission borrows the concept (Ref. [2], Figure 5) that the solution space can be described in the starshade radius / starshade telescope distance plane. Figure 3-2 illustrates the team's design point with a 13 m radius and IWA = 103 milliarcsec at Fresnel number equals 8.1.

A Fresnel number is a dimensionless parameter, widely used in scalar diffraction theory and determines the scaling of the size and distance of a starshade. For a given mask shape, along the curves of constant Fresnel number, the diffraction pattern in the image plane is preserved, but scaled in size.

Because the diffraction pattern defines the contrast, it too is preserved. This means that once we have a defined mask with desired contrast, we can then scale that mask to a size that meets the other key science requirement, IWA. Such a mask has been developed by the S5 team. The following design detail is for a starshade mask that achieves

 $4 \times 10^{-10}$  contrast with appropriate margin ( $1 \times 10^{-10}$  required).

In Figure 3-2, the minimum size starshade, 26 m diameter, at minimum distance, 26,000 km, is used to simultaneously achieve both the contrast requirement  $1 \times 10^{-10}$  and the IWA = 103 mas.

It is useful to consider other design points to elucidate the usefulness of the Fresnel number. If science requirements demanded the same contrast with a smaller IWA, say 74 mas, Figure 3-2 shows that an 18-meter radius (36 diameter)



FIGURE 3-1. System elements and definitions.



**FIGURE 3-2.** Solution space for probe study showing three different IWAs and two wavelengths. The purple and green curves are lines of constant Fresnel number, F=8.1.

starshade flying at 50,000 km in front of WFIRST would be needed. Alternatively, if science relaxed IWA to 190, a 7 m radius (14 m diameter) starshade flying at 7,500 km could be used. In fact, going further to the left on the green F=8.1 curve leads to very small starshades with larger IWAs, which are extremely useful for ground testing to validate the diffraction models.

#### 3.2.2 Flux Sensitivity

Another science driver is flux sensitivity. With the sensitivity of WFIRST/CGI instrument taken as a given, the limiting factor is stray light from the starshade. The starshade, having very little angular separation from the exoplanet, must not emit or scatter stray light (for example, from the Sun) into the telescope at a level that impairs exoplanet imaging performance. Less scattered light is always better, but reducing the stray light below the limit imposed by resolved foreground and background light does little to improve the mission science yield.

#### 3.2.3 Mission Duration

The Starshade Rendezvous Probe Mission is a 2-year prime mission, with a 1-year extended mission. The payload must deploy and maintain thermal mechanical stability for a minimum of 3 years (design lifetime) in the Sun-Earth L2 space environment.

#### 3.3 Contrast Error Budget

The contrast error budget is the tool used to balance and suballocate science driven contrast requirements to engineering requirements. The contrast error budget addresses all key characteristic features that impact the amount of undesirable light reaching the image plane from: the target star, from stray light, and other sources. The spreadsheet-based error budget has been in development for nearly a decade [4-7].

Our approach remains fundamentally unchanged although the fidelity of the tool has significantly improved. The electric fields at the focal plane of the telescope have been analyzed using diffraction algorithms that have been independently developed [4, 8, 9] and tested against laboratory data [10, 11]. The analysis is performed as a function of both wavelength and working angle. The error budget is a bottoms-up summation of all the significant errors resulting in a prediction of the mean expected contrast at different radial positions in the telescope image plane (Figure 3-3).

#### 3.3.1 Starshade Shape Errors

For starshade shape errors, we model the leakage of starlight to the telescope image plane from a large number of independent starshade perturbations, each assumed to be drawn from a normal distribution with an allocated standard deviation. The perturbations fall into the categories of petal shape, petal size, petal position. and formation flving. The shape are applied assuming random perturbations uncorrelated errors, e.g., each petal has a random orientation error, as well as uniformly, e.g., all petals are radially displaced by the same amount.

Allocations begin with a current best estimate (CBE) and contingency based on either tested prototype hardware [12, 13], or engineering and experience lightweight analyses with deployables where test verification on hardware has not yet occurred. The contingency estimate is typically a factor of 25% to 100% depending on the nature of the error source. For manufacturing errors, such as on the shape of the petal edge, the contingency allows for the additional complexity expected with real flight hardware compared to the prototype hardware. For thermal errors, a 100% contingency is applied and will be held until thermal cycling tests have been performed.

#### 3.3.2 Margin Philosophy

When rolling up individual performance contributions, the combined maximum expected (ME = CBE + contingency) allocations lead to a top-level performance prediction that is considerably better than the required contrast of  $10^{-10}$  at the IWA. The difference between the ME contrast and required



FIGURE 3-3. Contrast error budget block diagram.

performance is held as margin. A contrast performance margin of 50% is set aside at the top of the shape error budget. Then, additional engineering margin of 41% (manufacturing and deployment) to 100% (thermal) are applied throughout the error budget in addition to the aforementioned contingency.

#### 3.3.3 Scattered Light Errors

Sunlight, starlight, and planet light may scatter off the telescope-facing side of the starshade. The most significant instrument contribution to scattered light is expected to be solar glint from the starshade edges. Optical edge scatterometry has been performed on both specular and diffuse edges [14, 15] resulting in a baseline design employing a sharp, smooth edge [16].

Contributions including leakage due to micrometeoroid holes in the optical shield, and reflection of astrophysical sources from the telescope-facing surface, are also included [6]. The leakage and reflection are expected to be fainter than exozodiacal light surrounding the target star, while solar glint will have local components that are brighter than the exozodiacal light.

#### 3.3.4 Driving Requirements

The starshade requirements that flow down from science performance requirements through the contrast error budget are summarized in Table 3-1.

#### 3.4 Mechanical System

The 26-meter starshade is a passively controlled precision optical structure. To meet mission performance requirements, the starshade mechanical system must reliably deploy on orbit, and meet its shape accuracy, stability, and stray light requirements. The mechanical system is based on existing heritage deployable structure technology. Maximum use of heritage minimizes uncertainty in technology development and flight implementation.

The approach allows the precision structure of the starshade mechanical system to be functionally separated into two distinct subsystems: 1) the petal and 2) inner disk, which have separable requirements. A third subsystem, PLUS, restrains and unfurls the petals through launch and on-orbit, respectively, and is then jettisoned before the science mission.

TABLE 3-1	<ol> <li>Summary o</li> </ol>	f driving re	quirements.

Requirement	Description	Threshold Value
Starlight Suppression	Instrument contrast	1×10 <sup>-10</sup>
Solar Scatter	Lobe brightness visual magnitude	V ≥ 25 mags
Lateral Formation Sensing & Control	Later position sensor accuracy that supports ±1 m control	≤ ±30 cm
Petal Shape	Pre-launch accuracy	≤ ±70 µm
	On-orbit thermal stability	≤ ±80 µm
Petal Position	Pre-launch accuracy	≤ ±300 µm
	On-orbit thermal stability	≤ ±200 µm
Figure 3-4 shows how these subsystems combine to form a complete starshade.

The mechanical system is decoupled by design, in that the deployments of the petals, and the truss are sequential and independent from each other via separate mechanisms, as shown in Figure 3-5. Deployment will be discussed in more detail in Section 3.5.

## 3.4.1 Inner Disk Subsystem

The starshade inner disk is an adaptation of the Astromesh antenna perimeter truss, and is the core of the structure to which the petals attach. The Astromesh antenna is lightweight, precise, and has a large deployed diameter to stowed diameter ratio, allowing for very large deployed diameters that fit within a small fairing. The Astromesh antenna has successfully deployed at least nine times on orbit, providing confidence in the deployment technology [17].

The entire disk is covered with an inner disk optical shield, consisting of multiple layers of carbon impregnated black kapton, a material that meets the opacity requirements. Separation between the kapton layers mitigates the effect of micrometeoroid impacts by reducing the percentage of micrometeoroid puncture holes that will provide a direct path for starlight to enter the telescope. The

inner disk optical shield fold lines are designed to spirally wrap with no stowed strain energy in the negative space between the perimeter truss and the hub in the stowed configuration. Upon deployment, the optical shield has no surface accuracy or in-plane profile requirements, just the opacity requirement.

## 3.4.2 Petal Subsystem

To fit within the launch vehicle fairing, the petals must furl, or wrap. To deploy, the petals unfurl, illustrated in Figure 3-5. The mechanical design wraps the petals spirally around the stowed perimeter truss for launch. This is similar to the way ribs are stowed in the Lockheed wrap-rib design.

It is important to note that wrapping of the petals is in the out-of-plane direction, so as not to directly strain the in-plane shape of the petal, the critical dimension for petal performance. Unfurling the petals is accomplished quasi-statically with the PLUS, a separate "unfurl" mechanism, discussed in Section 3.5.1.

The starshade petal is designed to be a thermally stable structure, which does not require the articulation of any joints or tensioned members. Figure 3-6 shows its detailed construction. The petal is a thin and gossamer carbon fiber composite structure. As manufactured, the petal meets its inplane shape requirements, most critically its width.



FIGURE 3-4. Major mechanical subsystems.

The stability of the petal width is provided by thermally stable pultruded carbon fiber composite tubes-battens that hold the petal structural edge. The optical edge is provided by discrete meter-long segments that are bonded to the structural edge at precise locations along its width and at the petal tip. The optical edge has the precise shape profile that provides the starlight suppression. The optical edge is manufactured from a thin strip of amorphous



FIGURE 3-5. Starshade deployment.

ed 3.4.3 Petal Launch Restraint Unfurl System

metal alloy, with a sharp bevel chemically etched into it that limits stray light into the telescope (see the inlay in Figure 3-6). The entire petal is loosely covered with the same opaque optical shield material as covers the inner disk.

The petals are made thin so that they can be wrapped for launch, but it is desirable that they be stiff after deployment. The out-of-plane stiffness of a deployed petal is provided via two ribs running the length of the petal that attach near its base to the perimeter truss at a distance from the petal plane. These ribs are piano-hinged on the petal and passively deploy via reliable and redundant overcenter sprung hinges.

## Once on orbit, the petal preload mechanisms on the cage posts are released, at which point each petal is only lightly preloaded by its furled strain energy by the restraining roller assembly on the post that is centered vertically on the petal, aligning with the petal central spine.

PLUS is a large carousel assembly that rotates about the spacecraft hub long axis (Figure 3-4). For launch, the PLUS is locked in rotation, and the vertical cage posts around its perimeter serve as an external boundary condition that preloads radially aligned launch restraint interfaces on the



FIGURE 3-6. Details of starshade petal.

central spines of the spirally wrapped stack of petals. Two petal edge restraint features extend tangentially from the top and bottom of the vertical cage posts to control dynamic excitation of the petal edges during launch and also align with radially oriented features on the petal battens, the width-wise members of the petal.

## 3.5 Deployment

## 3.5.1 Petal Unfurl

First, the carousel rotational constraint is released. Then a single, redundant motor system slowly and deterministically rotates the carousel with respect to the wrapped petals, allowing for controlled release of the petals' furled strain energy and ensuring no damage to the petals' edges. Once the petals have fully unfurled, they passively rotate to a radial orientation in response to torsion springs in the hinges that attach them to the perimeter truss, with the roller assemblies continuing to provide restraint through the rotation. The vertical cage posts are then released to rotate radially down and out of the way of the petals/truss system, via a release mechanism and torsion spring, allowing for the entire PLUS subsystem to be jettisoned before truss deployment. During petal unfurling, the perimeter truss remains stowed. Figure 3-7 shows the JPL test article undergoing petal deployment test.

## 3.5.2 PLUS Jettison

After the completion of petal unfurling, when all the petals are at 90 deg tangential to radial as in Figure 3-5, top-right image, the PLUS must be jettisoned. The 90-deg petal orientations allow for clearance for the PLUS arms (also called vertical cage posts) and can be swung out of the way.

## 3.5.3 Perimeter Truss Deploy

After the PLUS is jettisoned, the perimeter truss can be deployed. Deployment is controlled by a motorized spool that reels in a braided steel cable that serpentines the truss diagonals, unfolding and expanding the perimeter truss as shown in Figure 3-8. The deployment of the truss pulls out the





FIGURE 3-7. Test article petal unfurling.





spirally folded opaque optical shield. ADAMS models of truss deployment are well developed and correlation to hardware is very good.

The truss is composed of thermally stable carbon fiber composite tubes, 'longerons,' which form a perimeter ring that is placed in compression upon final deployment. The carbon fiber composite spokes that connect the ring to the central spacecraft hub are in tension (much like a bicycle wheel).

The truss deployment rotates the longerons, to which the petals are attached, from vertical to horizontal, rotating the petals into their radial and planar state through a single actuation. This stiffens and thus stabilizes the structure to which the petals attach.

The perimeter truss deployment is fundamentally the same as that successfully used in the Astromesh antenna [17]: However, starshade truss longerons are much stiffer than Astromesh lightweight members.

## **4 DESIGN REFERENCE MISSION**

This section presents the Design Reference Mission (DRM) for the Starshade Rendezvous Probe Mission. It serves as the baseline for the costing in Section 5. The DRM includes results from JPL's Team X study [1] with input from the Goddard Space Flight Center (GSFC) Mission Design Lab (MDL). The DRM is driven by the target observation schedule, integration times, and revisits. Table 4-1 presents key mission parameters and features as a summary.

The baseline DRM is a Class B mission based on a chemical propulsion bus with a 2-year science prime mission, plus a 1-year extended mission. In addition to the GSFC baseline bus, the team also studied several commercial bus variants, including the Ball Aerospace BCP500, the Ball Deep Space bus, and Lockheed Martin's LM-2100.

#### 4.1 Retargeting Delta-V

Delta-V requirements flow directly from the science observation schedule, and, in turn, drive propellant mass. Because the Starshade Rendezvous Probe Mission involves a lot of maneuvering, the more delta-V, the more targets can be observed. The retargeting slews were optimized to maximize observation time while minimizing delta-V.

TADLE T-I.	wiission summary.	
Orbit type	Sun-Earth L2 Halo	
Mission Class	Class B	
Mission	2 years prime mission	
Duration	1 year extended mission	
D-14- 1/	1,400 m/sec total	
Delta-V	1,100 m/sec for retargeting	
	Dual Mode System	
Duanulaian	Biprop for retargeting	
	Monoprop for attitude control system, formation	
	control	
Launch Mass*	3784 kg	
	Peak: 1054 W at deployment	
Power	Science and retargeting 660-747W met with	
	>30% margin	
	DSN 34 meter antenna:	
Navigation	Nominal 2 hours/day, 3 days/week	
-	4 days/week during maneuvers	
	Interspacecraft S-band RF link	
Formation	Acquisition: 100 km beacon and camera	
Sensing	Science: ±1 m using diffracted starlight in pupil	
<u> </u>	plane imager	
Attitude	3-axis stabilized for retargeting maneuvers	
Control	spin stabilized 0.33 RPM for science observations	

TABLE 4-1. Mission summary.

\* The TeamX report indicates 4% less dry mass margin than that recommended by the JPL design principles (Section 6.3.2). With mass reduction on the order of 100 kg the required margin of 30% will be met. This can be achieved by a more detailed design of the payload and in particular of the PLUS system on the payload.

The target list is set by the science team to meet science Objectives 1–3. Then, the target observations are integrated into the science observation schedule. Figure 4-1 shows an example two-year observation schedule integrated into the



**FIGURE 4-1.** Mission timeline. Red line segments are translational retargeting slews (described in Section 4.4), which may take a couple days up to two weeks. Each red dot is a single day's observation. The horizontal bars represent time windows where the starshade to Sun angular constraints have been met and the star is possible to observe. The observation days are chosen to be at the beginning of the window.

mission timeline and the delta-V costs for each retargeting maneuver.

### 4.2 Concept of Operations

#### 4.2.1 Launch and Early Mission Operations

The starshade spacecraft would launch from Cape Canaveral in January 2029 on a Falcon 9 expendable booster. Near-continuous Deep Space Network (DSN) tracking with a 34-meter antenna is required for the first week. During this time, the rest of the spacecraft systems are checked out with high downlink data rates.

The first trajectory correction maneuver (TCM1) occurs on mission day 3 (Figure 4-2) and is performed with the main engine. The purpose of TCM1 is to remove launch injection errors. This first burn is statistical and could be as high as 50 m/sec, and must be performed early as the delta-V cost to correct launch errors grows very rapidly.

After TCM1, the operations team must deploy the starshade. Deployment (described in Section 3.5) has three sequential steps: a) petal unfurl, b) Petal Launch Restraint Unfurl Subsystem (PLUS) jettison, and c) inner disk deploy. It is important to note that the PLUS is only needed for starshade petal deployment and must be jettisoned before the inner disk deployment. PLUS jettison significantly reduces mass for the next maneuvers.

TCM2 is required to set up the L2 insertion phasing conditions and is executed at about



FIGURE 4-2. Starshade mission trajectory.

L+30 days. Thirty days after that, at around L+60 days, the starshade spacecraft performs the L2 insertion burn to rendezvous with the Wide Field Infrared Survey Telescope (WFIRST) and start science operations.

#### 4.2.2 Science Operations

Once the starshade spacecraft is in L2 halo orbit, the spacecraft will perform all of the translational maneuvering. WFIRST participates in acquisition and formation control but does not maneuver for the Starshade Rendezvous Probe. There are four operational phases repeated for each stellar target: initialization, acquisition, science, and retargeting (Figure 4-3). The approach outlined here is evolved from Scharf et al. [2].



FIGURE 4-3. Overview of starshade concept of operations.

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The Starshade Rendezvous Probe Mission will have a minimal impact on WFIRST operations. WFIRST will be performing multiple types of surveys/observations and starshade science will just become another type of observation to accommodate. Dedicated blocks of time will be negotiated for starshade observations as part of the overall planning. WFIRST activities will be folded into the eventdriven operations sequences that get loaded to the WFIRST observatory. In parallel, starshade activities will be loaded to the starshade spacecraft. When it is time for the starshade science block, WFIRST will slew to point towards the target star and the spacecraft-to-spacecraft S-band communications link will be enabled (Section 4.4.3). A limited number of status flags will be passed back and forth between the two spacecraft to trigger the initialization.

Initialization. After the starshade spacecraft reaches L2 halo orbit, it will rendezvous with the observatory. Ground-based WFIRST orbital determination of both the telescope and starshade are used to issue commands to the starshade to move it from its initial orbit to alignment between the telescope and the first target star to within 100 km absolute accuracy. At the close of this phase, a laser beacon on the starshade will be within the 3,000 arcsec field of view (FOV) of the starshade acquisition camera (SAC) on WFIRST (Section 4.4.1). Throughout science operations, when the communications link is operating, radio range accuracy is  $\pm 0.5$  km.

Acquisition. First, the ground commands the WFIRST observatory to point at the target star. Ground also commands the starshade spacecraft to enable the beacon. WFIRST measures the starshade offset with the SAC and relays to the starshade. The measurements are processed on board the starshade into a TCM command. After a small maneuver, the starshade spacecraft's beacon will be within the FOV of the direct imager (within  $\pm 4$  arcsec). A final pulse is commanded to bring the starshade spacecraft within 10 meters of the line of sight (LOS) between the telescope and the target star. The starshade will then be within the FOV of the low order wavefront sensor (LOWFS) and ready to start science.

Science. The lateral position of the starshade relative to the telescope/LOS is sensed using the LOWFS pupil plane detector in the Coronagraph Instrument (CGI). The lateral sensing accuracy is  $\leq$ 30 cm. Performance is based largely on the

inherent properties of the optics (e.g., pixel scale and signal-to-noise ratio [SNR]).

The LOWFS captures images of the leaked of out-of-science passband starlight around the starshade (see Section 4.4.2). Minimum impulse bits from the 1 lbf engines will provide control.

Once the starshade is within 1 meter of the LOS, it will use coupled 1 lbf thrusters to slowly spin up around its optical axis to 0.33 RPM. Spinning up provides spin stabilization during exoplanet observations and also averages out petal edge glint and residual diffraction artifacts. To maintain control on the LOS, the 1 lbf thrusters must fire about every 10 minutes.

A science observation can be anywhere from a single day to several weeks. At the end of the observation period, the starshade spacecraft spins down to prepare for translation to the next target star.

**Retargeting.** This phase is similar to the initialization phase, except that it begins at the end of a science phase and repositions the starshade to the next target star. Before retargeting, the position of the starshade spacecraft on the LOS is well known; ground-based orbit determination is not expected to be necessary to calculate the first burn of retargeting.

The translation maneuvers are broken into three TCMs: ramp up, ramp down 1, and ramp down 2 (Figure 4-4). Each ramp maneuver fires the main engine continuously to attain a desired slew velocity. The burns take on the order of hours to days. The translational slews could take up to two weeks. After the ramp-up burn, the DSN will be able to get Doppler range rate of the starshade. This information will help refine the prediction for the ramp-down burns. The first ramp-down burn removes most of the



FIGURE 4-4. Single observation operations timeline.

velocity with respect to the target. More DSN tracking will help improve the final burn. The second ramp-down burn removes all remaining velocity and places the starshade within 100 km of the next target position, at zero relative velocity. Then, the four phases repeat for the next science observation cycle.

A future trade study will evaluate in more detail the navigation solution. It may be possible to blend DSN navigation with onboard accelerometers to achieve a lower cost and higher performing system.

## 4.2.3 Extended Mission and Disposal

After the prime science mission is completed, the science team has the option to revisit targets of interest, perhaps to take longer duration spectral observations, or revisits to refine orbit determination. The extended mission delta-V is sized for a repeat of one year of the prime mission, but it is not likely to unfold that way. The extended mission will be proposed based on the scientific findings of the primary mission.

The mission ends when the propellant is consumed. The spacecraft will be disposed in L2. Since this is an unstable trajectory, the disposed starshade spacecraft will eventually end up in a near-Earth-sized solar orbit. No disposal burn is required.

## 4.3 Coronagraph Instrument on WFIRST

The Starshade Rendezvous Probe Mission is enabled by the WFIRST CGI (Figure 4-5), which is already in development. On WFIRST, the CGI's mission is to characterize roughly a dozen known exoplanets previously detected with radial velocity techniques, and photometrically discover new planets down to super-Earths. The CGI includes an imaging camera and an integral field spectrograph (IFS). The Starshade Rendezvous Probe uses both the CGI



FIGURE 4-5. WFIRST CGI.

camera and spectrograph to enable detection and characterization of Earth-sized planets in the habitable zone, and the CGI direct imager and LOWFS for rendezvous and formation control (see Section 4.2.2).

## 4.4 WFIRST Accommodations

The WFIRST observatory includes several functions required by the Starshade Rendezvous Probe Mission. WFIRST development is well underway and the starshade team has flowed requirements to WFIRST through an Interface Requirements Document (IRD) [3].

As shown in Figure 4-4, WFIRST participates in rendezvous, formation control, and science. There are four areas of impact to WFIRST, each with a unique feature: SAC, formation control sensing and commanding, S-band radio, and coronagraph filters.

## 4.4.1 Starshade Acquisition Camera

The SAC on WFIRST is used to acquire the starshade beacon after each retargeting slew. The SAC must be able to simultaneously image the starshade with the illuminated beacon, and a 0 to 6th magnitude background star in order to measure the angular offset between the starshade and the target star. Measurement data from the SAC is used to guide the starshade to the target star in order to acquire the target star on the 4×4 arcsec CGI direct imager FOV. To accomplish that, the SAC must have a measurement error no greater than  $\pm 2$  arcsec within its 6,000 arcsec FOV (Table 4-2).

The starshade requirements described here have been incorporated into the WFIRST baseline.

"Current plans call for a technology demonstration of the WFIRST CGI using 90 days of noncontiguous observations during the first 18 months post-commissioning. Following this, there will be an evaluation of the CGI performance to determine if continued use is warranted by the demonstrated capabilities. WFIRST is also designed to be starshade ready. If a starshade is launched, this evaluation would include the possibility of both CGI-only and starshade operations for the remainder of the 5-year primary mission and any extended mission. Even devoting substantial time to starshade and CGI observations would allow WFIRST to accomplish its primary scientific goals of dark energy studies, exoplanet microlensing, and infrared sky surveys." Jason Rhodes, JPL WFIRST Project Scientist

Full field of view	6,000 arcsec
Centroid accuracy	2 arcsec
Proposed array size	6,004
Maximum projected pixel	0.19 m

## 4.4.2 Formation Control Sensing and Commanding

Formation control between the starshade and WFIRST is critical to achieve the required contrast. This control loop is non-collocated, with WFIRST performing the sensing function and starshade performing the control. WFIRST carries processor, memory and throughput margin to accommodate new sensing flight software.

Formation sensing uses the LOWFS detector (in the CGI), which captures pupil plane images of outof-science band starlight. In this band, the position of the starshade is revealed. Multiple images are processed on board WFIRST and compared to a library of pre-computed images to measure the lateral position of the starshade with respect to the LOS. This lateral position offset is transmitted to the starshade over the spacecraft-to-spacecraft S-band link. Starshade then calculates the relative velocity between the two vehicles and uses the offset/velocity state to determine when to execute a short maneuver to maintain the formation. Starshade will execute the maneuver at the determined time. The control is phase plane, bang-bang, minimum impulse bit commanding, and keeps the starshade within  $\pm 1$  meter of the WFIRST/target star LOS.

## 4.4.3 S-band Radio Link to Starshade

WFIRST must have a spacecraft-to-spacecraft S-band radio frequency (RF) system in order to communicate with the starshade spacecraft. This low data rate system is used to pass a limited set of commands and data between WFIRST and starshade, e.g., SAC measurements, lateral offset measurements, status flags, etc. The simple S-band RF system is comprised of an S-band transponder and communications card within the WFIRST spacecraft command and data handling unit, and a directional medium gain antenna.

## 4.4.4 Coronagraph Filters

The mission requires WFIRST to perform exoplanet imaging and spectroscopy in the bands listed in Table 4-3 [3].

The spectrometer bands provide 20% bandpass and are selected to contain key spectral features, including: (water vapor centered at 720 nm and 940 nm and, oxygen centered at 760 nm). To accommodate the needs of the mission, CGI will provide a total of five filter slots in an existing filter wheel corresponding to the above bands.

TABLE 4-3. Additional starshade probe filter band	S
in the CGI.	

Filter	λ (nm)	Δλ/λ (%)
F489	425–552	26
F708	615–800	26
F863	750–975	26
F728	656-800	20
F877	799–975	20

## 5 COST AND RISK ASSESSMENT

The mission development and operations cost estimate and risk assessments are described in this section. The overall Starshade Rendezvous Probe schedule is presented in Figure 5-1, along with the Wide Field Infrared Survey Telescope (WFIRST) Project Schedule and the current schedule for NASA's Exoplanet Program Office's activity to develop starshade technology to TRL 5 (S5).

This program schedule profile results in some challenges, notably the approximately one-year period between achieving TRL 5 and Key Decision Point (KDP) C of the starshade mission development. System experts do not consider one year to be adequate. However, the presented schedule is nearly ideal in that it provides two years of overlap between the prime missions of WFIRST and the Starshade Rendezvous Probe. NASA may consider programmatic changes to create more time in the schedule prior to KDP-C of the probe mission.

## 5.1 Cost Assessment

The overall mission cost was performed by JPL's Team X, with the starshade payload cost as an input. The starshade payload cost and its PRICE H cost model were assessed by JPL mechanical and instrumentation experts for technical basis. This was used as payload input into the Team X sessions, and separately assessed by Team X engineers for credibility. The total mission cost estimate for the two-year baseline mission, by phase, is presented in Table 5-1. The \$967M project cost includes 30% Phase A–D development reserve and 15% operational reserve in Phase E.

Table 5-1 includes two columns: the Team X estimate and the Starshade Rendezvous Probe's

Work Breakdown Structure (WBS)	SRP Study	Team X
Elements	Team Estimate	Estimate
Development Cost (Phase A-D)	\$710M	\$788M
1.0, 2.0, & 3.0 Management, Systems	\$60M	\$60M
Engineering, and Mission Assurance		
4.0 Science	\$8M	\$8M
5.0 Payload System	\$221M	\$221M
6.0 Flight System	\$190M	\$250M
7.0 Mission Op Preparation	\$15M	\$15M
9.0 Ground Data Systems	\$14M	\$14M
10.0 ATLO	\$29M	\$29M
11.0 Education and Public Outreach	-	-
12.0 Mission and Navigation Design	\$7M	\$7M
Development Reserves (30%)	\$164M	\$182M
Operations Cost (Phase E)	\$44.5M	\$28.5M
1.0 Management	\$2.4M	\$2.4M
4.0 Science	\$22M	\$8.2M
7.0 Mission Operations	\$11.8M	\$11.8M
9.0 Ground Data Systems	\$2.5M	\$2.5M
Operations Reserves (15%)	\$5.8M	\$3.6M
Launch Vehicle (LV)	\$150M	\$150M
Total Cost (including LV)	\$905M	\$967M

estimate. The study team estimate was made after Team X delivery to supplement two areas: WBS 6.0, Flight System, and WBS, 4.0 Science.

The rationale for the WBS 6.0, Flight System, exception is that Goddard Space Flight Center's (GSFC) Mission Design Lab (MDL) costed the spacecraft bus at \$110M. This estimate includes project management and system engineering for the bus and integration and system test of the starshade payload. Team X used this estimate as input and added resource estimates for system engineering and project management for the bus build and starshade payload integration (along with that required for all other WBS items). This is typical for an out-ofhouse bus build, but in this case, GSFC's MDL included payload integration and associated project management and system engineering in the



**FIGURE 5-1**. Starshade Rendezvous Probe Mission schedule in the context of the WFIRST Mission Schedule and NASA Exoplanet Program Office's S5 Technology Plan schedule to mature starshade technology to TRL 5.

estimate. The study team finds the Team X estimate for the Flight System to be high as a result, and the standard cost model increases to project management and system engineering for an out-ofhouse bus build, estimated to be ~\$90M, are not appropriate in this case. The study team assesses there will be additional Project Management and System Engineering activities beyond the MDL estimate, as the MDL study did not consider interfaces to full the mission (all WBS elements). The study team assesses the increase to be ~\$30M over the 7-year development life cycle. This assumes approximately 100 full-time equivalent human resources over this time period, and results in a ~\$60M reduction in the Team X estimate, and a \$30M increase to the GSFC MDL estimate. Note that the Team X study also considered three commercial buses: Ball Aerospace BCP500, Ball Deep Space, and Lockheed Martin's LM 2100.

The rationale for the Phase E WBS 4.0, Science, exception is that the science team is likely to be larger than estimated at the time of the Team X study. WBS 4.0 includes technical and management efforts of directing and controlling the science investigation aspects of the project, as well as efforts associated with defining the science requirements; ensuring the integration of the science requirements with the starshade payload, WFIRST Coronagraph Instrument (CGI), and ground systems; providing the algorithms and software for science data processing and analyses; and science data analysis and archiving. Products include the Level 2 Science Requirements, Science Management Plan, Science Data Management & Archive Plan, and Memorandum of Understanding (MOU) with the science data archive provider. Products exclude hardware and software for onboard science payload.

The study team anticipates science team members from numerous organizations around the country in addition to those at JPL, Massachusetts Institute of Technology (MIT), Princeton University, and the Johns Hopkins Space Telescope Science Institute. The study team estimates that an additional 70 full-time equivalent scientists (with a mix of senior, junior, and postdoctoral students) for the two-year prime mission, a ~\$14M increase over the Team X estimate.

All of the other WBS element costs were estimated using JPL Team X models, based on historical averages for similar sized missions. Particular attention was paid to assessing Project System Engineering, which requires unique interfaces across the WFIRST project and rendezvous for formation flying, sensing, data collection, and downlink. This applies as well to the Project Management team as schedule alignment between the two projects is key.

WBS 5.0, Payload System, is also unique for this mission. In addition to the normal spacecraft support equipment, payload system includes costs for the starshade flight system, required ground support equipment, and facilities. Payload System includes costs of gathering and processing experimental, scientific and test data.

The cost of payload development was separated into two phases: development from TRL 5 to 6 [1], and development from 6 to a flight unit.

Mission assumptions for the cost estimates to TRL 6 include development of hardware and analysis beginning after the completion of the S5 activity with demonstrated TRL 5 for all key subsystems. TRL 6 will be reached prior to the end of a Phase B flight mission. The development plan includes all payload subsystem having a full-scale demonstration, with two separate deployment testbeds, "unwrapping," and "perimeter truss deployment." These testbed activities are followed by a full-scale article test. The full-scale starshade system requires: 24 full-scale flight petals, a fullscale perimeter truss with all flight features in-place, and a full-scale petal launch/unfurl system (see Section 6 for more detail). The development plan with extensive test campaign is a conservative approach to reduce risk early.

The cost estimate from TRL 5 to TRL 6 assumes successful execution of the S5 TRL 5 delivery as referenced in Section 6.

# With the assumptions above, the technical labor hours and parts and material cost were estimated to be ~\$67M in FY18 dollars.

The key inputs to the parametric costing modeling were derived from the TRL 5–6 effort, including relevant inputs from the S5 technology development plan.

Masses are assumed to represent current best estimate (CBE) values with 25% added for contingency. Two spares are included each for petals, trunnions, and roller arms. Starshade petals estimated as a production of 24 identical units. Trunnions and roller arms estimated as production of 12 identical units. Optical shield material is assumed comparable cost and mass to a multi-layer insulation (MLI) material.

Table 5-2 provides the estimate of the SEER payload WBS element. This is the cost estimate of the payload development from TRL 6 to the deliver the flight unit.

## 5.2 Risk Assessment

This section presents the assessment of technical risk, risk that the Starshade Rendezvous Probe Mission will not meet the science objectives documented in Section 2, and programmatic risks. Without a starshade, there is no known way, either with current or planned technology, to meet Objective 1 (Section 2.1). This objective drove the requirements of the mission design, including payload and bus, specifically delta-V requirements of the latter. The technical risk is assessed by project element, followed by programmatic risk assessment.

**WFIRST/Starshade Compatibility.** WFIRST is a Class B mission currently in development. The risk of WFIRST compatibility with Starshade Rendezvous Probe has been mitigated by the WFIRST accommodation effort summarized in Section 4.4 of this report. These risks are further summarized below. In addition, the programmatic risks to WFIRST and/or the starshade project are summarized in the memorandum "WFIRST Starshade Programmatic Assumptions Agreement" from the Exoplanet Program Office to Director of NASA's Astrophysics Directorate.

The WFIRST accommodation effort includes an Interface Requirements Document (IRD) between the WFIRST Project and NASA Exoplanet Program/ S5 Technology Project. This IRD specifies the key interfaces with WFIRST, with the intention of meeting Starshade Rendezvous Probe goals. Upon starshade project authorization, a mission IRD would need to be developed. The IRD is a product of the WFIRST Project and owned by the project system engineering team. The scope of the IRD covers all accommodations required of WFIRST to support the Starshade Rendezvous Probe mission and meet its science objectives.

**CGI.** This is a Class C flight instrument flying on WFIRST. As previously noted, the imaging detector and integral field spectrometer in the CGI

# **TABLE 5-2.** SEER cost estimates for starshadeflight payload.

WBS	SEER
05 Payload	
05.01 Payload Mgmt	3,247
05.02 Payload SE	7,230
05.03 Payload Prod Assurance	Included above
05.04 S/C Element (Hub)	28,600
05.05 Starshade	61,781
05.06 PLUS System	29,680
05.09 Payload I&T	16,384
Total Cost (FY18 \$K)	146,922

are required to support the starshade mission. Currently, the CGI project is in Phase B.

The CGI development team has recognized potential risk that radiation exposure could reduce the life of the electron multiplying charge-coupled device (EMCCD) imaging detector. Mitigation paths include:

- 1. Modifying readout to reduce the number of transfers for each image by half;
- 2. Adding an overspill register to reduce the impact of cosmic rays;
- 3. Adding a new type of output amplifier with an additional transistor designed to reduce the read noise of the sensor; and
- 4. Reducing the width of image charge transfer channels.

Test units are currently in house at JPL under evaluation. The plan is to irradiate the sensors in early 2019 and down-select the flight design in mid-2019.

Starshade Payload. Technical risks have been identified by the Exoplanet Program Office, and therefore S5 technology program, and are being mitigated within the scope of the technology plan summarized in Section 6. The plan is currently funded by NASA and the tasks are on track to complete milestones. With continued support by NASA, the technology plan will retire all technology risks. The development schedule supports TRL 5 readiness in FY2023, and TRL 6 readiness prior to Starshade Rendezvous Probe Preliminary Design Review (PDR) by Q2/3 of FY2024. It is important to note that with these efforts, risk that starshade will meet functional requirements will have been retired by ground test demonstrations. The remaining technical risk will be related to the flight payload system. JPL/NASA

**Spacecraft Bus.** The starshade bus has minimal technical risk and is within the design requirements of typical heritage spacecraft buses. The bus design is based on the WFIRST mission bus, which has not yet flown. However, WFIRST is derived from the very successful Solar Dynamics Observatory. GSFC's MDL took the WFIRST bus and modified it for the Starshade Rendezvous Probe. The bus was integrated into a mission by JPL Team X, and has appropriate margin in all technical areas [2].

Program Schedule. The nominal Starshade Rendezvous Probe Mission schedule is presented in Figure 5-1. Observe that with this schedule, the first two years of starshade operations overlap with the last two years of WFIRST operations, and the one year extended mission of the Starshade Rendezvous Probe overlaps with the WFIRST extended mission. If the Starshade Rendezvous Probe starts later than FY22, there is risk that operations required to meet the science objectives presented in Section 2 will not be accomplished. The mitigation for this risk is for the Decadal Committee to make clear and focused recommendations regarding the Starshade Rendezvous Probe so that the mission can enter Phase A mission by FY22.

With the program schedule of Figure 5-1, there is schedule risk for achieving TRL 6 maturity by the

end of Phase B. The current Exoplanet Program Office's technology plan schedule (S5 plan) has all critical elements reaching TRL 5 by mid-FY23. The probe mission start date and developing phasing is set so that the 2-year prime mission aligns with the last two years for WFIRST's prime mission. Schedule risk mitigation may be possible in a number of ways by adjusting phasing of elements of the program. NASA should explore appropriate program schedule adjustments.

## 5.3 Heritage Assessment

The GSFC WFIRST bus will have flown by the time the Starshade Rendezvous Probe launches. This was the baseline bus used in the Team X mission study. Additional buses considered in the Team X study are commercially available products, with minor modifications, these are the Ball BCP500,<sup>1</sup> Ball Deep Space,<sup>2</sup> and Lockheed Martin LM 2100.<sup>3</sup> The Mission Operations System / Ground Data System design leverages off of the one established for WFIRST. The payload elements, including the formation flying element and requirements for flight operations, do not have flight heritage. See a description of these elements in the Starshade Payload, and Technology Maturation Plan sections, Sections 3 and 6, respectively.

<sup>&</sup>lt;sup>1</sup> https://en.wikipedia.org/wiki/Comparison\_of\_satellite\_buses

<sup>&</sup>lt;sup>2</sup> https://en.wikipedia.org/wiki/Comparison\_of\_satellite\_buses

<sup>&</sup>lt;sup>3</sup> https://www.lockheedmartin.com/content/dam/lockheed-martin/space/documents/openspace/LM-2100-payload-accommodation.pdf

## 6 **TECHNOLOGY MATURATION PLAN**

The Exoplanet Exploration Program (ExEP) has received approval recently from NASA's Astrophysics Division to execute an activity to develop starshade technology to TRL 5. This activity, called S5, is designed to close the three technology gaps to starshade implementation identified in the ExEP Technology Plan Appendix [1]. These technology gaps are in formation flying between the starshade and telescope, starlight suppression, and mechanical shape stability and deployment accuracy. Within these three technology gaps are five separate technologies. The technology requiring development for formation flying is the sensing of transverse displacement of the starshade from the telescope/star axis. To close the starlight suppression technology gap, S5 must develop two technologies. One is a validated model that includes all significantly contributing optical physics and correctly predicts variation of contrast performance with change of shape, the validation to be demonstrated at flight-like Fresnel numbers. The other technology is an optical edge to the starshade that does not scatter sunlight into the telescope at a level that significantly impairs exoplanet imaging. The two technologies that close the mechanical technology gap are the fabrication of petals with sufficiently precise and thermally stable dimensions to achieve the requisite optical contrast performance, and the reliable deployment of these petals to their correct positions in a stable manner.

Technology Readiness Level (TRL) is defined within the context of a specific mission concept, which defines the necessary performance requirements for the technology and the relevant environments within which it must operate. S5 takes Starshade Rendezvous Probe as that mission concept. All of the Key Performance Parameters (KPPs) to be demonstrated within S5 are derived from the Starshade Rendezvous Probe science requirements, and the fidelity of S5 test articles is determined by comparison to the Starshade Rendezvous Probe reference design. For example, the size of the prototype starshade inner disk is the same as for the starshade rendezvous reference design. Table 6-1 lists the current TRL and the KPPs for starshade technologies to be at TRL 5 for Starshade Rendezvous Probe.

The S5 technology development plan has starshade formation flying reaching TRL 5 in December 2018 and starlight suppression reaching TRL 5 in January 2020. Figure 6-1 depicts the program schedule. The mechanical shape stability and deployment accuracy technology gap, which requires the fabrication and test of large prototype articles, reaches TRL 5 in June 2023.

At the close of the S5 activity, the individual subsystems will have had successful TRL 5 demonstrations for the key parameters. The test articles will have been at a mixture of scales and fidelities, with verification and validation activities for the KPPs as described above. Continuing the development to TRL 6 will build on these results for complete subsystems, at full-scale, against relevant environments for the same KPPs but now integrated into the next highest level of subsystem. A development campaign to achieve TRL 6 has been defined based on the TRL 5 exit criteria, with three main systems identified: 1) petal, 2) starshade unwrapping, and 3) inner disk deployment. This development will occur prior to Key Decision Point C (Phase C) per Figure 5-1.

Technology Gaps	Current TRL	KPP #	KPP Specifications	KPP Threshold Values	Threshold Contrast	KPP Goals
Starlight 4 Suppression		1	Demonstrate flight instrument contrast performance at inner working angle is viable via small-scale lab tests	1×10 <sup>-10</sup>	NA	5×10 <sup>-11</sup>
		2	Validate contrast model accuracy relative to flight-like shape errors	≤25%	NA	≤10%
Solar Scatter	4	3	Verify solar scatter lobe brightness visual magnitude	V ≥ 25 mags	NA	V ≥ 26 mags
Lateral Formation Sensing & Control	5	4	Verify lateral position sensor accuracy and that it supports $\pm 1$ m control via simulation	≤±30 cm	1×10 <sup>-11</sup>	≤±10 µm
Petal Shape	4	5	Verify pre-launch accuracy (manufacture, Al&T, storage)	≤±70 µm	1×10 <sup>-11</sup>	≤±50 µm
		6	Verify on-orbit thermal shape stability	≤±80 µm	8×10 <sup>-12</sup>	≤±40 µm
Petal Position	4	7	Verify pre-launch accuracy (manufacture, Al&T, storage)	≤±300 µm	1×10 <sup>-12</sup>	≤±212 µm
		8	Verify on-orbit thermal position stability	≤±200 µm	1×10 <sup>-12</sup>	≤±100 µm

## **TABLE 6-1.** Key performance parameters.



FIGURE 6-1. S5 schedule.

The optical edges ultimately provide the shape of the entire starshade. Full-scale petals will be developed for TRL 6 with all mechanical and deployment features in place. Twenty-four petals will be fabricated to the flight design: 2 "sharp" petals with exact flight-like shape and edge scattering requirements, and the remaining 22 of them with "dull" edges that are mechanically representative for shape and materials but not etched into the final sharpness. The petals will be retested against the TRL 5 criteria to verify shape accuracy: shape stability under repeated deployment cycles, accuracy under thermally induced shape deformations, and stability under long-term storage (creep). These petals will then be integrated into a perimeter truss under two deployment testbeds to demonstrate that both phases of deployment meet the requirements.

In the baseline starshade architecture, the petals are wrapped around the stowed perimeter truss for launch and must be unwrapped in the first phase of deployment. For TRL 6, a full-scale petal launchrestraint and unfurl system will be used to

demonstrate full-scale petal wrapping and unwrapping. The TRL 6 activity will include a verification that there is no edge contact or unwanted petal motion during deployment. This system will also be used for dynamics testing and launch model validation.

The second phase of deployment is the final system that will be developed under TRL 6, and ends in a fully deployed, full-scale starshade. It uses the same petals as the unwrapping testbed, attached to a fully functional deploying perimeter truss. The perimeter truss will be used to deploy the petals to their final position, including all of the inner disk structure opacity features such as the optical shield and closeouts. This requires verification of deployment repeatability under gravity offload under many deployed cycles, as well as verification of opacity for the inner disk system optical shield. This system will be a full-scale starshade, when deployed selected structural properties (e.g., disk shape vs. interface load, system stiffness) will be used to validate structural models.

## 7 MANAGEMENT PLAN

The point design presented in this report assumes the Starshade Rendezvous Probe Mission is managed by JPL, with a principal investigator (PI) leading a science team, and that the spacecraft is provided by NASA's Goddard Space Flight Center (GSFC). The project has identified that commercial spacecraft are an option for a future trade.

The PI leads the team to achieve the targeted scientific investigations discussed in the science section, and organizes the implementation team.

Probes are medium-class missions, similar in cost scope to NASA's New Frontiers missions. JPL is well prepared to manage probe missions, having managed the Juno New Frontiers mission (launched 2011) and also the development of the medium-class Spitzer Space Telescope (launched 2003). JPL is implementing the S5 (Starshade to Technology Readiness Level 5) technology project as well, with extensive industry engagement on starshade maturation. With JPL as the managing center for the Coronagraph Instrument, which would be the sensing instrument for the Starshade Rendezvous Probe Mission, and GSFC as the managing center for the Wide Field Infrared Survey Telescope (WFIRST) mission overall and spacecraft, the management partnership would allow for a high

bandwidth technical and programmatic coordination between the two projects. The JPL project manager provides project oversight for schedule, budget, and deliverables throughout the lifecycle between the PI organization, JPL, GSFC, and all subcontractors. The mission is managed to the requirements of NPR 7120.5E.

The project system engineer has system engineering oversight during formulation and implementation until launch and early on-orbit operations (30 days). Both the project manager and project systems engineer have unique roles in such a mission due to the nature of technical and programmatic interfaces with the WFIRST project. Appropriate ICDs will need to be negotiated early in a formal Phase A (draft versions have been developed already), and particular attention paid to the linked nature of the Rendezvous Probe to the WFIRST project.

The JPL safety and mission assurance (S&MA) manager has oversight and involvement between JPL and GSFC throughout during formulation, implementation, and up to launch and early on-orbit operations (30 days).

Figure 5-1 shows the projected schedule for mission development with a launch in FY2029 timeframe. The technical tall poles and lifecycle reviews are presented.

## 8 CONCLUSION

The Starshade Rendezvous Probe Mission concept, system engineered to achieve the focused scientific objectives, demonstrates that a realizable, highly capable starshade mission could be launched and operated in formation with the Wide Field Infrared Survey Telescope (WFIRST) Mission. The combined mission could perform space-based direct imaging capable of discovering and characterizing exoplanets around our *nearest neighbor star systems*. This first-of-its-kind combined mission will enable a *deep-dive* exoplanet investigation around these neighbor star systems.

The concept includes a starshade spacecraft to fly in formation with the WFIRST Mission, and utilizes the Coronagraph Instrument (CGI) on WFIRST as an imager and spectrometer. The study demonstrates that a robust mission is achievable in the timeframe necessary to integrate with WFIRST. The starshade probe spacecraft is comprised of two major elements: the starshade occulter payload and the spacecraft bus. The occulter is directly based on the technology and designs (~26-meter-diameter starshade) being matured by NASA's Exoplanet Program activity, S5. The S5 plan is to have the necessary technology matured to Technology Readiness Level (TRL) 5 in the 2023 timeframe. This schedule allows further maturation of starshade technology to TRL 6 prior to Key Decision Point C and supports a starshade probe mission that overlaps with the WFIRST prime mission. The baseline spacecraft bus is based on Goddard Space Flight Center's WFIRST spacecraft bus, with commercial buses also identified as potential solutions.

To ensure hardware needed is in place for the future Starshade Rendezvous Probe Mission, the WFIRST Mission currently includes starshade-ready requirements, including formation flying equipment, and a broadband instrument for planet detection (imaging) and spectral characterization. The impact on WFIRST starshade readiness is minimized; the existing CGI performs detection and spectral characterization of exoplanet science targets, and imaging supporting formation flying. The starshade spacecraft provides the propulsion for retargeting and precision formation.

The starshade spacecraft would launch on a Falcon 9 v1.2 expendable booster from Cape Canaveral in fiscal year 2029. The WFIRST 2.4 m

telescope is assumed to have previously launched to a halo orbit about the Earth-Sun L2 point. The Starshade Rendezvous Probe Mission is a 2-year mission, with a 1-year extended mission.

The Starshade Rendezvous Probe Mission has three science objectives.

*Objective 1a: Habitability and Biosignature Gases.* Determine whether super-Earth size or smaller exoplanets exist in the habitable zone around the nearest sunlike stars and have signatures of oxygen and water vapor in their atmospheres.

*Objective 1b: The Nearest Solar System Analogs.* Detect and characterize planets orbiting the nearest sunlike stars. Within Objective 1a is the possibility of discovering Earth-size exoplanets in the habitable zones of nearby sunlike stars, if they exist. If an Earth-like planet exists around one of the mission's target stars, the starshade probe can obtain spectra. Under Objective 1b, the mission would produce an imaging and spectroscopic portrait of the major components, including larger exoplanets, of the nearest equivalents of our solar system.

*Objective 2: Brightness of Zodiacal Dust Disks.* Establish if the zodiacal cloud of our inner solar system is representative of the population of our nearest neighbor stars. Observations under Objective 2 will shed light on the dust-generating parent bodies (asteroids and comets), as well as assess exozodi levels for future missions

*Objective 3: Giant Planet Atmosphere Metallicity.* Determine the atmospheric metallicity of known cool giant planets to examine trends with planetary mass and orbital semi-major axis, and to determine if these trends are consistent with our solar system. The third science objective achieves high science return as the set of known giant planets are detectable by virtue of their positions in 2029.

In summary, the Starshade Rendezvous Probe can reach to the discovery of Earth-size planets in the habitable zones of nearby sunlike stars using the relatively small WFIRST space telescope in the next decade. Achieving this significant scientific milestone, along with other compelling science, can occur simultaneously with development of the scientific framework and operational experience for future use of starshades in flagship missions for exoplanet discovery and characterization. The Starshade Rendezvous Probe Mission can serve as the first step in-space for utilizing starshades to achieve NASA's grand goal of "Searching for Life Elsewhere."

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Section 7

None

Section 8

None

## PUBLIC COST TABLE

Master Equipment Lis	t Based Parametric Total Lifecycl	
Mission Name / Acronym:	Starshade Rendezvous Probe	
Cost Estimator:	JPL Team X	
Date of Cost Estimate:	September 7, 2018	
Cost Estimate Based On:	Final Master Equipment List	
PROJECT PHASE		<u>COST [FY18 \$M]</u>
Phase A		(see Note 1)
	Mgmt, SE, MA	\$60
	Science	\$8
	Starshade Payload	\$221
	Spacecraft, including ATLO	\$280
Phase B–D	MOS/GDS	\$29
	Mission and NAV Design	\$7
	Launch Vehicle and Services	\$150
	Reserves	\$182
	Total Cost Phases A-D	\$938
	Mission Operations	\$17
	Science Operations	\$8
Phase E–F	Reserves	\$4
	Total Cost Phases E-F	\$29
	TOTAL LIFECYCLE COST	\$967

included in Phase B–D.

2. This parametric cost estimate is based on the Probe's Master Equipment List derived from the Final Engineering Concept Definition Package that accurately reflects the mission described in the Probe's Final Report. This estimate is to be used only for non-binding rough order of magnitude planning purposes.

3. Team X estimates are generally model-based, and were generated after a series of instrument and mission-level studies. Their accuracy is commensurate with the level of understanding typical to Pre-Phase A concept development. They do not constitute an implementation or cost commitment on the part of JPL or Caltech.