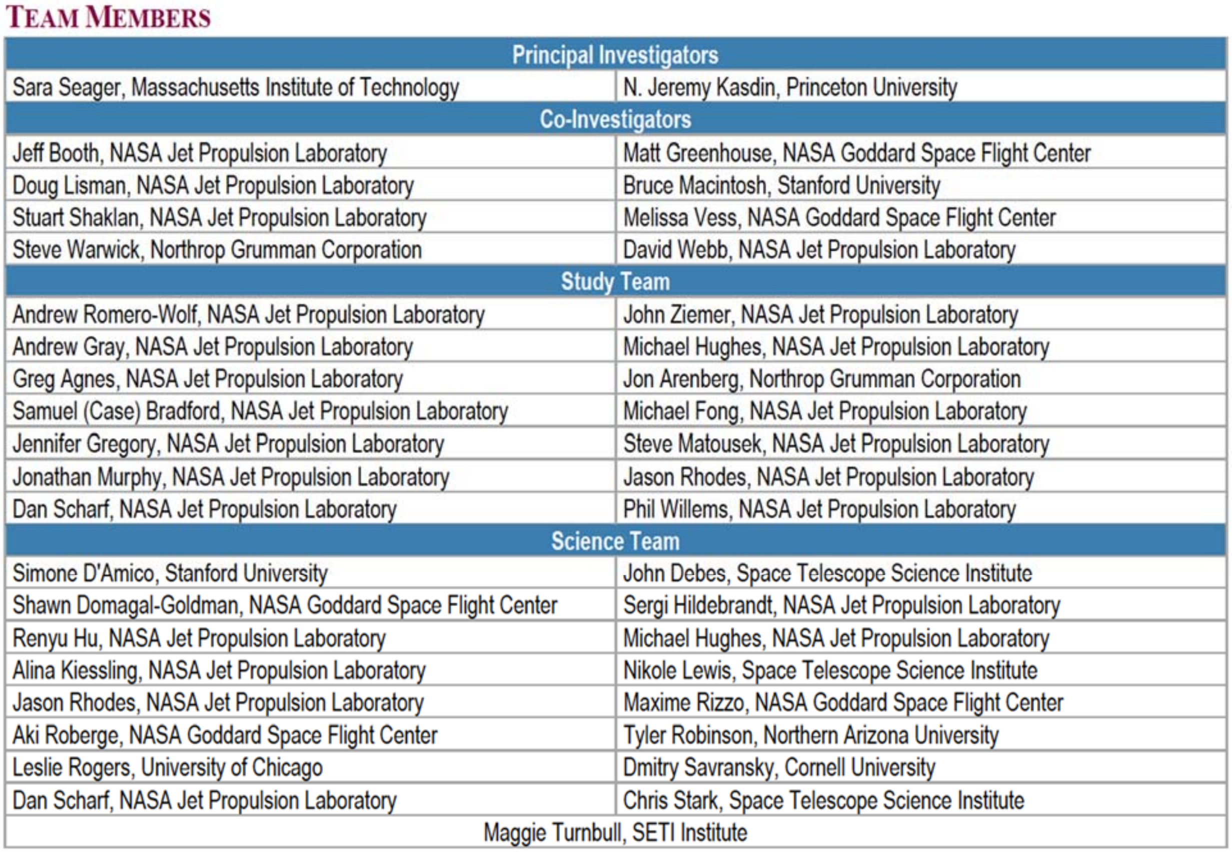
White Paper on

Starshade Rendezvous Probe

A Submission to the National Academy of Sciences



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The Starshade Rendezvous Probe Mission (https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Starshade2.pdf) [1] will be the first space-based, high-contrast imaging mission with the potential to detect and characterize Earth-like planets in the habitable zone (HZ) around sunlike stars while at the same time exploring entire planetary systems about our nearest neighbors. Over the last two decades, astronomers have discovered and cataloged thousands of planets around other stars. Nevertheless, we have yet to find a planetary system like our own or to characterize discovered small planets to determine if they are similar to Earth. The next step in exploration is to image full planetary systems, including their HZs, and to obtain planetary spectra with enough sensitivity to determine if a planet is Earth-like. A space-based direct imaging mission to ultimately find and characterize other Earth-like planets is a long-term priority for space astrophysics [2, 3].

1. Overview

The Starshade Rendezvous Probe Mission concept consists of a starshade flying with the Wide Field Infrared Survey Telescope (WFIRST) at L2 during the later stage of its prime mission. It utilizes the Coronagraph Instrument (CGI) on WFIRST to perform space-based direct imaging capable of discovering and characterizing exoplanets, down to Earth-size. The design reference mission (DRM) consists of a *deep dive* on our *nearest neighbor star systems* to find and characterize all planets within view (Figure 1). This will provide unprecedented information about planetary system formation, dust distributions, planet populations, and planetary compositions. The science case lays out specific science goals and focused investigations to image and spectrally characterize the dust disks and planets around at least 10 of our nearest sunlike stars. The science case also includes imaging another 10 slightly more distant sunlike stars to obtain spectra of known giant planets. *The Starshade Rendezvous Probe go is to place our Earth and Solar System into context with the nearest planetary systems.*

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 2 and Ref. [4]). 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 of better than ~100 µm for petal shape and ~1 mm for petal positioning, with lateral position tolerances of ±1 m at distances up to

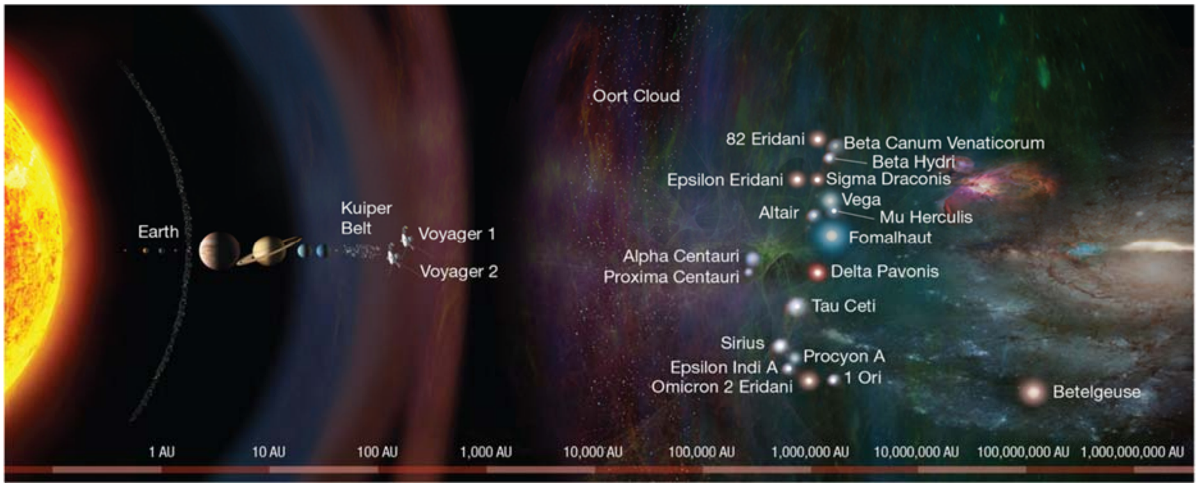

FIGURE 1. Moving outwards from our Sun by factors of ten (left). The Sun is followed by theterrestrial planets, asteroid belt, giant planets, and the Kuiper Belt. The Voyager spacecraft have recently crossed the outer edge of the Sun's influence. The Oort cloud, the final bound part of the solar system 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.

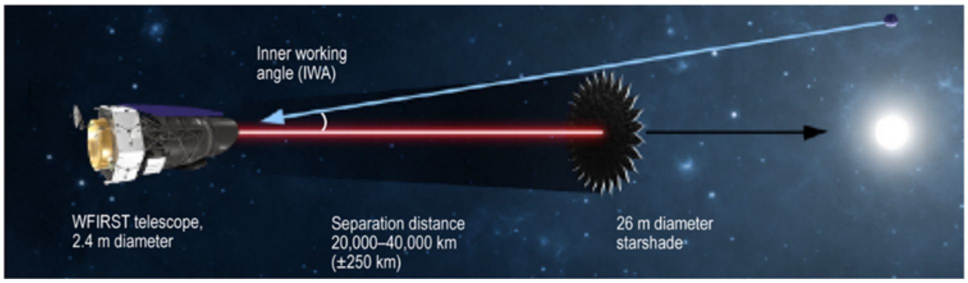

FIGURE 2. Schematic of the starshade-telescope system (not to scale) and observing geometry with the inner working angle independent of telescope size.

37,700 km, the starshade can reach inner working angles (IWAs) of ≤100 mas and reduce the residual starlight by more than a factor of 10^{10}.

First conceived of in the 1960s [5], and revisited nearly every decade since (see BOSS [6] and UMBRA [7], as well as Refs. [4, 8–10]), starshade technology builds upon heritage from large space-based radio antenna deployables [11]. The benefits of a starshade are many. 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) are easily achievable; 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; other telescope instruments can operate between starshade observations while the starshade is slewing to the next position.

The Starshade Rendezvous Probe Mission opportunity 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, while fitting within the proposed cap of a probe-class 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. Additionally, 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 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 Probe Mission concept study (Exo-S; [4]), for submission to the 2020 Decadal Survey. The Starshade Rendezvous Probe Study took place from 5/2017–12/2018.

2. Summary of Science Goals and Objectives

The Starshade Rendezvous Probe Mission targets the nearest 10 to 12 sunlike stars to explore any planetary systems found and to find other Earth-like planets, if they exist, around these stars, thus addressing NASA's first strategic objective to "Understand the Sun, Earth, Solar System, and Universe." An example of what the solar system would look like if imaged with the Starshade Rendezvous Probe imaging sensitivity at 8.44 pc is shown in Figure 3.

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

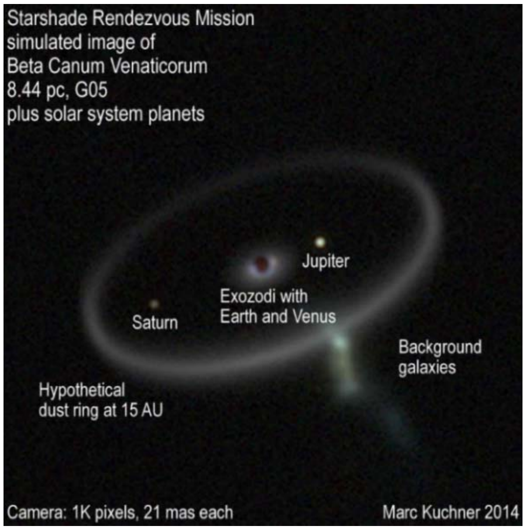

FIGURE 3. Starshade simulated image of the Rendezvous Probe's observation of a solar-system–like planetary system orbiting a nearby sunlike star.

- 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.

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

Objective 1a is focused on discovering Earth-size exoplanets in the HZs of nearby sunlike stars, if they exist. If an Earth-like planet exists around one of the mission's target stars, Starshade Rendezvous Probe can obtain spectra (Figure 4). While searching for potential Earth-like planets, Objective 1b will be achieved automatically. 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.

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. Many of the known giant planets will be detectable by virtue of their positions in the late 2020s.

To put the Starshade Rendezvous Probe in context, 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 only around M-type stars. On the ground, future extremely large telescopes 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

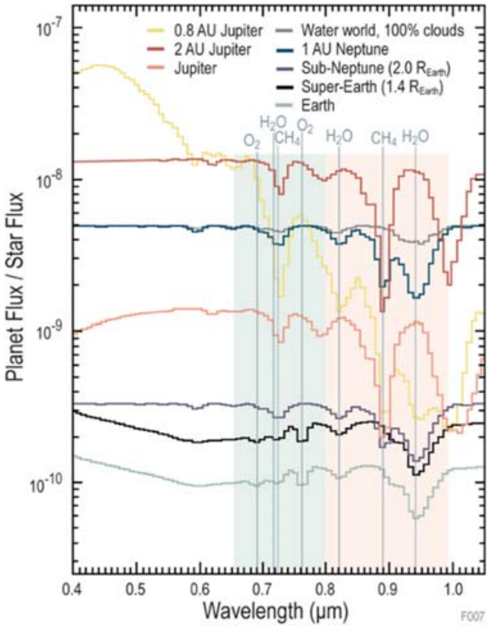

FIGURE 4. Earth-like planets drive the sensitivity requirements that enable observation of a wide variety of exoplanet types. Simulated spectra with the CGI spectral resolution R=50 for various planet types are shown in relation to the spectroscopic bands available. The Starshade Rendezvous Probe (656–800 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

HZ planets around nearby M-type stars. Direct imaging and characterization of exoplanets in reflected light around sunlike (FGK) stars requires at least 10^{-10} contrast or better and is only accessible from the vantage point of space (Figure 5).

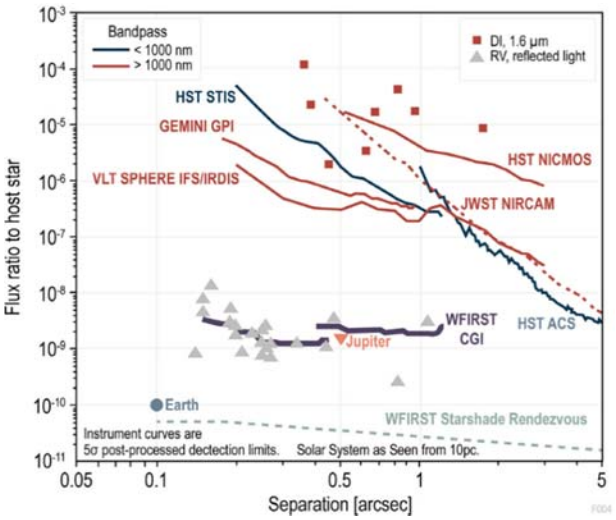

FIGURE 5. Direct imaging capabilities of current and future instrumentation. Shown are the 5 σ contrast limits after post-processing one hour's worth of data for various coronagraph instruments and 100 hr integration times for the WFIRST CGI and starshade. The state of the art is located in the upper-right 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 Earth- like planets in the HZs of nearby sunlike stars. Figure and caption adapted from Refs. [12] and [13], and Stapelfeldt (private communication 2015). Image credit: T. Meshkat and V. Bailey.

Yields for various planet types is a key issue and it is important to note that WFIRST observations with starshade will be sensitive to a wide variety of planets. Figure 6 shows the expected number of planets discovered by a single visit imaging (SNR>5) the stars in the target list with the possibility to obtain spectra with SNR>15. For Earth-like exoplanets, with the more stringent requirements of spectroscopically characterization with SNR≥20, and that the orbit is constrained to the HZ, the expected yield is ~0.4. It is worth emphasizing that the 1 σ uncertainty interval estimated by SAG-13 is [0.08, 0.7], nearly spanning an order of magnitude. Here the assumed value of $\eta_{\text{Earth}} = 0.24$ adopted by the EXOPAG SAG-13 [14] is ~1.3.

It is worth noting that 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.

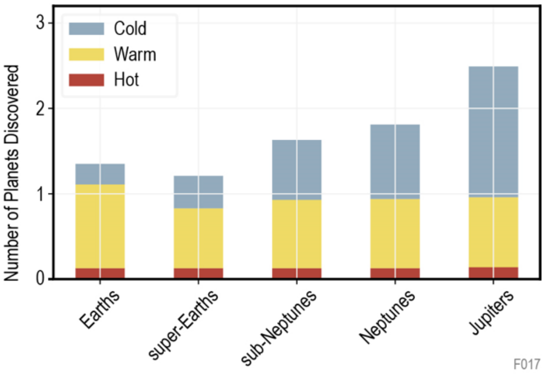

FIGURE 6. Planet yield as a function of planet type and approximate temperature. The yield was obtained based on the single-visit completeness assuming detection with an SNR≥5. All observations assume a zodiacal dust disk brightness of 4.5 zodi. The bar chart assumes that the top 10 targets for the habitability and biosignature gases investigation are visited at least once. The planet parameters are taken from the Exo-S report [4]. Each detected planet is amenable to SNR=15 spectra.

To discover Earth-size planets in the HZs of nearby stars and to answer many other outstanding questions requires the large-scale dedicated effort of the Starshade Rendezvous Probe Mission. Appendix A shows a science traceability matrix (STM) that captures the above discussion and includes the key observables and instrument and spacecraft performance requirements.

3. Mission Overview, Schedule, and Cost

Mission Architecture: The starshade payload is a large, optically precise deployable mask that when flown along the line of sight between WFIRST and a target star, blocks the starlight from entering the telescope, 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. Details of the starshade system including science drivers, concept of operations, mechanical system, deployment, formation flying and retargeting, and error budget are all provided in the Starshade Rendezvous Probe Mission Report.

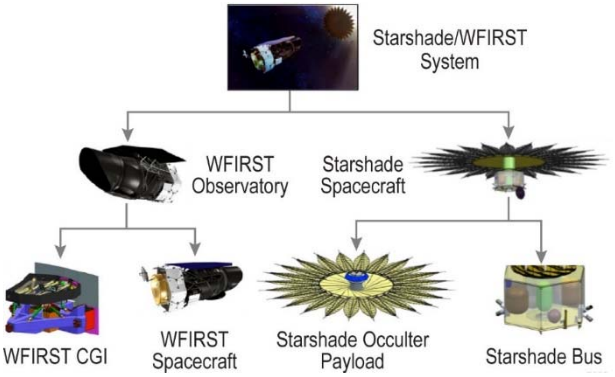

FIGURE 7. System elements and definitions.

The Starshade/WFIRST system includes two spacecraft: the starshade spacecraft and the WFIRST observatory (Figure 7). The starshade spacecraft itself is comprised of two major elements: the starshade S/C bus and the starshade occulter payload designed to meet the optical requirements of the mission. The payload contains three mechanical subsystems: 1) the petals, 2) the inner disk, and 3) the Petal Launch Restraint Unfurl System (PLUS). The payload design, a 26 m deployable, in-space starshade, is enabled by and based upon the technology developed under NASA's Exoplanet Exploration Program's (ExEP's) S5 effort (Starshade to Technology Readiness Level (TRL) 5; see Section 4 [15]), an activity to address all critical starshade technologies and raise them to TRL 5.

The Starshade Rendezvous Probe Mission is enabled by the WFIRST CGI, 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 camera and IFS to enable detection and characterization of Earth-sized planets in the HZ, and the CGI direct imager and low-order wavefront sensor (LOWFS) for rendezvous and formation control.

The WFIRST observatory includes several functions required by the Starshade Rendezvous Probe Mission. In particular, there are four areas of impact to WFIRST, each with a unique feature: SAC, formation control sensing and commanding, S-band radio link, and starshade-specific filters. The starshade requirements and supporting equipment described here have been incorporated into the WFIRST baseline. WFIRST development is well underway and the starshade team has flowed requirements to WFIRST through an Interface Requirements Document [16].

At the time of this writing, the WFIRST mission is assessing the scope of CGI as the project prepares for the next gate milestone. If changes to CGI spectroscopic capability are considered, it will affect the ability of the Starshade Rendezvous Probe to meet some of the science objectives. However, the complete impact and potential alternative approaches to meeting the science with changes in CGI would need to be studied in more depth. The Starshade Rendezvous Probe team has the capability to rapidly assess science return as a function of instrument performance and could make those assessments in the future, if necessary.

Mission Summary and Operations Schedule: The Starshade Rendezvous Probe DRM is driven by the target observation schedule, integration times, and number of revisits. Table 1 summarizes key mission parameters. 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. Delta-V requirements flow directly from the science observation schedule, and, in turn, drive propellant mass. The retargeting slews were optimized to maximize observation time while minimizing delta-V.

The starshade spacecraft would launch from Cape Canaveral in January 2029 on a Falcon 9 expendable booster (see Figure 8). Three trajectory correction maneuvers are needed for the mission to reach L2. At L+60 days, the starshade spacecraft will rendezvous with WFIRST and start science operations. 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 8 shows an example 2-year observation schedule integrated into the WFIRST mission timeline and the delta-V costs for each retargeting maneuver.

TABLE 1. Mission summary.

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

Mission Cost: The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech. The overall mission cost was determined 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 2-year baseline mission, by phase, is presented in Table 2. The $967M project cost includes 30% Phase A–D development reserve and 15% operational reserve in Phase E. Table 2 provides the Team X estimate and the study team's estimate, which was made after Team X delivery to supplement two areas: WBS 6.0, Flight System, and WBS, 4.0 Science. Full details including rationale are provided in the Starshade Rendezvous Probe Report. Note that the cost of

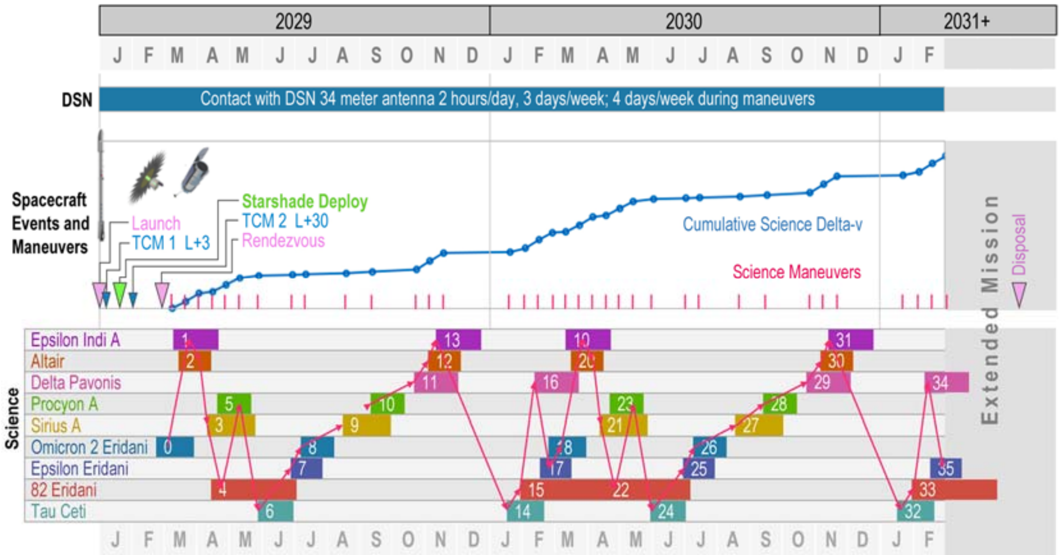

FIGURE 8. Mission timeline. Red line segments are translational retargeting slews, which may take from a couple of days to up to two weeks. Each red dot is a single day's observation. The horizontal bars represent time windows where the starshade to Sun angular constraints have been met and the star is possible to observe. The observation days are chosen to be at the beginning of the window.

starshade readiness on WFIRST, up to approval of Rendezvous as a mission, is carried by the WFIRST mission.

Mission Development Schedule: The overall Starshade Rendezvous Probe schedule is presented in Figure 9, along with the WFIRST Project Schedule and the current schedule for the NASA ExEP S5 activity. 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.

TABLE 2. Summary of baseline mission cost.

Work Breakdown Structure (WBS) Elements	SRP Study Team Estimate	Team X Estimate
Development Cost (Phase A-D)	$710M	$788M
1.0, 2.0, & 3.0 Management, Systems Engineering, and Mission Assurance	$60M	$60M
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

4. Technology Maturation Plan

The ExEP has recently received approval from NASA's Astrophysics Division to execute an activity to develop starshade technology to TRL 5. This activity, called S5 (https://exoplanets.nasa.gov/exep/technology/starshade/), is designed to close the three technology gaps to starshade implementation identified in the ExEP Technology Plan. 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.

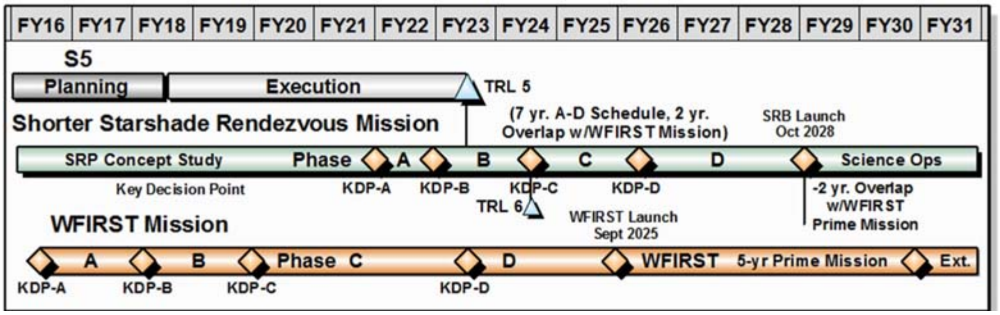

FIGURE 9. Starshade Rendezvous Probe Mission schedule in the context of the WFIRST Mission Schedule and NASA Exoplanet Program Office's S5 Technology Plan schedule to mature starshade technology to TRL 5.

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 the 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. Table 3 lists the current TRL and the KPPs for starshade technologies to be at TRL 5 for Starshade Rendezvous Probe.

TABLE 3. Key performance parameters.

Technology Gaps	Current TRL	KPP #	KPP Specifications	KPP Threshold Values	Threshold Contrast	KPP Goals
Starlight Suppression	4	1	Demonstrate flight instrument contrast performance at inner working angle is viable via small-scale lab tests	1×10^{-10}	NA	5×10^{-11}
		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 ±1 m control via simulation	≤±30 cm	1×10^{-11}	≤±10 μm
Petal Shape	4	5	Verify pre-launch accuracy (manufacture, AI&T, storage)	≤±70 μm	1×10^{-11}	≤±50 μm
		6	Verify on-orbit thermal shape stability	≤±80 μm	8×10^{-12}	≤±40 μm
Petal Position	4	7	Verify pre-launch accuracy (manufacture, AI&T, storage)	≤±300 μm	1×10^{-12}	≤±212 μm
		8	Verify on-orbit thermal position stability	≤±200 μm	1×10^{-12}	≤±100 μm

5. 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 the science team. The spacecraft would be provided by NASA's Goddard Space Flight Center (GSFC), though the commercial spacecraft are an option for future trade studies. This organizational structure leverages JPL's experience in managing mid-size missions and the fact that it is implementing the S5 technology project as well as the CGI. This 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. Appropriate Interface Control Documents (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 formulation, implementation, and up to launch and early on-orbit operations (30 days). For more details, see the Starshade Rendezvous Probe Final Report [1].

6. Concluding Remarks

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 WFIRST. The combined missions will perform, in the next decade, space-based direct imaging in a deep dive on our nearest neighbors, discovering and characterizing exoplanets down to Earth size in the HZ. 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."

Appendix A – Science Traceability Matrix

Investigation	Goals	Objectives	Scientific Measurement Requirements: Physical Parameters	Scientific Measurement Requirements: Observables	Instrument Functional Requirements		Instrument Predicted Performance		Mission Functional Requirements Common to all Investigations	Mission Functional Requirements Specific to Each Investigation
					Starshade	WFIRST-CGI	Starshade	WFIRST-CGI		
Habitability and Biosignature Gases & The Nearest Solar System Analogs	NASA Science Plan 2014: • Discover and study planets around other stars, and explore whether they could harbor life. New Worlds, New Horizons (2010 Decadal Survey): • Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet? • Discovery area: Identification and characterization of nearby habitable exoplanets. 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.	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 characterize planets orbiting the nearest sunlike stars.	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, ≥ 12% depth) with SNR≥20 with R=50. Oxygen absorption at 760 nm: detect current Earth's atmosphere (10 nm width, ≥65% depth) with SNR≥20 with R=50. Astrometric planet position and time: capable of at least 3 detections with ≤13 mas uncertainty (1σ) in 4 observations spread over 2 years. Number of targets: ≥4 stars	Inner working angle: ≤103 mas Instrument contrast ≤10^{-10} at angular distances greater than the inner working angle. Bandpass: ≥26% at 700 nm	Telescope (WFIRST): PSF: 65 mas Collection area: 4.4 m^2 Instrument (WFIRST-CGI): Imaging: Bandpass: 615–800 nm End-to-end efficiency: 2.4% Spectral: End-to-end efficiency: 1.5% Bandpass: 656–800 nm R ≥ 50 Detector: Noise rate: <10 counts/hour Field of view: 5,000 mas (radial)	Inner working angle: 103 mas Instrument contrast: 4×10^{-11} at angular distances greater than the inner working angle. Bandpass: ≥ 26% at 700 nm.	Telescope (WFIRST): PSF: 65 mas Collection area: 4.4 m^2 Instrument (WFIRST-CGI): Imaging: Bandpass: 615–800 nm End-to-end efficiency: 3.5% Spectral: End-to-end efficiency: 2.5% Bandpass: 656–800 nm R = 50 Detector: Noise rate <10 counts/hour Field of view: 5,000 mas (radial)	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	New Worlds, New Horizons (2010 Decadal Survey): • How do circumstellar disks evolve and form planetary systems? 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.	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^{-10} 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	New Worlds, New Horizons (2010 Decadal Survey): • How diverse are planetary systems? 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.	O3: 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.	Metallicity via abundance of atmospheric carbon (Methane) and oxygen (water vapor): to solar system giant planet levels with uncertainty log(species/H) <=0.3. Orbit inclination with ≤ 15° [TBR] uncertainty (provided by WFIRST-CGI observations or Gaia). Semi-major axis with ≤ 50% [TBR] uncertainty (provided by radial velocity measurements). Planet mass with ≤ 30% [TBR] uncertainty (provided by existing radial velocity measurements).	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^{-10} 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.

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