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# A Starshade for JWST: Science Goals and Optimization

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## ABSTRACT

The James Webb Space Telescope will be an extraordinary observatory, providing a huge range of exciting new astrophysical results. However, by itself it will not be capable of directly imaging planets in the habitable zone of nearby stars, one of the most fascinating goals of astronomy for the coming decade. In this paper we discuss the New Worlds Probe (NWP) concept whereby we use an external occulter (or starshade) to cast a shadow from the star onto the telescope, therefore canceling the direct star light while the light from a planet is not affected. This concept enables JWST to take images and spectra of extrasolar planets with sufficient contrast and inner working angle to be able to discover planets down to the size of the Earth in the habitable zone around nearby stars. JWST's instruments are appropriate to achieve low resolution spectroscopy ( $R \simeq 40$ ) of these planets, and address a series of fundamental questions: are there planets in the habitable zone around nearby stars? What is the composition of their atmosphere? What are the brightness and structures of exozodiacal disks around nearby stars? What is the mass and composition of currently known giant planets? In this paper we study the starshade optimization for JWST given the instrumental constraints, and show that the modest optical quality of the telescope at short wavelength does not impact the possibility of using a starshade. We propose a solution to enable imaging and spectroscopy using target acquisition filters. We discuss possible time allocation among science goals based on exposure time estimates and total available observing time. The starshade can be launched up to 3 years after JWST and rendezvous with the telescope in orbit around L2.

**Keywords:** exoplanets, extrasolar, JWST, occulter, starshade, earth-like, coronagraphy

## 1. INTRODUCTION

The discovery of habitable planets and the search for biosignatures is among the most compelling goals in all of the sciences. In the past few years, numerous planets have been discovered mainly using radial velocities and transits.<sup>1,2</sup> These detections are no longer limited to giant planets and now include much lower-mass objects,<sup>3</sup> with a few detections in the range of Neptune-mass and super-Earths. A few transiting planets have been characterized with spectroscopy.<sup>4</sup> Recently direct imaging has produced extremely exciting results.<sup>5-7</sup> Several mission concepts are under study for space-based high-contrast imaging missions\*. For visible and near-infrared wavelengths searches, these missions usually consist of internal coronagraphs<sup>8</sup> or external occulters such as New Worlds Observer<sup>9</sup> or THEIA.<sup>10</sup> For infrared missions, these missions involve interferometers.<sup>11</sup>

The basic principle of the starshade is shown in Fig.1. With two spacecraft involved (the telescope and the starshade) occulter missions are typically in the flagship cost range, well above one billion dollars. However, both THEIA and NWO studies have shown that most of the cost resides in the telescope. An occulter mission

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can be envisioned for a medium mission cost if a host telescope can be found. In this paper, we study the possibility of using the James Webb Space Telescope<sup>12,13</sup> (JWST) for this purpose,<sup>14,15</sup> and we focus on science goals and starshade design based on existing constraints. Technology and operations for NWP are discussed elsewhere.<sup>14,15</sup> One of the main constraints for the starshade design is that JWST detectors are sensitive over a range of wavelengths typically larger than the capabilities matching a reasonable size starshade. We identify filters to limit the bandpass for starshade use. However, because of the high dynamic range considered for terrestrial planets (typically  $10^{10}$  to 1), the effect of the out-of-band rejection of these filters must be studied carefully.

With JWST's large aperture and sensitive instruments,<sup>12</sup> the New Worlds Probe (NWP) would open the possibility of studying terrestrial planets in the habitable zone of nearby stars in the next decade, and would serve as a precursor for much more ambitious projects such as ATLAST.<sup>16</sup> NWP would solve unknowns about the exozodiacal brightness and structure, which is critical for future flagship missions,<sup>17</sup> and validate technology<sup>18</sup> for a more ambitious starshade with ATLAST.

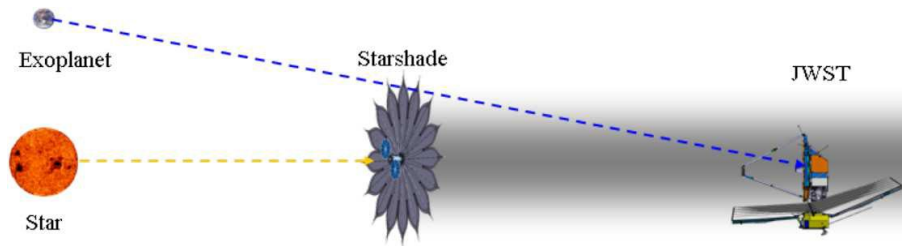


Figure 1. Principle of a starshade on a separate spacecraft to block the light from the star, while allowing the light from an exoplanet to pass the edge of the occulter unimpeded. *Figure credit: Northrop Grumman Corporation*

## 2. SCIENCE OBJECTIVES

The science enabled by using a starshade with JWST is extensive. NWP may be the only opportunity in the next decade to make progress on many of NASA's grand themes such as finding planetary systems like our own and discovering life in the universe. By the middle of the next decade, NWP can discover terrestrial planets around other stars and study their habitability. This would be a valuable addition to JWST's science program.

The science program of NWP is constrained by the capabilities of JWST's existing instruments, which makes the design approach different from a stand-alone mission. As discussed below, instruments on board JWST are well suited for exoplanetary science goals. A major constraint is the limited amount of possible observing time with the starshade: we assume that 7-9% of the total exposure time could be allocated to the starshade (approximately  $10^7$ s for a 5-year mission given the observatory efficiency).

This time allocation budget is much smaller than the typical amount available for dedicated missions (NWO, THEIA) where about 30% of the observing time is available for the starshade. Thanks to the large diameter of JWST, this budget is compatible with the general goals of a probe-size mission as discussed in the Exoplanet Community Report,<sup>19</sup> and NWP appears very competitive compared to a small (1-1.5m) coronagraphic telescope. The science program needs to balance the characterization of known objects with a small-size survey of nearby stars for habitable zone planets and exozodiacal light imaging. The main goals are identified as:

- Find and characterize planetary systems around (10-20) nearby stars, and study the habitability of terrestrial planets with spectroscopy
- Determine the atmospheric composition and measure the mass (via orbital inclination constraints) of known radial velocity (RV) planets (this includes mostly giant planets, Jupiter analogs, Neptune masses and potentially super-Earths by launch date).
- Determine brightness and structures and spectra of exo-zodiacal disks, and architecture of planetary systems.

Direct images of exoplanets can have a tremendous impact on the community and on the public, however most of the science will be brought by spectroscopy. The highest priority in designing a starshade mission is to find ways to enable spectroscopic capabilities and we propose a solution using NIRSpec.

The first goal is the most ambitious. The starshade with JWST can be designed with the sensitivity to detect a terrestrial planet in the habitable zone of a nearby star. Although a strict Earth-twin would be a very challenging goal close to the limit of the JWST sensitivity, larger terrestrial planets will be within reach. Recent progress and results from Radial Velocity and from microlensing surveys suggest that super-Earths planets are common,<sup>3,20</sup> and terrestrial planets have been detected around late-type stars very close to their parent stars, which does not make them favorable candidates for direct imaging. A large range of brightness can be expected between Earth-like planets and Super-Earths in the HZ. For example, the brightness ratio between Earth and the Sun at 10pc is  $2 \times 10^{-10}$  at quadrature for a 0.3 geometric albedo. Assuming the same density and albedo as the Earth, a 5 Earth-mass planets would be about three times brighter, and a 10 Earth-mass planet 4.6 times brighter. Planets at the inner edge of the habitable zone defined between 0.75 AU and 1.8 AU<sup>21,22</sup> are 1.7 times brighter than at 1AU. Therefore, the brightness of terrestrial planets in the HZ spans roughly an order of magnitude. We show in Fig.2 a simulation of the Sun-Earth system at 10pc including a model of the zodiacal disk<sup>23†</sup>. Although JWST's aperture is segmented with modest optical quality (diffraction limited at  $2\mu\text{m}$ ), the starshade prevents the light from entering the telescope and NWP is insensitive to JWST's optical quality at short wavelengths (here the simulation is done for F090W with NIRCcam).

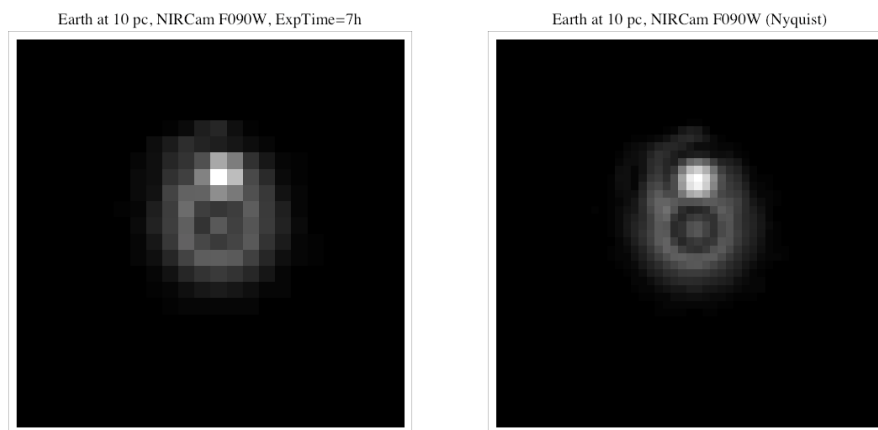


Figure 2. Simulation of the Sun-Earth system at 10pc as imaged with NWP with NIRCcam in the F090W filter centered around  $0.9 \mu\text{m}$ . The star is at the center of the image and appears as the dot at the center. The bright ring around the star is the zodiacal disk. The structure around the Earth PSFs (top left of the PSF) are due to the JWST PSF structure. The zodiacal disk was simulated using Kuchner's zodipic software.<sup>23</sup> The simulation includes the effects of the actual JWST segmented aperture with appropriate wavefront errors. The starshade delivers a  $10^{-10}$  suppression at the telescope aperture with a geometric IWA of 0.1 arcsec. Photon noise and detector noises are included for a 7h exposure, and the simulation includes the effect of the out-of-band filter transmission over the entire wavelength range of sensitivity of the detector. Left: image at NIRCcam sampling. Right: Nyquist sampled image.

We show in Fig.3 the single visit completeness<sup>24</sup> or probability of detection for the Sun at 10pc, and  $\alpha$  Centauri for a range of terrestrial planets (Earth-size to Super Earths). In Fig.4 we show the completeness for a Jupiter twin and by extension giant planets, assuming that they have the same radius and albedo as Jupiter. Because of the observing time constraint, NWP would not be able to conduct a very large survey, and will have to focus on a small number of stars ( $\approx 20$ ) which can be found close to the Sun ( $\leq 10\text{pc}$ ) among the  $\approx 55$  stars (F and G) with no companion within 10 arcsec, and for which a 1AU orbit can be detected with a 0.1 arcsec IWA. Even with a modest IWA to limit the starshade dimensions (more aggressive IWA require larger occulter), NWP can obtain significant probabilities of detection (10-50%) in the HZ at 10pc and much higher values outside the HZ. These probabilities increase significantly for closer stars. Smaller IWAs are possible but require a larger

<sup>†</sup> zodipic software available at: <http://asd.gsfc.nasa.gov/Marc.Kuchner/home.html>

starshade. In the current context, we consider trading IWA in favor of spectroscopic access over a large range of wavelength. Note that the actual detection capabilities extend below the geometric IWA.

Access to the near infrared up to about  $2.0 \mu\text{m}$  opens the possibility for the detection of other species such as  $\text{CO}_2$  (which is a good indicator of a terrestrial nature), water ice, or  $\text{CH}_4$  which was present in larger quantity in the early Earth atmosphere.<sup>25</sup> This range of wavelength is compatible with one of the proposed starshade modes discussed in Sec.3. The most interesting detection would certainly be to find a potential bio-indicator such as oxygen.<sup>26,27</sup> The detection of oxygen would be extremely challenging with JWST, but may be within reach for favorable targets (large terrestrial planet).

Although mass is not directly measured by imaging alone, colors and low resolution spectroscopy can provide some indications of the terrestrial nature of the planet, and habitability can be discussed from the detection of water vapor in its atmosphere. Water is easily detected in the near infrared at low resolution ( $R \simeq 40$ ) available with the NIRSpc prism (Fig.5). However some ambiguity can remain whether the planet is terrestrial or massive enough to retain water. An Earth-mass planet in the HZ of a sun-like star would induce a radial velocity wobble of about  $0.1 \text{ m s}^{-1}$ , which measurement is extremely challenging. However, RV signal is proportional to the planet mass and inversely proportional to the  $2/3$  power of the mass of the star, so that large terrestrial planets will be detectable in the near future around solar-type or lower mass stars. Indeed, Doppler precisions well below  $1 \text{ m s}^{-1}$  have already been achieved,<sup>3</sup> and new instruments are being designed with ultra-high stability ( $10 - 20 \text{ cm s}^{-1}$ ).<sup>28</sup> Therefore we anticipate a significant overlap between RV detections of Super-Earths and Neptunes, and the capabilities of an imaging mission such as NWP by mission launch. The combination of indirect and direct methods opens the possibilities of more complete characterization.<sup>17,19</sup> Moreover, once a terrestrial planet candidate is detected with NWP, radial velocities can be used to measure its mass using a very large number of observations if the star is quiet enough. RV should be able to place upper-limits on the mass and therefore rule out more massive (e.g. Neptune-mass) planets, with possible indications on the inclination from the exozodiacal disk structure in a single image or direct constraints if more images along the orbit can be obtained.

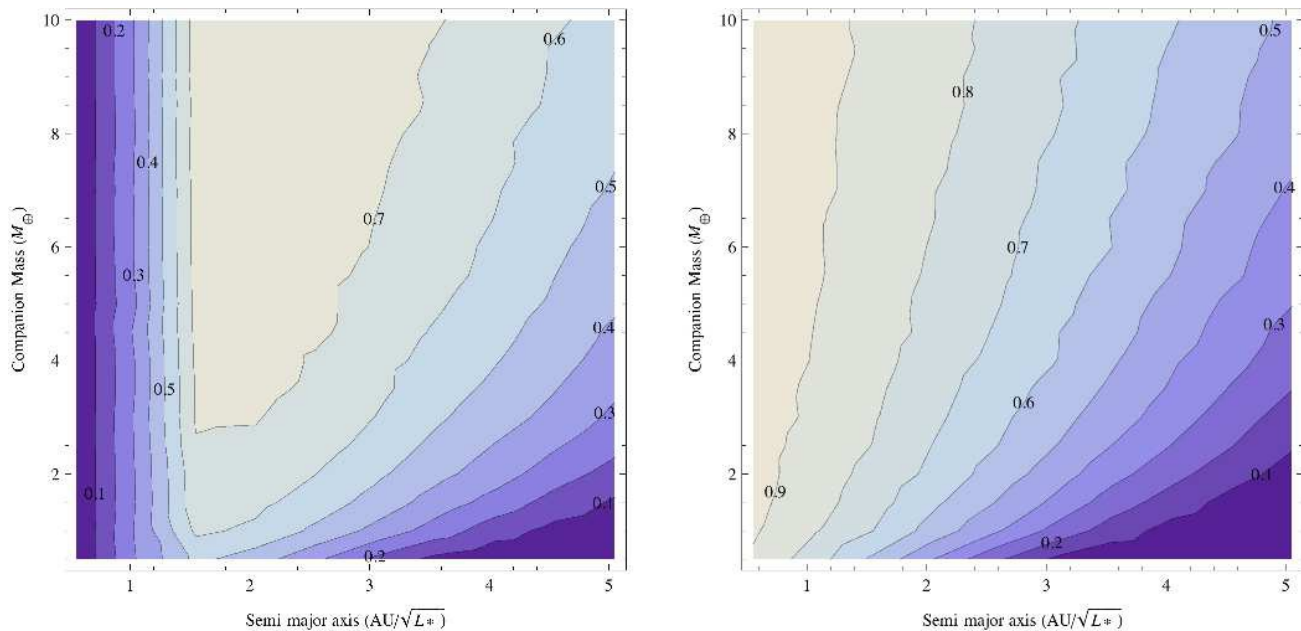


Figure 3. Single visit completeness or probability of detection for the Sun at 10pc (left) and Alpha Centauri (right). Here we assume that the planet has the same albedo and density of the Earth for a range between 1 and 10 Earth masses. The x-axis is normalized by the square root of the luminosity so that a planet at a given position on the chart has the same flux regardless of the stellar luminosity. The probabilities are calculated assuming random eccentricities between 0 and 0.35 and random inclinations and orbital positions along their orbit. The starshade is assumed to deliver  $10^{-10}$  suppression with an IWA of 0.1 arcsec.

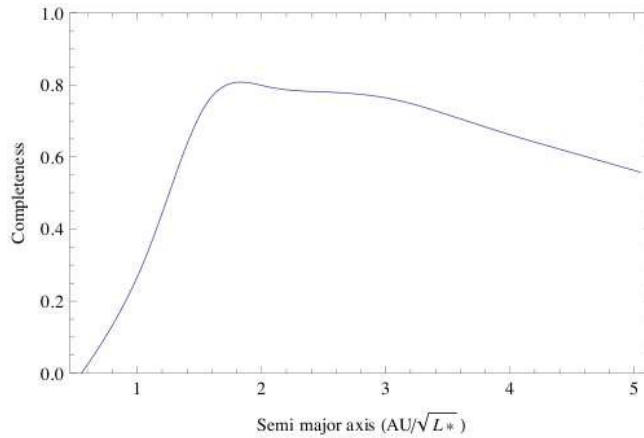


Figure 4. Single visit completeness or probability of detection for the Jupiter around the sun at 10pc and by extension giants planets, assuming they have the same albedo and radius as Jupiter. The starshade is modeled assumed to deliver  $10^{-10}$  suppression at 0.1 arcsec.

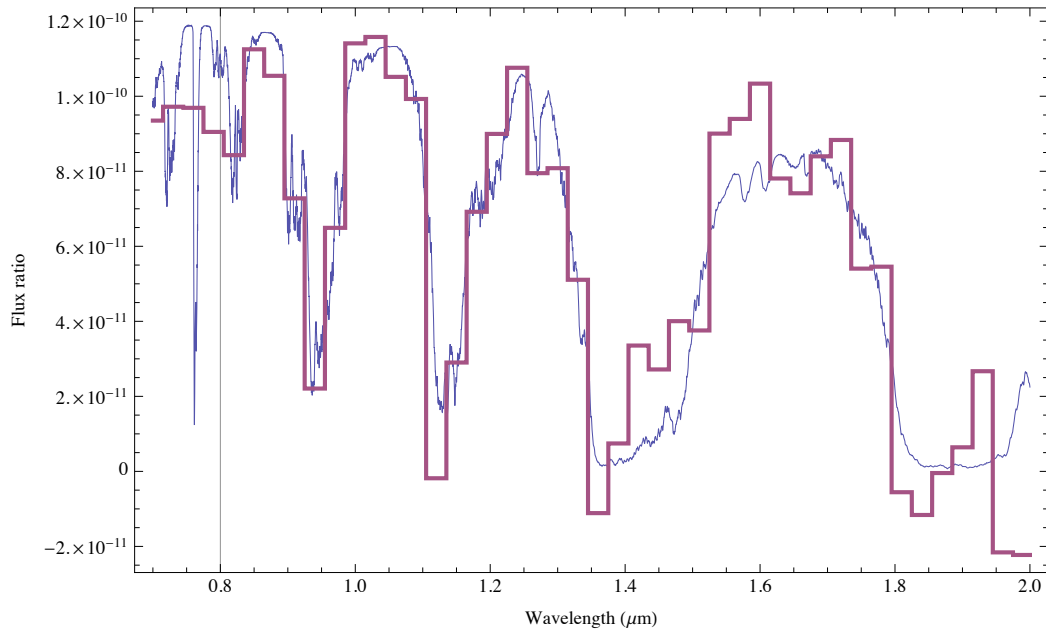


Figure 5. Simulation of an Earth spectrum at 10pc for NIRSpec low resolution ( $R=100$  prism). The simulation includes the actual prism resolution ( $R=30-50$ ) as a function of wavelength, noise from the Zodiacal background and detector noise. The spectrum has a signal to noise ratio of 5 obtained in  $3 \times 10^5$  s and does not include the effects of the out-of-band filter transmission. The vertical line shows the lower limit of the target acquisition filter F140X. The large water bands are easily detected at this resolution and signal to noise ratio.

The second goal focuses on the characterization of known planets by launch date. Among the  $\sim 300$  exoplanets discovered so far, a number of them have fairly large semi-major axes and could potentially be imaged and characterized with a high-contrast mission.<sup>19</sup> There are already 24 giant planets with projected semi-major axes larger than 0.1 arcsec (Table 1). This list is likely to expand significantly with time as radial velocity surveys extend their time baseline. These planets are typically in the  $10^{-9}$  contrast range with their parent star, and readily accessible to NWP both for imaging and spectroscopy. However, because of their position along their orbits they might not all be detectable with imaging at a given time. Some targets might also not be favorable for direct detection, for example Epsilon Eridani with its very bright disk.

With radial velocity measurements, the inclination of the system  $i$  remains unknown and only the minimum mass  $M \sin i$  is measured. In principle, a single image is sufficient to constrain the inclination angle and therefore provide a measurement of the mass, if the mass and distance of the star are known. Otherwise, two images at different phase angles are needed. In practice because of measurement errors, one image might not be sufficient. With these large-separation planets, this is further complicated by their long periods, and it might be difficult to obtain images at different phase angles if needed, under the constraints of a mission lifetime. Mass is an essential parameter for understanding planets, and its knowledge narrows the range of possible interpretation for a given spectrum. In addition, well characterized planets will help validate models deduced from other observations where all parameters are not accessible directly.

Giant planet spectra depend on the abundance of heavy elements, and physical conditions (gravity, temperature) determine which molecules are present in gas form or condensed into clouds. Cloud properties also influence the observable spectrum making interpretation and modeling of these objects uncertain. Spectroscopy at low resolution ( $R \simeq 40$ ) for Jupiter twins and even  $R = 1000$  with deep exposures on favorable targets will provide information about main atmospheric absorbers, and gravity estimations. Radius can be inferred from gravity and mass if these parameters are available. Temperature cannot be inferred directly from reflected light and its measurement would require measurement of emitted light at longer wavelengths. Occulters can trade IWA for observations at longer wavelength. However, the self emission of the starshade then becomes an important issue, and detailed thermal analysis is required. Because of the strong scientific motivation for longer-wavelength observations, solutions should be considered to render the starshade thermally quiet at these wavelengths, for example using more layers. Preliminary thermal analysis shows that observations might be possible up to  $4 - 5\mu\text{m}$ . This possibility could be used on very favorable targets to image a planet at  $4 - 5\mu\text{m}$  with the long arm of NIRCcam, or possibly at  $10\mu\text{m}$  with MIRI if the occulter can be made thermally quiet enough. In the Earth spectrum, the transition between reflected light and emitted light occurs around  $4\mu\text{m}$ .<sup>27</sup> This would increase the IWA respectively to 200-250mas and 400-500mas based on our starshade design (note that the contrast requirement is relaxed at longer wavelengths). An IWA of 250 mas would leave only 10 stars for which a 1AU orbit (scaled to  $\sqrt{L}$ ) is detectable. An IWA of 400 - 500mas would leave no stars for the HZ observations, so this case would only apply to giant planets in larger orbits. Although the feasibility needs to be studied more in details and these long-wavelength observations would be limited to a very small number of possible targets and mostly giant planets because of their much relaxed contrast requirement, this would open a possibility for a measurement of temperature and radius, therefore completing the physical characterization of the planet.

The third main goal of NWP is to study exozodiacal dust in planetary systems, which is generated by comet and asteroid collisions. Because of the very high contrast enabled by the starshade, combined with the absence of outer working angle, *i.e.* absence of field of view limit for the high-contrast zone, NWP will provide a complete picture of the architecture of planetary systems with dust and planets. Observing exozodi is necessary, both for its science return and as a source of background noise for future exoplanet exploration.<sup>17</sup> The distribution of the exozodiacal dust is a tracer of the systems orbital dynamics, where planetary orbital resonances create gaps and enhancements in the dust. Very low-mass planets, too small to be seen directly, should leave distinct marks as well. Imaging the exozodi should determine the inclination and orientation of the systems ecliptic plane, which can provide clues to the planets orbit from a single image.

Currently known debris disks are  $10^2$  to  $10^4$  times brighter than the level of an equivalent solar system zodiacal disk.<sup>30</sup> Zodiacal and exozodiacal dust create background flux that is mixed with the planet signal in both images and spectra. Even if nearby systems have exozodi levels no greater than the Solar System level, zodiacal and exozodiacal background will be the largest source of confusion for most targets. Unfortunately,

Table 1. Known radial velocity planets for which the angular separation reaches larger than 60mas. The contrast is calculated for a separation corresponding to the semi-major axis at quadrature. There are 18 planets for which the separation is larger than 120mas, respectively 23 for 100mas, 31 for 90mas, 38 for 80mas, 44 for 70 mas, and 57 for 60mas. There are 41 RV planets for which the maximum elongation  $a(1 + e) > 100\text{mas}$ . Data from The Extrasolar Planets Encyclopaedia,<sup>29</sup>

Planet Name	M sin(i)	period	sma	excentricity	separation	contrast
Epsilon Eridani b	1.6	2502	3.4	0.70	1.059	2.97E-09
GJ 832 b	0.6	3416	3.4	0.12	0.688	2.95E-09
55 Cnc d	3.8	5218	5.8	0.03	0.443	1.02E-09
HD 160691 c	3.1	2986	4.2	0.57	0.273	1.96E-09
Gj 849 b	0.8	1890	2.4	0.06	0.267	6.17E-09
HD 190360 b	1.5	2891	3.9	0.36	0.247	2.22E-09
47 Uma c	0.5	2190	3.4	0.22	0.243	2.97E-09
HD 154345 b	0.9	3340	4.2	0.04	0.232	1.94E-09
Ups And d	4.0	1275	2.5	0.24	0.186	5.41E-09
HD 62509 b	2.9	590	1.7	0.02	0.163	1.19E-08
HD 39091 b	10.4	2064	3.3	0.62	0.160	3.15E-09
14 Her b	4.6	1773	2.8	0.37	0.153	4.44E-09
47 Uma b	2.6	1083	2.1	0.05	0.151	7.66E-09
Gamma Cephei b	1.6	903	2.0	0.12	0.148	8.16E-09
HD 217107 c	2.5	4210	5.3	0.52	0.142	1.23E-09
HD 89307 b	2.7	3090	4.2	0.27	0.126	1.98E-09
HD 10647 b	0.9	1040	2.1	0.18	0.121	7.73E-09
HD 117207 b	2.1	2627	3.8	0.16	0.115	2.39E-09
HD 181433 d	0.5	2172	3.0	0.48	0.115	3.79E-09
HD 70642 b	2.0	2231	3.3	0.10	0.114	3.13E-09
HD 128311 c	3.2	919	1.8	0.17	0.106	1.10E-08
GJ 317 b	1.2	693	1.0	0.19	0.104	3.78E-08
HD 216437 b	2.1	1294	2.7	0.34	0.102	4.68E-09

we know very little about exozodi levels in other systems. Measuring them is crucial to the future of direct exoplanet observations.<sup>17</sup> The surface brightness of the exozodi is the main determinant in how long it takes to detect an exoplanet buried in that system; the exposure time required to detect a planet is proportional to the exozodi brightness. Such background-limited observations strongly favor telescope diameter, where the signal to noise ratio is proportional to  $D^4$ .

### 3. INSTRUMENT CAPABILITIES AND CONSTRAINTS

Both science goals and starshade design depend on existing instrument capabilities and constraints from the observatory, and differs from the case of designing a mission from scratch. We develop this analysis under the general principle that JWST cannot be modified, but we also consider a few designs requiring minor modifications. In addition to the instrumental constraints, the occulter needs to be compatible with planned operations for JWST. Technology and operations are discussed in other papers.<sup>14,15</sup>

#### 3.1 Assessment of JWST instruments for a starshade

JWST offers a large range of scientific instruments and wavelength coverage, and we study their possible combination with a starshade. The four JWST instruments (NIRCam, NIRSpec, TFI, MIRI) could potentially be used with the external occulter. JWST is sensitive to wavelengths longer than  $0.6\mu\text{m}$ . The wavelength regions from the visible to near infrared are of particular interest for both terrestrial and giant planets.<sup>22</sup>



### 3.1.1 NIRCcam

The Near Infrared Camera (NIRCcam) includes two instruments (arms), one for shorter wavelengths (0.6 to 2.3  $\mu\text{m}$ ) and one for longer wavelengths (2.4 to 5.0  $\mu\text{m}$ ). The short arm can be used with broadband filters in the visible and near infrared for planet detection and imaging. However, it does not have spectroscopic capability. The platescale of 31 mas/pixel produces slightly under-sampled images at the shortest wavelength which is a potential issue for detection. Drizzling<sup>31</sup> can be used to recover critically-sampled images, which are necessary for matched-filter detection schemes.<sup>32</sup> The field of view of 2.2'x4.4' is larger than required and sub-array reads are possible. Several broadband filters can be considered for imaging: F070W (0.6 – 0.8 $\mu\text{m}$ ), F090W(0.8 – 1.0 $\mu\text{m}$ ), F115W (1.0 – 1.3 $\mu\text{m}$ ), F150W, F150W2. In addition, there are a number of medium band filters that can be used (F140M, F162M, F182M, and F210M) for the detection of water vapor or methane absorption bands.

It is interesting to note that the detector has almost no sensitivity beyond 2.55 $\mu\text{m}$ . However the out-of-band transmission of these filters is limited to  $10^{-5}$  or higher, which puts constraints on the starshade optimization.

An Earth-twin can be detected at 10pc with at S/N=10 with F070W in 23 hours, F090W in 7.3 hours, F115W in 5.8 hours, and F200W in 11 hours, given an exozodiacal background equal to our own. For a super-Earth of same density and albedo as the Earth and 5 times more massive, the exposure times become 2.7 h (F070W), 0.85h (F090W), 0.7h (F115W) and 1.3h (F200W). These calculations assume a perfect starshade delivering  $10^{-10}$  suppression at the pupil aperture (Design 1 below), and the error budget is dominated by the background. The actual transmission of the filters is not perfect with an out-of-band transmission in the range  $10^{-4}$  to  $10^{-5}$ . We include the actual filter profile in the optimization of the starshade design in order to keep the star leakage negligible in the sensitivity range of the detector. We show in Fig.6 the effective light suppression over the entire range of sensitivity of NIRCcam (0.6–2.5 $\mu\text{m}$ ) from combining the effect of the starshade, telescope and instrument transmission, beam splitter and F090W filter for example. A suppression level below  $10^{-10}$  guarantees that the error budget is largely dominated by background light. This starshade design provides adequate suppression profile for use with the other NIRCcam filters (F070W, F090W, F115W, F200W).

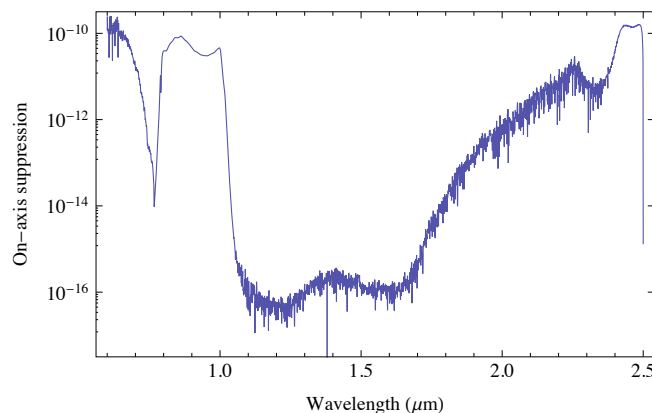


Figure 6. Overall suppression including the effects of the telescope, instrument, and starshade for the entire range of sensitivity of the NIRCcam detector (0.6 – 2.5 $\mu\text{m}$ ), which is significantly larger than the filter bandpass (here F090W). The starshade design is optimized over this entire range of wavelength in order to maintain a suppression level below  $10^{-10}$  which is adequate to keep the star leak contribution negligible in the error budget. One can recognize the top-hat transmission of the bandpass filter around 0.9  $\mu\text{m}$ . Other structures are due to the combination of the effects of starshade leakage and filter out-of-band rejection.

If the thermal emission of the starshade is sufficiently low, the long wavelength arm potentially can also be considered for broadband imaging in the filters F277W F356W, F444W and F322W2. A number of medium and narrow band filters can be considered as well (F250M, F300M, F360M, F410M, F460M, F480M), which are appropriate for methane, water ice, CO, CO<sub>2</sub>, or bright exoplanets. As discussed above, the long-arm would be particularly attractive to obtain emitted-light images in a few very favorable cases, in order to constrain radius and temperature. Because the starshade design is optimized for some suppression up to 2.5 $\mu\text{m}$  (the sensitivity limit of the NIRCcam detector), we would only lose a factor  $\simeq 2 - 3$  by using this starshade at the

longest wavelength ( $\simeq 5\mu\text{m}$ ). The IWA reduction would be a severe limitation for terrestrial planets in the HZ. However, this would be extremely interesting for giant planets in more distant orbits.

The long arm can also provide slitless spectroscopy using the  $R \simeq 2000$  grism. Spectra can be binned down to a resolution more appropriate for faint exoplanets ( $R \simeq 100$ ). However, for long exposure NIRSpec is more sensitive than NIRCcam grisms.<sup>33</sup> This makes the long-arm of NIRCcam less attractive than NIRSpec for spectroscopy and we do not consider it in this study.

### 3.1.2 NIRSpec

The Near Infrared Spectrograph (NIRSpec) covers a range of wavelengths from  $0.6\mu\text{m}$  to  $5.0\mu\text{m}$ , with  $QE > 70\%$  for  $0.6\mu\text{m}$  to  $1.0\mu\text{m}$  and  $QE > 80\%$  for  $1.0\mu\text{m}$  to  $5.0\mu\text{m}$ . This range of wavelength is particularly interesting for exoplanet and disk science in that it provides access to a number of chemical species, as discussed in Sec.2. Spectroscopy with NIRSpec includes three modes of resolution with a  $R=100$  prism and two gratings with  $R=1000$  and  $R=2700$ . All three modes are potentially interesting for exoplanets, but the low-resolution mode is more appropriate in terms of sensitivity and exposure time. The actual resolution of the prism is lower than  $R=100$  for the shortest wavelengths and varies between 35 and 65 between  $0.6$  and  $2.0\mu\text{m}$ .

Spectroscopy can be obtained using a  $0.2$  arcsec slit, or an aperture from the micro-shutter array with size  $0.2 \times 0.45$  arcsec. The plate scale is  $0.1$  arcsec/pixel. In the low resolution mode, the sensitivity drops by a factor  $\simeq 2$  below  $1\mu\text{m}$ . Based on the current estimation of performance for NIRSpec (and with a perfect starshade), a  $S/N=5$  spectrum of an Earth-twin at  $10\text{pc}$  with solar-system zodiacal disk can be obtained in  $3 \times 10^5\text{s}$  between  $1.0$  and  $1.7\mu\text{m}$  but it would take about  $1.3 \times 10^6\text{s}$  at  $0.7\mu\text{m}$  to reach the same  $S/N$ , due to the lower sensitivity of the instruments for wavelengths below  $1.0\mu\text{m}$ .

Exposure time calculations show that the higher resolution ( $R=1000$ ) is usable for some giant planets, and potentially large terrestrial planets (solar-system zodiacal level) with very deep exposures  $5 \times 10^5$  to  $10^6\text{s}$ . Note that the higher resolutions would also be very interesting for much brighter (younger) giant planets (e.g. HR 8799). Based purely on considerations of resolution, the  $R=1000$  is critical to open the possibility of accessing the oxygen A band ( $760\text{nm}$ ) at a resolution of  $\simeq 100$  because the resolution obtained with the prism is not sufficient to detect this band. However, use of the high-resolution mode could be extremely challenging because the detection becomes limited by the detector noise.

One of the potential problems is the very large wavelength sensitivity range of the detector. Even with a starshade optimized up to  $2.5\mu\text{m}$  as required by NIRCcam, the starshade leak at  $5\mu\text{m}$  would be too high and we need to combine the starshade with filters. In particular, one of the two target acquisition filters (F140X) can be used during starshade observations. This filter covers the range from  $0.8$  to  $2.0\mu\text{m}$ , which provides a good overlap with existing NIRCcam filters and the general science goals defined above, and helps significantly reduce the red leak problem. Unfortunately this target acquisition filter has a red transmission bump of a few percent within the range of sensitivity of the NIRSpec detector. This does not have any impact for normal use in target acquisition mode, but might be problematic for the starshade. Because the light is dispersed, the combined red leak through the starshade and filter is mitigated thanks to NIRSpec's excellent stray light performance, and we are investigating the impact of the actual filter transmission on the exposure time. Another target acquisition filter could be used (F110W) which has a much smaller wavelength range ( $1.0\mu\text{m} < \lambda < 1.2\mu\text{m}$ ) intended for cross calibration between NIRCcam and NIRSpec. This filter enables a much smaller starshade but is less interesting for science.

### 3.1.3 MIRI

MIRI includes two sub-instruments, the imager module with the low resolution spectrograph (LRS) and the Medium Resolution Spectrograph (MRS). At MIRI wavelengths, the angular resolution is reduced (with a pixel size of  $0.11''$ ), but the contrast requirements to image planets is also much relaxed (typically  $10^6$  contrast for a terrestrial planet). However, the emission of the occulter is very likely to prevent any high-contrast observations, and a detailed study of this possibility is still necessary.

The imager includes of a number of filters that can be used for imaging of exoplanets and disks. In addition, 3 filters are combined with the Lyot stops for each of the three coronagraphs ( $10.65\mu\text{m}$ ,  $11.4\mu\text{m}$ ,  $15.5\mu\text{m}$ ). These filters are optimized for giant planets and could be used with the external occulter (the only drawback is the

degradation of the PSF by the complex Lyot Stop shape, with associated reduction of throughput). These coronagraph bandpass filters might enable measurements for a few favorable targets. With the occulter design delivering a suppression of  $\simeq 10^{-6}$  at  $2.5\mu\text{m}$ , this means the same performance could be obtained at  $10\mu\text{m}$  with a starshade four times closer and an IWA of 400mas. Although this will not be useful for HZ planets (no observable stars with HZ beyond 400mas), this might be interesting for a few giant planets in larger orbit, in order to measure their temperature and radius.

The LRS enables  $R \simeq 100$  spectroscopy from  $5\mu\text{m}$  to  $10\mu\text{m}$ , and possibly up to  $14\mu\text{m}$ . However, the system will have some sensitivity over a larger band. The detector sensitivity range is  $\sim 1\mu\text{m}$  to  $30\mu\text{m}$  (with  $\text{QE} > 50\%$  from  $5\mu\text{m}$  to  $10\mu\text{m}$ ). The split prism consists of two materials, Ge and ZnS, which together limit the wavelength transmission to approximately 1.8 -  $14\mu\text{m}$ . Unfortunately, the split prism is on the filter wheel and it is not possible to combine the prism with an additional filter to limit the wavelength range to  $5\mu\text{m}$  to  $10\mu\text{m}$  for example. Broadband leakage and thermal emission from the occulter are strong limitations and we do not consider this possibility here.

The Medium Resolution Spectrograph (MRS) would be interesting for disks and some planets in principle. However, the very large wavelength range is  $5\mu\text{m}$  to  $27\mu\text{m}$  is too challenging for the occulter both in terms of leakage and thermal emission.

### 3.1.4 TFI

In principle the Tunable Filter Imager (TFI) could also be used for spectral characterization using a few images at a resolution  $R \simeq 100$ . The wavelength coverage from 1.6 to  $2.5\mu\text{m}$ , and 3.3 to  $5.0\mu\text{m}$ , however using a single detector sensitive to the entire range of wavelength. The étalon is used in combination with blocking filters which have out-of-band transmission of  $\simeq 10^{-4}$ . Because TFI is an imager the light leaking through the starshade at long wavelengths directly affects the high-contrast sensitivity (as opposed to the case of NIRSPEC where the spectrum is dispersed), unless one of the blocking filters could be upgraded with better out-of-band rejection.

## 3.2 Observing time

A modest but non-negligible fraction of the total JWST observing time could be made available for observations with the occulter. In this study, we consider 7 – 9% as a reasonable amount. For a five year mission, this corresponds to a total of  $7.7 \times 10^6$ s assuming 70% observation minimum efficiency requirement.<sup>13</sup> For a 10 year mission, the maximum available time would be  $1.5 \times 10^7$ s. We consider here  $10^7$ s as a total exposure time in this study.

Given this observing time limitation, the starshade mission would not be suited for a large detection survey program like the New World Observer and THEIA, which are specifically designed for this purpose. The goals should therefore focus on a small number of targets, prioritizing the characterization of known exoplanets from radial velocity (this might include Super-Earths by mission launch), and the study of exozodiacal disks. In addition to studying the complete system architecture around these targets, a survey of a few nearby stars can be envisioned to study their habitable zones.

In Fig.7 we present a preliminary estimation for possible time allocation considering  $10^7$  s total observing time, and balancing observations given exposure time estimates. This is not the result of an optimization but merely an example of possible global time allocation with orders of magnitude for exposure times.

- Deep imaging exposures of mini survey and known RV stars ( $10^5$ s each, 30 exposures): Find multiple planet systems, outer planets, probe for planet in the HZ, identify exozodiacal disks structures and brightness, study interactions planets/dust.
- Shallow revisits and filter photometry ( $10^4$ s each, 40 exposures): Confirm candidates, measure photometry in various filters, build orbits, measure orbital motion of RV planets and disambiguate  $m \sin(i)$ . Possible exposures at longer wavelengths and closer starshade with NIRCams long arm, or MIRI.
- Low-resolution spectroscopy ( $R \simeq 40$ ) of 20 RV giant planets ( $10^4$ , 20 exposures): characterize major absorbers and identify species present in gasses and clouds

- Deep spectroscopy of giants, Neptunes and high-resolution spectroscopy on bright giants ( $10^5$ s each, 14 exposures): Deep spectroscopy at low-resolution for known neptunes and high-resolution of bright young giant planets. Find methane, carbon dioxide, ammonia
- Deep spectroscopy of terrestrial planets (R=100) and giant planets (R=1000) ( $10^6$ s, 5 exposures): Find water, carbon dioxide, methane, water-ice, provide indication of terrestrial nature and habitability.

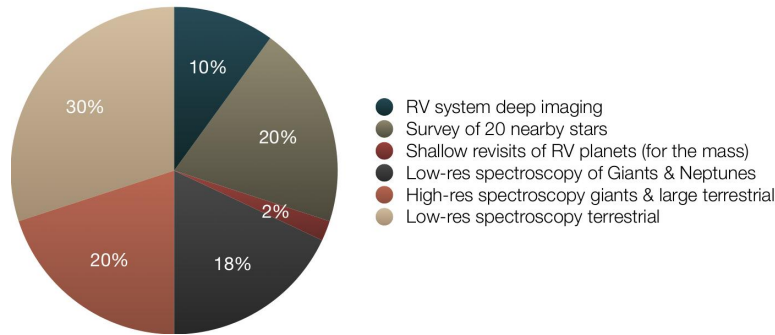


Figure 7. Example of possible global time allocation assuming a total exposure time available of  $10^7$ s (7-9% of the total mission time). Overall the balance is approximately 1/3 for imaging and 2/3 for spectroscopy in this example of a reference mission. This reference missions involves 60-80 slews.

## 4. STARSHADE DESIGN

### 4.1 Optimization method

Several authors suggested or studied the use of external occulters to produce high contrast images.<sup>34-38</sup> More recently, the possibility of using starshade occulters<sup>39</sup> to approximate continuous apodization functions opened new possibilities in terms of performance and manufacturing. The occulter is defined by an apodization function which can be optimized analytically using a hypergaussian profile,<sup>40</sup> or numerically by generating optimal apodizations for a set of constraints.<sup>41</sup>

In this paper, we reproduce the optimization described by Vanderbei et al. The electric field at the telescope aperture can be propagated from the starshade using a free-space Fresnel propagator and the Babinet theorem. The field at the telescope aperture is therefore a linear transformation of the field at the apodizer and linear optimization methods (linear programming<sup>42</sup>) can be used. Broadband optimization is obtained using a series of discrete wavelengths. Geometrical parameters include the apodizer diameter and distance, which define the IWA. Here we use the geometric IWA defined as the angle between the center and tip of the apodizer seen from the telescope aperture. In practice we chose the IWA and the starshade diameter. Another geometrical parameter is the diameter of the shadow, which we set at 7.5m diameter, i.e. 1m larger than JWST's diameter. A number of constraints can be added to the optimization. First, the suppression constraint is applied to both real and imaginary part of the electric field, and a smoothness constraint is necessary to avoid bang-bang solutions and guarantee broadband performance. More advanced schemes can be implemented where manufacturing tolerances are included in the constraints<sup>43</sup> but we use the basic optimization in this study.

### 4.2 Red leak

In principle, it is possible to find a starshade solution for any bandwidth. As discussed above, JWST detectors are sensitive to a very large range of wavelengths. In particular, the NIRSpec detector is sensitive to the full range from 0.6 to 5.0 micron, and it is difficult to optimize a reasonably sized starshade for such large bands (the larger the band the larger the occulter). For example, an optimization for the F140X filter in NIRSpec from 0.8 to  $2.0\mu\text{m}$  must be compatible with NIRCAM's filter out-of-band rejection up to  $2.5\mu\text{m}$ . With a straightforward optimization for F140X, the leakage in NIRCAM is too high. This problem can be overcome by using a weighting function to limit the amount of red leak beyond a certain wavelength.

We searched for solutions over the entire NIRSpec sensitivity range (0.6 to 5.0  $\mu\text{m}$ ) using a weighted optimization with 3 orders of magnitude of allowed red leak at 5.0 $\mu\text{m}$ . Solutions can be found with reduced suppression performance  $10^{-9}$ , increased IWA (120 mas), and increased occulter size (100m diameter), but these solutions are not relevant both scientifically and practically.

In Fig.8 we give an example of a weighting function to relax the suppression requirement above 1.7 $\mu\text{m}$ , with the motivation to include  $\text{CO}_2$  and  $\text{CH}_4$  at 1.6 $\mu\text{m}$  and 1.66 $\mu\text{m}$ , and relax the performance beyond. One of the effects of using such a weighting function to tailor the chromatic suppression is to provide solutions with smaller diameters. Typically, this calculation save 5m to 10m of occulter diameter compared to the case where the suppression is constant over the entire band.

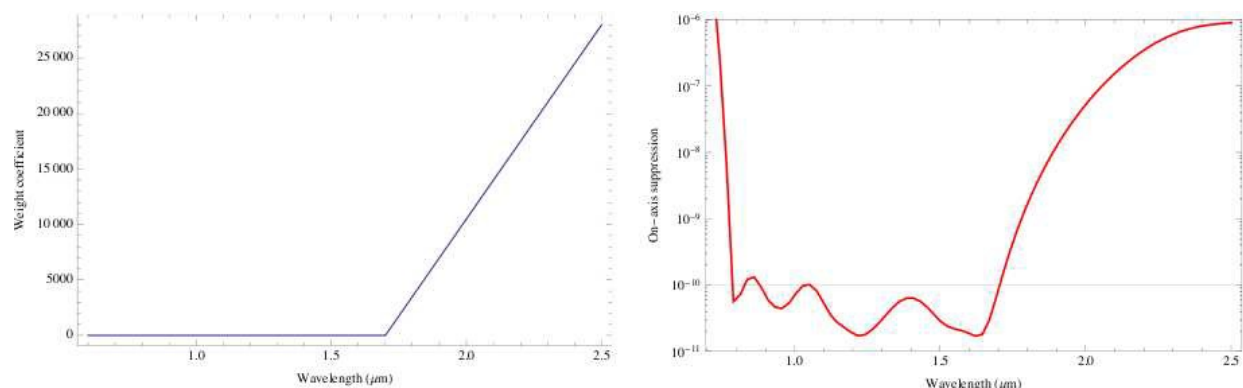


Figure 8. Left: weighting function used for Design 1. The suppression is  $10^{-10}$  in the F140X filter bandpass (0.8 to 2.0  $\mu\text{m}$ ) and is relaxed at longer wavelengths in order to be compatible with NIRCams out-of band filters. Right: Average intensity suppression in the pupil as a function of wavelength as a result of the optimization with this weighting function. The constraint on the 2.5 $\mu\text{m}$  leakage is set so that the overall transmission through NIRCams remain at  $10^{-10}$  level (See Fig.6)

### 4.3 Starshade design baseline

We define a few designs compatible with the science program and the JWST instrument constraints. Design baselines are based on the use of the target acquisition filters F140X and F110W and NIRCams filters. Because the properties of the shadow at the telescope aperture result from a Fresnel propagation, identical suppression is obtained for a constant Fresnel number  $D_s^2/(\lambda z)$  where  $D_s$  is the diameter and  $z$  the distance of the starshade. It is possible to bring the starshade closer to the telescope for identical shadow suppression at a longer wavelength with a larger IWA.

- Design 1: wavelength range 0.8 to 2.0  $\mu\text{m}$ . This design is based on using the existing F140X NIRSpec filter. The starshade can be moved further out for observations with NIRCams F070W and reduced IWA. The starshade diameter is 70m at a distance of 72193km. This is the design use in the paper.
- Design 2: wavelength range from 1.0 to 1.3  $\mu\text{m}$ , which covers F115W for imaging with NIRCams and F110W for spectroscopy with NIRSpec. This design provides a small-diameter starshade but little science. The starshade diameter is 43m at a distance of 44347km.
- Design 3: wavelength range 0.6 to 1.7  $\mu\text{m}$ . This assumes a different filter with smaller extent than F140X from 0.7 to 1.7  $\mu\text{m}$  and bringing the starshade further for use with F070W. This design includes access to all interesting molecular bands. The starshade diameter is 70m and distance 72193km.

## 5. CONCLUSION

We studied the possible science program and design optimization of a starshade for JWST. Instrument capabilities on-board JWST are well suited for the science goals, and a combination of NIRCams and NIRSpec would enable

both imaging and spectroscopy of planets and disks. New Worlds Probe can image terrestrial planets in the habitable zone of nearby stars, characterize known radial velocity planets in great detail, and solve the exozodiacal disk question by measuring their brightness and structure with planet disk-interactions. Sensitivity estimation shows that NWP can image an Earth-twin at 10 pc in 6 to 20 hours depending on the filter, and obtain a low-resolution spectrum in 83 hours between 1 and 1.7  $\mu\text{m}$ . These exposure times are expected to be 10 times shorter for larger terrestrial planets (5 Earth masses). NWP can detect water on a terrestrial planet down to the size of the Earth, and potentially discover oxygen in a favorable Super-Earth.

We propose a solution to enable spectroscopy with a starshade by using target acquisition filters to reduce the range of wavelengths. Based on existing filters, we derive a few designs compatible with the science program with starshade diameters (tip to tip) ranging from 43 to 70m and distances from 44347 to 72193km. The starshade baseline design is compatible for observations with NIRSpec and NIRCam and includes considerations of the actual filter transmissions. We are investigating the impact of the out-of-band transmission of the NIRSpec filter on the final performance, using stray light analysis.

Among the other constraints for NWP, the amount of available observing time and limitation of the field of regard also need to be considered carefully in designing a reference mission. With a tilted occulter the field of regard can be extended to an annulus of 20-25 degrees which is sufficient to be compatible with the deepest exposures.

A study of the technical aspects of NWP, including deployment, alignment and formation flying, as well as operations will be presented in a future work. With its large diameter and sensitive instruments, JWST with starshade is an very interesting and competitive alternative to dedicated coronagraphic missions on small (1-1.5m) telescopes.

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