New Technologies for Exploring New Worlds

Technology White Paper Submitted to The Discipline Panel on Electromagnetic Observations from Space (EOS)

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ABSTRACT

We argue that the most cost-effective way toward finding Earth-like planets is through the development of two new technologies: photon-counting p-channel CCD's and external occulters for starlight suppression. To make our case, we compare the costs and scientific performance of different-size space telescopes with and without these two technologies. We find that not only does a 4-m telescope with an external occulter and with photon-counting, p-channel CCD's cost significantly less than a 8-m coronagraphic telescope using conventional CCD's, but it can search the spectrum of 30% more planets for evidence of habitability and life. We therefore strongly recommend that NASA support the development of photon-counting p-channel CCD's and external occulters as soon as practicable so that the results of these technological developments can inform NASA's decision-making for missions to find Earth-like planets.

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1. Introduction

The 2000 Decadal Panel highly endorsed a mission called Terrestrial Planet Finder (TPF), which used an infrared interferometer to search for Earth-like planets, but given the immaturity of the technology, the panel[1] directed that funding be restricted to technology development:

> "By a large margin, TPF is the most costly and the most technically challenging mission discussed in this report…NASA should pursue a vigorous program of technology development to enable the construction of TPF to begin in this decade. The committee attributes $200 million of the $1,700 million total estimated cost of TPF to the current decade.

Since the 2000 decadal survey, attention has shifted to single, optical telescopes to search for Earth-like planets. When NASA's *Vision for Space Exploration* was issued in 2004 calling for the launch of TPF in 2014, the optical-coronagraph version of TPF was selected for rapid development because it judged to be more technologically mature. Then in 2006, Cash[2] presented a novel method of starlight suppression: a large (~50 m), free-flying occulter centered on the line of sight from the telescope to the target star. This TPF concept came too late for follow-up study and technology development, because by that time, the TPF program had been put on hold. Now, 3 years later, we return to the question of technologies for finding Earth-like planets.

What technologies should we be developing to support the search for Earth-like planets? There are three contenders: improved detectors, new starlight suppression systems, and larger optical telescopes. In this paper, we consider all three: photon-counting, p-channel CCD's, optical coronagraphs and external occulters, and large (8 and 16 m) telescopes. But first, we describe the scientific goals of an Earth-like planet-finding mission, and we define a metric for the scientific yield of such a mission (Section 2). We then compare the costs (Section 3) and scientific yield of the 4, 8, and 16-m telescopes with and without photon-counting p-channel CCD's (Section 4). These comparisons show that not only does a 4-m telescope with external occulter and photon-counting, p-channel CCD's cost >$1 B less than an 8-m telescope designed for coronagraphy with conventional CCD's, but it can search 30% more planets for evidence of habitability and life. Finally, we describe the current status of photon-counting p-channel CCD's and technologies for external occulters, and we recommend developing them as soon as possible so that development of a mission to find other Earths can proceed.

2. Scientific Goals and Their Implications

The ultimate goal of exoplanet research is to find other Earth-like planets, and thus, to answer the question, Are we alone? The only way to answer that question is to observe the planets directly. Logically, the search for life on other worlds has two steps (although the two steps may be taken simultaneously). The first step is to find out whether a planet is habitable. Life as we know it depends on the continuous availability of liquid water on the planetary surface, so to be judged habitable, the spectrum of a habitable planet must show absorption features of water vapor, e.g. H_2O 0.94 μ. If the planet appears habitable, the second step is taken, which is usually to look for evidence of photosynthesizing organisms using the biomarkers, oxygen (O_2 0.76 μ) or ozone (O_3 0.2-0.3 μ). There is also the possibility of finding evidence of methanogens, which produce methane (CH_4 0.89 μ) but not when oxygen is present, as methane is easily oxidized. There is also the possibility of detecting the "vegetation red edge" produced by the sharply increased reflectance of chlorophyll, which on Earth occurs at ~0.7 μ.

We cannot expect an exoplanet with life to have a spectrum like that of Earth. Even the Earth's spectrum did not always look the same as it does now. Figure 1 shows a simulation[3] of the spectral evolution of the Earth. At an age of 1 Gyr, the spectrum would show no evidence of life except for CH_4 0.89 μ produced by methanogens, but methane can also be produced by non-biological processes. Then, at an age of 2.5 Gyr, strong UV ozone absorption at λ<3000A appeared, ultimately due to the presence of photosynthesizing organisms. These microbes also produced oxygen directly, but not in enough quantities for the A-band of O_2 at 0.76 μ to have been visible. Only when the oxygen abundance rose to near its present level (21%) did this oxygen feature become visible at moderate S/N. However, H_2O 0.94 μ absorption, the signature of habitability, would be readily detectable throughout its history.

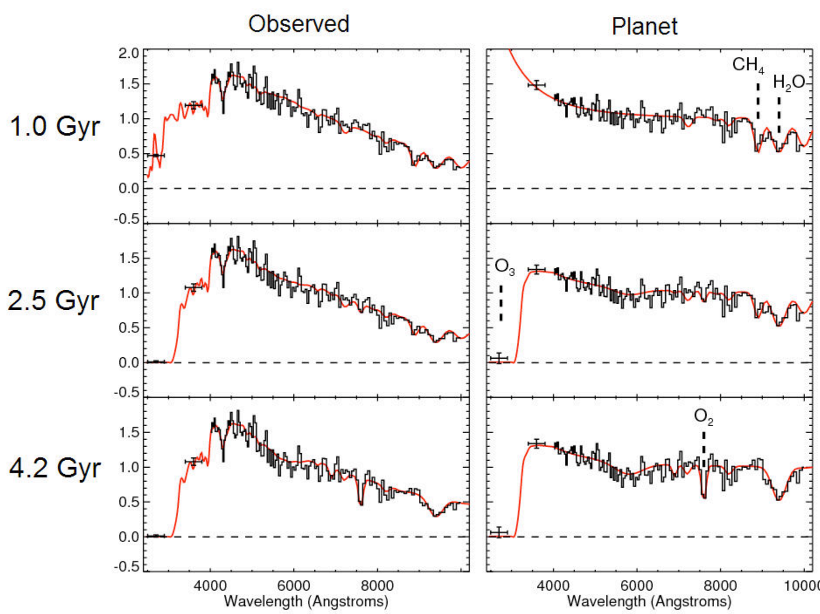

Figure 1. Spectral evolution of an Earth-twin at 10 pc as observed in a 10-day exposure by a 4-m telescope utilizing an external occulter for starlight suppression. The red line shows the spectrum without noise, the black line is the observed R=70 spectrum having a S/N=12 per resolution element (the S/N needed to make a 5-σ detection of O_2 at 21%. The left column shows the predicted spectrum as it would be observed; the right column, the planet spectrum after dividing out the stellar spectrum.

Except for the Hartley absorption band of ozone at λ<0.3 μ, all the important spectroscopic signatures below 1.0 μ fall in the wavelength range, 0.7-1.0 μ. The importance of the near-IR (0.7-1.0 μ) puts a premium on detectors with high sensitivity at long wavelengths. As shown in Figure 2, thick, fully depleted p-channel CCD's[4] from Lawrence Berkeley Labs (red curve) are best suited for assessing habitability and the presence of biomarkers. The tolerance of p-channel CCD's to particle radiation[5] is another important reason to greatly prefer these CCD's for exoplanet spectroscopy.

Direct imaging detection of faint exoplanets is difficult enough, but spectroscopy, even at low-resolution, is extremely difficult with today's telescopes and instrumentation, because the flux per pixel is so low. Not only is the spectral range covered by a spectral pixel lower than in an image pixel (e.g. 1500 A per pixel in an image vs. 100 A in a spectrogram), but in an integral field spectrograph that we assume here, the counts in each image pixel are distributed over 6 pixels in the spectrogram (2 pixels in the spectral direction times 3 pixels in the cross-dispersion direction).

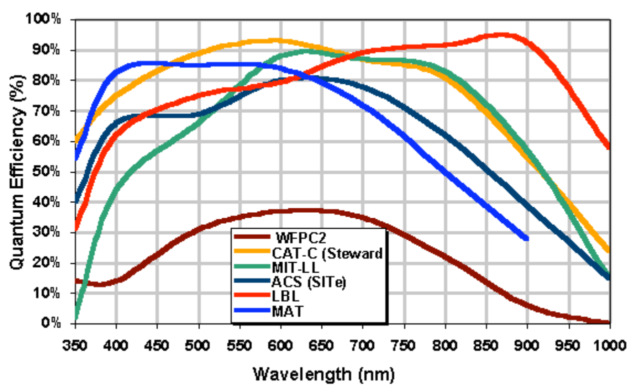

Figure 2. Typical CCD quantum efficiencies circa 2002. From Clampin[6].

In fact, Beckwith[7] (2008) argues that "single telescopes with coronagraphs to isolate the light from the planet will have to be 8 m or larger in diameter to generate sample sizes with a reasonable probability of finding at least one life-bearing planet". His rationale makes use of several scaling relationships involving telescope diameter, D: (1) Larger coronagraphic telescopes can probe more closely to the star, i.e. they have a smaller inner working angle, IWA$\propto\lambda/D$, where λ is the wavelength; (2) Larger telescopes have greater light-gathering power, $\propto D^2$; (3) Larger telescopes can reach planets at greater distances, and thus, the sample size will be larger, $N_{pl}\propto D^3$; (4) Larger telescopes will have shorter exposure times, $t\propto(S/N)^2(d_{pc}/D)^4$.

Following Beckwith, we adopt as the metric of science yield, the number of Earth-twins (Earth-size planets orbiting their central stars at mid-habitable zone) that could be fully characterized spectroscopically in an exposure time of 25 days or less (Beckwith's metric used 1 day).

3. Cost Comparisons

Large space telescopes are costly. To demonstrate, we take the cost model described in *The Design and Construction of Large Optical Telescopes*[8], which has the form:

$$\text{Cost} \propto \frac{D^{1.6} M_f D_f D'_f}{\lambda^{1.8} T^{0.2} e^{0.033(Y-1980)}},$$

where M_f is a factor depending on the material of the optics and telescope structure; D_f=1.0 for on-axis, 1.3 for off-axis; D'_f =1.0 for solid or 1.3-1.4 for lightweighted mirrors, λ is the operational wavelength of the telescope assumed to be diffraction-limited, T is the operating temperature in ^{o}K, and Y is year of completion.

For space telescopes, cost$\propto D^{1.6}$, all other factors being equal. But all other factors are not equal: coronagraphic telescopes and occulter-telescopes are quite different. Coronagraphic telescopes have to be off-axis to avoid contamination by the diffraction spikes by the support of the secondary mirror, whereas occulter-telescopes are free to be normal, on-axis telescopes. More importantly, coronagraphic telescopes assume all the burden of suppressing starlight, so they have to be *better* than diffraction-limited. According to the *TPF-C Technology Plan*[9], "the telescope needs to deliver a ~10-nm rms wavefront to the coronagraph, where a deformable mirror will further reduce the wavefront error to an unprecedented sub-nm level. The wavefront correction must be maintained over the entire observation period". Achieving a 10-nm wavefront error at 0.5 μ corresponds to a specification: WFE ≲ λ/50! We adopt a looser specification for the telescope, WFE≲λ/30, since later, informal assessments suggested that such high image quality and stability were not needed. Thus, the wavelength to be used in the cost formula is then: λ =14/30* λ_{min}, where λ_{min} is the shortest wavelength of the operating spectral range (Δλ).

TABLE 1: COST ESTIMATION

D \ Cost	Case 1	Case 2
Telescope Type WFE Δλ λ	Telescope With Occulter WFE= λ /14 Δλ=0.25−1.0 μ λ =0.30 μ	Coronagraphic Telescope WFE= λ /30 Δλ=0.7−1.0 μ λ =0.33 μ
4 m	$ 1.0 B	$ 1.1 B
8 m	$ 3.0 B	$ 3.3 B
16 m	$ 9.2 B	$10.1 B

Table 1 shows the estimated costs for the 4, 8, and 16-m telescopes alone (no starlight-suppression system, no science instrumentation, no spacecraft, etc.). These cost estimates are based on the assumption that the 4-m occulter-telescope costs $1.0 B, which is not a bad estimate. Case 1 makes an "apples-to-apples" comparison, where only the size of the on-axis, diffraction-limited telescope is changed. It is not a realistic case, for it is highly doubtful that large (≥8 m) space telescopes could make use of external occulters, because of the intractably large size of the occulter (≳90 m) and large telescope-occulter separation (≳200,000 km) involved[10]. A proper comparison should therefore compare the cost of a 4-m external-occulter telescope with that of an 8-m or 16-m coronagraphic telescope. This comparison is shown in Case 2. In this case, the telescope and coronagraph mirrors are coated with highly reflective (R=0.97) protected-silver in order to compensate for the many reflections in the optical train. As silver is not reflective in the UV, the spectral range of observation must be restricted to the visual/near-IR, so these coronagraphic telescopes could not search for ozone, the most sensitive tracer of life. However, they could search for photosynthesizing life through observation of O_2 0.76 μ.

Other cost items for comparison are the starlight suppression system and the detectors. The cost of developing, constructing, and testing an external occulter[11] is nearly $1 B including the spacecraft, whereas a wavefront correction system + internal coronagraph might cost 1/10th of that. Thus, the cost of a 4-m telescope + external occulter ($2.0 B) is more than a billion dollars cheaper than an 8-m coronagraphic telescope ($3.4 B). The cost of developing photon-counting CCD's[12] was recently estimated at only $12.2 M. This estimate is less than half that of the uncertainty in the cost of an integral field spectrograph for TPF-C due to its specification of photon-counting CCD's, but it might reflect the very real advances in CCD technology since 2005.

4. Comparisons of Scientific Performance

It is highly doubtful that funding will be available for an 8-m or 16-m telescope in the foreseeable future, so we ask whether we can make significant progress with a 4-m, on-axis telescope (the largest telescope with a monolithic primary that can be fit into existing launch vehicles) using photon-counting CCD's? To help answer this question, we compared the computed count-rates of planets and various noise sources of a 4-m, 8-m, and 16-m telescope. Other than size, the three telescopes are the same: all three are on-axis, diffraction-limited telescopes with the same (high) optical throughput, as is appropriate (only) for exoplanet telescopes using external occulters for starlight suppression (Case 1).

Rather than follow Beckwith's analytic approach comparing "perfect" coronagraphic telescopes, we assume telescopes with instrumental noise, and we compute exposure times and sample sizes for earth-size habitable planets orbiting real, nearby stars. These stars are taken from Turnbull's (2008) target list[13]. We assume that all three telescopes use modern but conventional CCD's, i.e. CCD's having a read noise, $\sigma_{rd}=3e^-$

Figure 3 shows the count-rates encountered in low-resolution (R=70) spectroscopy of the biomarker, O_2 0.76 μ. Regardless of aperture size, the count-rate produced by read noise is over 6 times greater than that of total sky (zodi+exozodi) background even when we make a full accounting of the exozodi. (We adopted the historical average zodi brightness, which is 1.5 times is current value[14], and we took into account that our view from Earth intersects only half the zodiacal cloud. Thus the total sky (zodi + exozodi) background is 2x1.5+1=4 times the observed zodi. We assumed that each planetary system is viewed 60^{o} from pole-on, so the total sky background is 8 times the zodi at the ecliptic pole.) The count-rates produced by these various backgrounds are independent of telescope size and nearly constant from planet to planet; what changes with aperture size is the count-rate of the planets.

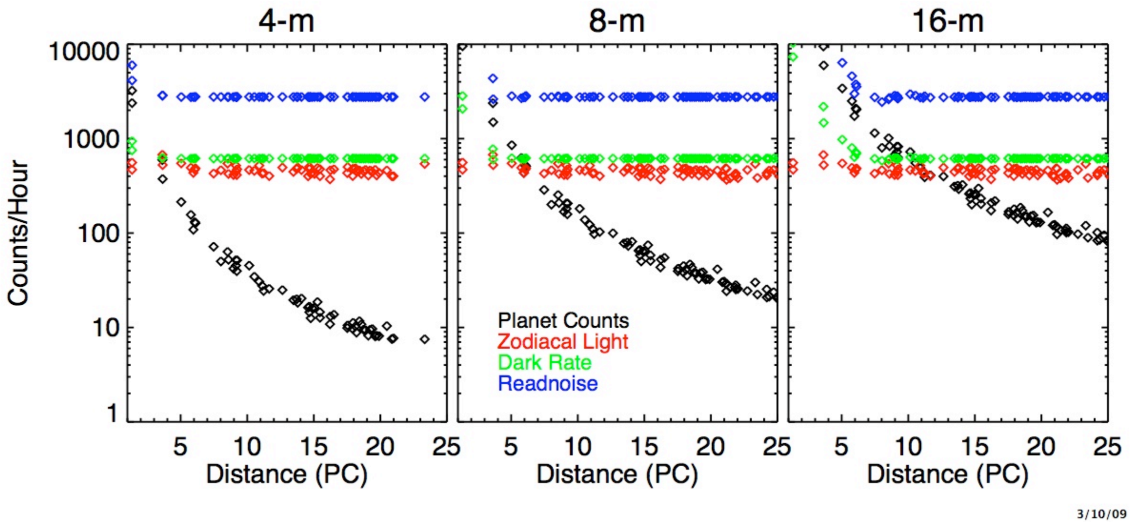

Figure 3. Count-rates for integral field spectra in search of O_2 0.76 μ in the atmospheres of Earth-like planets orbiting Sun-like stars. The assumed oxygen abundance is 21%.

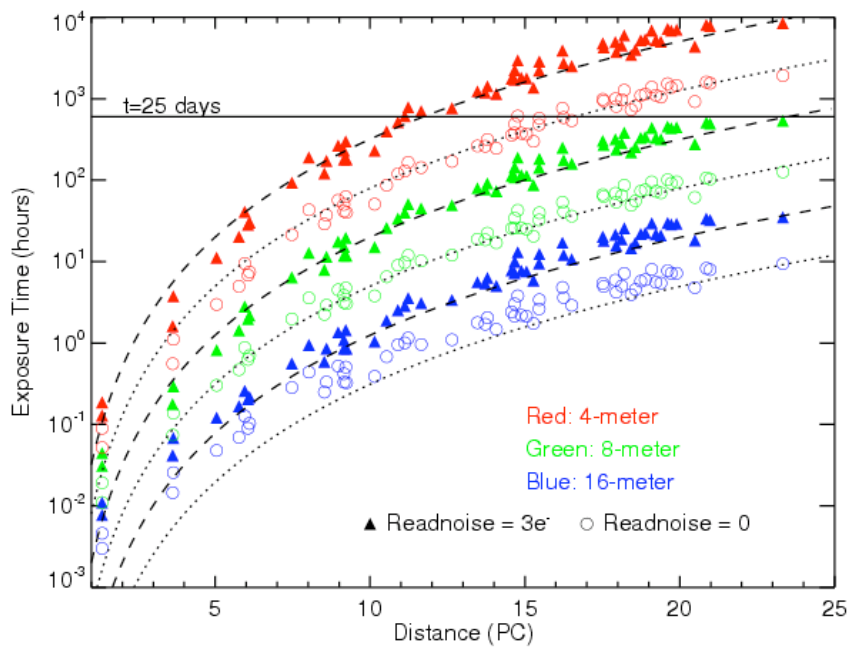

Figure 4. Exposure times required to make a 5-σ detection of the A-band of oxygen at 0.76 μ in the spectrum of an Earth-like planet (O=21%, which requires a S/N=11 in the adjacent continuum). The exposure times for a conventional CCD (σ_{rd}=3e$^-$) are shown as filled triangles, and for a photon-counting CCD (σ_{rd}=0), as open circles. The dotted and dashed lines show the t~distance^4 relationship; they are not fits to the data. The horizontal line at an exposure time of 25 days sets the maximum exposure time, and hence the sample size available for the discovery of oxygen at a present-day level.

Figure 4 compares the exposure time to make a 5-σ detection of the O_2 0.76-μ biomarker for a 4-m, 8-m, or 16-m telescope using an external occulter. It shows how the use of a photon-counting CCD leads to significantly shorter exposure times for any size telescope. In the case of the 4-m telescope, exposure times using a photon-counting CCD are typically 1/5th of those of a CCD with 3 e^- read noise; for the 8-m and 16-m telescopes, the exposure times are cut down to ~1/4th and ~1/3rd respectively.

The main points of Figures 3 and 4 are: (1) Except for the closest targets, CCD read noise is the largest source of noise, regardless of telescope size, so telescopes of all sizes (and types) can benefit from photon-counting CCD's, and (2) Because the use of a photon-counting CCD makes exposure times shorter, it enlarges the sample size available to a telescope having a maximum exposure time (in our case, 25 days).

On paper, at least, external occulters are far superior to internal coronagraphs for searching for other Earths. The virtues of telescopes utilizing external occulters include:

- *The same inner working angle at all operational wavelengths* (0.25-1.00 μ), because the IWA is set by the size and distance of the occulter from the telescope. The constant IWA means that if a planet is detected in the V-band, its near-IR spectrum can be searched for water and biomarkers like oxygen and methane.
- *Sensitivity to the UV-blue region of the spectrum* (0.25-0.45 μ), because the telescope has no need of a coronagraph, so the total number of reflections can be minimized, and UV-reflective mirror coatings (Al + MgF_2) can be used. The near-UV spectrum of a planet can be searched for ozone, which is not only a feature that can be easily measured by photometry, but it is 100 times more sensitive to the presence of oxygen than oxygen itself (see the middle plot of Figure 1)! This strong ozone feature is beyond the reach of coronagraphic telescopes which have an effective short-wavelength cut-off at ~0.45 μ.
- *Wide wavelength range that can observed simultaneously,* because the starlight suppression properties are set by the occulter, not the telescope. With the use of dichroics, the full UV-optical spectrum (0.25-1.00 μ) of all image elements in a planetary system can be recorded by integral field spectrographs and cameras simultaneously. In contrast, a coronagraphic telescope with a single wavefront correction+coronagraph system can observe over a wavelength range equivalent to $\Delta\lambda/\lambda$ ~0.1, so it is reduced to observing one spectral feature at a time. To observe over a wider spectral range requires multiple wavefront correction + coronagraphic systems.
- *Sensing and Control does not require science-band photons*

In this paper, we adopt the occulter design of Vanderbei[15] and colleagues at Princeton. In this design, the occulter is 50 m across and 72,000 km from the telescope. It produces a deep shadow over the wavelength range, 0.25-1.1 μ. Its inner working angle is 72 mas over that wavelength range.

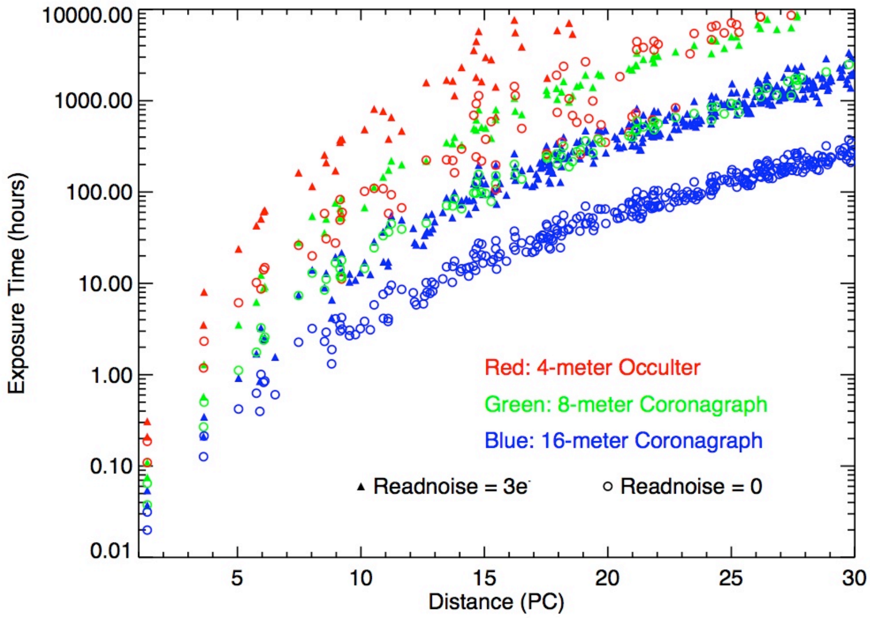

Figure 5. Comparison of exposure times for detecting the spectroscopic signature of photosynthesizing organisms, O_3 or O_2 assumed to have an abundance of 10%. The optical throughput of the 8-m coronagraphic telescope is half that of the 4-m external-occulter telescope to allow for a Lyot stop, and the optical throughput of the 16-m coronagraphic telescope is a quarter of that of the 4-m external-occulter telescope to also allow for masking the edges of mirror segments.

Figure 5 compares the exposure times and sample sizes of the 4-m external-occulter telescope and the 8-m or 16-m coronagraphic telescopes. This plot should be viewed with the understanding that the exposure times for the 4-m occulter telescope refer to the collection of data simultaneously over the whole UV/optical/near-IR spectrum containing water vapor, ozone, oxygen, and methane absorption bands, whereas they refer to the collection of data only on the O_2 0.76 μ absorption band in the case of the 8-m or 16-m coronagraphic telescope. In this figure, the oxygen abundance is only half of its present-day abundance. This figure shows that the exposure times for the 4-m telescope with photon-counting CCD's are generally the same or shorter than for the 8-m coronagraphic telescope with conventional CCD's (3 e^- read noise).

The exposure-times shown above affect the sample size, since all valid targets must have exposure times shorter than 25 days. In the case of the 4-m external-occulter telescope, however, we have our pick of biomarker -- oxygen or ozone – whichever has the shorter exposure time. In addition, an Earth-like planet must lie outside the inner working angle, which is set at IWA≡72 mas for the 4-m external occulter and computed as IWA=3 λ/D for internal coronagraphs. In agreement with Beckwith (2008), we set the wavelength for evaluating the IWA at 1.0 μ, in order to include the primary diagnostic for habitability, H_2O 0.94 μ. The inner working angle, IWA=77 mas for the 8-m telescope, and IWA=39 mas for the 16-m telescope. Table 2 compares the number of Earth-size planets whose spectra can be searched for evidence of habitability and the presence of life, for an oxygen abundance of 10%.

Table 2: Number of Fully Characterizable Planets for O_2 Level of 10%

Telescope	N (σ_{rd}=3 e^-)	N (σ_{rd}=0)
4-m occulter telescope	21	45
8-m coronagraphic telescope	34	64
16-m coronagraphic telescope	174	>308

These results might seem too generous towards the large, coronagraphic telescopes, because they are for a relatively high atmospheric oxygen abundance of 10%. If the oxygen abundance were much lower than that, the O_2 spectral feature would become undetectable at moderate S/N, so the number of targets whose spectra can be search for evidence of photosynthesizing life would diminish rapidly. The UV ozone band, however, which is accessible only to external-occulter telescopes, would remain at full strength down to an oxygen abundance level of only 0.2%! The 16-m coronagraphic telescope, however, is truly a powerful telescope. Even for an O_2 abundance of only 1%, it could fully characterize 64 targets with conventional CCD's, and 191 targets with photon-counting CCD's, because it can achieve the high S/N=38 needed to detect this weak feature.

5. Status and Development of New Technologies

Photon-counting, p-channel CCD's. The underlying principle of photon-counting CCD's is to amplify the charge via impact ionization and to distinguish between signal and noise in the amplified charge via thresholding. The gain is given by $(1+m)^n$, where m is gain per stage, and n is the number of stages. Regular n-channel photon-counting CCD's use electrons as the signal carrier, whereas p-channel CCD's use holes. The advantages of hole transport in scientific CCD's are: vastly superior radiation hardness when compared to n-channel CCD's and significantly improved near-infrared response due to their thick, fully depleted, high-resistivity substrates. The challenge of using holes in a charge-multiplying device is their significantly smaller impact-ionization coefficient in silicon relative to the electron impact ionization coefficient. While photon-counting n-channel CCD's are commercially available from Texas Instruments in the USA and *e2v* in the UK, photon-counting p-channel CCD's don't exist.

Another issue observed in electron-multiplying CCD's is increased background noise from spurious charge, a major component of which is thought to be clock-induced charge (CIC). However, this effect should be minimized by operation at low temperatures, and LBNL CCDs have been shown to perform well in terms of dark current and CTE at temperatures as low as -140 ^oC.

Fully depleted, p-channel CCDs fabricated on high-resistivity silicon have been developed at Lawrence Berkeley National Laboratory (LBNL). The LBNL group is currently supplying large-format CCDs for the Dark Energy Survey (DES) Camera and the Baryon Oscillation Spectroscopic Survey (BOSS) spectrograph. In addition LBNL has developed unique, high-voltage compatible CCDs with enhanced spatial resolution for projects such as the Joint Dark Energy Mission. The LBNL group has expertise in device and process simulation, wafer layout, and CCD design, fabrication, and testing. They develop CCDs in collaboration with DALSA Semiconductor, a CCD foundry that produced the CCDs for the Mars Rovers. Most of the fabrication steps are performed at DALSA Semiconductor, with the steps needed to produce back-illuminated CCDs done at the LBNL MicroSystems Laboratory. The LBNL group is actively involved in the development of p-channel, photon-counting CCDs. They have devised a technical approach for developing thick, fully depleted, p-channel charge-multiplying CCD's to NASA technology Readiness Level 6. Goddard stands ready to do performance testing and space qualification of prototype CCDs produced by LBNL.

External Occulters. The optical theory of coronagraphic masks, whether a coronagraph internal to the telescope or an external occulter, is in its infancy. Of computational necessity, at least four approximations in mask optics are made: (1) Kirchoff approximation, (2) Scalar field approximation, (3) Infinitely thin, perfectly conducting aperture approximation and (4) Fresnel approximation. Of the four, only the Fresnel approximation has been shown to produce negligible errors in the case of an external occulter[10] (Lyon 2007). The scalar field approximation is clearly wrong[16], but there is no hope of carrying out a full model of an external occulter allowing for a 3-D electric field. Even if there were, it would be unwise to fly a fixed external occulter based on solely on analysis. We need an occulter testbed sufficient to validate the predicted performance. This testbed should be the functional equivalent of the High Contrast Imaging Testbed (HCIT), which has been developed for internal coronagraphs at JPL.

The many technologies[17] feeding into an occulter include: the occulter system (e.g. thermal, materials, thermal/optical/mechanical, stray glint from sunlight) and its deployment system, formation flying, positioning control, response to micro-meteroids. The current state of these technologies and possible paths of maturing these technologies are described in the responses to the Request for Information issued by the Astro2010 programs Subcommittee to be submitted by the New Worlds (PI=Cash) and THEIA (PI=Spergel) ASMCS study teams.

6. Recommendation

We strongly recommend that NASA support the development of photon-counting p-channel CCD's and external occulters as soon as practicable so that the results of these technological developments can inform NASA's decision-making for missions to find Earth-like planets. To obtain the best information possible, NASA should sponsor the development and evaluation of external occulters via open competition, and if possible, it should support multiple, independent evaluations. Evaluations of external occulters should include theoretical studies, laboratory testing, and sub-scale deployment tests.

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