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Detection of Earth-like planets around nearby stars using a petal-shaped occulter

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Direct observation of Earth-like planets is extremely challenging, because their parent stars are about 10^{10} times brighter but lie just a fraction of an arcsecond away[1]. In space, the twinkle of the atmosphere that would smear out the light is gone, but the problems of light scatter and diffraction in telescopes remain. The two proposed solutions—a coronagraph internal to a telescope and nulling interferometry from formation-flying telescopes—both require exceedingly clean wavefront control in the optics[2]. An attractive variation to the coronagraph is to place an occulting shield outside the telescope, blocking the starlight before it even enters the optical path[3]. Diffraction and scatter around or through the occulter, however, have limited effective suppression in practically sized missions[4–6]. Here I report an occulter design that would achieve the required suppression and can be built with existing technology. The compact mission architecture of a coronagraph is traded for the inconvenience of two spacecraft, but the daunting optics challenges are replaced with a simple deployable sheet 30 to 50 m in diameter. When such an occulter is flown in formation with a telescope of at least one metre aperture, terrestrial planets could be seen and studied around stars to a distance of ten parsecs.

A starshade suitable for planet hunting must be designed such that the diffracted light is minimized. This means the sum of the phases of the light from all the paths through and around the shade must be extremely close to zero, implying a wide range of phases in the focal plane. The number of extra wavelengths ($m\lambda$) a ray must travel to reach the centre of the shadow around an occulter of radius R at a distance F is given by $R^2 = 2m\lambda F$. Noting that R/F is the angular diameter of the shade, the relation becomes $R = 2m\lambda/\theta$. For planet-finding θ is 5×10^{-7}, so a planet just 0.1 arcsec from its parent star may be detected, and in the visible band $\lambda = 6 \times 10^{-7}$ m. If m is at least 10, then to create a large range of incident phases, R must be at least 20 m. So, based only on wavelength and planet–star angle, one finds that the starshade must be a large distance ($R/\theta \approx 40{,}000$ km) from the telescope. Conveniently, occulters with diameters of tens of metres can also fully shade the large (up to 10 m in diameter) telescopes suitable for studying the planets.

A recent study of transmitting apertures showed it was possible to efficiently suppress diffraction over a broad spectral band to the 10^{-10} level very close to a stellar image[7]. The results had the further key feature of being 'binary' (either fully transmitting or fully opaque at each and every point), thus avoiding the problem of a partially transmitting sheet that would be difficult to manufacture to the needed tolerances and might reintroduce scatter. Then, a class of circularly symmetric apertures was shown to enable suppression in all directions simultaneously between some inner and outer working angles[8]. These apertures could be made binary and still function well by approximating the circularly symmetric fall-off with an array of petal-shaped apertures.

By numerical integration of the Fresnel diffraction equations and by subsequent mathematical derivation (provided in the Supplementary Information) I have shown there exists a class of shaping

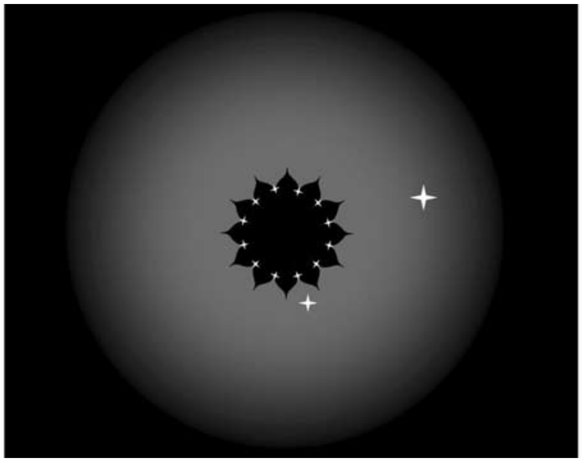

Figure 1 | **Schematic showing how a starshade in position against a nearby star might appear.** If a telescope of sufficiently good quality is stationed at the centre of the shadow, it would see the shade outlined against the zodiacal light of the target star system. At the base of each petal a small amount of light from the parent star diffracts around the shade. Planets simply appear as faint stars in the field of view. The shape of the starshade is based on the parameters used to calculate performance in Fig. 2.

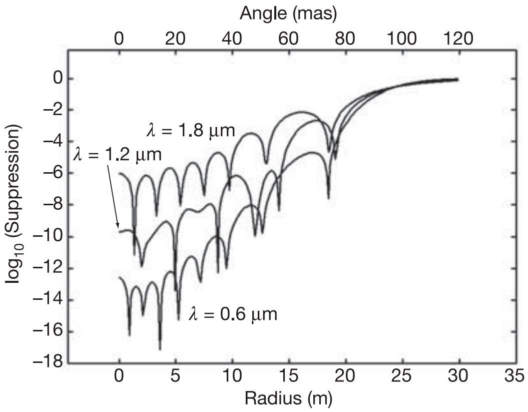

Figure 2 | **Achieved stellar suppression.** The stellar suppression ratio of a typical starshade is shown for three wavelengths: $\lambda = 0.6\,\mu$m, 1.2 μm and 1.8 μm. The depth of the shadow is plotted versus the radius across the bottom of the graph and against the effective angle across the top. The transmission is nearly 100% just 0.1 arcsec off-axis, while the suppression ratio is below the desired 10^{-10} for the two shorter wavelengths at the centre of the shadow. The design values are $a = b = 12.5$ m, $n = 6$, $F = 50{,}000$ km.

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Table 1 | **Characteristics of the occulter compared to the coronagraph**

		Coronagraph		Occulter
Mission				
Architecture	+	Single spacecraft		Multiple spacecraft
Telescope		Dedicated	+	Existing
Mechanical		Monolithic mirror		Large deployable sheet
Field of regard	+	All sky		Restricted
Optics				
Wavefront control		Challenging	+	None
Diffraction		Shaped aperture	+	Shaped occulter
Scatter		Internal optics	+	Edge scatter
Degradation in flight		Risky	+	Robust
Technical readiness		Poor	+	Good
Science				
Sensitivity to Earth-like planets		Good		Good
Sensitivity to Jupiter-like planets		Limited	+	Excellent
Sensitivity to disks		Poor	+	Excellent
Targeting	+	Fast		Slow

A range of mission considerations for the occulter and coronagraph approaches are compared. Features providing a significant advantage to one approach or the other are marked with a plus sign. Coronagraphs are single-spacecraft missions allowing quick, wide-field response, whereas occulters can take advantage of existing telescopes. The occulters are easier to implement in all areas of the optics. Scientifically, both approaches are sensitive to Earth-like planets, but the occulters provide extra sensitivity to outer planetary systems and debris disks. Overall, the large, high-quality optics push the cost of coronagraph missions significantly higher than the cost of occulter missions. I note that an occulter can be used with any existing or planned telescope (like JWST) whereas a coronagraph must be specially designed and built. A coronagraph can view (field of regard) most of the sky at any given time, whereas occulters are restricted to lines of sight perpendicular to the sun–spacecraft line to reduce scattered sunlight. All stars can be studied by either, but a coronagraph can revisit a system more often. Coronagraphs scatter starlight inside the optics, whereas occulters scatter sunlight off their edges—easier to control. Pitting from micrometeor impact or reflectivity loss from surface contamination (degradation in flight) can cause scatter in coronagraphs. Occulters can suffer tiny holes from micrometeor impacts, but a triple layer of material keeps the shade from transmitting starlight. Coronagraphs still need development of basic optical technology, while the technology for occulters already exists (technical readiness). The presence of an outer working angle keeps coronagraphs from simultaneously observing inner and outer planetary systems (planet sensitivity). Coronagraphs have high residual internal background, which makes extended sources like disks difficult to detect (debris sensitivity).

(apodization) functions that creates high levels of diffraction control for occulting masks. The diffraction suppression factors achieved are many orders of magnitude more effective than predecessor designs at any given size and finally allow the design of practically sized occulters. The function (shown in binary form in Fig. 1) is:

$$A(\rho) = 1 - e^{-[(\rho-a)/b]^n} \quad \text{for } \rho > a$$

$$A(\rho) = 0 \quad \text{for } \rho < a$$

This bipartite function features an opaque central circle of radius a, and petals that start at a and rise to $1 - e^{-1}$ at a radius of $a + b$. The suppression ratio S of diffraction in the centre of the shadow, relative to the unobscured light, is given by:

$$S \leq (n!)^2 (\lambda F / 2\pi ab)^{2n}$$

in a well-designed occulter system large enough that $b^2 \gg n(F\lambda/2\pi)$. In the Supplementary Information I show that the solution is remarkably robust and scale invariant. I also estimate the range of the allowed fabrication errors and establish they are within the current state of the art of aerospace engineering.

In Fig. 1 I show the shape of an occulter where $a = b = 12.5$ m, $n = 6$, $F = 50{,}000$ km as it might appear through a telescope in alignment with a nearby star. Figure 2 shows the suppression ratio to be expected with such an occulter at three wavelengths. The off-axis angle is plotted across the top of the graph, showing that a planet just 0.1 arcsec off-axis will reach the telescope essentially unobscured. For the shorter wavelengths, the deep zone of the shadow is 10–20 m in diameter, wide enough to hide a large telescope with room to spare.

There may eventually be other applications for optimally deep shadows, but the invention has been applied to the planet-finding mission named The New Worlds Observer[9]. It comprises two spacecraft, a flower-shaped starshade about 50 m from tip to tip, and a conventional-quality telescope. The telescope optic must be diffraction-limited in the visible band and at least 1 m in diameter. The mission operates by flying the starshade into the line of sight of a nearby star, a move that can take several days. After alignment, the starshade must hold its position against tidal forces by using small thrusters.

The New Worlds Observer offers major advantages over other approaches to direct studies of nearby planetary systems. In Table 1 I compare its strengths and weaknesses with the Terrestrial Planet Finder Coronagraph (TPF-C), which has been extensively studied[2]. The TPF-C is a single-spacecraft observatory that features a very large, very-high-quality telescope, correcting optics for wavefront control, and a pupil-plane coronagraph. It requires a 6–8-m-class monolithic mirror that corrects its optical figure to better than λ/5,000 and holds or corrects its reflection uniformity to high precision across a broad spectral band after several years in orbit. From Table 1 it is clear that the challenges the New Worlds Observer must meet are the deployment of a large shade and automated station-keeping relative to the celestial sphere, but these attributes can be added to any space telescope already in deep space. Overall, the large, high-quality optics of TPF-C are more expensive and risky than the extra spacecraft with the large, deployable sheet needed for the

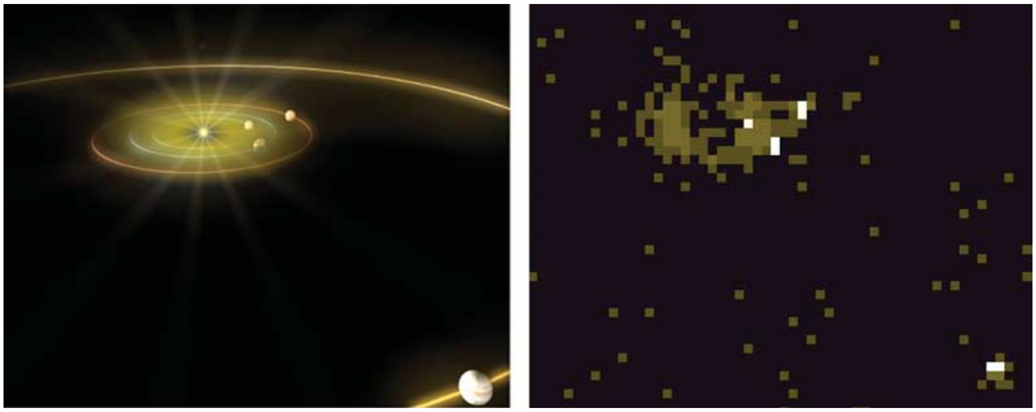

Figure 3 | **Seeing Earth-like planets.** The left panel is an artist's conception of our Solar System as viewed from outside. The planets from Venus to Jupiter are shown along with their orbits. The glow around the Sun represents the zodiacal light, caused by dust scattering in the inner Solar System. In the right panel I show a simulation of how this system would look when viewed from a distance of 7 parsec using an occulter and the James Webb Space Telescope. The strength of the zodiacal light has been reduced a factor of ten over solar and is still clearly visible, with the dark spot in the middle caused by the starshade itself. Earth, Mars and Jupiter are visible as bright white spots. (Artwork courtesy of Ball Aerospace.)

New Worlds Observer. Surprisingly, because occulters can observe over a wider angular range with lower noise, they are significantly more sensitive to outer planets (like Jupiter and Saturn) and to debris disks.

Simulations such as those in Fig. 3 show that the New Worlds Observer will be able to photograph directly the major features of planetary systems to ten parsecs and beyond. It can detect all the major planets (from the habitable zone outward), the zodiacal light, debris disks and possibly even comets. Photometric variations might show the presence of surface features like oceans and continents. Follow-up spectroscopy of the detected planets would enable classification by type, and the presence of water would be clearly visible in atmospheric absorption lines. Atmospheric markers (like free oxygen absorption lines) could potentially provide the first evidence of life outside our Solar System.

The New Worlds Observer is actively being studied in academia, industry and government. The technical challenges related to building such a mission appear to be within the reach of existing engineering and within the budgetary scope of NASA's science programme. One particularly appealing option is to fly a starshade to work in concert with the upcoming, powerful James Webb Space Telescope. If Earth-like planets around the nearby stars do exist, use of an occulter could find them within the next decade.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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