UMBRAS: A Matched Occulter and Telescope for Imaging Extrasolar Planets

A. B. Schultz[a], I. J. E. Jordan[a], M. Kochte[a], D. Fraquelli[a], F. Bruhweiler[b], J. M. Hollis[c], K. G. Carpenter[c], R. G. Lyon[c], M. DiSanti[b], C. Miskey[b], J. Leitner[c], R. D. Burns[c], S. R. Starin[c], M. Rodrigue[d], M. S. Fadali[e], D. Skelton[f], H. M. Hart[g], F. Hamilton[a], and K.-P. Cheng[h]

[a]Science Programs, Computer Sciences Corporation, and the Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

[b]Department of Physics, Catholic University of America, Washington, DC 20064

[c]NASA's Goddard Space Flight Center, Greenbelt, MD 20771

[d]Department of Physics, University of Nevada, Reno, NV 89557-0058

[e]Department of Electrical Engineering, University of Nevada, Reno, NV 89557-6627

[f]Orbital Sciences Corporation, 7500 Greenway Center Drive, Suite 700, Greenbelt, MD 20770

[g]Science Programs, Computer Sciences Corporation, and The Johns Hopkins University, Baltimore, MD 21218

[h]Department of Physics, California State University Fullerton, Fullerton, CA 92634

ABSTRACT

We describe a 1-meter space telescope plus free-flying occulter craft mission that would provide direct imaging and spectroscopic observations of Jovian and Uranus-sized planets about nearby stars not detectable by Doppler techniques. The Doppler technique is most sensitive for the detection of massive, close-in extrasolar planets while the use of a free-flying occulter would make it possible to image and study stellar systems with planets comparable to our own Solar System. Such a mission with a larger telescope has the potential to detect earth-like planets.

Previous studies of free-flying occulters reported advantages in having the occulting spot outside the telescope compared to a classical coronagraph onboard a space telescope. Using an external occulter means light scatter within the telescope is reduced due to fewer internal obstructions and less light entering the telescope and the polishing tolerances of the primary mirror and the supporting optics can be less stringent, thereby providing higher contrast and fainter detection limits. In this concept, the occulting spot is positioned over the star by translating the occulter craft, at distances of 1,000 to 15,000 km from the telescope. Any source within the telescope field-of-view can be occulted without moving the telescope.

In this paper, we present our current concept for a 1-m space telescope matched to a free-flying occulter, the Umbral Missions Blocking Radiating Astronomical Sources (UMBRAS) space mission. An UMBRAS space mission consists of a Solar Powered Ion Driven Eclipsing Rover (SPIDER) occulter craft and a matched (apodized) telescope. The occulter spacecraft would be semi-autonomous, with its own propulsion systems, internal power (solar cells), communications, and navigation capability. Spacecraft rendezvous and formation flying would be achieved with the aid of telescope imaging, RF or laser ranging, celestial navigation inputs, and formation control algorithms.

Al Schultz is an Instrument Scientist at the Space Telescope Science Institute (STScI). He has worked at STScI for ∼12 years. Since launch, Dr. Schultz has supported HST operations in PODPS, which is now part of OPUS, the GHRS, STIS, NICMOS, and WFPC2 instruments. (Send correspondence to schultz@stsci.edu; Telephone: 410-338-5044)

Keywords: UMBRAS, coronography, extrasolar planets, occulter

1. INTRODUCTION

Our studies have shown free-flying occulters to be a promising means to detect and study nearby extrasolar planets.[1, 2] At optical wavelengths, conventional Lyot coronagraphs have at best achieved contrast enhancements of $\sim 10^4$ in the 5-10 Airy ring annulus. Simulations of an apodized telescope suggest that a contrast enhancement of $\sim 10^6$ could be achieved in the same annular region. Further simulations of an apodized telescope in combination with a free-flying occulter indicate that the contrast enhancement could be boosted to $\geq 10^8$. Thus, a space-based apodized telescope plus external occulter system will be able to directly detect (image) extrasolar planets. The formation configuration of a space telescope/occulter system is presented in Figure 1.

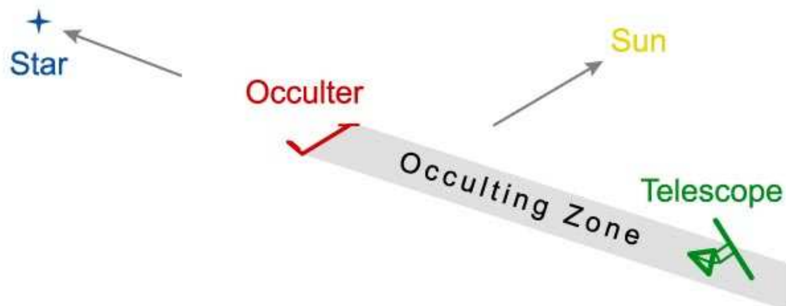

Figure 1. Relative configuration of an occulter operating with a space telescope. The view is from above the plane containing the Sun, occulter, and telescope. The separation and sizes of the occulter and telescope are not drawn to scale.

1.1. Telescope/Occulter Mission Concept

The history of examining free-flying occulters as a means to search for extrasolar planets can be traced back to Lyman Spitzer's (1962) brief analysis of the concept which he attributed to R. Danielson.[3] Woodcock (1974) extended Spitzer's analysis and suggested a parasol-like spacecraft design.[4] Marchal (1983, 1985) further found that the ability of an occulting screen to suppress star light varied strongly with screen shape.[5, 6]

In the mid-1990s, Copi and Starkman (1997) proposed the Improved Resolution and Image Separation (IRIS) satellite to serve as a space-borne occulter for either ground or space telescopes.[7] Evolving from the IRIS concept, the Big Occulting Steerable Satellite (BOSS) was an apodized occulter suggested to work with space-based telescopes.[8–10] Recently, the same team has proposed X-BOSS to operate with x-ray space telescopes.[11]

In a series of papers and poster presentations, we have developed different telescope/free-flying occulter schemes, collectively called the Umbral Missions Blocking Radiating Astronomical Sources (UMBRAS) project. We have explored the problems of deployability, formation flying, survivability and redundancy, operations, scattered light suppression, and vehicle dynamics and control.[1, 2, 12–15] Early investigations concentrated upon operating constraints, science goals, and occulter design. Systems analysis led to more sophisticated operations modeling and a formation control concept.[14] Several occulter designs have emerged from this analysis including a Discovery-class 1-m telescope mission.[13, 16]

1.2. Distinct Advantages

These preliminary studies clearly indicate that free-flying occulters provide distinct advantages over conventional coronagraphs. First, a free-flying occulter can substantially reduce the amount of starlight that enters the telescope. This reduces background light scattered into the focal plane, thus enhancing the planet detection limit. Since the occulter is not built into the telescope as an add-on instrument, scattered light is further reduced without additional optical surfaces and apertures. In addition, fewer optical surfaces translate into less signal loss. There are no unwanted diffraction spikes from coronagraphic supports, and the complexity of internal instruments is reduced.

Difficulties with conventional coronagraphs, which result from small scale imperfections in component materials and their manufacturing processes, are avoided with an external occulter. Precise alignment of internal coronagraphic masks is often impossible due to drifts which affect the quality of the achievable science. Masks are not needed for a matched apodized telescope and external occulter system. Moreover, external occulters promise high levels of knowledge and control of on-target alignment. External occulters can be used with any focal plane spectrograph or camera without adding extra apertures, reflecting or refracting surfaces, or additional diffraction edges.

The principal outcome of our investigations of an apodized telescope plus external occulter system is the design for a Discovery-class 1-m telescope mission. This system will be of low cost and require minimal technological development. The external occulter technique has more relaxed metrology requirements than those needed by other methods now being considered for the Space Interferometry Mission (SIM)[17] and the Terrestrial Planet Finder (TPF) mission,[18] which implies a lower required level of technological development. Together, these suggest that a 1-m apodized telescope plus external occulter system can achieve many of the Astronomical Search for Origins (ASO) science goals and will also test formation flying concepts and techniques for TPF.

2. THE CURRENT UMBRAS CONCEPT

UMBRAS is a two spacecraft system comprised of a telescope and a free-flying occulter, known as a *Solar-Powered Ion-Driven Eclipsing Rover* (SPIDER). A 1-m telescope and SPIDER could be bundled together and launched from a single launch vehicle, possibly on an Atlas IIAS. Alternately, the SPIDER spacecraft could be delivered to orbit from a separate launch vehicle, which could be either an expendable rocket or the Space Shuttle. Figure 2 depicts a preliminary conceptual design for the SPIDER spacecraft.[1]

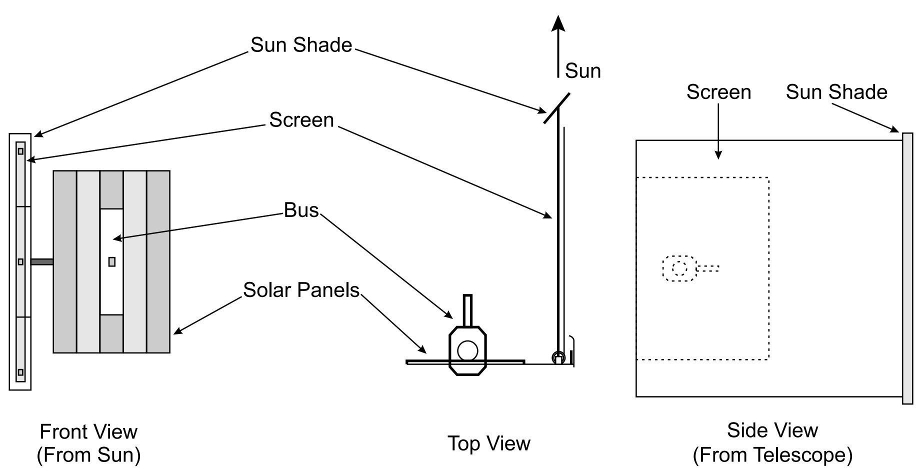

Figure 2. SPIDER overview. The four main structures are the occulting Screen, the Sun Shade, the spacecraft Bus, and the Solar Panels. The propulsion unit is not shown. Top view is referenced from the pole of the plane containing the Sun, telescope, and occulter.

2.1. Propulsion and Attitude Control

The SPIDER craft must be able to move thousands of kilometers between target stations, to perform rendezvous maneuvers, target acquisition, and formation control in the inertial frame of the telescope. Solar electric propulsion provides the minimum specific impulse and thrust necessary to achieve reasonable target observation rates in an occulter mission. Short bursts from onboard thrusters would provide the maneuverability necessary to achieve and maintain formation control.

Both Earth-trailing and Earth-Sun Lagrange Point L2 orbits are feasible options for the solar-electrically propelled occulter mission. Due to downlink bandwidth advantages and the current preference for placing space telescopes at L2, we have focused on L2.

2.2. Target Acquisition & Formation Flying

The primary requirements of the UMBRAS mission are to achieve formation control of the SPIDER with the space telescope and to maintain the occulter on the target-telescope line-of-sight (TTLOS) vector. Target acquisition requires the telescope to have onboard image processing capabilities to independently identify and locate the target and the SPIDER within the field-of-view (FOV) and to store the images and locations for later use. In addition, a command link must be established between the telescope and the SPIDER. Once the SPIDER is within the imaging instrument's FOV, formation control thrust sequences are initiated as determined by science imaging requirements for each observation. The automated tasks are controlled by the SPIDER's attitude and translational control system (ATCS). This target acquisition and formation control scenario is based in part on experience of the authors with target acquisition and slew commanding capabilities of the Hubble Space Telescope (HST) science instrumentation.[14]

2.3. Occulting Screen

The occulter, square or any other shape, acts as an opaque apodizing screen,[19] and redistributes the remaining star light over the telescope aperture. The purpose of apodizing the telescope aperture is to redistribute the intensity of the light in the wings of the stellar point spread function (PSF), thus increasing the contrast at the position of the planet.

In order to block the target starlight sufficiently, the size of the occulter screen must be at least the size of the telescope aperture. The occulter has a minimum operational distance from the telescope of ∼1,000 km, otherwise it blocks too much of the area of interest surrounding the target star. The alignment of the occulter along the TTLOS must be maintained for the duration of the scientific observation to within a small fraction of the dimensions of the occulter and to within a fraction of the angular resolution of the telescope's optical configuration. In addition, the occulter must be designed to minimize the scattering of sunlight into the telescope.

2.3.1. Diffraction Simulations

The physical size of the occulter and its distance from the telescope are major factors in the resulting on-axis light intensity and the average intensity over the aperture. The larger the physical size of the occulter for a given distance from the telescope, the greater the reduction in the light entering the telescope aperture. However, the occulter size must still be small enough or the telescope-occulter separation be large enough to maximize the size of the planetary detection zone. Optical diffraction simulations for a 1-m apodized telescope and 10-m occulter are presented in Figure 3. The simulation consist of a Fresnel diffraction propagation to the entrance aperture of a square telescope; then a Sonine apodization mask is applied at the entrance aperture; then Fraunhofer propagation is used to propagate to the focal plane. They indicate that a 1-meter apodized telescope/external occulter system can achieve 10^8 suppression, or more, in the wings of the PSF. In another paper in this session [Lyon 4860-47], it is shown that using another more optimal apodization that 10^{11} suppression can be achieved.

The optical modeling indicates that a 1-m apodized telescope plus occulter (5-15 m in size) could be used to detect and study Jovian-size planets around the nearest stars including some already known to have extrasolar planets. A faint planet could be detected between the bright fringes in the diffraction spikes, but would more likely be detectable in the low intensity regions between the diffraction spikes.

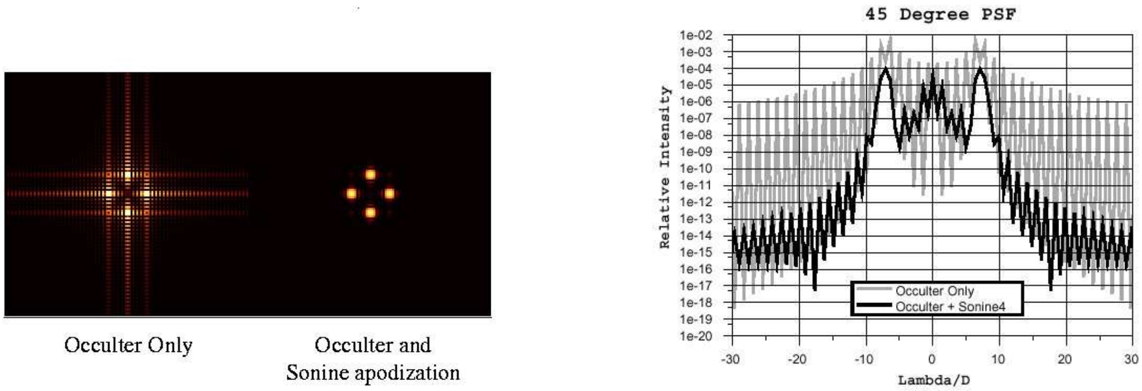

Figure 3. Left, diffraction simulations (1 μ) for a 1-m square aperture telescope + 10-m square occulter separated by 1,000 km. The log-stretch images show unapodized and apodized results for a point source. The bright spots are the stellar PSF leaking over the occulter edges. Right, diagonal slices through each image trace the diffraction pattern modulations. Vertical scale is relative to the unocculted peak intensity normalized to unity. Gray slice is the square aperture telescope + 10-m square occulter without Sonine apodization, and the dark slice is with the Sonine apodization applied.

2.4. Imaging Performance

Modeling of the point spread function (PSF) for a 1-m apodized telescope/free-flying occulter system with $\lambda/100$ to $\lambda/200$ optics rms surface error yields PSF intensity of $\sim 10^{-8}$ at λ/D = 3.5 for the normalized telescope, where D = mirror diameter. This indicates that Jupiter-like planets (at 5 AU) could be detected around stars at distances as great as ~14 pc. For comparison, assuming that PSF relative intensities of 10^{-8} are achievable for $\lambda/D \geq 3.5$, Table 1 indicates the required exposure times to obtain a S/N=10 detection for Jupiter (5 AU) around selected stars.

Table 1. Estimated visual magnitudes/projected maximum angular separations ($''$) of a Jupiter-like planet orbiting other stars. The estimated exposure time (ExpTime) is for a Jupiter-like planet observed in the V-bandpass with a 1-m telescope and CCD camera. (ExpTime scaled from the WFPC2 Exposure Time Calculator (ETC).)

Star	mv	Dist. (pc)	Sp.Type	Jupiter mv	Jupiter MaxSep	ExpTime (S/N=3)	ExpTime (S/N=10)
ϵ Eri	3.73	3.2	K2 V	25.4	1.62$''$	130 sec	1,300 sec
τ Ceti	3.50	3.7	G8 V	24.7	1.41	105	1,050
Altair	0.77	5.1	A7 V	22.4	1.01	7	70
Fomalhaut	1.16	7.7	A3 V	22.8	0.68	15	150
55 ρ^1 Cnc	5.95	12.5	G8 V	27.6	0.42	1,000	10,000
υ And	4.09	13.4	F8 V	25.7	0.38	150	1,500

If a 10-m wide occulting screen were operated at 10,000 km from the telescope, the screen would appear ~0.2$''$ across (half width 0.1$''$) and would attenuate target starlight by a factor of 60 in the visible. Five of the currently reported Doppler-detected Jovian planets reach as far as 0.15$''$ separation (47 UMa c, ϵ Eri b, HD 39091b, HD 145675b, υ And d) and might be directly imaged with this technique when near maximum elongation. Exposures of ~1,000 sec for a 1-m telescope/occulter would easily detect these planets and would provide low resolution spectrophotometry for the brightest planets. A mission of this type could determine if additional Jupiter-like planets (i.e. beyond $\lambda/D = 3.5$) exist around these stars.

3. A TYPICAL OCCULTER MISSION

A typical occulter mission consists of mission operations, science planning, and data management. Here we assume that the delivery of the telescope and SPIDER craft are provided by a single launcher to the Earth-Sun L2 locale.

3.1. Mission Operations

The mission plan will consist sequentially of launch, delivery and deployment, and the science phase. The science phase of operations for each target will cycle between maneuvering the SPIDER between targets, alignment along the TTLOS, target acquisition, and formation control. Target-to-target maneuvers need to be efficient to optimize target observation rate and propellant consumption. L2 operations will be conducted similarly to how the Microwave Anisotropy Probe (MAP)[20] and the Solar and Heliospheric Observatory (SOHO)[21] mission operations are conducted, while science planning and scheduling may contain elements similar to those in the HST and Chandra[22] ground systems.

Upon completion of science observations for a target, the occulter vehicle will reorient itself in preparation for transit to the next TTLOS and begin accelerating toward it. The vehicle architectures we have explored all provide only a minimum number of solar-electric thrusters, and so require a turnover maneuver at mid transit in advance of decelerating toward the inertial frame of the telescope for rendezvous at the next TTLOS. The transit maneuvers are largely pre-planned, however timing of the acceleration, deceleration, and turnover phases may be adjusted in-flight from analysis of the trajectory either by ground support staff or by onboard navigation analysis algorithms. Deep Space 1 successfully used a related technique to control its own flight path numerous instances in its mission.[23]

More than one SPIDER craft moving about the telescope would improve the observing rate for occulted observations. With two SPIDER craft, one could observe a planetary system with SPIDER #1 and continue the observations when SPIDER #2 arrives for a second visit. In principle, the efficiency of occultation observations would be doubled.

3.2. Science Planning

Daily and long range planning of science observations will be the responsibility of the ground support staff. While occultation observations would be fairly rigorous to plan and execute, they present unique opportunities to obtain additional unscheduled science observations. "Realtime" monitoring of the science observations would allow spectrophotometric and spectroscopic observations to be added to the mission schedule in the event of planetary discoveries. In addition, occultation observations could be obtained of low-mass stellar and brown dwarf companions to nearby stars, outer regions of planetary nebulae, astrophysical jets, regions surrounding the centers of galaxies, and host galaxies of quasars. In survey mode, the mission could observe many of the F,G,K stars within 50 pc of the Sun searching for giant planets.

During movement of the SPIDER from one occultation target to another, the non-occultation observing time of the telescope ($\sim$80%) would be used to search for planetary transits and micro-lensing events or to obtain other target-of-opportunity (ToO) observations.[14] Although we have emphasized the role of low-mass companion searches around nearby stars in the mission goals, observations of other astrophysical targets can be obtained.

Target sequence planning must accommodate the potential for extended observations of a particular target as determined from prompt quick-look analysis of the science observations. Candidate stellar targets for the occultation observations will be selected well in advance of execution since the choice of target sequencing must be optimized along with occulter propellant consumption, target observation rate, and total number of mission targets. Flexibility in changing targets can be preservable when new selected targets lie close on the sky to pre-selected targets.

The lifetime of the mission depends upon the amount of propellant carried, the thrust levels of the propulsion unit, the distance between the telescope and occulter, the number of targets, and the rate of supported occultation observations. If half the mass of the occulter craft were fuel, then depending upon the telescope/occulter range (1,000-15,000 km), a 5 year mission with repeat visits to 30-70 different science targets per year can be conducted.[12] Target sequence strategies are very important for mission pre-observation planning, since different strategies can result in observation rates that differ by a factor of two or more.

3.3. Data Management

The ground support staff would be tasked not only with monitoring and controlling the relative positions of the space telescope and the SPIDER and science planning, but also with data management. Data management would consist of scheduling data transmission from the telescope, pipeline processing to perform data conversion and initial calibration, and data archiving.

4. CONCLUSIONS

When stationed at distances of 1,000 to 15,000 km from a telescope, the occulter will provide imaging and spectroscopic studies of extrasolar Jovians as close as 0.10-15″ from the target stars. In survey mode with this imaging detection capability, it would be possible to resolve giant planets as close as 5 AU from stars at distances from the Sun as great as 15 pc. At this distance, Jupiter would have an apparent visual magnitude of mV ∼27. There are approximately 300 stars within 15 pc of the Sun, all representing potential occultation mission targets.

A number of different concepts to detect and study extrasolar planets have been and are currently being studied; e.g. square aperture telescope (Nisenson and Papaliolios 2001).[24] It is not yet clear which concepts are superior in terms of performance, cost, sky coverage, etc. The external occulter concept has distinct advantages over other methods with less stringent tolerances and thereby significantly reducing the cost. Our preliminary investigation indicates a Discovery-class matched 1-m apodized telescope/external occulter system would provide a cost-effective method of directly detecting and studying extrasolar planets now, with minimal extension to technology that is currently available. This UMBRAS mission affords an excellent opportunity for a proof of concept project as a forerunner for future missions with a telescope of much larger aperture.

ACKNOWLEDGMENTS

We appreciate the encouragement of Dr. Phillipe Crane to investigate the occulter concept by means of a team approach.

Support for this work has been provided by Computer Sciences Corporation, Laurel, MD and by the Space Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

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