Imaging Planets About Other Stars with NGST

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ABSTRACT

We propose to use the *Next Generation Space Telescope* (NGST) with a unique observing technique to image terrestrial and giant planets as close as 0.15″ from the parent stars. Two of the Doppler detected planets are at this separation and could possibly be directly imaged. We describe a proof of concept design for a free-flying occulter. This paper is to provide the scientific justification for this mission.

To achieve our scientific goals, we propose a free flying occulter, the *Ultimate Mechanism to Block Radiation from Astronomical Sources* (UMBRAS), to be launched in conjunction with NGST. The UMBRAS space mission will consist of two separate spacecraft, a *Solar Powered Ion Driven Eclipsing Rover* (SPIDER) and possibly one or two metrology platforms. The UMBRAS spacecraft will be semi-autonomous, with their own propulsion systems, internal power (solar cells), communications, and navigation capability. The metrology platform may be necessary for station keeping and to help navigate the SPIDER to target locations. The three spacecraft (SPIDER, the metrology platform, and NGST) will define a reference frame for aligning NGST and the SPIDER with the same target and for positioning each spacecraft relative to each other. UMBRAS will perform station keeping by communicating with NGST.

When stationed at distances of 1000 km to 15000 km from NGST, the occulter will enable NGST to image very faint sources as close as 0.15″ from the target stars. Giant planets could be detected as close as 5 AU from parent stars at distances from the Sun as great as 30 pc. This occulting technique will make it possible to detect terrestrial planets around nearby stars within the next decade. We briefly discuss the diffraction effects caused by the occulter. An in-depth description for various NGST-UMBRAS separations and configurations as well as a more detailed discussion of the operational capabilities will not be presented in this report, but will be reported in a future paper. Finally, we suggest types of observations other than planet finding that could be performed with UMBRAS.

Keywords: NGST, Next Generation Space Telescope, coronography, extrasolar planets

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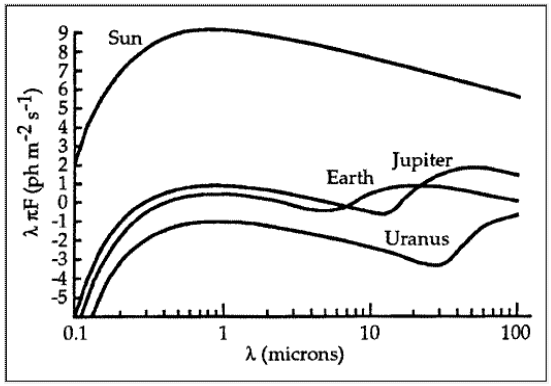

Figure 1. The spectral energy distribution of the Sun and planets in the Solar System as seen from a distance of 10 pc (NASA ExNPS Roadmap).

1. INTRODUCTION

Direct imaging of extrasolar planets is extremely difficult due to their low brightness and close proximity to the parent stars. In the optical and near-infrared (IR), planets shine by reflected light. The difference in apparent magnitude (ΔM) between a planet and a star can be as high as 20-30 magnitudes, while in the infrared, the ΔM could be in the range of 15-25 magnitudes. Figure 1 shows the expected idealized spectral energy distribution of the Sun and planets in the Solar System at a distance of 10 pc. Ground-based and previous *Hubble Space Telescope* (HST) searches using direct detection methods (imaging) have concentrated efforts for detecting planetary-like objects at separations $\geq$1.0$''$.[1,2] Ongoing HST search programs utilize the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), Wide Field and Planetary Camera 2 (WFPC2), and the Space Telescope Imaging Spectrograph (STIS). The NICMOS Camera 2 programs utilize the coronagraphic hole to search for companions at separations $\geq$0.5$''$.[3] The NICMOS Camera 2 spatial scale is $\sim$0.07$''$pixel^{-1} and the useful radius of the coronagraphic hole is $\sim$0.4$''$.[4] However, except for nearby stars, within $\sim$4 pc, planets will generally be at separations less than $\sim$0.3$''$ from the parent star. UMBRAS will be able to reach half this separation.

Prevailing theory indicates planets form from accretion disks about stars where disks are the remnants of molecular clouds out of which the stars formed. Planets are cold bodies and radiate most of their energy in the infrared, while stars fuse hydrogen or other heavy elements and emit most of their energy in the optical and ultraviolet. In visible wavelengths, Jupiter at a distance of 5 AU from the Sun is $\sim$10^9 times fainter than the Sun. The basic physics for hydrogen-rich objects governs both stars and substellar bodies. An object with a mass below $\sim$12 M_J would not fuse deuterium during its early stages of formation. This theoretical boundary could be considered an upper limit for a giant planet. Current theoretical models for isolated giant planets (no reflective light) indicate that objects with masses several times Jupiter could be detected through their own infrared luminosities with NICMOS onboard HST.[5,6] It must be noted that in the visible and near-IR (1-3μm), reflected light will dominate the infrared flux from a planet close to a star. Table 1 presents theoretical intrinisic infrared magnitudes for isolated giant planets for different ages as viewed from given distances.

Astronomers using Doppler techniques have detected possible planet-induced wobbles for at least 9 solar-like stars. A star and its companion planet orbit a common center of mass and the motion of a star about the center of mass can be measured, and from this, the presence of a planet can be inferred. The distances to these suspected planetary systems are 13-32 pc (40-105 lyr). The maximum projected angular separation on the sky of a planet 5 AU from a star (roughly the distance Jupiter is from the Sun), 13 pc from Earth, would be $\sim$0.38$''$, while at a distance of 32 pc the maximum apparent separation on the sky would be $\sim$0.15$''$. The physical characteristics of stars with Doppler detected planets are listed in Table 2. In addition, the derived mass and predicted maximum separations for the planets are provided. In visible light and at separations $\leq$0.3$''$, a planet would most probably be lost in the glare of the parent star when using direct imaging without an occulter or coronagraph to reduce the light from the parent star.

Table 1. Theoretical H-mag (1.6 μm) of giant planets[6]

mass (M_J)	age (Gyr)	10 pc	15 pc	20 pc	25 pc	30 pc
3	0.5	22.14	23.02	23.64	24.13	24.52
	1.0	24.02	24.90	25.52	26.00	26.40
	5.0	32.10	32.98	33.60	34.08	34.48
5	0.5	20.08	20.96	21.58	22.07	22.46
	1.0	22.43	23.31	23.93	24.42	24.82
	5.0	28.21	29.09	29.72	30.20	30.60
10	0.5	17.37	18.25	18.88	19.36	19.75
	1.0	18.70	19.58	20.20	20.69	21.08
	5.0	22.88	23.76	24.38	24.87	25.26

Table 2. Stars with Doppler Detected Planets[7–15]

Star	Name	Spectral Type	Distance (pc)	V-mag	Planet Mass (v sin i)	Predicted Separation
HD217014	51 Peg	G2.5IVa	13.7	5.49	0.47 M_J	0.004″
HD95128	47 UMa	G0V	14	5.1	2.4	0.15
HD117176	70 Vir	G4V	24	5.0	6.6	0.02
HD75732	55 ρ^1 Cnc	G8V	14	6.0	0.84	0.008
HD9826	υ And	F8V	16	4.09	0.68	0.003
HD114762	LHS 2693	F9V	28	7.3	10.0	0.02
HD186427	16 Cyg B	G2.5V	29	6.0	1.7	0.06
HD143761	ρ CrB	G0Va	24	5.40	1.1	0.009
HD120084	τ Boo	G7III	32	5.91	3.8	0.001
-	GL 876	M4V	4.7	10.2	1.86	0.04
HD145675	GL 614	K0V	18.9	6.67	3.3	0.14

Several fundamental challenges must be overcome before we can directly detect (image) extrasolar planets. These challenges are their faint brightness and small separations from the parent stars and the bumpy Point Spread Function (PSF) of current multi-mirror optical assembly designs for NGST. The NGST with an 8 meter diameter mirror using visual and infrared detectors has the potential to detect faint sources with exposures of tens of seconds compared to tens of minutes using NICMOS onboard HST with its 2.4 meter diameter mirror. UMBRAS is one solution to the problem of how to reduce the light from the parent star to allow detection of faint planets. Most ground-based observers use a modified classical coronagraph design with a field stop, occulting disk, and Lyot stop to search for close faint companions about nearby stars. NICMOS onboard HST, trapping the light from a star using a coronagraphic hole with a cold stop, provides coronagraphic potential to detect planets at large separations ($\geq 0.5''$) from the parent stars.[3] However, except for nearby stars, NICMOS cannot detect close planets. In the following sections, we outline a proof of concept design for a free flying occulter, the *Ultimate Mechanism to Block Radiation from Astronomical Sources* (UMBRAS), to be launched in conjunction with NGST. UMBRAS could enable NGST to image terrestrial and giant planets at 5 AU or closer about the nearest stars within the next decade.

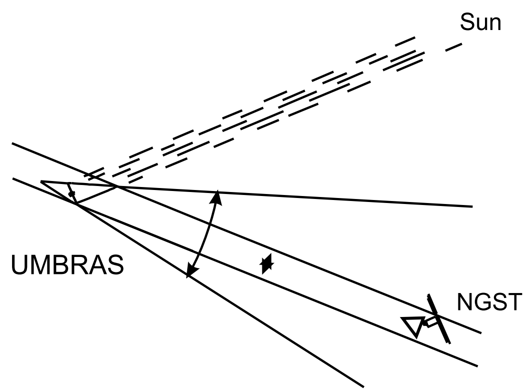

Figure 2. UMBRAS spacecraft flying in formation with NGST.

2. THE UMBRAS SPACE MISSION

The UMBRAS free flying occulter space mission consists of two separate spacecraft, a *Solar Powered Ion Driven Eclipsing Rover* (SPIDER) and a metrology platform, flying in formation with NGST as depicted in Figure 2 (metrology platform not shown). The UMBRAS spacecraft could be launched from a single launch vehicle, either with an expendable rocket or the space shuttle. After launch, the two spacecraft would rendezvous with NGST and deploy into formation. This mission is designed to provide coronagraphic capability for NGST by blocking the light of bright stars and other targets from reaching NGST detectors. The metrology spacecraft would provide navigational support and stability control during station keeping, distance ranging, and communication between NGST and the SPIDER spacecraft. The metrology platform would also provide navigational support during transit of the SPIDER spacecraft between targets. The propulsion system used for moving the SPIDER spacecraft to different targets and station keeping should be designed for a minimum lifetime of 3 years, allowing observations of around 50-200 targets per year.

2.1. Expanding the Bounds of Coronography

The purpose of the occulter is to reduce the intrinisic brightness ratio between the parent star and a faint companion. This can be accomplished by blocking most of the star light from reaching NGST and by reducing the intensity of the diffraction rings surrounding the stellar image. The occulter, square or rectangular in shape, will act as an opaque apodizing screen,[16] redistributing the energy over the aperture of NGST. Theoretically, a faint companion could be detected between the bright fringes in the diffraction spikes, or in the low intensity regions between the diffraction spikes.

To define the energy distribution at the aperture of NGST, one must calculate the Fresnel diffraction pattern for a rectangular or square (10m or larger) occulter at distances from NGST of $1,000 - 20,000$ km. We have chosen these distances due to the desire to observe ∼70 targets/year, be able to move between targets and set up in a reasonable length of time, and to have a ∼3 yr mission lifetime. There are many sources that describe diffraction phenomena related to this basic problem (Born and Wolf,[17] Hecht and Zajac,[18] etc ...), and we give only a brief description here. Fresnel diffraction occurs because the diffracting aperture (occulter) is at a finite distance from the observation plane. To do the calculations, we apply Babinet's Principle about complementary pupil functions; two diffracting apertures are complementary if the transparent parts in one are the opaque parts in the other. The electric field amplitude in the shadow of a square obstacle is the difference between the amplitudes of an unobstructed wavefront and a wavefront which passes through a complementary square aperture. The intensity is the complex square of the amplitude difference. The on-axis intensity of the diffraction pattern, normalized to unity for an unobstructed beam, can be represented by:

$$i \approx (4/\pi)^2 \lambda r_o / d^2 \approx (4/\pi)^2 \lambda / \beta d \tag{1}$$

where $\beta = d/r_o$ is the angle subtended by the obstacle at NGST, d is the width of the square obstacle, and r_o is the distance of the obstacle from NGST. The relation in (1) is a good approximation when $d^2 \geq\sim 20 \times \lambda r_o$. The average normalized intensity over the aperture of NGST is roughly a factor of 3 smaller than the peak normalized intensity.

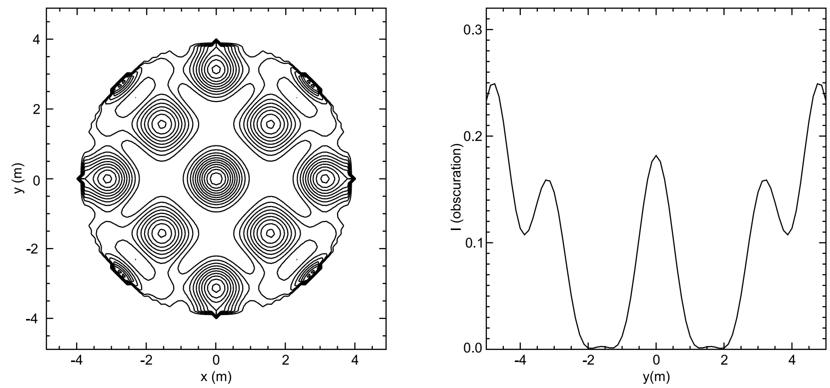

Figure 3. The contour map (left) of the Fresnel diffraction pattern covers an 8-m diameter circle in the shadow of a 16-m occulter. The region outside the circle is not of interest and has been eliminated from the figure. The intensity profile (right) is down the center of the diffraction pattern including regions outside the 8-m diameter circle.

We consider a square occulter 16m on a side at a distance of 16,000 km from NGST, yielding a width of $\sim 0.21''$. A pattern of light will be visible within the shadow of the occulter. The average normalized intensity i will be $\sim 5\%$ ($\lambda \sim 1.6\mu$m) of the unocculted beam. The Fresnel diffraction pattern within the shadow area will be surrounded by a series of bright and dark (null) fringes with bright diffraction spikes due to straight edges of the occulter. Figure 3 presents the Fresnel diffraction pattern in the shadow of a 16 m square occulter.

The physical size of the occulter and its distance from NGST are the deciding factors in the resulting on-axis intensity of light and the average intensity over the NGST aperture. The larger the physical size of the occulter (occulter subtends larger angle), the greater the reduction one can achieve in the on-axis and average intensity. But, a larger subtended angle defeats the goal of looking for planets near their parent stars. Our preliminary results for small occulters supplement those presented by the *IRIS* Satellite team[19] for larger occulters.

For example, a 16×24m screen at a distance of 15,000 km from NGST would subtend a solid angle of $0.22'' \times 0.33''$ on the sky. However, the actual area of the occulting screen projected on the sky in the NGST field of view will depend upon the viewing angle. The long axis of the screen may be shortened ($0.33'' \times \cos\theta$) due to projection. Table 3 presents estimated visual magnitudes and angular separations for planets in the Solar System as seen orbiting other stars. For the nearby stars α Cen A and τ Ceti, the angular separations are large and correspondingly, the planets (points of light) would be at large distances from the edge of the occulter. For the more distant stars 55 ρ^1 Cnc and β Pictoris, the planets would be closer to the edge of the occulter where diffraction effects dominate. Possibly, the SPIDER could be commanded to rotate (or translate) about a target star and move the diffraction pattern to a more favorable position to detect the planet.

Table 3. Estimated visual magnitudes/projected angular separations for planets in the Solar System as seen orbiting other stars.

Planet	Sun		α Cen A (1.3 pc)		τ Ceti (3.7 pc)		55 ρ^1 Cnc (14.3 pc)		β Pic (18.2 pc)	
	mv	Distance								
Venus	-4.7	0.72 AU	23.1	0.55″	26.6	0.19″	29.1	0.05″	26.9	0.04″
Mars	-1.2	1.52	27.4	1.17	31.0	0.41	33.4	0.11	31.3	0.08
Jupiter	-2.9	5.20	21.0	4.00	24.7	1.41	27.2	0.36	25.0	0.29
Saturn	0.0	9.54	22.5	7.34	26.1	2.58	28.5	0.67	26.4	0.52
Uranus	5.7	19.18	26.6	14.75	30.1	5.18	32.6	1.34	30.4	1.05

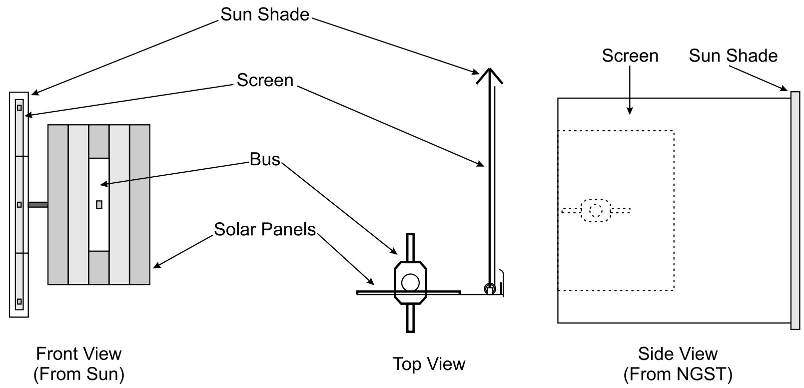

Figure 4. SPIDER overview. The four main structures are the occulting Screen, the Sun Shade, the spacecraft Bus, and the Solar Panels.

3. THE SPIDER

The *Solar Powered Ion Driven Eclipsing Rover* (SPIDER) consists of four main structures: the occulting screen, the screen shade, the spacecraft bus, and the solar array collector. The occulting screen will face obliquely toward NGST, hiding the spacecraft bus and solar array collector from view. The screen shade attached to the edge of the screen pointing toward the Sun will shield the screen from direct sunlight. If necessary, the spacecraft bus and solar array collector may face directly toward the Sun to optimize power generation.

3.1. Occulting Screen and Sun Shade

The occulting screen could be 15 meters or larger in size along its short axis in order to fit folded or coiled within the shuttle bay, rectangular or ellipsoidal in shape, rigid or inflatable, and most probably composed of different materials or multiple layers. The screen could be packaged in a cassette conceptually similar to a 35mm roll of film. One example of this would be the HST solar arrays. One option is to keep the screen stored in the cassette until UMBRAS rendezvous with NGST, and then deploy it at that time. This would reduce the probability of damage during transit and possibly reduce the complexity of transit from the Earth to the NGST.

When in an observing configuration after deployment, the screen will be erected about $\sim 90°$ from the plane of the solar array collector, while the plane of the solar array collector will be perpendicular to the light from the Sun. The screen will present a minimum cross sectional area to the Sun during observations. Even with a minimum surface area toward the Sun, the lead edge of the screen and its large surface area may heat up appreciably and also scatter light toward NGST. Shading the screen from the Sun will minimize both of these effects. A sunshade affixed to the leading edge is depicted and labeled in Figure 4.

Each side of the occulting screen will radiate different amounts of thermal energy due to different thermal and illumination conditions. The side of the screen facing NGST should be in darkness and must be very cold with low emissivity if it is to be useful at infrared wavelengths. The thermal flux of this side of the screen must be less than the objects to be imaged, otherwise, NGST will image the screen as a warm background object in the infrared swamping astronomical sources. The bus-ward side of the screen must have high reflectivity (low absorptivity from 0.1-10 μm), as well as relatively high emissivity. The screen must be constructed so as to dump heat on the side facing away from NGST. The amount of thermal energy to be dumped from each side of the screen will dictate the types of materials used, the construction, the coatings for the two sides of the screen, and whether or not active cooling is necessary.

3.2. Spacecraft Bus and Solar Panels

The bus structure contains all of the spacecraft primary systems, communication, navigation, computer, data storage, propulsion systems, and fuel storage. Attached to the bus will be the solar array collector. The SPIDER generates electrical power from the solar array collector which can then be stored in onboard batteries. The use of high efficiency InPh (19%) or GaAs (18%) solar cells with an array size of 7.5×12m would produce enough electrical power to charge the batteries and power the electrical systems as well as to provide sufficient energy for the ion propulsion systems.

The weight of the SPIDER spacecraft including the bus, solar array collector, and the occulting screen is estimated to be 3000-4500 kg (dry weight).

3.3. Station Keeping and Maneuverability

Once the SPIDER is maneuvered into position, station keeping maneuvers are performed with the aid of laser and/or submillimeter wave ranging between NGST, SPIDER, and the metrology platform. In order to properly position SPIDER with respect to NGST, relative position measurements of the metrology platform as viewed from NGST and SPIDER are also necessary. Station keeping may be accomplished with cold-gas thrusters during long exposures to avoid a luminous ionized cloud (Xenon-ion thrusters) from spoiling observations.

NGST and UMBRAS will not be in the same orbit. The required level of velocity matching depends upon the selected orbit for NGST, the separation between NGST and UMBRAS, and the length of the exposures. The relative velocity between NGST and SPIDER in inertial space must be made very small, and could range anywhere from millimeters per second (achievable with ranging) down to tens of microns per second (requiring interferometry). Velocity matching is a control consideration which is essential to the performance of the mission.

Once an occultation observation is complete, the occulting platform (SPIDER) then moves under low acceleration to rendezvous at a predetermined point in space for the next planned observation using the occulter. If the transit time is long enough, which in general it will be, NGST may slew to perform other observations while awaiting SPIDER's arrival on station. We estimate approximately one half of the total weight (mass) of the SPIDER spacecraft should be propellant (Xenon gas) to achieve a minimum 3 year mission.

4. THE UMBRAS OBSERVING PROGRAM

The lifetime of the UMBRAS space mission depends upon the amount of propellant, the average distance between NGST and UMBRAS, the expected number of targets, and the average rate of UMBRAS supported observations. For 200 targets scattered about the sky, the average angle between targets is $\sim 14°$. At a separation distance of 15,000 km between NGST and UMBRAS, the average UMBRAS transit distance between targets is $\sim$3,600 km, resulting in an average transit time between targets of $\sim$5 days. This assumes an average low acceleration of 0.8×10^{-4} m s^{-2} (Xenon-ion propulsion system) and accelerating half the distance to the new target location followed by decelerating half the distance to a stop. On the order of $\sim$70 different targets could be observed in one year using UMBRAS, which doesn't take into account multi-visitations to a target.

4.1. Extrasolar Planets

The detections announced by Michel Mayor and Didier Queloz (Geneva Observatory),[7] Geoffrey Marcy and Paul Butler (San Francisco State University),[8–12] William Cochran and Artle P. Hatzes (University of Texas),[13] David Latham and colleagues (Harvard-Smithsonian Center for Astrophysics),[14] and Robert Noyes and colleagues (Smithsonian Astrophysical Observatory)[15] of Doppler detections of giant Jupiter-sized planets orbiting other stars has created a revolution in our understanding of planetary systems other than our own. None of these new planets can be directly imaged using existing instruments except possibly the outer of two planets about the star 55 ρ^1 Cnc, but two of these planets are just at the UMBRAS detection capability. Marcy and Butler report a residual in the Doppler measurements of this star that could be interpreted as resulting from a second giant planet in orbit (period $\sim$20 yr).[11] In addition, ISO observations indicate 55 ρ^1 Cnc has an infrared excess and might be surrounded by a circumstellar disk.[20] If verified, this would validate the notion of planet formation in disks and provide information about the inclination of the planetary orbit. Once the inclination of the planetary orbit is known, the ambiguity in the planetary mass estimate ($v\ sin\ i$) is removed. In the next decade, we can expect more Doppler detections of planets about solar-like stars. The number of such stars could double or triple before the launch of NGST and should be added to its prime target list.

4.2. Circumstellar Disks

Far-infrared observations obtained with the *Infrared Astronmical Satellite* (IRAS) indicate that some stars have excess emission at far-IR wavelengths,[21,22] and they have been labeled Vega-excess or Vega-like due to their excess fluxes at wavelengths ≥ 60 μm.[21] Presumably, the radiated flux from these stars is absorbed by surrounding dust particles, and this energy is re-radiated in the far-IR. The southern star β Pictoris is the only IRAS target for which a substantial circumstellar disk has been optically imaged.[23] Ground-based and space-based imaging and spectroscopy reveal a dynamic system in which it is postulated that the disk may in part consist of material from the destruction of comets. It is suggested that a planetary system is forming or has formed in the disk and the resulting interaction between this planetary system and the disk is triggering the infall of comets.[24] A short list of infrared excess stars is presented in Table 4. Presumably, holes in disks are due to planet formation and these planets could possibly be imaged with UMBRAS. These stars should be considered prime targets to be observed with NGST.

Table 4. Stars with Infrared Excess (circumstellar disks)[22,20,25]

Star	Name	Spectral Type	Distance (pc)	V-mag	Imaged
HD39060	β Pic	A5III	18.2	3.85	optical,infrared
HD172167	Vega	A0V	8.4	0.03	submillimeter
HD216956	Fomalhaut	A3V	6.9	1.17	submillimeter
HD22049	ϵ Eri	K2V	3.3	3.73	submillimeter
HD102647	β Leo	A3V	13.1	2.14	no
HD158643	51 Oph	A0V	30.3	4.80	no
HD139006	α CrB	A0V	23.2	2.21	no
HD109573	HR4796A	A0V	?	5.78	far infrared
HD75732	55 ρ^1 Cnc	G8V	14	6.00	no

4.3. Other Types of Targets

The UMBRAS space mission could be used to observe any low brightness target which is lost in the glare of a much brighter object. These include low mass companions to nearby stars, the surrounding nebulosity in planetary nebulae, astrophysical jets, the surrounding regions of the centers of galaxies, and the host galaxies of quasars.

In addition, several unique observing programs could be achieved with high time resolution scanning of the SPIDER across close binary stars, Kuiper Belt objects, asteroids, and even stellar photospheres to map the surfaces.

5. SUMMARY: WHY UMBRAS?

The UMBRAS space mission could revolutionize the field of planetary studies by providing numerous extrasolar planet detections, and enable NGST to advance our understanding about how planetary systems form by imaging circumstellar disks closer to the primary star than what has been achieved with HST. Direct detection (imaging) of extrasolar planets may even be augmented with spectroscopic observations using UMBRAS. Studying terrestrial and giant planets about stars is one of the primary goals of NASA's Origins Program.

The UMBRAS space mission as described in this report has several advantages over other types of coronagraphic designs. Since the occulter is not built into NGST as an add on instrument, scattered light is reduced due to fewer optical surfaces using UMBRAS, no unwanted diffraction spikes resulting from coronagraph supports, and the complexity of NGST instruments is reduced. UMBRAS can move while the science instrument is fixed on a background target. The screen can occult any target in the the image plane. All science instruments can be used with UMBRAS, imaging arrays as well as spectrographs. We can now study the properties of extrasolar planets, photometrically and spectroscopically, and determine statistically the prevalence of solar-like versus 51 Peg-like planetary systems. The UMBRAS mission concept as described here is complex, with two (or more) spacecraft requiring mission operations and spacecraft management.

Our primary goals in presenting the UMBRAS space mission are to stimulate thinking about adding coronagraphic capability to NGST and to suggest several types of coronagraphic science programs with the ultimate goal to enhance the science return from NGST.

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