Laboratory Demonstrations of High-Contrast Coronagraph Imaging at JPL

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We report the laboratory demonstration of coronagraphic imaging at angular separations and contrast levels that could permit exoplanet detection at visible wavelengths; hence the existence of at least one viable solution for the "physics problem" of designing an instrument to detect Earth-like exoplanets, leading ultimately to the design of a TPF-C mission to detect and characterize planetary systems orbiting the nearby stars. The demonstration involves a collaboration of many individuals, including Chris Burrows, Brian Gordon, Brian Kern, John Krist, Andreas Kuhnert, Dwight Moody, Al Niessner, Fang Shi, Dan Wilson, and Marie Levine.

Coronagraphs are not new to astronomy, but only recently has the concept been considered for the imaging of Earth-like exoplanets from space. In space, free of the blurring effects of atmospheric turbulence, a coronagraph must further suppress the Airy rings diffracted from the edges of the primary mirror as well as the surrounding field of speckles due to irregularities in the surface figure of the optics. Diffracted light from the mirror edges can be removed by a variety of well-studied coronagraph configurations, each with its specific characteristics and limitations including efficiency, spectral bandwidth, and complexity. Here we demonstrate diffraction suppression with a Lyot-type coronagraph, and speckle suppression with a technique that is applicable to all coronagraph types.

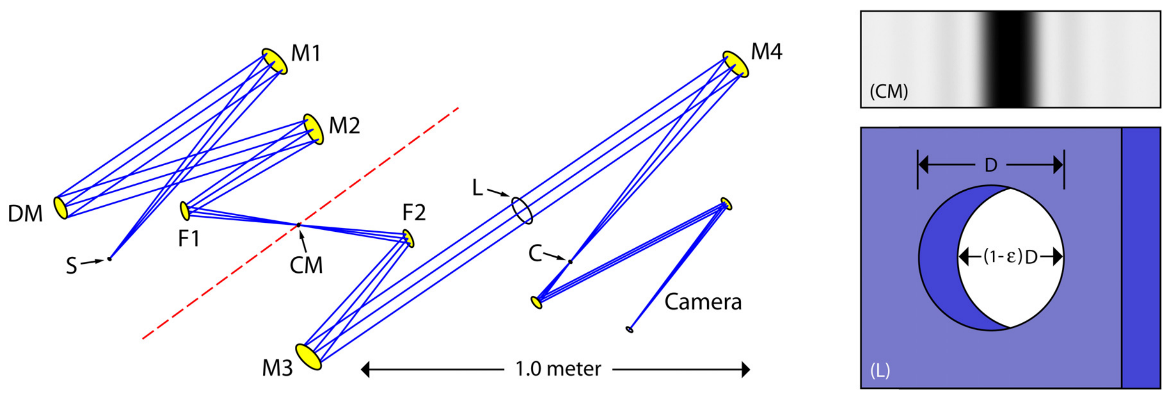

Figure 1. Laboratory coronagraph optical layout. *The essential optical elements, shown to scale, are the simulated star (S), four identical off-axis paraboloidal focusing mirrors (M1-4), a deformable mirror (DM) which also defines the pupil of the system, two flat fold mirrors (F1-2), focal-plane coronagraph mask (CM), Lyot stop (L), high-contrast coronagraph focal plane (C), and the science CCD camera. Detail at right shows the measured transmission profile of the coronagraph mask (CM) and the geometry of the Lyot mask (L), fashioned from a pair of circular stops, each with opening diameter D and offset by εD. A one-meter fiducial indicates the overall scale of the optical system. The pupil diameter D is 30 mm and the CM attenuation profile measures 82 μm (corresponding to 4 λ/D) from the center of the pattern to the half transmittance point.*

Our laboratory setup, the High Contrast Imaging Testbed (HCIT), is shown in Figure 1. Enclosed in a space-like environment inside a vibration-isolated, temperature-controlled vacuum chamber, this system captures the essential optical features of a space coronagraph. We report here the results of two experiments with the HCIT, a "snapshot" and a "movie". The snapshot experiment simulates a single exposure of a star and exoplanet system by a space coronagraph, allowing a view of a one-sided region near the star. The movie experiment simulates a series of snapshots taken as the space coronagraph is rotated about the line of sight to the star, thereby allowing a search for exoplanets in an annular region around the star.

In the snapshot experiment, the image of the star is centered on the coronagraph mask and the deformable mirror is commanded, via iterations of a speckle nulling algorithm, to minimize the speckle intensity in the target field of view. This experiment used a simulated star, but no simulated planet. By offsetting the star to a clear part of the mask, we record what a planet would look like, shown in Figure 2a. With the star centered, a dark target field appeared (Figure 2b). If a simulated planet had been present in this D-shaped field, it would have appeared as a bright spot resembling Figure 2a. Quantitatively, the data plotted on the right in Figure 2 show: (a) the azimuth-averaged intensity of the star in the target field, without the focal plane mask present; (b) the azimuth-averaged intensity of the star in the target field, with the focal plane mask, and with the DM set to minimize the average intensity in this field; and (c) the same as (b) except prior to DM correction. As shown in (b) the average intensity is about 6×10^{-10} times the peak intensity of the star in a field between 4 and 10 λ/D on one side of the star. This snapshot experiment shows that the present apparatus, in a single exposure, is capable of suppressing both the diffracted and scattered light around a star, down to a contrast level that is slightly better than a Jupiter, but not quite as low as an Earth.

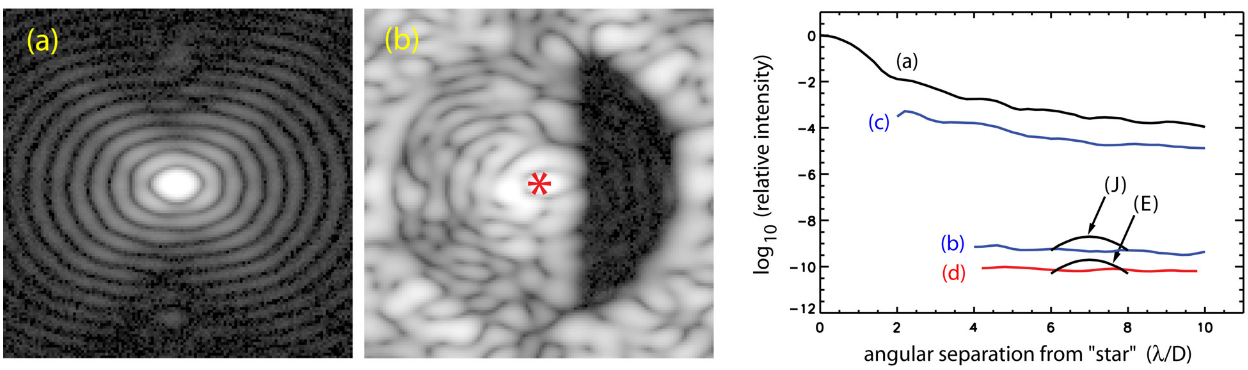

Figure 2. Representative coronagraph images and intensity profiles. *Image (a) and curve (a) illustrate the appearance of a "planet" offset from the star (and therefore not occulted by the coronagraph mask). The horizontal elongation of the diffraction rings is a result of the Lyot aperture in Figure 1. Image (b) and curve (b) show the high-contrast coronagraph "dark half-field" to the right of the masked central star (at the location of the red asterisk). Also shown are curves for (c) the coronagraph contrast prior to wavefront correction (with the DM nominally flat) and the improved contrast (d) obtained by roll deconvolution of a set of coronagraph images (cf., Figure 4c). Intensity profiles for a nominal Earth (E) and Jupiter (J) in reflected starlight are included for reference. Images and intensity curves are displayed on logarithmic scales.*

This experiment validates many, but not all, of the critical elements of an actively corrected space coronagraph for exoplanet imaging. It is an extremely simple, stable coronagraph configuration, operating in a space-like environment, with contrast performance that can be accurately modeled end-to-end using the known characteristics of the optical elements. It illustrates a robust method of optical wavefront sensing and control that requires only the DM and science camera to analyze the image of a star. It shows that current DMs are capable of suppressing scattered light to contrast levels and separations representative of a planet-finding mission and, as the movie experiment will show, that the precision DM settings remain stable over periods of hours or more without feedback. However, the experiment lacks a simulator for the dynamics of a large telescope structure in space, and the experiment was performed in polarized, narrowband laser light rather than unpolarized, continuum starlight filtered to a 10–20% (δλ/λ) bandwidth as would be required for photometric studies in astronomy. As verified by splitting the light into its component polarizations just prior to the CCD camera, our coronagraph is insensitive to polarization, working equally well in polarized and unpolarized light to the reported contrast levels.

While not reported here, we note that the question of spectral bandwidth is being addressed in stages. Early experiments with 2% bandwidth have demonstrated contrast of 1.5×10^{-9} using the same coronagraph masks and speckle nulling procedure as above. Our optical model indicates that an optimal choice of Lyot mask will improve this to the contrast levels seen in narrowband light. Initial experiments with 10% bandwidth light, again with the same coronagraph mask and speckle nulling procedure, produced a contrast of 6×10^{-9}. Our model predicts that this 10% contrast will be reduced by about an order of magnitude using a new coronagraph mask now being manufactured with standard techniques and common materials. This is an active area of development and a pathfinder for the TPF-C mission design.

In the movie experiment, to simulate a coronagraph operating in space, we continuously repeated the snapshot experiment 480 times over a period of 5 hours. The apparatus was very stable during this period; it was not adjusted in any way between exposures. The background speckle field evolved slowly, owing to room temperature changes and mechanical relaxation, much as might be expected in a coronagraph in space.

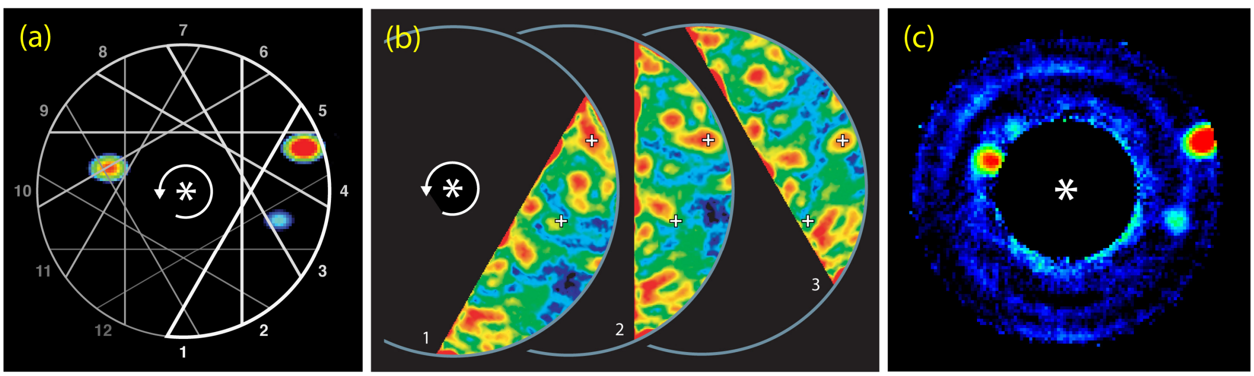

***Figure 3. Laboratory images demonstrate contrast at levels required to detect an Earth-twin**. (a) Three planet images are shown on the sky. The planets are copies of the measured star but reduced in intensity by factors of (10, 5, and 1) $\times 10^{-10}$, corresponding to the typical intensities of Jupiter, half-Jupiter, and Earth, respectively. The Earth-twin is at about 4 o'clock, and Jupiter-twin at 2 o'clock. The D-shaped field of view rotates on the sky as the spacecraft is rotated about the line of sight to the star (asterisk). (b) Three sample images at different rotation angles illustrate the observing sequence. Note that the planets (white + signs) are fixed in inertial space, and just barely visible. The rotation sequence continues to fill a full annular field of view. (c) Roll deconvolution is applied to the data, removing the background speckles that rotate with the spacecraft, and keeping the part of the image (planets) fixed in the sky (see also Figure 2 for relative intensities). The planets stand out clearly against the residual background noise, which is the time-varying part of the speckles.*

The movie experiment demonstrates the process of planet discovery with a space coronagraph, as follows. As shown in Figure 3a, we hypothesize a space coronagraph that is aimed at a nearby star (the asterisk), with the background starlight suppressed in the target field, as in the snapshot experiment. We assume that the space coronagraph is rotated in small increments, so that the dark target field successively covers regions that ultimately fill the complete annular region between angular separations of 4 and 10 λ/D on the sky. For illustration we show twelve discrete 30° steps in Figure 3a, but in the example here we use 48 steps of 7.5° each, and in each step we co-add 10 sequential exposures, using a total of 480 exposures.

Lacking a simulated planet, we added attenuated copies of the star to each exposure, at the sky locations shown in Figure 3a. This procedure is valid because we have previously shown that the presence of a planet in the speckle field of a star has no effect whatsoever on our wavefront correction algorithm. The orbital positions were chosen artificially so that the projected planetary system could be captured in a single image here.

Three snapshots of the planets-plus-speckle field are shown in Figure 3b. With a relative speckle intensity of about 6×10^{-10} in each snapshot, the planets (centered under the white "+" signs) are barely visible. This combination of a slowly evolving instrumental background that is fixed with the rotating spacecraft, plus an astronomical object that is fixed in inertial space, has been encountered before with images from the HST. A roll deconvolution algorithm was applied to the sequence of these images of laboratory background plus superposed planets by John Krist. The result is shown in Figure 3c, where we see that all three planets stand out clearly against the remaining background. Quantitatively, the azimuth-averaged relative intensity is plotted in Figure 2 (right), where curve (d) is the roll-deconvolution background averaging about 0.9×10^{-10}, which is well below the single-snapshot intensity of 6×10^{-10}. The Earth and the Jupiter intensities are shown added to the background from roll-deconvolution, and superposed for clarity.

The movie experiment is an existence proof that it is possible to extract exoplanets close to a star, even when the residual speckle intensity is comparable the planet intensities. We believe, however, that for planet detection and characterization a space coronagraph should be designed to even stricter standards, with roughly a factor of 10 weaker speckles than achieved in the present experiments. The present work is a step toward this goal, but more work remains. Future laboratory work will focus on pushing the speckle background lower, broadening the spectral bandwidth, suppressing speckles simultaneously on both sides of the star with a pair of DMs, and increasing the radial field of view, both inward and outward. The present work lays the groundwork for the development of a TPF mission that will, for the first time, explore nearby Earth-like exoplanet systems by direct imaging and spectroscopy.

REFERENCE

J. Trauger and W. Traub, A laboratory demonstration of the capability to image an Earth-like extrasolar planet, Nature **445**, pp. 771–773, 2007.