Study of High Performance Coronagraphic Techniques

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Report for Year 1 of the Project
"Study of High Performance Coronagraphic Techniques"

P.I.: Volker Tolls, SAO
And the CoronaTech Team

1. Introduction

The goal of the Study of High Performance Coronagraphic Techniques project (called "CoronaTech") is: 1) to verify the Labeyrie multi-step speckle reduction method and 2) to develop new techniques to manufacture soft-edge occulter masks preferably with Gaussian absorption profile. In a coronagraph, the light from a bright host star which is centered on the optical axis in the image plane is blocked by an occulter centered on the optical axis while the light from a planet passes the occulter (the planet has a certain minimal distance from the optical axis). Unfortunately, stray light originating in the telescope and subsequent optical elements is not completely blocked causing a so-called speckle pattern in the image plane of the coronagraph limiting the sensitivity of the system. The sensitivity can be increased significantly by reducing the amount of speckle light. The Labeyrie multi-step speckle reduction method implements one (or more) phase correction steps to suppress the unwanted speckle light. In each step, the stray light is re-phased and then blocked with an additional occulter which affects the planet light (or other companion) only slightly. Since the suppression is still not complete, a series of steps is required in order to achieve significant suppression. The second part of the project is the development of soft-edge occulters. Simulations have shown that soft-edge occulters show better performance in coronagraphs than hard-edge occulters. In order to utilize the performance gain of soft-edge occulters, fabrication methods have to be developed to manufacture these occulters according to the specification set forth by the sensitivity requirements of the coronagraph.

With great sadness we report that the project suffered a large set-back and therefore started with some delay. The original principal investigator of the project, Dr. Pete Nisenson, became sick right before the project started. Everybody was expecting him to recover and return to the project. But his condition suddenly worsened and he passed away in June 2004. Since most of the individual tasks of the project were divided among the co-investigators, we decided to continue the project. Subsequently, we asked for transfer of the lead of the project to Dr. Tolls. The transfer was completed in August 2004 and the project work restarted. In the next sections, we will summarize the work accomplished during the first 10 months of the project and in progress.

2. Work Accomplished and in Progress

2.1 Coronagraphic Testbed

An overview of the coronagraphic testbed is shown in Figure 1. The coronagraphic testbed is based on Pete Nisenson's testbed that verified the performance of the apodized square aperture (ASA). The elements left over from his experiment are the light sources, HeNe lasers to simulate a host star and its faint companion planet. The light from the companion can be adjusted with neutral density filters to cover a star-to-companion contrast ratio from 10^{-0} to 10^{-10}. The light from the simulated source can be apodized before and after a test mirror simulating a telescope. This mirror has a high surface accuracy of λ/1000 to simulated expected amounts of stray light (speckles).

The next stage is the coronagraph under test with a single step of Labeyrie's multi-step speckle reduction method (see Figure 2). The phase corrector will be a deformable mirror. SAO has purchased a 140 element deformable mirror from Boston Micromachines Corp. including driver electronic and software interface. This deformable mirror is currently implemented into the coronagraph of the testbed. The occulters for the coronagraph and the multi-step stage are fabricated here at SAO using the Harvard approach of occulter manufacturing (see Chapter 2.4).

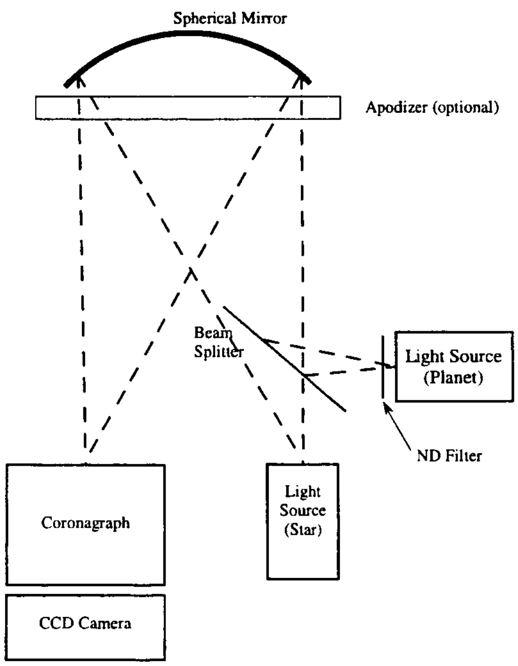

Figure 1: Schematic of SAO's coronagraphic testbed (not to scale). For details about the coronagraph see Figure 2. The CCD camera is a temperature-stabilized SBIG laboratory CCD camera mounted on a translation stage to change the position of the CCD along the optical axis around the image plane of the coronagraph.

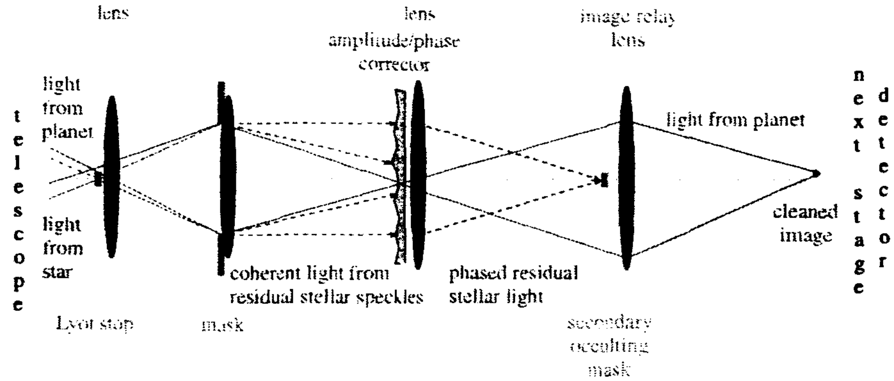

Figure 2: Schematic of the coronagraph in SAO's testbed with a single step of Labeyrie's multi-step phase correction method. The optics will look slightly different from this schematic to fully implement the deformable mirror and to utilize its full extend requiring matching optics.

The CCD camera is SBIG's ST-7XME laboratory camera with a low-noise, temperature-stabilized Kodak CCD KAF-0401E NABG. This camera incorporates a low noise CCD and differs from the astronomical version by the absence of a guiding CCD. The camera is mounted on a Newport translation stage and can be moved over a ±12.5 mm range with micro-meter precision along the optical axis around the focal point in the image plane of the coronagraph. This way its position can be computer-controlled in order to measure the intensity of the image at various positions around the focal point as it is required for the phase diversity method to estimate the phase of the wavefront to be corrected. The control software for automatic measurements will be developed during the second year of the program. However, the system is immediately functional utilizing the software supplied by the vendors: SBIG's software for camera control and Newport's software for translation stage control.

The initial setup of the coronagraphic testbed will be finished by the end of January 2005. The next phase will be testing the testbed, performing test measurements for the phase diversity development, and developing automatic test and control software for the testbed.

2.2 Simulation of Soft-Edge Occulters

We have improved our models of coronagraphs by implementing soft-edge occulters as an option compared to hard-edge occulters. We have models maintained by Rick Lyon at GSFC and by Robert Gonsalves, Tufts University. We are still comparing the results of both models. In addition, Rick Lyons is developing an advanced model to evaluate the 3-dimensional effects of soft-edge occulters with more arbitrary absorption profiles derived from the absorber parameters, e.g. real and complex parts of refractive index, and thickness of absorber material as function of distance from the optical axis. First results are shown in 2.3.

2.3 Development of Occulters: Harvard Approach

The Harvard approach of soft-edge occulter fabrication was to place droplets of a suspension of an absorber material in a carrier. By chance, we were able to perform preliminary experiments as part of a summer student project which was supported by SAO's summer student program. The summer student tested several readily available absorber materials: copier toner, graphite powder, and ink, in combination with several carriers: vacuum grease, optical cement, and epoxy. The best combination was graphite powder in optical cement. He produced a few test droplets for optical performance testing. These tests showed that the absorption profiles of the produced droplets were not Gaussian. These results led to two tasks for this project: 1) a more in-depth theoretical investigation of the droplet absorbers and 2) inclusion of soft-edge occulters in our coronagraph simulation models. The results of both were that droplets cannot produce a Gaussian absorption profile (Spherical Caps Memo by V. Tolls) and that their performance in coronagraphs was close to that of hard-edge occulters. Figure 3 shows the transmission profile of a spherical cap with 200 mm radius, 20 mm footprint radius, and a 5.7° contact angle for graphite powder in optical cement. This transmission profile has clearly a non-Gaussian shape.

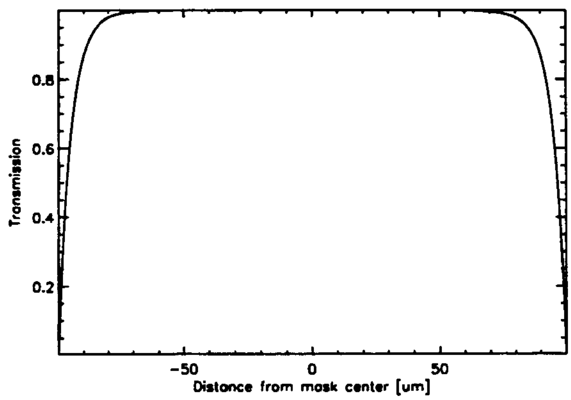

Figure 3: Theoretical transmission (absorption) profile of an ideal droplet occulter (spherical cap occulter).

The simulated point-spread function (PSF) at the output of a coronagraph with a droplet occulter (Figure 4) shows a greater width than the PSF of a coronagraph with an occulter with Gaussian transmission profile.

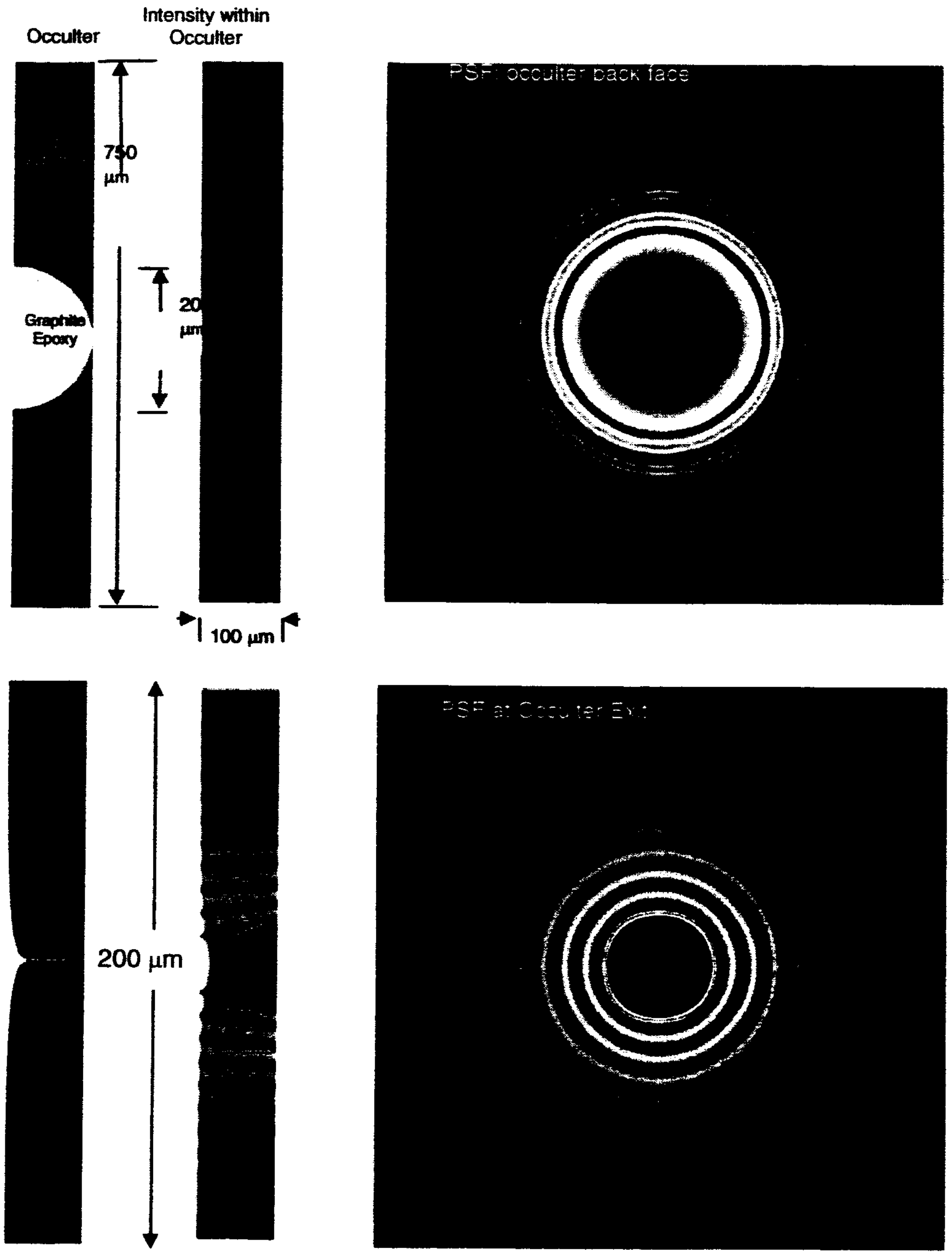

Figure 4: Simulation of coronagraphs with droplet occulter (top) and with occulter with Gaussian absorption profile (simulations performed by Rick Lyon, GSFC).

Currently, we are trying to reproduce some of the results of the summer student to fill in some missing information in the material characteristics and to produce a set of droplet occulters for additional tests in the coronagraphic testbed. The goal of these tests is to verify the simulations conducted and to create a reference set of occulters. In addition, we are working on improvements on the droplet method and how we can modify this method to achieve occulters with Gaussian absorption profile. An additional notable result of the simulations was that the critical parameters of the occulters are the wing shape and the transition to the substrate. The wing shape is the critical parameter for determining the width of the PSF while the center of the occulter can almost be shaped arbitrarily. We will use the latter result to increase the thickness of the absorbing material in the center of the mask to achieve the high absorptivity required to observe extra-solar planets in close proximity to their bright host stars. The transition from the absorbing material to the substrate needs to be as smooth as possible. If the remaining step is too large, the phase changes cause unwanted diffraction effects which lead to performance degradations. The details need to be investigated through simulations and experimental verifications.

2.4 Development of Occulters: Lockheed-Martin Approach

Currently, Lockheed-Martin is evaluating methods for the fabrication of soft-edge field masks. They have set as a goal that the resultant masks have repeatable characteristics, so that defects can be corrected deterministically in the next generation. Two classes of approaches have been identified for further trades: replication technique and photographic technique. The trades are supported by vector analysis. The trades will be completed early next year such that test masks will be available later that year.

2.5 Miscellaneous

We have issued contracts to Robert Woodruff, Lockheed-Martin for the development of soft-edge occulters and to Prof. Dr. Robert Gonsalves to develop the phase diversity phase retrieval approach for Labeyrie's multi-step speckle reduction method. Both contracts will be renewed on a yearly basis until the end of the regular grant period.