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Brian Hicks

Nulling Interferometers for Space-based High-Contrast Visible Imaging and Measurement of Exoplanetary Environments

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Supervisor's Foreword

Compared to many other pursuits in experimental astrophysics, observational studies of extrasolar planets (exoplanets) is a relative newcomer. Nonetheless, the spectacular success of ground-based and space-based observations is already rewriting our understanding of how planets form and evolve. Today we stand at the threshold of the next step in this quest – the detailed characterization and inventory of these alien worlds.

Direct imaging of exoplanets is being pursued by a number of research groups around the world. The primary impediment to directly image an exoplanet is not their low brightness – our observatories routinely image and study much fainter celestial bodies. The key challenge is contrast – the brightness ratio between the planet and the star. In visible light a typical star is a billion or more times brighter than the planets. A mental image that represents the challenge of directly imaging an exoplanet around a star is the task of imaging a marble sitting next to a lighthouse in Boston by an observer in San Francisco!

For various reasons such a task is best accomplished from a space-based platform. This dissertation describes our attempts to develop a rugged instrument that belongs to a family called nulling interferometer (or nuller) or internal coronagraph. In simple terms, a nuller is an interferometer that destructs light from a point source (a star) located on its optical axis, while at the same time it allows off-axis light be recorded without any attenuation. There are many different optical approaches that have been studied theoretically or experimented with in the laboratory and some have been deployed in the field. Another type of instruments that can provide the same information belongs to the class called external occulter, where a carefully designed mask blocks out the on-axis starlight in a manner similar to that of solar or lunar eclipses. Depending upon the characteristics of the system, a planet could be observable very near the edges of the shadow cast by the occulter.

The key parameters that are used to describe the performance of all such systems include, contrast, bandpass (the range of color of light over which the instrument operates satisfactorily – a large value being desirable), inner working angle, which describes how close to the star the planet could be for instrument to measure its physical parameters, optical throughput and suitability for spaceflight. Laboratory measurements have shown that a planet-star contrast as low as 10^{-9}, a bandpass of 20 % (±10 % of the operating wavelength) and an inner working angle of 1.5 λ/D, where λ is the operating wavelength and D is the diameter of the telescope are possible. As of now, only one coronagraph flew aboard a sounding rocket (the Planet Imaging Concept Testbed Using a Rocket Experiment – PICTURE), which unfortunately could not collect any science data due to the failure of a radio communication link.

This dissertation describes in detail the design and implementation of the Monolithic Achromatic Nulling Interference Coronagraph (MANIC). It belongs to a subclass of internal coronagraph that has been described as Rotational Shearing Interferometer (RSI). MANIC splits incident light into two beams. One of the beams undergoes a π phase shift and a pupil flip before being combined with the other beam, which results in the desired interference.

Chapters 1–4 provides the necessary background and science relevance for high contrast imaging along with key engineering considerations for possible future applications. Chapter 5 delves into nullers and their characteristics and introduces MANIC. It followed the implementation path of interferometric spectrographs such as Wide-Angle Micheson Doppler Imaging Interferometer (WAMDII) and others that eliminated sensitivity to misalignment of key optical components. MANIC, being a carefully designed optical monolith, is impervious to the rigors of spaceflight. The details of the implementation of MANIC is described in Chap. 6 and the final chapter provides some concluding thoughts.

On a personal note, it has been great to be a part of the journey that transformed Mr. Hicks into Dr. Hicks. As his dissertation advisor, I rejoiced and shared the successes and has been dispirited by the setbacks, that is common in a highly technical and multidisciplinary endeavor. MANIC could not have been developed without Professor Timothy Cook, the other half of Brian's advising team or without the technical support from LightMachinery, its fabricator. MANIC has taken the first step of a long journey that will, one day, allow us to take the first image of a planet like those we find in our solar system.

Lowell, USA Supriya Chakrabarti

Supervisor's Foreword

Imaging planets orbiting other stars is the most exciting challenge of our time. The idea of other worlds has gripped human imagination since the time of HG Wells and Edgar Rice Burroughs, and no other branch of science so thoroughly excites our curiosity as the study of what are now called exoplanets. As discoveries continue to grow in this field the first few planetary systems have been imaged but we need to do much more. Ultimately we want to be capable of imaging Earth-like planets orbiting Solar-type stars, but even imaging Jupiter like planets in Jupiter-like orbits is not currently possible.

In the last two decades the idea of taking a picture of a planet orbiting a distant star has moved from purely speculative to accomplished fact. In 1990 we did not know of any planet outside our solar system. Today we know of thousands. We have already discovered more planets, in more places, with more exotic characteristics than we would have thought possible just a few decades ago. This acceleration of discovery has been brought about by a similar explosion in the instruments designed to detect, study, and image exoplanets. A great many new systems have been developed and many more have been discussed. While we have made great progress more, higher performance systems await.

The essential problem is that to image an exoplanet near its host star one must image the faint planet next to the bright star; one must make measurements with a contrast of between a part per million and a part per 10 billion. In order to do this one needs to control the optical system to between one thousandth and one hundred thousand of the wavelength of the light being observed. This is obviously quite difficult.

Building systems to study exoplanets is not easy, nor is it cheap. The most capable systems under consideration will cost tens of billions of dollars. These costs necessitate that they will not be on line for decades, if then. We cannot wait that long. In this volume, Dr. Hicks lays out a system capable of making significant progress at a using smaller telescopes and less capable satellites. Such systems will be essential in our field for the next decade or two. The keys to an exoplanet imaging system which can be realized in the near future are stability, simplicity, and size. As described here, these properties are inherent to the design of MANIC. By reducing the optics at the heart of this instrument to a single monolithic prism the high stability, operational simplicity, and small size are assured.

Given the rapid progress in the study of exoplanets I suspect that our expectations for future missions, instruments, and discoveries will prove to be dashed, and exceeded, and completely incorrect, and fulfilled beyond our wildest dreams – all at the same time. This volume should serve well as both a first step to new and exciting instrumentation and a solid reference on the state of the art at the dawn of the era of exoplanetary observation.

Lowell, USA Timothy Cook

Contents

Acronyms

The following acronyms are used throughout this work.

(CP)AIC	*(Common-path) Achromatic Interferometric Coronagraph*
BS	Beamsplitter
DLA	Delay Line Assembly
DM	Deformable Mirror
EFC	Electric Field Conjugation
FFT	Fast Fourier Transform
FWHM	Full-Width at Half Maximum
FSM	Fast Steering Mirror
GPI	*Gemini Planet Imager*
HCB	Hydroxide Catalysed Bonding
HST	*Hubble Space Telescope*
IWA	Inner Working Angle
JWST	*James Webb Space Telescope*
LOWFS	Low-Order Wavefront Sensor
MANIC	*Monolithic Achromatic Nulling Interference Coronagraph*
MEMS	Micro-Electro Mechanical System(s)
OPD	Optical Path Difference
OWA	Outer Working Angle
PICTURE	*Planetary Imaging Concept Testbed Using a Rocket Experiment*
PIAA	*Phase-Induced Amplitude Apodization*
PSD	Power Spectral Density
PSF	Point Spread Function
PZT	Piezoelectric Transducer
RMS	Root Mean Square
RSI	Rotational Shearing Interferometer
SCC	*Self-coherent Camera*
SHWFS	Shack-Hartmann Wavefront Sensor
SMA	Static Mirror Assembly
SNR	Signal to Noise Ratio