INSTITUTO DE ASTROFISICA DE CANARIAS

GRADUATE STUDIES DIVISION

PROPOSAL FOR PhD PROJECT - 2023

(Do not exceed 4 pages – excluding annexes)

Name of Supervisor (or Supervisors): Jeff Kuhn (IAC)
Name of Co-Supervisor (if there is any): Rafael Rebolo (IAC), Jannick Rolland (external)

Name of Tutor (if different from Supervisor):

Title: Developing optical Innovation for future large telescope and space systems

Related IAC Research Project:
The PhD student will benefit from interactions with several groups:
(1) IAC Optics group
(2) Center for FreeForm Optics at the University of Rochester, NY, USA
(3) Members of the Laboratory for Innovation in Opto-Mechanics (LIOM)
(4) Low-mass, brown dwarf, and exoplanets group at the IAC

Abstract:
The broader goal is to develop novel solutions for addressing the challenging and crucial problem of eventually imaging faint habitable planet/s around a star that is typically 7-9 orders of magnitude brighter. Laboratory for Innovation in Opto-Mechanics (LIOM) is an international collaboration that is building a large (35 m-scale aperture) multi-aperture telescope called the ExoLife Finder (ELF) to achieve this goal. This PhD thesis aims to examine and utilize new tools and techniques that make it possible to create low mass, large area multiple sub-apertures to preferentially suppress the star light and image the planet light. The ultimate goal of this thesis would be to develop and demonstrate a laboratory optical system for co-phasing and interferometrically nulling pupil sub-apertures on a smaller implementation of ELF called Micro-ELF (0.5m aperture) and possibly to begin observing with the Small-ELF under construction on Teide. This technology demonstrator with Micro-ELF will pave the way for designing such capability for the full-fledged 35-m ELF telescope and possibly space-based telescopes requiring low mass optics.

Short List of Goals:

Below is a list of science/technology objectives during the PhD thesis:

1) Explore laser-based, precision mechanical shaping, and spherical polishing techniques to achieve rapid mirror shaping with non-conventional (thin) glass substrates. These will be used in combination in multiple sub-apertures geared towards direct imaging of exoplanets from ground- or space-based Fizeau telescopes.
2) Refine the design, and build a laboratory test of these optical components.
3) Refine the design, and build a 0.5m Fizeau (micro-ELF) optical system that tests interferometric nulling techniques.
4) Extrapolate the Micro-ELF technologies to ELF-scale optics and create a high-fidelity model of the performance and sensitivity of ELF.
5) Learn about combining machine learning algorithms to improve Small-ELF/ELF direct imaging capabilities
6) If timing allows work with the Small-ELF team to test Fizeau optics on-sky with the Teide Small-ELF telescope

Type of Research to be developed: (describe the observational, theoretical or instrumental content of the work to be developed by the PhD student)
This PhD thesis is mainly instrumental and requires the student to become familiar with the concepts of optics, adaptive optics, wavefront sensing, and their lab implementation. The student will work on design and mathematical formulation of the optical curvature shaping problems with Multiphysics numerical models. He/She will work on the experimental demonstration of curvature polished mirror systems. He/she will learn about all processes related to astronomical research, mathematical methods such as neural networks and their implementation in Python. He/she will also acquire valuable skills such as writing proposals and scientific papers and planning+performing experiments for astronomical instrumentation.

We also envision one or several long-term visits to collaborating institutions e.g. the Rochester Center for Freeform Optics and the MorphOptic Laboratory in Hawaii, and other institutions participating in LIOM in order to broaden the vision and training of the student.

Project Summary:

<u>Scientific background:</u>

- Technology now exists, or is on the immediate horizon, that will enable large optical systems that are capable of resolving and measuring faint sources that are not accessible with current remote sensing instruments and detectors. The possibility of creating ground-based telescopes at the 35m-scale with sufficient wavefront control to both fully overcome the effects of the atmosphere, but with exquisite coronagraphic capability starting at the telescope entrance pupil, means we may solve some of the most fundamental cross-cutting scientific questions: like, “is there life outside of the solar system?” The creation of these optical systems will pull together broad research disciplines, novel optical systems, and including machine learning.

- Since the discovery of the first extrasolar planet orbiting a solar-type star, 51 Peg b (Mayor & Queloz 1995; Nobel prize of Physics 2019), the numbers of exoplanets has grown up tremendously. After several decades studying a large variety of exoplanetary systems, the main objective is now the detection and characterization of telluric exoplanets. One of the major discovery of the next decades would be the detection of biomarkers and exolife. This requires collecting images and spectra of planets that can be up to 10^9 times fainter than their host star. Such unprecedented contrast, angular resolution and spectral stability require several technological innovations and a novel telescope concept that LIOM is designing.
- New large telescope concepts will replace stiff mass with pre-tensioned cables (also known as tensegrity) as well as lighter active optical control systems. The ExoLife Finder **(ELF)** telescope depends on using active wavefront control technologies to decrease the mass and cost of a 35m-scale telescope by an order of magnitude or more. Developing novel solutions for decreasing the mass of the mirror payload in these instruments is important. ELF uses sub-aperture off-axis telescope units in a Fizeau interferometry optical configuration where the light of all sub-apertures is brought to a common coherent focus. The optical concepts developed in this research program will advance the technical readiness of an ELF telescope.
- The **Small-ELF** telescope is a 4m-scale 15 sub-aperture Fizeau telescope that is now being built on Teide mountain in the Canary Islands by the IAC as a prototype for ELF. It will test tensegrity concepts, Fizeau imaging, and Machine Learning and Mach Zehnder wavefront measurement technologies.
- **Micro-ELF** is a laboratory 0.5m version of a tensegrity telescope with 5 sub-apertures that will be used for developing and testing the creation and performance of low mass optical systems.
- **Why laser and curvature polishing is ideal?** The low scattered light and mass of curvature polished optics practically enables large increases in telescope size and photometric dynamic range performance. Since there is always a bright object in the FOV, it is important to demonstrate these new technologies with laboratory experiments to improve our models of the ultimate performance of large Fizeau optical systems. These optics are also key for optical space applications, especially in the rapidly expanding space optical communication community.

Key steps: Expanding curvature polishing techniques, designing then building the laboratory microELF, measuring its performance and extrapolating to high-fidelity ELF and space optics performance models.

Scientific objectives of the PhD:

- **Identify** the requirements, strengths, and weaknesses of various new technologies for creating lightweight optics and numerical simulation
- **Demonstrate and devise metrology techniques** For curvature polishing of mm-scale thickness small optics
- **Create** and measure the performance of a microELF optical system in the laboratory for developing and demonstrating interferometric nulling in Fizeau optics

Schedule: (The project needs to be carried out in three years)
We emphasise that reading literature about adaptive optics, wavefront sensing, optical metrology and optics creation should be conducted continuously during the length of the PhD thesis. Reading will be more intense at the beginning but should continue during the PhD to remain up-to-date with discoveries by other groups.

Below is a tentative time frame for the different phases of the PhD:
Year 1: semester 1: read papers to get knowledge on the subject of laser curvature shaping. Get familiar with the multi-physics modeling techniques and tools that will be used during the project
Year 1: semester 1: Learn to use optical interferometry metrology tools and high-power CO2 gantry machine control systems. Design Micro-ELF and off-axis optical systems
Year 1: semester 2: Create and measure 10cm-scale diameter mirrors for the microELF optical system.

Year 2: semester 1: Construct Micro-ELF optical system.
Year 2: semester 2: Implement detector, phasing and computer control systems

Year 3: semester 1: Measure optical performance (PSF, scattered light, coronagraphic performance)
Year 3: semester 2: Write the resulting papers from Micro-ELF on-sky demo and the PhD thesis. Build and refine high-fidelity ELF optical performance model.

Supervisor's experience on the research subject:

Prof. Jeff Kuhn is a professor at the University of Hawaii Institute for Astronomy and is now the ERA Chair of LIOM at the IAC in La Laguna. He's been the PI or coI for nearly $300M of experimental research grants and contracts and has supervised graduate students for approximately 35 years in a range of instrumental, observational, and calculational astrophysical problems. He is fully devoted to the educational goals of advancing graduate research with LIOM. His role in co-advising the PhD will be to provide guidance with the optics and curvature polishing technologies (that he recently patented in the US) he will help to generalize this detailed optics graduate thesis to the range of practical LIOM problems and serve as a bridge to Prof. Rolland and the optics program at the University of Rochester.

Prof. Jannick Rolland: Prof. Jannick Rolland is director of the Center for Freeform Optics and the Brian J. Thompson Professor of Optics Engineering at the Institute of Optics at the University of Rochester. She is the director of the NSF/IUCRC: Center for Freeform Optics and the Director of the R.E. Hopkins Center for Optical Design and Engineering
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