INSTITUTO DE ASTROFISICA DE CANARIAS

GRADUATE STUDIES DIVISION

PROPOSAL FOR PhD PROJECT - 2023

Name of Supervisor: Prof. Jeff Kuhn (IAC)
Name of Co-Supervisor: Nicolas Lodieu (IAC), Pradip Gatkine (external)

Title: Developing astrophotonic tools for direct imaging of exoplanets

Related IAC Research Project:
The PhD student will benefit from interactions with several groups:
(1) IAC Astrophotonics group
(2) Caltech Astrophotonics group (Exoplanet Technology Lab)
(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 aperture) multi-aperture telescope called the ExoLife Finder (ELF) to achieve this goal. This PhD thesis aims to examine and utilize astrophotonic tools and techniques to address the critical challenge of combining light from 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 this capability of co-phasing the subapertures using photonic lanterns as wavefront sensors on a smaller implementation of ELF called Micro-ELF (0.5m aperture). This technology demonstrator on Micro-ELF will pave the way for designing such capability for the full-fledged ELF telescope.

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

1) Explore the concept of using a photonic lantern as a wavefront sensor (PL-WFS) and for phased combination of multiple sub-apertures geared towards direct imaging of exoplanets from ground- or space-based Fizeau telescopes.
2) Simulate the photonic lanterns as wavefront sensor for a multi-aperture telescope and identify the strengths and weaknesses of this approach
3) Lab demonstration of photonic lanterns for extracting wavefront state (eg: Zernike

coefficients) using Neural Networks or other non-linear techniques
4) On-sky demonstration of the photonic lantern WFS for the 5-aperture micro-ELF
5) Design the PL-WFS for the Small-ELF telescope
6) Learn about and explore other possible photonic techniques for wavefront control of the SELF or ELF telescope systems
7) Learn about combining machine learning algorithms to improve SELF/ELF direct imaging capabilities

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, turbulence, wavefront sensing, photonic lanterns, and their lab implementation. The student will work on mathematical formulation of the wavefront sensing problem, perform numerical simulations of photonic lanterns, study wavefront reconstruction methods for photonic lanterns (including neural networks), and work on the experimental demonstration of the PL-WFS system. 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. California Institute of Technology and other institutions participating of LIOM, to broaden the vision 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, including machine learning and astrophotonics.
- 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 of a 35m-scale telescope by an order of magnitude or more, hence, its cost. ELF uses subaperture 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 photonic concepts developed in this research program will advance the technical readiness of an ELF telescope.
- The **Small-ELF** telescope is a 4m-scale 15 subaperture 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 photonic lantern and tensegrity concepts for larger Fizeau optics.
- **Why PL-WFS is ideal?** An astrophonic solution for the low order wavefront piston/tip/tilt wavefront corrections that drive the Fizeau wavefront corrections is required. Since there is always a bright object in the FOV, it is likely that a PL observing the central star can be a fast and efficient tool for finding the Piston-Tip-Tilt (PTT) corrections for the Fizeau apertures.

Key steps: Simulations of PL-WFS system, examining its advantages and limitations, performing a lab demo of the PL-WFS system, building a laboratory and possibly an on-sky demonstration for Micro-ELF.

Scientific objectives of the PhD:

- **Identify** the requirements, strengths, and weaknesses of various astrophotonic lantern for wavefront sensing for a multi-aperture co-phased telescope like ELF, through mathematical modeling and numerical simulation
- **Demonstrate** the concept using lab-based instrumentation and identify real-world problems that need to be accounted for in the simulations or addressed separately
- **Create** and characterize a laboratory demonstration to achieve closed-loop adaptive optics control for a Micro-ELF and possibly an on-sky science target like close-in binaries.

Schedule: (The project needs to be carried out in three years)

We emphasise that reading literature about adaptive optics, wavefront sensing, and photonic lanterns 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 and get familiar with the physics and mathematics of adaptive optics, and photonic lanterns that will be used during the project
Year 1: semester 1: Learn to develop simulations of wavefront sensing and photonic lanterns, identify the strengths and weaknesses of this approach for co-phasing the sub-apertures
Year 1: semester 2: Build a laboratory model to test the PL-WFS concept, and learn/develop methods for wavefront reconstruction from experimental data, identify the deficiencies or problems that need to be addressed by improving the mathematical models or through separate instrumentation.

Year 2: semester 1: Experimentally implement/test the improvements learnt from the previous step. Write papers on the lab demo and the results of reliable wavefront reconstruction using photonic lanterns
Year 2: semester 2: Design the photonic lantern WFS for the Micro-ELF telescope. Collaborate with other IAC staff and external collaborators to build the PL-WFS hardware as well as wavefront reconstruction software for the Micro-ELF.

Year 3: semester 1: Design and lab testing of the PL-WFS system for the Small-ELF telescope by incorporating the learnings and addressing pitfalls in the Micro-ELF PL-WFS system.
Year 3: semester 2: Write the resulting papers from Micro-ELF laboratory and possibly on-sky demo and the PhD thesis.

Supervisor's experience on the research subject:

Prof. Jeff Kuhn is a professor at the University of Hawaii Institute for Astronomy. 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 the Chair of the IAC's Laboratory for Innovation in OptoMechanics (LIOM) and is fully devoted to the educational goals of advancing graduate research with LIOM. His role in co-advising the PhD will be to provide optics and metrology expertice, and generalize the detailed astrophotonic graduate thesis to the range of practical LIOM problems while serving as a bridge to Dr. Gatkine who has detailed domain expertise.

Dr. Pradip Gatkine is NASA Hubble Postdoctoral Fellow at California Institute of

Technology. He has advised 10 undergraduate students and 2 graduate students (included 1 Master's thesis). He has multi-disciplinary research expertise in design, simulation, and characterization of astrophotonic instruments that offer unique advantages over conventional bulk optics in astronomy. He has published extensively in the fields of Astrophotonics and extragalactic astronomy. He will serve as a co-advisor of the graduate student in various aspects of astrophotonics.