TACKLING THE GREAT SCIENCE QUESTIONS OF OUR TIME

II CHAMELEON SCHOOL

CHAMELEON ITN

CHAMELEON is a Marie Curie Innovative Training Network for European Joint Doctorates. The network is developing a virtual laboratory to research exoplanets and protoplanetary disks that will play a key role in simulating yet unexplored physico-chemical environments. CHAMELEON aims to retrieve and predict chemical compositions of planet-forming disks and exoplanet atmospheres, transfer knowledge, codes and models between planet and disk communities, and share state-of-the-art scientific concepts with the wider community.

CHAMELEON is made up of 15 early stage researchers (ESRs) and a supervisory board. There are both single discipline ESRs (astronomy) and interdisciplinary ESRS (astronomy + social sciences). The single-discipline ESRs are using models and simulations to learn more about exoplanets and protoplanetary disks. The interdisciplinary ESRs are exploring the intersections that scientific topics from the network have with both the arts and education.

WINTERSCHOOL II

The CHAMELEON network holds bi-annual network schools. The second CHAMELEON school was held in January of 2022 and focused on putting the research that the network is conducting into the context of the big science questions of our time. For this, discussions were had about the science questions that are driving instrument development and future observational facilities and the processes and difficulties that accompany these developments.

The final project of the school consisted of the development of proposals for future space missions that would answer some of the big science questions of our time. These proposed missions were pitched to a panel of supervisors who provided feedback and assessed the value, validity and innovativeness of the missions. To develop the missions the ESRs were divided into four teams, with the exception of the multidisciplinary ESRs who acted as consultants. The consultations included helping with presenting and pitching the ideas to a general audience and helping to determine what these missions could bring to the scientific community and society as a whole.

PROJECTS

PINEAPPLES ALONE PlaDiPro SLOTH

Solar Lens for Observing Terrestrial Habitats

Imaging the surface of an exoplanet: how can we prove extraterrestrial life beyond any reasonable doubt?

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Introduction

The SLOTH mission (Solar Lens for Observing Terrestrial Habitats) will use the sun as a gravitational lens in order to get clear images of the surface of exoplanets at a resolution unmatched by any other method, bar traveling to the planet itself!

SLOTH will make use of the sun's gravitational pull to bend rays of light coming from an exoplanet behind the sun in such a way that they will focus onto a telescope that will be orbiting 550 AU* from the sun. This light can be deconvoluted in order to reconstruct an image of the surface of the exoplanet.

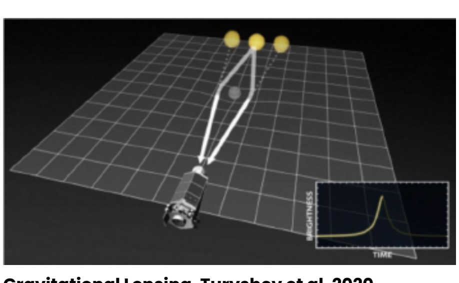
**AU = Astronomical unit = the mean distance from the centre of the earth to the centre of the sun = 149.6 million kilometres*

Scientific Background

Gravitational Lensing

When an astronomical object (for example a star) is massive enough, it will have a strong enough gravitational pull to bend rays of light to a significant, measurable degree. This can be used to our advantage through a technique known as gravitational lensing. Imagine that there is a telescope pointing towards a large amount of matter (henceforth referred to as the lens), this matter could be anything from an individual star to a cluster of galaxies. Now imagine there is another object of interest (henceforth referred to as the target) some distance behind the lens, this could be a star, a galaxy or even an exoplanet. The light from the target travels out in all directions, and some of this light will travel close enough to the lens to be affected by its gravitational pull. The lens will bend light from the target towards it, therefore re-directing light towards the line of sight of the observer. This means that we get more light from the target than we would if it was being observed directly.

The light that is collected from the target will arrive at the observer as a ring of light, called an Einstein ring. This ring contains the light that has been collected from the target, but not necessarily in the right place. Each pixel in the image contains some contributions of light from other pixels, so deconvolution is required to reconstruct the image and get a clear picture of the target.



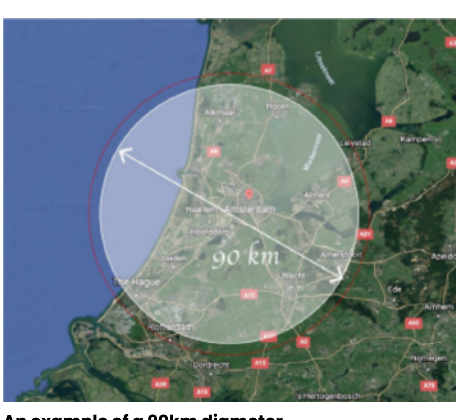
Gravitational Lensing, Turyshev et al. 2020

The grey object in the centre of the image acts as a gravitational lens. The gravitational force of the lens distorts the path of the light from the object behind it thus amplifying the signal from it.

SLOTH

Goals

When it comes to the detection of life on other planets, there is a large potential for false positives. There are many different types of potential signs of life (biosignatures) on planets, for example: gasses, chemical disequilibria, surface features and temperature variations. However, many of what we may believe to be signs of life may actually be due to some other effect or feature on the planet. SLOTH (Solar Lens for Observing Terrestrial Habitats) aims to tackle this by sending a telescope out to 550 AU away from the sun, and using it to observe a planet that is already suspected to have life. The resultant high resolution image of the surface of the planet can be used to determine what features or effects are really causing the biosignatures that were found on this planet. These images of exoplanets will also help us to look at things like weather and clouds on the planet, and other features on the planet such as geographical features or possible vegetation



An example of a 90km diameter

Using existing telescopes, this figure shows the size of telescope that would be needed to fit an earth-like exoplanet that is 30 parsec (~98 light-years) away into just one pixel of a detector. This would be both expensive and difficult to build.

Why use gravitational lensing?

In order to fit an Earth-like planet 30 parsecs (~98 light-years) away into just one pixel on a telescope detector, you would need a telescope with a 90 km wide aperture. This would be incredibly difficult and expensive to build, and even then you would end up with no detail in the image of the planet, as all of the light from it is just in one pixel. Another option to observe exoplanets would be to use interferometry (a big grid of telescopes all working together), but even with this method we would need the telescopes to cover a distance of 9,000 km, and it would take about one hundred million years to integrate the data enough to achieve a reasonable signal-to-noise ratio.

If we use gravitational lensing, the signal from the planet can be amplified by approximately 11 orders of magnitude! With an integration and deconvolution time of the order of a few months, an image of an exoplanet 98 light years away could be constructed that could resolve features down to 90km in size.

Created using Pixel Planet Generator

Visualisation of a 100 x 100 pixel planet

With a 1m telescope positioned 650 AU from the sun (acting as a gravitational lens), it would take only a year to resolve a 100 x 100 pixel image of an exoplanet 30 parsecs away with a signal to noise ratio of ~7 (based on the work of Turyshev et al. (2020))

The SLOTH Telescope

Gravitational lenses do not have a single focal point like a magnifying glass does, instead they have a focal line. For the sun, the focal line begins at about 550 AU, and amplification increases with distance along this line. For this reason, the SLOTH telescope will travel out to 550 AU away from the sun. SLOTH will use a coronagraph to block interfering light from the solar corona. SLOTH is a follow-up mission, therefore it is expected that it will not be launched within the near future as there must be convincing and verifiable reason to believe that the planet that will be studied may have signs of life. Due to this, the propulsion methods of SLOTH will rely on advances in propulsion theory and technology that will come about in the near future, for example ion thrusters. SLOTH will also use slingshot maneuvers to aid its travel, meaning it will use gravitational assistance from bodies in the solar system. Due to the long travel time and high cost of SLOTH, it will also have some secondary purposes. The spacecraft can be used to investigate and image the outer solar system, and to measure the parallax of stars.

SLOTH will make use of both direct imaging and spectroscopy to analyse the target exoplanet(s). SLOTH will have a 2 meter optical telescope on board, along with a spectrograph covering the 150-2000 nm range and an MKID detector. This will allow for colour images with no read noise and no dark current. The multi pixel images obtained from the observations can also be used for spectroscopy, allowing us to get detailed maps of the chemical compositions of different parts of the planet. Spatially resolved spectroscopy can help to confirm biogenic features on the planet.

Target

SLOTH is a follow-up mission, so the targets are dependent on which suitable exoplanet(s) are the most promising for life at the time that the technology available to make the telescope is viable. That being said, there are already a few promising targets, the current primary target for SLOTH is Proxima Centauri b. This is the closest terrestrial exoplanet to earth, and with an observation time of just 6 hours per image we could already achieve a resolution of 120 km per pixel. 10 days per image would result in 50 km per pixel, and if there was a very promising feature that needed observing, with an observation time of 2.4 years a resolution of just 12 km per pixel could be achieved.

The secondary target for SLOTH is the Trappist-1 System. The benefits of this target is that it is a nearby system with multiple planets that could be observed. However Trappist-1 is a transiting system (the planets' orbital plane is parallel to our line of sight), so there would be some times when each planet would not be observable as they would be hidden behind the star, or else too close to the star for the coronagraph to be able to separate the star and the planet.

Scienfitic & Societal Output

The SLOTH mission could have a significant scientific, technological and societal impact. There are many potential benefits of the SLOTH mission that would come to fruition even before the first data was received: the technological advances that would be necessary for this mission would have many uses both on earth and in other space missions. In addition, during SLOTHs travel out to its ultimate destination it could observe, and image the outer solar system in a way that has never been done before.

Atists illustration of a tidally locked exoplanet

Many of the possible targets for SLOTH would be tidally locked. This means that one face of the planet always faces the host star. For tidally locked planets factors such as the terrain, weather, atmosphere and chemistry will be very different on the day side and the night side. There will also be a strip around the centre of the planet that will be perpetually in twilight, it is possible that if there is life or vegetation on an exoplanet it could be within this strip of less extreme conditions.

Of course, the exoplanet observational data from SLOTH has potential to be even more impactful. Having spatially resolved spectroscopic maps of exoplanet surfaces would allow us to learn a lot about the features and processes on exoplanets, and learn more about their atmospheres and dynamics SLOTH would also allow us to see weather, clouds and surface features on the target planets. These detailed, colour images would allow us to learn more about exoplanet geography, geology, biology and more. For example, it could be that vegetation on earth is only green because of the strength and wavelengths of light emitted by the sun, so the data from SLOTH could help us to see if vegetation on other planets would be a different colour as a result of being irradiated by a different star.

In addition to the scientific significance of the data from SLOTH, there would also be a profound societal impact to receiving detailed, colour optical images of other worlds. The majority of images that the public see of exoplanets are either artists impressions or images of point-like sources, often in a wavelength range unfamiliar to the audience. By providing optical images of exoplanets, the public can immediately and accurately understand the significance and excitement behind the image. The data from SLOTH could help to spark the public's excitement and imagination, resulting in benefits for funding for space missions as well as an increase in public engagement in STEM.

"[There is a] high societal and scientific impact to have a visual image of a terrestrial exoplanet"

"Maps of exoplanets would be amazing"

"Clearly and convincingly presented"

The panel agreed that being able to obtain images of the surface of exoplanets would be a huge step both scientifically and societally, however a few points for originality were docked due to the fact that many of the underlying technical aspects of the mission are derived from a pre-existing concept. The potential of the mission is very exciting, and the proposal was presented clearly and convincingly, although a little risky as due to the nature of the mission, only one planetary system could be observed, so there would be a lot of pressure in selecting the correct target!

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