**LOGBOOK**

Put into method on february 10, 13, 14, 17, 21, 25

12 and 13 feb - made diagrams for Physics of solar sails

13, 14, 17 feb - explained diagrams for solar sail physics

10 feb - intro to physics equations

21, 25, 26 feb - velocity equations introd and explained

March 2nd - worked on electromagnetic waves and finished velocity equations

March 6th: created first 3D model of square solar sail

March 5-8th finished 1.3 of solar sails and started 1.4 (design and types)

March 10th - worked on feedback from sung

March 11th - made three 3D models (heliogyro, re done square model, and my own design, the hybrid which combines heliogyro and square)

* Added description to project

March 12th - worked on types (1.4)

March 13-15 - worked on SGLs (2.0 -2.1)

March 16-17 worked on SGLs (2.1-2.3) this is the physics and practical aspects of SGLS

March 18th - worked on acknowledgements, almost finished 2.3 -- plan is to finish project tomorrow and do citations and record on the 20th and 21st.

March 19th - I FINISHED ALL THE SECTIONS!!! I did some revisions and added an abstract. All I need to do is the conclusions, presentation video, and citation list. I hope to do all three of these tomorrow and Friday.

March 20th - I finished all sections, including the conclusion and analysis!! All I have left is my presentation video and citation list.

March 21st - This is the final day. I’ve gone through and added in text citations and the citation list, and recorded my 10-minute presentation.

# 

# Here are some edits/ suggestions for the SGL section. Your research is comprehensive \*\* VERY good!!!\*\* - Ms. Sung

### **2. Solar Gravitational Lensing (SGL)**

With a newfound understanding of solar sail design, physics, and benefits compared to other propulsion systems, we can begin to explore how to harness **Solar Gravitational Lensing (SGL)** to directly image exoplanets, using solar sails as an effective method of transport. **This section will cover the physics of SGL, its challenges (such as image distortions and restoration), observational methods, and the potential exoplanet targets for such a mission.** Using this knowledge, we will evaluate whether SGL, in combination with solar sails, is a viable technology capable of revolutionizing telescopy.

**Brief Information:**Solar Gravitational Lensing (SGL) is a powerful method to magnify light from distant objects, such as exoplanets, by using the Sun's gravity as a lens. **This technique has significant applications in astrophotography, particularly for directly imaging exoplanets with unprecedented resolution.** However, the distortions caused by gravitational lensing pose significant challenges.

According to Einstein's general theory of relativity, gravity warps spacetime, including the path of light. **This means that massive objects, like the Sun, can bend and focus light, similar to a refractive lens.** Gravitational lensing has been observed in distant galaxies, where galaxy clusters act as lenses for background galaxies.

### **Figure 2.1.1: Galaxy Cluster Gravitational Lensing Captured by Hubble**

**Source:** [HubbleSite](https://hubblesite.org/contents/articles/gravitational-lensing)*(Note: Ensure the figure is properly cited and labeled.)*

**Description:**The image features galaxy cluster Abell 370 (~4 billion light-years away) warping and distorting images of remote galaxies behind it, evident through the blue "arcs" of light. **Without gravitational lensing, the Hubble Space Telescope would not be able to detect these distant galaxies due to their faint light.** This phenomenon is also applicable in our solar system, where the Sun's gravity can act as a lens.

### 

### **2.1.1 The Sun as a Gravitational Lens**

In our solar system, only the Sun has sufficient mass (and gravity) to act as a gravitational lens. **However, to utilize the SGL, a mission must be placed at a minimum distance of ~550 AU (astronomical units), which is the focal line where light bent by the Sun converges.**

**Key Benefits of SGL:**

* **Brightness Amplification:** The SGL can amplify light by a factor of ~6,400, making it equivalent to an 80 km diameter telescope.
* **Angular Resolution:** The SGL achieves an angular resolution of ~10<sup>-9</sup> arcseconds, enabling detailed imaging of exoplanets up to ~100 light-years away.

**Physics of Light Bending:**The gravitational deflection angle of light can be calculated using the following equation:

θ = (4GM/c<sup>2</sup>)(1/r)

**Where:**

* θ (Theta) = deflection angle
* G = gravitational constant
* M = mass of the Sun
* c = speed of light
* r = impact parameter (distance of light rays from the Sun's center)

**Minimum Focal Distance Calculation:**The minimum distance to the SGL focus can be calculated using:

F = r<sup>2</sup>c<sup>2</sup>/4GM

**Where:**

* F = distance to the SGL focus
* r = impact parameter

For the Sun, this distance is approximately **550 AU**.

### **Figure 2.1.2: The Line of Focus Points on a Gravitational Lens**

**Source:** [NASA Technical Reports](https://ntrs.nasa.gov/api/citations/20180003479/downloads/20180003479.pdf)*(Note: Ensure the figure is properly cited and labeled.)*

**Description:**The diagram illustrates how light is bent by the Sun's gravity to converge at a focal point. **The focal line extends beyond 550 AU, with the exact focal distance depending on the object being imaged.**

### **2.1.2 Image Distortions and Restoration**

**Einstein Ring:**A telescope at the SGL focal line would observe the exoplanet as a distorted annulus, known as an Einstein ring. **To reconstruct the exoplanet's image, computational models and algorithms are required to reverse these distortions.**

**Magnification Factor Calculation:**The magnification factor can be calculated using:

Magnification Factor = Ao/Ai = 4r/a

**Where:**

* Ao = area of the annulus
* Ai = angular area of the source
* r = apparent radius of the Einstein ring
* a = angular diameter of the source

### **2.2 Benefits and Drawbacks**

**Benefits:**

* **Unprecedented Resolution:** SGL can produce exoplanet images with a resolution of 1000x1000 pixels, far surpassing current telescopes like JWST and ESO SPHERE.
* **Brightness Amplification:** The SGL can collect light equivalent to an 80 km diameter telescope.

**Drawbacks:**

* **Image Distortions:** The Einstein ring requires complex computational methods to reconstruct the exoplanet's image.
* **Spherical Aberration:** The Sun's gravity causes spherical aberration, leading to focal blur.
* **Solar Corona Effects:** The solar corona introduces additional blur due to its refractive properties.

### **2.3 Exoplanet Selection and Imaging Methods**

**Exoplanet Selection Criteria:**

* **Proximity:** Within 100 light-years for optimal resolution.
* **Habitability Potential:** Exoplanets with conditions suitable for life are preferred.
* **Stable Host Star:** The exoplanet's star should be stable and bright.

**Imaging Methods:**

* **Scanning:** The telescope could scan the Einstein ring to collect data for image reconstruction.
* **Swarm of Satellites:** Multiple small satellites could work together to capture the large image plane.

Additional Things to explain:

* Brief explanation Einstein Ring and spherical aberration ( esp to judges)-
* More images for light bending, einstein Ring, image reconstruction
* A hook for introducing SGL - explain its significance and how it can potentially revolutionize exoplanet imaging

# 

# 

# Methods

* Abdallah this already looks awesome.!!
* I added some changes on bold:

Some other content additions to consider.:

* Re-state why solar sails are the best mode of transportation at the end
* How will heat be managed (thermal management) on sail and payload
* I know you were going to revisit- but have a material science section explaining the properties of each material used.- reflectivity etc
* Implications: in Astronomy( images of far off exoplanets), economics( cheaper than fuel), environmental studies ( decrease space debris)
* At the end ( Challenges section) you can talk about the degradation of the solar sail via micrometeroids and radiation. How far solar sails can travel- when there is not enough solar radiation will lasers be used?
  + Conveniently, this isn’t much of a problem! Micrometeroids are spread out, and even if they do impact the solar sail, it’s like burning a hole in a piece of paper the size of a house, maybe larger. The efficiency impacts are negligible. \*\* Perfect!! Add that in the section to show that you were thinking about this

### **1.2 Broad History and Review**

**Solar sails represent a revolutionary advancement in space propulsion, offering a fuel-free and efficient method for long-term space exploration.** While traditional propulsion systems, such as chemical and ion thrusters, have dominated space travel for decades, solar sails have emerged as a promising alternative for missions requiring sustained acceleration over vast distances. **To appreciate their potential in Solar Gravitational Lens (SGL) missions, it is essential to explore their historical development and technological evolution.**

**The concept of solar sailing dates back nearly 400 years to the work of Johannes Kepler, the astronomer who formulated the laws of planetary motion.** Observing comets, Kepler noticed that their tails always point away from the Sun, leading him to hypothesize the existence of a "solar breeze" that could propel spacecraft. **Although his idea of harnessing solar winds was later refined, Kepler's insight laid the foundation for the modern understanding of solar sails.** Today, we know that solar sails rely not on solar winds but on the pressure exerted by photons from sunlight.

**In the 1860s, James Clerk Maxwell's groundbreaking work on electromagnetism provided the scientific basis for solar sailing.** Maxwell demonstrated that light exerts pressure on physical objects, transforming solar sailing from a speculative idea into a scientifically plausible concept. **The first practical demonstration of this principle occurred in 1962, when NASA engineers used solar pressure to reorient the Mariner 1 spacecraft after a navigation error.** By adjusting the spacecraft's solar panels and antennae, they successfully corrected its course, proving that solar pressure could be harnessed for propulsion.

**A more deliberate test of solar sailing occurred in 1964 with NASA's Echo II satellite.** This 41-meter inflatable spacecraft, placed in a near-polar orbit, was designed to minimize solar pressure torque, allowing scientists to directly observe the effects of solar thrust on its orbit. **The data gathered from Echo II advanced NASA's understanding of solar sailing and paved the way for future developments.**

**The first true solar sail spacecraft, IKAROS (Interplanetary Kite-craft Accelerated by Radiation of the Sun), was launched by the Japan Aerospace Exploration Agency (JAXA) in 2010.** IKAROS successfully demonstrated solar sailing as a primary propulsion method, navigating past Venus using only photon pressure. **More recently, NASA's Advanced Composite Solar Sail System (ACS3), launched on April 23, 2024, tested innovative boom arm technology for optimal sail deployment, marking another milestone in solar sail development.**

**From its theoretical origins to practical applications, solar sailing has evolved into a viable propulsion technology.** Its fuel-free nature and efficiency make it an ideal candidate for deep-space missions, including those to the SGL. **By harnessing the constant acceleration provided by sunlight, solar sails could enable humanity to explore the farthest reaches of our solar system and beyond.**

### **1.3 Propulsion and Physics of a Solar Sail**

**To understand how solar sails can benefit SGL missions, it is crucial to examine the physics behind their propulsion.** Unlike traditional rockets, which rely on finite fuel supplies, solar sails generate thrust by harnessing the momentum of photons. **This allows them to accelerate indefinitely, provided they remain within a light source's influence.**

**Solar sails operate on the principle of photon momentum transfer.** When photons from sunlight strike the sail's reflective surface, they impart momentum, creating a reaction force that propels the spacecraft. **Although photons have no mass, their high velocity enables them to carry momentum, as described by the equation:**

-----enter equation break down---

**For a reflective surface, the momentum transfer is enhanced.** If the sail has a reflectivity coefficient

K

*K*, the equation becomes:

P=(1+K)Ec

*P*=

*c*

(1+*K*)*E*

​

**For example, a sail with a reflectivity of 0.89 transfers 1.89 times more momentum than a perfectly absorbent surface.** This increased efficiency allows solar sails to achieve significant acceleration over time.

**The force generated by a solar sail can be calculated using the equation:**

**Over time, this continuous force results in exponential velocity gains.** For instance, a solar sail with a reflectivity of 0.89 and an area of 15,376 m² (equivalent to the Sunjammer design) could reach velocities of up to 1,000 m/s in approximately 63 hours, assuming a constant solar intensity.

**However, solar sails face limitations.** As the distance from the Sun increases, solar intensity decreases, reducing the sail's acceleration. **Additionally, interstellar particles and micrometeoroids can degrade the sail's surface over time.** Despite these challenges, solar sails remain superior to traditional propulsion methods for deep-space missions due to their unlimited fuel supply and potential to reach speeds of up to 10% the speed of light.

### **1.4 Types of Solar Sails**

**Solar sails come in three primary designs, each with unique advantages and challenges.** This project focuses on the square solar sail due to its simplicity, effectiveness, and proven track record.

1. **Square Sail:**
   * **Design:** Three-axis stabilized, supported by extendable boom arms that deploy four triangular masks into a large, square shape.
   * **Advantages:** Maximizes surface area for photon capture, provides thermal protection, and minimizes hot spots.
   * **Disadvantages:** Heavier due to boom arms.
2. **Heliogyro Sail:**
   * **Design:** Spin-stabilized, with multiple blades deployed using centrifugal force.
   * **Advantages:** Lightweight and maneuverable, with adjustable blade pitch for steering.
   * **Disadvantages:** Smaller surface area and reliance on continuous rotation.
3. **Spinning Disk Sail:**
   * **Design:** Rotating disk with thin tethers and small gaps to maximize surface area.
   * **Advantages:** Combines large surface area with lightweight construction.
   * **Disadvantages:** Requires constant rotation and has not been tested in space.

**The square sail's balance of efficiency, durability, and simplicity makes it the most suitable design for SGL missions.** Its ability to generate high thrust while protecting the payload from solar radiation ensures its viability for long-duration space travel.

### **Conclusion\*\*\*\***

**Solar sails represent a transformative technology for space exploration, offering a sustainable and efficient alternative to traditional propulsion methods.** From their theoretical origins to practical applications, they have demonstrated their potential to revolutionize deep-space missions, including those to the Solar Gravitational Lens. **By harnessing the power of sunlight, solar sails could enable humanity to explore the farthest reaches of our solar system and unlock new frontiers in astronomy and science.**

# Abdallah Baloch - [abdallahb2@educbe.ca](mailto:abdallahb2@educbe.ca)

# ***~ Pre***-***Research (Links to Look into) ~***

## Satellite Collision Avoidance: Potential Idea (scrapped) November 14-20

[*https://thewaterbear.com/obstacle-avoidance-a-i/*](https://thewaterbear.com/obstacle-avoidance-a-i/)

* AI obstacle avoidance

[*https://www.sciencedirect.com/science/article/pii/S0094576522000364*](https://www.sciencedirect.com/science/article/pii/S0094576522000364)

* AI in satellites

[*https://www.sciencedirect.com/science/article/pii/S0376042123000763*](https://www.sciencedirect.com/science/article/pii/S0376042123000763)

* More AI in satellites

[*https://www.esa.int/Space\_Safety/Space\_Debris/Automating\_collision\_avoidance*](https://www.esa.int/Space_Safety/Space_Debris/Automating_collision_avoidance)

* Automating collision tech

[*https://www.hou.usra.edu/meetings/orbitaldebris2023/pdf/6043.pdf*](https://www.hou.usra.edu/meetings/orbitaldebris2023/pdf/6043.pdf)

* AI in satellite collision avoidance

## Solar Sails in Gravitational Lensing: (Brainstorming) and Link Compiling - Worked on throughout November 14-20 2024

[*https://ntrs.nasa.gov/api/citations/20180003479/downloads/20180003479.pdf*](https://ntrs.nasa.gov/api/citations/20180003479/downloads/20180003479.pdf)

* Solar Gravitational Lens explained: Problems, Solutions.\*\*

[*https://ntrs.nasa.gov/api/citations/20180002197/downloads/20180002197.pdf*](https://ntrs.nasa.gov/api/citations/20180002197/downloads/20180002197.pdf)

* Solar Gravitational Lens Mission: Problems, Solutions.

[*https://www.planetary.org/articles/what-is-solar-sailing*](https://www.planetary.org/articles/what-is-solar-sailing)

* Solar Sails - How do they work?

[*https://ntrs.nasa.gov/api/citations/20200002438/downloads/20200002438.pdf*](https://ntrs.nasa.gov/api/citations/20200002438/downloads/20200002438.pdf)

* Advances in Low-Cost Manufacturing and Folding of Solar Sail Membranes

[*https://ntrs.nasa.gov/api/citations/20130014932/downloads/20130014932.pdf*](https://ntrs.nasa.gov/api/citations/20130014932/downloads/20130014932.pdf)

* Selection and Manufacturing of Membrane Materials for Solar Sails

[*https://ntrs.nasa.gov/api/citations/20030093608/downloads/20030093608.pdf*](https://ntrs.nasa.gov/api/citations/20030093608/downloads/20030093608.pdf)

* THE PHYSICS OF SOLAR SAILS

<https://link.springer.com/article/10.12942/lrr-1998-12>

* Gravitational Lensing in Astronomy

[*https://en.wikipedia.org/wiki/Gravitational\_lens*](https://en.wikipedia.org/wiki/Gravitational_lens)

* Wikipedia. (look into for understanding, but not a source for research or any tangible data)

<https://ntrs.nasa.gov/api/citations/20120015076/downloads/20120015076.pdf>

* Solar sail propulsion (and history)

<https://www.elprocus.com/solar-sail/?form=MG0AV3>

* Types of solar sails

<https://phys.org/news/2022-10-solar-gravitational-lens-humanity-powerful.html>

* Best targets of an SGL\*\*

<https://www.mie.utoronto.ca/wp-content/uploads/2023/09/Quaternion-Based-Attitude-Control-of-a-Solar-Sail.pdf>

* Quaternion-Based Attitude Control of a Solar Sail Using a Gimballed Mass and Tip Vanes

***Advanced Scholarly Resources: (Found November 20)***

[*https://academic.oup.com/mnras/article/515/4/6122/6652111*](https://academic.oup.com/mnras/article/515/4/6122/6652111)

* Resolved imaging of exoplanets with the solar gravitational lens

[*https://bis-space.com/membership/jbis/2018/JBIS-v71-no10-October-2018-5fpe41.pdf#page=15*](https://bis-space.com/membership/jbis/2018/JBIS-v71-no10-October-2018-5fpe41.pdf#page=15)

* Similar resource to first two; more legible

[*https://arc.aiaa.org/doi/full/10.2514/1.A35493*](https://arc.aiaa.org/doi/full/10.2514/1.A35493)

* Mission Architecture to Reach and Operate at the Focal Region of the Solar Gravitational Lens

# ~ Checklists (Possible Projects) ~

## Satellite Collision Avoidance: (scrapped Idea (november 14-20)

* Look into ai collision avoidance (in cars, maybe satellites, etc)
* Look into satellite anatomy
* Understand the data points that need to be measured for ai to learn collision avoidance
* Look at the difference between human-altered satellite paths vs ai altered satellite paths
* Code. (python/MATLAB satellite sim)
  + This simulation should be able to show ai corrections real-time and should be manipulatable, allowing judges to see effects real-time. The avoidance system should aim to move in advance, before encountering threatening objects.
    - Innovate?
* Use AI to locate and analyze dark matter?
* Research space debris:
  + What parts of a satellite are the most weak?
  + How many collisions per year?
  + How much space debris is there? What size (micro debris)?
  + What types of space debris has the biggest threat?
* Study the characteristics of LEO, MEO, HEO
* Collaborate with aerospace engineers, maybe astrophysicists, computer scientists, and AI designers (UfC)?
  + (Hopefully) Collaborate with space corporations/organizations such as NASA, (private companies): SpaceX, Boeing, Blue Point, Lockheed Martin.
    - More probable: CSA, ESA, etc.

## Solar Sails in Gravitational Lensing: (final idea, created november 14-20)

Exploring the Production of Solar Sails And Their Applications in an SGL (Solar Gravitational Lens):

* ~~Look into Solar Sail Physics - How they work~~
* Look into gravity assists to help trajectory and velocity\*\*\* - (idea feb 17th)
* ~~Look into history of solar sails~~
* ~~Broad history and review of telescopy and types of telescopes (refracting, etc) which one will benefit this mission/be used.~~
  + ~~Connect to SGLs, talk about a brief overview of SGLs and einstein rings.~~
  + ~~Note/idea - Feb 9th: talk about previous attempts to image other solar systems, their limitations ,na show an SGL will improve it, and talk about why previous methods done before are very hard to do?~~
* ~~Look Into the Japanese Aerospace Exploration Agency (JAXA) and their IKAROS spacecraft?~~
* ~~Understand the production of solar sails~~
  + Materials
  + ~~Dimensions?~~
  + ~~Components~~
* ~~Understand parameters for an effective solar sail~~
  + ~~Type of solar sails - what makes them effective? (Surface area, reflectivity, etc)~~
* ~~Create a rough outline of a mission for a solar gravitational lens~~ 
  + ~~Array of sails~~
  + ~~Distance of sails~~
  + ~~Ideal focal point~~
* ~~Look into physics of an SGL~~
  + ~~How does it work?~~
  + ~~Look into focal points, diagrams on how it refracts light.~~
  + ~~How much does an SGL magnify?~~ 
    - ~~Look into resolution~~
  + ~~Look into light collecting/observing technology for the SGL (essentially the camera)~~
    - ~~How will it block out the sun’s light?~~
* ~~What exoplanet are we imaging?~~
  + ~~Look into exoplanets nearby and have high chances of habitability~~
  + ~~Look into parameters of a solar sail (distances able to travel to reach focal points) - What exoplanets are plausible/are we able to image?~~
    - ~~What time of year?~~
* ~~Collaborate with aerospace engineers, maybe astrophysicists, and people experienced in solar sails (UfC)?~~
  + ~~(Hopefully) Collaborate with space corporations/organizations such as NASA, The Planetary Society, or private companies; SpaceX, Boeing, Blue Point, and Lockheed Martin.~~
    - ~~More probable: CSA, ESA(?), the Planetary Society, etc.~~
* ~~Design a prototype solar sail(?)~~
  + ~~3D print?~~
  + /\* depending on design this is totally do-able (overall appearance looks simplistic ( basic flattened square based pyramid) We have access to 3d printer (As robotics teacher as well) \*/ - Ms. Sung
  + WOOHOO!!
* ~~Explain how Einstein rings work/what they are~~
  + ~~How do we recover the distorted image through an Einstein ring?~~
    - ~~Talk about how an image is warped~~
      * ~~What parts of the image are stretched and seen in the ring? (Potential graphs/diagrams?)~~
* ~~How long will the mission take?~~
* ~~Possible challenges? Solutions? (INNOVATE!)~~
  + Ai Applications? - no

***Problem (Draft): Worked on December 8th 2025***

Throughout the history of imaging technology, we have seen repeated breakthroughs in imaging technology with the ultimate goal of capturing an image of another world, or, an exoplanet. Advancements in telescopy have created large jumps in our ability to understand and perceive the world. This project will aim to bridge the gap that exists between our current telescoping technology and our ultimate goal; resolution and magnification. By creating unique applications and approaches to imaging technology, we can bend the sun’s gravitational field to act as a lens. Through this, we can *directly* image an exoplanet with resolutions that allow us to discern features and characteristics accurately. This problem will be addressed through two key elements. First, the production, design, and propulsion of a solar sail. By understanding the processes of a solar sail and their applications in long-term travel, we can use their benefits to construct a telescope capable of taking advantage of a solar gravitational lens (SGL). In order to accurately design a telescope capable of this, we must understand the physics and properties of solar gravitational lensing and einstein rings. By understanding these phenomena, we can accurately design a telescope tailored to combat image distortions and challenges created by them.

***Problem 2.0: Worked on January 20-22 2025***

***Links used (need to cite in text):***

[**https://jwst.arizona.edu/mission#:~:text=It%20will%20study%20every%20phase,of%20our%20own%20Solar%20System**](https://jwst.arizona.edu/mission#:~:text=It%20will%20study%20every%20phase,of%20our%20own%20Solar%20System)

[**https://ntrs.nasa.gov/api/citations/20180003479/downloads/20180003479.pdf**](https://ntrs.nasa.gov/api/citations/20180003479/downloads/20180003479.pdf)

The James-Webb Space Telescope (JWST) is considered by many to be the largest, most powerful telescope to be launched into space, providing insights into every phase in the history of our universe, including the start of the big bang, formation of bodies capable of supporting life, and evolution of our own solar system. However, a significant recurring challenge we encounter with every telescope to date is magnification and resolution; limiting our ability to directly image exoplanets. Current telescopes have a limit in their capacity to image objects far away. The farther away an object we attempt to image is, the blurrier our images become. In order to appetize our imaging needs, we need telescopes exponentially larger than ever before. That reality is becoming more and more implausible as our innovations in telescopy start to slow down. This setback has hindered our ability to deepen and confirm our understanding of celestial bodies outside our solar system, preventing us from taking the next major leap in space sciences. A potential solution to evolve our technology and create the next breakthrough in telescopy is the use of the sun as a solar gravitational lens (otherwise known as an SGL). We can combine our technologies with the immense gravitational powers of the Sun to essentially create a telescope with a lens far larger than ever conceived, capable of magnifying images greater than current capabilities. The benefits this implies are numerous, including the potential to visibly confirm and map out the geography of an exoplanet . Furthermore, an SGL has the possibility to identify liquid water or macroscopic life on an exoplanet: Such a discovery would no doubt inspire future interstellar missions and pave the way for a future in space travel, research, and documentation.

Despite the undeniable benefits, the intricacies of such a mission of this magnitude poses challenges that are particularly interesting, as they allow for applications of other technologies. There are concerns about transporting the instruments required to a magnification point capable of using the sun as a lens. The minimum distance required is 550 AU, an incredibly far distance, surpassing the orbit of Pluto. The propulsion demands for such distances can be circumvented through the use of solar sails. The application of solar sails in a potential mission to the focal point of an SGL is an effective way to address transportation complications. Solar sails require extremely low amounts of energy compared to standard rocket fuel or ion thrusters, by propelling themselves through solar radiation, making them clear candidates for transportation in a potential mission. Paired with an array of solar sails, we can create a telescope capable of capturing the numerous rays bent by the sun. This approach is unique compared to others, efficient in energy consumption, providing a plausible way to propel a spacecraft 550+ AU, and simultaneously keeping adequate photon absorption capabilities. 3D printing a potential prototype for such a solar sail will allow us to demonstrate the scalability of such a propulsion system. Moreover, distortions (Einstein rings) created by the magnification of an SGL are an additional concern, requiring complex computer software and mathematical algorithms to reverse. Further challenges that would need to be addressed include managing communication delays and maintaining power at such extensive distances. Nonetheless, the abilities of an SGL are countless, expanding our current imaging capabilities beyond what is known.

**\*\*3.0 on platform**

# ~Research (Compiling Information)~

<https://samueli.ucla.edu/reinventing-solar-sail-technology-to-push-space-exploration-boundaries/>

Presentation/Project image^

## Research Entry: The Physics behind Solar Sails (How they work, what they are made of, etc) - Started Work on January 23

Part of checklist I will be working on:

* Look into Solar Sail Physics - How they work
* Understand the production of solar sails

Research With Link Used: <http://ffden-2.phys.uaf.edu/webproj/212_spring_2015/Robert_Miller/index.html>

Citation for BioRender Diagrams: Created in [https://BioRender.com](https://biorender.com)

* Solar sails use photons to propel themselves.
  + This is done through harnessing the momentum of a photon with an extremely light ‘sail’, consisting of a thin, reflective material.
    - The photons that hit the reflective surface bounce off. According to Newton's 3rd law, for every action there is an equal and opposite reaction, meaning the solar sail will also start moving in the opposite direction the photons bounce off from.
    - Photons absorbed end up being re-emitted as thermal energy through the emissivity layer. This has a negative effect on the solar sail, slowing it down.
* Solar sails can essentially move ‘forever’ but require a light source. They heavily rely on light as fuel, and the less intense a light source is, the less acceleration a solar sail gains.
  + Solar sails can move without light, but eventually they will slow down due to atmospheric interference (space is not 100% vacuum, solar sails will encounter interference with dust and other particles)
  + For example, Jupiter has about 1/24th of the light intensity of Earth. A solar sail starting at Jupiter would have to be 24x larger to produce the same amount of acceleration.
  + However, solar powered spacecraft are usually faster than regular rocket fuelled spacecraft because they have constant light pressure creating constant acceleration, propelling the spacecraft forward.
* The maximum speed of a solar sail is 10% the speed of light, equating to roughly 18,600 miles per second (29933.798 kilometers per second)
* Two diagrams in the link mentioned above (note to self, refer to these diagrams when writing the project, create your own version of diagram?)
* How the force and momentum works:
  + Initial Momentum: This is the momentum of the photon from the light source. This is the momentum that applies force onto the sail.
  + Reaction Momentum: when the initial momentum reacts with the light sail, reaction momentum is created. This momentum is always *perpendicular* to the solar sail’s surface (see graphs in link - physics tab - specifically case 2)
  + Reaction Force: This is the ‘negative’ reaction force that slows down the solar sail slightly. This is due to the thermal energy from the solar sail being heated up. The emissivity layer emits heat, creating a negative force against the trajectory of the solar sail.
* Parts of a solar sail / definitions:
  + The Solar Sail:
    - Main part that is responsible for propulsion. Holds the reflection and emissivity layers.
  + Reflection Layer:
    - This layer faces the sun or incoming light source. This layer is made up of a highly reflective material, allowing it to reflect incoming protons. However, because our current materials cannot have a perfect reflective value of 1.0, the reflective layer also absorbs some heat.
  + Emissivity Layer:
    - Responsible for emitting the thermal energy absorbed by the reflection layer. Has a small negative impact on the velocity because it faces away from the light source, but is crucial to get rid of heat.
  + Reflectivity Scale:
    - This scale characterizes the properties of different materials and their reflectivity. Perfectly reflective materials (impossible) have a reflectivity rating of 1.0. Perfectly absorbent materials (also impossible) have a reflectivity of 0. See the scale in the physics tab of the above link. Solar sails fit within the 0.88-0.90 range of the reflectivity scale.
* Momentum of light particles:
  + The momentum of a 0.0 reflectivity surface can be calculated through the equation p = e/c (p = photon, e = energy of photon, and c = speed of light in a vacuum). A surface that absorbs a photon perfectly would only take the momentum of the photon hitting into the surface.
  + The momentum of a 1.0 reflectivity surface can be calculated through the equation p = 2e/c. A surface that reflects a photon perfectly would double the momentum of the photon (once for impact, second, for reflecting it back), this is why the equation has 2e compared to just e with the 0.0 reflectivity surface.
    - Using this information, and knowing that solar sails fit within the 0.88-0.90 range of the reflectivity scale, we can conclude that the equation for momentum for a light particle on a solar sail would be roughly p = 1.89e/c (1.89 because the average of 1.88 and 1.90 is 1.89).
* Velocity/Time graph to reference and use at bottom of physics tab in the above link.
  + try to understand the velocity and force equation so to create a velocity time graph showing the increase in distance travelled one time (can be used to calculate amount of years needed to transport solar sails)
* IDEA: research the three main types of solar sails and create 3D printed models for each, highlighting which one is most effective and would theoretically be used.
  + Go into material selection/processing
  + Highlight the key parts that go into the production of a solar sail, their dimensions, materials, and how they work -- need to be understood in order to create an accurate 3D model.
* Ask Mr Hornick about momentum, force, and velocity equations. (done)!
* Solar Sail Types:
* There are three main types of solar sails; the heliogyro sail, spinning disk sail, and the most common of the three, the square sail.
  + The heliogyro sail was developed by JPL in the 1970s. It uses four blades and has a stronger structure than the square sail. By using angular momentum, it can eliminate the need for supports and struts, as the blades spin keeping them extended. Blades are controlled similar to a helicopter, and change the pitch and cycle to maneuver.
  + Spinning disk sails, also developed by JPL, have small gaps in between their sail masks, and the sail takes on a circle-shape. As the name suggests. As the name suggests, these sails spin like the heliogyro sail.
  + Square Sails are the most common type of sail due to their simple design and high surface area, which allows them to generate higher forces than others. These sails have four triangle shaped ‘masks,’ making up a square shape, supported by beams. The sails are deployed in space. A large advantage of these sails is that their sails prevent hotspots from occurring as they shield the rest of the spacecraft from incoming solar radiation.
  + <http://wiki.solarsails.info/index.php/Circular_Sail>
  + This link was also used in the method for types of solar sail (march 8th)

January 28th notes

* Send ms sung the sources about materials, send the solar sail research research over and formulas for photon momentum/ force

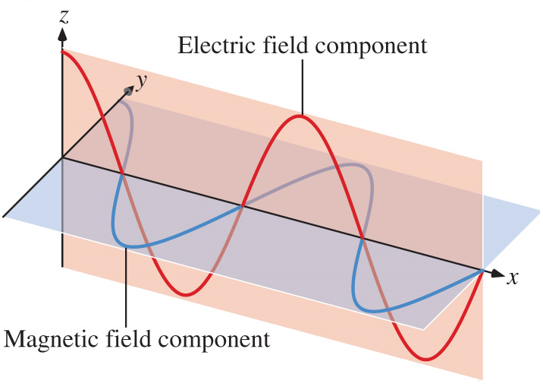
February 4th notes

* Start explaining velocity equations, now that mr hornick explained it; start research on solar sail history

February 12th notes:

* Finished editing problem and 1.2 of method per ms sung’s feedback.
* Electric field component and Magnetic field component:

<https://general.chemistry.msstate.edu/books/chem1/electromagnetic-radiation.html>



## Research Entry: The History of Solar Sails - Worked on February 4th

Put into method february 6 - 8

Part of checklist I will be working on:

* Look into history of solar sails

Research With Links Used:

1. <https://phys.org/news/2008-08-history-solar.html>
2. <https://ntrs.nasa.gov/api/citations/20120015076/downloads/20120015076.pdf>

* The history of solar sails:
* Solar sails are not a new idea. They can be traced all the way back to Johannes Kepler almost 400 years ago. He saw the tail of a comet and used this observation to come to the conclusion that there must be some sort of “solar breeze,” that blows onto the comet. He theorized that if we were to travel through space, ourspacecraft should be fashioned with sails capable of harnessing the “solar breeze,” in order to glide through space. However, it isn’t the power of solar winds that can be used to travel through space, rather the light of the sun itself. (1)

Using source (2)

* The first evident proof for solar sails being a possibility was found by James Clerk Maxwell, who developed the modern theory of electromagnetism in the 1860s. This proved that light can exert pressure.
* Fridrickh Tsander from Russia took the theory of solar sails further. In 1924, he wrote “For flight in interplanetary space I am working on the idea of flying, using tremendous mirrors of very thin sheets, capable of achieving favorable results.”
* Up until 1962, solar sails were still a very theoretical thing. NASA put these theories to the test with the Echo II and Mariner 10.
* The Mariner 10 (1962), was the beginning of solar sails. Solar sails were initially tested in a makeshift way in the Mariner 10 as a measure to save it after losing large amounts of propellant. They used solar winds to try and change the attitude of the probe, successfully saving it. This proved that solar sails were mature technology that could be advanced.
* The Echo II (1964) was a large, inflatable balloon sphere-shaped satellite that was 135ft (41.148m) wide in diameter. It was made out of laminated Mylar plastic and aluminum and placed in near-polar orbit (orbiting around the poles instead of equator, essentially vertically in relation to the equator). This satellite was used to test the effects of solar thrust on spacecraft orbit. Spheres have no solar pressure torques, making them easy to use for direct observations of the sun’s light on thrust.
* In 2010, JAXA (The Japan Aerospace Exploration Agency) launched the first “true” solar sail on a mission past Venus, proving the technology has value.

<https://www.nasa.gov/smallspacecraft/what-is-acs3/>

* NASA launched the Advanced Composite Solar Sail System on April 23 2024, with the mission to test boom arm technology in order to boom arm technology for optimal solar sail deployment.

## Research Entry: SGL General Information, Potential targets for an SGL(?), Refracting vs reflecting telescopes/Physics of SGLs - Worked on February 5th -

Part of Checklist I Will be working on:

* What exoplanet are we imaging?
* Broad history and review of telescopy and types of telescopes (refracting, etc) which one will benefit this mission/be used.
  + Connect to SGLs, talk about a brief overview of SGLs and einstein rings.

Research With Links Used:

Potential Links:

<https://phys.org/news/2022-10-solar-gravitational-lens-humanity-powerful.html>

* Look into this link\*\*

<https://www.centauri-dreams.org/2023/02/08/a-mission-architecture-for-the-solar-gravity-lens/>

Used Links:

## Research Entry: The Production of Solar Sails (Material selection, parts of a square solar sail) - Worked on

Part of Checklist I Will be working on:

* Understand the production of solar sails
  + Materials
  + Dimensions
  + Components

Research With Links Used: