Introducing the telescope

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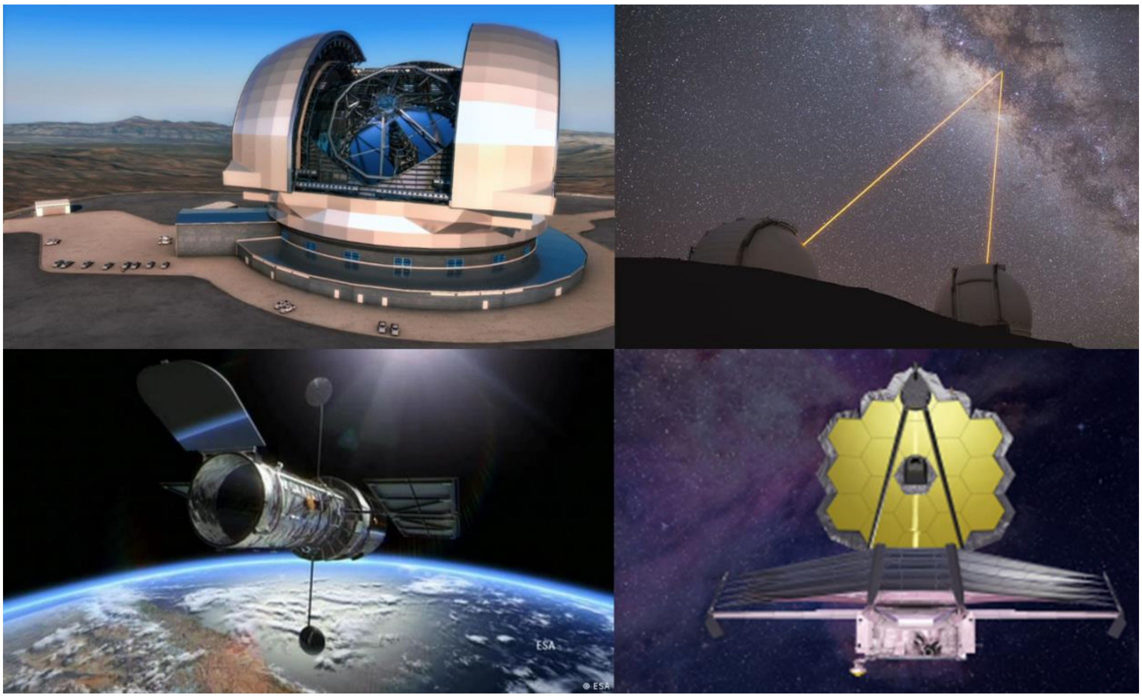


Metadata

General information

Title: Introducing the telescope

Short description: Students learn about the principle of operation of the telescope. Through a series of puzzles, they investigate fundamental optics behind the instrument using interactive apps and obtain a deeper understanding of it. We start with an introduction to modern observatories and then proceed to create a simple model of a telescope. Then we investigate: magnification, upside down images, focusing, the impact of the Earth's rotation and telescope light gathering power.

Keywords: Telescope, Lens, Optics, Ray, Observation, Magnification, Focus

Educational Context

Connection to the Greek Curricula:
Physics 3rd grade of Junior High school: Converging and Diverging lenses.
Physics (General Education) 2nd grade of senior High school: Light

Age: 14-16

Prerequired: Understanding how lenses work and what ray tracing is.

Duration: 4-13 school hours
(Within 4 hrs it is expected that 1 challenge can be fully iterated. Every extra challenge is expected to add 100 minutes in the implementation procedure. If the teacher has access to a telescope and decides to demonstrate the key points of the activity instead of having students investigate them, the full activity can be implemented in 4 hrs).

Educational objectives

Cognitive

- To understand the principle of operation of a telescope.
- To identify the key components of a telescope.
- To realize the role of the key components of a telescope to the observation procedure.
- To understand key observational challenges encountered when we use a telescope.

Affective

- To notice how a simple instrument can open a new window to the Universe.
- To be able to communicate their interest in aspects of Astronomy

Psychomotor

- To be able to follow instructions in order to investigate the use of a telescope
- To be able to build a generic telescope model
- To be able to formulate and investigate their own hypotheses.

Orienting & Asking Questions

Orienting: Provide Contact with the content and/or provoke curiosity

For many people, the telescope is the very symbol of Astronomy: the most important instrument at our disposal with the mission to study the heavens and unlock their secrets. The telescope has been the Astronomer's most faithful companion from the first decade of the 17th Century, when Galileo Galilei pointed the telescope to the sky for the first time.

Fig. 1: *The first ever telescope that observed the heavens made by Galileo Galilei in 1609 (Source: Museo Galileo*

In the year 2022, 413 years after Galileo's "premiere" with a telescope, humankind has already launched two space telescopes (The Hubble Space Telescope and the James Webb Space Telescope), while gigantic terrestrial telescopes, utilizing the cutting edge of modern technology to offer us an unprecedented view of the Cosmos, have been built or are in construction phase at this very moment.

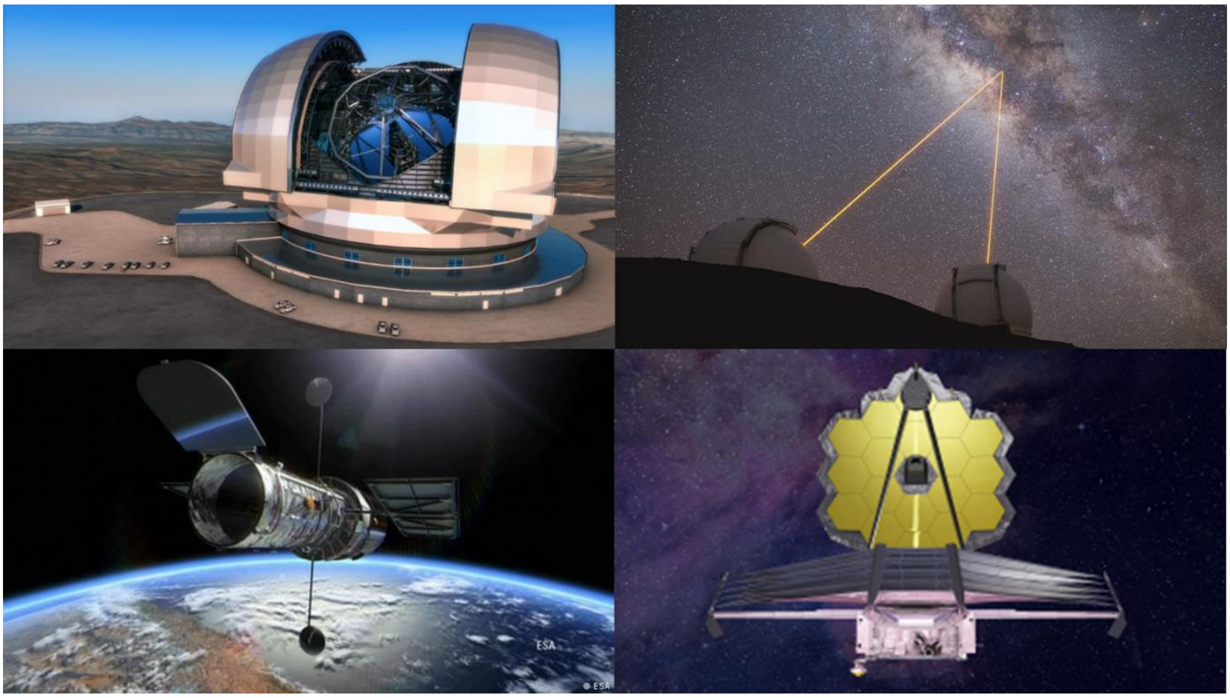


***Fig.2**: (Top Left): Artistic view of the Extremely Large Telescope (ELT: https://elt.eso.org/) in Chile, estimated to be completed in 2024. Please note the scale of ELT (Source: ESO/L. Calçada); (Top Right): The W.M.Keck Observatory (Keck: https://www.keckobservatory.org/) on top of the Mauna Kea mountains of Hawaii (image from video by SEAN GOEBEL/W. M. KECK OBSERVATORY); (Bottom Left): The Hubble Space Telescope (https://www.nasa.gov/mission_pages/hubble/main/index.html Source: NASA); (Bottom Right): An artist's depiction of the James Webb Space Telescope (https://webb.nasa.gov/) at work. (Image credit: Northrop Grumman)*

Watch the videos below and take a tour to the greatest observatories spearheading humankind's research in Astrophysics!

Ground based telescopes:

https://www.youtube.com/watch?v=XR_uEhoqhk4

Space based telescopes:

The Hubble Space Telescope

https://www.youtube.com/watch?v=rYebpogLg6w

The James Webb Space Telescope

https://www.youtube.com/watch?v=1C_zuHf6lP4

Teacher Guidelines:

You can dedicate time to watch the full videos with your students, or focus on showing them the big observatories/space telescopes and key discoveries. The goal here is to provoke their curiosity as well as point out the fact that in order to search for objects that are very far away we need to build continuously larger and more sophisticated telescopes.

Define Goals and/or questions from current knowledge

We have taken a tour to the world's largest observatories and space telescopes. However, do we really know what a telescope is and what it does? Why do we need it and why do the telescopes grow bigger and bigger as time goes by? How can a telescope pick something that looks so small with the naked eye (or, more usually, invisible for the naked-eye observer) and make it appear so spectacular?

These and many more are the questions that we are going to tackle in this activity! To tackle them we need to take one step back and investigate: What is a telescope and how does it operate?

Fig.3: *Jupiter as it is observed with the naked eye (left) and as it was observed by the Hubble telescope (right/ "ESA/Hubble")*

What is the telescope?

The telescope is an arrangement of lenses (and/or mirrors) in a tube which is used in order to **collect light** and magnify the image of a distant object. The telescope has three basic utilities:

1. It collects light from a far away object
2. It brings close a far-away object by creating an image.
3. The eyepiece magnifies the image so that we can study it in detail.

What is the principle of operation of the telescope?

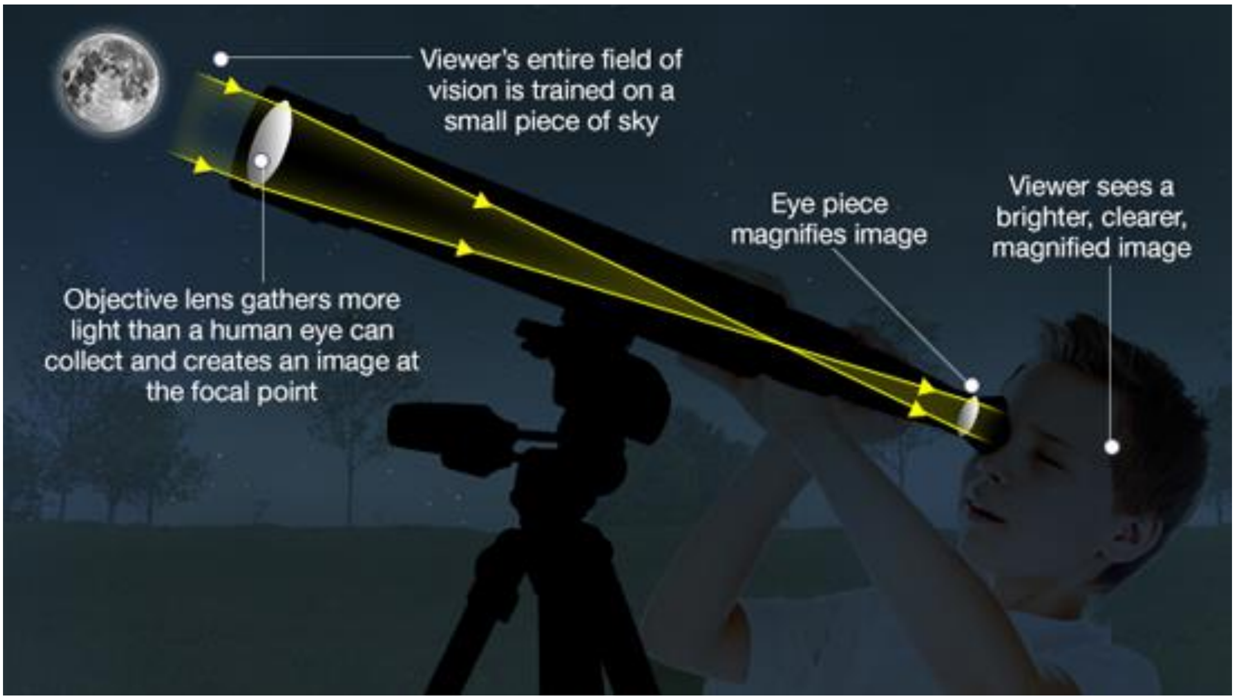


***Fig.4**: The anatomy of a refracting telescope. The telescope points to a selected piece of the sky and the observer's entire field of view is trained on that piece. You can observe the **Objective lens** up front, which collects light and brings the far-away image close to us by creating an image of it within the tube of the telescope. The objective lens is bigger than the human eye and thus can collect more light than it. Finally, the **Eyepiece,** a smaller lens from which we observe, magnifies the image.*

The first patent for the telescope was submitted in 1608 by Hans Lipperhey, Zacharias Janssen and Jacob Metius in the Netherlands and was used for military applications. The first person to utilize the telescope for the study of the heavens was claimed to be Galileo Galilei in the year 1609 AD.

Let's watch this video from Museo Galileo in Florence, Italy, and learn more about the history and the principle of operation of the telescope:

https://catalogue.museogalileo.it/multimedia/Telescope.html?_ga=2.150798014.901370273.1643963649-1804151026.1523866092

Teacher guidelines

It is suggested that you build a small telescope from simple materials with your students. To do that you can use this short guide you step by step in the process https://nso.edu/wp-content/uploads/2018/06/Build-a-Telescope_Activity.pdf.

Describe briefly the principle of operation of a refracting telescope and its different components.

Are there more than one types of telescopes?

The answer to this question is yes. Telescopes come in three main varieties: Refracting telescopes or refractors, reflecting telescopes and catadioptric telescopes. Each type of telescope has its advantages and disadvantages and can be optimized for different types of observations.

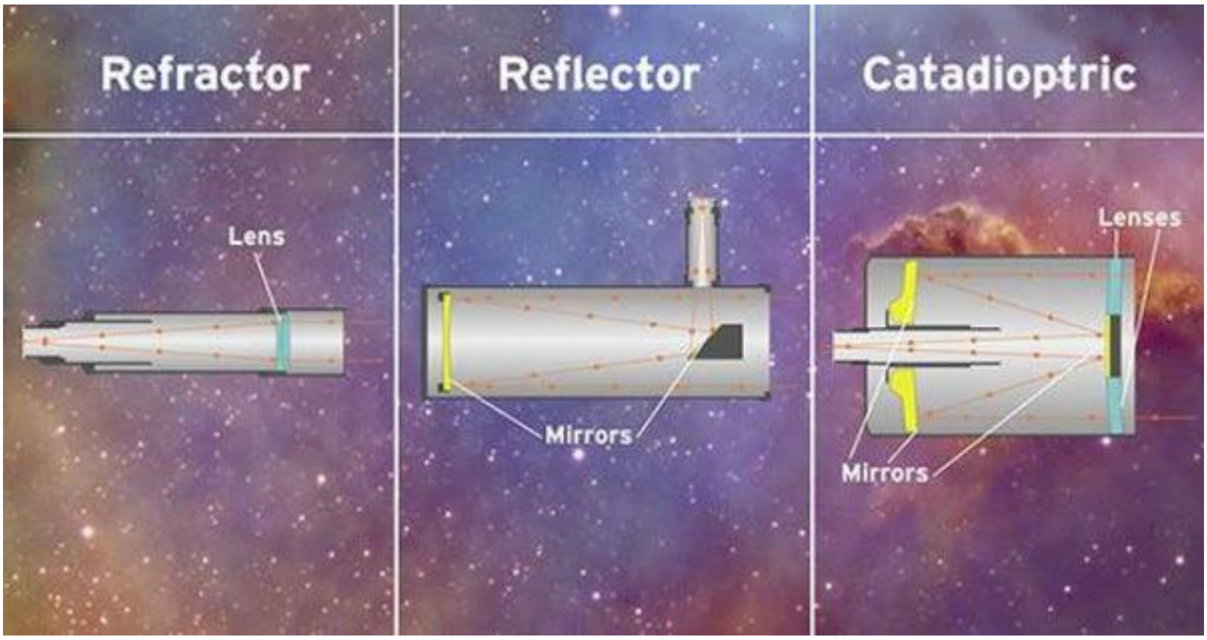


***Fig.5**: Different types of telescopes: (Left) The refracting telescope, (Middle) the reflecting telescope, (Right) the catadioptric telescope. (Source: https://optcorp.com/blogs/telescopes-101/buying-your-first-visual-telescope)*

You can watch this video to learn more about the different types of telescopes. https://www.youtube.com/watch?v=_v1RWyzQAng

Teacher Guidelines:

The following steps of our activity will focus on refracting telescopes, therefore if you don't have the time to discuss other types of telescopes you could only make a passing reference. If you want to focus on the evolution of the telescope it is proposed that you watch this video :

https://www.youtube.com/watch?v=InXWTQw_Wpc and if you have time

show it to your students and discuss with them. This can be a very nice follow-up project.

The following steps of our activity will be devoted on the operation of a refracting telescope.

Hypothesis Generation and Design

Generation of Hypotheses or Preliminary Explanations

Teacher Guidelines

In this section we invite students to formulate hypotheses regarding key observational characteristics of telescopes. Students are asked to formulate hypotheses on 4 separate "puzzles". Then, the hypotheses for each puzzle will be investigated in the next section (Investigation) and analysed in the section after that (Analysis) where the students will be asked to reflect on their initial hypotheses. You can work with each Puzzle as a separate activity or with all of them one by one.

Every amateur observer who targets the night sky for the first time with their telescope will face not only the wonders but also the puzzles that come hand in hand with the use of this instrument.

Puzzle Nr.1 : Magnification

If you took a small commercial refracting telescope and targeted planet Jupiter with it, you would observe something like this through your eyepiece:

Fig.6: *Image of Jupiter and its moons through a small commercial telescope*

This is not that far from what Galileo observed back in 1610. And it is definitely more interesting than what I would observe with my naked eyes. However, this image is definitely not as big as the one from the Hubble telescope we presented before. We say that our small commercial telescope has smaller ***angular magnification*** than the Hubble telescope. **The angular magnification M** of an astronomical telescope, used visually, is defined as the angle subtended by the image of an object seen through a telescope, divided by the angle subtended by the same object without the aid of a telescope.

$$\boldsymbol{M} = \frac{angle\ subtended\ by\ the\ image\ of\ an\ object\ seen\ through\ the\ telescope}{angle\ subtended\ by\ the\ same\ object\ without\ the\ aid\ of\ a\ telescope}$$

If we state therefore that our magnification is 20X this means that we will observe the image through the eyepiece of our telescope to be 20 times larger than what we would observe with our naked eye.

Fig.7 *: (Left) Moon magnified 65 times or 65X; (Right) Moon magnified 182 times or 182X compared to its angular diameter observed without the aid of a telescope. (Source: https://www.skyatnightmagazine.com/astronomy-field-view-calculator/)*

Formulate a hypothesis based on what you have read so far: What could magnification depend on?

Teacher guidelines

This problem will be solved in the next section where students will work on ray diagrams.

Puzzle Nr 2: Upside Down

A puzzling issue we usually face when we observe with a refracting telescope is the fact that the images, we observe are upside down:

Fig.8: *Observing a tree through your eyes (left) and through the eyepiece of a refracting telescope.*

Would the problem be solved if we turned the telescope upside-down? Where does this "upside-down" problem come from? Write down your hypothesis here:

Teacher guidelines

This problem will be solved in the next section where students will work on ray diagrams

Puzzle Nr 3: Where did the target go?

If you have ever tried to observe the night sky through a telescope that you hold in your hands you must have realized that even a small movement might result in the target leaving your field of view. To solve this problem, we need to place our telescope into a sturdy mount and operate it from there.

Fig.9*: A telescope on its mount*

It appears therefore that the problem has been solved. Or has it? Indeed, your telescope now won't be affected by your heartbeat or the small motions of your hands. Furthermore, if you pointed your telescope at a tree far away, the tree would remain in your field of view without moving a fraction of the arcsecond. **What about celestial targets though?** Our friend Dave has tried this for us by targeting the moon with his telescope mounted on a sturdy mount. Check this short video to see what happened:

https://www.youtube.com/watch?v=pVJb-eCi6To

Where did the moon go? Would the same happen if I targeted Jupiter instead? Write down your hypothesis here:

Teacher guidelines

This problem comes from the fact that the Earth rotates with a rate of 15^{o}/hr . The moon has an angular size of 0.5^{o}. If the field of view of my telescope is wide enough to accommodate the full disk of the moon, then within 2 minutes, the moon would have left the target. You can discuss this with your students as you let them formulate their hypothesis. To solve this problem, Astronomers are using motorized mounts that fit on top of a tripod and allow a camera or telescope to follow the stars (or a planet, a comet, or anything else) as they are carried across the sky by the rotation of Earth.

Puzzle Nr 4: Why is the moon so blurry?

If you set up your telescope, place it on a mount point to the moon and go observing, you will -most likely- observe something like this:

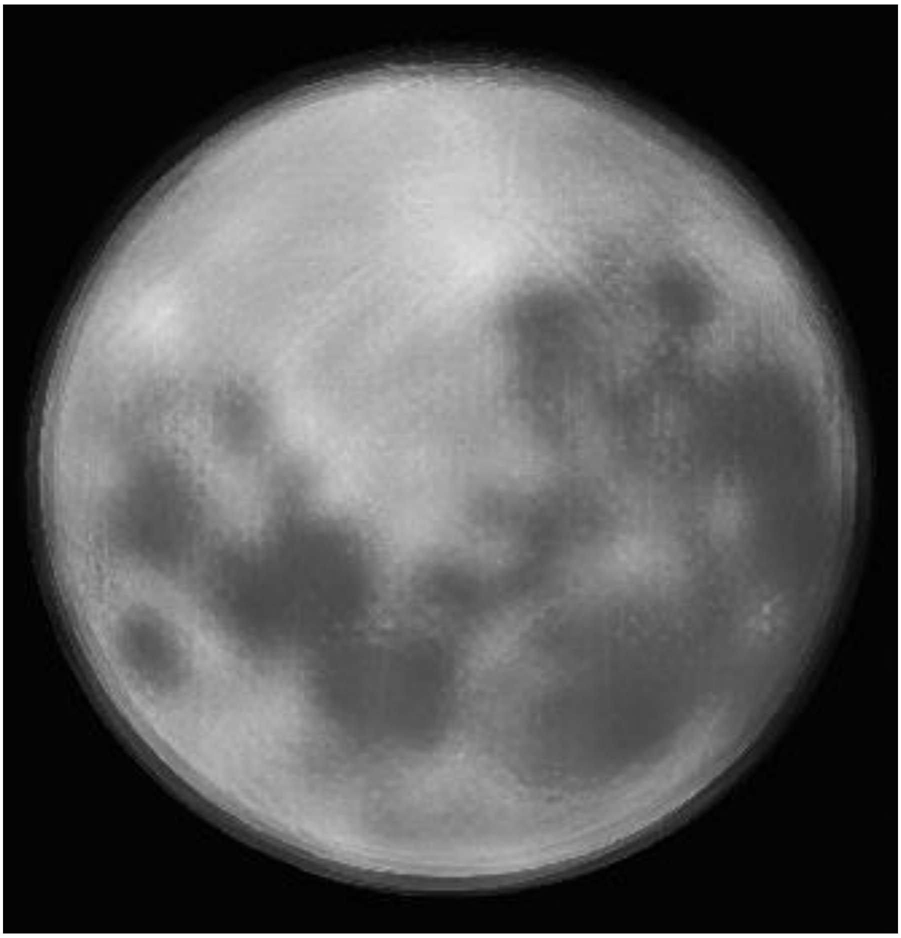


***Fig.10**: A blurry moon through our eyepiece*

Where does this blur come from? Can we solve it somehow? Write down your hypothesis.

Teacher guidelines

This image of the moon is out of focus. To solve the problem, we need to put the telescope in normal adjustment which means that the telescope is adjusted so the virtual image seen by the viewer is at infinity. Practically, for a refracting telescope this means that the distance between the two lenses, the objective and the eyepiece, is equal to the sum of their focal lengths. To adjust this , a telescope has a knob close to the eyepiece which we turn in order to find the position where the image is the most focused.

Puzzle Nr 5: Is the size of the telescope important?

If you have participated in Astronomers' or amateur Astronomers' discussions you may have noticed that they usually compare the specifications of different telescopes. One of the most commonly discussed variable is the aperture of the telescope, which means the diameter of the objective lens (or the objective mirror).

If you also follow the development of telescopes over time you will observe that most modern telescopes are designed with increasingly larger apertures.

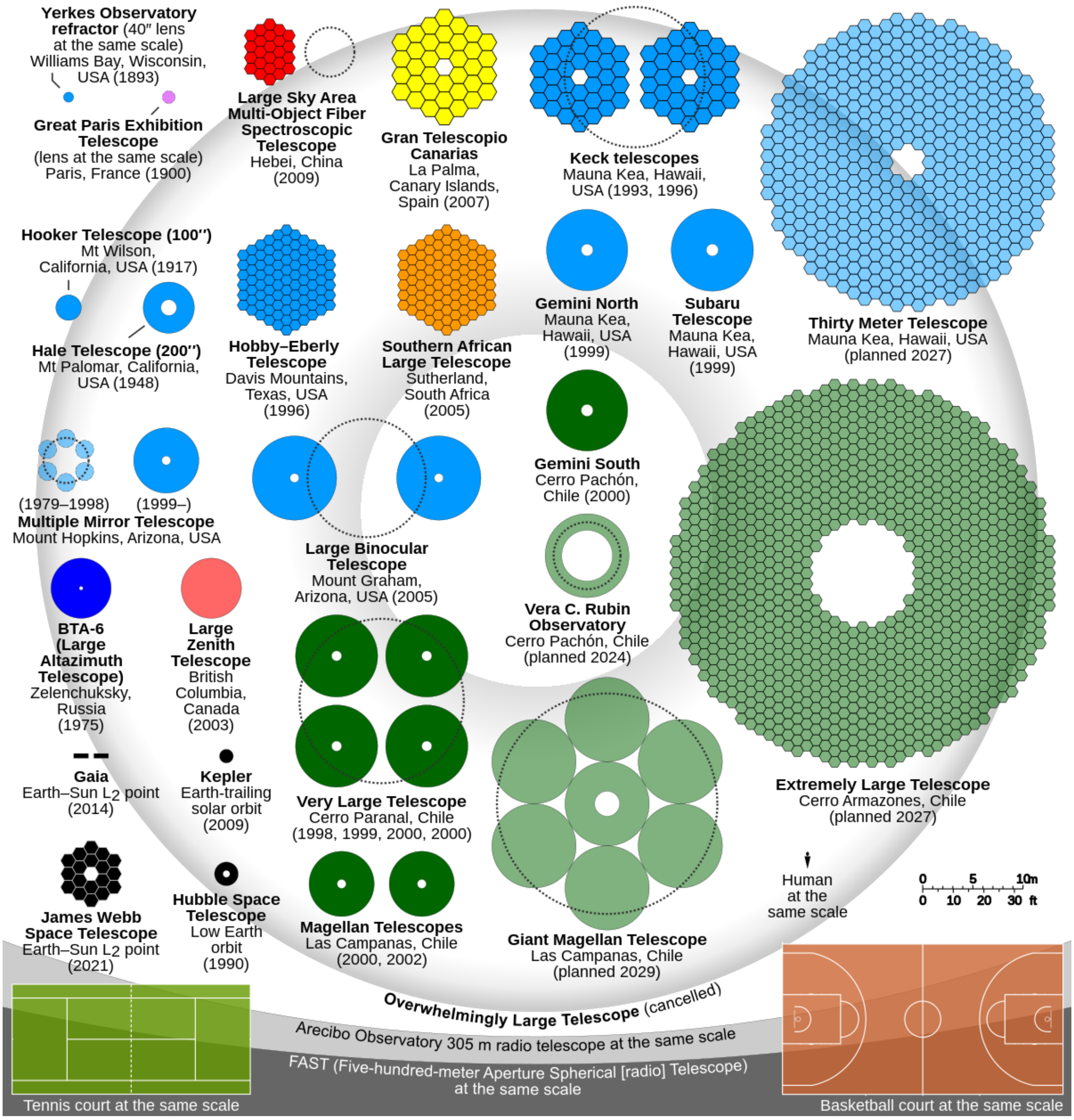


***Fig.11**: Apertures of different telescopes. Observe the scale. (Source: https://zh.m.wikipedia.org/wiki/File:Comparison_optical_telescope_primary_mirrors.svg)*

Why do we need big telescopes? Why do new telescopes have increasingly larger apertures? Write down your hypothesis.

Teacher guidelines

It is suggested that you make sure that students understand the scale of the apertures discussed here.

Design/Model

Teacher Guidelines

It is quite important to make sure that you discuss this topic after you discuss thin lenses and ray tracing in your lesson.
You can find here a video on ray tracing for a system of two lenses. We suggest that you discuss this with your students after the activity, at the analysis level.
https://www.youtube.com/watch?v=4DANl-2SsPM
Here you can find an interactive application that might help you:
https://www.walter-fendt.de/html5/phen/refractor_en.htm

For the needs of our activity, we will limit ourselves to refractive telescopes. We will model our refractive telescope as a set of two converging (convex) **thin** lenses placed some distance apart within a tube.

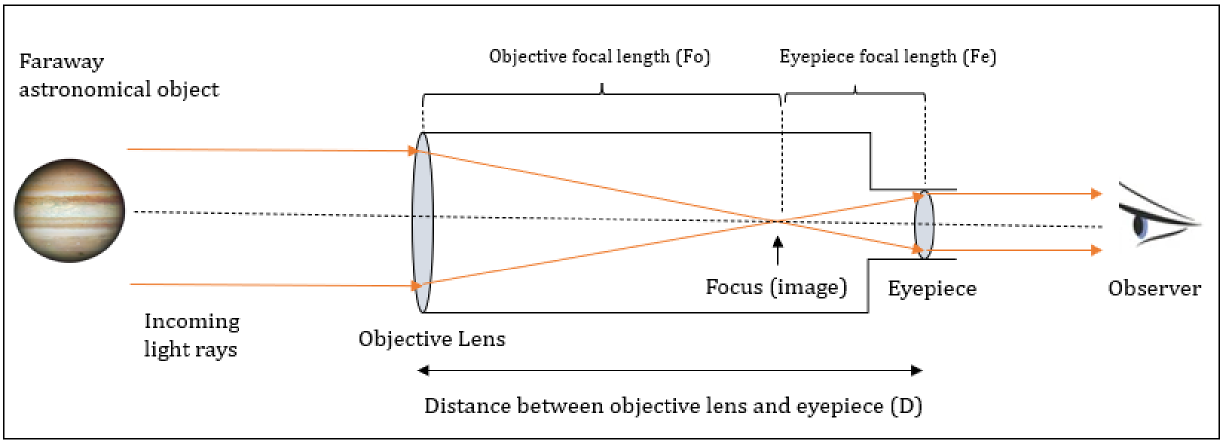


Fig. 12*: A model of a refracting telescope: Two converging lenses (the objective lens and the eyepiece) are adapted in the telescope tube.*

A faraway astronomical object emits light rays. The rays are considered parallel as they arrive in our telescope. The rays are bended by the objective lens, and they meet at the focus. This is where the image of the faraway object is formed. The rays continue their path until they enter the eyepiece and are bended from it. Then they arrive in our eye. The distance between the objective lens and the focus is called the objective focal length (Fo) and the distance between the focus and the eyepiece is called eyepiece focal length (Fe).

In our model, the telescope is in normal adjustment: The focus of both lenses coincides in the focus position. This implies that: *The distance between the center of the objective and the center of the eyepiece is equal to the sum of Fo and Fe* :

$$\boxed{D = Fo + Fe}$$

When the telescope is in normal adjustment, the image we observe through the eyepiece is focused (therefore not blurry). If the image is blurry, we need to move the eyepiece until the normal adjustment condition is met.

Planning and Investigation

Plan Investigation

This investigation aims to help you investigate the answers to puzzles: 1,2,3 and 4 stated before and investigate the accuracy of your original hypotheses. To achieve this, you will be using a series of interactive simulations detailed below.

Teacher guideline

All parts of the investigation can be also implemented with the use of a real telescope on a mount (preferably motorized) and a zoom lens or series of lenses with different focal lengths. If time doesn't permit it, investigate only 1 puzzle, for example Puzzle 1. Puzzle 5 will be investigated as part of proposed follow-up activities.

Puzzle 1
Magnification: What could it depend on?
To investigate it you will use the following two apps:

- The telescope simulator developed by University of Nebraska, Lincoln
  Telescope Simulator (unl.edu)

Puzzle 2
Upside down: Why are the images we observe upside down?

To investigate it you will use the following app:

- Ray optics simulator
  https://ricktu288.github.io/ray-optics/simulator/

Puzzle 3

Where did the target go : Why do objects we observe move ?

To investigate it you will use the following app:

- Stellarium Web
  https://stellarium-web.org/

Puzzle 4

Why is the moon so blurry?

To investigate it you will use the following app:

- The telescope simulator developed by University of Nebraska, Lincoln Telescope Simulator (unl.edu)

Puzzle 5
Is the size of the telescope important?

To investigate this you will use the following app:
- Stelvision's telescope simulator: https://www.stelvision.com/astro/telescope-simulator/

Perform Investigation

Investigation of Puzzle 1:
Magnification: What could it depend on?

Launch the Telescope Simulator app:
https://astro.unl.edu/classaction/animations/telescopes/telescope10.html

You will see an image like this:

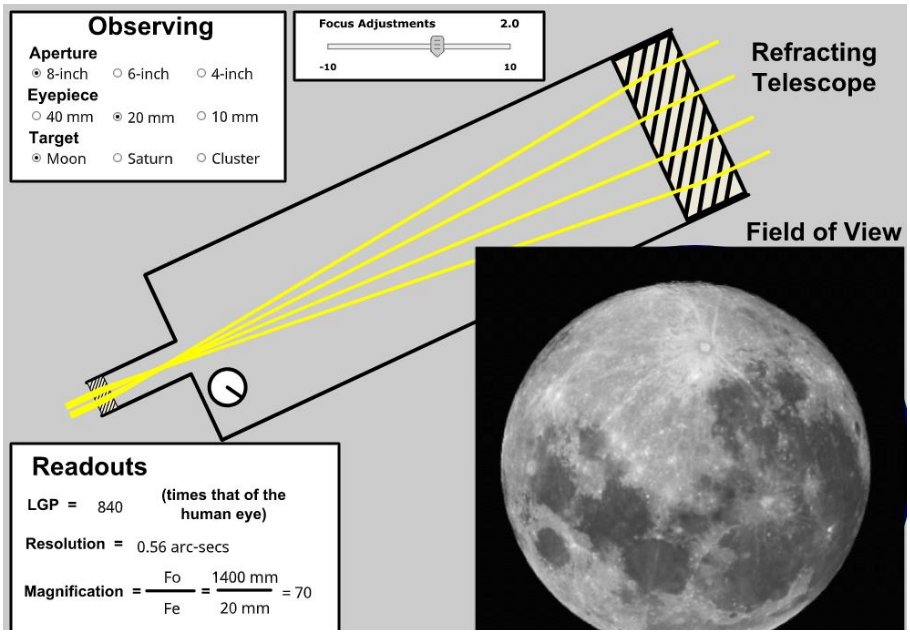


***Fig. 13**: Screenshot from the UNL Telescope Simulator App.*

You are controlling a virtual refracting telescope of which you can alter the following parameters:
- Aperture : The diameter of the objective lens
- Eyepiece: The focal length of your eyepiece
- Focal adjustment: The relative position of the objective lens and the eyepiece

The focal length of the objective lens is fixed and equal to 1400mm. The eyepiece can be changed.

Step 1

Fix the aperture to 8 inches and your target to be the moon. You will keep these parameters constant throughout this part of the investigation.

Step 2

Select the eyepiece with focal length equal to Fe=10mm.

Step 3

Adjust the focus so that the image of the moon is not blurry. Observe how the size of the moon in our eyepiece changes.

Step 5

Repeat steps 2,3 and 4 for Fe= 20 mm and Fe = 40 mm. Note your observations.

Teacher Guideline

Students will analyze their findings in the analysis part of the activity.

Investigation of Puzzle 2
Upside down: Why are the images we observe upside down?

Launch the Ray optics simulator:
https://ricktu288.github.io/ray-optics/simulator/

Step 1
Select the **Ray** Option and draw a ray from top left to bottom right (like Fig.18)

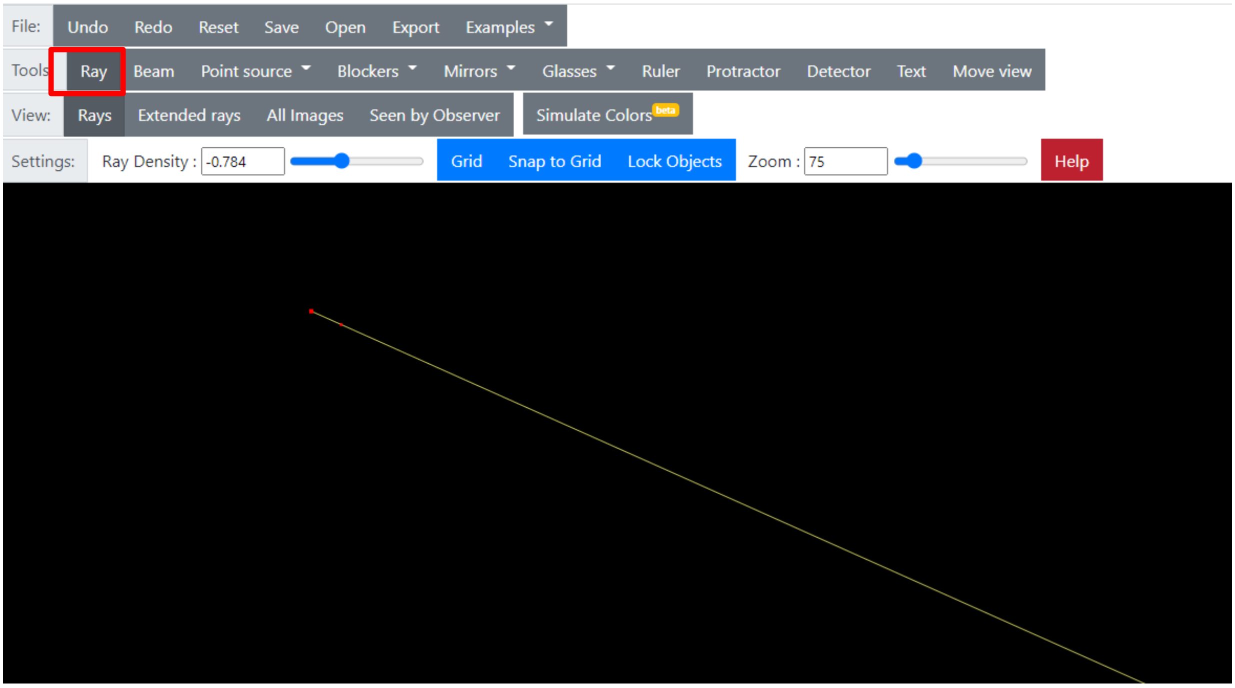


Fig. 14: *Selecting the "Ray" Option*

Step 2

From the option "Glasses" select "Ideal Lens". Once the selection is made, draw a set of two ideal lenses as shown in figure 15 (up). Make sure that their centers are along the same line and that their "optical axes" are parallel (figure 15 down). You can draw a ruler (Option: "Ruler") to help you in the visualization. Make sure that the zero mark of the ruler is placed below the starting point of the ray and that the ruler connects the two centers of the lenses.

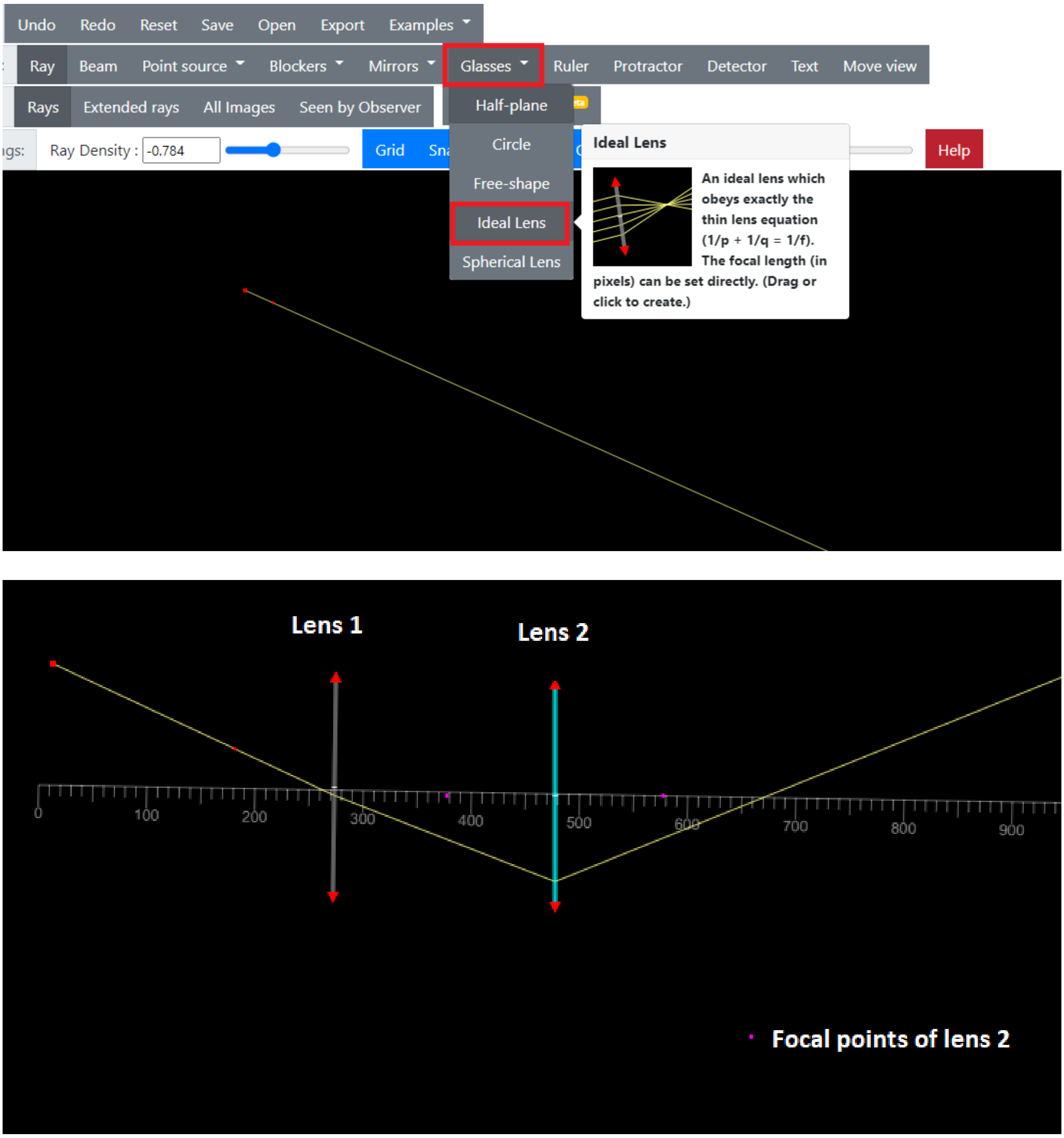


Fig. 15: *Drawing two thin lenses and making sure that the ray passes through the two of them. Up: The lens option; Down: The final drawing.*

<u>Step 3</u>

If you click on each lens you will see two magenta dots appearing one on its right and one on its left. These are the focal points of the lenses. Make sure that your lenses are in normal adjustment as per our model (Fig. 15). The right focus of the left lens must coincide with the left focus of the right lens. If you have followed the steps correctly then you will observe something like the Down part of Figure 15 this in your screen. **Congratulations! You have created a digital edition of our telescope model!**

We will consider that Lens 1 is the objective and Lens 2 the eyepiece. Now, assume that we place our eye on the right of lens 2 exactly on the path of the outgoing ray. Furthermore, assume that the point P where the rays are emitted from is the tip of an object we are trying to observe (Fig.20). If we trace backwards the outgoing ray then we are going to observe what you see in figure 16.

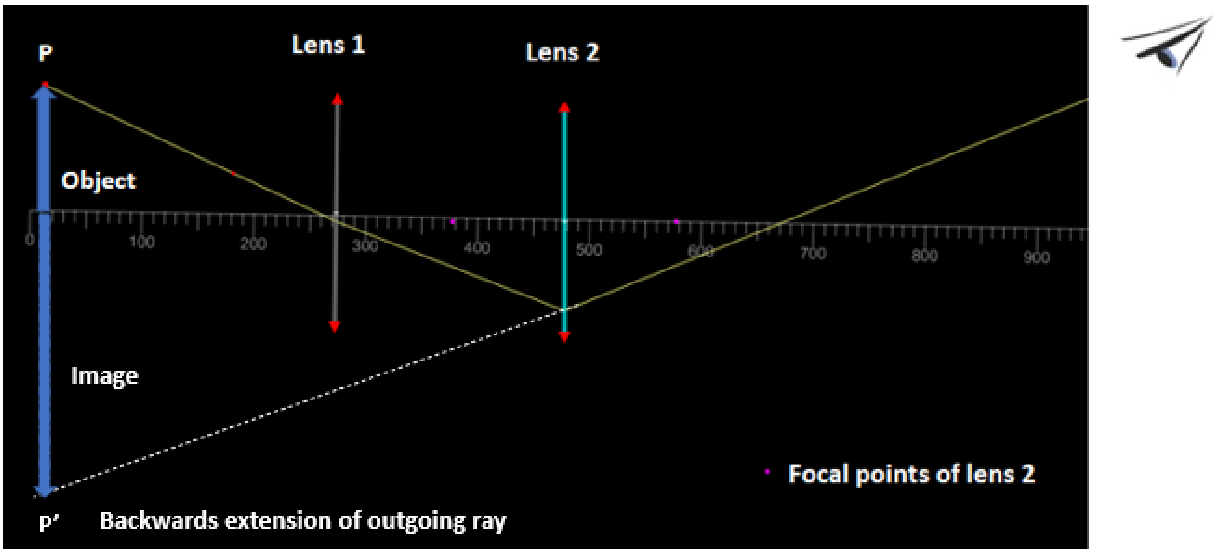


Fig.16: *The image of an object as observed through our set of lenses (our "telescope").*

You will observe that the image is both inverted and magnified in the y-axis. Its position in the horizontal axis is exactly at the same point as that of the object. **Therefore, we will observe the image being equally far away , inverted and magnified. This is exactly what happens with a simple refracting telescope.**

Step 4

Experiment with the setup and try different arrangements of the two lenses. Document your findings.

Teacher Guidelines

The goal here is for the students to "build the telescope" themselves and understand what ray tracing means. The teacher is asked to make sure that students understand how to find the position of the image.

Investigation of Puzzle 3
Where did the target go : Why do objects we observe move ?

To investigate the motion of the target through the eyepiece of our telescope, we will emulate the observation process with the use of the digital planetarium software called "Stellarium".

Teacher Guideline
You can find a detailed guide on the use of Stellarium in the LaSciL toolbox: https://lascil.eu/wp-content/uploads/2022/10/Stellarium.pdf . **To proceed with this part of the exercise, make sure that you are signed in to Stellarium Web.**

Step 1
Enter the Web Version of Stellarium: https://stellarium-web.org/. Select a time and date when the moon is observable from your location.

Fig. 17*: Selection of time and date when the moon is observable from our location.*

Step 2
Click on the time and date button and start moving time forward in steps of one hour at a time. Note your observations.

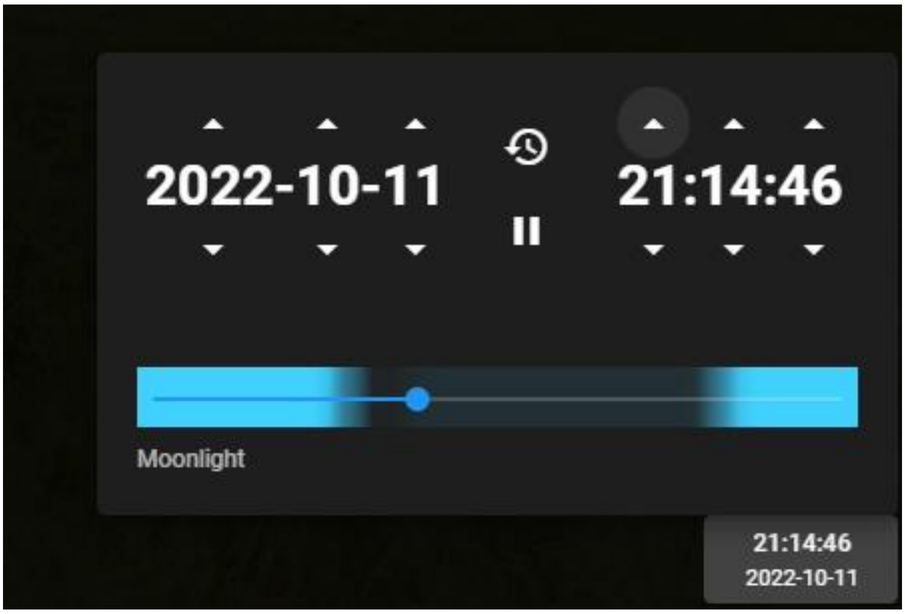


***Fig.18**: Moving time and date backwards and forward.*

Do you observe the moon moving? If yes, try to explain why.

<u>Step 3</u>

After signing in to Stellarium Web, go to the "Observe" option on the top right and left click on it. Left click on the moon in your monitor and an observing option will appear on the Observation Menu.

***Fig. 19:** Stellarium Web Observation Menu.*

Left click on that option and select your observation mode. You will observe the "Naked eyes" option. Click on the Pencil on the right (Fig. 24) and then select the option telescope.

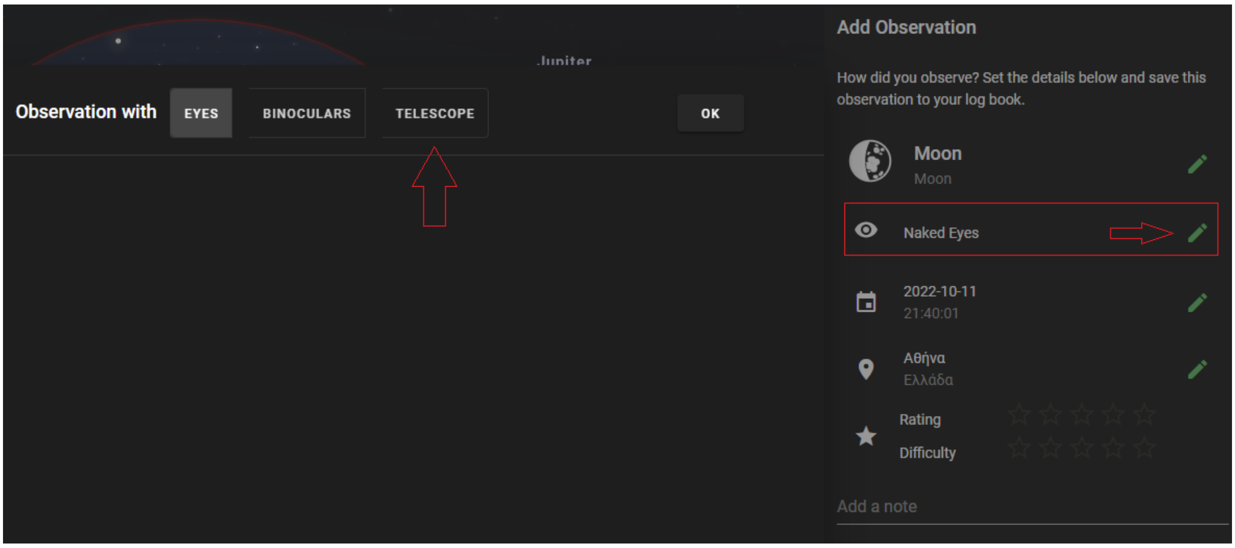


Fig. 20*: Stellarium Web Observation Mode.*

<u>Step 4</u>

Select: "Observation with Custom telescope" and insert the following parameters:

Optical Tube: Custom Optical Tube
Aperture 114 mm
Focal Length 900 mm

Eyepiece: Custom Eyepiece
Focal Length 25mm
Apparent FOV 50°

Barlow / Reducer: No Barlow

Mount: Generic Mount

Then click ok. You have just emulated a simple refracting telescope with magnification M=36X.

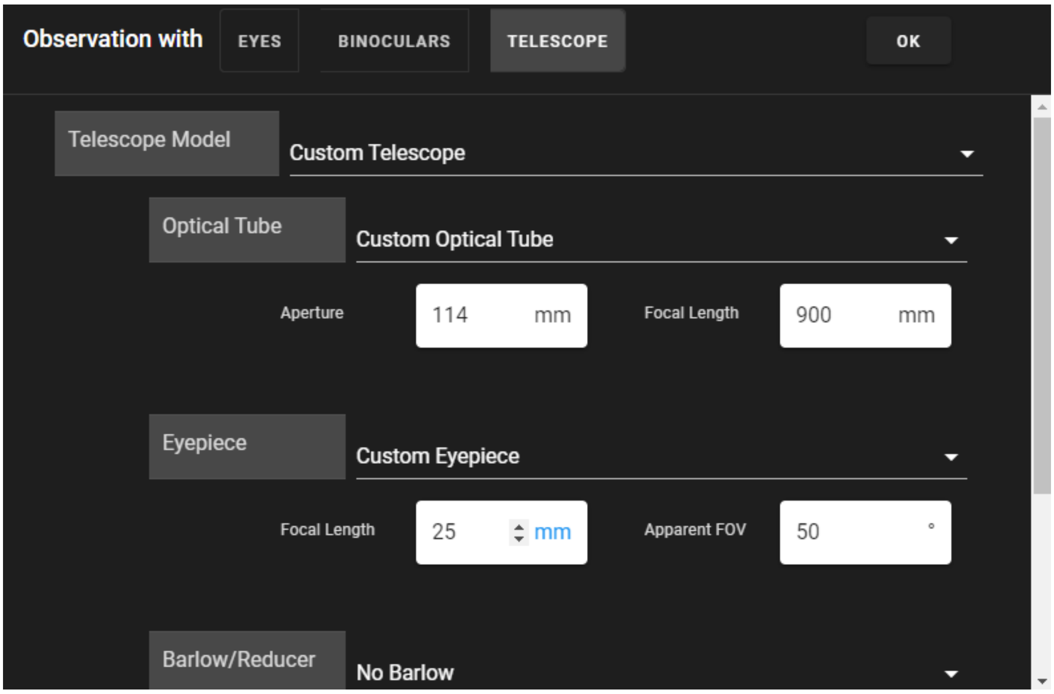


***Fig. 21**: Selecting telescope parameters.*

<u>Step 5</u>

If you have done steps 1 to 4 correctly, you will observe this in your monitor

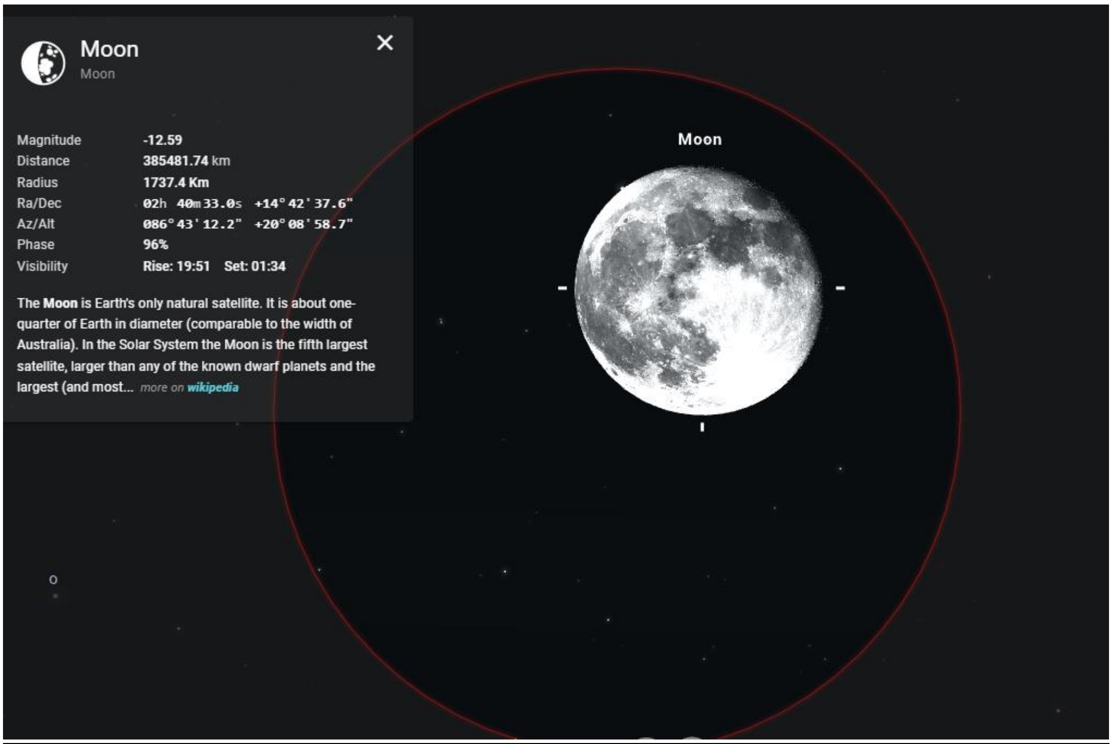


***Fig. 22:** Observing the moon through our virtual eyepiece*

Observe the moon. Is it moving through our eyepiece?

-Observe it for a set amount of time that you will decide.

-Write down your observations in your notebook.

- Go back to step 2 and remember the explanation you gave there. Is there a connection between the two?

- Think if there is a way to keep your telescope fixed to an object you observe and write it down.

Investigation of Puzzle 4
Why is the moon so blurry?

Launch the Telescope Simulator app:
https://astro.unl.edu/classaction/animations/telescopes/telescope10.html

Step 1

Fix the aperture to 8 inches and your target to be the moon. You will keep these parameters constant throughout this part of the investigation.

Step 2

Select the eyepiece with focal length equal to Fe=40mm.

Step 3

Observe how your image changes as you move the Focus adjustments slider. Observe the image of the telescope to see what physical changes happen as you move the slider. Do not note the number of the Focus Adjustment value.

Step 4

Write down your observations. You can repeat this step for different eyepieces.

Teacher Guideline

Students will analyze their findings in the analysis part of the activity.

Investigation of Puzzle 5
Is the size of the telescope important?

Step 1:
Enter this link: https://www.stelvision.com/astro/telescope-simulator/
Click on Detailed Simulation: Choose your Eyepieces

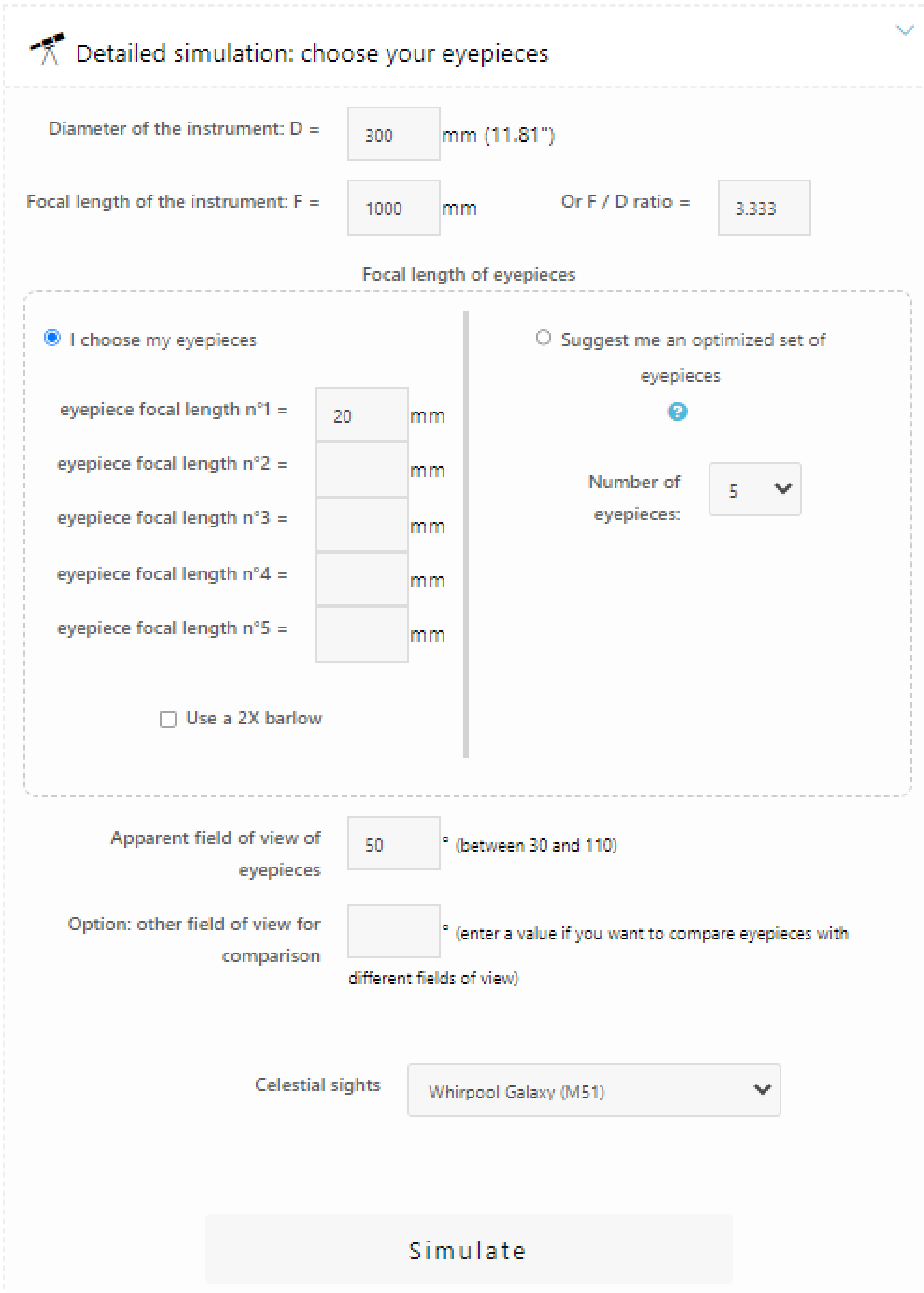


Fig. 23: *Observing menu*

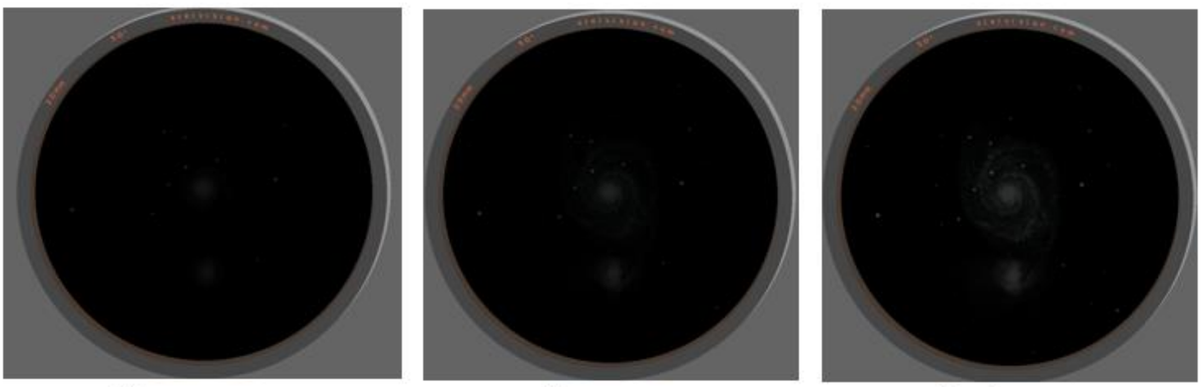
Step 2
Click on Celestial Sights and Select the **Whirlpool Galaxy (M51)**

Step 3
-Select focal length of the instrument to be equal to **2000mm**.
-Select Diameter of the Instrument D to be equal to **100mm**
-Select: "I choose my eyepieces" and similarly to the image above select eyepiece focal length to be equal to **20mm**.
-Click on "Simulate".

Step 4
Repeat Step 3 by changing only the Diameter of the Instrument, first to 300mm and then to 600mm.

Important!
Take into account that in a real telescope **you cannot alter the objective lens**. Therefore this exercise should be **considered equivalent to having 3 different telescopes** with different objective lens diameters (100, 300 and 600 mm).
You will also observe that as you change the diameter of your objective, D, focal length will change. **It is very important that for the three values highlighted here, you set the value of the focal length again to 2000mm.**

Step 5
Take a snapshot of the Whirlpool Galaxy for the three different diameters (remember to make sure that everything else is kept constant).
You will observe something like the following image



D=100mm D=300mm D=600mm

Fig.24: *Snapshot of the Whirlpool Galaxy for three different objective apertures*

Step 6

Write down your observations.

Teacher Guideline

Students will analyze their findings in the analysis part of the activity.

Notebook page

Observations on Puzzle 1

Observations on Puzzle 2

Observations on Puzzle 3

Observations on Puzzle 4

Observations on Puzzle 5

Analysis & Interpretation

Analysis and interpretation : Gather result from data

Analysis of Puzzle 1:
Magnification: What could it depend on?

Based on your observations of the investigation of Puzzle 1, write down in a sentence:

How does magnification change with respect to the focal length of the eyepiece?

Go back to your initial hypothesis in the Hypothesis Generation and Design phase for the same Puzzle. There, you were asked to ***formulate a hypothesis based on what you have read so far: What could magnification depend on?***

Reflect on the initial hypothesis and write down any observations/ideas/changes you would like to make.

Analysis of Puzzle 2
Upside down: Why are the images we observe upside down?

Based on your observations in the investigation of Puzzle 2 write down in a sentence: **Why are the images we observe with our simple model of a refracting telescope upside down?**

Go back to your initial hypothesis in the Hypothesis Generation and Design phase for the same Puzzle. There, you were asked to formulate a hypothesis whether ***the problem would be solved if we turned the telescope upside-down? Where does this "upside-down" problem come from?*** Reflect on the initial hypothesis and write down any observations/ideas/changes you would like to make. Take into account the findings of your "ray tracing exercise".

Analysis of Puzzle 3
Where did the target go : Why do objects we observe move ?

Based on your observations in the investigation of Puzzle 3 write down in a sentence: **Why does the image we observe with our simple model of a refracting telescope move through the eyepiece?**

Go back to your initial hypothesis in the Hypothesis Generation and Design phase for the same Puzzle. There, you were asked to formulate a hypothesis regarding ***where did the moon go? Would the same happen if I targeted Jupiter instead?*** Reflect on the initial hypothesis and write down any observations/ideas/changes you would like to make.

Analysis of Puzzle 4
Why is the moon so blurry?

Based on your observations in the investigation of Puzzle 4 write down in a sentence: **Why does the image we observe with our simple model of a refracting telescope appear blurry some times? What can we do to fix it?**

Go back to your initial hypothesis in the Hypothesis Generation and Design phase for the same Puzzle. There, you were asked to formulate a hypothesis regarding ***Where does this blur come from? Can we solve it somehow??*** Reflect on the initial hypothesis and write down any observations/ideas/changes you would like to make.

Analysis of Puzzle 5
Is the size of the telescope important?

Based on your observations in the investigation of Puzzle 5 write down in a sentence:
What is the impact of the diameter of the objective lens on the image we observe?

Go back to your initial hypothesis in the Hypothesis Generation and Design phase for the same Puzzle. There, you were asked to formulate a hypothesis regarding ***why we need big telescopes and why new telescopes have increasingly larger apertures.*** Reflect on the initial hypothesis and write down any observations/ideas/changes you would like to make.

Teacher Guideline

It is very important that students write down their own explanations and do their own self reflection here. The "expert answers" will be given in the next phase .

Conclusion & Evaluation

Conclude and communicate result/explanation

Explanation of Puzzle 1: Magnification, what does it depend on?

We have worked hard to understand the principles behind a telescope's magnifying power. To consolidate our knowledge, let's do a short exercise to investigate how we can find magnification from the parameters of our model.

Teacher Guidelines

It is suggested that you do this exercise with your students. If you don't have the time then make sure to explain to them that magnification equals the ratio of Fo over Fe (M=Fo/Fe).

Two parallel rays enter our lens with an angle equal to **θin**. This is the angle subtended from the object seen through naked eye. After bending in the objective lens and in the eyepiece they come out of our telescope with an angle equal to **θout**. This is the angle subtended from the image of the object seen through the telescope. Magnification is defined as :

$$\boldsymbol{M} = \frac{\text{angle subtended by the image of an object seen through the telescope}}{\text{angle subtended by the same object without the aid of a telescope}} = \frac{\theta out}{\theta in}$$

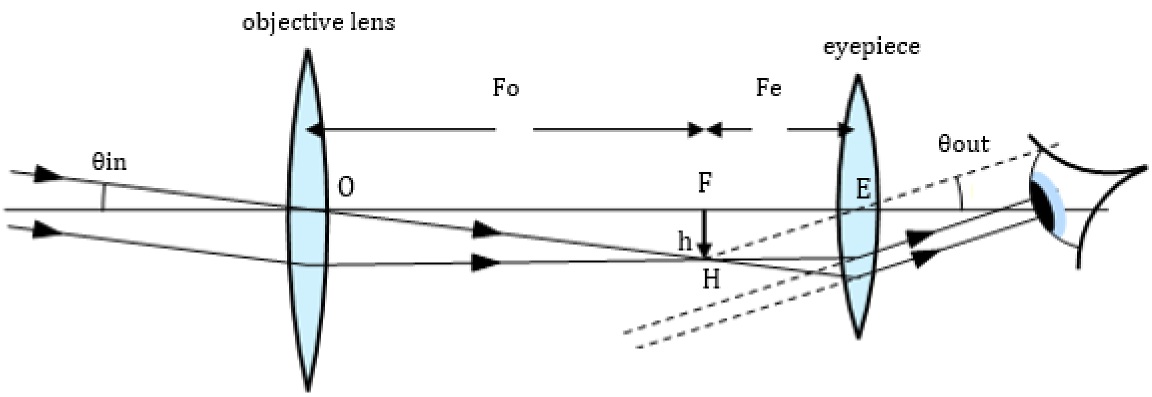


***Fig. 25**: Geometrical considerations for the calculation of telescope magnification*

Our goal is to prove that $M = \frac{\theta out}{\theta in} = \frac{Fo}{Fe}$

The magnification is equal to θout/ θin. For small angles, this ratio is equal to

$$M = \frac{\theta out}{\theta in} \approx \frac{\tan(\theta out)}{\tan(\theta in)}$$

From figure 25, $\theta in = (F\hat{O}H)$, $\theta out = (F\hat{E}H)$.

Then,

$$\tan(\theta out) = \frac{h}{Fe}, \tan(\theta in) = \frac{h}{Fo}$$

Therefore

$$M = \frac{\theta out}{\theta in} \approx \frac{\tan(\theta out)}{\tan(\theta in)} = \frac{\left(\frac{h}{Fe}\right)}{\left(\frac{h}{Fo}\right)} = \frac{Fo}{Fe}$$

We conclude that the magnification is equal to the ratio of the focal length of the objective lens to the focal length of the eyepiece.

$$\boxed{M = \frac{Fo}{Fe}}$$

An observation worth mentioning here is that the objective lens is fixed but the eyepiece can be changed in a telescope. Therefore, the "zoom" of a specific telescope can be increased by adapting eyepieces with shorter focal length.

You can repeat the steps of this exercise in your notebook. Discuss the solution to the above exercise and consider your findings from the previous steps.

Teacher Guideline

In this part of the discussion, you can show your students this video and ask them to repeat the calculations made there.That exercise is similar to the one we solved here. https://www.youtube.com/watch?v=4DANl-2SsPM .

If you have a telescope with various eyepieces in your disposal, try to experiment hands on and discuss magnification with your students.

If you want you can adapt this activity using the Astronomy field of view calculator developed by David Campbell (www.12dstring.me.uk) and showcased in the Sky at Night Magazine. You can choose different types of eyepieces for a dedicated target and dedicated telescope and see how magnification changes in order to give a more "realistic view" of the problem. https://www.skyatnightmagazine.com/astronomy-field-view-calculator/.

Explanation of Puzzle 2

Upside down: Why are the images we observe upside down?

The main reason behind this feature is the nature of the lenses, the structure of our setup and the geometry of our problem as you observed throughout your activity. In Fig. 20 you saw that the image formed in our model telescope is magnified and inverted. This is not the case though in all telescopes. Dedicate some time to read more about the upside-down puzzle here:

https://www.skyatnightmagazine.com/advice/why-does-telescope-show-everything-upside-down/

Write down your observations in your notebook or here:

Explanation of Puzzle 3
Where did the target go : Why do objects we observe move ?

Let's do a small calculation to understand better the nature of the problem.

We know that the Earth makes a full rotation about its axis in 24 hrs. Therefore, it has an angular velocity equal to:

$$\omega = \frac{\Delta\varphi}{\Delta t} = \frac{360^0}{24\,hrs} = \frac{15^0}{hr} = \frac{15'}{min}$$

This means that every minute, our planet revolves about its axis by 15 arcminutes, or ¼ of a degree. This is what will be observed by someone floating outside our planet.

Fig.26: *Earth's rotation (Source: http://commons.wikimedia.org/wiki/Image:Rotating earth (large).gif)*

What does a terrestrial observer observe though? To them, it is the sky that rotates around them with ¼ of a degree per minute! This is called diurnal motion. All the stars in the sky will be rotating around an imaginary axis which coincides with the Earth's rotation axis and has its "tip" on the North Celestial Pole, close to where the star Polaris is found. **This is why we have day and night.**

Fig.27*: Sky's rotation (diurnal motion) from the Earth's vantage point. Observe Polaris, the seemingly unmovable star around which all other stars revolve.*

A telescope mounted on our planet will rotate together with it at a rate of ¼ of a degree per minute. As a result, an observer who is zooming in a small slice of the sky will see the object they so painstakingly pinpointed to move and eventually get out of the field of our eyepiece. In order to be able to "lock" our telescope on a target and observe for a long time without the target moving, we need a motorized mount that will be programmed to follow the object we observe. Please note that observation of the moon and the Sun require a bit different "tracking settings".

Fig.28*: A telescope mounted on a motorized mount following the diurnal motion of the stars in the night sky. (Source: https://www.ar15.com/forums/general/ARFCOM-Astrophotography-PART-II/5-2335582/&page=2)*

Write down your observations in your notebook or here:

Explanation of Puzzle 4
Why is the moon so blurry?

As we discussed before, an image out of focus will be blurry. To obtain a focused image in our telescope model, we need to make sure that it is in normal adjustment, ergo, that the distance between objective lens and eyepiece is equal to the sum of the focal lengths of the two lenses.

In order to understand this statement a bit better, consider the following figure:

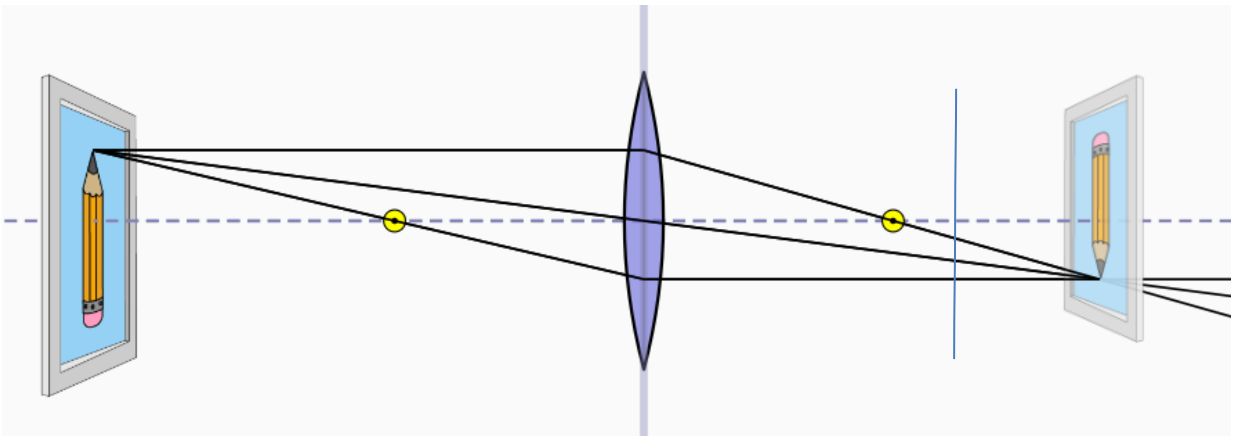


***Fig.29**: Ray tracing from a single thin lens*
(Source: https://phet.colorado.edu/sims/html/geometric-optics/latest/geometric-optics_en.html)

You observe three lines emanating from our object (a pencil) on the left, passing through the lens and bending. The image is formed on a plate on the right. Now what would happen if I moved the plate a bit to the left (where the blue line is)? In that case, the three lines would end in three different locations of our plate. As a result we would have the tip of the pencil appearing three times in different locations. Now if you consider all the light rays emanating from all points on the pencil, what you will observe on your "slightly moved" plate is a blurred image of the pencil (with each point appearing in more than 1 positions). We say that then, the image is out of focus.

Write down your observations in your notebook or here:

Explanation of Puzzle 5
Is the size of the telescope important?

In order to answer this question, we need to remind ourselves the principles of operation of a telescope. According to these: The telescope is an arrangement of lenses (and/or mirrors) in a tube which is used in order to **collect light** and magnify the image of a distant object. The telescope has three basic utilities:

1. **It collects light from a far-away object**
2. It brings close a far-away object by creating an image.
3. The eyepiece magnifies the image so that we can study it in detail.

We will focus on the first utility, that of collecting light from a far-away object.

One of the most important assumptions that we make in observational Astronomy is that **light from point sources far away from us (such as stars) arrives to us in parallel rays.**

Even though a star emits light radially outwards, the star is very far away from us and much bigger than our telescopes (and actually much bigger than the Earth itself). Exactly the same thing happens with light rays from the Sun (which is much closer to us than other stars).

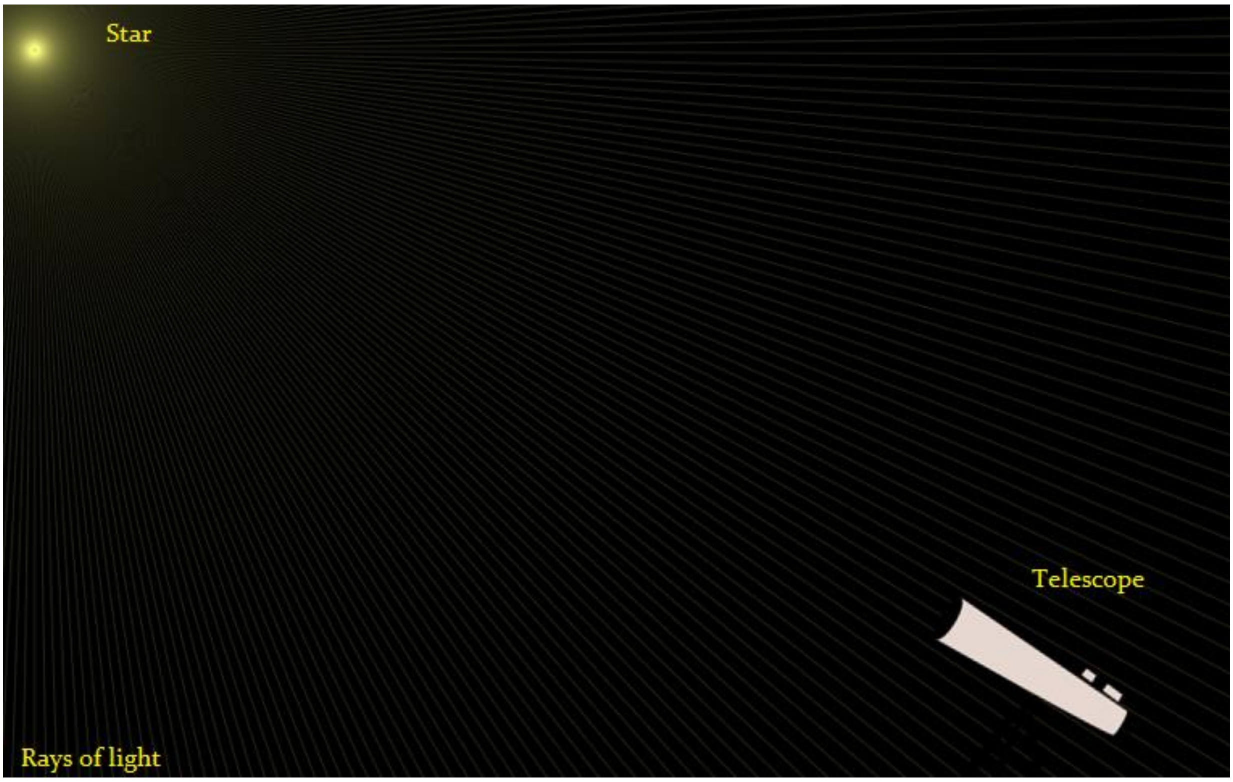


Fig.30: *Image of a star emitting rays of light, some of which arrive in the telescope's objective lens. The image is not to scale. Observe the fact that even though the star emits rays radially, the distance to the telescope ensures that the rays arriving in the objective lens are parallel.*

Based on the image above, one can conclude that the objective lens of the telescope acts as a "basin" which collects light rays. It is easy now to understand that more rays will be collected if the **area** of the "basin" (our objective) increases. If the diameter of the objective becomes twice as large, the area will increase 4 times. (Remember that the area of a circle is analogous to diameter squared: $A \sim D^2$).

But what does it mean that more light will be collected?

Collecting more light means that the object will appear brighter. This is why objects appear brighter when we observe them through the telescope compared to what we observe with naked eye, and this is why larger telescopes produce sharper images.

Now you are in a position to understand why we were able to observe better the Whirlpool Galaxy with a larger aperture telescope in our investigation phase.

Write down your observations in your notebook or here:

New telescopes are becoming increasingly larger in order to be able to observe fainter objects in the sky (why will they be able to observe them? Because they will be able to collect the few light rays that will come from them to us – and also because they will have superior resolution).

Teacher Guidelines

The diameter of the objective affects also the telescope resolution. The following puzzle can be investigated as part of a follow-up activity with more advanced students:

Can we observe the first human footstep on the moon?

On July 20, 1969, Neil Armstrong put his left foot on the rocky Moon. It was the first human footprint on the Moon.

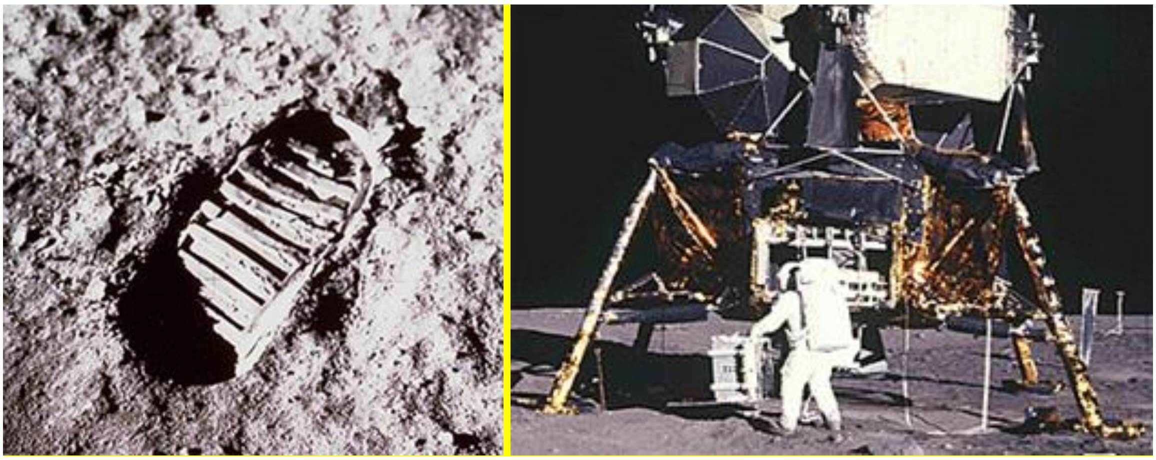


Fig. 31: *(Left):The first footprints on the Moon will be there for a million years. There is no wind to blow them away. (Right): Footage of humans' first landing on the moon from video camera that the astronauts of Apollo 11 had brought with them.*

As the puzzle title asks: Can we observe the first human footstep on the moon using a telescope? Write down your hypothesis.

Teacher Guidelines

The extent of the detail that can be seen in a telescope image depends on the atmospheric conditions and the diameter of the objective. Imagine viewing two celestial objects, for example two stars, near each other in the night sky. The angular separation of the two stars is the angle between the straight lines from the Earth to each star, as shown in the next figure .

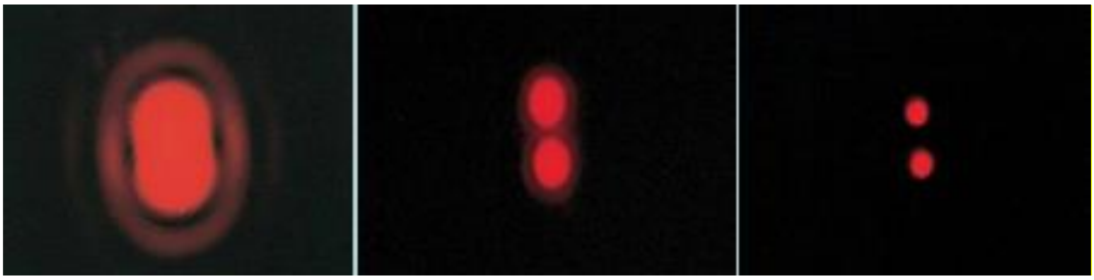


Fig. 32: *The same object observed from three different telescopes with increasing diameter of the objective (from left to right). We see that increasing diameter of the objective improves our angular resolution.*

Usually, for telescopes mounted on the earth "seeing" is one of the limiting factors in our resolution. "Seeing" is identified as the cumulative effect of atmospheric disturbances affecting our view of a celestial object. Figure 33 demonstrates the effect of seeing on the observation of a celestial object.

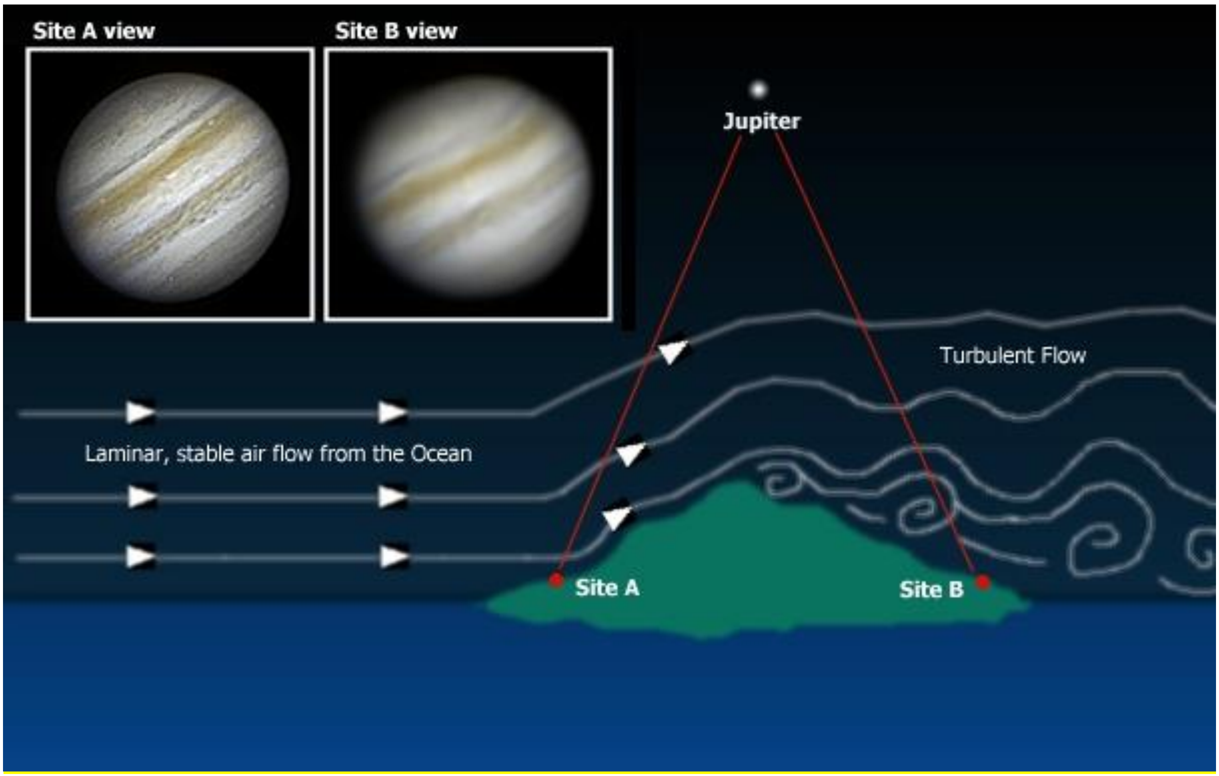


Fig. 33: *The effect of "seeing" in the view of the Jupiter from two different sites: Site A has low seeing and site B has high value of seeing. (Source: Views of the Cosmos, Astrophotography by Damian Peach http://www.damianpeach.com/seeing1.htm)*

The final limit in angular resolution is set by the atmosphere and is called "the diffraction limit": Even in the cases where no seeing exists (for example in the case of a space telescope), we cannot resolve as much as we would like.

The limit comes from the fact that light is a wave : When a light wave passes through a hole, the waves of light are bent at the edge of the hole, and the wave fans out a bit. This is called diffraction, and you can observe it in ocean waves striking a breakwater.

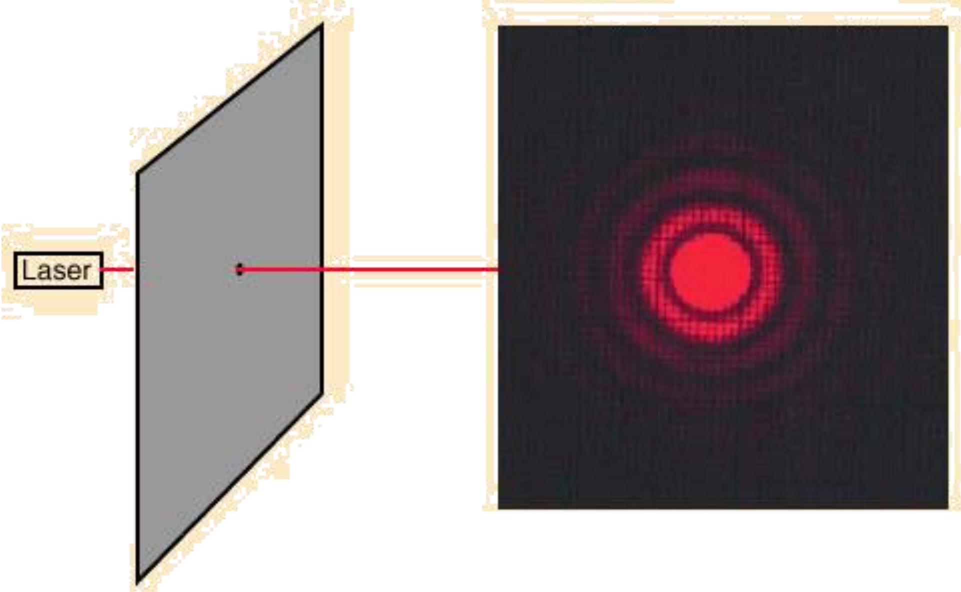


Fig.34: Diffraction of a laser beam passing through a circular aperture. (Source: Hyperphysics http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/cirapp2.html)

When you focus light waves with a lens (or curved mirror), however well-made, it's like combining a "perfect" lens with a hole, and the light waves are diffracted as well as refracted. The relationship determining the diffraction limit of our telescope is:

$$\delta\theta(rad) = 1.22\frac{\lambda(m)}{D(m)}$$

Here, $\delta\theta$ is the limiting angular resolution in radians (1 rad = 206265"), λ is the wavelength of light (measured in meters here), D is the diameter of the objective (lens or mirror) measured in meters.

Let's do an exercise together to understand more:

What should be the diameter of the objective of a telescope in order to observe an orange on the moon? We will assume that the orange has a diameter D of 10cm, that the earth – moon distance is equal to R=384,400 km and that the wavelength of the light coming from the orange is equal to 600nm.

Answer:

First we will calculate the angular size of the orange. To do that, we will use the relationship: $D(m) = \theta(rad) * R\ (m)$

(D is the diameter of the orange, R the distance of the orange to the observer on Earth which is equal to the Earth-Moon distance and θ is the angular size of the orange).

We have: $\theta(rad) = \frac{D}{R} = \frac{0.1(m)}{384400000(m)} = 2.6 * 10^{-10}\ rad = 0.00005''$

To be able to observe the orange on the moon, we need a telescope with limiting angular resolution δθ equal to or less than 0.00005".

For λ = 600 nm, and δθ = 0.00005", the diameter of our mirror must be:

$D(m) = 1.22*\lambda(m)/\delta\theta\ (rad) = 1.22*(600*10^{-9})/(2.6*10^{-10}) = 2{,}815$ m

Thus, the diameter of the telescope's objective should be equal to something less than 3km!

Evaluation/Reflection

Collect your final observations per puzzle and discuss with your classmates and your teacher. Reflect on your practice. Do you now feel confident regarding the use of a telescope?

Teacher Guidelines

It is very important that you collect your students' feedback in this part of the exercise. Make sure that their understanding is evaluated and any misconceptions that may arise are properly addressed. As a next step, it is proposed that students use some hands-on time with a telescope to test their newly acquired knowledge in situ.

Perhaps now we are in a better position to answer questions like:
-"How does a telescope operate"?
-"Is a 100mm aperture telescope enough to observe distant galaxies, like the Whirlpool Galaxy?"
-"How do I find the magnification of my telescope with a dedicated arrangement of lenses?"
- "Why do modern observatories have very large objective lens/mirror?"
- "Why do people use motorized mounts for their telescopes?"

Also, you are now in a better position to understand that there is no simple answer to the question "What telescope should I buy?"

Teacher Guidelines

If students ask you "What telescope they should buy" the answer is "it depends on what you want to do". Some combinations of telescope parameters are optimal for astrophotography, other for planetary observation and so on.

For beginners it is proposed that you

point them to this article.

https://www.skyatnightmagazine.com/advice/a-buyers-guide-to-telescopes-choosing-your-first-scope/

You are now invited to watch this final video about the telescope and its history

https://www.youtube.com/watch?v=InXWTQw_Wpc

Follow up project

Create a short video detailing the principle of operation of the telescope and its development through the years. You can dedicate some time to focus on one specific telescope of your interest and discuss its design and discoveries. You can present a modern telescope or a historical one.