Microlensing

Name of your institution: Institut d'Astrophysique de Paris

Title of the educational scenario template: KLiC scenario

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Version: 1.0

Subject

This scenario is based on the deviation of the light by massive objects. The light is emitted by a background source (star or galaxy) and received on Earth. In the absence of deviation, only one ray is received on Earth, along the direction to the source. If a mass (the lens) is located between Earth and the source, general relativity states that light rays are deviated towards Earth. If the source, the lens and the observer are perfectly aligned, a luminous circle will be seen. If there is a slight misalignment, this will result in multiple images, and an enhanced luminosity according to the mass of the lens. The students will discuss the geometrical aspect of this phenomenon, the different orders of magnitude of the lensing, and then apply this to a case of 'microlensing' to infer the mass of a lens in our Galaxy.

Student Age

15-18 years old.

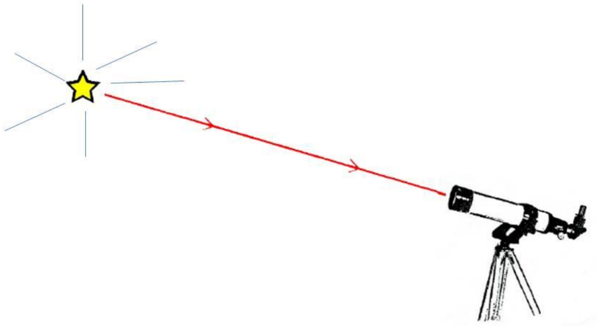
Science content

- needed science background for the teacher

  - the deviation of light

It is well known that light-rays travel along a straight lines. But why is it the case?

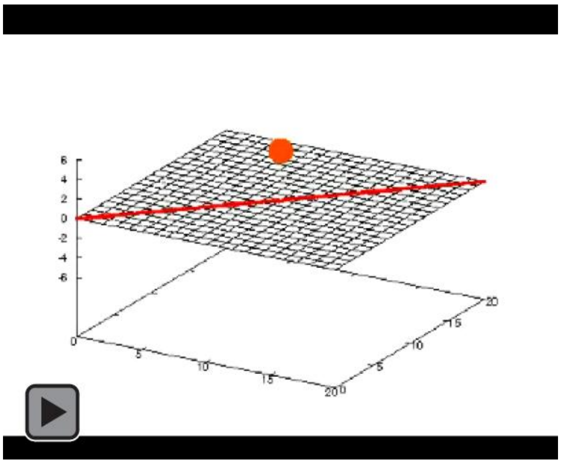
When a star shines (or when the lamp shines), it emits particles called photons in every directions around it. The light that one receives corresponds to the beam of photons whose track ends up in the telescope or in our eyes. So this is only a small portion of all photons emitted by the source.

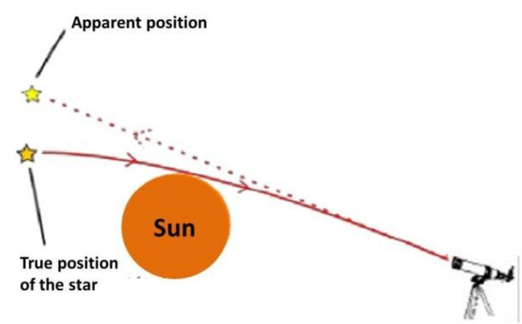


Those photons always choose the shortest path to go from one point to another (this is called the 'geodesic') in order to minimize the loss of energy. In general, the space that surrounds us is well described by a flat grid (this is the 'Euclidian geometry'), where geodesics are straight lines. If we were in a special position, where the particles were obliged to stay on the surface of a sphere, then geodesics would be curved.

- Gravity

In his general relativity theory published in 1916, Albert Einstein stated that any object with a large enough mass (stars or galaxies) may curve the space-time geometry. This is illustrated in the Figure on the right and in the animation. As the large mass approaches the light ray, it curves the space time (the horizontal grid), and deviates the path of the beam. Then, the light does not travel along a straight line anymore but along a curved line (which is again the shortest path).

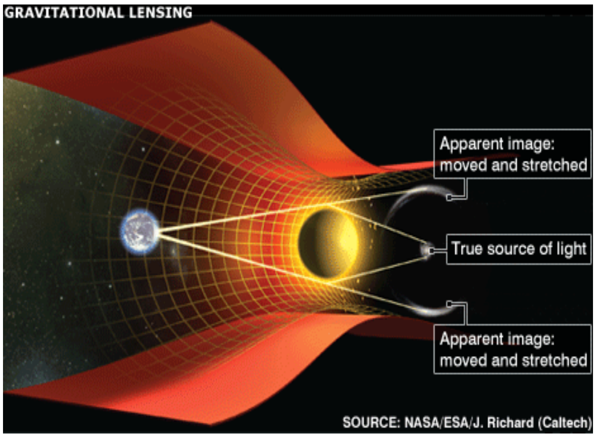


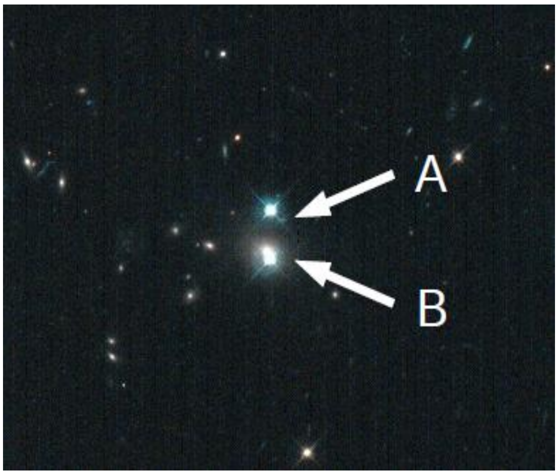


The first observation of light deflection was performed by noting the change in position of stars as they passed near the Sun. The observations were performed in 1919 by Arthur Eddington and his collaborators during a total solar eclipse, so that the stars near the Sun could be observed. The light emitted by the star is deviated by the Sun (solid track in the Figure). Thus, the image of the star is observed at a different angle (dashed track)!

- Gravitational lensing

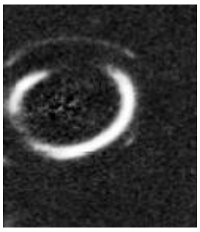
The effect of the gravitational lens depends on the mass of the lens. In the case of the eclipse, this is called a gravitational mirage where the apparent image is only slightly shifted. In case of a strong gravitational lens, multiple images can be seen since different paths followed by the photons ends up at the same point as illustrated below (left cartoon).





To observe multiple images, the angular separation between the images must be large enough, so the mass of the lens must be huge. For example, some galaxies at high redshift (or very large distance from our Galaxy), called quasars, are very luminous. If another galaxy is located in the same direction, it may curve the light emitted by the quasar. Dennis Walsh and his team observed the first gravitational lens in 1979. They observed two quasars (A and B in the figure on the right above) with identical properties (their spectrum essentially) and conclude that it was two images of the same galaxy, located at 8,7 billion light-years. The separation observed from Earth is 6 arcsec. And the galaxy that forms the lens is located at 3,7 billion light-years.

The luminosity of the quasar is then enhanced since more photons reach the telescope.



If the quasar is perfectly aligned with the lens, all rays will have a similar curvature around the galaxy-lens, and will end in our telescope. In such a case, one observed a ring, called the Einstein ring. In the picture on the left, one actually observes two rings, due to the alignment of three galaxies!

- Micro lensing

Now, what happens if the curvature is not as strong as in the cases above? For example, consider a source star around the Galactic center, at a distance of the order of a few thousand of light-years from us, and another one in-between, the lens, whose mass corresponds to the mass of a star, much smaller than the mass of a galaxy!

This will create curvatures of a few micro-arcseconds. Such cases are called ‘micro-lensing’. One cannot distinguish multiple images with the today instrumentation, but the amplification of the luminous intensity can be observed.

This is the subject of this exercice.

- prerequisite for the students
  Ability to work with different units and order of magnitude

  Some understanding of geometrical constructions and light

Learning objectives

The learning activity proposed is significant because it favors creatively the pupils’ knowledge concerning the concepts of: movement, gravity and light (emission and reception) in an unusual context of general relativity. It also challenges common conception of space. It also offers to the pupils the opportunity to test their own scientific hypothesis and also to test these hypotheses’ applicability in new learning contexts.

At the end of the learning activity the pupils will be able to improve and develop the competencies of:

- communication and interpersonal relationship
- working with different order of magnitudes
- Constructing a table of data and a graph

Inquiry-based character

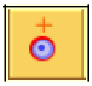
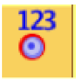
- The students explain possible solutions
- The teacher gives new concepts and expects students to use them
- The students infer new scenario

Applied technology

- SalsaJ software

Discussion guide

A. Preliminary discussion
   1. Discussion about light
      i. Isotropic emission
      ii. Light-rays and detection of photons that reach our eyes
      iii. You may use two mirrors to create multiple images
   2. Discussion about general gravity
      i. Explanation of the geodesic
      ii. Discuss an Einstein ring and/or a multiple image and/or the 'Eddington eclipse'
      iii. General gravity as a curvature of the space-time.
      iv. Consequences for the luminosity of the image
   3. Orders of magnitude
      i. Distance to galaxies, to stars; units of distance (light-years)
      ii. Separation: knowledge of arcsecond, degrees… Comparaison between multiple images separation and eyes/telescopes angular resolution
B. Application to micro-lensing
   1. Look at the different exposures (use SalsaJ to open all images)
      i. Comments: is there a lensing event? which case is it ?
      ii. Evaluate the evolution of the luminosity as a function of time. The date corresponding to each exposure and the value of the luminosity for one date is given in the excel file.

- The students have to decide which star is concerned by the lens effect (they must probably do a zoom on the central region to see it)
- Click the button  to open the photometry panel.
- Enter manually the position of the star (it should be 150 for X and Y, right at the center of the images) and the radius. The radius should be small (around 2) to focus on the luminosity around the star only; you may let the students choose different radius and see if they can see an effect.
- Click the button  to start the acquisition of data. When you click on a photo, the value of the luminosity in the circle around the star is given.
- Enter those values in the response file. The luminosity curve is plotted automatically (if you want students to learn how to use a spreadsheet, you may simply not provide them with the response file)

2. Analysis of the data

Different formulas related to the microlensing geometry and physics are required. The students cannot justify the physics behind, but they can infer which parameters are involved and they can sometimes do a simple dimensional analysis.

i. Estimate of the duration of the event, t_E : it is when the luminosity is higher than 7000 (arbitrary units).
ii. One derives then the radius of the Einstein ring over which the lens acts: $R_E = \frac{v_L . t_E}{2}$, where v_L = 2.10^5 m.s^{-1} is the velocity of the lens (one cannot derive this value from the data only; it is roughly the velocity derived in the exercise on “How to weigh a galaxy” but for our Galaxy).
iii. The distance between the telescope and the lens (careful: the lens is not the star, but another massive object between the telescope and the star) is assumed to be $d_L =$ 15000 light-years (half the distance to the center of the Milky Way).
Estimation of the angle: $\theta_E = \frac{R_E}{d_L}$ in radians.
iv. Finally, one computes the mass of the lens (in kg) using $M_L = \frac{(\theta_E . c)^2 . d_L}{2.G}$ where c is the speed of light, and G the gravitational constant. You should find about 5.7 10^{29} kg.
v. You may compare the result to the mass of the Sun. Is this coherent ?

Note that one derives a physical parameter of an object without any photons from this object !

Note that if there is a planet orbiting the lens star, it can also produce a magnification of light (during a shorter time); it is a method to detect distant extrasolar planets.

Assessment

STUDENT WORKSHEET

Unit Title

Introduction

You must learn

- **how to read an astronomical image**
- **how to interpret photometric data in terms of physical quantities**

Materials

- Suite of images of the same field but taken at different dates.
- The software SalsaJ.

Investigation

Observation worksheet

Name and surname of the participants at the experiment:

Category: □pupil; □ teacher student; □ teacher

Age: ___________, Gender: □ M, □ F

A. ?

Hypothesis You have discussed with your teacher about the lensing events observed in astronomy. What can you say about the suite of images ?

Data analysis What would you like to measure to confirm your hypothesis about the lensing event in those images? Do this measurement on each photo, and plot the associated curve in a spreadsheet.

Infer one or more relation(s) between the mass of the lens M, its velocity, the distance from the telescope to the lens, the duration of the observed event and other general parameters of the gravitation theory.

Your teacher provides you with the required formulae to analyze the curve you obtained.

Infer the mass of the lens and discuss your result.