EKA Advanced Physics Laboratory

Gravitational Lensing Experiment

Getting Started Guide

In this experiment, you will be studying gravitational lensing by simulating the phenomenon with optical lenses. The purpose of this document is not to explain the physics involved (and assumes you are somewhat familiar with the theory), but to provide a step-by-step guide to get started with the experiment, which is described on the following pages.

The equipment used in the experiment include: one logarithmic lens (simulating a point mass such as a black hole), one linear lens (simulating singular isothermal galaxies), an adjustable light source, a pinhole to represent the “observer,” a CCD camera to image what the “observer” sees, and a rail on which the equipment is mounted, as pictured in Figs. 1-4.

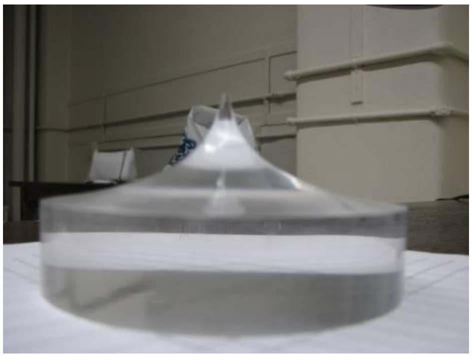


Fig. 1: Logarithmic lens (simulating a point mass such as a black hole).

Fig. 2: Linear lens (simulating singular isothermal galaxies).

Fig. 3: Light source, attached a cardboard with a small hole to make it a point source.

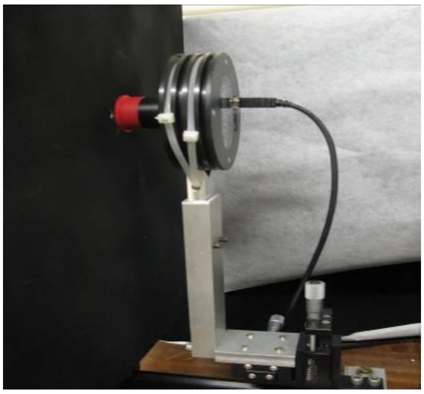
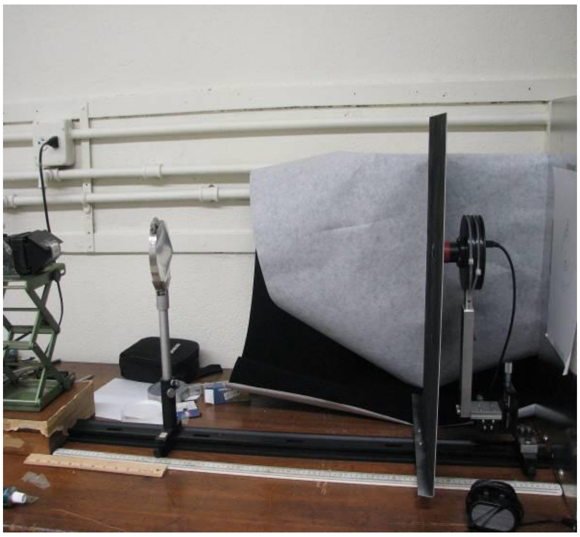


Fig. 4: CCD camera facing onto the pinhole “observer.”

Setup for the experiment

Mount the lens and board with pinhole on the optical bench in line with the light source, as pictured in Fig 5. The CCD camera should be positioned right behind the pinhole, although you will want to remove the CCD camera for the initial alignment.



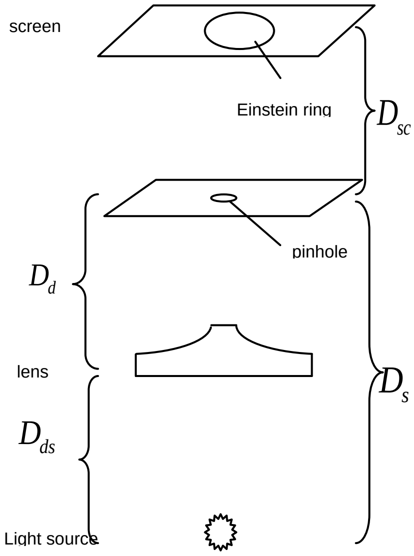


Fig. 5: Setup of experiment.

NOTE: Use gloves to touch the light source, as it can get very hot.

Preliminary Observations

Logarithmic Lens

(1) With the CCD camera removed, place a sheet of blank white paper at some measured distance from the pinhole.

(2) Align the light source, lens center, and pinhole "observer" in one line. Trace the Einstein ring as it is seen on the paper.

(3) Repeat this process for several different values of D_d, D_s and D_{ds}, and trace out the Einstein ring in each case.

(4) Mark your best estimate for the Einstein rings' center on the paper (they should be coincident if the paper did not move; if not, mark a separate center for each). How does the Einstein ring radius (in radians, the ring radius divided by the pinhole-screen distance) scale with the dimensional parameters? Are you able to reproduce the relationships shown in the *Summary of Basic Knowledge* document?

(5) Set up the equipment again as in (1), choose some values of D_d, D_s and D_{ds}, and trace out the observed Einstein ring for that configuration on a new piece of paper.

(6) Now move the source from the in-line configuration by a distance η, and observe how the Einstein ring "splits" into two images. Mark these images on the paper.

(7) Repeat this for several different values of η, to observe what happens to the image positions.

(8) After removing the paper, you can mark the center of the Einstein ring, and measure the distances from the ring center to each of the images for off-axis configurations. You should be able to qualitatively reproduce the results depicted in the graphs in the *Summary of Basic Knowledge* document.

Repeat steps 1-8 using the linear (isothermal) lens.

Measurements using the CCD Camera

In the following section, you will be using two programs. ***Maxim DL Essentials*** *deals with camera control, and* ***fv*** *deals with analysis of the collected data. You can find both of them on the computer's Desktop.*

Logarithmic Lens

(1) Mount the CCD camera behind the pinhole. Turn on the computer, and open the software ***Maxim DL Essentials***.

NOTE: Be sure to attach the battery pack to the camera when taking the pictures, as this will provide the power to the chiller to reduce thermal noise.

(2) Choose **focus** in ***Camera Control*** window, taking pictures sequentially.

(3) Align to get the Einstein ring, and move the camera so it is centered on the screen.

(4) Take a picture of the Einstein ring and save the file in FITS format. Open this file in the program *fv*, and determine the ring radius r_1.

NOTE: Use **Ruler** in **Tools** menu in ***fv*** to read the ring radius *r* (or diameter, and divide by 2). The ruler has a right triangular shape, and is set by clicking and dragging the mouse. It is better to do this several times and take the average. The value is in the units of pixels. Each pixel is 8.6μm by 8.4μm, so use 8.5μm in the experiment.

NOTE: It may be helpful in determining the extent of the Einstein ring to use several tools:

-You may adjust the image contrast by left-clicking on the image and dragging the mouse across, and change the color scheme in the **Colors** menu.

-You can zoom/resize the image using the options in the **Zoom** menu and also the arrow at the lower right corner of the image.

-You can generate a contour map using **Tools → Make Contour Map**.

-You can generate a 2-D intensity profile along any straight line using the options in **Tools → Draw Profile**.

(5) Determine the radius R of the Einstein ring as seen on the paper (at a distance D from the pinhole) in the previous section, using data with the same lens configuration as the current setup. Use the formula $r/R = X/D$ to accurately determine X, the distance between the camera chip and the pinhole. *This serves as your calibration relating physical image size to angle*. For example, the Einstein angle is arctan (r*8.5μm/X), where r is the ring radius in pixels. As long as the camera is not moved, this calibration will remain constant.

(6) Find the center coordinate of the Einstein ring; this value will be used later. The best way is to use the **Region Files** option in the **Tools** menu - choose **Circle**, plot the circle to overlap the Einstein ring, and the center coordinate will be indicated. (You may wish to use a Contour Map to aid in determining where the ring is.)

(7) Go back to ***Maxim DL Essentials***, and set up your background subtraction, which you will use in the last part of the experiment**.** ***(****Please see the section on intensity measurement at the end of this document for details. You will not need the background-subtracted images now, but you will need them later.)*

Use a book to block the light passing through the lens. Use **Single** to take an image with the same exposure time as what you are using. You will use this file as the background to subtract in the last part of the experiment.

(8) Change the values of D_d, D_s, D_{ds}, measure the ring radius r, D_d, D_s, D_{ds}, and use the value of D_{sc} calculated from step (5). Calculate $D = \frac{D_d D_s}{D_{ds}}$,

$\theta_E = \arctan \frac{r}{D_{sc}}$, and verify that $\theta_E \propto D^{-\frac{1}{2}}$.

(9) Choose one set of values of D_d, D_s and D_{ds}. Move the light source from the axis a distance η, and choose **Single** to take a picture. Measure the distances δ_+, δ_-

between the two images and the center of the Einstein ring (as determined in (6)). This can be repeated for several values of η.

Calculate $\theta_E = \arctan\frac{r}{D_{sc}}$, $\beta = \arctan\frac{\eta}{D_s}$, $\theta_+ = \arctan\frac{\delta_+}{D_{sc}}$, $\theta_- = \arctan\frac{\delta_-}{D_{sc}}$.

Verify that $\theta_\pm = \frac{1}{2}(\beta \pm \sqrt{\beta^2 + 4\theta_E^2})$.

(10) Do this about 5 times for different positions of the light source and lens, to map out the dependence of $\theta_\pm$ on the dimensional parameters. You will want to produce graphs similar to those shown in the *Basic Knowledge* document.

Linear Lens

Follow the same procedures as for the logarithmic lens.

In this case, bear in mind that if $\beta < \theta_E$, $\theta_\pm = \beta \pm \theta_E$; if $\beta > \theta_E$, there is only one image at $\theta = \theta_+ = \beta + \theta_E$.

Intensity measurement

How to set up background subtraction

There are two ways to do the background subtraction in ***Maxim DL essentials***.

Method 1: Take an image as described in step (7) above and save it as a FITS file. This file will be the background file that you want to subtract. Choose **Process** – **Setup Dark Subtract**, and add this file, click OK. Then open each file that needs background subtraction (i.e. your data files), and select **Process** – **Dark subtraction**.

Method 2: After adding the background file in **Setup Dark Subtract**, check the box before **Dark subtract** in **camera control window** before you take each image, then the background will be automatically subtracted.

Measuring the intensity

Use **Region Files** in ***fv*** to approximate the two images seen for non-aligned setups in the pictures taken in the above steps. Generally, the **Ellipse** option is best, although you may want to try other shapes if they are more applicable. The flux inside each such region (i.e. I_+, I_-) can be read in the ***Edit Region*** dialog box that pops up.

NOTE: If you have multiple regions in your image, the listed total flux will be the total summed over all regions. If you want to see only the flux in one particular region, you must delete all the others first.

Determine the ratio I_+ / I_- in each of your images.

Compare the measured intensity ratios with the theoretical ratios μ_+ / μ_-, where $\mu_\pm = \frac{u^2+2}{2u\sqrt{u^2+4}} \pm \frac{1}{2}$, with $u = \beta\theta_E^{-1}$ for the logarithmic lens, and $\mu_\pm = \frac{\theta_\pm}{\beta} = 1 \pm \frac{\theta_E}{\beta}$ for the linear lens.