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Modern Gravitational Lens Cosmology for Introductory Physics and Astronomy Students

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Recent and exciting discoveries in astronomy and cosmology have inspired many high school students to learn about these fields. A particularly fascinating consequence of general relativity at the forefront of modern cosmology research is gravitational lensing, the bending of light rays that pass near massive objects. Gravitational lensing enables high-precision mapping of dark matter distributions in galaxies and galaxy clusters, provides insight into large-scale cosmic structure of the universe, aids in the search for exoplanets, and may offer valuable insight toward understanding the evolution of dark energy. In this article we describe a gravitational lensing lab and associated lecture/discussion material that was highly successful, according to student feedback. The gravitational lens unit was developed as part of a two-week summer enrichment class for junior and senior high school students. With minor modifications, this lab can be used within a traditional classroom looking to incorporate topics of modern physics (such as in a unit on optics).

Preparing students for gravitational lensing

Before discussing gravitational lensing, it is helpful to briefly introduce the essential concepts and consequences of general relativity. Gravity, according to general relativity, is not a force, as suggested by Isaac Newton. Instead, space and time "bend" near massive objects, such as the Sun, creating an illusion of a force. For example, when light passes near a massive object, it is traveling in a curved space, "forcing" its path from Euclidean straight-line motion. The light becomes *gravitationally lensed*. This effect is well modeled by ordinary optical lenses. By exploring the consequences of the equivalence principles (EPs) and engaging with in-class demonstrations, students can better appreciate how matter bends space. Below we briefly describe how these concepts were introduced to the students.

At the heart of general relativity, the EPs state that no experiment can distinguish between a force due to gravitational attraction (in a uniform gravitational field where, importantly, the field's gradient vanishes) and a force due to accelerated motion. The following thought experiment nicely demonstrates the counterintuitive predictions of these principles: Suppose an astronaut, in deep outer space, experiences a force and wonders if her ship's rockets have been activated. Through experiments performed within the ship, and without looking outside, can she determine if the ship is accelerating because the rockets have fired or, instead, the ship is accelerating due to the gravitational pull of a nearby massive planet? The EPs simply say the astronaut cannot distinguish between these two scenarios, yet the consequences are extraordinary. Suppose the astronaut fires a laser beam across the ship. If the ship is accelerating upward, then, according to her description of events, the path of the light will appear to curve downward. Applying the EPs, we are forced to conclude that light must travel in a curved path if the ship is placed near a massive object, say, on the surface of Earth (see, for example, Chapter 6 of Ref. 1 for a more complete discussion). As light is massless, how does it "feel" the effects of gravity? This paradox led Einstein to make an astonishing suggestion: *space* itself is curved.[2] Light is trying to travel in a straight line but cannot! During a 1919 solar eclipse, Arthur Eddington observed the deflection of light by the Sun's gravitational field. This was the first evidence in support of general relativity over Newton's theory of gravity. Light's deflection near massive celestial bodies is the key mechanism behind gravitational lensing and worthy of additional discussion with the students.

The concept of "bent" space was unfamiliar to most students. We found it helpful to present both in-class demonstrations, such as Leon's triangles[3] and the curved space bucket,[4] as well as captivating simulations[5] or other online resources, such as ComPADRE.[6] Many students had heard of black holes. These astrophysical objects represent an extreme bending of space, making them an excellent tool to explore the strange behavior of light in strongly curved space. Our black hole demonstrations included many online media simulations, such as an astronaut's journey toward a black hole[7] followed by a final plunge past the event horizon.[8] Perhaps along the way our astronaut momentarily illuminates a candle. The light would exhibit weird effects such as echoings and caustics.[9] Finally, students might find the classic books written by Einstein,[10] Feynman,[11] and Gamow[12] to be helpful and inspiring.

Introducing gravitational lensing

Armed with this relativistic foundation, students were prepared to tackle gravitational lensing. To motivate the lab, we first presented the students with images of galaxy-galaxy lensing, where a galaxy is lensed by another galaxy instead of a galaxy cluster or other massive body (Fig. 1). We then asked the students to speculate on the relevant features in the images. After this discussion, we described the physical mechanism of gravitational lensing. Gravitational lensing is a conse-

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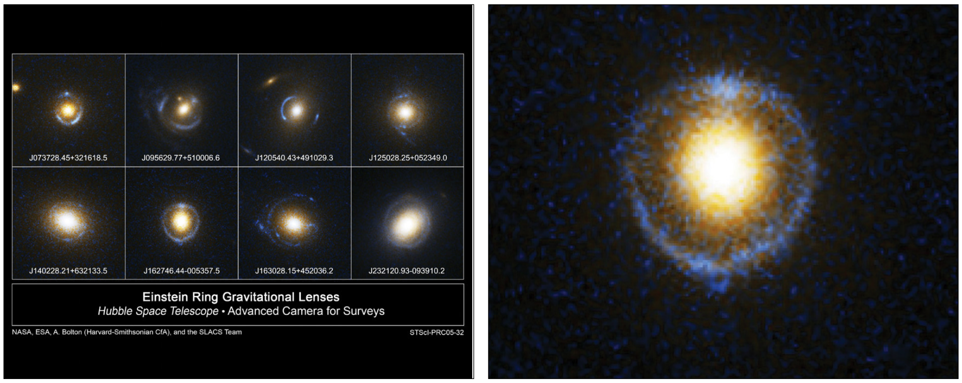

Fig. 1. Einstein rings.[13] The left figure depicts Einstein rings captured with the Hubble space telescope. The yellowish blobs in the middle of each ring are giant elliptical galaxies roughly 2 to 4 billion light-years away. The blue ring around each blob originates as light from a background galaxy roughly 4 to 8 billion light-years away being distorted through the process of gravitational lensing. The blue color, which is often enhanced for publicly released photos,[14] suggests these are young galaxies with active star formation. The right figure depicts a zoom-in of one of the galaxy-galaxy lensing images from the left. It is instructive to allow the students to speculate upon the physical process causing the ring structure. As a comparison, we also showed galaxies without gravitational lensing.

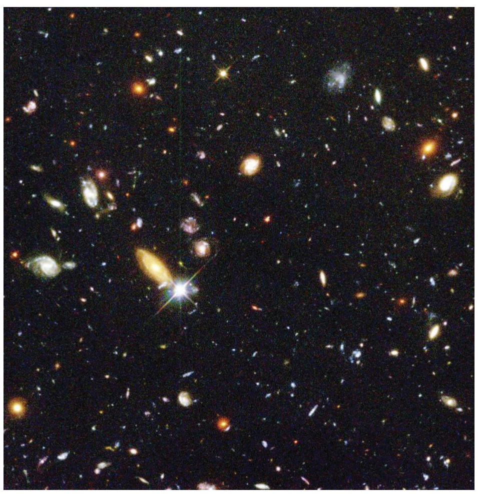

Fig. 2. The Hubble Deep Field image. This image (taken from Ref. 19) represents an extremely narrow sliver of the sky, about the size seen through a (transparent) dime at a distance of 75 feet away. It captures around 1500 galaxies at various stages of their evolution and dating as far back as 10 billion years ago.[19] Distribute a high-quality full-sized version of this figure, which is required to answer question 5, as part of the laboratory materials. In our experience, it is worth the extra trouble to obtain a high-quality color printout of the Hubble Deep Field image so that the students may readily identify a variety of galaxy sizes and shapes.

Fig. 3. The "gravitational" lens. The lens is a broken off wine glass base. For safety, we smoothed the stem's top with a Dremel tool and placed black tape over the rough edge. Additionally, this tape serves a scientific purpose: it blocks visibility down the center of the glass. For a cluster or other massive and luminous lensing object, background sources are not generally visible down the center of the gravitational lens.

quence of the bending of light's path as described by general relativity. As mentioned above, a large distribution of mass (the lens), such as a galaxy or clusters of galaxies, deflects light emitted by other, distant background galaxies or clusters of galaxies (the source) located behind the lens. This causes a distortion and magnification of the background sources. In the weak lensing regime, these distortions are small (percent level) and are thus only measurable statistically. However, in the strong lensing regime, these distortions are extreme and noticeable by eye. The lensing in Fig. 1 displays a special feature of strong lensing: Einstein rings. An Einstein ring is a special case of strong lensing that occurs when the source, lens, and observer form a straight line.

One of the most important aspects of gravitational lensing is that the observed distortions are only due to the presence of mass. This simple yet powerful feature allows astronomers to indirectly measure the distribution of dark matter, which is not directly observable by telescopes, as well as improve mass measurements of astronomical objects that might be difficult to calculate.

Gravitational lensing optical lab

The purpose of this lab is to provide students with an understanding of gravitational lensing via an optical lens model. Necessary materials are minimal: a lab manual/sheet for the students to record their observations and answer questions, a sheet of graph paper representing space as a Euclidean coordinate system, the Hubble Deep Field image shown in Fig. 2, and an optical "gravitational" lens. A number of excellent articles describe the construction of gravitational lens demonstrations.[15-18] To make our lenses we closely follow the procedure described by Ref. 14. Using an inexpensive wine glass, we break off the base, which will serve as the gravitational lens simulator shown in Fig. 3. The wineglass' base and stem should be cylindrically symmetric and the lens' profile approximately logarithmic.[15] For safety the stem is filed down and covered with tape. The tape also hides the center of the lens, which would normally be blocked by the foreground galaxy or galaxy cluster.

Students were placed in groups of two. Each group was provided with the aforementioned lab materials. To assist with their observations, students should close one eye and look directly down the center of the lens, fixing their eye with the center as it moves. The following questions, some of which refer to Figs. 2 and 4, were given in the lab handout.[20]

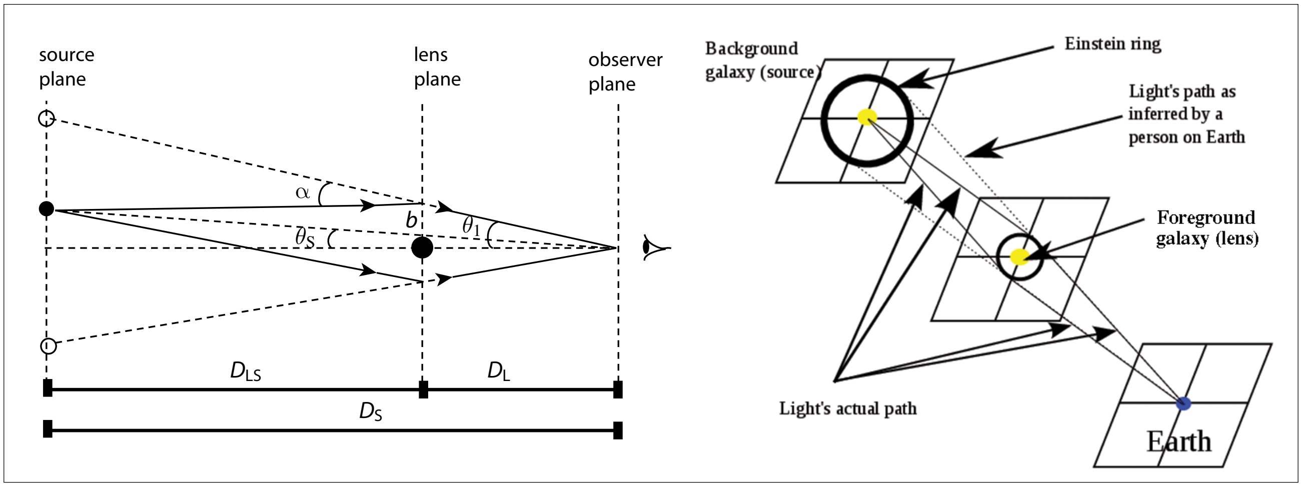

Fig. 4. Typical gravitational lens setup. A schematic diagram (left) was included as part of the lab manual and is required for answering many of the questions. The cartoon diagram (right) nicely complements the schematic. In the particular configuration shown, the background galaxy, lensing galaxy, and Earth are aligned. Light from the background galaxy is gravitationally lensed. To an observer on Earth, the background galaxy will appear as an Einstein ring.

1. Take the graph paper and move the lens over the grid lines. How do the lines warp? (Inward? Outward? Circular? Square? Symmetrically?) If the grid lines represent flat space, what is causing the observed distortion? Next, explore how a gravitational lens will distort other shapes such as triangles, ovals, and circles.

2. When should the wine stem mimic the effect of an astrophysical gravitational lens? When does the wine stem become a poor model of gravitational lensing?

3. Draw a solid oval (galaxy) about half the size of a fingernail on an intersection of grid lines. As you move the lens about the galaxy, you will notice four configurations: an undistorted galaxy, a single distorted galaxy, two strongly distorted galaxies, and an Einstein ring. (See Fig. 5, which was not provided to the students.)

- As you move the lens, how does the galaxy stretch with the space-time lines?
- In your own words, describe the galaxy's location (in relation to the lens' center) when it appears undistorted yet still under the lens. This is weak lensing.
- In your own words, describe the galaxy's location when it is distorted, but you only see one image of it. This is strong lensing.
- In your own words, describe the galaxy's location when you see two images of it.
- Briefly explain how this is possible. *Hint:* it will be helpful to imagine how the light travels from the galaxy to you. Astronomers regularly observe this phenomena, for example, as double quasars. This is another example of strong lensing.
- In your own words, describe the galaxy's location when it appears to spread into a ring? This feature, called an Einstein ring, is also characteristic of strong lensing.

4. Draw four galaxies of varying radius. How does the Einstein ring depend on the galaxy's radius. What happens for galaxies of "zero" radius?

5. A typical gravitational lensing configuration is shown in Fig. 4. D_L is the distance from your eye to the lens, D_{LS} is the distance from the lens to the paper/galaxy, and D_S is the distance from your eye to the paper/galaxy.

- In your own words, describe the significance of the variables θ_S, θ_I, and α.
- During a 1919 solar eclipse, Arthur Eddington observed the deflection of distant starlight by the Sun. Which variable characterizes the amount of angular deflection? Which two variables can Eddington directly measure with his telescope? Bonus: Can you write an equation relating these three variables?

6. Now you will observe the effect of distances between your eye, the lens, and the source (paper). Line up the lens (sitting flat on the graph paper) to make an Einstein ring. Do this before every step below.

- What happens to the size of the ring when you lift the lens but keep your eye in place? Which variables (D_L, D_{LS}, and D_S) change? Which remain constant?
- What happens to the size of the ring when you lift your eye, keeping the lens in the same place (held above the source)? Which variables (D_L, D_{LS}, and D_S) change? Which remain constant?
- What happens to the size of the ring when you lift your eye and the lens together, keeping the distance between the two constant? Which variables (D_L, D_{LS}, and D_S) change? Which remain constant?

7. Now examine the HST Deep Field image. Place the lens somewhere on the image.

- Describe the change that occurs in what you see (with and without the lens).
- Describe how one could look for black holes using gravitational lensing.
- Describe how you can differentiate between "small" stellar mass black holes (about five times more massive

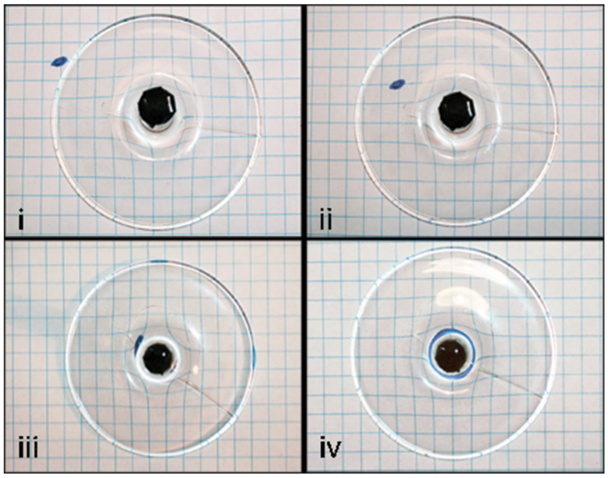

Fig. 5. A lensed oval "galaxy." Four possible lensing situations are viewable in this experiment. No lensing (top left): the galaxy shape is unaffected, but notice that "empty space" (i.e., the Euclidean coordinate grid) appears warped. Weak lensing (top right): the distortion in shape is too small to be discerned by the student. Strong lensing (bottom left): a strong distortion to the galaxy *along with a second image of it on the other side of the lens.* Strong lensing (bottom right): with direct alignment, an Einstein ring is formed.

than the Sun) and supermassive black holes. Supermassive black holes are at the centers of most galaxies and are about 10,000 times more massive than the Sun.

Hint: consult Fig. 4 and use your intuition.

8. Write your own questions and experiment to find the answer! Some to consider:
   - How do wine stems of varying shape and thickness effect the lensing observations? (*Note*: Students should be provided with a diverse set of wine stems.)
   - How might an astronomer detect dark matter from gravitational lensing observations?
   - Suppose the dark matter is spread over large distances. How can you model a dark matter distribution as a collection of many smaller lenses of the type you have used in this lab? How would the mass distribution of dark matter influence the lensing?

Going further

Directly following the lab, the students were given a 30-minute lecture and Q&A session. The primary focus was on detecting black holes and searching for dark matter.

What if a black hole passes close to Earth? Suppose you have a very clear, crisp view of the night sky. Describe what you might see. At such close distances the black hole will act as a strong gravitational lens that streaks across the sky. These simulations[21,22] show a black hole as it moves across a field of background galaxies or stars. Students should observe highly distorted galaxies and short-lived Einstein rings.

Utilizing gravitational lensing, astronomers are able to indirectly "observe" dark matter. Figure 6 shows the mass maps of two different clusters of galaxies. In each figure, both x-ray and gravitational lensing mass maps are shown. The x-ray observations directly observe the luminous matter, due to stars, which is represented by color concentrations (sometimes called a heat map, as warmer colors are used for higher concentrations). The contour lines in each map represent the mass concentrations as derived from gravitational lensing analysis. To construct these mass profiles, astronomers examine the weak lensing signal in thousands of galaxies behind the cluster and statistically combine them. With these figures displayed, ask the students to identify the "missing matter" and have them suggest theories for the discrepancies between the gravitational lensing contours and the x-ray heat map (some popular answers we heard were extra dimensions, planets, neutrinos, incorrect distance measurements, and dust clouds). The areas with high mass concentrations in the

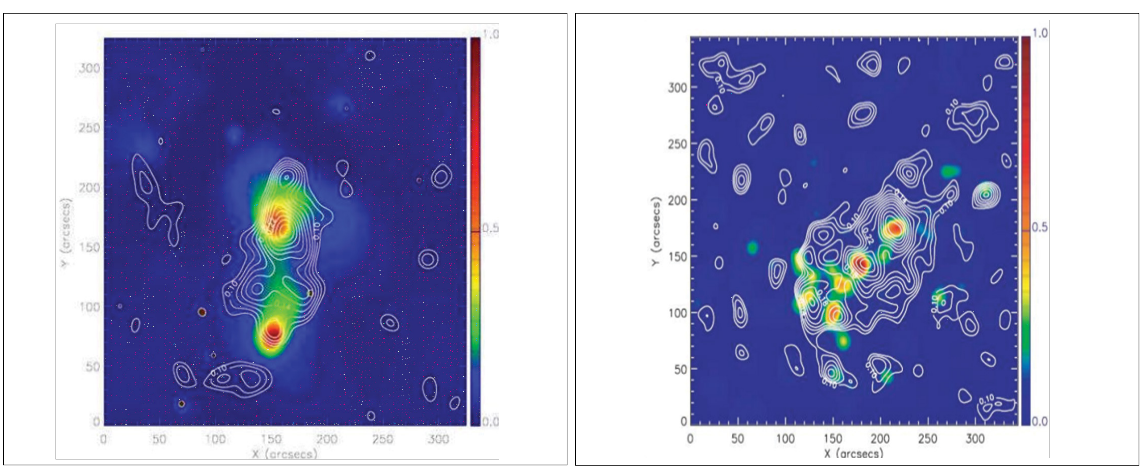

Fig. 6. Map of dark and luminous matter. These figures (taken from Refs. 23 and 24) show the distribution of luminous matter (color map) and matter inferred from gravitational lensing (contour lines). Notice an abundance of matter concentrated in regions for which there is no luminous counterpart; the discrepancy is evidence for dark matter. Before revealing dark matter as the currently accepted explanation, ask students to suggest their own theories explaining the discrepancy.

lensing map, but not in the heat map, are explained by dark matter. Gravitational lensing is a popular method to measure dark matter in astronomical bodies. Figures such as these provide valuable information about the dark matter distributions in these clusters and, by extension, our universe and its evolution.

The lab, lecture, and discussion described in this article provide inspiration for further investigations with out-of-class projects and/or assigned problems. For example, from results of question 6 students can propose empirical relationships between the independent variables and the radius of an Einstein ring. Many of the resulting student projects, as well as additional resources, can be found on the class website.[25]

Acknowledgments

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References

1. J. B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (Addison-Wesley, 2003).
2. A. Einstein, "Die Grundlage der allgemeinen Relativitatstheorie," *Ann. Phys.* **354**, 769822 (1916).
3. https://wiki.brown.edu/confluence/display/physlecdemo/8C10.60+Leon%27s+ Triangles.
4. http://www.physics.brown.edu/physics/demopages/Demo/astro/demo/8c2000.htm.
5. http://www.youtube.com/watch?feature=endscreen&v=f0VOn9r4dq8&NR=1.
6. http://www.compadre.org/portal/items/detail.cfm?ID=11451.
7. http://imagine.gsfc.nasa.gov/docs/science/know_l1/black_holes.html.
8. http://www.youtube.com/watch?v=eI9CvipHl_c%22.
9. http://www.youtube.com/watch?v=Pe8sRjqtldQ.
10. A. Einstein, *Relativity: The Special and the General Theory* (Empire Books, New York, 2013).
11. R. Feynman, *Six Not-So-Easy Pieces: Einstein's Relativity, Symmetry and Space-Time*, 4th ed. (Basic Books, Philadelphia, 2011).
12. G. Gamow, *Mr. Tompkins in Paperback* (Cambridge University Press, 1993).
13. http://www.cfa.harvard.edu/news/2005/pr200537_images.html.
14. See http://www.ifa.hawaii.edu/info/press-releases/Bolton7-08/.
15. Maria Falbo–Kenkel and Joe Lohre, "Simple gravitational lens demonstrations," *Phys. Teach.* **34**, 555 (Dec. 1996).
16. Vincent Icke, "Construction of a gravitational lens," *Am. J. Phys.* **48**, 883 (Oct. 1980).
17. J. Higbie, "Gravitational lens," *Am. J. Phys.* **49**, 652–655 (July 1981).
18. http://www.physics.brown.edu/physics/demopages/Demo/astro/demo/8c2040.htm.
19. http://hubblesite.org/newscenter/archive/releases/1996/01.
20. Readers can view the answers at *TPT Online*, http://dx.doi.org/10.1119/1.4917429.
21. http://www.het.brown.edu/people/ian/astro/Cool_Stuff.html.
22. http://www.youtube.com/watch?v=2-My9CChyBw.
23. M. J. Jee, R. L. White, H. C. Ford, J. P. Blakeslee, G. D. Illingworth, D. A. Coe, and K. V. H. Tran, "Hubble Space Telescope Advanced Camera for Surveys weak-lensing and Chandra x-ray studies of the high-redshift cluster MS 1054–0321," *Astrophys. J.* **634** (2), 813 (2005).
24. M. J. Jee, R. L. White, N. Bentez, H. C. Ford, J. P. Blakeslee, P. Rosati, R. Demarco, and G. D. Illingworth, "Weak-lensing analysis of the $z \approx 0.8$ cluster CL 01521357 with the Advanced Camera for Surveys," *Astrophys. J.* **618**(1), 46 (2005).
25. http://www.dam.brown.edu/people/sfield/teaching.html.

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