Mimicking of gravitational lensing and microlensing in a classroom

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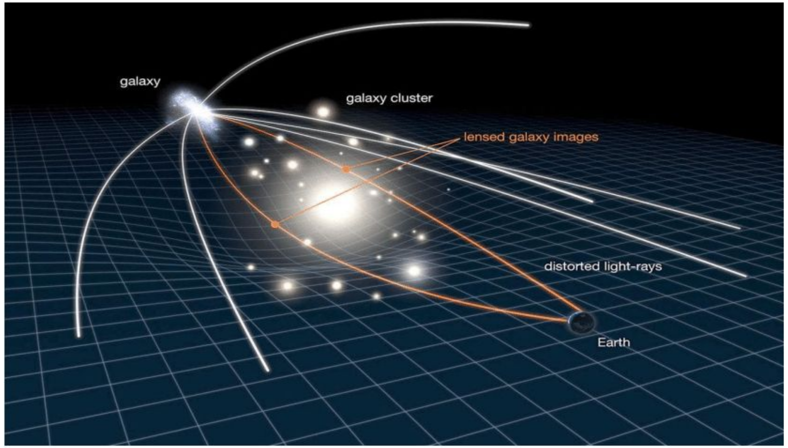
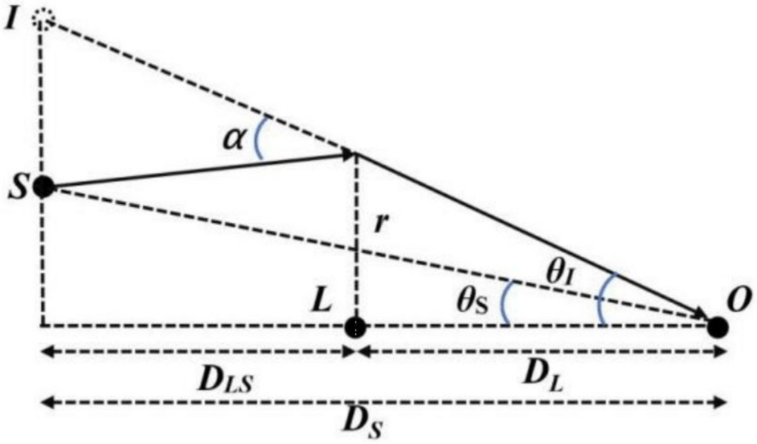
Based on Einstein's theory of general relativity, a light ray is deflected when it travels around a massive body, thereby generating a gravitational lensing effect. If the image is too small to be resolved by telescopes, we simply detect the sum of the light of the images, which is also known as gravitational microlensing. When a point-like object passes between a background light source and an observer, the background illuminance fluctuates due to the gravitational microlensing effect. These objects are called massive astrophysical compact halo objects (MACHOs). In this poster, an optical lens corresponding to a gravitational lens was printed using a 3D printer to demonstrate the images of an Einstein ring and a light source. Meanwhile, a process for searching for MACHOs and exoplanets was simulated based on the 3D printed lens, which could well present the total brightness change of the gravitational microlensing effect.

Theoretical background

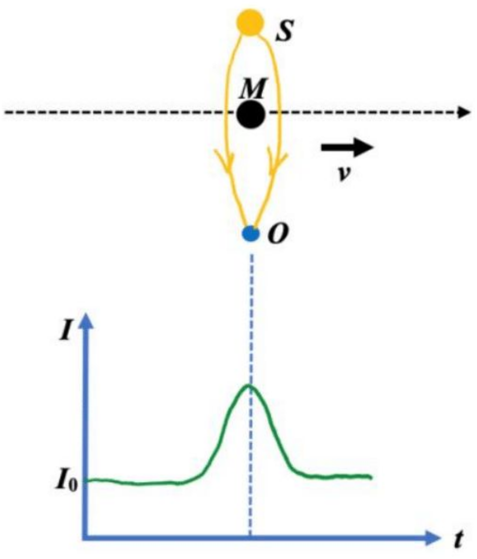




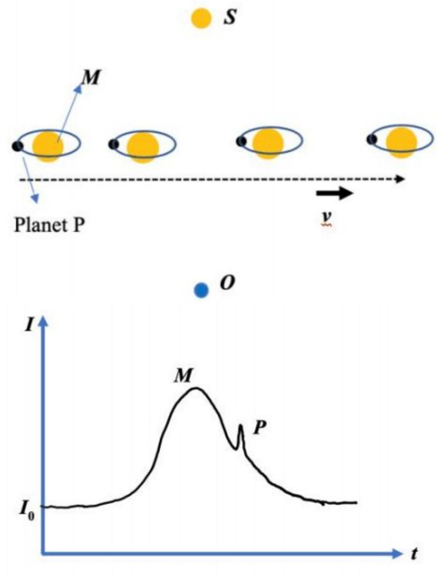
Based on Einstein's theory of general relativity, a massive body can deflect a nearby light ray. Thus, the body produces a gravitational lensing phenomenon. This is similar to the deflection of a light ray by an optical lens.

A light ray is deflected by a gravitational field when it passes near a point-like object L. When the three objects are collinear, the image of S is a symmetric ring, which is called an Einstein ring. If S is not collinear with the line connecting L and O, the light source has two images.

Theoretical background

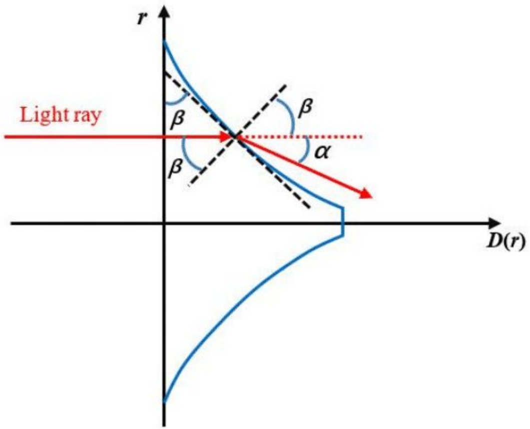


when a point-like object M travels between the source S and an observer O at a speed of *v* and in a direction perpendicular to the line of sight, the illuminance of the star S fluctuates due to the gravitational microlensing effect.



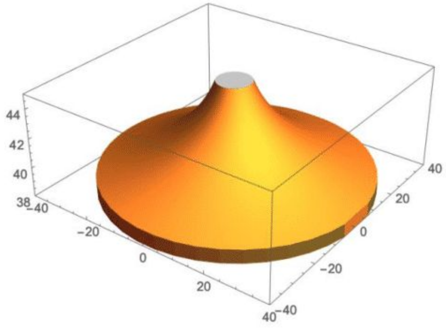
When a star-planet system travels between S and O, gravitational microlensing also occurs due to the gravitational field of the planet, where the change in the relative position between the star M and the planet P is ignored.

Lens manufacturing

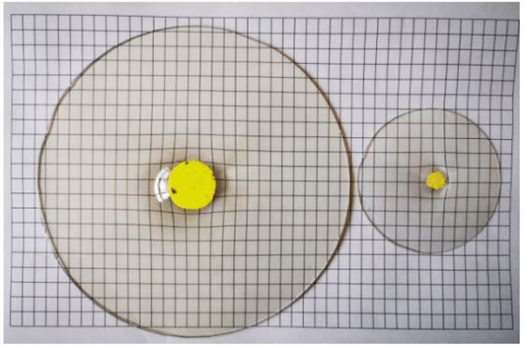


A lens was produced with a 3D printer using the proposed method by Sidney Liebes *et al.*
(Liebes, Sidney. "Gravitational Lens Simulator." Am. J. Phys. 37.1 (1969): 103-104)

Assuming that $D(r)$ is the thickness of the lens at the bottom radius r, and that n is the refractive index of the lens, where the incident angle is β and the deflection angle is α, then the slope of the tangent line satisfies $\frac{D(r)}{dr} =-\tan\beta$, and the light ray is incident perpendicular to the bottom of the lens. According to Snell's law, $n\sin\beta = \sin(\alpha+\beta)$. When α and β are small, $\frac{D(r)}{dr} \approx -\beta$ and $n\beta \approx \alpha+\beta$. Therefore, $\frac{D(r)}{dr} =-\frac{4GM}{(n-1)c^2}\frac{1}{r}$. Let $A=\frac{4GM}{(n-1)c^2}$, then the following expression can be derived through integration: $D(r) =-A\ln(r)+B$, where B is an integration constant.

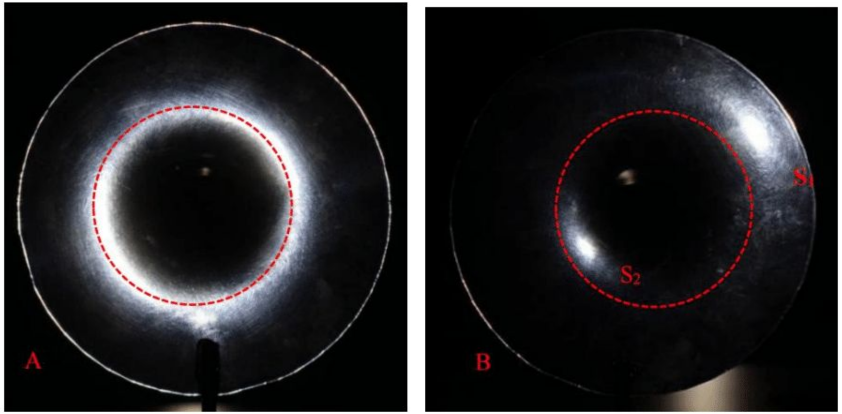


A 3D graph was plotted in *Mathematica*

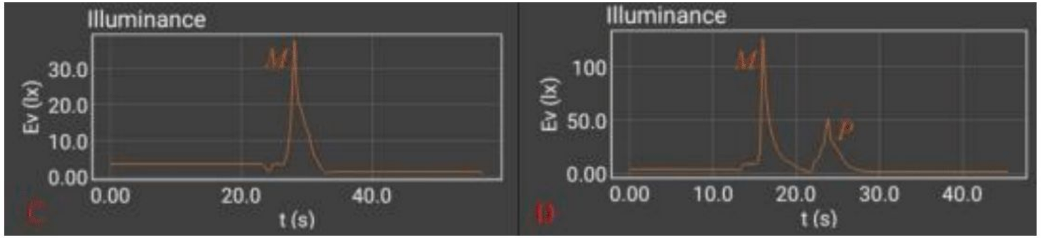


Two lenses with different sizes were printed using the 3D printer, where a transparent photosensitive resin was used as the consumable material.

Simulation of gravitational lensing



The lens was moved along the vertical direction of the connecting line between the camera and the light source so as to change the lens position. When the three objects were collinear, an Einstein ring appeared, as shown in Fig. A. When these three objects were not collinear, two images could be observed, as shown in Fig. B.



To simulate the fluctuations in the illuminance of the background light source during the MACHOs movement, the change in the illuminance was measured using the Phyphox software application. A mobile phone was placed in the camera position. Lens L_1 was moved slowly along the direction perpendicular to the line connecting the mobile phone and the light source. Fig. C shows the change in the illuminance when the lens was used to scan the line connecting the phone and the light source.

The centers of the two lenses were adjusted to lie at the same height, and these two lenses were moved slowly so that they swept the line connecting the phone and the light source in succession. Two illuminance peaks could be observed, as shown in Fig. D. Accordingly, the gravitational microlensing effect of the star-planet system could be conveniently simulated.