Investigating gravitational lensing diffraction in the laboratory with structured light

Enrique J. Galvez[1,*], *Thao* Nguyen[1], *Valeria* Rodriguez-Fajardo[1], *Kwakye* Kendja[1], *Anna* Moreso Serra[2], and *Oleg* Bulashenko[2]

[1]Department of Physics and Astronomy, Colgate University, Hamilton, New York 13346, USA
[2]Institut de Ciències del Cosmos (ICCUB), Facultat de Física, Universitat de Barcelona, Martí i Franquès 1, E-08028 Barcelona, Spain

Abstract. We use spatial light modulation to investigate the diffractive effects of gravitational lensing in the laboratory. Using this new platform for laboratory astrophysics, we can overcome the coherence challenges that prevent the observation of diffraction in astronomical imaging. These studies will inform gravitational lensing of gravitational waves when imaging of gravitational waves becomes available. Our previous work involved studying lensing by a single mass, symmetric and elliptical. This work focuses on the patterns produced by a binary-mass system. We observed rich 2-dimensional interference patterns bounded by caustics. Comparison of experimental results with preliminary theoretical calculations is excellent.

1 Introduction

Gravitational lensing of electromagnetic waves is a phenomenon that reveals multiple images of far away objects produced by deflections of light by the curvature of space created by a massive object between the source and observer on Earth. [1]. Current observations are limited to the geometric-optic aspects of the phenomenon. One observes an Einstein ring around the lens when the lens is symmetric and when the source, lens, and observer are aligned. When the alignment is imperfect or the lens asymmetric, one observes multiple arcs about the lens. The spatial incoherence of the source, combined with the temporal incoherence due to less-than-perfect alignment, has prevented the observation of diffractive effects in gravitational lensing thus far. However, these diffractive effects are expected to be more observable for gravitational waves, given their long wavelength and coherence [2].

In this work, we study the diffraction of the lensed light by setting the astrophysical lensing conditions in the laboratory. We use a laser source to provide spatial and temporal coherence on an optical table. The deflection of light due to gravity is provided by a spatial light modulator (SLM) programmed to impart position-dependent deflections predicted by general relativity. We observed the diffractive effects in gravitational lensing because of the attained spatial and temporal coherence. These wave patterns and geometric-ray far-field features were obtained by imaging with a digital camera. Our previous work showed that a single source plus a symmetric lens produces a diffraction pattern consisting of concentring rings, described by Bessel functions [3]. We also observed numerous other patterns of lensed light, such as astroid caustics bearing diffractive features due to the ellipticity of lenses. By imparting orbital angular momentum to the light, we could observe the diffractive patterns when the light is also deflected by the gravitational rotational drag produced by spinning Kerr black holes [4]. In this work, we investigate the asymmetric case of lensing caused by a binary lens system, which features caustic patterns with modulations produced by interferences [5].

*e-mail: egalvez@colgate.edu

2 Methods

2.1 Theoretical

Gravitational lenses are characterized by their Schwarzchild radius

$$r_S = \frac{2GM}{c^2}, \qquad (1)$$

where G is the gravitational constant and c the speed of light. Light incident on a lens of mass M with an impact parameter r is deflected by an angle

$$\alpha = \frac{2r_S}{r}. \qquad (2)$$

The binary system consisted of two objects, each of mass $M/2$, separated by a distance d, and contained in a plane perpendicular to the light's propagation direction. The observing plane is at a distance z from the lens. The binary separation can be scaled, and is given by

$$\hat{d} = \frac{d}{r_E}, \qquad (3)$$

where d is the separation and

$$r_E = \sqrt{2r_S z}. \qquad (4)$$

This scaling allowed the determination of the pattern with a single parameter.

2.2 Experimental

The light mimicking a faraway source consisted of an expanded and collimated laser beam spatially filtered by a single-mode fiber. We used several wavelengths λ in this study: 442 nm, 476 nm, 532 nm, 590 nm, 633 nm, and 685 nm. The beam was incident on a phase-only SLM programmed with the phase that imparts deflections following Eq. 2

$$\phi_{SLM} = -2kr_S \left[\ln\left(\frac{r - d/2}{r_0}\right) - \ln\left(\frac{r + d/2}{r_0}\right) \right], \quad (5)$$

where k is the wave-vector of the light ($k = 2\pi/\lambda$), d the displacement of each mass, and r_0 an integration constant. We obtained phase and amplitude modulation of the lensed light via diffraction. The lensed light was imaged onto a digital camera at distinct locations along the propagation direction.

3 Results

The experiment simulated gravitational lensing via deflections by a lens with individual masses with $r_S/2 = 2 - 7$ μm. We imaged the diffraction patterns at $z = 20$ cm from the lens. We varied the mass separation from $d = 0$ to $d = 5.9$ mm, resulting in a scaled distance ranging from 0 to 3.3.

An astroid caustic appears as the $\hat{d}$ increases from zero [3]. For higher values, it deforms to become a six-cusp hypocycloid, as shown in Figure 1 (where $\hat{d} = 1.17$). All the caustics contain interference modulations, as shown in the image. The interference patterns consist of modulations of caustic arcs that merge or bifurcate, ending in cusps. The size and shape of the envelope caustic is wavelength independent, but the modulations within depend on the wavelength. The caustic shown in Fig. 1 deforms further as $\hat{d}$ increases, becoming a pair of deltoid caustics. Preliminary comparisons with theoretical calculations show excellent quantitative agreement size and shape of the caustic envelope patterns as a function of $\hat{d}$.

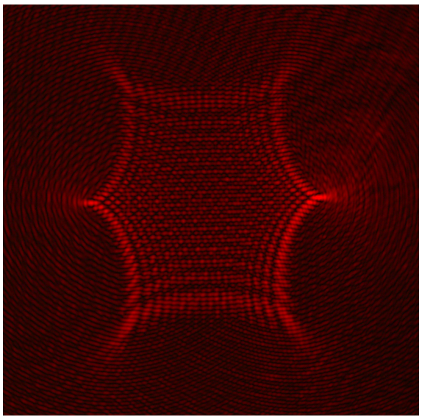

Figure 1. Measured diffraction pattern of a binary lens with scaled separation $\hat{d} = 1.17$, taken with 633-nm light.

This type of laboratory-astrophysics platform is a unique opportunity to test gravitational lensing in a controlled setting. It uses computational holography to study a cosmic phenomenon, providing coherent properties not available in astronomical observations. Thus uncovering diffractive phenomena that have not been possible to observe. In this work we use this platform to test the predictions of general relativity for the case of a binary system, which is asymmetric. Our studies will inform gravitational diffraction when imaging of gravitational waves becomes available.

References

[1] P. Schneider, J. Ehlers, E. Falco, *Gravitational Lenses* (Springer, 1992)

[2] O. Bulashenko, H. Ubach, JCAP **2022**, 022 (2022)

[3] V. Rodrǵuez-Fajardo, T.P. Nguyen, K.S. Hocek, J.M. Freedman, E.J. Galvez, New J. Phys. **25**, 083033 (2023)

[4] V. Rodríguez-Fajardo, T. Nguyen, K. Hocek, J. Freedman, E. Galvez, Proc. SPIE **12436**, 124360C (2023)

[5] M.V. Berry, J. Opt. **23**, 065604 (2021)