

HANDS-ON VIRTUAL COSMOLOGY WITH GRAVITATIONAL LENSING IN CELESTIA.SCI

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This paper describes a project undertaken at the International Space University (ISU) Master of Space Studies program between 2013-2014. The project aimed to create an open-source educational tool for studying gravitational lensing phenomena from arbitrary points in space and time. Gravitational lensing (GL) is a phenomenon by which light rays are bent by gravitational sources due to General Relativity. While existing work in the field has focused on the use of GL as a tool for mapping dark matter and detecting exoplanets, we aimed instead to help students understand intuitively how GL works and how it can be applied in cosmological and exoplanetary research. Similar software in the past has been used to teach concepts of Special Relativity and black holes. We implemented GL in *celestia.Sci*, a 3d, interactive simulation of Space extending from the scale of spacecraft around Earth and the Solar System, into deep space and the cosmological regime. Educational exercises were designed around the new feature, and a workshop for ISU students was created to allow hands-on experience with detecting exoplanets using GL. Finally, the open-source nature of the software allows us to reach a potentially wider audience by allowing any user on the Internet to freely download the source code and exercises, understand the program logic, and run the exercises independently. The end result is enhanced user understanding of an important astrophysical phenomenon, and an increased appreciation of astrophysics, astrobiology, and the visual beauty of Space.

I. INTRODUCTION

Gravitational lensing (GL) is a phenomenon by which light rays are bent by gravitational sources due to General Relativity. Gravitational lensing was predicted by Albert Einstein (1879 - 1955), and confirmed by Sir Arthur Eddington (1882 - 1944) who observed the apparent displacement of stars during a total solar eclipse in 1919. More recently, GL has become an indispensable technique used to image quasars [1], faint galaxies [2], to map dark matter [3], and to detect exoplanets [4].

We have listed several of many studies to observe the effects of gravitational lensing in astronomical observations, but less has been done to visually simulate gravitational lensing on the computer. In particular, there is a lack of software for interacting with GL in real-time, and to view GL from arbitrary viewpoints within a realistic cosmic environment populated with a wide gamut of celestial objects such as stars, exoplanets, and galaxies.

Interactive simulation software has previously been used to effectively educate students on subjects such as Special Relativity (e.g. ref. [5]). By providing interactivity, simulations can provide additional insight on otherwise complex concepts.

Ref. [6] reviews many gravitational lens modeling software available for general and research use. Most software are found to be non-interactive, requiring substantial off-line processing time, and are better suited to recover-

ing mass distributions from astronomical images. Some software exists that visually simulates lensing interactively (e.g. ref. [7]) but none exist that are able to do so within a complete three-dimensional stellar/galactic environment.

Building on prior work [8] that created an educational interactive GL software for manipulating a Schwarzschild black hole, the authors created a generalized GL visualization feature for stars and galaxies within the open source software *celestia.Sci* [9]. *celestia.Sci* builds upon *Celestia* [10], and benefits from its long heritage.

The new features of *celestia.Sci* described in this paper include visual simulation of macroscopic effects of GL such as Einstein rings and stellar displacement. Plotting of planetary microlensing light curves is also implemented. Planetary microlensing is a GL phenomenon and also a technique for detecting extrasolar planets. Other techniques include radial velocity (doppler shift), transit, astrometry, and direct imaging [11].

Section II introduces the *celestia.Sci* software. Section III describes the implementation of GL within *celestia.Sci*. Results from the software are shown in Section IV. Section V outlines a design for a student workshop using *celestia.Sci*'s microlensing feature. Finally, Section VI gives concluding remarks.

II. DESCRIPTION OF CELESTIA.SCI

celestia.Sci is a real-time, three-dimensional, interactive simulation of space extending over a huge range of scales, from spacecraft around Earth and the Solar System, into deep space and the cosmological regime (Fig. 1). It aims to be easily usable by the general public, while delivering an astrophysically-accurate rendering of space. The software is based on Celestia [10], a mature open-source program. Celestia has been used by NASA [12] and ESA [13] due to its visualization accuracy and extensive astronomical database using peer-reviewed scientific data. It was also recently used to strengthen communication and scientific reasoning skills of graduate students as part of the INSPIRE (Initiating New Science Partnerships in Rural Education) program [14].

The primary goals of celestia.Sci are to expand its extragalactic and cosmological visualization capabilities [15]. Gravitational lensing is thus an important new feature. Also, the rendering engine; stellar, galactic, and exoplanetary database; and high usability of celestia.Sci provide a strong foundation for implementing interactive GL through an attractive, classroom-friendly interface.

III. SOFTWARE IMPLEMENTATION

We apply the approximations of a weak gravitational field (this excludes compact objects such as black holes), slowly moving masses, and a lens that is thin compared to the distances to the source and observer. These approximations are valid for many lensing situations that are encountered in astronomy such as planetary, stellar, and galaxy cluster lensing [16]. The thin lens approximation is particularly useful, because the geometry simplifies into a cylindrically symmetric one. The problem then reduces to that of computing the deflections of one-dimensional light

rays in a two-dimensional domain, which is essentially image warping and can be efficiently computed using GPU shaders on many commodity PCs.

We also assume that lenses are modeled as point masses or collections of point masses; since the gravitational field outside a spherically symmetric body is identical to that of a point mass this is a broadly applicable approximation.

The lensing deflection angle $\hat{\alpha}$ in radians for a single mass is then shown to be the following (ξ : impact parameter):

$$\hat{\alpha} = \frac{2R_s}{\xi} \quad [1]$$

where $R_s = 2GM/c^2$ is the Schwarzschild radius.

For multiple masses (e.g., galaxy clusters, planetary systems), the total deflection angle $\hat{\alpha}(\xi)$ from the center of mass can be calculated as the sum of the deflection angles of the components [16]:

$$\hat{\alpha}(\xi) = \sum_i \frac{4Gm_i}{c^2} \frac{\xi - \xi_i}{|\xi - \xi_i|^2} \quad [2]$$

where ξ_i is a vector within the lens plane in the direction of a mass component m_i .

Based on the geometry in Fig. II, the *lens equation* can be derived:

$$\theta_s = \theta - 2R_s \frac{D_{ds}}{D_d D_s} \frac{1}{\theta} \quad [3]$$

The lens equation (3) has two angles θ_s and θ , both of which can be positive or negative. This implies that multiple images are possible [16].

If the source is directly in line with the lensing mass ($\theta_s = 0$), then the Einstein radius $\theta = \theta_E$ at which a *ring*

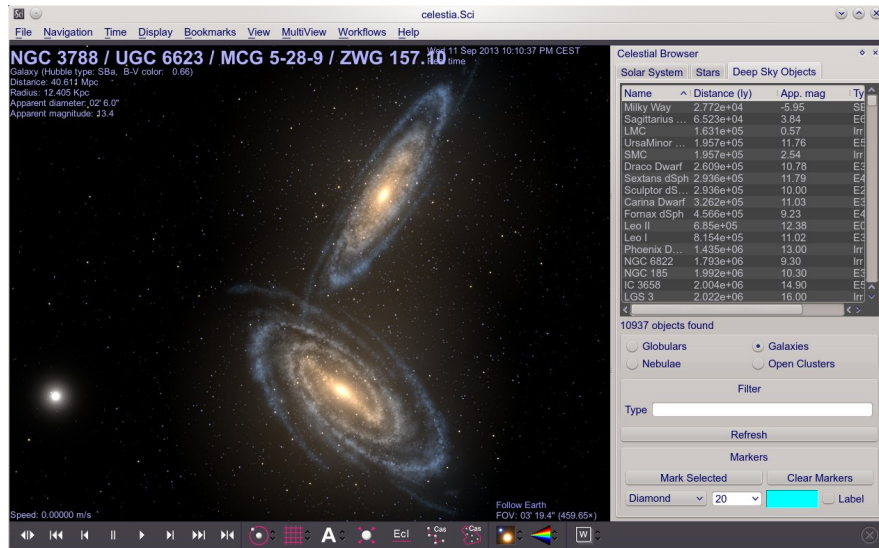


Fig. I: celestia.Sci user interface

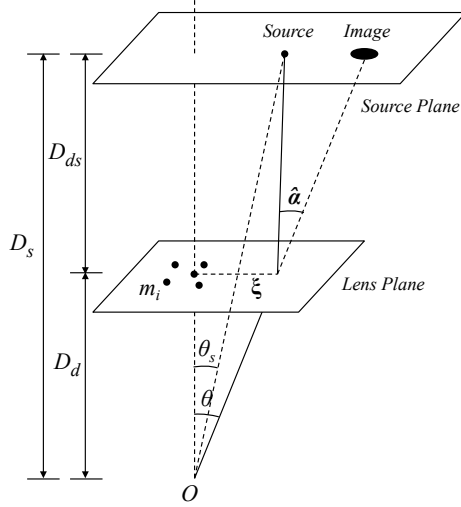


Fig. II: Typical lensing geometry for a collection of point masses m_i at a distance D_d from an observer O . θ represents the apparent angular displacement of the source due to lensing, and θ_s is the actual angular displacement (adapted from ref. [18]).

of light is observed is defined as follows [18]:

$$\theta_E^2 = 2R_s \frac{D_{ds}}{D_d D_s} \quad [4]$$

The size R_E of the Einstein ring is just $\theta_E D_d$:

$$R_E = 2R_s \frac{D_{ds}}{D_s} \quad [5]$$

The Einstein ring is only visible if $R_E > \text{radius of the lensing mass}$. This can only happen if the Schwarzschild radius R_s is large. For our Sun, R_s is only about 2,950 km, which is much less than the solar radius. Rings have been observed for more massive objects (e.g. refs. [19, 20]).

Gravitational lenses can also magnify the intensity of light passing through them. Very high magnifications can result near *caustics*, which are curves on the source plane

where the intensity of light undergoes a dramatic, nearly discontinuous change. The bright caustics that can be observed when light is refracted by a wine glass are very similar to those produced by GL [21]. Magnification due to caustics can enable detection of objects that are too small or distant to be observed directly.

If lensing results in multiple images that are too small to resolve, we call this *microlensing*. What we can observe are momentary increases in the apparent brightness of the object, due to the combined magnification of multiple lensed images [18]. Peaks in the light curve (brightness variation over time) correspond to caustics.

The magnification A is [18]:

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \quad u = \frac{|\theta_s|}{\theta_E} \quad [6]$$

In an exoplanetary system, the star and planets each act as lensing masses. We can compute the total magnification A_{tot} by rewriting u_i of each mass in the system in terms of the impact parameter ξ_i and the deflection angle $\hat{\alpha}(\xi_i)$:

$$u_i = \frac{\xi_i}{D_d} - \frac{D_{ds}}{D_s} \hat{\alpha}(\xi_i) \quad [7]$$

According to Equation 2, deflection angles sum and total $u = \sum_i u_i$. By moving ξ_i in time across the critical curves of the system (which correspond to caustics on the lensing plane), the resulting *light curve* will exhibit sharp increases in magnitude. The sizes and shapes of these peaks are tell-tale indicators of the number and masses of exoplanets in the system.

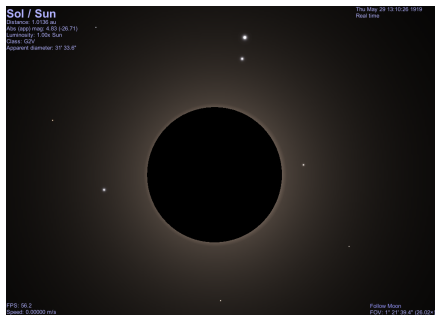
IV. RESULTS

The results of implementing GL in celestia.Sci are presented in this section as a series of exercises.

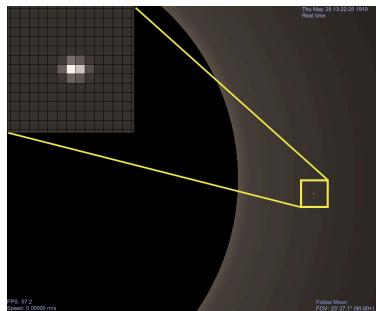
IV.1 Exercise 1: Reproduce the Eclipse of 1919

We now proceed to reproduce the eclipse of 1919 in celestia.Sci. Fig. III shows our result.

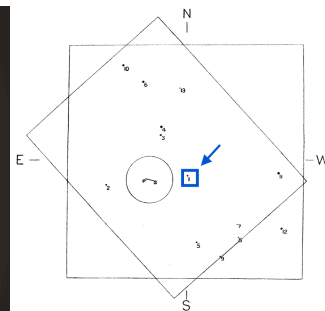
celestia.Sci has an eclipse finding feature that allows us to go back in time and precisely simulate the eclipse. The



(a) The eclipse of 1919 in celestia.Sci



(b) Zoomed in view of star



(c) Eddington's observations [17]. Zoom indicated.

Fig. III: Simulating the 1919 solar eclipse in celestia.Sci

arrangement of stars in the simulation can be seen to match those observed by Eddington. Fig. IIIb magnifies a star very close to the corona; again we have superimposed the lensed image over the unlensed star. The diameter in pixels of the Sun in Fig. IIIb is 1100 pixels. Given the known angular diameter of the Sun = $1914''$, and the expected angular separation between the lensed and unlensed images $\sim 1.75''$, we can expect the separation between the images to be $= 1914/1.75/1100 \sim 0.99$ pixels. The actual separation between the two simulated images is 1 pixel, as expected.

IV.2 Exercise 2: Find an Einstein Ring

We now turn our attention to GL at the cosmological scale of a galaxy cluster. While catalog data for distant clusters such as the Bullet Cluster are not available, the Coma Cluster (Abell 1656) is another good candidate for testing our lensing code due to the presence of two very massive BCGs (brightest central galaxies) NGC 4874 and NGC 4889. Additionally, the cluster is near our own galaxy; thus, reliable catalog data is available within celestia.Sci. Fig. Va shows the result of our simulation in celestia.Sci and Fig. Vb is a photographic reference for comparison.

Several characteristics of strong and weak lensing can be seen near NGC 4874 (large galaxy in the lower right of Fig. Va and magnified in Fig. Vc): arclets, multiple images and the emergence of a ring-like structure. In fact, the feature is an Einstein ring, as can be seen in Fig. Vd where the apparent magnitudes in the scene have been artificially boosted. Note that the center of the distortion is not located at the centers of any of the BCGs or the midpoints between them; qualitatively, this is to be expected because of the asymmetric mass distribution.

IV.3 Exercise 3: Reveal Exoplanets

celestia.Sci does not yet have any exoplanetary systems discovered by microlensing in its database, so we created an add-on. Our add-on models OGLE-2012-BLG-0026L, an exoplanetary system where two planets of mass 0.11 and 0.68 Jupiters were found orbiting a Sun-like G-type main sequence star via the Optical Gravitational Lensing Experiment (OGLE) microlensing warning system [23]. Some parameters such as orbit eccentricities and periods are not known, but we were able to model the system based on astrometric and photometric parameters from the paper. Unknown parameters were assigned reasonable values such as zero for the orbit inclinations.

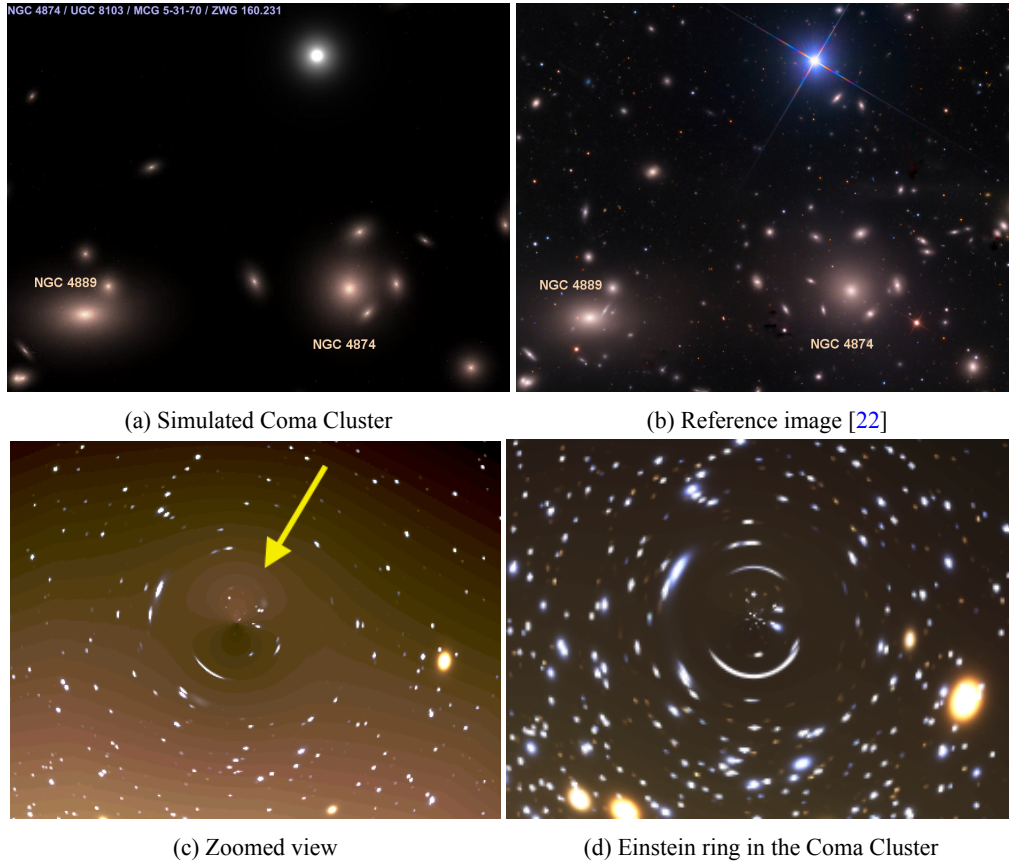


Fig. V: The Coma Cluster.

Fig. VI displays the result of simulating the OGLE-2012-BLG-0026L microlensing system in celestia.Sci. The light curve plot on the left displays apparent magnitude versus time in units of Barycentric Julian Date (BJD) - 2450000. The plot is the result of celestia.Sci smoothly varying the angle θ across two critical curves created by gravitational interaction between the star and its two planets. The shape of the light curve is similar to Fig. 1 of ref. [23], but the leftmost and rightmost peaks are too high. However, two characteristic features described by ref. [23] are also reproduced by our curve; these are the dip before the rightmost peak, and the relative amplitude reached by the rightmost peak as compared to the other peaks. Any differences are probably caused by discrepancies in the lensing geometry such as viewing alignment or path taken by the impact parameter, and the modeling of lensing masses as point sources.

V. WORKSHOP DESIGN

This section outlines the plan for a student workshop using the exoplanet microlensing feature of celestia.Sci described in Section IV.3. The workshop is intended to be combined with a lecture or short course in exoplanets and astrobiology at the International Space University (ISU), a university that offers interdisciplinary, graduate-level courses in all aspects of space. The two major programs offered by ISU that could integrate this workshop into their curricula include the one-year Master of Space Studies (MSS) academic program (starting in September annually at the ISU central campus in France), and the shorter two-month Space Studies Program (SSP) for professionals (convening in June at a different host institution every year).

V.1 Audience

The workshop is aimed at Masters-level ISU students to allow hands-on experience with detecting exoplanets using GL. Since ISU students come from a wide range of backgrounds, no prior detailed knowledge of General Relativity, GL, or exoplanets is assumed. The number of participants is expected to be between 10 to 20.

V.2 Learning Objectives

After completing this workshop, participants should understand the basics of GL, including the minimum of General Relativity that is required to understand GL. Participants should also be able to understand the different types of gravitational lensing and, in particular, what gravitational microlensing is and why it is useful in detecting exoplanets.

Finally, participants should become comfortable in the basic operation of celestia.Sci, and be able to "detect" the presence of exoplanets within the program by correctly interpreting light curves of extrasolar systems.

V.3 Prerequisites

While no prerequisites are assumed of participants, computers able to run celestia.Sci are required. celestia.Sci can run on most desktop and laptop computers built within the last four to five years, and requires Mac OS X, Linux, or Windows (Android or iOS mobile devices are not supported). Ideally, computers should be available for every workshop participant, but participants can also work in pairs and share computers. Internet access is not required by celestia.Sci during installation or operation, although Internet access is required for downloading the program and add-ons.

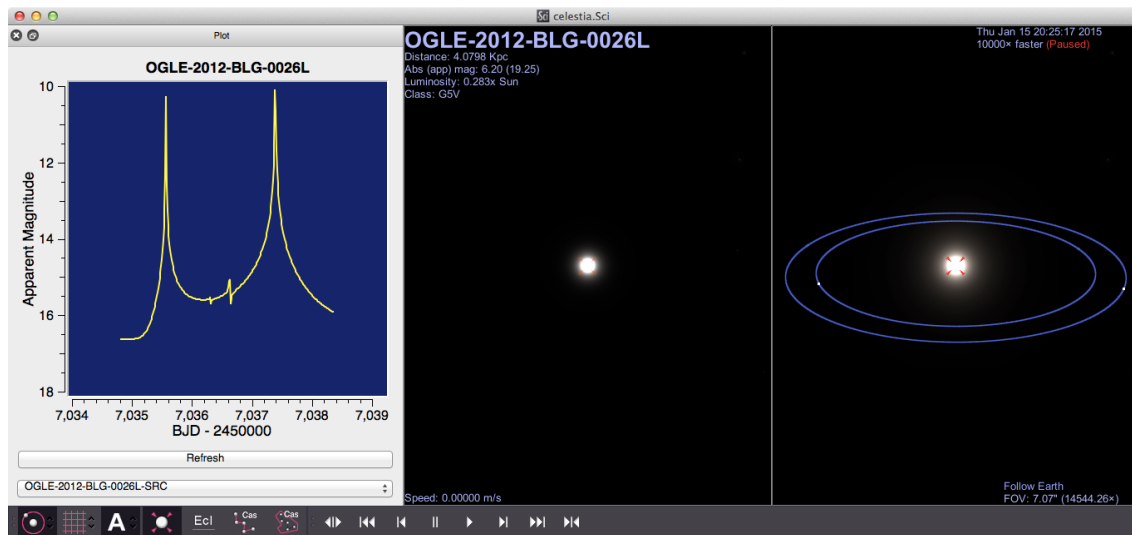


Fig. VI: celestia.Sci microlensing user interface displaying the light curve for OGLE-2012-BLG-0026L.

V.4 Duration

Approximately 1.5 hours should be sufficient to cover the objectives of this workshop.

V.5 Outline

The following is an outline of the various activities of the workshop.

1. Introduction to General Relativity and GL: 15 minutes
2. Introduction to the software: 15 minutes
3. Hands-on exercises using the software: 30 minutes
4. Collection of results, analysis: 15 minutes
5. Discussion: 15 minutes

The hands-on exercises consist of virtually discovering two or three known exoplanet systems that are designated at the start to the workshop, plotting their light curves, and noting the properties such as masses and orbital radii of the stars and planets discovered.

VI. CONCLUSIONS

We have demonstrated the implementation of a general framework for interactive 3d visualization of gravitational lensing, using the open-source software celestia.Sci as a base. While existing work in the field has focused on the use of GL as a tool for mapping dark matter and detecting exoplanets, we aimed instead to help users understand intuitively how General Relativity and GL works and how it can be applied in cosmological and exoplanetary research. To this end, we have demonstrated a capability to flexibly view simulated gravitational lenses from arbitrary viewpoints and times.

Educational exercises were designed around the new feature, and a workshop for graduate-level ISU students with no prior knowledge of the software or subject matter was created to allow hands-on experience with detecting exoplanets using gravitational microlensing.

The open-source nature of the software allows us to reach a potentially wider audience by allowing any user on the Internet to freely download the source code and exercises, understand the program logic, and run the exercises independently. The end result is enhanced user understanding of GL, and an increased appreciation of astrophysics, astrobiology and the visual beauty of Space.

ACKNOWLEDGEMENT

D.J. is very grateful to the IAF for the Emerging Space Leaders grant.

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