Visualizing Gravitational Lensing Phenomena in Real-time using OpenGL shaders in celestia.Sci

Individual Project Plan

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Master of Science in Space Studies degree

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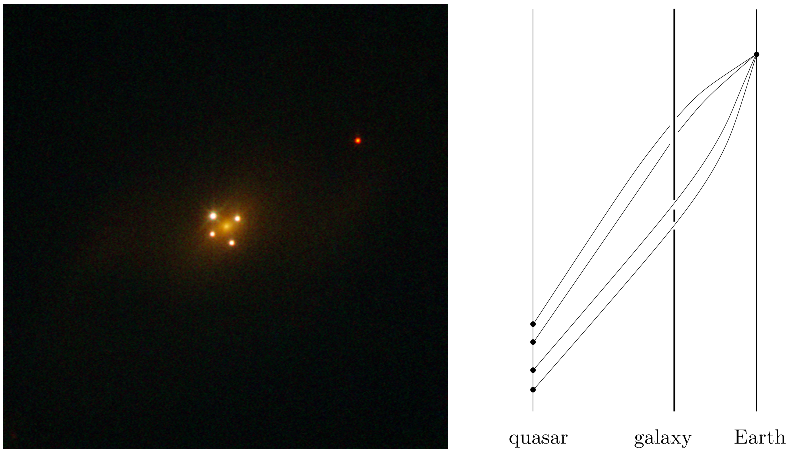
1 Introduction

1.1 Gravitational Lensing

Gravitational lensing is a phenomenon by which light rays are bent by gravitational sources due to General Relativity. Gravitational lensing was predicted by Einstein, and confirmed by Eddington in 1919 by observing the apparent displacement of stars during a total solar eclipse. (Natário, 2012) More recently, gravitational lensing has become an indispensable technique used to image distant quasars (Walsh et al., 1979), faint galaxies (Bradač et al., 2009), to map dark matter (Clowe et al., 2006), and to detect exoplanets (Mao and Paczynski, 1991).



(a) Hubble image (ESA/Hubble and NASA, 2012)

(b) Space-time diagram (Natário, 2012)

Figure 1: Four images of the same quasar are produced by lensing in the Einstein Cross

Gravitational lensing can be classed into several types based on the amount of distortion seen in the image (Narayan and Bartelmann, 1997):

1. *Strong* lensing: Multiple images or large arcs are produced
2. *Weak* lensing: Arclets and some shearing are seen
3. *Micro*lensing: Brightness varies over time due to relative movement of multiple bodies (e.g., an orbiting exoplanet)

More massive bodies lead to more pronounced lensing due to stronger gravitational forces; for example giant arcs and multiple images have been observed in Hubble observations of the Abell 2218 galaxy cluster. (Kneib et al., 1996) However even relatively light bodies such as our Sun can cause visible lensing at Earth distances and beyond as demonstrated by Eddington. More recently, Maccone proposed a mission called FOCAL that would place a spacecraft >550 au from our Sun at the gravitational lensing *focal point* to magnify the Galactic Center. (1999)

1.2 Motivation for this Project

We have listed here so far, several of many studies to observe the effects of gravitational lensing in astronomical observations. But less has been done in the field to visually simulate gravitational lensing on the computer. In particular, there is a need for software that can allow the user to interact with the simulation in real-time, and to view the simulation from arbitrary geometries. By providing interactivity, the simulation can not only provide additional insight that might otherwise be overlooked in a static model, but it can also appeal to educators and students. In this project, we will attempt to construct a general gravitational lensing framework that can be used from stellar to cosmological scales, while at the same time limiting ourselves to what can be *displayed* by commodity computer hardware in real-time.

1.3 The Software

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. It aims to be easily usable by the general public, while delivering an astrophysically-accurate rendering of space. The software is based on Celestia, a mature open-source program. Celestia has been used by NASA (2004) and ESA (2004) thanks to its high visualization accuracy and extensive astronomical database using peer-reviewed scientific data exclusively. The author has been a regular developer on the Celestia team for about six years, and the co-advisor is a theoretical astro-particle physicist who has been one of the core developers for over ten years and is now project lead of celestia.Sci.

The goals of celestia.Sci are to expand its extragalactic and cosmological visualization capabilities (Schrempp, 2013). In this respect, the ability to simulate gravitational lensing will become an important addition. Also, the rendering engine, stellar, galactic, and exoplanetary database, and high usability of celestia.Sci will provide a strong foundation for this project.

Previous work on visually simulating gravitational lensing has relied mainly on substantial off-line processing and long turn-around times. OpenGL shaders will be used in this project to visually simulate lensing phenomena at interactive framerates.

2 Project Aim and Objectives

2.1 Project Aim

To add the capability to view and interact with astronomical gravitational lensing effects in real-time to celestia.Sci running on commodity computer hardware, as a means for scientists to verify and visualize lensing observations, to educate the general public on the phenomenon of gravitational lensing, and to further the goals of celestia.Sci by expanding its extragalactic and cosmological visualization capabilities to encompass gravitational lensing.

2.2 What this project is and isn't

What this project is: Producing interactive, accurate renderings of gravitational lensing
What this project is not: Producing an algorithm for computing masses from astronomical images, or computing lensing probabilities

2.3 Objectives

1. After a preliminary reading of introductory texts on General Relativity, perform a literature review of gravitational lensing

2. Design a strategy for implementing a general three-dimensional gravitational lensing framework in celestia.Sci

3. Implement the strategy and perform performance tests and optimizations with an aim to providing interactive frame rates
4. Demonstrate the following lensing phenomena using the functionality implemented:
    - Gravitational focusing of starlight around our own Sun at >550 au, by assuming a single, symmetrical mass
    - Strong lensing due to a galaxy, e.g., Twin Quasar 0957+561 A/B
    - Weak lensing around the Bullet Cluster by using known dark matter distribution models and comparing the result with actual astronomical observations
5. Identify directions for further enhancements and research

The following **extended objectives** could also be considered upon completion of the above:

1. Design an International Space University workshop on gravitational lensing, targeting SSP or MSS participants, based on the exercises that are to be outlined in the Project Report
2. Submit a peer-reviewed journal article based on the Project Report. Due to the project's pedagogical content, *The Physics Teacher*, published by the American Association of Physics Teachers, could be a suitable target journal. A conference paper could also be written and presented

3 Project Deliverables

This project will result in the following deliverables:

- **Project Plan** (the current document)
- **Project Report**: A written thesis containing literature review, the underlying theory and design of the new software code, results, possible educational exercises that could be performed by users of the software, and directions for further research
- **Project Presentation**: A fifteen-minute oral presentation based on the Project Report and consisting of slides and a live demonstration of the software, followed by a ten-minute defense session
- **Software**: Open-source implementation of gravitational lens visualization in celestia.Sci, based on a design that is to be detailed in the Project Report and Presentation

Optional deliverables include a workshop on gravitational lensing, and a peer-reviewed journal article or conference paper. These are not included in the Work Breakdown Structure that follows but time for them could be allocated during the Project Presentation phase.

4 Analysis of Tasks

4.1 Work Breakdown Structure (WBS)

An iteration normally represents a review by the advisors, followed by improvements as necessary. For the Software phase, iterations are to be performed internally as often as possible following the *Agile* method, but reviews are to be undertaken only for the iteration tasks shown in the WBS. Regular tasks such as biweekly meetings with advisors are omitted from the WBS for brevity.

1. Project Plan
    1.1. Preliminary Research
    1.2. Plan Draft
    1.3. Plan Iteration 1
    1.4. Plan Iteration 2
    1.5. Plan Delivery
2. Literature Review
    2.1. Introductory Reading
    2.2. Literature Review
3. Project Report
    3.1. Report Draft
    3.2. Report Iteration 1
    3.3. Report Iteration 2
    3.4. Educational Exercise Design
    3.5. Report Iteration 3
    3.6. Educational Exercise Iteration
    3.7. Report Delivery
4. Software
    4.1. Design
        4.1.1. Requirements Definition
        4.1.2. Requirements Iteration 1
        4.1.3. Design
        4.1.4. Design Iteration 1
    4.2. Implementation/Testing
    4.3. Implementation/Testing Iteration 1
    4.4. Implementation/Testing Iteration 2
    4.5. Software Delivery
5. Project Presentation
    5.1. Slide Preparation
    5.2. Slide Iteration 1
    5.3. Scenario Preparation
    5.4. Rehearsal 1
    5.5. Slide Iteration 2
    5.6. Scenario Iteration 1
    5.7. Q/A Preparation
    5.8. Presentation and Defense

5 Project Timeline

Figure 2 is a GANTT chart showing each work package from the Work Breakdown Structure. In summary, 20 workdays are allocated for literature review, about 65 workdays for the Project Report, and 50 workdays for programming for a total of 90 workdays considering overlaps.

	Task	Start	Finish	Duration	
1	**Project Plan**	**11/18/2013**	**11/22/2013**	**5**	**5**
2	Plan Draft	11/18/2013	11/20/2013	3	3
3	Plan Iteration 1	11/20/2013	11/21/2013	2	2
4	Plan Iteration 2	11/21/2013	11/22/2013	2	2
5	Plan Delivery	11/22/2013	11/22/2013	0	0
6	**Literature Review**	**11/25/2013**	**12/20/2013**	**26**	**20**
7	Introductory Reading	11/25/2013	11/29/2013	5	5
8	Literature Review	12/02/2013	12/20/2013	19	15
9	**Report**	**01/06/2014**	**04/11/2014**	**96**	**70**
10	Report Draft	01/06/2014	02/23/2014	49	35
11	Report Iteration 1	02/24/2014	02/28/2014	5	5
12	Report Iteration 2	03/10/2014	04/04/2014	26	20
13	Exercise Design	03/27/2014	04/01/2014	6	4
14	Exercise Iteration	04/02/2014	04/04/2014	3	3
15	Report Iteration 3	04/07/2014	04/11/2014	5	5
16	Report Delivery	04/11/2014	04/11/2014	0	0
17	**Software**	**12/09/2013**	**02/28/2014**	**82**	**60**
18	Requirements	12/09/2013	12/11/2013	3	3
19	Requirements Iteration 1	12/12/2013	12/13/2013	2	2
20	Design	12/16/2013	12/18/2013	3	3
21	Design Iteration 1	12/19/2013	12/20/2013	2	2
22	Impl./Test	01/06/2014	01/24/2014	19	15
23	Impl./Test 1	01/27/2014	02/14/2014	19	15
24	Impl./Test 2	02/15/2014	02/28/2014	14	10
25	Software Delivery	02/28/2014	02/28/2014	0	0
26	**Presentation**	**04/14/2014**	**05/19/2014**	**36**	**26**
27	Slide Prep.	04/14/2014	04/18/2014	5	5
28	Slide Iteration 1	04/21/2014	04/23/2014	3	3
29	Scenario Prep.	04/24/2014	04/30/2014	7	5
30	Rehearsal 1	04/30/2014	04/30/2014	0	0
31	Slide Iteration 2	05/01/2014	05/06/2014	6	4
32	Scenario Iteration 1	05/07/2014	05/13/2014	7	5
33	Q/A Prep.	05/14/2014	05/16/2014	3	3
34	Final Presentations	05/19/2014	05/19/2014	0	0
35	Winter Break	12/21/2013	01/05/2014	16	10
36	Spring Break	03/01/2014	03/09/2014	9	5

Figure 2: GANTT chart

6 Discussion

Currently the project is in the Project Plan phase, with this document as the first deliverable on track for delivery.

Preparations for the Literature Review and Software phases are also underway. An introductory textbook on General Relativity (Natário, 2012) has already been acquired, and the definitive textbook on gravitational lensing, *Gravitational Lenses* by Schneider, Ehlers, and Falco is to be ordered from the library. Some test code demonstrating strong lensing near our Sun has already been written to prove that the concept is feasible.

Note that the Software phase of the project ends midway through the Project Report phase, in order to allow time to prepare results and exercises for the Project Report.

The main difficulty expected for this project, is the design and implementation of weak lensing around asymmetrical mass distributions (e.g., galaxies or clusters). Gravitational fields will no longer be symmetrical, and influences from multiple bodies may need to be considered. Analytical solutions for the lens equations may become intractable, potentially requiring stochastic techniques such as Monte Carlo. In this case, maintaining interactive framerates may become an issue.

Additionally, accurately verifying the results of simulations is expected to be difficult, especially in the weak lensing case. Qualitative comparisons with actual astronomical observations may need to be preferred over quantitative ones, as computing the amount of distortion in our results might be constrained by the screen resolution. Tests will have to be performed to confirm this.

7 Conclusion

The aim of this project is to add the capability to view and interact with astronomical gravitational lensing effects in real-time to celestia.Sci. By doing so, scientists can use the software to verify and visualize lensing observations. Moreover, as the feature is designed to run comfortably on commodity computer hardware, the general public will find the software to be an accessible and enjoyable tool to learn about gravitational lensing.

To increase the pedagogical impact of the software, extended objectives have been suggested for this project. The first, is the design of a companion workshop to the software, based on exercises created for the Project Report. Secondly, a journal article targeted at educators could be written to invite further discussion and to increase adoption of the software by teachers.

The tasks required for successful completion of this project have also been identified. Tasks are typically iterated multiple times to allow the author and advisors to identify points for improvement and to increase the quality of the work.

Finally, the project tasks have been presented in timeline form, with dependencies between tasks indicated. A summary of the expected workload has also been given. The total workload is estimated at 90 working days, or approximately 180 hours at a rate of 2 hours per working day.

References

Maruša Bradač, Tommaso Treu, Douglas Applegate, Anthony H. Gonzalez, Douglas Clowe, William Forman, Christine Jones, Phil Marshall, Peter Schneider, and Dennis Zaritsky. Focusing Cosmic Telescopes: Exploring Redshift z ˜ 5-6 Galaxies with the Bullet Cluster 1E0657 – 56. *The Astrophysical Journal*, 706(2):1201–1212, December 2009. ISSN 0004-637X. doi: 10.1088/0004-637x/706/2/1201. URL `http://dx.doi.org/10.1088/0004-637x/706/2/1201`.

Douglas Clowe, Maruša Bradač, Anthony H. Gonzalez, Maxim Markevitch, Scott W. Randall, Christine Jones, and Dennis Zaritsky. A Direct Empirical Proof of the Existence of Dark Matter. *The Astrophysical Journal Letters*, 648:L109–L113, September 2006. doi: 10.1086/508162. URL `http://dx.doi.org/10.1086/508162`.

ESA. Closing in on the Red Planet: Mars Express orbit lowered, 2004. URL `http://www.esa.int/Our_Activities/Space_Science/Mars_Express/Closing_in_on_the_Red_Planet_Mars_Express_orbit_lowered`. (Accessed 21 November 2013).

ESA/Hubble and NASA. Seeing quadruple, 2012. URL `http://www.spacetelescope.org/static/archives/images/screen/potw1204a.jpg`. (Accessed 21 November 2013).

J. P. Kneib, R. S. Ellis, I. Smail, W. J. Couch, and R. M. Sharples. Hubble Space Telescope Observations of the Lensing Cluster Abell 2218. *The Astrophysical Journal*, pages 643+, November 1996. doi: 10.1086/177995. URL `http://dx.doi.org/10.1086/177995`.

Claudio Maccone. Tethered system to get magnified radio pictures of the Galactic Center from a distance of 550 AU. *Acta Astronautica*, 45(2):109–114, July 1999. ISSN 00945765. doi: 10.1016/s0094-5765(99)00110-1. URL `http://dx.doi.org/10.1016/s0094-5765(99)00110-1`.

S. Mao and B. Paczynski. Gravitational microlensing by double stars and planetary systems. *Astrophys. J. Lett.*, 374:L37–L40, June 1991. doi: 10.1086/186066. URL `http://dx.doi.org/10.1086/186066`.

Ramesh Narayan and Matthias Bartelmann. Lectures on Gravitational Lensing, October 1997. URL `http://arxiv.org/abs/astro--ph/9606001`.

NASA. NASA: Solar System Website and Celestia Software, 2004. URL `http://teachspacescience.org/cgi-bin/search.plex?catid=10000913&mode=full`. (Accessed 21 November 2013).

José Natário. General Relativity Without Calculus - A Concise Introduction to the Geometry of Relativity, 2012. URL `http://www.math.ist.utl.pt/~jnatar/RM-12/Geom_Rel.pdf`. (Accessed 19 November 2013).

Fridger Schrempp. Welcome: Aims and Status of celestia.Sci, 2013. URL `http://forum.celestialmatters.org/viewtopic.php?f=11&t=473`. (Accessed 21 November 2013).

D. Walsh, R. F. Carswell, and R. J. Weymann. 0957 + 561 A, B: twin quasistellar objects or gravitational lens? *Nature*, 279(5712):381–384, May 1979. doi: 10.1038/279381a0. URL `http://dx.doi.org/10.1038/279381a0`.