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Astrophysics

Innovative techniques to find strongly lensed systems

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Abstract

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Introduction

A gravitational lens, also known as cosmic mirage, is a distribution of mass able to bend the light coming from a distant source. This phenomenon is similar to a light beam bended through a lens by refraction. This is why we call it gravitational lensing.

Already in 1704, Isaac Newton speculated that "[...] Bodies act upon Light at a distance, and by their action bend its Rays; and [...] this action [is] strongest at the least distance." [1]. Later John Mitchell proposed to Henry Cavendish, a method to measure the mass of stars by detecting a reduction of the speed of light affected by gravity [2]. In those letters, Mitchell suggested that a massive enough body could stop the light: a black hole. This pushed Cavendish to calculate the Newtonian light deflection. Unfortunately he never published his manuscript dated around 1784 [3]. Johann Georg von Soldner published the same result in 1801 [4] assuming light is a corpuscule. Finally, Einstein calculated the same value thanks to the equivalence principle only in 1911 [5], and corrected it by twice the value in 1915 [6] in the frame of General Relativity.

The first observation of light deflection were performed in 1919 by Arthur Eddington and Frank Watson Dyson by observing a change in position of stars near the sun during the solar eclipse of May 29 [7]. Later in 1937, after the new discovery of Galaxies, Fritz Zwicky speculated that those massive objects could act as both source and lens with a larger effect much likely to be observed [8]. It was necessary to wait 1979 to observe the first gravitational lens. Dennis Walsh, Bob Carswell and Ray Weymann observed two identical Quasistellar objects (QSO) using Kitt Peak National Observatory. Their paper [9] arises difficulties in describing them as two distinct objects and the hint of the observation of two images of the same object formed by gravitational lensing is discussed. SBS 0957+561 was renamed "Twin QSO".

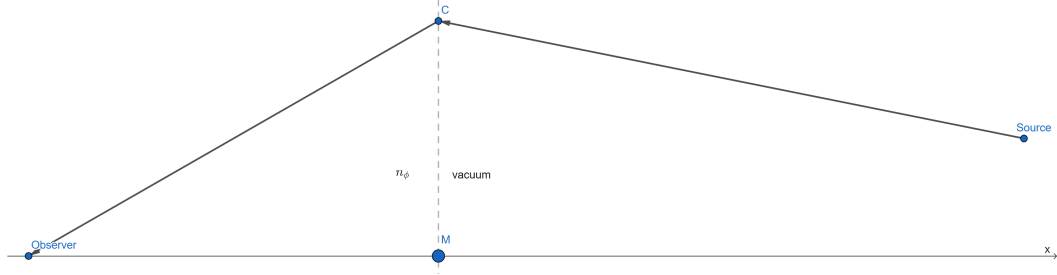


Fig. 1.2.: Analog situation of light traveling in vacuum from a distant source and propagating through a medium of refractive index n_ϕ .

By tacking the null geodesic corresponding to the light path and $\frac{1}{1+\frac{2\phi}{c^2}} \approx 1 - \frac{2\phi}{c^2}$ with $\frac{2\phi}{c^2} \ll 1$:

$$ds^2 = 0 \quad (1.2)$$

$$\left(1 + \frac{2\phi}{c^2}\right) c^2 dt^2 = \left(1 - \frac{2\phi}{c^2}\right) (dx^2 + dy^2 + dz^2) \quad (1.3)$$

$$dt^2 = \frac{1 - \frac{2\phi}{c^2}}{1 + \frac{2\phi}{c^2}} \frac{(dx^2 + dy^2 + dz^2)}{c^2} \quad (1.4)$$

$$dt^2 = \left(1 - \frac{2\phi}{c^2}\right)^2 \frac{(dx^2 + dy^2 + dz^2)}{c^2} \quad (1.5)$$

$$dt = \left(1 - \frac{2\phi}{c^2}\right) \frac{\sqrt{dx^2 + dy^2 + dz^2}}{c} \quad (1.6)$$

$$\frac{\sqrt{dx^2 + dy^2 + dz^2}}{dt} = \frac{c}{\left(1 - \frac{2\phi}{c^2}\right)} \quad (1.7)$$

equation 1.7 is analog to $v = \frac{c}{n_\phi}$. We identify $n_\phi = 1 - \frac{2\phi}{c^2}$. That being said, let's establish the lens equation and the deflection angle.

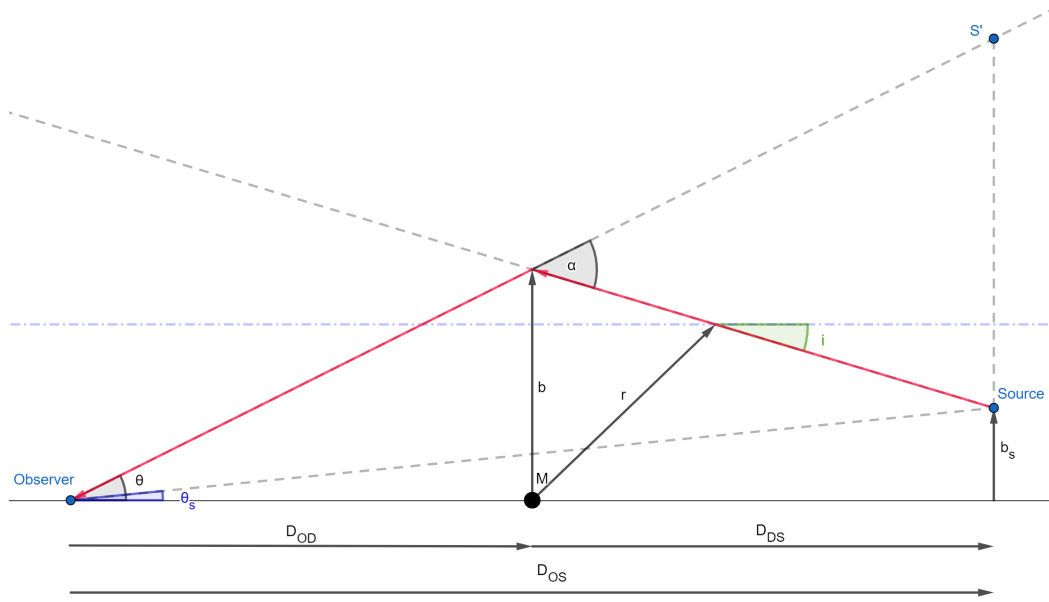


Fig. 1.3.: Scheme of the general situation of a gravitational lens

1.1.2 The lens equation

To solve this problem we need to link the viewing angle θ to the deflection angle α . By geometric considerations thanks to figure 1.3 this relation is given by the following equation :

$$\theta_s = \theta - \frac{D_{DS}}{D_{OS}} \alpha(b) \quad (1.8)$$

$$b = D_{OD} \theta \quad (1.9)$$

Now we have to link the deflection angle α to physical parameters like the mass of the deflector M . In the following, $\frac{di}{dx}$ is the variation of the direction along x axis. α is thus the deflection angle which is the integration of all direction variation along x.

$$\vec{\alpha}(b) = - \int_{-} \frac{d\vec{i}}{dx} dx = - \int_{-} \frac{1}{n} \vec{\nabla}_b n dx = \frac{2}{c^2} \int_{-} \vec{\nabla}_b \phi dx \quad (1.10)$$

In this demonstration we will take as simple example a point mass deflector. It's gravitational potential is :

$$\phi = -\frac{GM}{r} = -\frac{GM}{\sqrt{b^2 + x^2}} \quad (1.11)$$

The deflection angle α becomes:

$$\vec{\alpha}(b) = \frac{4GM}{c^2 b^2} \vec{b} \quad (1.12)$$

We effectively find twice the value obtained with the Newtonian framework. Now that we find what Einstein predicted, let's generalize. To do so, we use the thin lens approximation. This approximation allows us to describe a deflector by its surface mass density $\Sigma(\vec{b})$ projected in the deflector plane. The deflection angle is then expressed :

$$\vec{\alpha}(b) = \frac{4G}{c^2} \int_S \frac{\Sigma(\vec{b}')(\vec{b} - \vec{b}')db'_1db'_2}{|b - b'|^2} \quad (1.13)$$

In the case of a circularly symmetric mass distribution, with $M(b)$ the mass inside a the radius b :

$$\vec{\alpha}(b) = \frac{4GM(b)}{c^2 b^2} \vec{b} \quad (1.14)$$

1.1.3 Einstein Ring

Let's now assume the following circularly symmetric lens mass distribution:

$$M(b) = M_0 \left(\frac{b}{b_0} \right)^\beta \quad (1.15)$$

$\beta = 0$ correspond to a point mass distribution, $\beta = 1$ is the singular isothermal sphere distribution and $\beta = 2$ yield the uniform distribution of matter.

Now that we have the general case, let's study a particular case which is the Einstein ring solution. This case correspond to the simple case when the observer, the deflector and the source are aligned ($\theta_s = 0$). The Einstein ring is thus defined by its angular size θ_E .

$$0 = \theta_E - \frac{D_{DS}}{D_{OS}} \frac{4GM(b)}{c^2 b} = \theta_E - \frac{D_{DS}}{D_{OS}} \frac{4G}{c^2 b} M_0 \left(\frac{b}{b_0} \right)^\beta \quad (1.16)$$

$$0 = \theta_E - \frac{D_{DS}}{D_{OS}} \frac{4GM_0}{c^2 b_0^\beta} (D_{OD}\theta_E)^{\beta-1} = \theta_E \left(1 - \frac{D_{DS}}{D_{OS}} \frac{4GM_0}{c^2 b_0^\beta} D_{OD}^{\beta-1} \theta_E^{\beta-2} \right) \quad (1.17)$$

$\theta_E = 0$ is a solution but not relevant.

$$\frac{D_{DS}D_{OD}^{\beta-1}}{D_{OS}} \frac{4GM_0}{c^2 b_0^\beta} \theta_E^{\beta-2} = 1 \quad (1.18)$$

$$\theta_E = \left(\frac{4GM_0}{c^2 b_0^\beta} \frac{D_{DS}}{D_{OD}^{1-\beta} D_{OS}} \right)^{\frac{1}{2-\beta}} \quad (1.19)$$

with M_E the mass inside the radius $b_E = D_{OD}\theta_E$ we get the expression of the Einstein ring angular size:

$$\theta_E = \sqrt{\frac{4GM_E}{c^2} \frac{D_{DS}}{D_{OD}D_{OS}}} \quad (1.20)$$

1.1.4 Images positions

By tacking a point mass deflector case ($M(b) = M_0$):

$$\theta_s = \theta - \frac{D_{DS}}{D_{OS}} \frac{4GM_0}{c^2 b} = \theta - \frac{D_{DS}}{D_{OS}} \frac{4GM_0}{c^2 D_{OD}\theta} \quad (1.21)$$

$$\theta\theta_s = \theta^2 - \frac{D_{DS}}{D_{OS}D_{OD}} \frac{4GM_0}{c^2} \quad (1.22)$$

with $M_E = M_0$

$$\theta^2 - \theta_s\theta - \theta_E^2 = 0 \quad (1.23)$$

we are in presence of a second order polynom with a determinant $\delta = \theta_s^2 + 4\theta_E^2 > 0$ and its two solutions:

$$\theta_{1,2} = \frac{1}{2} \left(\theta_s \pm \sqrt{\theta_s^2 + 4\theta_E^2} \right) \quad (1.24)$$

Let's now study two interesting properties. By considering a small misalignment ϵ between the source, the lens and the observer; at first order the angular separation of the image $\Delta\theta$ is:

$$\theta_1 = \frac{1}{2} \left(\epsilon + \sqrt{\epsilon^2 + 4\theta_E^2} \right) = \frac{1}{2}\epsilon + \frac{1}{2}\sqrt{4\theta_E^2} = \frac{1}{2}\epsilon + \theta_E \quad (1.25)$$

$$\theta_2 = \frac{1}{2} - \theta_E \quad (1.26)$$

$$\Delta\theta = \theta_1 - \theta_2 = 2\theta_E \quad (1.27)$$

This means that the angular separation between 2 images increases with the mass of the deflector or increases when the deflector is closer to the observer.

The second property is about the mean surface density within θ_E which remains constant. We define this quantity as the critical surface mass density:

$$\bar{\Sigma}(\theta_E) \equiv \frac{M_E}{\pi(D_{OD}\theta_E)^2} = \frac{c^2 D_{OS}}{4\pi G D_{OD} D_{DS}} \equiv \Sigma_{crit} \quad (1.28)$$

This property implies that a finite massive object is a gravitational lens which produces multiple images if its central mass density $\Sigma > \Sigma_{crit}$

1.1.5 Magnification

Another property of gravitational lenses is the magnification. This quantity μ is given by the ratio between surface brightness of the image and the source. In the following we will stay in a 1D case but the magnification can be generalized using Jacobian given by this definition:

$$\mu = \frac{d\Omega_{image}}{d\Omega_{source}} = \left| \det \left(\frac{\partial \theta_s}{\partial \theta} \right) \right|^{-1} \quad (1.29)$$

Assuming a circular symmetry of the lens: $\mu = \frac{\theta}{\theta_s} \frac{d\theta}{d\theta_s}$

by considering $u = \frac{\theta_s}{\theta_E}$ the lens-image separation in units of Einstein ring radius, we get:

$$\mu_{\pm} = \frac{u^2 + 2}{2u\sqrt{u^2 + 4}} \pm \frac{1}{2} \quad (1.30)$$

The + solution is always magnified while the – solution can be magnified or demagnified depending on the value of u . If the source is inside the Einstein radius, $\mu > 1.34$.

Finally, the total magnification gives:

$$\mu = \mu_+ + \mu_- = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} > 1 \quad (1.31)$$

For a point-like source, if $u \rightarrow 0$, $\mu \rightarrow \infty$. If $u \rightarrow \infty$, $\mu \rightarrow 1$. In the case of a too small image separation, the magnification can still be measured. This is used when the mass of the deflector is too small and this technique is called micro-lensing.

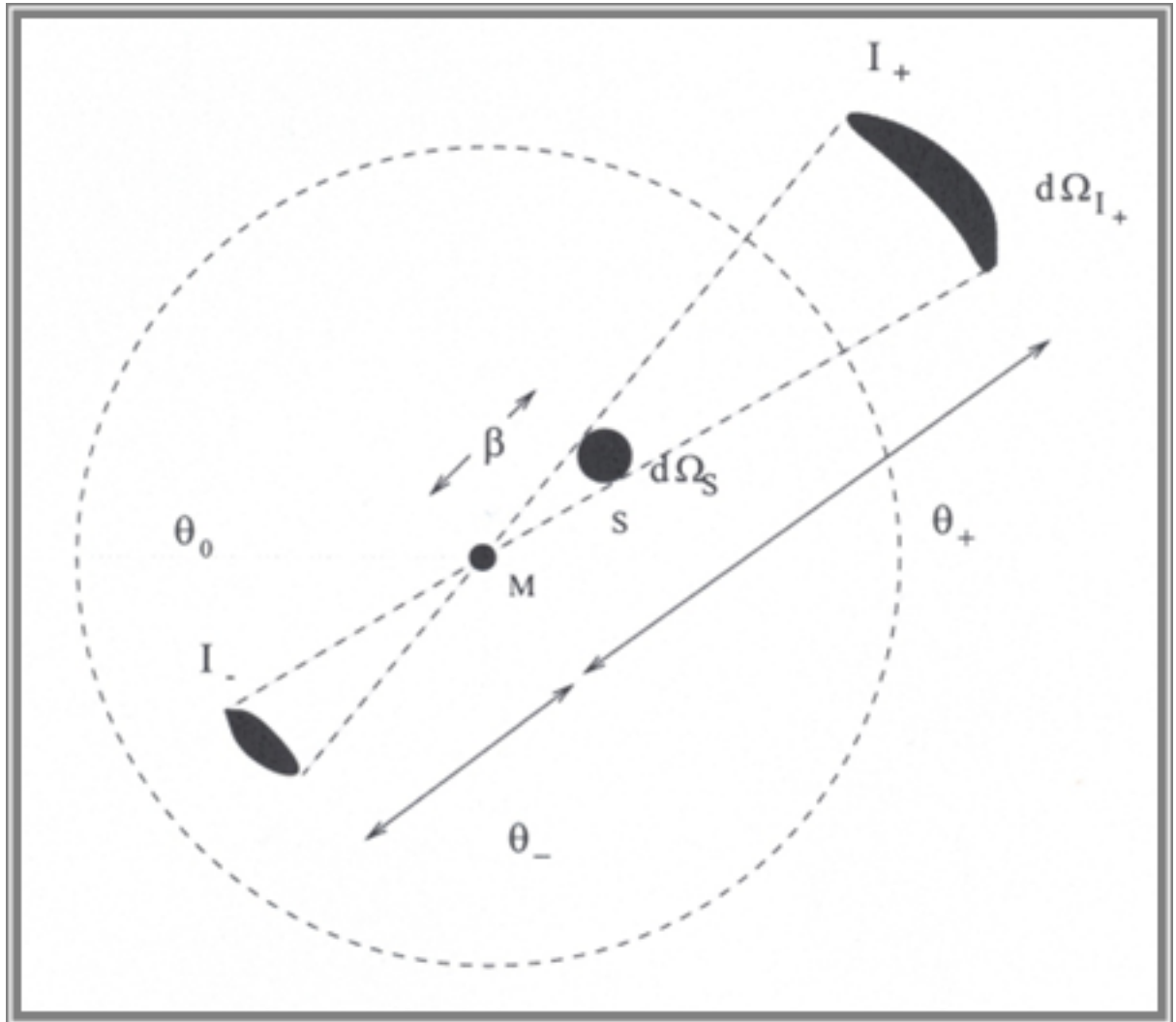


Fig. 1.4.: Illustration of a gravitational lens with magnification. β correspond to the angle between deflector and source which is θ_s in the previous demonstration. θ_- and θ_+ are respectively the demagnified and magnified images positions. The dotted circle correspond to the Einstein ring position.

1.2 Scientific context

Lenses used to be serendipitously found; but nowadays we are looking for gravitational lenses in large amount thanks to large survey programs. One can cite the Cosmic Lens All-Sky Survey (CLASS) which was one of the first survey dedicated to gravitational lenses. Twenty two lensed systems were found using the Very Large Array (VLA) radio telescope [10].

We generally subdivide lensing in 3 categories: Strong, Weak and Micro-lensing. The strong lensing is the case where a distortion of the background source is clearly identified. For a weak lensing, distortion is much smaller and statistical studies are needed in order to find distortion of about few percents. The micro lensing does not show any distortion but a variation of the background source light. The lensing object in a micro lensing case may be a star while strong and weak lenses are typically galaxies or even galaxy clusters. Micro lensing is often used to detect exoplanets [11]. In this work, I will focus on strongly lensed systems.

Studying gravitational lenses has a huge scientific interest. As F. Zwicky already mentioned in his paper in 1937 [8], they constitute a good source to test general relativity, they enable us to observe very distant galaxies and they allow us to determine masses of galaxies. In fact, it has many more applications like the determination of cosmological parameters (Ω_0 : density parameter, λ_0 : cosmological constant, and H_0 : the Hubble constant).

With the rise of Large surveys and their ability to store a large amount of data, we are facing Big Data problems. Processing this tremendous amount of data by hand is just impossible. In addition, the Euclid spacecraft will be soon launched and will provide more data with stunning quality. This is why it is important to detect lensed systems autonomously. The strategy adopted today is the rise of candidates from data to be followed up later with ground-based telescopes.

1.3 Convolutional Neural Network approach

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List of Listings

Example Appendix

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

A.1 Appendix Section 1

This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

| Alpha | Beta | Gamma |
|-------|------|-------|
| 0 | 1 | 2 |
| 3 | 4 | 5 |

Tab. A.1.: This is a caption text.

A.2 Appendix Section 2

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like

at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

| Alpha | Beta | Gamma |
|-------|------|-------|
| 0 | 1 | 2 |
| 3 | 4 | 5 |

Tab. A.2.: This is a caption text.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Colophon

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, *June 2023*

Laisney Clément

