How gravitational lensing was experimentally proved and what are its major applications at present?

Report on Gravitational Lensing

Modern Physics, Spring 2015
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Background

One of the greatest breakthroughs in the history of modern physics was the scientific formulation of the General Relativity Theory by Albert Einstein (that is now arriving to its 100th anniversary), one by one the predictions made by his theory were proved showing the masterpiece created by a genius.

Selected problem

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Introduction

If we pass through a lens the light that comes from a source, we will have a refraction of that light due to optic processes, as the following example taken from Stanford University, we have a candle as a light source and a lens created by a wineglass base:

It will be shown that gravitational lensing due to relativistic phenomena occurs in the Universe with the same pattern, and it is one of the proofs of the General Relativity Theory.

Gravitational Lensing in Classical Mechanics
Since Sir Isaac Newton proposed his gravitational theory and published his optics observations, the effect of a massive object to the behavior of light was proposed simply as “light particles should be affected by gravity in the same way as is ordinary matter”, but he didn’t add any relevant information about the subject.

In 1804 Johann Soldner published an article based in Newtonian Mechanics, in which it was predicted that a ray of light passing close to a sun-like mass would be deflected by an angle of $\theta = 0.84$ arcsec.

More than a century later, Albert Einstein developed the General Relativity Theory and made his own calculations about the deflection of light in presence of a massive object.

**General Relativity Theory and Gravitational Lensing**

In 1915 Einstein started to publish his gravitational theory now known as General Relativity Theory, which was harder to scientifically prove as to understand. In this theory Einstein proposed that Newton’s gravitational theory was incorrect in the sense that space and time are not constant, and proposed his field equations:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Where $R$ is the Ricci curvature tensor, $g$ is the metric tensor, $T$ is the stress-energy tensor, $\Lambda$ is the cosmological constant, $G$ is Newton’s gravitational constant and $c$ is the speed of light in vacuum. A tensor is a geometrical representation of a curved four-dimensional space-time, and the laws of physics must be expressed in a way that are valid independently to the coordinate system used to describe points in any space-time where inertial reference frames exist. To solve particular problems a metric should be calculated, and to demonstrate that a massive object alters the light’s trajectory, the Schwarzschild metric is used (space-time geometry outside a stationary spherical distribution of matter), with it the Einstein’s field equations are expressed as:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 0$$

as the stress-energy tensor (with zero cosmological constant) is not required as the space outside the object is empty. Having this considerations, assuming a spherical lens the space-time around the lens is described by the Schwarzschild metric as:
where s is the distance between 2 points.

At first, Einstein’s proposal for a gravitational lens was described by the following figure:

With that approach Einstein concluded that the lensing effect wouldn’t be noticeable because the angle between the two objects are dependent of the lensing object’s mass and the distance between the objects; the actual configuration for a gravitational lensing is shown next:

With this and simplifying the above formulas Einstein could calculate the angular deflection having the Sun as massive object as:

\[
\alpha = \frac{4GM}{c^2} \frac{1}{r^2} = \frac{4GM_{\odot}}{c^2} \frac{1}{R_{\odot}^2} = 1.74 \text{ arcsec}
\]

\textit{Arthur Eddington and the solar eclipse}

Previous to this prediction, Einstein had showed Eddington that his relativity worked to explain the precession of the perihelion of Mercury, precession that Newton’s mechanics failed to explain, but at the time scientists were skeptical about his proposal, as they found Newton not only valid but simple to understand, and the sole prediction of the precession wasn’t enough for them to replace Newton. For that, Eddington devised a way to experimentally prove that relativity was valid, taking advantage of the coming solar eclipse in 1919 and the pass of the Sun in front of the Hyades cluster, the idea was that when the Moon completely covered the Sun, the light from the stars that were behind the Sun would be visible thus a photography of them could be taken, and later compared with an actual photography of the cluster to measure the deflection angle and compare it with Einstein’s predictions.
The results were positive having calculated within 20% margin of error, due to that many scientist remained skeptic about relativity even claiming that the experiment was either ill-conducted or fitted to calculated data. For that reason, another expedition was set to 1922 with more accurate measures than the 1919 one, and it was published by Campbell and Turner in 1923 with the following figure attached:

**The Shapiro Delay**

Nowadays, with the space exploration as a tool, Einstein’s theories related to space-time curvature due to massive objects can be tested with planetary radar observations, especially with Mars; in 1960, Irwin Shapiro proposed that an accurate way to test the gravitational lensing was to send a pulse to a probe orbiting Mars and back to Earth, making it to pass close to the sun and measure how it is affected. First it has to be measured without having the Sun in its path, and then compare the time when the Sun is in its path, as the signal is deflected it will have a delay that can be measured, with this the error from experimental data has decreased to 5%.

**Present day applications**

Motivated by a letter sent by a Czech physicist in 1936, Einstein predicted that if a sufficiently bright object was located exactly behind a massive object, then a ring of the bright object could be seen as the light would be scattered out the lens, but he said that it was just a theoretical principle with small chance to be seen in nature because of the precise locations of the objects. His affirmation came when solving the tensors, for an “Einstein ring” we have that:

\[
\beta = \sqrt{\frac{4GM}{c^2} \frac{d_{LS}}{d_L \cdot d_S}}
\]

where \( \beta \) is the ring’s angle, \( d_L \) is the angular diameter to the lens, \( d_S \) is the angular diameter distance to the light source and \( d_{LS} \) is the angular diameter distance between the lens and the light source; the possibility to actually detect those lenses comes from the angular resolving of the instruments used by astronomers compared to this angle.

However in 1979 astronomers in the Very Large Array were capable to confirm the first “Einstein ring” after a report from an optical observation. It comes from a quasar (the brightest object in the Universe), at first it was thought to be two quasars, but VLA confirmed that the source was the same object.
After that observation, gravitational lenses have been photographed (mostly by Hubble Space Telescope) in a wide variety:

- One of the most exotic ones is the “Einstein cross”, a quasar that is lensed four times by a massive galaxy:

- One “smiley face”, an Einstein ring from a background galaxy lensed three times:

- The “five star” gravitational lens, as the same quasar is lensed five times (and a galaxy three times):

One of the applications of this phenomenon is the detection of black holes, as their name suggests, a black hole cannot be directly seen because there is no light coming from them, for that reason at first they could only be detected due to the gravitational lensing created by their massive nature, the following figure shows a simulation of a black hole’s gravitational lensing:

Black holes can be detected now by other methods, but there is another objects in the nature that cannot be detected by their light or any other emission, that is the case of the black matter, it was theoretically proposed and later on confirmed by the lensing it creates. As the lensing can be calculated and the galactic mass can be estimated with accuracy, astrophysicists noticed that the lensing created by galaxy clusters was greater than the one observed, thus, there are more mass present in those galaxy clusters than the one estimated by the visible matter, as the following figure shows:

Summary

To experimentally prove Einstein’s Relativity Theory just by predicting the precession of the perihelion of Mercury’s orbit wasn’t enough, thus a new method had to be devised and Arthur Eddington suggested that the gravitational lensing could be proved by measuring the deflection of the stars’ light that were behind the Sun during a solar eclipse; later Irwin Shapiro devised a new experiment in which a radio signal could be sent back and forth to measure the delay of a signal without having a massive object in the signal path compared to sending the same signal without having a massive object in the signal path. All the experiments having the deflection gave enough data to prove that gravitational lensing actually occurs, proving that Relativity Theory works. Gravitational lensing is used to detect non-emitting black holes and dark matter, as direct optical observations of those phenomena are almost impossible.
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