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Light Slowed Near Sun

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ABSTRACT
The sun, a star which consists a luminous spheroid of plasma compacted together by its gravity. When light beam passes it, the curvature of gravitational field and gravitational lensing will give rise to a bending light path, base on the theoretical foundation provided by general relativity. Also, the plasma plays a role, it performs a medium and gives a refractive index in coronal layer, and then the speed of light is slowed. According to these three reasons, time delay happens near sun.

Keywords: *General relativity, gravitational lensing, time delay, Schwarzschild radius, tenuous plasma.*

1. INTRODUCTION

During the period when modern physics was discovered, Newton's and Einstein's thoughts about our world were not same. Their explanations were different but reasonable and able to explain the common phenomena in daily life. However, on the large scales like cosmos, although Newtonian physics can give words and formulas, it cannot be as accurate as Einstein's ideas. Therefore, a new concept called general relativity became well-known.

One of the predictions from general relativity is the gravitational lensing. The gravitational lens effect has emerged as a cutting-edge topic in modern physics and astronomy, fuelling a vast research effort with far-reaching implications. Nowadays, astrophysicists use this effect to explore further secrets of universe. They use this effect to detect the light from those stars which are far away from Earth. Because of the time for photons to travel, the light they accept is the brilliant rays emitted by those stars from the early universe. For the only star in solar system, the sun not only play a role on nourishing lives, but also give physicists another mysterious and attractive field to explore. The light path around sun is actually curved, by some special reasons, which will be explained in part 4 and 5, the linkage to gravitational lensing will be mentioned as well.

To ensure that the article reaches the widest potential audience, this article does not contain too much sophisticated mathematical deductions, the technical terms are only used for conclusions.

2. A BRIEF REVIEW OF GENERAL RELATIVITY

Before analysing the gravitational lensing, it is necessary to do a revision on its theoretical foundation, general relativity. This part not only introduces the history, but also introduces the inspiration, main principles and comparison with the popular Newtonian physics theory.

2.1. History of General Relativity

General relativity is a theory pointed out by Albert Einstein in 1915, ten years after he published the Special relativity. Special relativity is a theory about speed and time. Relativity has two main principles. First, the laws of physics are the same in all reference frames [1]. Second, the speed of light in a vacuum has the same value, about $c = 2.99792458 \times 10^8\ m/s$, in all inertial reference frames, regardless of the velocity of the observer or the velocity of the source emitting the light.

However, it can only deal with some special cases in which gravity is absent. Einstein spent almost ten years to complement the gravity into the theory. Finally in 1915, he published a new and sensational thesis, General Relativity. He got inspiration when he was standing in an elevator. When the elevator is going down, people inside cannot feel the gravity, but as the elevator goes up, their feet seem to stick on the floor. Then Einstein summarised this phenomenon and took gravity and acceleration into account and finally concluded the general relativity.

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2.2. General Relativity versus Newtonian Physics

Before relativity was published, Newtonian physics provided dominated notion of time and space. Newton stated that time is absolute, it is independent of reference frame, the timing results of the same motion process are the same. Also, Newton's law of gravitation suggests the motion of planets around sun is because of the gravity, they all follow circular paths which deviate their inertia. The equation showing the gravitational attraction between two objects is given by:

$$F = \frac{Gm_1m_2}{d^2} \quad (1)$$

where m_1, m_2 refer to their masses, and d refers to their separation distance. However, in general relativity, Einstein gives a different notion: he states that, when a planet is moving around the star, it follows a geodesic path in the curved spacetime near the massive objects. The geodesic equation is:

$$\frac{d^2x^\lambda}{ds^2} + \Gamma^\lambda_{\mu\nu}\frac{dx^\mu}{ds}\frac{dx^\nu}{ds} = 0 \quad (2)$$

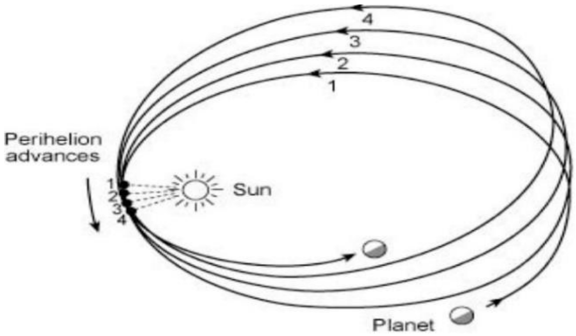

Figure 1. The precession of Mercury's perihelion. [2]

Nonetheless, although each view is able to give an interpretation, there is a phenomenon that Newtonian physics cannot explain fully, the Mercury Perihelion. Mercury orbits the Sun, the perihelion advances by a small amount [2]. There is a time difference about 43 arcsecond per century, when we compare the data we measured and Newton's expectation concluded by the gravity from other planets. However, general relativity can confirm this phenomenon persuasively, it announces that Mercury moves deeper into the Sun's gravity well, when moving towards the perihelion. It enters a spacetime with larger curvature. The figure calculated from general relativity expects precisely the amount of perihelion advance seen in Mercury.

At that time, this result became the most critical test to the theory of general relativity.

2.3. Equivalence Principle and Einstein's equation

There is a remarkable principle called equivalence principle, it indicates the equity of gravitational mass and inertial mass [3]. According to Newton's second law and Newton's law of gravitation, we distinguish them by using different subscripts and their relation is:

$$m_g = m_i \quad (3)$$

There is a further definition concluded from the constant ratio of m_i/m_g called Weak Equivalence Principle. It states that the trajectory of a freely-falling test-particle is independent of its internal structure and composition [1].

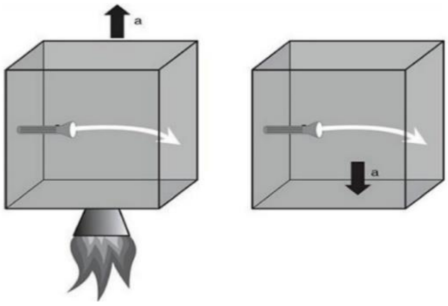

Figure 2. The equivalence principle in photon version. [3]

To understand how Einstein found general relativity, we do a thought experiment. Imagine yourself in a sealed box and hold a flashlight. In the left box, the beam of photon bends downward, the photon path enters the box from the upper left side and reaches the lower right side. The reason is the acceleration, the bottom of box accelerates towards those moving photons. According to the equivalence principle, we can imagine another stationary box and do the same experiment, same results will be given. But this time, the prime reason is the gravitational field. Then Einstein states that the presence of mass-energy make neighbour spacetime be curved, light will follow a geodesic path when enters. Finally, Einstein got inspiration from the equivalence principle, so he summarized the theory of general relativity, and gave out the field equation:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu} \quad (4)$$

3. WHAT IS GRAVITATIONAL LENSING

Lens, literally shows the bending of light through a transparent glass. But how an opaque planet can act as a lens to make the planet behind it detect the light from a sheltered star. This part will give the reason and also some magnificent sightseeing formed by gravitational lensing, as well as the necessary role it performs in astronomical field.

3.1. Introduction and basic notions

A gravitational lens is a matter distribution between a far-away illuminant and an observer, which helps to bend the light path and make sure observer is able to detect it. In the halo of Milky Way galaxy, those MACHO can generate the phenomenon of gravitational lensing, which short for short for Massive Astrophysical Compact Halo Objects. The fundamental principle is general relativity. In general relativity, massive objects distort the neighbouring space-time fabric, and light follows a geodesic path regardless of wavelength or energy. When one planet is shielded by another, the middle planet functions as a lens, bending and magnifying light, which shows a similar result as an optic lens.

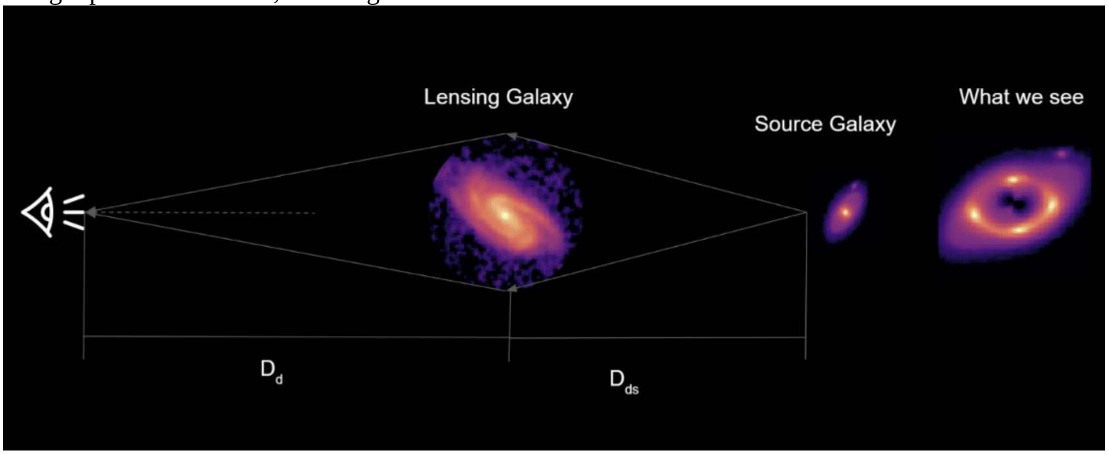

Figure 3. A simple illustration of strong gravitational lensing. [4]

Gravitational lensing can be classified into three categories by their various effects: strong gravitational lensing, weak gravitational lensing and microlensing [5]. Strong gravitational lensing generally refers to the phenomenon that single image of the light source becomes double image or multiple images after passing through the lens. Weak gravitational lens refers to those lenses whose function are insufficient to produce multiple images, but which can cause image geometry distortion or a huge number of little light arcs. For microlensing, generally speaking, the image generated by the light travelling through the galaxy is predicted to show intensity fluctuations if the stars in the lens Galaxy approach the light emitted by the background light source and produce more deflection over time. Micro gravitational lenses are the result of such variations induced by a single star. The distribution of stars in the lens galaxy, their mass, velocity, and the size of the light source disc all influence the intensity variation induced by micro gravitational lens.

3.2. Einstein ring

Einstein ring is a sight produced by strong gravitational lensing. It is the simplest and most symmetrical effect of gravitational lens, generated when the source, lens, and observer are precisely aligned across a horizontal line [6]. The angle formed by light rays traveling directly to the observer θ_E is known as the Einstein angle, and it is the characteristic magnitude of the Einstein ring. In radians, it can be given by the formula:

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}} \tag{5}$$

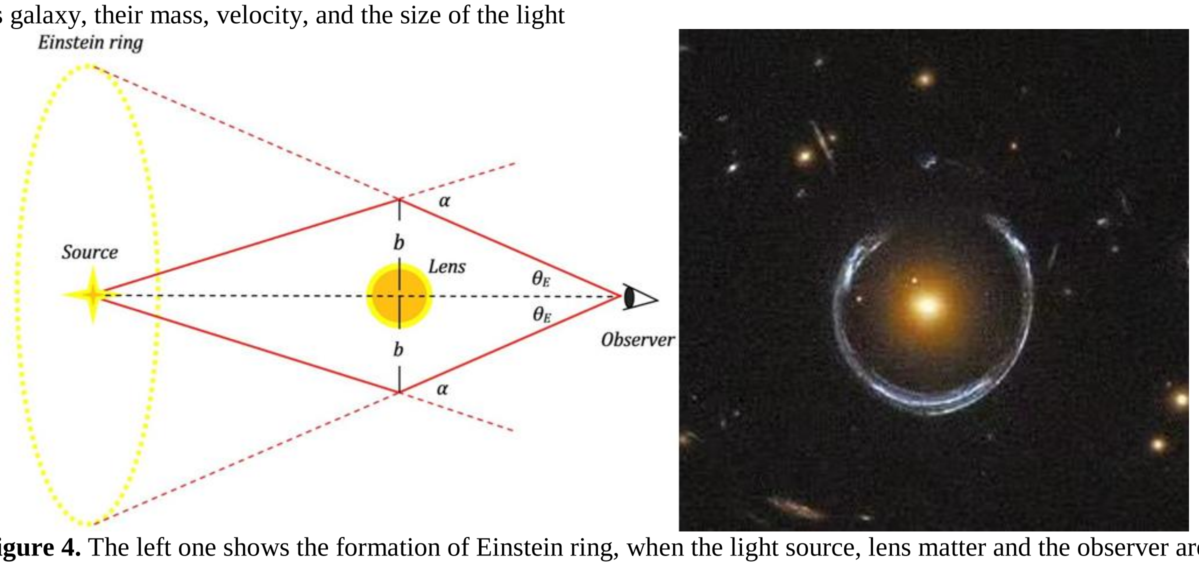

Figure 4. The left one shows the formation of Einstein ring, when the light source, lens matter and the observer are perfectly aligned [6]. The right picture gives a typical sightseeing of Einstein ring, image from HST.

3.3. Application

Since its discovery, gravitational lensing has been a significant tool for researching the secret of the cosmos. For example, astrophysicists can use them to detect the presence of dark matter or explore early universe.

Lensed image distribution depicts the distribution of all matter, both visible and dark [7]. Maps of dark matter in galaxy clusters were created using Hubble's gravitational lensing photos. As a result, a map of matter in a galaxy cluster aids in the comprehension and interpretation of gravitationally lensed pictures. A matter distribution model can aid in the identification of numerous photographs of the same galaxy or the prediction of where the most distant galaxies are expected to appear in a galaxy cluster image. A map of the matter in a galaxy cluster, on the other hand, aids in the comprehension and interpretation of gravitationally lensed pictures. A matter distribution model can aid in the identification of several photographs of the same galaxy or the prediction of where the most distant galaxies would appear in a galaxy cluster image. Gravitational lenses allow Hubble to see further into the cosmos though the very distant galaxies are dim. Gravitational lensing may increase the intensity of light from a background galaxy and distort it. Hubble can view fainter and further galaxies via a lensing galaxy cluster than he could otherwise.

4. HOW IS LIGHT SLOWED NEAR SUN

When travelling via a big sun, the light path alters from a straight line to a geodesic line. What about the speed of it? Is it going to change or stay the same? What is the major cause for the change if it does? Why the Schwarzschild radius is considered for time delay? This part will provide the answers.

4.1. Gravitational time dilation

For every mass, the Schwarzschild radius is a critical radius eigenvalue. It's a crucial idea in physics and astronomy, particularly in theories like universal gravitation and general relativity. If matter is compacted within that radius, there is no known sort of force that can prevent it with a specific mass from collapsing into a black hole under its own gravity. The formula of Schwarzschild radius is deducted by the escape velocity formula. Assuming the speed of an object is equal to light speed c , while R refers to the distance between the centres of mass of the body and the attracted item. The equation of escape speed is:

$$v = \sqrt{\frac{2GM}{R}} \tag{6}$$

If an object's velocity is less than a celestial body's escape velocity, it will be drawn to the celestial body, preventing it from escaping orbit and reaching interstellar space. According to Newton’s law of gravitation and Newton’s second law, in this case, the acceleration at the surface of a celestial body is equal to the gravitational acceleration, therefore:

$$g = \frac{GM}{R^2} \tag{7}$$

Substitute this into the gravitational energy equation and get:

$$E_g = mgh = \frac{GMmh}{R^2} \tag{8}$$

The height is equal to the distance at the surface. Assume the object has kinetic energy $E_k = \frac{1}{2}mv^2$, it should be $E_k > E_g$, we take the critical value, $E_k = E_g$, and obtain:

$$\frac{1}{2}mv^2 = \frac{GMm}{R} \tag{9}$$

$$R = \frac{2GM}{v^2} \tag{10}$$

Substitute v with c and get final equation of Schwarzschild radius:

$$R_s = \frac{2GM}{c^2} \tag{11}$$

There is also an equation for gravitational time dilation near a huge, slowly rotating, almost spherical mass like the sun. [8]:

$$\frac{t_r}{t} = \sqrt{1 - \frac{R_s}{R}} \tag{12}$$

where t_r is the elapsed time for a radial coordinate observer r, t is the elapsed time for an observer far away from a large object, and r is the observer's radial coordinate. If we take the figures of sun into this equation, we can get the approximated time dilation near sun.

If we express the coordinates of photon in terms of z and t, and mass of sun is $M_\odot$, the velocity can be expressed as:

$$\frac{dz}{dt} = 1 - \frac{2GM_\odot}{r} \tag{13}$$

This demonstrates that the velocity is frequency independent [9]; as a result, there is no dispersion and the signal velocity and phase velocity are identical. The speed of light propagation is slowed by the gravitational field from the sun.

4.2. Deflection of photons in coronal layer

The corona is the outer atmosphere of sun [10]. It stretches thousands of kilometres above the Sun's visible surface, eventually converting into the solar wind that blows outward through our solar system. The material in the corona is a tremendously hot yet exceedingly tenuous plasma. The temperature in the corona is over a million degrees, which is much hotter than the Sun's surface temperature of roughly 5,500 degrees Celsius. The corona has a far lower pressure and density compared with that in Earth's atmosphere.

The tenuous plasma has the ability to deflect light. It consists of cations, anions and neutral atoms, and has a feature of oscillation, the frequency is:

$$\omega_0 = \sqrt{\frac{4\pi e^2 N}{m}} \tag{14}$$

where terms N, e and m refer to electron density, electron charge and electron mass respectively. If a beam of light travels among plasma, its angular frequency ω will remain but the wavelength and speed will change. According to the Maxwell's Electromagnetic Wave Theory, light speed c can be expressed as:

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \tag{15}$$

where μ is the magnetic permeability and ε is the permittivity. Therefore, the light speed is inversely proportional to $\sqrt{\varepsilon}$. While the magnetic permittivity is related to the dielectric polarization, and due to the interaction between the electromagnetic waves sun emits and the electron system of atoms, light will become slowed by the tenuous plasma inside the coronal layer.

5. DISCUSSION OF LIGHT SLOWED NEAR SUN AND THE TIME DELAYS IN GRAVITATIONAL LENSING

According to the above possible explanations, the reasons are emerging to the surface. But how they are related or which factor dominates the effect for the slowed light around the sun. How does the gravitational lensing give the influence to the time delay on the theory of general relativity. These questions are talked about in this sector.

Base on the assumption that our universe is homogeneous and isotropic, the Friedmann-Lemaître-Robertson-Walker metric with spatial curvature $\boldsymbol{k}$ is deducted:

$$ds^2 = -dt^2 + a^2(t)(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)) \tag{16}$$

which was deducted by Robertson and Walker independently in 1936, and used in demonstrating the cosmos. $a(t)$ is the scale factor that tells us the expansion of the universe is dependent on time.

Recall general relativity, the light passes a massive object like sun will bend and follow by a geodesic path. The light near a lensing object, the gravitational field will give the time delay. If we consider the celestial body of gravitational lensing is a Schwarzschild black hole, we first calculate the time for a point to travel from $\{r, \theta = \frac{\pi}{2}, \phi = \phi_1\}$ to $\{r_0, \theta = \frac{\pi}{2}, \phi = \phi_2\}$ [11]. Then we can get an equation of motion:

$$\left(\frac{dr}{dt}\right)^2 = \frac{A(r)}{B(r)}[1 - \frac{A(r)}{A(r_0)}\frac{C(r_0)}{C(r)}] \tag{17}$$

After the integrations and other mathematical deduction [12], we get:

$$t(r, r_0) \approx \sqrt{r^2 - r_0^2} + (1+\gamma)M ln\left(\frac{r+\sqrt{r^2-r_0^2}}{r_0}\right) + M\left(\frac{r-r_0}{r+r_0}\right)^{\frac{1}{2}} \tag{18}$$

The former term is the expected value for the light beam, the latter terms are the time delay by the gravitational field from the lensing object. If we transmit electric signal and make it pass the sun's surface and reflect back to Earth by Mercury, expressing the figures for the sun's radius, distance from Earth to sun and distance from sun to Mercury in terms of $R_\odot, r_E, r_M$ respectively, we get the time delay:

$$\Delta t_n = 2[t(r_E, R_\odot) + t(r_M, R_\odot) - \sqrt{r_E^2 - R_\odot^2} - \sqrt{r_M^2 - R_\odot^2}] \approx 240\mu s \tag{19}$$

when the electric signal reflects back.

Recall what we did in Part 4, as the light is passing the sun, the gravitational field is getting stronger and stronger. The speed of light is slowed, time delay happens. However, this approximated result provides a clear and persuasive evidence for the important role of gravitational lensing on time delay as well. Therefore, their relation is, although gravitational field is the dominated reason, the gravitational lensing effect is another significant factor in making the light near sun become slowed. Or we can say, the presence of gravitation is the principle of slowed and curved light near sun.

6. CONCLUSION

We can conclude the importance of gravity and the presence of gravitational lensing based on general relativity theory. The light beam approaching the sun is slowed according to their concepts and calculations. Light is deflected in the coronal layer due to the effect of tenuous plasma as well.

This phenomenon is not something new that contemporary technology has uncovered. Some classic notions can be used to deduce the principles and numbers that support it. Those concepts were discovered by various well-known physicists in the previous century. At the time, the physics building they had constructed was already adequate. In other words, if they considered this phenomenon, they came to the same conclusion.

Nonetheless, thanks to the advanced technology, we can now see these phenomena and provide convincing proof as well as many precise computations, as I mentioned above. Scientists are putting this hypothesis into practice. We will be able to calculate more accurate data and prove more previous hypotheses in the future. Therefore, base on the combination of classic physical foundation and superior modern technology, we are able to employ this slowed light to study more secrets of the cosmos and satisfy the endless desire of human exploration.

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