Gravitational Lensing

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GRAVITATIONAL LENSING:

NATURE'S LARGEST TELESCOPES

Gravitational Lensing: Nature's Largest Telescopes

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(Dated: Jan 6, 2023)

The process of light distortion as the visible electromagnetic waves pass through generously large celestial areas such as huge galaxies is called gravitational lensing (GL). Due to the light of a smaller object being bent behind a larger object, strong gravitational lensing can lead to the potential visibility of two or more images of the same object, when really there should only be one. On the contrary, weak lensing can form stretched or magnified images of galaxies. The curvature of the light is caused by the gravitational pull of a bending object creating a curve in the space-time continuum.

1. GENERAL THEORY OF RELATIVITY

The General Theory of Relativity is at the heart of the idea of gravitational lensing because the theory predicts the idea. Albert Einstein came up with the astute idea of the General Theory of Relativity in the early 1900s. Up until that time, the society held a more Newtonian view of the universe, which entailed spacetime itself is constant no matter which point is taken in the expanding universe and light is the variable. His idea was contradicting as he believed the spacetime continuum was relative to a particular position based on the varying forces of gravity at a certain object. The warping of the fabric of space-time can be analogous to a trampoline. The dip you create by standing on one area of a trampoline is similar to how mass is related to the curvature of space and time. By warping the geometry of the surrounding spacetime, a massive object creates a gravitational field. The more massive an object is, the stronger the gravitational forces it creates, and the larger the spacetime curves it warps. General relativity treats space as malleable and states the very shape of space itself can be distorted. In Einstein’s theory, objects do not orbit other objects because they are attracted together. Instead, objects travel in straight lines in curved space. Light travels in a straight line; if it turns out you see a curved path of light in outer space, which means space has been bent. According to Einstein's theory, the mass of a star will bend space, and light passing nearby will follow a curved path. In 1919, Sir Arthur Eddington harnessed a total solar eclipse to see past the Sun. When he looked at the position of distant stars very close to the Sun, he found the positions of some of them were not as expected. The effect of gravity had altered the path of light. Therefore, Eddington proved Einstein's theory.

2. ANALYZING LIGHT DISTORTION

Lensing clusters are elliptical galaxy clusters whose gravity is so strong, the light from the galaxies behind them is distorted. This aids the formation of blurred background images of the galaxy, and sometimes several ones. However, despite the bending, gravitational lenses allow for dramatically enhanced observ-ations when gravity bends the direction of light to Hubble, amplifies the light, and renders visible objects otherwise opaque. A distant galaxy is seen first in figure 1, with very little of its light moving to Earth. If we introduce a galaxy cluster between the galaxy and Earth, we see how the light's trajec-

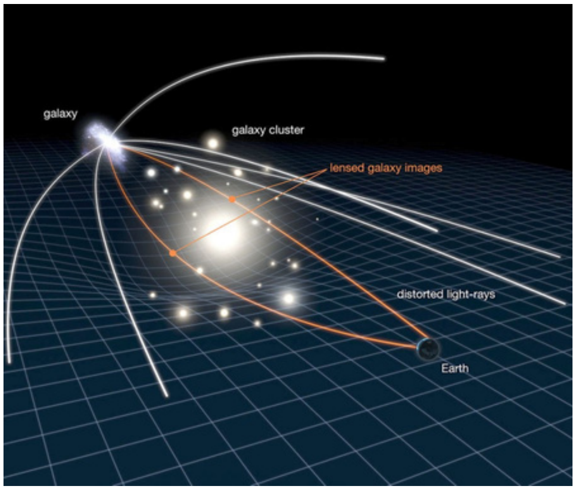

FIG. 1: GL Diagram
by NASA, ESA & L. Calçada

tory is modified and the light visible from Earth is intensified. Note the size was dramatically inflated in the diagram in order to distinctly display the gravitational lens bending light. The distant galaxy, in fact, is much farther away and exceedingly smaller, which is why it only appears as small points of light. The large galaxy is therefore a gravitational lens. They are created by massive clusters composed of thousands of galaxies and dark matter. The cluster bends and magnifies the light of galaxies behind it, like an ordinary lens. However, the same process occurs on a much larger scale. This technique allows scientists to study ancient galaxies in high resolution with unprecedented detail. In a few cases, it enables them to look eleven billion years in the past and directly witness the formation of the first primitive spiral arms of a galaxy. A gravitational lens not only distorts the images of background sources into weird arcs but it actually makes them brighter as well. That means that when using a gravitational lens, it is found that we can actually see fainter and therefore more distant objects than would otherwise be possible. Also, the images are magnified so that we can see more detail just like when using an ordinary magnifying glass.

3. ABELL 2218 AS A LENS

Located in the Draco constellation, Abell 2218 is a galaxy cluster that is 2 billion light-years away, with a rough estimate of about 10,000 galaxies. This galaxy cluster is used as a powerful gravitational lens because of its intense mass of

$$M_{gas}/M_{tot} = (0.04 \pm 0.02) * h^{-3/2}$$

It bends the light of many galaxies behind it, acting like a real-life lens. The lensed galaxies are visible in figure 2 below.

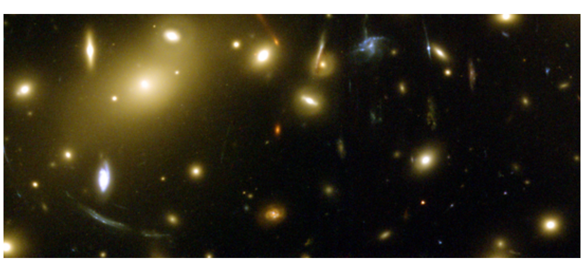

FIG. 2: Abell 2218 by NASA, ESA, and Johan Richard (Caltech, USA)

The concave shape of some galaxies centered around a massive part of the cluster, proving evident to gravitational lensing. Due to the advanced telescopic technology that the Hubble possesses, multiple arcs in the picture can be analyzed in depth. By comparing the shape of the galaxies and their color, several warped representations of the same galaxies can be described. There have been several smaller arclets found in addition to the giant arcs. The light distortion caused by the lensing of Abell 2218 was used to view a galaxy about 13 billion years old from Earth. The distortion was an extremely relatively early sight considering the Big Bang was just 750 million years prior. Taking into account the fact spacetime itself is flexible, it creates hills, valleys, and contortions. Even though light wants to go in a straight line, it is obligated to follow those bumps caused by gravity in the spacetime continuum because the geometry underneath it is dynamic. The idea of these abnormalities is similar to traveling through a mountain range. You may want to just get from one place to another quickly in a straight line, but the bumps along the way require you to follow the path of the ground beneath you. The bending of light by gravity can bend galaxies behind a massive foreground cluster into an arc.

Sometimes if the positions are placed correctly, a full ring may even be visible.

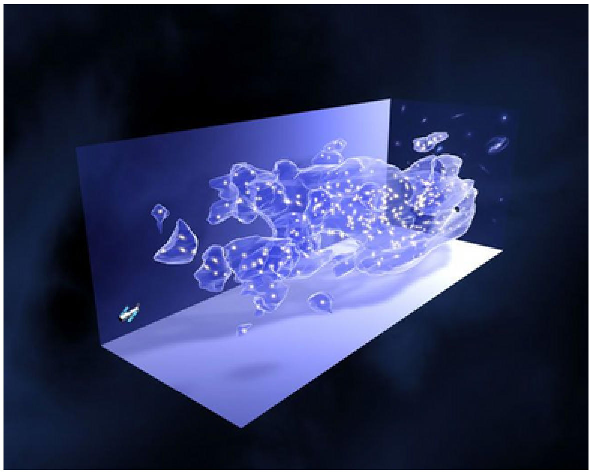

FIG. 3: Dark Matter Distribution by NASA

4. DARK ENTITIES OF THE UNVIERSE

DARK MATTER:

Gravitational lensing is one of the prime pieces of evidence to the existence of dark matter. When we look through a galaxy cluster at a background galaxy, we can now figure out a large magnitude of activity occurring inside that certain galaxy with advanced technology, whether we can see it or not. Some examples include the Bullet Cluster, Train Wreck Cluster, and many more within the Abell catalog. Gravitational lensing allows physicists to map out detailed distributions in vast regions of outer space.In figure 3, entire galaxies appear as individual white spots and dark matter as pale blue shapes. According to renowned studies based on the orbital, brightness, and lensing methods, there is strong evidence for the existence of vast amounts of dark matter within galaxies as well as between them. Looking closely at figure 3, it can be observable there is almost 40-50 times the amount of dark matter as visible light. Although dark matter can not be viewed by scientists, they can observe its presence by studying how the gravity of enormous superclusters containing dark matter stretches and manipulates light behind the cluster from various distant galaxies, which in essence, is gravitational lensing.

DARK ENERGY:

The American astronomer Edwin Hubble explored in the 1920s how the wavelength of electromagnetic radiation released from distant galaxies is expanded over a longer range and changes as it extends across space into the red end of the electromagnetic spectrum. He noticed galaxies that were fainter and more distant, showed a great degree of redshift; nearby galaxies showed more blueshift which is on the opposite end of the EM spectrum. Hubble concluded this was due to the expansion of the universe itself and the redshift happens because of the wave-lengths. One theory is the density of dark energy stays stagnant and it does not dissipate as the universe expands, and ordinary matter and radiation become more diluted. Therefore as the universe expands, more and more of it is created because the density of dark energy remains constant. Dark energy acts as the catalyst which pushes apart the cosmos. Although it cannot be physically, scientists can detect its presence and characteristics using the amount of mass of an object and the curvature of space near the object. The following equation is a result of this idea:

$$H^2 = \overbrace{\frac{8\pi G}{3}\rho}^{\text{matter density}} - \overbrace{\frac{kc^2}{R^2}}^{\text{curvature}} + \overbrace{\frac{\Lambda}{3}}^{\text{dark energy}}$$

In this equation: H = Hubble's constant, c = speed of light, G = gravitational constant, p = matter density of the universe, k = curvature of the universe, and Λ = cosmological constant. Astronomers can be aware of the way dark matter is spread within galaxies and their distance by studying the nature of gravitational lensing processes. This approach offers a test to examine both the progression of structure in the universe and the expansion of the universe. Einstein's theory of general relativity has allowed us to determine the structure of the universe both visible and invisible.

5. EINSTEIN'S CROSS AND RING

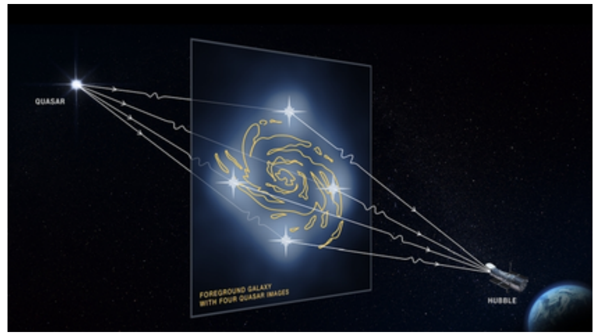

FIG. 4: Einstein's Cross Diagram by NASA, ESA, A. Nierenberg/JPL and T. Treu/UCLA

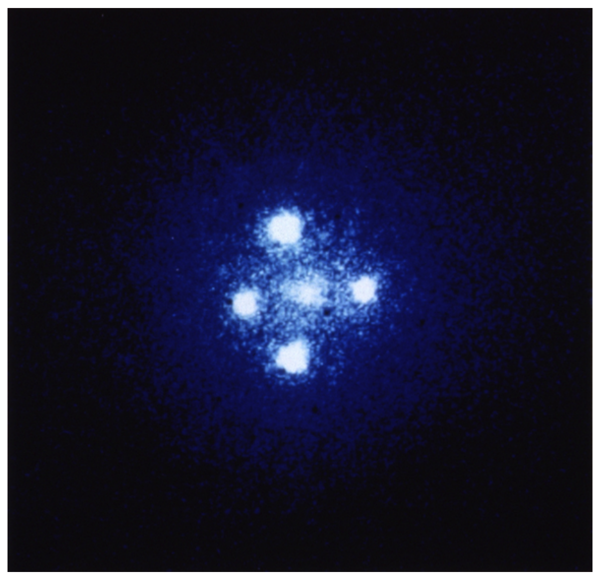

FIG. 5: Einstein's Cross by NASA/ESA/STSCI

In 1985, for the first time, another kind of gravitational lensing effect was seen. That was what astronomers called an "Einstein Cross," or four views of the same object positioned around the lens perpendicular to each other. In this case, the lens was a galaxy distortting the light which went through it and became known as the Lens of Huchra. And astronomers detected their first Einstein Ring back in 1988 (figure 5). An Einstein Cross is the effect of strong gravitational lensing. Strong gravitational lensing is the result of an extremely powerful gravitational distortion of light produced by a massive celestial object, such as ZW 2237+030 (QSO 2237+0305 G or Lens of Huchra), that usually results in two or more visibilities of the same structure (figure 4). Huchra's Lens is the galaxy that lensed the famous Einstein's cross. The quasar that was gravitationally lensed is called Q2237+0305 in the Pegasus constellation. The 0.04 galaxy redshift whose nucleus is conveniently bracketed by the quasar forms the four distinct appearances of the same 1.7 quasar redshift. While it is very bizarre, this multiple imaging can be highly useful to astronomers and allows us to figure out how light from the distant object has traveled all the way to Earth. These weird cosmic doppelgangers can be used to explore both the characteristics of the gravitational lens and the universe itself. Similarly, if everything is perfectly aligned, a ring of light encircling the huge galaxy (as seen in figure 6) in the foreground can be seen. This is a result of weak gravitational lensing which creates rings of light. If the

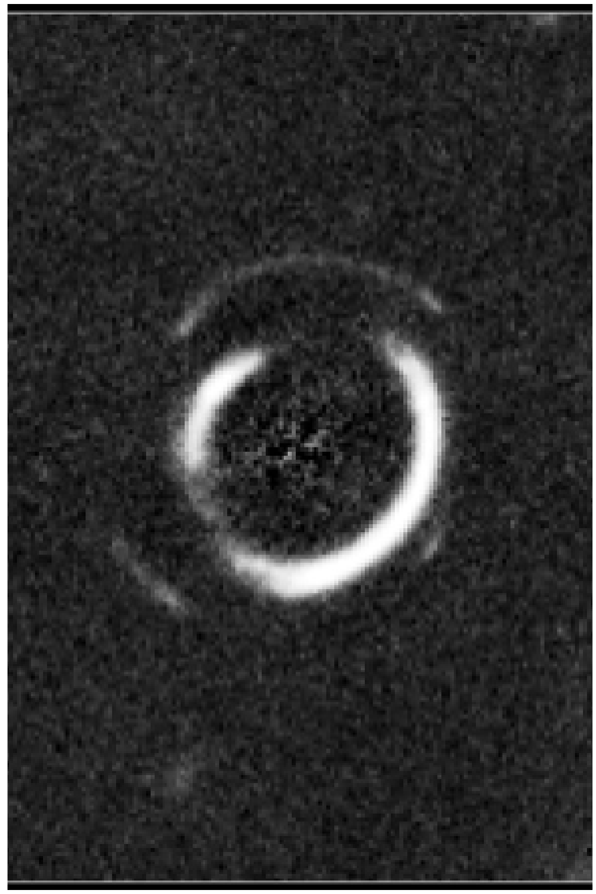

FIG. 6: Double Einstein Ring by HST/NASA/ESA

light fluctuations are very minimal, it is not possible to detect them on individual galaxies, so it is considered weak lensing only objectively, by averaging over a large number of galaxies. These perfect rings known as Einstein rings are so rare that only a few have ever been observed in visible light. In 2008, Hubble observed an even rarer cosmic coincidence: an incredible double ring where Hubble can see the light from not one but two galaxies perfectly aligned behind a closer galaxy (figure 6).

6. THIRD TYPE: MICROLENSING

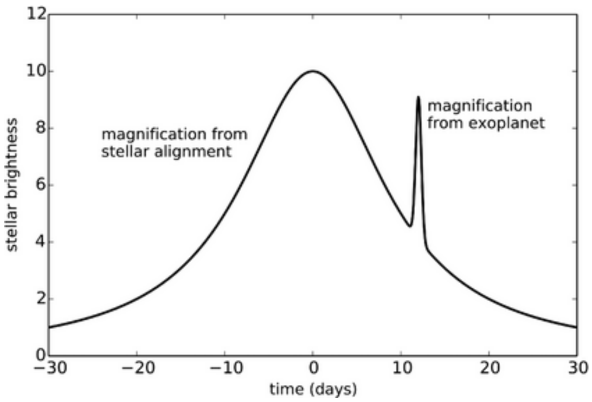

FIG. 7: By Joshua Krissansen-Totton, David C. Catling

There exists multiple types of gravitational lensing. We already delved into strong and weak lensing. The third type is micro-lensing. In gravitational micro-lensing, scientists look for a small blip in the light coming from a distant star caused by the warping of space as shown in figure 7.

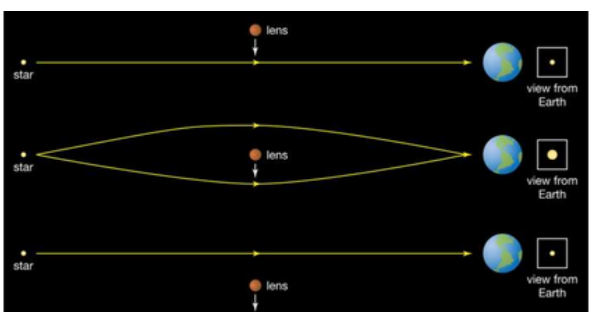

FIG. 8: Encyclopædia Britannica, Inc.

In the presence of a planet, to be able to see this blip, they need the light from the distant star to be magnified. This happens when a closer star passes in between us and the distant star. In these cases, the distant star is usually a bright star and the closer star is one we could not ordinarily see from Earth (figure 8). This method of detection allows us to find exoplanets that are far from their star. It also allows us to find small exoplanets and potentially exo moons orbiting exoplanets. Although most other approaches have a disadvantage to find smaller planets, the most efficient means of detecting planets that are around 1-10 astronomical units (AU) away from Sun-like stars is the microlensing process. In larger orbits, microlensing is also the only validated way of detecting low-mass planets, where both the transit and radial velocity approaches are unsuccessful. These advantages allow microlensing the most powerful way around Sun-like stars to locate Earth-like planets. Furthermore, using ground-based equipment, microlensing surveys can be installed efficiently. The Microlensing process, like Transit Photometry, benefits from the fact that it can be used to concurrently a large magnitude of stars.

7. CONCLUSION

The lens arrays of telescopes have revolutionized the way we view celestial objects in the universe such as planets, moons, and the entire cosmos since Galileo Galilei, who made extraordinary telescopic

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discoveries. Now scientists are aiming to explore into the farthest corners of the universe with nature's largest telescopes made of distorted spacetime. Many benefits have come from gravitational lensing, such as allowing scientists to see many distant galaxies that may otherwise be too faint to spot. Because light takes time to travel through space, the further a galaxy is the farther it actually is back in time; hence, studying these galaxies reveals knowledge of the early universe and gives us insight into the past. Another instance is that through gravitationally lensing, a galaxy cluster that is about 2,000 times the mass of the Milky Way, we discovered a galaxy that existed when the universe was about 500 million years old. Researchers estimate this galaxy (MACS 1149-JD), based on its phase of evolution, is around 150 million times the mass of the sun and developed fewer than 200 million years after the Big Bang, far earlier than scientists once believed the first galaxies had formed. Observing the number of galaxies in the early universe could help astronomers understand the mysteries that prevailed between 150-800 million years after the Big Bang, such as the period of reionization. The dark cloud of atomic hydrogen that once permeated the universe by ionizing it into its constituent protons and electrons was cleared by extreme ultraviolet radiation during reionization. It could help to understand what caused reionization by studying early galaxies seen by gravitational lensing. Gravitational lensing also sheds light on the massive foreground galaxies. For example, on the basis of how it bent light, researchers recently observed a dwarf galaxy currently invisible to telescopes. This galaxy, which is approximately 7 billion light years distant and 190 million times the mass of the sun, can be made up almost entirely of dark matter, and it could allow researchers to better explain what dark matter is by learning more about it by gravitational lensing.

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