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Analysis of the Current Status and Means of Studying Gravitational Lensing

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Abstract:
Lens in physics is a kind of mirror that deflects light and results in a deflated and distorted image of the light-emitting object. Hence, the phenomenon of a massive celestial object deflecting light to form a distorted, magnified image of a luminous object is well known as gravitational lensing. In this paper, a brief summary of the concept and the status quo of the research and methodology related to it is rendered. This study offers a review of the overall founding history of the concept, and presents the current advances in relevant research. Later, the principles of generation and construction modeling of the concept, basic methodology are demonstrated. Subsequently, the applications of gravitational lensing in dark matter research, celestial body relationship research and validation of research results will be illustrated with examples of recent research. Then, the potential discrepancies in the use of gravitational lensing and future prospects are discussed in short. These results intended to help scholars who lack an understanding of the concept to have a primer on the field of gravitational lensing.

Keywords: Gravitational lensing; dark matter searching; celestial body relationship.

1. Introduction

Lens is a kind of refracting mirror. The image of the object through the lens will show the effect of magnification or reduction due to the deflection of light. Gravitational lensing, as the name suggests, is the result of massive objects space deflecting the light emerged by stars etc. Though the first detection of such deflection traced back into the 1910s, it wasn't until the discovery and naming of Q0957 + 561 in 1979 that gravitational lensing became a formal concept in astrophysics. Initially, 2 quasars separated by 6 arcsec in the sky were detected [1]. Their commonality in several properties, such as redshifts, led scientists to hypothesize that they were actually images in question pertain to a single quasar [1]. This hypothesis was later confirmed to be true by their chemical similarity and their same position in space. In the later decades, several other images of gravitational lensing were captured and identified by scientists. In recent years, more progress on this topic have been made. For instance, Natarajan et al. made a brief summary of the status quo of lensing mainly by clusters while providing an insight into capabilities that are currently being developed [2]. As well as the research brought by Prasenjit Saha et.al research into the essential factors of strong gravitational lensing, giving emphasis on ideas that are less unknown in details simultaneously [3]. While both papers focus on strong gravitational lensing, studies such as Benjamin Giblin et.al in 2021 has also offered physical insights into the measuements of weak gravitational lensing [4].

Since the basic principles of gravitational lensing is clear, it can be applied to other studies in cosmology. The main application of gravitational lensing is to model the mass of a lens. Especially when studying dark matter or galaxy clusters whose physical properties cannot be measured in other ways, gravitational lensing can contribute to such studies by restoring the structure of the background sources. Currently, there has been progress in both combining observation and new models bringing back some of the lenses previous models could have missed. It is anticipated that observations made by the James Webb Space Telescope (JWST) will transform the field of cluster lensing [2]. This expectancy is signified by highly promising and intriguing preliminary findings, as a majority of studies employing JWST observational data have presented mass models of the inaugural strong gravitational lens [2]. An example of the progress in modeling, Etherington A et.al aimed to solve the problem that the current labor-intensive analytical methods are insufficient for addressing the mass number of lensing by galaxies recently observed on a larger scale [5].

With new methods presented by these researchers, the potential of lensing for investigating galaxy evolution and so on will be more clearly demonstrated. Undoubtedly, gravitational lensing is at the forefront of current astrophysical research. This study aims to help readers get a brief understanding of the basic principles and history of gravitaitonal lensing. Moreover, a basic knowledge of the results of recent investigations of gravitational lensing and the methods used will be presented to the readers. This study will be focusing on the status quo of the study of gravitational lensing. In the next section the basic principles of the concept gravitaional lensing will be presented, supplementing and enriching relevant background knowledge in the field for the readers. Next, some principles of studying and modeling gravitational lensing will be introduced, including details, e.g., some general considerations. Then, in Sec. 4 a introduction of the specific applicaiton of gravitational lensing in the field of astrophysics along with several examples of recent studies will be presented in detail. Sec. 5 will mainly focus on the future prospects and the limitations of lensing or lensing models that currently exist. Lastly, a conclusion of what this paper have dicussed will be presented.

2. Descriptions of Gravitational Lensing

Simply put, massive objects, such as dark matter, massive compact halo objects (MACHOs), and of course, galaxy clusters, can deflect light. Therefore, they can act as gravitational lenses. The working principle of these lenses are simple. Suppose there is one such massive object lying on the line of sight between the observer and the target star. Apparently, the massive object will deflect the light from the star. This results in an exaggerated and twisted image of the star. Furthermore, the fact that the effect of gravitational lensing can occur at all scales of mass flow, including all the massive objects mentioned previously, should be noted.

To be more specific, as shown in Fig. 1, suppose the origin of the light rays are infinitely far above the picture, and as they approach the center of the figure (the strong gravitational field), where the light rays gradually diverge [3]. Then, acting as the lens, it starts pulling the light rays together. There is no such thing as a focal point in this situation, though there is indeed a kind of like focal line which can lead to a misconception of the presence of focal points. From paths on opposite sides of the lens, rays converge symmetrically along this sort of focal line [3]. As the distance from the center increases, the field weakens, showing a negative corrolation, and the deflections diminish in magnitude, although they remain considerably larger than those observed in the actual systems under consideration.

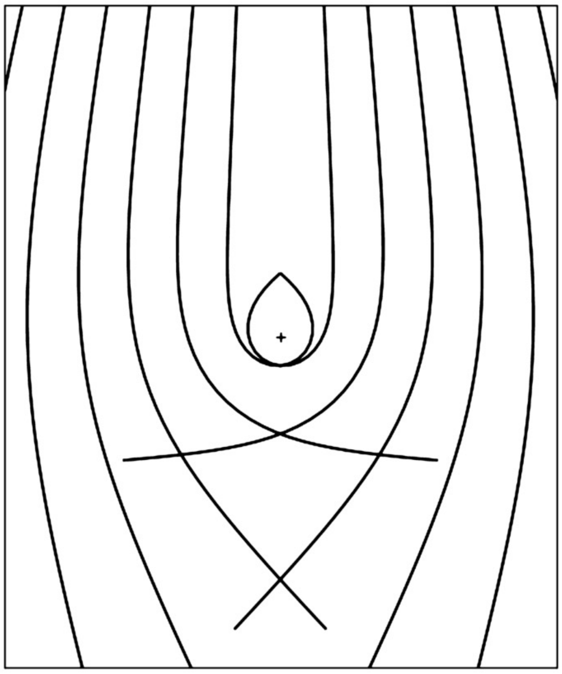

Fig. 1 The deflection of several light rays by a gravitational lens. The source is positioned at a considerable distance above and beyond the boundaries of the figure. A pronounced gravitational field is concentrated near the center of the figure (indicated by a plus sign), resulting in substantial deflections (exceeding 180 degrees).

In the lower part of the figure, two intersections of the light rays can be seen [3]. Observers at different locations will see the light coming at disparate shapes, which is intriguing [3]. If the lens happens to be a circuitously symmetric one, the observer located at these intersections will see light appeared as a ring [3]. Additionally, the figure depicts asymmetric ray intersections, two of which are shown in the lower portion and not on the focal line. Observers situated at this location will perceive the source light emanating from two distinct directions within their field of view [3].

3. Principles of Studying and Modeling Gravitational Lensing

Undoubtedly, lens modeling has an crucial role in the study of gravitational lensing, and it is also the main use of lensing in the field of astrophysics. In this section, some general introduction of the modeling work and previous examples will be discussed briefly. Lens modeling is the process of reconstructing the lensing mass distribution and the unlensed source brightness distribution from the observables, which are the data that can be used to determine the aforementioned distributions [3]. At present, a number of available modelling methods can provide results that are reliable to a certain extent [3]. However, there is also a range of other results that vary from the assumptions made in the modelling process [3]. An example in which lens modeling is combined with the Bayesian Neural Networks (BNNs) is shown in Fig. 2 [6]. The steps the research uses to construct the Hubble Constant inference pipeline along with the BNNs, turning these into the lens model [6].

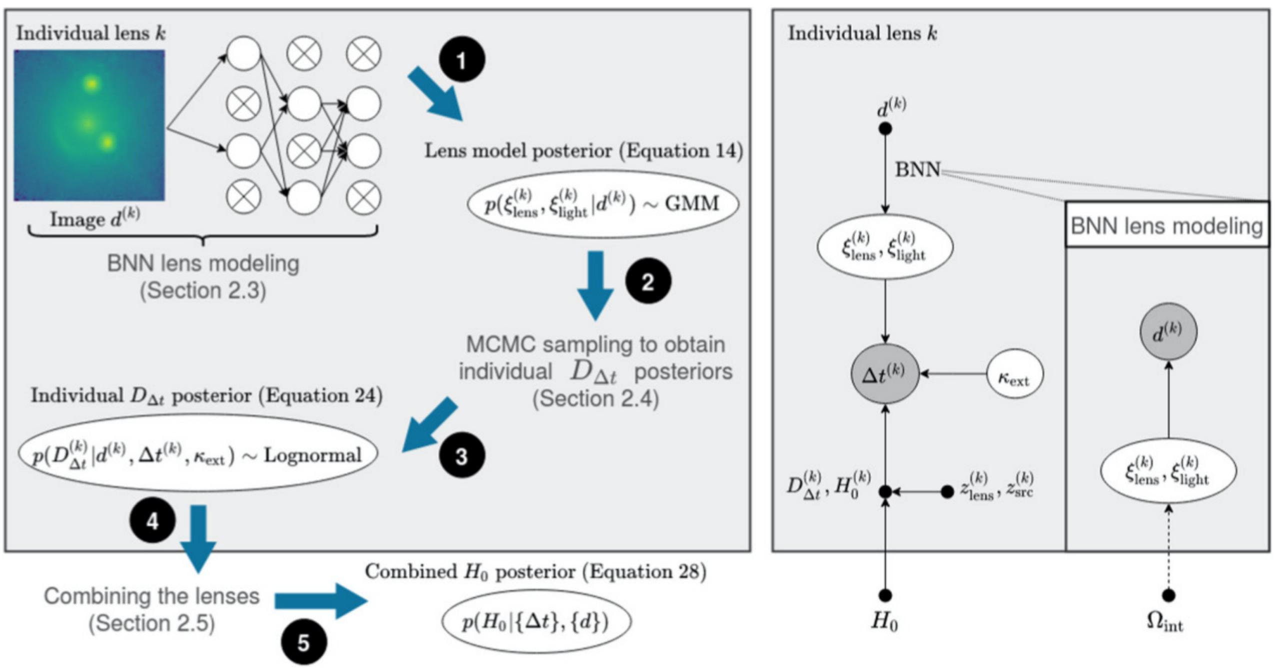

Fig. 2 The illustration of the H_0 inference pipeline, presented in the form of a flowchart (left panel) and the dependence relation as a probabilistic graphical model (PGM) [6]. The use of dots to represent delta functions, or fixed values, and the use of shaded ovals to represent observed values, or data, is standard practice in this field of study. Unshaded ovals are used to represent random variables.

4. Current Applications in the Field of Astrophysics

Despite the physical properties of gravitational lensing which is discussed previously in section 2, it should aslo be noted that changes in the mass and shifts in the position of a lensing object can change the specific expression of gravitational lensing. Therefore, it offers researchers a tool for mapping the matter of the universe. In other words, by analyzing observed gravitational lensing events, researchers can reconstruct the distribution of matter around lensing objects. Normally, when observing the existence of celestial bodies or studying the properties of luminous matter, scientists are going through the important feature of light. This means that gravitational lensing will play an important role when dealing with non-luminous matter such as dark matter.

One of the most recent studies exploiting gravitational lensing to study dark matter, Vegetti al. effectively utilizes strong gravitational lensing on galactic scales to detect dark matter and constrain its physical nature [7]. One of the physical properties of strong gravitational lensing, which the authors mention in the paper, is that it is sensitive to the distribution of matter and dark matter between the observer and the source [7]. As a purely gravitational probe, gravitaitonal lensing does not depend on the presence and distribution of baryons, thus allowing it to be well utilized in probing dark matter. It also discusses in detail the role played by degeneracy, systematic errors and unknowns, as well as the whole modeling process of the lens [7].

The application of gravitational lensing is not limited to dark matter studies, however; strong gravitational lensing has also been used in recent years to detect quasar-host relationships beyond the own universe. This is attributed to the research work done by Martin et al. [8]. In their study, strong gravitational lensing helps overcome the use of stellar population models or velocity dispersion measurements, both of which are prone to degeneracy. It presents in detail the study of one of the three known cases of strong lensing of quasars, combined with precise measurements of the mass of the quasar‘s host, and extrapolates the total lensing mass over a range of Einstein radii [8]. The authors argue that this wayof measurement through gravitaitonal lensing is of greater accuracy than any other currently existing alternatives, demonstrating the indispensable role of gravitational lensing in this field.

In addition to its ability to aid in the construction of models for research purposes, the strong lensing system can also be data sets taken into consideration while performing tests required in certain researches. As Holanda et.al did in their research, in which they test the redshift dependence of the cosmic distance duality relation using large-scale structure observations [9]. Another example of gravitational lensing related data being used to test accuracy of models or data is provided by Zamani et al. [10]. In this case, a study of strong and weak gravitational lensing data for 19 high-mass galaxy clusters observed by the CLASH survey was used to test the models used in the experiment [10]. The usage of models and data related to gravitational lensing in these studies is a testament to the wide range of applications of gravitational lensing in the broad field of astrophysics.

5. Limitations and Propspects

Previously, in former sectisons, the current application of gravitational lensing or related models and data has been introduced in detail. It is acknowledged that gravitaional lensing is a crucial part of the studies of for instance the physical propertied of dark matter. The very existence of gravitational lensing allows generation of mass distribution figures which help proving the existence of dark matter and determining its qualities. Through discusions of recent studies correlated with lensing, the fact that the use of gravitational lensing is an indispensable tool for testing models and experimental results in astrophysics is shown. Furthermore, gravitational lensing allows for the exploration of the relationships between celestial bodies and the modelling of space exploration cruises. In other words, gravitational lensing plays a fundamental and precise role in the current astrophysical developments. Due to the fact that the basic principles and physical properties of gravitational lensing is clear to scientists now, an increasing number of models established on the basis of gravitational lensing and their role to play in studies that remains somehow a mystery can be expected. The potential issues and inaccuracies inherent in the prevailing dark matter models may be elucidated and rectified through the use of gravitational lensing in the future. However, while utilizing gravitational lensing as means of measurement, errors and discrepancies still exist. For instance, when performing lensing-dark matter correlated studies, it is likely that discrepancies occur due to factors such as degeneracies effects, which current models of gravitaitonal lensing can not prevent. The selection of lensing models can also possibly produce errors during subsequent experiments. These problems, if not found and addressed , can lead to biased conclusions and results. It is anticipated that future enhancements and updates to lensing models will facilitate the effective prevention of these errors and discrepancies.

6. Conclusion

To sum up, the concept of gravitational lensing is dicussed in detail in this study, covering aspects including its principles of studying and modeling, its current application in the field of astrophysics, and its limitations as well as future prospects. The introduciton part provides the readers with the overall history of the concept as well as the development of the study. The second section of the paper describes the origins of gravitational lensing and how it works. It explains that a massive object deflects light from, for instance, a planet, forming a distorted and magnified image.

Gravtiational lensing is active in the studies correlated with dark matter, relationships between celestial objects and the examination of the results of the study etc. In the future, current errors in gravitational lensing model selection and influences that cannot be erased by current models are expected to be addressed and upgraded. Gravitational lensing may in the future assist scientists in correcting kennel errors in current models and help take the study of non-luminous matter, such as dark matter, one step further. This paper offers a summary of the status quo and means of studying gravitational lensing, and includes the basic information of the concepts. The objective of this paper is to assist readers who have a fundamental lack of comprehension of the concept of gravitational lensing in order to facilitate their acquisition of a basic and comprehensive understanding of it.

References

[1] Meneghetti M. A Brief History of Gravitational Lensing. In: Introduction to Gravitational Lensing. Lecture Notes in Physics Springer Cham, 2021, 956.

[2] Natarajan P, Williams L L R, Bradač M, et al. Strong Lensing by Galaxy Clusters. Space Science Reviews, 2024, 220(2): 19.

[3] Saha P, Sluse D, Wagner J, et al. Essentials of strong gravitational lensing. Space Science Reviews, 2024, 220(1): 12.

[4] Giblin B, Heymans C, Asgari M, et al. KiDS-1000 catalogue: Weak gravitational lensing shear measurements. Astronomy & Astrophysics, 2021, 645: A105.

[5] Etherington A, Nightingale J W, Massey R, et al. Strong gravitational lensing's 'external shear'is not shear. Monthly Notices of the Royal Astronomical Society, 2024, 531(3): 3684-3697.

[6] Park J W, Wagner-Carena S, Birrer S, et al. Large-scale gravitational lens modeling with Bayesian neural networks for accurate and precise inference of the Hubble constant. The Astrophysical Journal, 2021, 910(1): 39.

[7] Vegetti S, Birrer S, Despali G, et al. Strong Gravitational Lensing as a Probe of Dark Matter. Space Science Revie, 2024, 220: 58.

[8] Millon M, Courbin F, Galan A, et al. Strong gravitational lensing by AGNs as a probe of the quasar–host relations in the distant Universe. Nature Astronomy, 2023, 7(8): 959-966.

[9] Holanda R F L, Lima F S, Rana A, et al. Strong lensing systems and galaxy cluster observations as probe to the cosmic distance duality relation. The European Physical Journal C, 2022, 82(2): 115.

[10] Zamani S, Salzano V, Bettoni D. Gravitational lensing from clusters of galaxies to test Disformal Couplings Theories. The European Physical Journal C, 2024, 84(6): 618.