

The Early History of Gravitational Lensing

Within the last twenty years, gravitational lensing, or the deflection of light by massive bodies and the phenomena resulting therefrom, has changed from being considered a geometric curiosity to a helpful and unique tool of modern astrophysics. Unlike most other astrophysical discoveries made during the twentieth-century, the basic physics of gravitational lenses were understood well before the first example was actually found. The significance of gravitational lensing for the history of general relativity and of cosmology makes it natural to explore the question of its theoretical origins. Particular episodes in the history of physics and astronomy show that this question cannot easily be answered.

One of the consequences of Albert Einstein's General Theory of Relativity is that light rays are deflected by gravity. Though this discovery was made in the early twentieth-century, Newton and Laplace, among others, had suspected the possibility that there could be such a deflection much earlier. Einstein himself, in his 1936 *Science* paper (considered the classic starting point for the officially recorded history of gravitational lensing), did not consider gravitational lensing a great idea nor did he believe that its astrophysical detection was probable. Yet almost immediately after Einstein's publication, a number of other papers were published, which further developed the theory, taking it very seriously. Various authors claimed that either they or others had thought of the lensing first, complicating the history of the theoretical development. The deflection of light at the solar limb was successfully hailed as confirmation of a prediction of Einstein's theory of General Relativity in 1919, but it took more than half a century to establish this phenomenon observationally in another environment.

Gravitational lensing has a number of attractive features as an academic discipline. Its principles are very easy to understand and to explain due to its being a geometrical effect. Its ability to produce optical illusions is fascinating to scientists and laypeople alike. Most importantly, of course, its usefulness for a number of astrophysical problems makes it an attractive tool in many branches of astronomy. In its thirty-year existence as an observational branch of astrophysics, the field of gravitational lensing has grown rapidly. New realizations of the phenomenon have been found: multiple quasars, giant luminous arcs, quasar microlensing, Einstein rings, galactic microlensing, weak lensing, galaxy-galaxy lensing, all of which answer old cosmological questions and ask new ones. This trend is reflected in the growing number of people working in the field. In Figure 1, the number of publications in scientific journals that deal with gravitational lensing is plotted over time [21]. Lensing is clearly booming as an area of astrophysics.

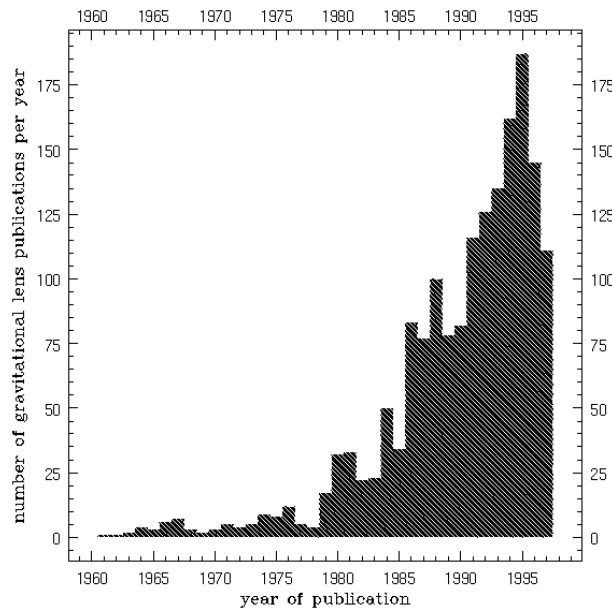


Figure 1. A gravitational lensing bibliography from 1960 – 1997.

This paper recounts the history of gravitational lensing and synthesizes the few works that have considered the phenomenon's history besides Einstein's 1936 paper. We examine the theoretical work on the bending of light by a massive body. Based on the fact that the earliest work relied on Newton's gravitational law, we demonstrate that it was possible in the early 1700s to determine the deflection angle of a light ray near the solar limb. We next consider theoretical work from the 1790s, when several natural philosophers explored the interactions between massive bodies and light. The first publication on the deflection of light by a gravitational field appeared in print in 1801; we consider the paper's ideas as well as give a brief biography of its author. Moving forward over a century, we come upon Einstein and his theories of special and general relativity. We discuss his re-derivation of the 1801 result, as well as the failed 1914 expedition to test his prediction of light deflection along the solar limb.

The theory of general relativity altered the predicted deflection angle of a light ray near a massive body, and we recount the 1919 expedition to test Einstein's theory via a solar eclipse. As the topic received more attention, several scientists published work on what is then termed "gravitational lensing." In 1924, the St. Petersburg physicist Orest Chwolson publishes work that anticipates Einstein's 1936 *Science* short article on the "halo effect" of a gravitational lens system in which the source, lens, and observer are in near-perfect alignment. The role of amateur scientist Rudi Mandl in the publication of the 1936 *Science* article is recalled, as well as the immediate reaction of the scientific community to the short note. After noting the dearth of gravitational lensing work between 1937 and 1964, we recount the resurgence of it in combination with the discovery of quasars. Finally, we recall the serendipitous discovery of the first gravitational lens system in 1979, as well as the observational results since then.

The deflection of light is described by equations of general relativity theory. Yet, long before general relativity, some scientists suspected that gravity influences the behavior of light and they discussed the bending of light rays soon after the development of classical mechanics. Sir Isaac Newton noted in Query 1 of his *Opticks*: "Do not bodies act upon light at a distance, and by their action bend its Rays; and is not this action strongest at the least distance"[20]. One could say that Newton did, indeed, formulate a law about the bending of light in a gravitational field. A light ray with velocity c at large separation from the gravitating mass is deflected by the angle Θ , given by

$$\Theta = \frac{2GM}{c^2 R}, \quad (1)$$

where G is the gravitational constant, M is the mass of the lensing mass, and R is the impact parameter.

To be more accurate, Newton recognized the relationship $\Theta \sim R^{-1}$, since the numerical coefficients were not defined at that time, as there was not yet a common systems of units. In the *Principia*, Newton, in Proposition XII (Problem VII), considered the motion of a test body in a hyperbola; it follows that acceleration is decreased as the unit divided by squares of the distance between a test body and the gravitational center [19]. He proved similar assertions in the assumption that a body moves in a parabola (Proposition XIII, Problem VIII) and in an ellipse (Proposition X, Problem VIII). In Corollary 1 to Proposition XIII, Newton asserted that a body attracted by an inverse-square centripetal force toward the gravitational center moves in a conic section having its focus at the fixed point of attraction. Because Newton calculated semi-axes during consideration of a body in motion in a hyperbola, he knew the angle between asymptotes. Taking into consideration the fact that very often Newton did not published his discoveries and

presented the results in non-ordinary form, one could assert that he likely understood a form of equation (1).

In fact, he probably knew the corresponding value of the bending angle of light near the Sun because all necessary constants had been determined by the 3rd edition of the *Principia* [2]. Giovanni Cassini calculated the distance between the Earth and the Sun in 1672, and Tycho Brahe calculated the period of revolution of the Earth around the Sun with accuracy up to one second. Knowing the Sun-Earth distance and the period of Earth's revolution around the Sun, one can calculate GM_{sun} via Johannes Kepler's third law of planetary motion. Ole Rømer published speed of light measurements based on the period of revolution of the satellite Io of Jupiter in 1677. Nevertheless, equation (1) is not in Newton's scientific papers and the value of the bending of a light ray near the Sun is absent; it may be because of its very small value, $0''.87$. As a historical irony, if one calculated the bending of a light ray near the Sun, using the deflection of light calculated by Rømer $c = 2 * 10^{10} cm/s$, then the angle of the bending would be equal to $\Theta = 1''.73$. This result almost coincides with the result obtained in the framework of the general relativity theory. Despite the fact that equation (1) was probably known in the early eighteenth-century, the angle of the bending of light was not mentioned until 1784.

In 1784, the British geologist and astronomer Reverend John Michell, later regarded as the "Father of Seismology," began formulating an experiment to weigh the earth and considered consequences of massive bodies. Motivated by the design of his torsion balance for his experiment, Michell communicated in a letter to Henry Cavendish that,

... if the semi-diameter of a sphere of the same density with the Sun were to exceed that of the Sun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its surface a greater velocity than that of light, and consequently, supposing light to be attracted by the same force in proportion to its, with other bodies, all light emitted from such body would be made to return towards it, by its own proper gravity [17].

He proposed even how one might discover such black bodies, by observing companion stars revolving around these invisible objects. Presumably stimulated by the correspondence, Cavendish calculated the deflection of light by a body, deriving equation (1) by assuming the corpuscular theory of light and Newton's law of gravitation. Cavendish did not publish his calculation, but stated the result on "an isolated scrap" of paper [33]. He also employed Michell's torsion balance in his experiments, one of which led to the earliest accurate calculation of the mass of the earth.

Independently of Michell and Cavendish, Pierre Laplace noted in 1796 "that the attractive force of a heavenly body could be so large, that light could not flow out of it" [12]. Laplace translated the geometrical study of mechanics used by Newton into one based on the calculus. In his work in mathematical astronomy and celestial mechanics, he often considered gravitational field effects of cosmic bodies. For example, a test particle can leave the gravitational field of a spherical mass M of radius R , starting at the surface, if its initial velocity is larger than the escape velocity,

$$v_e = \sqrt{\frac{2GM}{R}}. \quad (2)$$

The escape velocity increases with increasing compactness of the attracting object, reaching the velocity of light c if the radius is smaller than

$$R_S = \frac{2GM}{c^2} \approx 2.95 \frac{M}{M_{sun}} \text{ km}, \quad (3)$$

where the mass of the sun is $M_{sun} \approx 2.0 * 10^{33}$ g. Like Michell, Laplace concluded that a body of mass M , with radius smaller than R_S , is so compact that even light cannot escape from its surface:

the object would appear completely black. In exploring the interactions of massive bodies and light, Michell and Laplace anticipated the existence of black holes.

One of the few to respond to Laplace's invisible bodies hypothesis was Johann Georg von Soldner, an assistant to Johann Bode at the Berlin Observatory.¹ Soldner's response to Laplace came in an article about the motion of stars in the Milky Way [29]. Laplace's mathematics was unobjectionable, but Soldner could not agree with the constancy of the speed of light. He argued that the possibility of a large mass in the center of a star system like our galaxy was not possible because the motion of the stars around it would be too fast not to be noticed. Soldner concluded this having calculated the relative velocities of stars closer and farther from the center of a homogeneous distribution of stars, resembling a highly flattened spheroid.

In 1804, Soldner published his theoretical work on deflection of light by large gravitational bodies [30]. This first published account of such a deflection appeared in the

¹ As Johann Georg von Soldner's life is not well documented in the literature of gravitational lensing history, this footnote provides a quick summary of his major accomplishments. See also: Stanley Jaki, 1978, "Johann Georg von Soldner and the Gravitational Bending of Light," *Foundations of Physics*, 8, 927. Born on July 15, 1776 in a Bavarian village, he was the son of a peasant and never had formal schooling. At age twenty, he was steered by an official of the Prussian government to work as an assistant to Bode in the Berlin Observatory. In 1803, he published an article responding to the analysis of Laplace regarding "invisible bodies," i.e. bodies with so strong a gravitational field that light cannot leave their surface. Soldner concurred with Laplace's mathematics, but did not agree with the constancy of the speed of light. He argued that the center of a star system like the Milky Way did not have a massive body governing the motion of stars. He was invited to accept the directorship of the Observatory of the University of Moscow, but instead became director of Prussian land surveying. He was charged with plagiarism for his 1813 paper on the reduction of observed azimuths. Soldner was defended by Delambre and was completely vindicated; his accuser was even removed from his post, and Soldner appointed to it afterward. He supervised the construction of the Munich Observatory, which was equipped with Fraunhofer telescopes. Soldner recommended that Fraunhofer be nominated to the Munich Academy. In 1825, Soldner was knighted by the King of Bavaria and the King of France and, thanks to John Herschel, he was elected a corresponding member of the Astronomical Society in London. He worked on several problems in geodesy, astronomy, and surveying. At his death, in 1833, he was the director of the Bogenhausen Observatory.

journal *Berliner astronomisches Jahrbuch*, of which Bode was managing editor. He investigated the error in the determination of the angular positions of stars due to the deflection of light. He also computed the orbit of a body with constant velocity that passes near a spherical mass. If we consider only very small deflection angles, Soldner found that the solution could be approximated by equation (1), the Newtonian value for the deflection of light, in agreement with Cavendish's unpublished result. He inferred that a light ray close to the solar limb would be deflected by an angle of 0.87 arcseconds. Of historical interest to the history of gravitational lensing is Soldner's friendship with Fraunhofer, whose instruments equipped the Munich Observatory once Soldner took over as its director. Fraunhofer telescopes were of good enough quality by the 1830s that their resolving power enabled the measurement of stellar parallaxes much smaller than 1", and, therefore, could have been used to test Soldner's deflection prediction around the solar limb.

More than a century later, Albert Einstein addressed the influence of gravity on light in a 1911 paper titled "Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes" ("On the Influence of Gravity on the Propagation of Light") [6]. Unaware of Soldner's earlier work, Einstein obtained the same value for the deflection angle from the principle of equivalence and the assumption that the spatial metric is Euclidean, unaffected by gravity. As the theory of general relativity was not fully developed at this time, Einstein, using the framework of special relativity, obtained the same value as Soldner had calculated using Newtonian physics. Einstein determined the value

$$\alpha = \frac{2GM_{sun}}{c^2 R_{sun}} = 0.87 \text{ arcsec} \quad (4)$$

for the deflection angle of a ray grazing the sun where M_{sun} and R_{sun} are the mass and the radius of the Sun, and c and G are, respectively, the velocity of light and the gravitational constant.

Einstein emphasized his wish that astronomers investigate this question, writing “Es wäre dringend zu wünschen, daß sich Astronomen der hier aufgerollten Frage annähmen, auch wenn die im vorigen gegebenen Überlegungen ungenügend fundiert oder gar abenteuerlich erscheinen sollten” (“It would be very desirable that astronomers address the question unrolled here, even if the considerations should seem to be insufficiently founded or entirely speculative”) [6].

In 1912, Einstein was still trying to persuade astronomers to test the astrophysical consequences of his new ideas on gravitation that he published the previous year. Erwin Freundlich was one of the few astronomers actually engaged in such work.² In the spring of 1912, Einstein visited Berlin and he met with Freundlich. Einstein did gravitational lensing calculations during his Berlin visit as evidenced by notes recently found in a small notebook dated to the period [25]. These calculations appear interspersed between various notes referring to Berlin appointments during his April 1912 visit. The notes primarily deal with the possibility of a double image of the source as a result of gravitational light bending and the magnification of the intensity of these images.

In 1913, Einstein contacted the director of the Mt. Wilson Observatory, George Ellery Hale to inquire whether it would be possible to measure positions of stars near the sun to establish the angular deflection effect. In his letter, Einstein asked Hale if they could determine

² Erwin Freundlich’s contributions to the history of gravitational lensing are well documented, so this footnote contains a brief biography of his scientific work. Born in 1885, he studied physics, mathematics, and astronomy at the University of Göttingen, earning a Ph.D. in 1910. Soon after, he became an assistant at the Royal Observatory in Berlin. He assisted Einstein by making accurate observations of Mercury’s orbit, which became the first confirmation of Einstein’s general theory of relativity. Interested in measuring the deflection of a light ray passing the solar limb, he organized a 1914 expedition, only to be captured by Russians as World War I began. In 1939, he and his family moved to Scotland where he created both the University of St. Andrews’s department of astronomy and its associated observatory, of which he remained head of until 1964.

light deflection at the solar limb during the day, though the value for the deflection angle he included in an accompanying sketch was incorrect. This correspondence did not prove fruitful, but his relationship with Freundlich did. Freundlich called attention to the total eclipse of August 21, 1914; because it would be visible in the Russian Crimean peninsula, he planned an expedition to test Einstein's prediction of the deflection angle. A few weeks after they had arrived in the Crimea, the First World War began and Russians captured all the astronomers, though they were later exchanged for Russians captured by Germans. Fortunately for Einstein, the measurement of the deflection angle at the solar limb had to be postponed.

With the completion of the General Theory of Relativity in 1915, Einstein predicted that a massive object would curve the space-time in its vicinity and that any particle, massive or not, will move along the geodesics of this curved space [7]. He then derived the deflection angle, α , of a light ray passing at a distance R from an object of mass M as

$$\alpha = \frac{4GM}{c^2 R} = \frac{2R_s}{R}. \quad (5)$$

The additional factor of two, as compared to the Newtonian value, reflects spatial curvature, which is missed if photons are treated just as particles. With the solar values for radius and mass, Einstein predicted that a light ray passing near the solar limb would be deflected by an angle

$$\alpha = \frac{4GM_{sun}}{c^2 R_{sun}} = 1''.74, \quad (6)$$

where G stands for the gravitational constant, c for the velocity of light, and M_{sun} , R_{sun} for the mass and radius of the Sun, respectively [8].

Soon after the end of the First World War, observations of the bending of light were finally realized during the total eclipse of May 29, 1919. As noted in the publication of the

results of the expedition, the main purpose of it was to choose one of three alternatives: first, that the gravitational field of the Sun does not bend light; second, the gravitational field of the Sun influences bending of light according to the Newtonian law of gravity, so the deflection angle of a ray near the Sun is equal to $0''.87$; and lastly, the gravitational field of the Sun influences bending of light according to the general relativity, so the deflection angle of a ray near the Sun is equal to $1''.74$ [4]. Led by Sir Arthur Eddington, the observations were carried out at Sobral in northern Brazil and on the island of Principe off the western coast of Africa. The astronomers at Sobral measured the deflection of $1''.98 \pm 0''.12$, and the group on Principe measured it as $1''.61 \pm 0''.30$. Although these measurements were not very precise, the Newtonian value could clearly be rejected. When the results of the observations confirmed the Einstein's prediction, he quickly became an international celebrity.

In 1920, O.J. Lodge, who remarked that it is “not permissible to say that the solar gravitational field acts like a lens, for it has not a focal length”, first used the term “lens” in the context of gravitational light deflection [15]. Lodge discussed the radial dependence that the refractive index must have in order to provide the same relativistic deflection of light in its passage by the sun. He argued that an extended solar atmosphere “would have to vary with the inverse distance, which seems unlikely, but this is just the way the ether tension ought to vary in order to cause gravitation.” In the same year, Eddington was the first to point out that multiple images can occur if two stars were at sufficiently different distances from an observer, but were seen in the same line of vision to within about $1''$ [5]. Besides the primary image of the more distant star, there should appear a dimmer, secondary image on the opposite side of the nearer star as seen from Earth. He observed that as the alignment improved, the divergence of the rays from the primary image should increase in the direction parallel to the plane containing the

observer and the two stars. As he overlooked an associated convergent tendency in the orthogonal direction, he mistakenly concluded that the primary image should fade.

In 1924, the Russian physicist Orest Chwolson³ published a very brief article in the prestigious journal *Astronomische Nachrichten*, where he describes the idea of a “fictitious double star” [3]. He considered a star in the foreground of much more distant star. Given a certain maximum deflection angle of light that can be caused by the foreground star, then all background stars with angular separation should produce a secondary image very close to the foreground star, and on the side opposite to the primary image (referring to the mirror-reversed nature of the secondary image). This secondary image, together with the foreground star, would form a fictitious double star, which would not be separable with an optical telescope, but perhaps via spectroscopic observations, as they would have different spectra. He also remarked that if the background stars, foreground stars, and observer were perfectly aligned along the optic axis, a ring-shaped image of the background star centered on the foreground star would appear to the observer. Chwolson’s note, though written by an established physicist in a prestigious journal, did not provoke any scientific interest; it could be argued that it did not have any effect at all.

Rudi W. Mandl, a Czech amateur scientist, noted in an April 1936 letter to Einstein that a star should be expected to act as a “gravitational lens” when light from another star passes it. He

³ Orest Chwolson (or Khvolson) is not well known figure in the scientific community, nor is his involvement in the theoretical development of gravitational lensing fully appreciated. This footnote contains a brief biography of his scientific accomplishments. Chwolson was a Russian physicist and honorary member of the Soviet Academy of Sciences. He graduated from St. Petersburg University in 1873 and began teaching there in 1876, becoming a full professor in 1891. He authored a number of works on electricity, magnetism, photometry, and actinometry. He proposed the designs of actinometer and pyrheliometer, used by Russian weather stations for several decades afterward. After 1896, Chwolson was engaged in compiling the five-volume *Physics Course*, which would improve the teaching of physics throughout the country and remain a principal textbook for many decades. It was also translated in German, French, and Spanish. He was awarded the Order of the Red Banner of Labor, a decoration for accomplishments in labor and civil service, and a crater on the moon is named for him.

was looking for a respectable scientist to help him publish his ideas and persuade professional astronomers to take up investigations on his proposal. He requested an audience with Einstein and, after a series of meetings and correspondence, he asked him to publish the results that Einstein completed for him [25]. Einstein calculated the deflection, due to a star, of the light from a background star, and also found that the apparent luminosities of the images are changed by the gravitational light deflection; in particular, an image can be highly magnified if the observer, source and deflector are sufficiently aligned and would appear as a “halo effect.” Einstein’s conclusion is based on the fact that the angular separation of the two images of the background star would be too small to be resolved with optical telescopes then available. Einstein gave a negative assessment on the observability of the phenomenon, given the low probability of a precise connecting line of the centers of two stars and different distances.

Mandl continued to press him for a “modest publication” and in the December 4, 1936 issue of the journal *Science*, Einstein complied with his wish. He published a brief article about the appearance of a “luminous circle” for perfect alignment between source and lens, and of two magnified images for slightly displaced positions [9]. The reluctance to publish is evident in the introductory statement of the paper, which reads: “Some time ago, R.W. Mandl paid me a visit and asked me to publish the results of a little calculation which I had made at his request. This note complies with his wish.” It reads less like giving credit to Mandl, and more as a general disclaimer. In the final paragraph of his paper, Einstein notes, “there is no great chance of observing this phenomenon.”

For a moment, let us consider the question of whether or not the luminous circle Einstein refers to in his 1936 article, now referred to as an Einstein ring, should perhaps be called a Chwolson ring. There has been little debate over how to recognize that Chwolson was aware of

and published in 1924 that the image effect would be a ring when the lens, lensed object, and observer are along the optic axis. Einstein appears to have been unaffected by Chwolson's 1924 note on the gravitational lensing phenomenon. It is likely that Einstein was familiar with Chwolson's note and yet simply ignored it or did not fully consider it. Chwolson's paper was published in the most important astronomical journal in Europe at the time, Einstein read and published in the journal as well. In fact, a brief letter by Einstein on electron gas came to be printed in the very same issue in which Chwolson's note appeared; in fact, just below Chwolson's note on the very same page! While both Chwolson and Einstein refer to a circular image in their papers on lensing, Einstein specifies some characteristics of the ring, including a specific radius and flux luminosity, and Chwolson does not. The ring radius and flux are currently referred to as the Einstein ring radius and the Einstein flux, and we are in agreement with these definitions since Chwolson did not examine specific characteristics of the ring. The positing of an image ring was first published by Chwolson and calculated by Einstein twelve years later. Therefore, it is more accurate to say Chwolson-Einstein ring instead of Einstein ring.

Although Einstein, like Chwolson, did not believe in the ability of humans to observe the lensing phenomenon, several publications on this topic immediately followed Einstein's *Science* article. One publication stimulated by Einstein's 1936 *Science* paper was by Henry Norris Russell, entitled "A Relativistic Eclipse," and it appeared in the February 1937 issue of *Scientific American* magazine [26]. Russell focused on the issue of observability and agreed that the lensing effect would not be verifiable for terrestrial observers, but he was not disheartened by this and further pursued the idea. Discussing the orders of magnitude of the lensing effect with a white dwarf, Russell considers taking Sirius's companion as a gravitational lens, and Sirius itself as the light source. He imagines a small planet orbiting Sirius's companion with just the right

distance and considers how Sirius would appear for observers on this planet if distorted by the lensing effect of its companion. The paper gives some sketches of the distorted forms of Sirius's image as seen from the imaginary planet when its lensing companion passes through the line of sight. Russell compares the event to an ordinary solar eclipse. The final drawing shows the case of perfect alignment, or the "halo effect." While the planet in Russell's article is purely imaginary, the paper contributed much to keep interest alive and was often cited. It also gave a realistic twist to the abstract question of how a world would have to look to make gravitational lensing an important observable effect.

The challenge of using gravitational lensing in order to probe cosmic dimensions was taken up in another immediate response to Einstein's paper, which was sent to the *Physical Review* and appeared in the February 1937 issue of that journal [35]. It was entitled "Nebulae as Gravitational Lenses" and was written by Swiss astronomer Fritz Zwicky, who was then working at the California Institute of Technology. Zwicky's concern was the observability of the phenomenon, noting that he had first encountered the problem of gravitational lensing as an indirect consequence of Mandl's search for professional assistance from the physics community. He points out that extragalactic nebulae, as a consequence of their masses and apparent dimensions, were much more likely candidates for the observation of gravitational lenses and one could use the lensing effect as a natural telescope. He writes,

The discovery of images of nebulae that are formed through the gravitational fields of nearby nebulae would be of considerable interest for a number of reasons. First, it would furnish an additional test for the general theory of relativity; secondly, it would enable us to see nebulae at distances greater than those ordinarily reached by even the greatest telescopes. Any such extension of the known parts of the universe promises to throw very welcome new light on a number of cosmological problems. Thirdly, the problem of determining nebular masses at present has arrived at a stalemate.... Observations on the deflection of light around nebulae may prove the most direct determination of nebular masses [35].

In the final sentence of his article, Zwicky optimistically announced the publication of a “detailed account of the problems sketched here.”

Two months later, Zwicky submitted another letter to the editor of *Physical Review*, entitled “On the Probability of Detecting Nebulae Which Act as Gravitational Lenses” [36]. Zwicky argued that given the great masses of the extragalactic nebulae, the observability of gravitational lens effects from nebulae is “practically a certainty.” The revolutionary character of this claim is clear because at that time it was believed that the masses of extragalactic nebulae, or galaxies, were about $10^9 M_{sun}$. Zwicky, however, estimated the mass of these nebulae to be much higher, averaging about $4 * 10^{11} M_{sun}$, because he was applying the virial theorem to the Coma and Virgo clusters of galaxies. He estimated that about 1/400 of the area of photographic plates is on average covered by nebular images; including the effect of gravitational focusing, he obtained the result that for “around one in about one hundred nebulae the ring-like image of a distant nebula should be expected.” Finally, Zwicky noted “among others, E.B. Frost, late director of the Yerkes Observatory, as early as 1923 outlined a program for the search for lens effects among the stars.” There is, to this date, no other publication evidence for any ideas or research performed by Frost on this matter.

Gavriil A. Tikhov, in a publication also triggered by Einstein’s note and dated June 1937, claimed in the introductory paragraph that he had had the idea as early as the summer of 1935 and that he had sent a first communication to the Pulkovo Observatory in January 1936 [28]. He then gives a derivation of the lensing formula both for what he calls the classical and the relativistic case. Tikhov drew attention to the 1924 publication by Chwolson. As Tikhov observed, it was the only reference he had found in the literature that already had discussed the idea of a gravitational lens [18]. He notes that Chwolson’s work discussed both the possibility of

observing double stars as well as the possible effect of a ring-shaped image for perfect alignment.

Gravitational lensing was forgotten for several decades before the advent of radio astronomy in 1963 led to the discovery and identification of quasars, ‘quasi-stellar radio sources’, so-called because of their point-like appearance on optical plates [27]. Owing to this appearance, their prominent spectral features (strong, broad emission lines), their high redshift and thus large distance (with correspondingly high probability of intervening material), and their high luminosity, they are ideal sources for gravitational lensing. At the same time, the topic of gravitational lensing, essentially dormant since Zwicky’s work, resurfaced in the astronomical literature. Originally, gravitational lensing was discussed for stars or for galaxies. When quasars were discovered, Barnothy was the first to connect them with the gravitational lens effect [1]. Yu. G. Klimov, S. Liebes, and S. Refsdal independently reopened theoretical research on the subject {[11], [14], [22]}. Klimov considered lensing of galaxies by galaxies, concluding that, for sufficient alignment, a ring-shaped image would occur and could be easily singled out from the general field of galaxies, whereas if the alignment were imperfect, multiple galaxy images would appear, which would be difficult to separate from double or multiple galaxies. Liebes considered lensing of stars on stars, of stars on globular clusters in our galaxy, and of stars on stars if both are members of the same globular cluster; he also considered the possibility that stars in our galaxy can lens stars in the Andromeda galaxy. In his paper, Liebes also estimated the probability that lensing events of the kind just mentioned could actually be observed, emphasizing the importance of space-based observations.

Refsdal, as did Liebes, gave a full account of the properties of the point-mass gravitational lens; Refsdal also considered the time delay for the two images, due to the different

light-travel-time along light rays corresponding to each image. In particular, he argued that geometrical optics could be used safely in considering gravitational lensing effects. In a second paper, Refsdal considered potential applications of gravitational lensing. His abstract stated:

The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by Δt , the redshifts of the supernova and the galaxy, the luminosities of the supernova 'images' and the angle between them. The possibility of observing the phenomenon is discussed [23].

Refsdal also pointed out the possibility that lensed quasi-stellar objects could be used for the determination of lens masses and, via the relation $t = l/H_0$, the Hubble constant, H_0 .

From the 1960s to the late 1970s, a few scientists explored various theoretical aspects of lensing further, for example, statistical effects of local inhomogeneities on the propagation of light; lensing applied to quasars and clusters of galaxies; development of a formalism for transparent lenses; and the effect of an inhomogeneous universe on distance-redshift relations. In spite of clear theoretical predictions, observers showed little interest and no systematic search for lenses occurred.

In 1979, D. Walsh, R. F. Carswell, and R. J. Weymann announced the serendipitous detection of the first gravitational lens candidate [31]. The source 0957+561 was selected from a radio survey. It has two optical image counterparts A and B, which turned out to be quasi-stellar objects at a redshift of $z \sim 1.4$; their angular separation is about six arcseconds. The similarity of the spectra of A and B, and of the ratio of optical and radio fluxes, and the subsequent detection of a lensing galaxy at redshift $z_d \sim 0.39$ verified the lens nature of this system [34]. Only one year later a second gravitational lens candidate was found [32]. The first gravitational lens discovered in a systematic search was in 1984 [13]. The discovery of the first gravitational lens

systems triggered an enormous outpour of publications, concerning both observational and theoretical work.

A second type of gravitational lens system was announced in 1987 at the 169th American Astronomical Society meeting. Roger Lynds and Vahe Petrosian discovered luminous arcs in clusters of galaxies, which are understood to be highly distorted images of high-redshift galaxies, seen through a compact foreground cluster of galaxies [16]. A year later, in a systematic search for gravitational lens systems with radio telescopes, a third type of lensed image was found: radio sources with the shape of nearly full rings [10]. The discovery of the first microlens, a star lensing another star, came in 1994 from an organized search run by a group of astronomers, the MACHO (MASSive Compact Halo Objects) collaboration [24]. Since 1979, the number of papers devoted to gravitational lensing is so great, and the discussions so varied that the most recent developments in gravitational lensing must be left for another time.

A more complete account of history of gravitational lensing helps us to see the evolution of theoretical work on gravitation and light and to understand its interactions with observation. The complicated history of the theoretical development of gravitational lensing shows how the spread of scientific knowledge and credit for scientific discoveries are delicate matters. The theoretical development of gravitational lensing, or the deflection of light by a body, illuminates the role of contingency in scientific productivity; shows science as a social enterprise; and finally, how theory and observation interrelate in astrophysics and cosmology. The study of gravitational lensing has motivated new developments and provided inspiration for answering some of the fundamental cosmological questions. Virtually all of Zwicky's predictions have come true; lensing by galaxies and galaxy clusters is currently a major sub-discipline of lensing research. The most accurate mass determinations of the central regions of galaxies are due to

gravitational lensing. The cosmic telescope effect has enabled the study of very distant galaxies, allowing us to reconstruct the shape of the lensed galaxy from its projected images. The statistics of gravitational lensing events, of which the order of magnitude Zwicky correctly estimated, offer an effective method to infer cosmological parameters (i.e., cosmological constant). The time delay measurements of lensed images are a promising way to measure the Hubble constant, H_0 . Microlensing, first suggested in Liebes' theoretical work, is now an effective tool for studying objects in our galaxy and may soon prove a productive method for detection of exoplanets.⁴ Gravitational lensing is a leading tool of cosmology and astrophysics; the laborious calculations and theorizing that took place over the past three centuries by a variety of scientists has given us the opportunity to explore some of the universe's more puzzling features.

⁴ David Bennett, a University of Notre Dame astrophysicist, is a member of an international team of astronomers that recently announced their discovery of a potentially rocky, icy body that may be the smallest and coolest extrasolar planet yet found. The planet, officially known as "OGLE-2005-BLG-390Lb," is located more than 20,000 light years away in the constellation Sagittarius, close to the center of our Milky Way galaxy. It orbits a red star five times less massive than our sun about once every 10 years and has a likely surface temperature of -364 degrees Fahrenheit (-200 degrees Celsius). See also: Beaulieu, J. P. *et al.*, 2006. Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing. *Nature*, 439, 437–440.

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