The conceptual origins of gravitational lensing

David Valls-Gabaud^{1,2}

Canada-France-Hawaii Telescope, 65-1238 Mamalahoa Highway, Kamuela, Hawaii 96743, USA
 GEPI – CNRS UMR 8111, Observatoire de Paris, 5 Place Jules Janssen, 92195 Meudon Cedex, France

Abstract. We critically examine the evidence available of the early ideas on the bending of light due to a gravitational attraction, which led to the concept of gravitational lenses, and attempt to present an undistorted historical perspective. Contrary to a widespread but baseless claim, Newton was not the precursor to the idea, and the first Query in his Opticks is totally unrelated to this phenomenon. We briefly review the roles of Voltaire, Marat, Cavendish, Soldner and Einstein in their attempts to quantify the gravitational deflection of light. The first, but unpublished, calculations of the lensing effect produced by this deflection are found in Einstein's 1912 notebooks, where he derived the lensing equation and the formation of images in a gravitational lens. The brief 1924 paper by Chwolson which presents, without calculations, the formation of double images and rings by a gravitational lens passed mostly unnoticed. The unjustly forgotten and true pioneer of the subject is F. Link, who not only published the first detailed lensing calculations in 1936, nine months prior to Einstein's famous paper in Science, but also extended the theory to include the effects of finite-size sources and lenses, binary sources, and limb darkening that same year. Link correctly predicted that the microlensing effect would be easier to observe in crowded fields or in galaxies, as observations confirmed five decades later. The calculations made by Link are far more detailed than those by Tikhov and Bogorodsky. We discuss briefly some papers of the early 1960s which marked the renaissance of this theoretical subject prior to the first detection of a gravitational lens in 1979, and we conclude with the unpublished chapter of Petrou's 1981 PhD thesis addressing the microlensing of stars in the Magellanic clouds by dark objects in the Galactic halo.

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INTRODUCTION

It is remarkable to note that the development of gravitational lensing has been marked by a wide shift between the detailed theoretical calculations, initiated in the 1930s, and the observations of the corresponding phenomena, the first of which was discovered in 1979. The fast pace at which both observational and theoretical progress has been made in this subject reflects the power of the methods and the advance in astronomical instrumentation. This makes the discipline mature enough to provide ground for its own history. Unfortunately most attempts so far have repeated the same baseless stories (with the notable exception of Trimble [43]), sometimes even verbatim, without paying any attention to the actual historical sources. The history of lensing is intimately related to the history of the concept of black holes [15] and the observational evidence for the gravitational deflection of light [e.g., 11, 18, 6]. The purpose of the present paper is to set the record straight by critically examining the papers and the context of their production, so as to present –as far as one can– an undistorted account of the evolution of ideas leading to the concept of gravitational lenses. A more detailed review is presented elsewhere [44].

The term gravitational lens appears in print for the first time in a rather dismissive and negative context:

[...] it is not permissible to say that the solar gravitational field acts like a lens, for it has no focal length.

Lodge (1919) [30]

Sir Oliver was of course right, and the reason is simple: the deflection, produced by the Sun at a radial distance r, of a light ray coming from infinity and reaching the observer is $\alpha(r) = 1.75$ (M/M_{\odot}) (R_{\odot}/r), and is therefore equivalent to a strongly astigmatic lens since the deflection decreases with increasing distance to the optical axis (compare for instance to the case of a convergent lens, where the deflection increases with increasing distance from the axis, so that all emerging rays do converge to a well-defined and unique focus).

This comment, published as a letter to *Nature* in the wake of the discussions on the results of the famous 1919 eclipse expedition, reflects part of the huge polemic that arose from the experimental verification of Einstein's theory. Although much of it has now faded, given the resounding experimental success of General Relativity on all fronts, the issue arose due to the uncertainties in the measures at both Sobral and Principe, the two sites of the expedition

to observe the eclipse of May 29, 1919. The plates taken with 4-in telescope at Sobral yielded a weighted average deflection of $1.^{\prime\prime}98\pm0.^{\prime\prime}18$ (after taking into account part of the systematics), while the plates taken with the 13-inch astrographic telescope of the Greenwich Royal Observatory were slightly diffuse, as a consequence of the change of focus caused by the heating of the mirror of the coelostat, and produced a measured deflection of $0.^{\prime\prime}93$. The observations at Principe were in principle of better quality, thanks to the temperature stability of the island, but were affected by clouds and yielded $1.^{\prime\prime}61\pm0.^{\prime\prime}30$ [9]. The gravitational deflection was clearly measured, and corresponded to the general relativistic prediction [see, for instance 11, 18, 6, for more details.]

It was in the context of this announcement that J.J. Thomson, president of the Royal Society at that time, and chair of the joint meeting of the Royal Society and the Royal Astronomical Society on November 6 1919, claimed that Newton had thought about the gravitational attraction of light by matter:

THE PRESIDENT. I know call for discussion on this momentous communication. If the results obtained had been only that light was affected by gravitation, it would have been of the greatest importance. Newton did, in fact, suggest this very point in the first query of his 'Optics' and his suggestion would presumably have led to the half-value. [...]

as reported in the minutes of the meeting (Royal Astronomical Society, 1919). It is unclear whether the large portrait of Isaac Newton in the background was decisive for this statement to be made or if some nationalism was required to compensate the intellectual 'victory' by a German scientist on the wake of the end of the first World War.

J.J. Thomson was referring to what was going to become the most famous quote extracted from Newton's *Opticks* (1704,[33] Book IV, Part 1), which reads

Query 1. Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action (caeteris paribus) strongest at the least distance?

Newton (1704)[33]

This is the very first Query that appears in the Book IV, Part 1 of the first edition of his *Opticks* published in 1704. The citation got a widespread diffusion and is to be found in almost every historical introduction on gravitational lensing. Unfortunately the citation is taken totally out of context and has nothing to do with a gravitational bending of light.

THE FIST QUERY OF NEWTON'S OPTICKS

The actual context (end of Book III) is the following:

Obs. 10. When the Fringes of the Shadows of the Knives, fell perpendicularly upon a Paper at a great distance from the Knives, they were in the form of Hyperbola's

that is, Newton is repeating Grimaldi's experiment on *diffraction* and there is no discussion whatsoever on the gravitational effects on light. As a matter of fact, Newton continues thus:

When I made the foregoing Observations, I design'd to repeat most of them with more care and exactness, and to make new ones for determining how the Rays of Light are bent in their passage by Bodies, for making Fringes of Colours with the dark lines between them. But I was then interrupted [...]

And since I have not finish'd this part of my Design, I shall conclude with proposing some Queries, in order to a farther search to be made by others.

This is the end of Book III, Part I. There is no Part II, and this abrupt end is very revealing¹. While the first (English) edition of 1704 contained only 16 queries, the second (1717) has 32, while the Latin edition published in 1706 had 23 ². The later ones became short essays, in contrast to the brief questions of the first edition. The reason of the "delay" in the publication is simple: Robert Hook had died in 1703. Hook, along with Pardies, was one proponent of a wave

Part of the ensuing Discourse about Light was written at the desire of some gentlemen of the Royal Society, in the year 1675, and then sent to their Secretary, and read at their meetings, and the rest was added about twelve years after to complete the theory; except the third Book, and the last proposition of the second, which were since put together out of scattered Papers.

 $^{^{1}}$ In fact, Newton indicates in his Advertisement I that his book is composed of various bits and pieces:

² A rather complete collection of the editions of Newton's works is available on-line at:http://dibinst.mit.edu/BURNDY/Collections/Babson/Online

theory of light and also a strong opponent of Newton's theory of colour as described in 1672. The controversies are well documented and will not be reviewed here. It is important to note that, unlike the *Principia*, the *Opticks* are first published in vernacular, to maximise the potential number of readers and to get a quick and widespread diffusion.

The first seven queries will not be changed through the various editions, and it has to be noted that the rhetorical form of Query is used by Newton to affirm statements for which he has no proofs. All the questions are formulated to always give implicitly affirmative answers.

Returning to the subject matter of the first queries, they do indeed all ponder about the nature of this bending produced by diffraction³:

- Query 2. [...] and after what manner are they inflected to make those fringes?
- Query 3. Are not the Rays of Light in passing by the edges and sides of Bodies, bent several times backwards and forwards [..]
- Query 4. Do not the Rays of Light which fall upon Bodies begin to bend before they arrive at the Bodies?
- Query 5. Do not Bodies and Light act mutually upon one another?

Newton is of course rightly worried about diffraction, a phenomenon difficult to explain within his corpuscular theory of light, and he is not thinking on the possible effects of gravitation on the light rays. The only mention of the effect of attraction on rays of light can be found in the *Principia* (Scholium to Prop. XCVI in Principia, Book I, Section XIV), but the attraction there is generic, not necessarily gravitational.

JEAN-PAUL MARAT : A POSSIBLE PRECURSOR

Given the (unfair) black legend that surrounds Marat, it is rather unexpected to find him as a possible precursor to the idea of gravitational lensing. Marat was not only the revolutionary politician who played a key rôle in the early French revolution, but also a writer and a physician (he received a MD from St Andrews, Scotland in 1775, a year after being admitted as a free mason in London). After eleven years spent in England, he returned to Paris in 1776 to become the appointed physician at the house of the Comte d'Artois, the king's brother. His success as medical doctor allows him to buy and make scientific instruments and carries out experiments on a variety of subjects mainly on fire and on electrical and optical phenomena. The initial reception of his books was rather warm, some of them being approved by the Académie Royale des Sciences. The experiments described in his published reports appear to be very careful and detailed, not better nor worse than the average experiment published in the learned journals of the time, and so the harsh criticisms made by some⁴ do not seem to be justified. A more balanced and fair account is provided by Conner [5] and by Bernard et al. [1].

The reception of Newton's ideas in Europe, dominated by the Cartesianism, was quite cold at the beginning, if not upright negative [e.g., 17]. It took translations, lobbying, polemics (Voltaire played a very important rôle with his Éléments de la philosophie de Newton⁵) and the expeditions to Lapland and Peru to measure the length of the arc of meridians for the gradual acceptance of newtonian ideas in Europe. In this context, it should be noted that Marat was one of the first (and faithful) translators into French of Newton's *Opticks* and entertained good relations with Benjamin Franklin, but very bad ones with Lavoisier (both in his rôle as Fermier Général and as an influential member of the Académie Royale des Sciences, which in the words of Marat, was becoming a club of modern charlatants). Remarkably, in his *Découvertes sur la lumière* published in 1780, Marat states that

Tous les corps connus décomposent la lumière en l'attirant [...] La sphère d'attraction de la lumière [...] dépend de la densité superficielle, [...] un facteur d'affinité, [...] et en raison du carré inverse de la distance Marat (1780)[31]

Inflected rays: those rays of light which, on their near approach to the edges of bodies, in passing by them, are bent out of their course, being turned either from the body or towards it. This property of the rays of light is generally termed diffraction by foreigners, and Dr. Hooke sometimes called it deflection.

³ The term inflection is used instead of diffraction, but they are the same concept. For instance, Priestley (1772) Priestley [35] states the following definition in his glossary:

⁴ For instance Gillispie [16] places him on the same level as charlatans such as Mesmer.

⁵ For a detailed account of Voltaire's ideas on the bending of light see [44].

However, the remaining text is ambiguous on whether this is truly a *gravitational* effect or mere attraction by yet another force. One can't but speculate whether Marat had read the encyclopedic compendium by Priestley (1772[35]) while he was living in England. Certainly his opthalmologic experience led him to think on the theory of vision [8]. We also note a number of similarities such as the use of a "solar microscope" and the description of "sphere of attraction". Marat's influence on the subject was, ironically, far greater within the romantics, thanks to the translation into German of several of his books. Goethe for instance, cites Marat's ideas when he develops his theory of colours.

THE FIRST CORRECT CALCULATION: CAVENDISH

Among the many papers and documents by Henry Cavendish found in the collection of the Duke of Devonshire, four were selected in 1921 for their astronomical interest: on the transit of Venus, on the precession of the equinoxes, on the influence of tides on the rotation of the Earth, and one on the bending of light by gravitation. Dyson [10] selected it for obvious reasons⁶, and comments that the calculation "may have been suggested by Query 1 of Newton's Opticks", repeating the claim made by J.J. Thomson. As far as we know, this is the first document that explicitly states the influence of gravitation of light. The manuscript is rather cryptic:

To find the bending of a ray of light which passes near the surface of any body by the attraction of that body. Let s be the centre of body and a a point of surface. Let the velocity of body revolving in a circle at a distance as from the body be equal to the velocity of light as 1:u, then will the sine of half bending of the ray be equal to $1/1 + u^2$.

Cavendish of course is well known for his discoveries of hydrogen, of the compound nature of water and for the measure of the gravitational constant and the density of the Earth, among many other subjects [21]. Cavendish was in close contact with John Michell⁷ on many problems such as the "Cavendish" balance, and especially on Michell's idea of weighting stars through the fact that if light is subject to gravitational attraction, its velocity will be decreased. Therefore the effect can be detected by the difference in refrangibility and Michell proposed a device based on a prism to measure the effect, which clearly depends on the mass of the star. Knowing the mass, and having a mass-luminosity relationship would give the distance of the stars. Cavendish supported the idea, which was presented at the meeting of the Royal Society on November 27, 1783.

The Cavendish manuscript could well have been written at this time, around 1783 or 1784, but it turns out that an examination of the watermark on the paper shows that it could not have been earlier than 1804 [21]. The calculation is perhaps then related either to the diffraction grating experiments carried out by the astronomer David Rittenhouse in 1787 or to Thomas Young's 1800 famous paper putting forward a wave theory of light. It seems unlikely that Cavendish had read Soldner's paper (discussed in the next section) which deals explicitly with the same problem. Alternatively, Cavendish may have carried out the calculation reading the discovery of bound binary stars by Herschel in 1803 and thought again on the Michell effect. Will [45] has provided a good way of reaching Cavendish's result, which illustrates the proper application of Newtonian dynamics. The important point to note is that Cavendish takes the proper boundary condition for the speed of light, which should be taken at infinity, where the acceleration produced by the Sun's attraction is negligible.

SOLDNER'S MISTAKES

This correct boundary condition is entirely at odds with the result that Soldner, an assistant of the Prussian royal astronomer J. Bode, published in 1801 [40]. Johann Georg Soldner was a curious character. Self-taught, he reaches a prominent position at Munich Observatory. He is well known in geodesy for his method for measuring length of arcs

⁶ [...]the possibility of the bending of a ray of light by a gravitational field is at present engaging attention, though Cavendish was working on a corpuscular theory. Dyson's only comment to the manuscript is the following note: [This deflection is half the amount given by Einstein's law of gravitation].

⁷ well known for his books on artificial magnets and on earthquakes but also for his ideas on the astronomical scale of magnitudes, on the clustering of stars –including the existence of physical binaries– and on black holes Eisenstaedt [15]. He also contributed extensively to Priestley's (1772) History and present state of discoveries relating to vision, light and colours[35].

over several km with an error smaller than 1 cm, and has also published some "cosmological" works: on motion of stars within the Milky Way, and on the invisible (Laplace-Michell) stars [see 20, for a detailed account].

The aims that Soldner sets in his paper are clear from the title:

On the deviation of a light ray from its motion along a straight line through the attraction of a celestial body which it passes close by

[...] to derive all circumstances that exercise an influence on the true or mean position of a celestial body from the general properties and interactions of matter

He considers the case of a star at the horizon and asks what is the effect, besides refraction, that will change the apparent position. The attraction produced by the Earth will clearly bend the trajectory and he wants to compute the corresponding astrometric error. It is a difficult paper to read (but see [20] for an English translation), with a confusing notation where for instance the acceleration is defined as $g = s/t^2$ and so v = 2gt instead of v = gt and $g = s/2t^2$. In addition the units are not consistent (for instance, velocities measured in units of length⁸). Crucially there are two misprints of a factor of two, and they fortuitously cancel at the end. The most important aspect, however, is that it is conceptually wrong. In contrast with Cavendish's calculations, he takes the speed of light at the minimum impact parameter, that is, nearest to the Sun, where Newtonian theory predicts that light will be accelerated and therefore its speed will be much larger than at infinity. The mistake that Soldner makes is to assume that the ray that leaves tangentially the surface of the star will have the same speed as the ray that, coming from infinity, will reach the star. The trajectories are almost the same, but they are not the time reversed equivalents since the speed of light will increase in falling case, and decrease in the emerging one. However, he does give the first quantitative result: 0."001 for the Earth and 0."84 at the limb of the Sun. He concludes that

Though the combination of several bodies which a light ray could encounter on its way, would be a larger result, for our observations it is nevertheless unnoticeable. Therefore it is clear that nothing makes it necessary, at least in the present state of practical astronomy, that one should take into account the perturbation of light rays by attracting celestial bodies.

Soldner's paper would resurface over a century later during the infamous antisemitic and antirelativist campaign led by Nobel prize winner Lenard, who published excerpts of Soldner's paper in 1924 and accused Einstein of plagiarism.

THE SECOND CALCULATION: EINSTEIN (1911)

Although this gravitational bending of light does appear in a few books during the 19c, the effect was largely forgotten and resurrected only in 1907 when Einstein, writing a review article on [special] relativity for the *Jahrbuch der Radioactivität und Elektronik* edited by J. Stark, indicates (at the very end) that the light rays must be bent by the gravitational field.

Einstein will publish the detailed prediction in 1911 [12], during his tenure at the German University of Prague, by simply using the equivalence principle to get the first-order Cavendish-Soldner result. The crucial point here is that with the astronomical technology of the time the predicted displacement of 0."83 should be observable during total eclipses of the Sun [12]. Curiously enough, this prediction attracted little interest at the time, and only a junior astronomer at Berlin, Erwin Freundlich, dedicated much efforts to the experimental verification. The history of the various attempts, from 1912 on, at measuring the predicted bending is a fascinating one [18, 6], which culminates with the 1919 eclipse, and only faded when the modern radar measures fully confirmed the predicted deflection.

It is in this context that Einstein thinks about the *lensing* effects associated with this bending, while sitting in the Prague-Berlin train journeys, when he was visiting Elsa. The analysis of his notebooks he used at this time show [37] the first derivation of the lensing equation and the position of the images, in sketches which are completely correct. Puzzingly, he forgets about these calculations *completely*, and will not even remark than on the very same page where one of his papers appears (in an astronomical journal, no less, [13]) there is a brief report by a Physics professor at Petrograd speculating on the images produced by a gravitational lens configuration [4].

⁸ This curious habit is still in use in some countries, where for instance the speed limits are given in miles or km, not miles per hour or km per hour.

A WILD SPECULATION: FAKE DOUBLE STARS

This professor at Petrograd was no less than O. Chwolson, famous world-wide through his encyclopedic *Treatise of Physics* [3], which was translated from the Russian into German, French and Spanish. Einstein thought highly of these volumes, and Fermi read them over the summer before his first year at the University of Pisa. The volume on varying magnetic fields gives a section on special relativity, where the predicted bending of light is mentioned as one of the possible tests of the theory. Chwolson would update the volumes, keeping pace of the tremendous progress made in both theoretical and experimental physics in the 1920s. While not known through his research papers, he published in 1924 in the astronomical journal of reference, the Astronomischen Nachrichten, a short note on the possibility of producing *fake double stars* due to the gravitational lensing effect. While he makes no detailed calculations, he points out the effect and remarks that a *perfect ring* will be produced if the lens, the source and the observer are colinear [4]. It is not known what the reaction of the local astronomers was, but in any case he writes that he cannot say whether these phenomena will actually be observed. The following paper, on the same page, is by Einstein [13], but there seems to be no trace of a possible interaction between the two on this matter.

THE TRUE PIONEER: FRANTIŠEK LINK

Eddington had used the analogy between the gravitational deflection and a refraction effect to explain in simple terms both the 1911 and the 1916 predictions. His 1923 book *Mathematical theory of Relativity* became a best-seller in academic circles and influenced an astronomer noted by his expertise [24] on lunar and solar eclipses, F. Link. Link realises that the Einstein deflection will produce images, in a fashion similar to the one considered when using refraction by the Earth's atmosphere during lunar eclipses. He computes not only the position of the images, but also their brightness, and considers both visible and invisible stars as possible sources, noting that the amplification produced may, in some cases, render visible an otherwise faint star. As a noted observer, he is optimistic about the chances of detection of this effect, especially when observing spiral nebulae, where the chances of having close-by approaches along the line of sight are increased:

such close configurations are obviously rare, except in some areas of the sky, in particular in spiral nebulae.

F. Link (1936) [25]

Settling for a while in Paris (although he will keep strong links with Prague all his life), he publishes his calculations in the French journals. Realising the importance of his prediction, he sends his first report to the *Académie des Sciences*, not only for a peer review, but also to ensure a quick diffusion. His paper published in the *Comptes Rendus de l'Académie des Sciences* [25], appears to have passed totally unnoticed, especially in the anglo-saxon litterature. The paper was read on March 16, 1936, and published along with the papers read during that session. It predates, therefore, by nine months, the famous Einstein *Science* paper, which deals with the same subject [14]. Over the 1936 summer, Link computes even more subtle details, such as finite-size effects, including the limb darkening in stellar atmospheres, and will be published, in French again, in 1937 [26]. The contents of this amazing 18-pages-long paper are reviewed in detail elsewhere [44] but can be summarised as follows:

- 1. Introduction. Link argues that the experimental confirmation of general relativity has been difficult, even though the results of the eclipses show the predicted effect beyond any doubt. Yet, while more precise measures are obtained, he proposes to use the photometric implications of the deflection. He notes the short paper by Chwolson who showed the geometrical implications, but failed to give any theoretical background or the photometric effect. He concludes insisting that the photometric effect can be measurable in some cases.
- 2. The deflection of the light rays. Here he uses Eddington's book (in his German edition) to get the basic equations for the total and partial deflections. The deflection depending upon the ratio $K = (M/M_{\odot})/(R/R_{\odot})$ of mass to radius, in this formalism, he notes that giant stars will have K around 0.06 while for the smallest star known at the time K = 600.
- 3. Changes in the intensity. He uses his general photometric theory which he successfully applied to lunar eclipses in 1933, noting that the formalism applies independently of the underlying physics of the deflection, and that in the case of solar eclipses the effect is negligible but there should be cases where it is important (citing his 1936 short paper). The general formalism applies to sources and lenses of finite angular size.
- 4. Discussion. Link analises the dependence with impact parameter, noting that the ratio of intensities may become negative for small impact parameters. This is due to the fact that it is a ratio of variation of areas, and the absolute

- value must be taken. He also notes that the light curve is symmetrical with respect to the time when the impact parameter reaches the minimum, and the amplification may be smaller than one at large distances.
- 5. Mutual occultation of two stars. The more realistic case where the lens may occult a fraction of the source is treated, along with the required effect from a finite-size source. He deals with both a uniform disc (*i.e.* no limb darkening) and a linear limb darkening term, and notes the small effect that darkening produces.
- 6. Invariance of surface brightness. Here he notes that the invariance of surface brightness combined with the variation of the intensity implies that the images will be distorted. He presents the first lensing diagram ever published and the positions of the two images produced by gravitational lensing. The calculation yields the same result as given previously in his section 5, as a mere application of his general lunar eclipse formalism.
- 7. Variations of the shape of the occulted star [source]. The positions of the images are analised in the lens plane, as function of the impact parameter, for the general case. He notes the formation of arclets and "lentils" (counterimages). For a central occultation (*i.e.* zero impact parameter) a concentric ring is formed, whose radius is very similar to the critical radius. He derives a simple criterion to check whether the shadowing effect due to the finite size of the lens can be neglected. He carries on noting that the net effect will depend on the relative brightness of the two stars, and that, in general, there will be spectral changes at the same time as the photometric effect takes place. He also speculates that the oddly-shaped deformed images will not be observed except perhaps with an interferometric method.
- 8. Numerical examples. Here he considers three cases
 - (a) An optical double system (i.e. two unrelated stars, close to each other along the line of sight). He takes as an examples a solar-type lens at 2.6 parsecs and a giant at 25.8 pc and computes the position and brightness of the images, for selected impact parameters, noting that the maximum amplification will be of about 2 magnitudes.
 - (b) A physical double star. Here he considers the binary system similar to Sirius and concludes that the effect is negligible, barely 0.05 magnitudes, due to the large size of the occulted star. Therefore physical binaries are not interesting configurations due to the small separation between the components.
 - (c) Clusters of stars (especially globular). Dense clusters are ideal places to look for this effect, and he starts speculating that the photometric amplification could be the reason for which the centres of globular clusters are so bright. He finds that for two stars belonging to the globular cluster M13, assumed to be at 30 pc [sic], the amplification could reach 5.85 magnitudes, but realises that most occultations will not be central and that there may be many occultations simultaneously along the line of sight. He concludes the section arguing that the spiral nebulae are also good places to look for the effect, which perhaps helps explaining their increased brightness at their centres.
- 9. Conclusions. Here is the translation of the conclusions:

The reality of the phenomena we have sketched here depends upon the validity of the Einstein deflection. It is extremely interesting to look systematically in all the domains of stellar astronomy for favourable instances where such events can take place, not only to constitute another proof of the theory, but also as an explanation of some brightness variations.

The second paper concludes stating that it seems extremely interesting to look systematically for such phenomena in all domains of stellar astronomy [26]. This optimism is in sharp contrast with Einstein's pessimism on this phenomenon.

MANDL AND THE 1936 EINSTEIN PAPER

It is indeed a visit paid by Robert Mandl to Einstein on April 17, 1936, that triggers a new calculation by Einstein on the lensing effect [38]. Mandl thinks that the focusing of light/radiation may explain: (1) the shape of annular nebulae, (2) the origion of cosmic rays (amplification of galaxy's light), and (3) the extinction of biological species by bursts due to stellar eclipses. Einstein is not impressed, and more than doubtful, to say the least:

I have come to the conclusion that the phenomenon in question will, after all, not be observable so that I am no longer in favour of publishing anything about it.

Einstein, 18 April 1936

In spite of this, Mandl will continue over the next months to press Einstein on publishing these calculations, and Einstein will eventually, but very reluctantly, agree, sending a brief note to *Science* to, in effect, get rid of this insistence [14]. It is not known whether Mandl knew about Link's paper, but in any case Einstein will remain very pessimistic

about the lensing effect. Unlike Link's papers, the brief note by Einstein attracted the attention of many astronomers, from Russell [39] to Zwicky [47, 48], and, ironically, the paper would be hailed as the trigger of the subject, even though Link would continue publishing further detailed predictions [27, 28] and a whole chapter in his monograph on eclipses [29]. Link died in 1984 and it is not known whether he was aware of the discovery of the first lens in 1979. While the papers by Link attracted little notice in the West, Russian astronomers were well aware of them, and some claimed (undue) priority in 1937 [41, 42]. A detailed account of these contributions, in particular by Bogorodsky, and their influence, is reported elsewhere [44].

ANNUS MIRABILIS: 1963–1964

It is remarkable that, in spite of this series of pioneering papers, hardly any attempts were made at refining the predictions or starting a systematic search for the lensing effect in the 1940s and 1950s. Perhaps the fact that general relativity remained a rather obscure and technical subject even in the physics departments during these decades could help explaining this (in retrospect) puzzling situation:

[...] I might refer to the circumstance that from 1936, when I joined the faculty at the University of Chicago, to 1961, no courses in General Relativity, not even for one single quarter, were given at the University. And the University of Chicago is not atypical.

Chandrasekhar (1979) [2]

However, starting in the late 50s, a new series of papers appear on the subject [44]. Darwin [7] made a detailed calculation of the positions and magnifications, but takes angles rather than solid angles and so gets the square root of the correct result. In the Soviet Union, the calculations by Idlis and Gridneva [19] may be considered as the precursors of the weak lensing idea. The subject remains a highly speculative one, as for instance Metzner [32], who corrects Darwin's mistake, concurs on the irrelevance of the topic:

Both Einstein and Darwin have pointed out that the magnitudes involved makes these results more or less irrelevant from the point of view of observational astronomy. [32]

Klimov [22] carries out further calculations with galaxies taken as lenses, and marks the beginning of serious and detailed studies: (1) Liebes [23] reviews gravitational lensing on all scales: stars of the Milky Way (and their optical depth), globular clusters, unobservable (dark) stars, non-stellar deflectors, stars in the Andromeda galaxy, gravitational waves, spikes/flashes, and galaxies. (2) Refsdal [36] publishes in a well-known astronomical journal, and notes that It seems safe to conclude that passages observable from the Earth occur rather frequently. The problem is to find where and when the passages take place [...] (3) Zeldovich [46] studies, for the first time, the effects of lensing on cosmological scales.

This series will launch the studies, mostly by astronomers, of further details of the wide range of phenomena produced by lensing. The process will accelerate after the discovery of the first lens in 1979.

THE FORGOTTEN CHAPTER OF PETROU'S PHD THESIS

It was in a different context that Maria Petrou studied the probability of lensing by objects in the Milky Way's dark halo on stars of the Large Magellanic Cloud. Her supervisor though the subject too speculative and argued against its publication, and so only appears as Chapter VII (Lens effect of halo objects) of her thesis dealing with *Dynamical models of spheroidal systems*. Remarkably, she concluded that the [...] expected number of amplified stars is about 20 and that [...] the variability of the star will be different from other kinds of variability because there will be no change in its colour. These are indeed the figures and properties that, over a decade later, the microlensing experiments used to detect a new population of dark compact objects in the Galactic halo.

CONCLUSIONS

The conceptual evolution of gravitational lensing brings to light the interplay between published and unpublished calculations, wrong and correct ones, justly influential and unjustly forgotten papers, perhaps just like any other subdiscipline of intellectual endeavour. However, we can't but try to set the record straight and acknowledge that F. Link was the true pioneer of the subject and a visionary, even though he did not succeed in convincing other astronomers,

let alone be recognized in his leading rôle. Similarly, we can't but speculate on the reasons that led Einstein, who always seeked the observational verification of his theoretical predictions (Brownian motion, gravitational deflection and redshift), to be –for once– extraordinarily pessimistic on one of Nature's most spectacular phenomena.

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