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Extragalactic Reality: the Case of Gravitational Lensing

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ABSTRACT

Representing and Intervening concluded with an experimental argument for scientific realism about entities that cannot in any literal sense be observed. It was based on the fact that we regularly use such entities to investigate other parts of nature, and that we reliably build apparatus to take advantage of some of the causal properties of such entities. Evidently the argument cannot apply to unobservable entities that are postulated to exist outside our galaxy. There might, however, be some other compelling argument about scientific realism for extragalactic entities. In this paper I defend a modest astrophysical antirealism. The argument is conducted by a quite detailed examination of one current body of research. It concerns a newly detected kind of entity, the gravitational lens. Gravitational Tensing is a relativistic phenomenon, although it seems first to have been suggested by a Newtonian in 1919. The first strong contender for a gravitational lens system was reported in 1979. Since then the field has been very active. Black holes and superconducting cosmic strings are, of course, even less amenable in principle to "observation" and "experiment" (no matter how in the future we extend our use of those terms) than are gravitational lenses. But lensing has several advantages for philosophical scrutiny of today's real-life observational and theoretical cosmology. First, the fundamental physical idea appears to be very simple. Secondly, there is widespread conviction that we now know the location of a number of lens systems, so that individual examples of these entities are not merely postulated, but actually given geographical coordinates. Fascinating though strings and holes may be, the unfanciful gravitational lenses provide a more serious test of an antirealism that professes something more than merely a foundation in semantics and the philosophy of language, an ancirealism, in short, tied to present scientific practice.

KEY WORDS: Extragalactic, grauitational lensing , detecting lenses , scareity of lenses.

INTRODUCTION

On april 12 , 1615 , while Galileo was publicizing his dramatic telescopic discoveries as evidence for the Copernican model of the solar system, Cardinal Robert Bellarmine (an influential papal advisor) wrote to father paolo foscarini (one of Galileo's allies) :

To say that by assuming the earth in motion and the sun immobile one saves all the appearances better than the eccentrics and epicycles [of ptolemy's geocentric model] ever could is to speak well indeed . this holds no danger and it suffices for the mathematician . But to want to affirm that the sun really remains at rest at the world's center … and that the earth … turns very swiftly around the sun, that is a very dangerous thing .[1]

That the aim of science is to discover truths about observables and unobservables alike is " scientific realism . " on this view , a proper reconstruction of scientific reasoning interprets accepting a scientific confirms the truth of claims concerning entities too small to be observed (such as subatomic particles or genes) or entities that are unobservable despite being large (such as the electromagnetic field , component forces , and my superego) just as it confirms the truth of predictions about observables that haven't yet been (and perhaps never will be) observed .

All of the essays in this section concern the venerable dispute between realism and antirealism. Be warned: in this introduction, I will not be discussing the essays one by one, in the order in which they appear in this section. Rather, I will be jumping back and forth among the essays in this section in order to trace some of the themes running through them and to highlight some of the similarities and differences among them.

Worrall must walk a fine line in distinguishing a theory's formal structure of mathematical relations from its descriptions of the relata. if we specify the relations too abstractly, then we have merely uninterpreted formalism, and so (if the theory is logically consistent and empirically adequate) any sufficiently large collection of things can be interpreted as exhibiting that structure.[2] But if too much content is identified as belonging to the) theory's mathematical form, then the pessimistic induction will suggest that we are not entitled to believe that our current theories' structures will , hold up. Perhaps only in hindsight can we identify a "structure" that remained constant as the electric field was variously interpreted as a state of a' jelly-like ether, a substance in its

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own right, the way that the electromagnetic field appears in some reference frame, and a sea of virtual quantum particles. Though Hertz famously declared that "Maxwell's theory is Maxwell's system of equations," Maxwell not only didn't say so (concerned as he was with mechanical models of the ether), but also didn't even formulate those equations in the now-familiar manner (which was codified by Hertz and independently by Heaviside). Indeed, Maxwell might have taken structural realism as dictating that something real, whose intrinsic character remains unknown, plays the theoretical role of magnetic field energy. But this turned out to be false; special relativity revealed that energy and the magnetic field itself are artifacts of our reference frame.[3]

Scientific realism treats alike all unobservable posited by the theories we accept. Constructive empiricism and structural realism also proceed in this wholesale manner. However, perhaps the scientific details demand a more case-by-case approach. Hacking is a realist about electrons and an antirealist about gravitational lenses and black holes. Like Worrall, Hacking deemphasizes theoretical descriptions in favor of the entities that theories posit. But although Worrall emphasizes the entities' roles in mathematical structures, Hacking emphasizes their causal roles.

Hacking gives an "experimental argument" for realism about entities:

We are completely convinced of the reality of electrons when we regularly set out to build - and often enough succeed in building - new kinds of device that use various well-understood causal properties of electrons to interfere with other more hypothetical parts of nature.[4]

1. Gravity Lenses, What

I shall proceed as follows .

Describe a philosophical problem about scientific realism in cscragalactic astrophNsics .

Present the gravitational lens effect and its history from 1919 to the end of 1986. 1 Then I return to the philosophical concerns, armed with this new and I hope rich example. Readers unfamiliar with the effect will want, however, to know at once what a gravitational lens is. At first the answer is easy. Imagine a light source (radio source or whatever) at a very great distance from us. Between this source S and the observer 0 is a massive object L. Suppose that L is very slightly off the line of sight OS. Then radiation from S grazing L on either side will be deflected by the mass of L so that 0 will observe S from two directions, seeing two images of S as in figure1, IfL were exactly on the line of sight OS, then S could be imaged as some sort of luminous circle around L. Not only would one see two (or more images) or a halo, but also there will be magnification. That is, the flux, or rate, of light (or radio or x-ray) energy from S entering a cross-section of the observer's "telescope" will be substantially greater than would be the case if L were not in the way and S were observed directly . 2

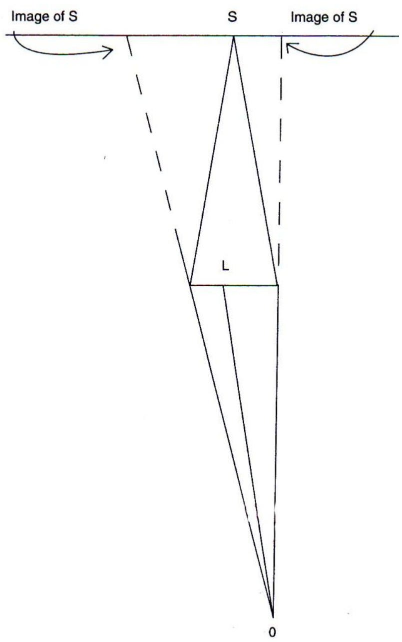

Figure.1. Simplest model of a gravitational lens system. The lens is L, slightly off the line of sight of a source Sand observer O. Light from S is deflected as it passes L, creating two images and Substantial amplification. This model is not even approximately sound unless L can be treated as a point mass.

Under these circumstances SLO constitutes a gravitational lens system and L is the gravitational lens. A glance at figure 1, combined with the predicted magnification, explains the metaphor of lensing. I should warn at once that things will not prove so simple as this introduction. In figure T& I we are really thinking of a point mass L. When correctly treated as a sphere, there must always be an odd number of images. Yet almost all, or perhaps all, of known lenses appear to have an even number of images. Theoretical prediction for more complex lens systems is terrible: for clumpy universes, for example, or for objects with singularities such as cosmic strains.

Everything in figure -1 could happen in our galaxy. First thoughts about gravitational lenses, including those of Einstein, did tend to think in galactic terms. But present candidates for lens systems are extragalactic. There are two good reasons for this. The lenses themselves are galaxies, which are massive enough to serve as lenses, and plentiful enough so that with non-negligible probability they will be on the line of sight to a distant source. Secondly, the present known sources are quasi-stellar objects, which, at the immense distances required, are bright enough to be observed [5]. Incidentally I shall use the name "quasi-stellar object" or QSO throughout (except when quoting) rather than the "quasar" of popular and textbook writing. The latter name is reifying for it suggests that there is one natural kind of thing - that for example there are (a) quasars and (b) pulsars, two natural kinds. QSOs are incredibly bright distant blue star-like objects originally noticed in radar sources, and first dubbed "quasi-stellar radio sources" or QSRS, hence "quasars".

In this paper I wish entirely to evade questions about QSOs. But it happens that all our probable lens systems use a QSO as a source. Hence I should say hoA many QSOs ha\e been detected.. At the beginning of their catalog they note that the question, "how many QSOs'" is not a precise one. QSOs are "star-like" and have a "very large redshift". Some definition, These cataloguers introduce what they call precise "operational" (that is, nontheoretical) criteria to obtain their 3594 QSOs. For comparison, the category of QSO was first used in 1963. A 1977 catalog lists 637; one for 1980 has 1549; and in 1985, 283 were compiled.

We can in a fairly natural sense "observe" QSOs - even if we don't know what they are, and even if "quasi-stellar object" corns_ out to denote several fundamentally different kinds of object. In the case of lenses, at most we can see multiple images and deduce that they are images of the same object, and we can look for a massive object in the right place that would do the tensing. 6 We may be able to observe an object A, but we can't observe that this object is a gravitational lens. One can only infer that from observations, where by "observation" I hope it is by now self-evident that I don't mean just looking at the night sky with the naked eye or even looking into a telescope. Certainly we cannot interfere with a gravitational lens system (except by choosing to look at its effects).

2. Astronomy and the Experimental Method

Only one commonplace philosophical thesis about science is inculcated in grammar school: the scientific method is the experimental method. The Baconian adage has, howerer, one intrinsic problem. Two of our earliest sciences were geometry and astronomy. Take geometry first. In the Babylonian era it may have been an empirical science, but we are taught that after Thales it became a matter not of experiment but of deduction. Doesn't that create a problem for identifying scientific method and experimental method' No, because the very identification of science and experiment one that arose only in the seventeenth century - by now takes for granted that geometry is not a science in the relevant sense of the term. On the other hand, if we do, in a post-Riemannian world, understand the propositions of geometry to be about our actual space, and we deny that geometry is a matter of convention, then geometry so understood is subject to experimental enquiry and hence no counterexample. The case of astronomy has no such swift resolution. True, we are already able to experiment on the moon and the planets which are close, but we cannot experiment on or with the sun. Galactic experimentation is science fiction; while extragalactic experimentation is a bad joke. Yet the study of the sun, the galaxy and the universe is assuredly science. Hence the scientific method cannot be the experimental method.

This is a fine poser for the alert child to put to the schoolteacher, but no one worries much about it. One element of the experimental method is observation, is it not? In astronomy we are largely restricted to observation, so our science is in certain ways truncated. But that is a fact of life, a fact about our size and powers, as opposed to the size and powers of the sun, the galaxy or the universe [6]. Astronomy, according to this reply of the schoolteacher, is not a counterexample to the identity of scientific method and experimental method. It just happens that we are able to study the nature of the macrocosmos without interfering with it, simply by observing it. Indeed were this not the case, we would probably never have attained to our conception of law of nature at all. The full experimental method of intervention in nature is needed for the microcosmos. Doubtless we would learn more about our galaxy were we able to explore it and manipulate iAVe certainly will learn more about our solar system by exploring it, and experimenting on bits of it just as we now experiment on rocks from the moon. But it happens that in astronomy we can get by without the full experimental method engineered into being in the seventeenth century.

3. Astrophysics and Scientific Realism about Entities

The nebulous worry of section 3 is more serious for me. I take a somewhat Duhcmian view of theories, holding them to be possible representations that are not, and perhaps could not be, literally and exactly true. But I am realistic about certain unobservable entities. Electrons do exist, I argue, even though we may be unable to give true descriptions of them over and above a purely phenomenological level. Naturally, such a point of view cannot be combined with a Russellian theory of denotation in terms of descriptions. It rides easily, however, with the sort of theory of reference advanced by Putnam.

I was not speaking about arbitrary cosmological objects. A black hole is as theoretical an entity as could be. Moreover, it is in principle unobservable, (Well, maybe there are problems about cosmic censorship, but let that be.) At best we can interpret various phenomena as being due to the existence of black holes.[7]

The putative counterexample to the Baconian identity "scientific method = experimental method" was, "there's no experimentation in astronomy°[1].1 The schoolteacher's reply was: "There's observation, not experimentation, and there is an instructive story - to tell about that". But now I have switched from astronomy to extragalactic astrophysics. Here we have entities, postulated by splendid theories, and which cannot be observed. That's a poser even for the schoolteacher. But it is worse for me. Do I really mean that, as part of my experimental philosophy of science, there can never he evidence for the existence of black holes' At the very least I need to articulate my position!

4. Why Use Gravitational Lensing as an Example?

Because I want to take a case that is as unfavorable to my ideas as possible. Black holes may in principle be unobservable but we cannot with any confidence point to any region of the sky and say, there's one there, even if we suspect that in fact indefinite [elv many are there. But we really can point to a few regions of the sky, and say with some confidence, there is a gravitational lens system there. Yet I am very disinclined to say that we can observe the lens system. I do not propose now to go into the semantics of that open-textured N-crb, "observe", but I would continue along lines set forth in chapters 10 and ll of m- book. The more valuable, if more demanding, exercise is to consider scientific realism about entities in the context of quite specific instances of a kind of entity that we cannot observe, and with which we cannot interfere.

5. Gravitational Lenses Not Idle Curiosities

Postulation of black holes and cosmic strings arises from profound theorizing. Gravitational ' lensing looks like a trivial corollary of more than one theory about gravitation. But gravitational lensing "pro' ides a potentially powerful tool for investigating two of the outstanding problems in astronomy: the distribution of mass in galaxies and clusters of galaxies, and the values of three fundamental cosmological parameters", namely, the Hubble constant (rate of expansion of the universe), the rate of change of expansion rate with time, and the cosmological constant, which defines the mass-energy density of the vacuum [4].

These are grand hopes, although not everyone is sanguine that they will be fulfilled. The idea of using gravitational lensing to determine the Hubble constant goes back to Refsdal [8]. His model, which supposes a lens to be point mass, is ideal for determining the Hubble constant, but it turns out to be unrealistic). we shall see, the geometry of more realistic models may be so messy that details internal to the lens system may entirely dominate subsidiary effects due to the rate of expansion of the universe. There is another idea afoot, that lenses may enable one to investigate the character of the "missing" mass of the universe [9]. Finally, as I note in section 17, gravitational lenses may be populating the universe with artifacts[10]. Whatever the upshot, lenses have captured the imagination of the astrophysical community.

6. A Shift in Philosophical Emphasis from Kinds of Entities to Individuals

Scientific realism about unobservable entities in physics has npicallc concerned itself with natural kinds: arc there compelling arguments for thinking that electrons exist" Neutrinos' Quarks? We are concerned with sorts, not particulars. Even when we have annic of uniquely designating a subatomic particle - the a-particle that caused that click - we have no interest in that very individual.

There are of course counterexamples. Since 1981 the Penning trap has enabled one to "trap" individual atoms and see how they behave. Yet even here we do not care about this atom, but use it solely as a specimen of the type. In the celebrated events first observed on Earth on 23 February 1987, several neutrino detectors around the world showed events that we assert indicate the passage of some neutrinos that left the explosion we call Supernova 1987A or Supernova Sheldon some 160,000 years ago. Moreover we are speaking of a small number of events, 5 here, 11 there. Nor are all the neutrinos identical, so in a sense we do discuss particular, individual neutrinos whose history is conjectured for 160,000 years. Yet even here the interest lies only incidentally in the individuals that have been observed. We study them to answer questions about the type: what (for example) is the mass of the neutrino, if indeed it has a mass at all[11]?

7. Newton: Hello and Goodbye

k "Newtonian", Sir Oliver Lodge, foresaw the possibility of gravitational lensing [12]. It was in the context of the first news of the famous Eddington-sponsored to test the general theory of relativity[13]. Lodge notes "that a gravitational force acting obliquely on light would probably be unable to alter speed, but through the co-operation of its transverse and longitudinal components, it might be expected to produce an extra dose of deflection - assuming light 1o be subject to gravitation, (is Newton sur7naseel" (my emphasis). He does not favor the lens metaphor:

I shall not develop Lodge's reasoning, which is a rearguard action, no doubt. "Dynamics have served us so well in the past that it must be still legitimate to try, wherever possible, to apply well established principles to new-phenomena". Eddington had more to say about such quasilenses the next year [14]. Searches for such lens effects among stars began immediately at the Yerkes Observatory.

8. Einstein: Hello and Almost Goodbye

"Some time ago, researcher paid me a visit and asked me to publish the results of a little calculation, which I had made at his request" [11]. Thus was Einstein induced to write about the "lens-like action of a star by the deviation of light in the gravitational field". He considers the light from a star S traversing the gravitational field of another star L whose radius is r. Let a be the angle of the deflection of a ray of light from S grazing L at distance r from the center of L. (According to theory, a = const./r, where const. _4 x gravitational constant x mass of L.) Then an observer at distance d from L, and exactly on the extension of the line SL will not see a pointlike star L, but L surrounded by a halo of angular radius $\sqrt{\alpha r d}$ /d. If the line of sight is slightly off the extension of SL, the source S is imaged as two point-like sources separated by about the same angle. The lcns-like effect of L increases the apparent brightness of S by roughly $\sqrt{\alpha r d}$ /x where .r is the distance at L of the line of sight from SL, and is small compared to $\sqrt{\alpha r d}$

Einstein noted that when S is directly behind L, one would not recognize S, for L would merely look brighter than it "really" is. Likewise, x must be so small that the two images would not be distinguished by "the resolving power of our instruments °. °' Therefore, there is no great chance of observing this phenomenon, even if the dazzling effect of the much nearer star L is neglected"[3]. What struck Einstein as interesting about this (undetectable) effect is that the increase in brightness of the source S does not decrease with increasing distance d of the observer, but actually increases as $\sqrt{d}$. Other cosmologists expressed deep regret that the "most perfect tests of general relativity furnished by the gravitational lens effect are unavailable" (Russell 1937). Einstein had no regrets. One speculates that he was delighted by this phenomenon of a magnification that increases as $\sqrt{d}$. Here is a fundamental phenomenon that is known but unobservable

If Zwicky had been simply' . straightforwardly right, gravitational lenses should have been known in abundance reasonably soon after 1945.

I titled this section, "Einstein: Hello and Almost Goodbye". He thought that the universe is full of gravitational lensing by' stars, but that «e would almost certainly never detect a single instance in the form of split images or luminous circles. This thought was long dismissed as either wrong or irrelevant, although sheer failure to detect lenses was a bit problematic. Einstein's discarded thoughts hace a habit of returning in new guise: see section 17 below, where my references are chiefly to articles published in 1986 through January 1987[11].

9. Detecting Lenses

Refsdal [8] brought new life to lensing with a yet y clear review analysis of the gravitational lens effect. His opening paragraph ends with a sentence of interest to the philosopher of experiment: "Due to progress in experimental technique we find, contrary to Einstein that the [gravitational lens] effect may be of practical interest" (my emphasis). He computes the probability of occurrence of a detectable gravitational lens and finds it substantial. Thinking of the passage of one distant object in front of another very distant object, he writes 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 [4].

I have already drawn attention to the most dramatic proposal about gravitational lensing, namely the Barnothys' idea that the quasi-stellar objects are mirages (imaged by Seyfert galaxies). Less iconoclastic conjectures also failed One was reported in 1974, a pair of quasars, 1548 + 115 A, B [9]. The prima facie evidence lay in the similarity of the spectrum of two nearby objects A and B. There were problems in providing an adequate detailed lens model for this couple [14-15].

There have been other suggested lenses [16] which have not survived further scrutiny. But the sequence of titles displays a growing confidence in the candidates for gravitational lenses. In "Observations of gravitational lenses" It was provided a survey of results to date (Lenses 1-111), wryly noting that in only one case (Lens I) is there a candidate for the massive object that is doing the lensing, "so that in only one case, 0957 + 561, has the lens been observed (notwithstanding the title of this paper)". These words seem contrary to my suggestion that one does not "observe" lenses, for Walsh is saying that we have done so. But what we have observed is a very large number of galaxies, most of which are, under some model, consistent with the observations and the hypothesis of some gravitational lens effect or other [12].

10. Why Do You Think It is a Gravitational Lens?

Lens system VI probably consists of a nearby galaxy almost directly - in front of a QSO, but in the preceding cases there were two or more apparent objects. It was conjectured that these are images of a single object. An advantage of gravity lensing as an example for a general audience is that the reasoning behind the conjecture is easy to follow. I take Lens I as typical, at least from the point of view of scientific method [17].

The quasi-stellar objects of Lens I were identified by the Jodrell Bank radio survey. They were optically identified by people from Jodrell Bank, using the Kitt Peak facilities in Arizona, March 29, 30, and April 1, 1979. The arguments for identifying A and B as images of a single quasi-stellar
. object are as follows. First, A and B are close, 5.7 arc seconds apart. Secondly, they have the same magnitude (17) and almost identical redshifts of about 1.40. What is fundamental, however, is that they have "almost identical spectra" (this becomes simply "identical" in later literature). In particular, emission and absorption lines of particular elements match strikingly well. In the blue part of the spectrum, A is brighter than B by about 1/3 magnitude, while in the redder parts they are about equal [18].
The observers then reason as follows.
(a) The great similarity in spectra of the two very close QSOs with the same red shift "seems to constitute overwhelming evidence that the two are physically associated, regardless of the nature of their red shifts, and we do not think that a useful a pnsterrore statistical test of this assertion can be carried out". They then assume that the red shift is in fact cosmological (that is, due to universal expansion and hence a measure of distance, and not, for example, a gravitational red shift). More recent work suggests that similarity of spectra is less compelling than at first thought. But there is more.
(b) Noting that (a) suggests two images of the same object, the team first examines "the more conventional explanation involving two distinct QSOs". This requires a large number of coincidences. Either the emission spectra are the same by coincidence, or else the two QSOs had the same initial conditions and the same subsequent history. Moreover the near identity of absorption lines is more mysterious still "regardless of the mechanism invoked to explain absorption". Absorption lines in QSO spectra are ill understood and a whole bunch of mechanisms have been suggested. But on any plausible model at present on the cards, it is very unlikely that two objects so close would have the same absorption lines.
(c) Then the lens hypothesis is considered. The relevant factors are: angular separation of the images, their shapes and sizes, and their amplification. Everything fits such a model. In particular, the fact that one image ought to be brighter than the other in an equivalent cosmological setting was already known. If we use the magnification of A compared to B to estimate the luminosity of the source, the postulated source has luminosity typical for a QSO.
(d) (Half a sentence, in passing: There is no strong C IV emission line of the sort to be expected from a strongly magnified Seyfert galaxy nucleus. The implication is that we need not trouble ourselves with the Barnothy hypothesis mention above in section 1.)[16].(e) There's a missing link. In (c) a source QSO was proposed to explain the phenomena. But where is the lens L? Only a probabilistic calculation is offered. If we have a lens system, then there should be a;alaxy of such and such a mass, a galaxy from which A + B is very distant, and which lies close to the line of sight to A + B. A calculation on the relative frequencti of massive elliptical galaxies of the right size cannot yield any precise number but, "while such coincidences [alignment, mass, etc.] must be very rare, it is not out of the question that we should have one example in the 1,000 QSOs known".

11. Inference to the Best Explanation

This looks like a classic example of what philosophers, following Harman (196-5) have come to call inference to the best explanation. Philosophers divide on the merits of such a mode of inference as a ground for scientific realism, with Salmon (1984) in favor of it and van Fraassen [19] against. But Walsh et al. are not arguing about scientific realism. They are comparing the merits of two rival hypotheses (with a half-sentence dismissal of a third rival, the Sarnothy hypothesis). Contrary to Harman's original scheme of inference to the best explanation, we have no prior probabilities of the two hypotheses, A# B vs. A= B. We have only the following: if the former is true we have some unquantifiable but extremely unlikely coincidence. If the latter is true, a conjuncture of only modest improbability has been observed.

Inference to the best explanation is often traced back to C. S. Peirce and what he called the method of hypothesis (and also retroduction, abduction). In maturity Peirce did not think that the method of hypothesis gave ground for belief, but only for further investigation, testing, and induction. Unknowingly writing in the spirit of Peirce. note that "further observations Would sbcd light on the gravitational lens hypothesis".1~hey suggest, for example, that if the conjectured source has variable flux, we would see similar curves for A and B but with a time lag due to the different path lengths. Time lags are a matter of greatest interest, for people thought that one ought to be able to determine the Hubble constant from the time lag and hence estimate the rate of expansion of the univcrse. Naturally more commonplace investigations are also in order, namely the radio spectrum, and for some theorists, this has been the decisive factor.

12. Observational Confirmation of Lens I

After sixty vears of off and-on predictions of gravitational lensing, a real live candidate is quite exciting. A spate of checks followed. Somewhat confusing studies of radio spectra were immediate [2]. So ~i crc initial reports of the possible Iensing object itself [1]. A more extensive search of the field of the QSO for a lensing object used a series of deep red pictures and revealed a cery large cluster of galaxies(Young, Gunn et al. 1980). Young's group used a standard galaxy model and noted that a very large number of configurations of the galaxy would produce, ~henomena like those discovered in 19791980 that does emerge clearly is that the galaxycluster combination should make multiple images, and that there are several plausible ways to reproduce the observations. We regard the case for some of these to be very good." All the models involve some sort of galaxy-cluster, not something that can be represented by a point mass gravitational lens. This enables one to understand the confusing results of radio maps of A + B, for the imaging will be complex, and there is the possibility that the imaging galaxy is itself a radio source.

13. Dh A Happy Ending Good for Traditional Philosophy of Science?

I seem to have described an unusually felicitous example of scientific method. There is an overall conjecture of the sort that Popper would have called metaphysical: gravitational lenses exist. For sixty years, from 1919 to 1979, we lacked any instance of a gravitational lens. The conjecture remained unfalsifiable and therefore "metaphysical". Then in the spring of 1979 it was proposed that 0957 + 561 A, B is a gravitational lens. This was argued by an inference to the best explanation, that is, it provided ground for further inquiry. The conjecture entailed that there is a lens to be found. It also implied that there is variability in the ratio of flux between A and B. Intensive study corroborated these predictions. The existence of gravitational lens was confirmed and the hunt was on for more. Unfortunately, as we all know, things are never that simple in the forefront of a scientific inquiry.

14. Doubts: The Odd or Even Number of Images

I have, for practical reasons, chiefly addressed observational practice and issues. The best theoretical review essay is that of Paczynski [20]. In the next few sections of this paper I shall address a very few of the problems that arise when theoretical modeling clashes with observation. One concerns the number of images.

It was then observed that for a transparent spherical mass distribution, one would always obtain an odd number of images [21] ."Transparent" here means that almost all rays from the source pass through the lens. Thus a solid object (a star) or a black hole is excluded. This result readily generalizes to any detectable arbitrary mass distribution in a transparent galaxy. Here "detectable" means that the lens is not so massive that it is within its own event horizon5y.The argument is an elementary topological one. The conditions for a ray from S to be deflected by I, and perceived at 0 are that the difference between the radial vectors SL_I and L, 0 should be zero. This occurs only for saddle points (which give "inverted" images), and peaks (maxima or minima), and there must always be one more of the latter than the former.

Here then we have a characteristic "anomaly". What is going on? Here are a few suggestions [22]. (1) The missing images are too faint to be detected. (2) The lensing potentials may be far greater than those of ordinary galaxies, so that the two observed images are relatively close together, while other images are separated from these by a great angular distance, hence not deemed to be candidates for multiple imaging. (3) The galaxies may not be entirely transparent, with some raNs being absorbed by passing through the center of the galaxy, or actually being impeded by stars in the center of the galaxy. (4) The compact cores of galaxy potentials deamplify the missing images to the point of undo [actability. (5) Our lens may be being impeded by stars in the center of the galaxy. (6) Our lens may be a singularity, for example, a black hole or a cosmic string. With respect to this final case, Blandford and tiarayan show that "a point singularity (for example, a black hole) can sometimes be observationally distinguished from one with a long singularity (for example, a cosmic string) using the parities of the observed images". At present, none of these six possibilities, which all break down into sub possibilities, is compelling.

15. Doubts: the Scarcity of Lenses

Statistical considerations enter our story in several ways. There are tests of significance of the hypothesis that A, B is a pair of images, against the "null hypothesis" of a pair of similar QSOs. There is statistical treatment of lensing discussed in section 17 below. Then there is the fact that lenses are too infrequent. With the notable exception of Einstein, everyone from Zwicky on to the present has thought that gravitational lenses ought to be quite easy to find, and they certainly are not. This casts doubt at least upon our specific modeling. Hacking [4] discusses all these probabilistic arguments, and provides further information on the unexpected rarity of lens systems.

16. Models

Philosophers say precious little about models. Cartwright has perhaps the most extended discussion, and, following her, there is a brief discussion in my 1983 book. The latter uses "theories, models and phenomena" as one possible framework in which to think about natural science. It notes a simple reason for not regarding models as true-of-the-world, namely, that it is absolutely standard practice to use a number of different models in solving the same class of problems, even though the models are formally inconsistent with each other, if taken to be making literal assertions about the world. In short, one must be antirealist about models, which is not to say that "anything goes".

I suspect that there is no branch of natural science in which modeling is not more endemic than astrophysics, nor one in which at every level modeling is more central. We do hay e what in a rather strict sense of the word are properly called theories. We have general relativity. We have imported almost all of the theories of particle physics, in the way made celebrated by writers. Now of course the word "theory" is as open-textured as you will, and I could cite a goodly number of tokens of the words "the theory of the gravitational lens effect", for example. There is no grave impropriety in speaking of Friedman's or Lemaitre's or Robertson's or Walker's theory of the universe, but it is standard practice, and one reflecting good sense, to speak of Friedmann-Lemaitre models or Robertson-Walker models.[17,23]

The topic of gravitational lensing is typical, in respect of models, of much astrophysics. We have a gamut of models of increasing level of specificity, starting with a model of the universe, and ending with a model of 0957 + 561 A, B. Better: we have on the shelf a number of models of the universe, and at the level of Lens I we have many local models. This talk of a lot of models should trigger any antirealist instincts harbored in the reader's soul.

Before proceeding to a particular lens, let us consider a stage of modeling intermediate between everything and one thing. A recent paper will serve: "Self-Consistent Probabilities for Gracitational Lensing in fnhomogeneous Universes" This is not concerned with individual lenses, that is, not with single, isolated distributions of mass that do the lensing. It is rather in the tradition that considers the statistical distribution of lenses, alluded to in section 17. Far from being peculiar to the question of microlenses, it was discussed long before there "as any observational point in discussing giant or tiny lenses [23]. There is a problem about the distribution of lenses at large, succinctly stated by Ehlers and Schneider: gravitational lensing takes place only in a universe in which matter is clumped. However, no solution to the equations of General Relativity is known which is appropriate to describe such a clump)' unn-erse.

Dyer and Roeder dealt with the difficulty in a way typical of applied physics. The} invented a differential equation for the diameter of a bundle of light rays, using certain (by then) rather routine procedures connected with the Friedmann Lcmaitre model. Here are Ehlers and Schneider again, with their emphasis [21]:

Although this description of light progagation in a clumpy universe has not been derived by a perturbation approach or otherwise from General Relativity, but is based in a number of inorc or less Plausible ad ho, assumptions' these "Dyer Roeder distances" are usually applied to the gravitational lens equation, due to the lack of any more founded theory.

Dyer and Roeder did what physicists who are not Diracs do: the ~. Pretended that on a large scale a clumpy universe can be described by a FriedmannLem£itre metric, which agrees almost nowhere with any clumpy universe. (Almost nowhere means probability 0 on any reasonable topology.)[7]

Now Ehlers and Schneider are critical of DverRoeder distances. As they see it, the Dyer-Roeder formulae are taken blindly, plugged into a gravitational lens equation, and then consequences are cranked out. But in effect the consequences combined with the original Dyer and Roeder assumptions are inconsistent. Ehlers and Schneider therefore make the next move of the working physicist. Take the assumptions of Dyer and Roeder and the gravitational lens equation, and find solutions that are consistent with both. Now let's move down to something more specific, our familiar Lens 1. In sections ll and 13 [lraeed the following story. First 0957 +i61 A, B was proposed as a pair of images in a lens system, on the basis of the extreme coincidence of emission and absorption lines. Then Young et al. (1980, 198L) studied this pair in depth. One project was to identify the lensing object. Although their conclusions have not gone unchallenged, they did produce a plausible set of objects for the lens. Now new do the) think that this set, picked out of the swarm of objects, is the immediate part of space? Is it because this "galaxy cluster combination should make multiple images, and ... there are several plausible ways to reproduce the observations. We regard the case for some of these to be very good". That is the way it has to be, even in the most favored case of Lens I where we actually have a candidate for the lensing object. There are a number of models, mutually inconsistent with each other, and which collectively justify the assertion.

In constructing the family of possible models for the lenses proposed at present, one does not in general even use the differential equation for ray bundles derived by - Dyer and Roeder, or by Ehlers and Schneider. One uses plain old geometrical optics, with a paragraph explaining why this, although false in space, makes things simple and is not too misleading.

16. conclusion :

"To Save the Phenomena"

This famous expression, a translation from the Greek, has a literal meaning: to reconcile observed phenomena and a theory that they contradict. The reference was astronomy. The phenomena did not conform to motions calculated from celestial models. Phenomena and models were regularly reconciled by adding epicycles to the models.

During the seventeenth and eighteenth centuries the expression was to some extent adapted to other sciences, but with a change in verb. Making a pun on the Latin salve, one got "to solve the phenomena". Here "solve" retained the ancient sense of solving a problem in geometry (that is, making a construction). To solve the phenomena was to construct an empirically adequate theory. The solving and even the saving of phenomena then dropped out of common usage. There were revived in this century by philosophers, with Pierre Duhem's book To Save the P{renon7ena and a chapter of that title in van Fraasscn [19].The history of astronomy was very present to Duhem but not to van Fraassen. The latter holds that all science aims only at saving the phenomena, at empirical adequacy, at ability to derive observable phenomena don't imagine that science "aims" at anything at all, but if w e do use the metaphor, then it seems to me that most natural science aims more at manipulating and interfering with the world in order to understand it. Hence saving the phenomena seems an entirely subsidiary aspect of scientific activity. There is one, and perhaps only one, branch of science where the tag "to save the phenomena" has a central place: astronomy and astrophysics.

Astronomy did experience a fundamental technological change at the time of Galileo. The advent of the telescope is a change in kind of observation, compared to which all subsequent changes, aside from interplanetary exploration, are changes of degree Yet it left unaffected the method of astronomy: observation and modeling. The data and the analysis of data have undergone massive technological change. We observe phenomena different in kind from any imagined by Galileo: radio emissions and absorption lines, for example. No science is in such a state of flux as today's astro-physics, not even molecular biology.

Van Fraassen [19] is fundamentally in error when he holds that all science is a matter of empirical adequacy and saving the phenomena. He holds this erroneous view because, like almost all philosophers, he is totally theory-oriented, and thereby blind to experiment. Natural (experimental) science is a matter not of saving phenomena but of creating phenomena in the sense of my 1983 book (ch. 13). But in astrophysics we cannot create phenomena, we can only save them.

We believe in the reality of many entities postulated by theory because we can construct devices that use those entities in order to interfere in other aspects of nature, and to investigate the inner constitution of matter. People, it has been said, are tool-making animals. When we use entities as tools, as instruments of inquiry, we are entitled to regard them as real. But we cannot do that with the objects of astrophysics. Astrophysics is almost the only human domain where we have profound, intricate knowledge, and in which we can be no more than what van Fraassen calls constructive empiricists.

Eddington [14] used a few lines from Milton as his epigraph. Because my antirealism about astrophysics hinges on a doctrine of modeling, I may use them as my conclusion:

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