Foreword

Eddington is well known for his leading role in the 1919 eclipse expedition, whose results marked the beginning of Einstein's worldwide fame, and for making general relativity known to the English-speaking world. Nevertheless, Eddington's reputation has become somewhat tarnished, due to the unfavorable reception of his later work on "fundamental theory", which has been branded as speculation, and also due to doubts about the objectivity of his work defending Einstein. Regarding the latter, the criticism has first of all been that Eddington, a quaker opposed to nationalism, saw an opportunity to bridge the gap between Germany and its former enemies via the uniting force of international science and thus had a "political" interest in making a biased selection of the eclipse data so as to favor Einstein [3, 11].

In order to judge the case one should know its context and historical background—of which the book *Space, Time and Gravitation* and the other writings republished in the present volume are a central part. Eddington became acquainted with general relativity during the first world war when the astronomer de Sitter—from the neutral Netherlands—sent Eddington, at the time secretary of the Royal Astronomical Society, a number of papers on Einstein's theory. These papers kindled Eddington's interest, and in 1918 he wrote an account of the subject in his *Report on the Relativity Theory of Gravitation* [5]. In his preface Eddington explains why he was attracted to Einstein's theory: it rests on a small number of simple, elegant and universal principles, so that "it claims attention as one of the most beautiful examples of the power of general mathematical reasoning." This statement should be taken seriously: as we shall see, the love of deductive simplicity and elegance is a resounding motif in Eddington's work.

The *Report* was directed at physicists and mathematicians, but in 1920 Eddington followed it up with *Space, Time and Gravitation*, aimed at a wider audience. In this book, reproduced here, Eddington again explains general relativity, but now in a non-technical way, paying extensive attention to conceptual issues and stressing a wider philosophical perspective. Significantly, the book adds to the topics of the 1918 *Report* by including a chapter on the 1919 eclipse expedition.

When one reads *Space, Time and Gravitation* now, one is struck by its high level of sophistication, lucidity and technical competence. Its non-mathematical explanation of general relativity still remains an excellent introduction to the subject—even the connoisseur will encounter illuminating passages. As said, the book's emphasis is on the conceptual and philosophical side, and here one finds several highlights. One example is the Prologue, "What is Geometry?", in which Eddington discusses the status of physical versus mathematical geometry. The account brings to mind the similar one in Reichenbach's highly acclaimed *Philosophy of Space and Time*, which appeared seven years later. However, whereas Reichenbach concludes that physical geometry is conventional and considers the choice between different possible descriptions (with and without "universal forces") as basically arbitrary, Eddington argues that it is the task of physics to describe empirical phenomena without indulging in the addition of superfluous, empirically unsupported, theoretical structure; this fixes a natural geometry. In chapter III, *The World of Four Dimensions*, Eddington offers an account of how four-dimensional spacetime with its Minkowski geometry combines and objectifies all the different "here-and-now" points of view—with a philosophical sophistication one would not expect from a 1920 publication.

There are many other remarkable passages that testify to Eddington's insight, both regarding physics and its philosophy. In one of them Eddington briefly and elegantly analyzes the relation between dynamical and kinematical interpretations of the Lorentz contraction (with a small elaboration in the first Note of the book's mathematical Appendix)—an issue about which even today confusion persists (as shown by debates surrounding Bell's paper [2]). Another of the book's highlights is the discussion of the status of absolute rotation in relativity and of Mach's principle (Chapter X). This chapter could still be used as background reading in a class about relationism and substantivalism with respect to spacetime.

Not unexpectedly, Eddington devotes much space to the question of how light behaves in a gravitational field, as a prelude to his story about the eclipse expedition. The equivalence principle tells us that light *falls* under the influence of gravity, just as ordinary matter. But *exactly how much* will light be bent by material bodies? As Eddington explains in a way that is still enlightening, there are two general relativistic contributions to the effect: one due to a deformation of Euclidean geometry in the presence of masses, and one due to a gravitational effect on time. The magnitude of the latter had already been calculated by Einstein in 1911, a couple of years before the definitive general theory, and turns out to be equal to what Newton's theory of gravitation predicts under the assumption that light possesses mass. The total general relativistic effect is the sum of these two contributions and amounts to twice the value found with Newton's theory. This offers a possibility of putting general relativity to the test of experiment, for example by measuring the deflection of stellar light by the sun. As Eddington writes: "It is this particular test which has turned public attention towards the relativity theory. We shall therefore tell the story of the eclipse expeditions in some detail."

The story is told in Chapter VII. As in the research paper on the subject [4], Eddington here pays ample attention to the reasons that made him and his coworkers select the data as they did (e.g., not all photographs could be considered reliable, in view of a variety of specific circumstances) and to how he came to his conclusion that Einstein's theory accords better with the data than Newton's. This interpretation of the experimental findings by Eddington and his colleagues convinced the scientific community, and the results of the expedition were hailed as a victory of Einstein over Newton.

As already mentioned, it has been objected that the selection of data by Eddington *et al.* was arbitrary and the statistical analysis biased, so that the conclusion in favor of Einstein was not objectively warranted. But as a recent commentator observes, these "criticisms fail to deal with the observers' stated reasons for treating the data as they did, nor do they acknowledge that Eddington *et al.*, as trained professional astronomers, had extensive experience in determining the accuracy and self-consistency of a measurement. Further, the astronomical community, with similar levels of experience and skill, had ample opportunity to check and evaluate their work" [10, p. 88]; see also [1, 7, 8, 9]. Moreover, Eddington's letters to colleagues about his data analysis have been preserved and show how much he was aware of the danger of any *a priori* prejudice and that he took explicit measures to avoid falling into this trap [10, p. 78]. There is no reason to doubt Eddington's sincerity here.

It is an undeniable fact that Eddington employed Einstein's theory as a means to promote internationalism. But that does not imply that he was drawn to the theory because of its possible political implications; it is much more probable that the mathematical beauty and coherence, in addition to the universal scope of the theory, made a decisive impression on him (as we already have seen him declare himself).

In fact, mathematical unification and simplicity played an increasingly important role in Eddington's work. Already in *Space, Time and Gravitation* he expressed the belief that the general theory of relativity could be extended to become a Theory of Everything: a theory that would make it possible to understand the whole universe on the basis of very few simple principles. We should not forget that at this time the only forces that were known in physics were those of electromagnetism and gravitation. Now, in 1918 Hermann Weyl had published his famous gauge theory, which seemed to unite Maxwell's electrodynamics with Einstein's theory of gravitation. This extension of Einstein's theory (in which bodies undergo changes in length when they are transported through regions with electromagnetic potentials) is enthusiastically embraced by Eddington in Chapter XI of *Space, Time and Gravitation.* Even though he notes the objection that this theory entails that the dimensions of, e.g., electrons must depend on their histories, in apparent conflict with experience, the sheer beauty of the theory incites him to theoretical reflections in which we can recognize the outlines of his later "Fundamental Theory".

In Chapter XII Eddington expands these thoughts into a doctrine about "the nature of things". One of the ingredients of this philosophy is remarkably modern: it is the idea that science is only about "structure", namely about the network of *relations* between things, and never about the *essences* of things. Even if there are such essences, these fall outside the scope of science because they are not accessible to us—it is only through our *relations* to physical entities that we acquire knowledge. Similar structuralist ideas are presently a focus of debate in the philosophy of science. The second ingredient in Eddington's philosophy comes more directly from his reflections on relativity theory: it is the idea that matter is not a *cause* of spacetime relations, but rather a *symptom* of them. Usually an equation like $G_{\mu\nu} = T_{\mu\nu}$ is interpreted as saying that the stress-energy tensor of matter $T_{\mu\nu}$ has an effect on the structure of spacetime as expressed by $G_{\mu\nu}$. However, the equation can also be read in the opposite direction, as saying that "material" properties are only an expression of geometrical relations in spacetime.

This line of thought leads Eddington to the idea that the basic things in the world are geometrical: they are "events", in the sense of points in the spacetime continuum. Being elements in a continuum, mathematically speaking these events stand in infinitely many relations to each other. However, some of these relations are more stable and more physically significant than others; in particular, only certain relations generate (via the relation between geometry and matter explained above) stable and lawlike material patterns. Now, Eddington ventures, since we are material ourselves, it is exactly these stable relational structures that we as observers are part of and to which only we respond. In this sense, we ourselves are responsible for the selection of the lawful features of the universe. This idealistic motif explains the famous concluding paragraph of *Space, Time and Gravitation*: “We have found a strange foot-print on the shores of the unknown. We have devised profound theories, one after another, to account for its origin. At last, we have succeeded in reconstructing the creature that made the foot-print. And Lo! it is our own.” These thoughts are certainly bold and speculative—although it should be noted that there are similarities to modern “anthropic reasoning” about selection effects. But they also testify to Eddington’s relentless desire to *understand* things that usually are taken for granted.

Eddington forcefully propagated his ideas about the philosophical importance of relativity and took part in many debates on the subject. The present volume reproduces two examples of this activity, both brief contributions to discussions published in Nature in 1921. In the first, *The Relativity of Time*, Eddington once again displays his philosophical acumen, among other things by pointing out how deceptive our immediate temporal intuitions are: we think to be aware of a *global now*, but in reality this “global now” is not a matter of perception at all. This brief article is still relevant for contemporary philosophical discussions about the nature of time. In the second piece, *“Space” or “Aether”?*, Eddington continues his thoughts about space, or perhaps better “aether”—geometrical extension being its sole attribute—as the fundamental building block of everything that is physical. Of course, with hindsight this attempt at an all-encompassing Theory of Everything was too premature, and the same can be said of Eddington’s later Fundamental Theory. However, this was an honest attempt at understanding the astonishing mathematical order of nature, a theme that is certainly as topical today as it was in Eddington’s days.

Summing up, Eddington’s writings collected in this volume still provide an excellent non-technical introduction to Einstein’s general theory of relativity, with exactly the right amount of detail and concrete examples to give the reader real understanding. Furthermore, and importantly, *Space, Time and Gravitation* and the debates following its publication remain both a milestone in and an indispensable source for the history of relativity theory and its reception—and for the history of twentieth century theoretical physics in general.

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