THE REALITY OF THE UNOBSERVABLE

Observability, Unobservability and Their Impact on the Issue of Scientific Realism

Edited by

EVANDRO AGAZZI

Department of Philosophy,
University of Genoa, Italy

and

MASSIMO PAURI

Department of Physics (Theoretical Division),
University of Parma, Italy

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ROBERTO TORRETTI

'SCIENTIFIC REALISM' AND SCIENTIFIC PRACTICE

The adjective 'scientific' as used in the title of this lecture refers in the first place to modern experimental and mathematical physics; and to the other natural sciences insofar as they follow the lead of physics and thrive in its light. I do not place this restriction on the word in the context of this lecture because I hold other forms of learning in contempt as non-scientific. Far from it. However, the issues of "scientific realism" which are the subject of this conference do not rise outside physics and its near relatives. Thus, I have never heard a musicologist or a philosopher of musicology question the reality of Bach's "Well-Tempered Clavier", or of the Fugue in C minor in Book I, or of the main theme of that fugue. Nor do linguists and philosophers of language have any doubts regarding the pervasive presence of the genitive absolute in classical Greek.

The main question concerning realism in science is whether the nouns and pronouns used in scientific discourse name real entities or refer to 'constructs', i.e. to figments of the scientific imagination. But our self-styled "scientific realists" will not be satisfied by a straightforward acceptance of the former alternative, in the plain naive sense of 'real' applied to ordinary things, which the Romans called 'res' - whence 'reality' and 'realism'- and the Greeks called *pragmata*. They expect the objects of scientific knowledge to be real in a stronger sense than the things of everyday life, such as my two hands, or a red flavorful apple, which they take to exist, so to speak, on loan, as mind-dependent appearances of the really real. Scientific realists fondly trace their ancestry to Democritus, who wrote: "By custom, sweet; by custom, bitter. By custom, hot; by custom, cold. By custom, color. In truth: atoms and void."[1] The dependence on human life of the main features of common sense reality was eloquently proclaimed by Galileo at the dawn of modern science:

> I do not believe that anything is required in external bodies besides their size, shape, multitude, and motions, fast or slow, in order to excite in us tastes, odors, and sounds; and I think that if ears, tongues, and noses are removed, the shapes and numbers and motions will remain, but not the tastes nor the odors nor the sounds. Apart from the living animal, the latter-I believe-are nothing but names, just as tickling and titillation are mere names if the armpit and the skin lining of the nose are removed.
>
> (Galileo, *Il Saggiatore*, §48 [EN, VI, 350])

Galileo gave this Democritean doctrine a Pythagorean twist which remains central to the practice of modern physics: The Book of Nature, he said, "is written in mathematical language and its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word of it" (*Il Saggiatore*, §6 [EN, VI, 232]). Therefore, as one would say today, the really real can be adequately represented as a mathematical structure. Similar views were held by Descartes, who neatly imbedded them in his mind-body dualism. These early modern

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scientists were also devout Christians and they believed that God, like a Renaissance architect, had designed a geometric plan after which he had created the universe. Their science was bent on retrieving that plan. Pascal complained that the reduction of physical objects to "number, shape and motion" was "uncertain, useless and depressing", but that reduction was taken up by Locke in his widely read *Essay concerning Human Understanding*, and became a paradigmatic trait of scientific realism. Locke's book was the main butt of Berkeley, the founding father of antirealism, who vindicated everyday reality by showing that the abstract idea of colorless, insipid matter favored by the scientific philosophers was founded on and nourished by our ordinary experience of colorful and tasteful things. By conceding that the latter were indeed dependent on mind Berkeley turned Locke's "way of ideas" into grist for his spiritualist mill, but the very cleverness of this move made his vindication of common sense both equivocal and unpopular.

Today's "scientific realists" are, more often than not, materialists, and therefore closer to Hobbes than to Descartes, but, all the same, they remain frozen in a 17th century frame of mind. Paradoxically, they speak persistently of the reality of the *external* world, as if they were disembodied spirits contemplating it from the outside, and, for all their godlessness, they put forward a view of it that is only conceivable from the standpoint of an omniscient God. The cultural distance from "scientific realism" to late 20th century philosophy is so big that someone nurtured, say, in the writings of Heidegger and Wittgenstein and in the tradition of American pragmatism may well despair of converting a "scientific realist" to more sensible views, by reasoning. And yet in our own generation Professor Hilary Putnam has undergone such a conversion, moving - no doubt, on his own initiative and through his own ripening and deepening reflection on how matters stand - from a garden-variety version of "scientific realism" to what he calls, with emphatic pleonasm, 'pragmatic realism',[2] which agrees well with the position I take in this lecture. Still, I am afraid that what I can offer in the guise of argument will be seen by "scientific realists" more like a confession or manifesto, edifying and perhaps enjoyable for those who share my dubious background but decidedly allergenic and not at all cogent for those who don't.

"Scientific realists" believe that reality is well-defined, once and for all, independently of human action and human thought, in a way that can be adequately articulated in human discourse. They also believe that the primary aim of science is to develop just the sort of discourse which adequately articulates reality - which, as Plato said, "cuts it at its joints"[3] -, and that modern science is visibly approaching the fulfilment of this aim. I find it very hard to accept any of these statements or even to make sense of them. The existence of a well-defined or - as Putnam called it - ready-made reality is no doubt implied by the standard monotheistic conception of God, but I have not the slightest ground for thinking that God's worldview can be articulated in human discourse. To entertain the notion that we could convey that view in words is a symptom of acute provincialism. I contend, moreover, that scientific discourse is just the verbal aspect of scientific practice and has no serious justification apart from it; that this verbal aspect is no closer to the aim of science than, say, its manipulative aspects; that science does not have a primary aim but that with her, as with any other form of human activity, the distinction between means and goals is continually shifting from one context to another, so that any goal attained will, while in our possession, be used sooner or later as a means, while most means have at some stage been goals. From this perspective, science is, if I may say so, the continuation of common sense by other means, as required by the overall pragmatic situation. When I search for my car in a parking lot I bear in mind its visual appearance but do not once think about the photon exchange going on between the sun, the car's surface and my eyes. When I reflect about the origin and evolution of the universe I mix the car and myself and everything else up in a single homogeneous worldwide purée. And these two ways of articulating reality - as well as many others - are quite appropriate for finding our own way in it on different occasions and with different purposes.

Enough of generalities. A few examples drawn from past and present scientific practice will, I hope, clarify these ideas and substantiate my contention that it is pragmatic realism, not the nostalgic kryptotheology of "scientific realism", that best expresses the real facts of human knowledge and the working scientist's understanding of reality.

A familiar argument against realism in science runs as follows: *Premise One*: Any set of empirical data can be accounted for by many different physical theories (i.e. by embedding it in different mathematical structures). *Premise Two*: We may prefer the one that *we* judge simpler, or prettier, or easier to calculate with, but we have no grounds for believing that our preferences are shared by the Creator of the universe or, worse still, that they were followed when the universe was born by chance. *Conclusion*: If science aims at establishing the true structure of reality from empirical data it faces an impossible task. Premise One can be readily demonstrated in the case of the simplest theoretical task, namely, to fit a curve to a set of data about two correlated quantities: the data can then be represented by small rectangles on the plane and infinitely many different curves will go through any finite set of them, no matter how small and how densely packed they are. Presumably, the variety of admissible theoretical accounts will only increase as the data to be accounted for grow more complex. However, in real life such variety is somewhat utopian: even if it is a logical certainty that many incompatible theories might account for all the available data, as a matter of fact we do not know a single one which does. What we have are theories that account *in part* for some *specific* family of phenomena. And whenever there are two or more rivals in one field, effects soon appear which give the victory to one. Still, such choices, though in no way uncertain, are often based on considerations of beauty and expediency. For example, data cannot easily clash with a theory involving several adjustable parameters, such as Ptolemaic astronomy or some of the recent rivals of Einstein's theory of gravity. But the very fact that they have such flexibility is enough to damn them if there happens to be a rival theory without adjustable parameters which agrees with the data. This manner of choice is natural if we aim at understanding the reality at hand in the context of our life and practices, yet I do not see how one can be sure that absolute reality, as it is supposedly structured apart from human history and human interests, is not best described by one of those theories with adjustable parameters we so cheerfully discard.

Clark Glymour (1977) studied an interesting case in which the vacillation between divergent theoretical accounts of the same set of data does not result from the fuzziness of the latter and cannot be resolved by criteria of beauty or expedience. Though purely academic, this example is quite instructive. Suppose for a moment that Einstein's General Relativity is the true theory of the world. Glymour was able to prove that Einstein's field equations have alternative, *topologically incompatible*, solutions which are nevertheless *observationally indistiguishable* in the following precise sense: Let $<\mathcal{M}_1, g_1>$ and $<\mathcal{M}_2, g_2>$ be two models of General Relativity, where $\mathcal{M}_1$ and $\mathcal{M}_2$ are four-dimensional real differentiable manifolds and g_i ($i = 1,2$) is a solution of the Einstein field equations defined on $\mathcal{M}_i$ ($i = 1,2$). $<\mathcal{M}_1, g_1>$ and $<\mathcal{M}_2, g_2>$ are (weakly) observationally indistinguishable if, for each point $p_1 \in \mathcal{M}_1$ there is a point $p_2 \in \mathcal{M}_2$ such that the past of p_1 is isometric with the past of p_2.[4] Glymour proved that in some such pairs of observationally indistinguishable solutions of Einstein's field equations, the underlying manifolds are topologically distinct. Glymour's proof could be carried out rigorously and abstractly, without regard to a particular hypothetical distribution of matter, because there is a precise topological relation between the two manifolds involved, viz., either one of them is a covering space for the other, or they both have a common covering space.[5] Now, in a relativistic world all empirical data for the corroboration of scientific hypotheses must be fished out of the scientists' pasts.[6] Hence, if the world they happen to live is topologically distinct yet observationally indistinguishable from another one, they must remain forever undecided as to the overall shape of their world. If they are "scientific realists", bent on getting an overall, "God's eye" view of what they consider "the external world", such indecision is fatal to their epistemic ambitions. But it is a matter of complete indifference to the pragmatic realist who, as being-*in*-the-world, seeks to understand the reality at hand. As time goes on, some of his expectations, based on data culled from an earlier past, will be seen as deceptive, but only in the light of data obtainable from the now current past. Thus, for him, two observationally indistinguishable relativistic world models, though topologically inequivalent, could well constitute epistemically equivalent descriptions of one and the same reality. A difference, to be a difference, must make a difference.[7]

The antirealist tendencies among recent historians and sociologists of science draw their sustenance not from a *conceivable* disjunction of *imaginary* theories between which one could not decide because they would all be equally good, but from the *actual* succession of *real* theories most of which one already has decided against because they are not so good as the last. Inevitably the point is made that even the currently accepted theory is not good enough to be final and will in all likelihood be superseded later. The accurate theoretical representation of reality would thus be deferred for ever. Against this conclusion it has been argued that, although science never quite hits the truth about reality, it comes closer and closer to it. This idea of truth by approximation can be held in two versions: either we assume that reality stands there ready made outside the process of scientific research, which aims at finding the truth about it; or we conceive the true articulation of reality as the limit to which the succession of scientific theories converges, and which is constituted by this succession in the sense in which a real number is constituted by a Cauchy sequence of rationals. The second version is perfectly acceptable to the pragmatist - in fact it was put forward by Charles Saunders Peirce - but the "scientific realist" can only countenance the first. I shall not rehearse the arguments that have been made for and against either version.[8] Let us just consider an example which is as good a case of approximation as any one can think of and see what comfort the "scientific realist" can derive from it. Nobody will question that 19th century chemists got very good values for the atomic weights of many elements. Our own values are only slightly better. However, the quantities they measured are now understood very differently. They thought they were reaching for the mass of each indivisible part of each one of the ultimate elements of matter. We no longer think that the parts in question are really indivisible, even though, oblivious of Greek, we still call them 'atoms'. But, more importantly, we now understand that an atomic weight measured by 19th century methods is not usually the mass of a particular kind of atom, but the weighted average of the masses of several kinds of atoms with the same chemical properties, in the proportions in which those kinds (isotopes) are normally mixed in our environment. So, in our view, 19th century analysts measured very nearly *the right numbers*, but *not of the quantity they had in mind*.[9]

Thus the way that scientific theories succeed and displace one another provides strong grounds for doubting the scientific realist's belief that science is getting ever closer to achieving an adequate grasp of the self-subsisting, uniquely defined structure of reality. Moreover, it seems to me that - even if, for the sake of the argument, one grants that there is such an absolute structure- science as it is actually practiced is not in the business of looking for it. I gather this from the manner in which conceptually disparate theories are jointly brought to bear on the understanding of specific phenomena and the solution of particular problems. In order to make this clear I shall propose two examples. I take the first one from Hawking's celebrated letter to *Nature* on black hole explosions (1974).[10] Roger Penrose, Stephen Hawking and Robert Geroch proved in the 60's a series of remarkable mathematical theorems which imply that, under some physically very plausible assumptions, a relativistic spacetime will contain black holes, that is, regions in which the gravitational field is so strong that no matter or radiation can ever come out of them and all incident matter and radiation gets trapped. In the said paper Hawking studied what would happen if matter inside a black hole obeys the laws of (classical, non-relativistic) Quantum Mechanics. As is well known, these laws imply that a particle trapped inside a potential well generally has some finite chance of tunnelling through the barrier surrounding it. Such chancy tunnelling through potential barriers is the key to the quantum-theoretical explanation of radioactivity, which is conceived as the sudden causeless ejection of certain quanta of matter and radiation from the atomic nucleus to which they are normally bound. Hawking applied the same general idea to black holes and calculated the time it would take for a black hole of given mass m to evaporate completely. (If m is the mass of the Sun, the time in years is of the order of 10^{63}). It must be emphasized (i) that the notion of black holes arises in General Relativity and in accordance with this theory they do not exist in the flat Minkowski spacetime underlying Quantum Field Theory, let alone in the Newtonian spacetime underlying non-relativistic Quantum Mechanics; and (ii) that the Einstein field equations do not set up a quantized field, so that Quantum Mechanics cannot be regarded as a local approximation to General Relativity. Hence, if Hawking's move is judged from the standpoint of scientific realism, one must say that it was made on credit, using both General Relativity and Quantum Mechanics as inaccurate provisional partial substitutes for a future Quantum Theory of Gravity, which would consistently account for the existence of black holes and the way they evaporate. Of course science needs credit no less than other trades; indeed, some methodologists *require* new theories to issue promissory notes redeemable by forthcoming observations and experiments. But to grant credit to a future, as yet unstated theory, which two mutually inconsistent and, according to scientific realist criteria, plainly false theories are expected to approximate, is more than a sensible person can do. I think, therefore, that Hawking's practice cannot be understood in terms of scientific realism, but should be seen simply as what it claimed to be, namely, the solution, based on the most suitable theories at hand, of a problem posed by black hole research (specifically, by the attempt to assign a temperature to black holes).[11]

Hawking's work on evaporating black holes makes my point very clear because it combines disparate theories, I dare say, outrageously. But scientific realists might question its relevance because the very assumption that Hawking's study has a referent - i.e. that there are black holes - rests even today on somewhat flimsy evidence. I shall therefore turn to another example which, though less extreme than the former, concerns an object whose reality is beyond doubt, namely, the planet Mercury and its motion. According to Newton's theory of gravity if Mercury were alone with the Sun it would trace over and over an ellipse of given size and eccentricity having the center of gravity of the Sun-Mercury system at one of its foci. With some abuse of language, I shall refer to this ellipse as Mercury's Keplerian orbit. As a matter of fact, Mercury's trajectory deviates slightly but consistently from its Keplerian orbit. Relatively to the geocentric system of polar coordinates used in observational astronomy, Mercury's perihelion advances each year by somewhat less than 1 minute of arc (close to 56″). Almost 90% of this advance can be explained by the general precession of the equinoxes and is thus due to the choice of a geocentric coordinate system. But, according to Newton's theory, the remaining 10% must be due to gravity. The greatest part of this - some 5.3″ per year or 530″ per century - was accounted for by the perturbational methods of classical celestial mechanics as a result of the gravitational interaction between Mercury and the other planets. However, there still remained a small yet inescapable balance of approximately 43″ of arc per century which never was satisfactorily accounted by Newtonian theory. On December 24, 1907, Einstein wrote to Conrad Habicht that he was working on a relativistic study of the law of gravity through which he expected "to explain the still unexplained secular variations in Mercury's perihelion".[12] The main motivation for this study was, of course, not this small astronomical anomaly, but the open clash between the theory - now known as Special Relavity - that Einstein introduced in 1905 to account for the electrodynamics of moving bodies, and Newton's theory of gravity, which, for good reason, was then acknowledged by everyone, including Einstein, as the most successful theory of physics.[13] As is well known, in Newton's theory gravitational influence propagates instantaneously throughout infinite space, whereas in Special Relativity no information can travel faster than light. Einstein's quest for a theory of gravity ended in November 1915, when in four hectic weeks he communicated to the Prussian Academy three different theories. The weekly succession of theories was interrupted on the third week of November when he derived the unexplained part of Mercury's perihelion advance from an approximate solution of the field equations proposed in the second week.[14] What we now know as the Einstein Field Equations of General Relativity were communicated in the fourth week, but, though they differ both in their mathematical shape and their physical meaning from those of the second week, they agree with them on empty space, through which planets are supposed to travel, and so they inherit from them the third week's solution of Mercury's anomaly.[15] Indeed, the first exact solution of the Einstein Field Equations, independently reached by Schwarzschild and by Droste early in 1916, fully confirmed the solution of the anomaly and has thereafter been regarded as one of the "three classic tests" of General Relativity. In order to see how this test works, we must recall that in General Relativity gravity is conceived as a property of spacetime analogous to the Gaussian curvature of ordinary surfaces, governed by the spacetime Riemann tensor. Test particles - that is material particles so insignificant that they contribute nothing to the gravitational field - follow spacetime geodesics. The Einstein Field Equations sport on one side the Ricci tensor, formed by contraction of the Riemann tensor on two pairs of indexes, and on the other side a tensor built from the stress-energy tensor representing the spacetime distribution of matter. In the absence of matter, Ricci = 0. Mercury's anomaly is overcome by because the very assumption that Hawking's study has a referent - i.e. that there are black holes - rests even today on somewhat flimsy evidence. 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Suppose then that the spacetime metric is spherically symmetric in space and that Ricci = 0 everywhere outside a small region surrounding the axis of symmetry. The Einstein Field Equations can then be solved exactly. The solution, which involves one constant of integration usually denoted by $2m$, is defined everywhere except on the field's axis of symmetry.[16] If one equates m with the mass of the Sun, a test particle moving through empty space with Mercury's speed at Mercury's distance from the axis of symmetry will have a spatial trajectory very similar to Mercury's Keplerian orbit (with the axis of symmetry at one of its foci), but which will differ from that orbit insofar as the point where it comes closest to the field's axis of symmetry advances on every turn at a rate of 43″ per century. Thus, the secular precession of Mercury's perihelion, unaccounted for in Newton's theory of gravity, is seen to follow from Einstein's. But please note how this result is achieved. Mercury, a chunk of matter about as dense as the Earth, bounded by a surface as least as large as that of Asia and Africa put together, is conceived as a particle of negligible mass, whose presence and motion do not in the least affect the perfect symmetry of space. This streamlined Mercury, suitably placed in the gravitational field of the lonely Sun, will, in accordance with Einstein's theory, display the unexplained perihelion precession of 43″ per century, but not, of course, the precession of 530″ per century that Newtonian celestial mechanics derived from Mercury's gravitational interaction with the other planets. In the symmetric Schwarzschild field, besides the source at the axis of symmetry, we meet only test particles which, by definition, cannot act on each other. And of course, neither Einstein, nor Schwarzschild, nor Droste, were in a position to even approximately solve the Einstein Field Equations for a 10-body system.[17] In their solution of Mercury's problem the relativists simply ignored the 530″ secular precession because they took for granted that, under the circumstances, this can be accounted for by Newtonian theory, and they could safely assume that a relativistic theory of the whole solar system would, if available, yield predictions agreeing with the Newtonian predictions within an acceptable margin of error. Now, a scientific realist can feel perfectly comfortable with such an arrangement if he assumes that General Relativity is the final physical theory of everything. It is then permissible, from his point of view, to describe Mercury's motion by using first Schwarzschild's idealized model because Mercury is negligibly small, then the Newtonian approximation because the contribution of the other planets to the gravitational field is sufficiently small (though, obviously, not negligible), and adding up the results. But if General Relativity is not the final theory the example of Mercury's motion does not differ essentially from my previous example of evaporating black holes: an otherwise unmanageable problem is solved within a margin of imprecision consistent with observational error by bringing to bear on it two conceptually very different theories, irreconcilable in God's eye, none of which can be true of reality in the strong scientific realist's sense.

I have given two examples from the one area of physics to which at one time I devoted careful attention, but I feel sure that similar examples can be found in other areas. In particular, experimental results notoriously depend for their interpretation on the theories involved in the design of the several pieces of equipment employed in the experiment; these are usually old theories, different from and ultimately incompatible with the frontline theory which the experiment is meant to test. Indeed, some methodologists believe that it is viciously circular to test a theory with instruments designed in the light of it. I don't think they are right, but as a matter of fact new theories are being continually tested with equipment built according to older theories that those new theories undercut. The scientific realist may indeed assume that the entire experiment can be satisfactorily reinterpreted in terms of the new theory, but once again this is to live on credit. The pragmatists, of course, do not need to feed on fanciful expectations and can make do from day to day with what is really there, because they readily accept that physics, like every other major human enterprise, is a patchy, makeshift affair.

University of Puerto Rico
Puerto Rico

NOTES

[1] Democritus, fr. 9, fr. 125. Translated by David Furley 1987, p. 177.

[2] Cf. Putnam 1987, p. 17: "The key to working out the program of preserving commonsense realism while avoiding the absurdities and antinomies of metaphysical realism in all its familiar varieties (Brand X: Materialism; Brand Y: Subjective Idealism; Brand Z: Dualism...) is something I have called *internal realism*. (I should have called it pragmatic realism!) Internal realism is, at bottom, just the insistence that realism is *not* incompatible with conceptual relativity."

[3] *Phaedrus* 265e1.

[4] This definition of weak observational indistinguishability is due to Malament (1977). The relation thus defined is not symmetric. To ensure symmetry, Glymour's original definition of observational indistinguishability is stronger. For observers who must decide on the basis of available data which of two topologically incompatible models of General Relativity represents their world, it makes no difference whether the relation is symmetric or asymmetric: the decision is not possible if the universe they happen to be in is weakly observationally indistiguishable from the other.

[5] Let A and B be two topological spaces. A is a *covering space* for B if there exists a *covering map* $f: A \rightarrow B$, i.e., a *continuous mapping of A onto B* that meets the following condition: every point $p \in B$ has an open neighborhood U whose inverse image $f^{-1}(U)$ is a union of disjoint open sets of A, everyone of which is mapped homeomorphically onto U by f.

[6] For the sake of mathematical expediency, Glymour's proof concerns the so-called *chronological* past of the points in question, which comprises, for any given point p, every point to which one can go from p along a past-directed timelike curve. Of course, the source of empirical data available at a point p is contained in p's *causal* past, i.e the set of points to which one can go from p along past-directed timelike *or* null curves.

[7] The following far-fetched but very simple example shows what is at stake here. Think of Nietzsche's fantasy of eternal return. We may assume that Nietzsche's world was spatially Euclidean. What shape should we ascribe to his spacetime? It is either topologically equivalent to $\boldsymbol{S} \times \boldsymbol{R}^3$, with each one of us going through the same events again and again; or topologically equivalent to $\boldsymbol{R}^4$, with each one of us living infinitely many distinct but indistinguishable lives. Pragmatically there is no difference between these two descriptions. (Note that $\boldsymbol{R}^4$ is a covering space for $\boldsymbol{S} \times \boldsymbol{R}^3$).

[8] See, for instance, Laudan 1984, Kitcher 1993. Two recent case studies by Psillos (1994, 1995) tend to undermine the main argument of Laudan's "confutation of convergent realism", viz. that respectable scientific research programs have in the past assumed the existence of such non-entities as the caloric fluid or the optical ether. However, in view of the growing compartmentalization of human knowledge, only a strong dose of animal faith can lead anyone to expect that the many disparate forms of understanding and inquiry which are alive today are actually converging.

[9] Likewise, I am quite confident that five hundred years from now current measurements of the microwave background radiation will be regarded as excellent approximations, to whatever decimal we now think has been reached; but I am not so sure that the interpretation of that phenomenon as a remnant of the very hot, very dense universe of current cosmology will be still accepted and will not have been displaced by a drastically different conception.

[10] See also Hawking 1975, 1976, and his article in the *Scientific American* (1977).

[11] This is how this problem is described by Hawking and Israel (1979, pp. 17-18):

"...the area of the event horizon of a black hole has the property that it can only increase and not decrease with time. This led Beckenstein in 1972 to suggest that it might be connected with the thermodynamic quantity, entropy, which measures the degree of disorder of a system or one's lack of knowledge of it. He pointed out that the 'no-hair theorem' implied that a very large amount of information about a star was irretrievably lost when it collapsed to form a black hole and he claimed that the area of the event horizon was a measure of this unobservable information which could be regarded as the entropy of the black hole. Other analogies between classical black holes and thermodynamics were found by Bardeen, Carter and Hawking (1973) but there was an apparently insurmountable obstacle to attributing a finite entropy to a black hole because that would imply that it should have a finite temperature and should be able to remain in equilibrium with thermal radiation at the same temperature. However this seemed impossible because the black hole would absorb some of the radiation but, by its very definition, it would not be able to emit anything in return. The paradox remained until Hawking (1974) discovered that applying quantum mechanics to matter fields in the background geometry of a black hole metric led to a steady rate of particle creation and emission to infinity. The emitted particles would have a thermal spectrum with a temperature proportional to the surface gravity of the black hole, which is a measure of the strength of the gravitational field at the event horizon and which is inversely proportional to the mass. This emission would enable the black hole to remain in equilibrium with thermal radiation at the same temperature."

[12] Einstein, GP 5, 82.

[13] In 1913, speaking to the 85th *Naturforscherversammlung* in Vienna, Einstein said that Newton's "laws of gravity and of the motion of heavenly bodies... have proved to be so exactly right that, from the standpoint of experience, there is no decisive ground for doubting their strict validity" (Einstein 1913, p. 1249). Giulio Maltese and Lucia Orlando (1995) draw attention to another, presumably stronger motivation for General Relativity, viz. the difficulties met in developing a general, consistent description of accelerated frames of reference in the context of Special Relativity.

[14] For a detailed analysis of Einstein's explanation of Mercury's perihelion advance, see Earman and Janssen 1993.

[15] I write down here the two sets of field equations for comparison:

$R_{ik} = -\kappa T_{ik}$ (11 November 1915)

$R_{ik} = -\kappa (T_{ik} - {}^1/_2 g_{ik} T^s_s)$ (25 November 1915).

Obviously, both sets of equations imply that $R_{ik} = 0$ wherever $T_{ik} = 0$.

[16] In the polar coordinates (r,φ,θ,t) used by Schwarzschild, the solution is also undefined on the hypersurface $r = 2m$ (if the units employed are such that the gravitational constant equals 1). However, this singularity can be eliminated by using other coordinates and is thus inessential. The singularity on the symmetry axis $r = 0$ is essential.

[17] I have taken the standpoint from which Einstein and his contemporaries could maintain in 1916 that Mercury's precession anomaly had been solved. Today one calculates the trajectories of a system of slowly moving particles, bound together by gravitational interaction, like the sun and planets, by means of the so-called parametrized post-Newtonian or PPN formalism. This is a method of approximative calculation which is neutral between several chronogeometrical theories of gravity, yielding the predictions of a particular theory when certain parameters are adjusted in a prescribed way (see the table in Will 1981, p. 117). General Relativity puts two of these parameters equal to 1 and the others equal to 0, but this privilege could be due to the fact that the PPN formalism stems from work done by Einstein and his collaborators on that very theory, in quest of a derivation of its equations of motion. As the term 'formalism' indicates, the PPN formalism is not meant as a conceptual framework for the *understanding* of phenomena and does not pose as a contribution to the "scientific world-view".

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