Laws of Physics and the Universe

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1. Introduction

Are the laws of nature real? Do they belong to the world or merely reflect the way we speak about it? And if they are real, what sort of entity are they?

These questions have been intensely debated by philosophers. Modern cosmology, however, has given such questions a new twist by introducing a unique perspective on physical reality, the perspective which I shall call the *cosmological point of view*. In this perspective, the universe as a whole presents itself as a single individual entity that undergoes a radical change with time. Laws of physics, on the other hand, have both local and global significance. They characterize how things behave locally. But they also characterize the entire universe. This suggests an interesting connection between the universe as a whole and what laws of physics hold in this universe. From the cosmological point of view, these two totalities, the laws of physics and the universe, may be related. But how exactly? Are the laws "inscribed" in the fabric of the universe or do they in some sense "precede" it in the order of being? If the latter, what is a "medium," over and above the physical universe, in which physical laws are "written"? If the former, are they but a consequence of the universe's very existence? And if so, how could the laws of physics survive the dramatic change the physical state of the universe underwent in the course of time?

In this paper, I argue that questions of this sort have played a significant role in the history of twentieth-century cosmology. They were, in particular, critically involved in the battle between the big bang and steady-state theories in 1948–65. As is well known, the steady-state cosmological model lost this battle. But a concern of the proponents of that model about the status of physical laws in a changing universe has survived the model itself. To set a case study in the steady-state theory in a relevant context, let

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me first indicate what sort of implications the cosmological perspective on laws may have in contemporary evolutionary cosmology.

2. Cosmology and History: Laws of Nature in the Evolutionary Perspective

The concept of physical law has traditionally been regarded as an essentially *atemporal* notion. The very idea of lawfulness seems to presuppose the independence of the *nomic* (lawful, pertaining to laws) characteristics of objects and systems of time. All physics, however, is performed on a stage that, taken as a whole, undergoes change. The time of cosmology is, in fact, the time of *history*. Because of its global character, cosmological evolution comprises everything that exists. And if "everything that exists" involves physical laws, should they be *a priori* excluded from the evolutionary perspective?

The idea that laws of nature may not represent absolutely immutable aspects of reality but undergo change is highly controversial. Yet it has been entertained at one time or other by an appreciable number of scientists and philosophers, although few of them have gone beyond mere conjecture and bothered to give a sufficiently clear account of what they meant by evolving laws. Among the advocates of the mutability of laws, one finds such diverse thinkers as Charles Sanders Peirce and Alfred North Whitehead. They were led to the idea by rather different considerations, but their common ground is found, as one can expect, in the broadly evolutionary worldview, which has made its way into various scientific disciplines in the last two centuries.

Peirce developed his views on the matter in a number of works written towards the end of the nineteenth century. His main concern in thinking about laws and lawhood was primarily epistemological. The idea that laws may evolve was a direct consequence of his belief that laws and regularities in nature require special explanation and that no explanation of laws is possible except a historical one:

> The only possible way of accounting for the laws of nature and for uniformity in general is to suppose them results of evolution. This supposes them not to be absolute, not to be obeyed precisely. It makes an element of indeterminacy, spontaneity, or absolute chance in nature. . . . Law ought more than anything else to be supposed a result of evolution. (Peirce 1956, pp. 162–163)

Whitehead, on the other hand, based his reflections on ontological rather than epistemological grounds. In his discussion of this topic in *Adventures of Ideas*, Whitehead (1933, p. 142) distinguished among what he believed to be the four prevalent contemporary doctrines concerning the laws of nature: the "doctrine of law as immanent," the "doctrine of law as imposed," the "doctrine of law as observed order of succession," and the "doctrine of law as conventional interpretation." Although Whitehead did not make it clear in *Adventures of Ideas*, his sympathies rested with the "doctrine of law as immanent," which is consistent with the all-embracing evolutionary view of nature, *process philosophy*, created and developed by him during the later stages of his philosophical career. Immanence of laws means, in this doctrine, their inherence in real properties and mutual relations of things. Common patterns of such relations exhibit themselves as laws of nature. One consequence of such an interpretation is that,

> since the laws of nature depend on the individual characters of the things constituting nature, as the things change, then correspondingly the laws will change. Thus the modern evolutionary view of the physical universe should conceive of the laws of nature as evolving concurrently with the things constituting the environment. Thus the conception of the Universe as evolving subject to fixed eternal laws regulating all behaviour should be abandoned. (Whitehead 1933, p. 143)

Organic and even social analogies played a major role in Whitehead's view of physical nature. As he observed in *Science and the Modern World*, "the laws of physics are the laws declaring how the entities mutually react among themselves" (Whitehead 1967, p. 106). Relations among fundamental physical entities are partially determined by their "environment," and if the latter undergoes a drastic enough modification, it is only natural to suppose that properties and relations of basic constituents and, hence, the laws of nature may also change.

> The assumption that no modification of these laws is to be looked for in environments, which have been observed to hold, is very unsafe. The physical entities may be modified in very essential ways, so far as these laws are concerned. . . . According to this theory the evolution of laws of nature is concurrent with the evolution of enduring pattern. For the general state of the universe, as it now is, partly determines the very essence of the entities whose modes of functioning these laws express. The general principle is that in a new environment there is an evolution of the old entities into new forms. (Whitehead 1967, pp. 106–107)

It should be noted that neither Peirce nor Whitehead, in their philosophical reflections on physical laws, referred to any particular scientific evidence of the day or explained how the idea of the evolution of laws could square with the available evidence favoring their essential immutability. This is not to say that these great philosophers were not familiar with the state of contemporary science. They most certainly were, and in the case of Whitehead, one can speak of a rather close, indeed first-hand, acquaintance with the most recent physical theories. The point is rather that Peirce's and Whitehead's conjectures concerning the evolution of natural laws were rooted in their respective *philosophical* cosmologies, not so much in their particular scientific beliefs.

Philosophical cosmologies of the evolutionary kind developed at the end of the nineteenth and the beginning of the twentieth centuries by such philosophers as Peirce, Henri Bergson, Whitehead, Samuel Alexander, Pierre Teilhard de Chardin, Jan Smuts and others were, however, themselves inspired, to a considerable extent, by contemporary scientific developments and cannot be adequately understood in abstraction from them. The philosophical style characteristic of the above mentioned thinkers more easily gives rise to broad extrapolation than rigorous scientific reasoning, which is always constrained by concrete empirical evidence. In this particular case, the organic model of development was taken to be the paradigm of any evolutionary process, including the realm of non-living physical matter. Nothing in the physics of the day suggested that such an extrapolation should be taken seriously. Subsequent progress of physical sciences, too, did not give much support to a global evolutionist perspective on physics. It was not until the 1970s, when the stage was set for a remarkable synthesis of fundamental physics and cosmology of the early universe, that physics began to assume a truly historical dimension. The idea that the temporal career of the universe may include not only the history of matter but also the history of its basic properties, which figure in the laws, is largely a product of this interplay between particle theory and cosmology in their joint effort to probe the physics of the very early universe.

This physics now includes symmetry breaking phase transitions in unified gauge theories, the transitions apparently changing the nomic properties of certain elementary particles, for example, the masses of the intermediate vector bosons responsible for weak interactions. Cosmological considerations suggest that such transitions may have occurred in the real history of the universe, as it cooled down from its initial hot state. We live in a low-energy epoch ($T \approx 3$K) with a broken symmetry between electromagnetic and weak interactions. Because of this, the photon is massless whereas the masses of $W^{\pm}$ and Z^0 bosons are not zero. But one has only to warm up the cosmic substratum to approximately 10^2 GeV (i.e., 10^{15} K), and the broken symmetry will be restored, and the masses of all bosons will vanish. In the history of the universe, the inverse process of separation of the electromagnetic and weak forces may have occurred at about 10^{-10} s after the big bang, and a similar process of separation of the strong force may have been operative at a still earlier epoch ($t \approx 10^{-35}$ s) corresponding to the energy 10^{14} GeV (i.e., about 10^{27} K). The scenario features, in Steven Weinberg's words, a "parallel between the history of the universe and its logical structure" (Weinberg 1977, p. 149). This expression is a bit misleading, for the universe does not have a "logical" structure. What Weinberg has in mind is its *nomic* structure. The idea is that if the material structure of the universe undergoes dramatic enough change, its nomic structure may not escape being influenced by this change.

Some physicists recognized the importance of a historical perspective on physics quite early in the process. Thus at the celebration of the hundredth anniversary of MIT in 1961, Richard Feynman conjectured that physics may develop a historical outlook and become deeply concerned with the "studies of astronomical history and cosmology": "There is at least the possibility that the laws of physics change with time, and if [so] . . . it is very likely that physics is enwrapped in the cosmological problem" (the quotation kindly provided by Sam Schweber, personal communication).

Feynman reiterated the same conjecture in his famous lectures:

> There is another *kind* of problem in the sister sciences [i.e., in biology, geology, and astronomy] which does not exist in physics; we might call it, for lack of a better term, the historical question. How did it get that way? . . . There is no historical question being studied in physics at the present time. We do not have a question, "Here are the laws of physics, how did they get that way?" We do not imagine, at the moment, that the laws of physics are somehow changing with time, that they were different in the past than they are at present. Of course, they *may* be, and the moment we find they are, the historical question of physics will be wrapped up with the rest of the history of the universe, and then the physicist will be talking about the same problems of astronomers, geologists, and biologists. (Feynman et al. 1963, pp. 3–9)

Biological analogies were used by other authors to illustrate the basic idea behind the historical view on physics. Yoichiro Nambu put the matter thus:

> In a more serious vein, one could ask whether the laws of physics are intimately bound up with the evolution of the universe, influenced not only by the initial conditions, but also by the subsequent evolutionary processes

> themselves. In a way I am suggesting biological evolution as a possible model for physical evolution.
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> One would have to be more specific, however, so let me entertain the idea that the term “generation” means more than just an analogy. Is it at all possible that the generations of quarks and leptons have “evolved” one after another in some sense, that each generation is “born,” so to speak, at the corresponding energy (or length) scale of an expanding universe, its properties being influenced, but not necessarily deterministically fixed, by what already exists?
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> Biological evolution is made possible by the vast degrees of freedom residing in complex molecules. If translated to particle physics, this might again bring back the compositeness issue. Are lower mass generations more complex than the higher ones? This is hardly likely although the opposite might be true. So what I should mean would be that the constants like mass are really dynamical quantities that were selected, with some degrees of chanciness, from among other possibilities in the course of the universal evolution. (Nambu 1985, pp. 108–109)

Walter Thirring recently took a similar position with regard to the laws of physics and their hierarchical order. The laws of an upper level, he maintained, may not be completely determined by the laws of a lower level and may, in a sense, present a “purely accidental fact” when looked at from the lower level, because the upper-level laws depend not only on the lower-level ones, but also on the particular historical circumstances. In this way, “the hierarchy of laws has evolved together with the evolution of the universe. The newly created laws did not exist at the beginning as laws, but only as possibilities” (Thirring, as quoted in Schweber 1997, p. 185).

The physicist and historian of physics Silvan Schweber takes the fact that “the notion of a natural selection of physical laws is being discussed in the most respectable fora of physics, astrophysics and cosmology” as an indication of the “changing metaphysics of physics” (Schweber 1997, p. 186).[1]

Enthusiastic as these views are, a word of caution is in order, because what is manifestly lacking in them is a serious analysis of the coherence and plausibility of the idea of nomic evolution.[2] But the fact that the idea is making its way into physics is notable. On the other hand, the fact is hardly surprising. If the laws of nature are real, they belong to the furniture of the world. From the cosmological point of view, the holding of particular laws in the universe can be considered as its basic property characterizing the kind of being the universe is. And if most, perhaps even all, of its other global properties undergo change in the process of evolution, should the laws be necessarily regarded as an exception?

One party's *modus ponens*, however, is another party's *modus tollens*. The above reasoning can be turned on its head. If there is, indeed, an interdependence between the structural properties of the universe and physical laws acting in it, then one might claim that the *permanence* of the latter requires, for its justification, the constancy of the former. This idea was instrumental in the emergence and development of the steady-state theory of the expanding universe (SST) put forward in 1948 by three Cambridge physicists, Hermann Bondi, Thomas Gold, and Fred Hoyle, as a principal alternative to the big bang cosmology.

3. Steady-State Cosmology: How a Scientific Failure Can Be Valuable

According to SST, the expanding universe, instead of evolving from the hot big bang, is stationary on the large scale. The dilution of matter due to the cosmic expansion is compensated for by the creation of new matter, and any other global process operative in the universe is regarded as being self-perpetuating. All evolutionary effects are thus merely local and no distinction between past, present and future can be made for the universe at large.

The 1964–65 discovery of the microwave background radiation, soon afterwards identified by the majority of cosmologists as relic of the hot big bang, effected a crushing blow to SST. As early as the 1950s, after recalibration of extragalactic distances, the pressing time-scale problem that afflicted the standard cosmology for more than two decades[3] had been taken off the agenda. The prevalent opinion was that there no longer existed any necessity for SST. One rarely reads about SST any more in textbooks.[4] In this view, SST looks like an awkward accident in the history of modern cosmology.

The case of SST raises an important question of the value of scientific failure, important from the points of view of both historiography and philosophy of science. It should be noted that even in its best days SST had far more opponents than advocates. It was often regarded as a good example of what a scientific theory should *not* be (see, e.g., Bunge 1962). But SST was the real mainspring of cosmology in the 1950s. To be convinced of this, one need only have a cursory look at the cosmological literature of the time. The mere presence of SST forced many astronomers and astrophysicists to invest a considerable amount of effort in observational and theoretical work for the purpose of refuting it. Its advocates, however, fought their case with persistence and ingenuity. It can be seen, in retrospect, how much benefit cosmology on the whole has gained from this controversy. At least two remarkable achievements, the theory of stellar nucleosynthesis and the development of radio astronomy, were directly stimulated by SST. In its initial stage, the idea of stellar nucleosynthesis showed a way to account for the observable abundance of chemical elements without recourse to a hot state in the remote past of the universe. That prompted Hoyle to work on this program. By an irony of fate, this contribution was later to become a part of the rival big bang cosmology. First counts of radio sources, on the contrary, gave strong promise of disproving SST. It is not at all obvious that these and some other achievements would have been made so rapidly if there had not been an SST to be defeated.

It proved, however, to be not so easy to defeat SST. The theory "died" several times, but invariably came back to a new life. This is not surprising. Cosmologically significant astronomical data being scarce and contradictory in those days, the general desire to refute SST quickly often led to hasty conclusions that were abandoned later on. In such circumstances debates moved to essentially theoretical issues. The parties were forced to resort to foundational arguments, and this is what makes the history of SST philosophically interesting.

The competition between SST and standard relativistic models in the 1950s was no less important for molding cosmology, as a scientific discipline with its particular methods, than were the discussions provoked by the ideas of Edward Milne, Arthur Eddington, and Paul Dirac in the 1930s.[5] In both cases disagreement about conceptual issues grew into controversies about foundational principles of science in general. It is still more important for the purpose of the present essay that a concern about the way in which the laws of physics relate to the universe as a whole played a vital role in the origin and development of steady-state cosmology. Various aspects of the relationship between the global properties of the universe and physical laws were explored both by the advocates of SST and by their opponents. Some of the questions they raised in this debate add new dimensions to the general concept of a law of nature.

My reconstruction of the early history of SST focuses on such questions.[6] I begin by recapitulating the two original versions of this theory (Bondi and Gold 1948; Hoyle 1948, 1960). First of all, however, I want to identify their common conceptual precursor. This precursor, I think, is to be found in a certain scientific school, the advocates of which were the first to argue explicitly that the methodology used in a science dealing with large-scale evolutionary processes cannot be independent of the particular resulting pattern of the historical unfolding of our actual world. This tradition is known as *uniformitarianism*.

4. Uniformitarianism as a Methodological Principle

Both cosmology and geology belong to what Whewell dubbed "palaetiological" sciences, which are concerned with events that happened in the remote past. The general problem of uniformity is common to all such sciences, though the particular form it takes depends on the context. No satisfactory explanation of the present state of the Earth, or of the universe, can be attained without inquiring into the former's geological, or the latter's cosmological, past. But obviously one has no direct observational access to either. Invoking hypotheses about the past is thus unavoidable in palaetiological sciences. Different schools of thought, however, hold divergent views about what kinds of hypotheses are admissible here.

The basic tenet of the uniformitarian school was that, unless the past of a global system under study is in some important way similar to its present, the freedom involved in hypothesizing about the former is so great that no genuine science of the system at hand is possible. A historically relevant interpretation of the basic uniformitarian requirement admits at least two senses of "similarity" sometimes blended together. In the weak sense, one can require that the *kinds* of processes at work in the geological past of the Earth be the same as at present. Put differently, this weak uniformitarian principle implies the temporal uniformity of natural *laws*. The strong uniformitarian assumption goes further and demands that not only the kinds of processes, but their *intensities* be the same in the past as at present.

It should be noticed that the weak principle of uniformitarianism was shared not only by the historical uniformitarians but also by many of their rivals (Rudwick 1971). It can reasonably be argued that the constancy of laws is an indispensable assumption of the scientific method in general, since no simple generalization of experience is possible without it. The weak uniformitarian thesis was in fact primarily directed against invoking non-scientific causes of past events explicitly violating the laws of nature. By itself, this thesis does not entail a particular, *non-developmental* geological scenario. A directional theory of geology (like that of the gradually cooling Earth) can be compatible with weak uniformitarianism, provided no currently unobservable *kinds* of processes are introduced to account for the present state of affairs. This by no means rules out a possible change in the *strength* with which the processes operate in various epochs.

Some geologists, and most notably James Hutton and Charles Lyell, believed this was not enough to make geology a science. They insisted that the particular *intensities* of processes, and not only the laws of their operations, should be the same throughout the entire geological history of the Earth. This does not exclude small-scale spatial and temporal fluctuations, and the latter were in fact used by Lyell for explaining climatic changes and the details of the fossil record. The overall large-scale picture, however, must be essentially *steady-state*. No systematic evolutionary effect (like the Earth's cooling) was allowed in it.

Strong uniformitarianism and the related steady-state pattern have been refuted by subsequent observations that have proved that some drastic changes did occur in the geological history of our planet. As to weak uniformitarianism, it has, in fact, lost its geological identity and become an implicit methodological presupposition of all natural sciences dealing with evolutionary phenomena. Although it poses some restrictions on theorizing, it is generally held that no particular picture of phenomena follows from weak uniformitarianism. One can easily see why this is the case in geology. The whole geological scene is nothing but a local superstructure over the basic level of the physico-chemical laws. The evolution of the "scene" can proceed against the unchanging background of the underlying laws.

The situation becomes more ambiguous in cosmology where the "scene" is not a local superstructure built above a more fundamental level, but an all-embracing totality coextensive with the realm of the most fundamental physical laws.

5. Cosmology Versus Local Physics

Philosophical considerations were centrally involved in the version of SST presented by Bondi and Gold (henceforth SST-I). Their seminal paper (1948) begins with an extensive methodological introduction. The history of SST is usually traced back to this work. The philosophy of the steady-state project, however, was already contained in the review of cosmology published by Bondi some four months earlier (Bondi 1948). Although there was no mention of the steady-state hypothesis in it, the ground was completely prepared for its introduction in the next issue of *Monthly Notices*. I shall follow both papers in my account of the philosophical foundations of SST-I.

Like his famous predecessor Milne, Bondi argued that, because of the uniqueness of its subject, cosmology is very different from "local physics." Hence, not all procedures employed in the latter may be entirely appropriate for the former. In local situations, one can always distinguish between laws and their particular instances. The laws reflect inherent, unchanging, and reproducible features of phenomena, whereas the laws' instances are normally taken to be accidental, contingent, and, generally speaking, irreproducible. Indeed, it is not possible to reproduce all conditions of a particular local experiment or observation, for a scientist does not have control over the time and place of their occurrence. It is, according to Bondi, a fundamental assumption of physical science that, while the "accidental" characteristics of the phenomena under study can obviously be affected by their temporal and spatial location (as well as by the entire collection of initial and boundary conditions), what is regarded as "inherent," or lawlike, cannot be so affected. Otherwise, no coherent physical explanation of the phenomena and processes could be attained.

For example, in any local branch of mechanics, such as ballistics (Bondi 1948, p. 105), actual motions can be infinitely varied by their initial conditions, including times and places of particular occurrences. But the law according to which the trajectories of all such motions are (approximately) conic sections is supposed to survive all the changing circumstances. Furthermore, it is usually taken for granted that "the law of motion does not only cover all the cases corresponding to the various initial conditions but all these cases are supposed to have a real or potential existence." In this sense, "the law of motion is neither too wide nor too narrow; it covers all existing and possible cases and no others" (Bondi 1948, p. 105).[7]

Does the "ballistic attitude" apply to cosmology? Not at all obviously. "The distinction between impossible and possible, but 'accidentally' not realized states, becomes absurd when we have to deal with something as fundamentally unique as the universe" (Bondi 1948, p. 106). In what way can this "fundamental uniqueness" manifest itself in cosmological theorizing? First of all, it can blur the demarcation line between the laws of nature and their particular instances. The universe is something more than just one particular instance of natural laws; indeed, the "instance" in question is coextensive with the laws themselves. With equal reason may the latter be regarded as a consequence of the universe's very existence.

One corollary of these considerations is this: the demarcation between what is "intrinsic" and what is "accidental," if it can be drawn at all for the universe as a whole, is not bound to coincide with that typical of local situations. In other words, there are reasons to doubt that observations of various features of the universe will tend naturally and automatically to sort themselves out into those pertaining to the "intrinsic" and those relating to the "accidental," as normally happens with observations performed in local physics. It is not so clear in advance where to draw a line separating these classes. Take, for example, two parameters, the constant of gravitation and the Hubble "constant." The former is usually held to be "inherent" and the latter "accidental." A measurement of the Hubble parameter, however, gives as unique a result as the determination of the gravitational constant (cf.: Bondi and Gold 1948, p. 252). And furthermore, there are theories in which the gravitational constant itself becomes "accidental," by virtue of its hypothetical dependence on the cosmological epoch.

The upshot is that as soon as one steps into the cosmological arena, the general arguments supporting a particular division of physical experience into "intrinsic" and "accidental" subcategories are no longer available. One should draw this division anew, based on some additional considerations. Big bang cosmology, as Bondi and Gold noted, chose the most straightforward way, that of a direct extrapolation of concepts, laws, and "demarcation principles" of the local physics to the cosmological scale, in the conviction that no problems will arise with this approach. In particular, a tacit agreement has been made to the effect that the global structure of the universe (say, the density and velocity distribution of matter) has no influence over the local physical laws. But this is not self-evident. One could recall Mach's principle stating that some local physical properties may be subject to the dynamic influence of distant matter in the universe. Any dependence of this sort, argued Bondi and Gold, could impede the appropriate interpretation of observations of distant objects so essential to cosmology.

According to the authors of SST-I, any possibility of such an influence must be precluded from the start. For this, a very special cosmology is needed, one that would postulate equality and indistinguishability of all parts and all stages of the physical history of the cosmos. Any large enough space-time fragment of the universe should be a fair sample of the whole.

By adopting the cosmological principle, the big bang theory made a first but insufficient step in this direction. The cosmological principle postulated the large-scale homogeneity and isotropy of the universe and ensured a uniform description of all parts of the universe at each moment of time, but not for the entire duration of its evolution. Any cosmological theory contemplating local laws in a universe undergoing changes must make, as Bondi later stressed, "definite assumptions about the effect of these changes on the laws of physics. Even the statement that there are no such effects is evidently an assumption, in fact a highly arbitrary assumption" (Bondi 1957, p. 197). Indeed, it is not at all clear that the laws of physics discovered here and now, at a later cosmic epoch, would be suitable for dealing with the early evolutionary stages, as depicted by the big bang cosmology, when the matter of the universe is supposed to have been in a rather different physical state.

One could adopt another strategy and posit a possible explicit dependence of the laws on the changing physical structure of the universe, as was done by Dirac (1937), or (somewhat anachronistically, but to the point) by Carl Brans and Robert Dicke in their scalar-tensor theory of gravity (1961). Generally speaking, many possibilities arise at this point, this freedom being, according to the steady staters, a defect, rather than an advantage, of the received methodology. For, again, there is only one universe, and its evolution is perhaps a unique cosmic event. It would not be unreasonable to require that the scientific picture of this event be also "unique" so as to cover "all existing and possible cases and no others" (Bondi 1948, p. 105).

The most radical way to avoid these problems, as well as arbitrary assumptions concerning possible effects of the changing cosmological environment on the physical laws, is to exclude such effects altogether, by extending the cosmological principle. Bondi and Gold's *perfect cosmological principle* (PCP) requires the large-scale structure of the universe to be not only uniform in space but also constant in time. "We do not claim that this principle must be true," Bondi and Gold observed, "but we say that if it does not hold, one's choice of the variability of the physical laws becomes so wide that cosmology is no longer a science. One can then no longer use laboratory physics without relying on some arbitrary principle for their extrapolation" (Bondi and Gold 1948, p. 255).

The uniformitarian leitmotif is clearly recognizable in this claim. The situation is unlike that in geology, however, as the distinction between weak and strong versions of the uniformitarian assumption disappears in steady-state cosmology. The whole point of Bondi and Gold is that once we let the "intensities" of physical processes in the past of the universe be drastically different from what they are at present, no guarantee can be given for the stability of physical laws themselves across the entire evolutionary track.

The universe is, of course, under no obligation to live up to PCP. But according to Bondi and Gold, no science of cosmology is possible in a universe that does not satisfy this principle. In other words, cosmology is only possible in a steady-state universe. Consequently, we either have to abandon any hope of building a viable cosmology or to explore the opportunities provided by the steady-state picture, as long as its consequences do not conflict with observations. It is only rational to try moving ahead rather than simply standing still, and Bondi and Gold proceeded to derive consequences from PCP.

Before following them in these derivations, I want to reflect a bit more on the idea of the interdependence of local laws and the large-scale structure of the universe presupposed in Bondi and Gold's "prolegomena" to SST.

6. The Origin of Inertia and the "Interaction Principle"

First of all, one has the impression that a shift of meaning occurs throughout the discussion of the issue "cosmology versus local physics" in Bondi 1948, Bondi and Gold 1948, and also in later works (Bondi 1957, 1960). The argument starts with the locally ascertainable distinction between the laws of nature and their particular instances. Such a distinction, then, is supposed to vanish or become blurred with respect to the entire universe. This seems to imply something like a "law of the universe" in the first place. Even if this hypothetical law collapses with its only instance, becoming thus "degenerate," it still has to possess some distinctive features of a law. Otherwise there is no reason to call it by that name. No examples of this type of law are given, though, and one wonders if there can be any. This does not impair the main argument, since the latter essentially hinges on quite a different usage of the term "law," to which the discussion eventually switches.

As a matter of fact, it is the familiar laws of local physics that, according to Bondi and Gold, may be non-uniformly affected by the structure of the universe, unless one adopts the perfect cosmological principle making such an influence uniform and hence imperceptible. "As the physical laws cannot be assumed to be independent of the structure of the universe, and as conversely the structure of the universe depends upon the physical laws, it follows that there may be a stable position," Bondi and Gold remark (1948, p. 254). Clearly they mean the local physical laws acting *in* the universe, and not some hypothetical law *of* the universe. It would be appropriate to assume, then, that in the steady-state universe satisfying PCP, the action of a local law may, in the general case, consist of two components: (a) an intrinsic local "source" and (b) a uniform global cosmological "contribution." Of course, there may be no such contribution at all. But even if there is, PCP guarantees the universal validity of the same local laws in the range of the whole universe and at any moment of time.

But this still leaves it unclear how the presumed *two-way* interaction between the laws of nature and the material content of the universe is to be conceived. Bondi and Gold frequently quote Mach's principle in this connection. This principle is ambiguous and has nearly as many interpretations as there are interpreters (see, e.g., Barbour and Pfister 1995). One particular attempt to conceptualize Mach's principle is worth dwelling upon, however, as it was put forward in 1953 by a young convert to the steady-state cosmology, Dennis Sciama (1953, 1957). He definitely derived inspiration not only from the physics of SST but also from its philosophy and, specifically, from the idea of a possible influence the universe as a whole may have on the local properties of matter.

The original thesis known as "Mach's principle" is often expressed as a requirement to reinterpret the dynamical theory of mechanics in purely relational fashion, so that kinematically equivalent motions be also dynamically equivalent. Since the former can only be defined in terms of irreducible relations among moving bodies, the dynamical properties of all bodies and, in particular, their *inertia* must be understood as arising out of their interaction with the rest of the matter in the universe.

Sciama (1953) suggested a tentative sketch of a theory of gravitation incorporating Mach's principle and based on a reasonable assumption that the total gravitational field induced by the matter of the universe should vanish in the rest-frame of any given body. As a first approximation, Sciama assumed this field to be derivable from a vector potential in Minkowski space. He considered a smoothed-out homogeneous and isotropic model of the universe of density ρ expanding in accordance with Hubble's law $\mathbf{v}_H = H\mathbf{r}$, neglected relativistic effects, and restricted the bulk of the matter inducing gravitation/inertia on a test particle, residing at the origin of the coordinate system, to the spherical volume V_H of radius c/H. A natural state of rest at each point in such a model universe is defined by the isotropic distribution of the redshifts of distant galaxies.

Now suppose the test particle moves with a rectilinear velocity $-\mathbf{v}(t)$ relative to the universe and to another body of mass M, which is at rest with respect to the universe. One straightforward way to describe the dynamics of the test particle is to determine its acceleration in the rest-frame of the universe by means of Newton's laws of motion and gravitation

$$-\frac{d\mathbf{v}}{dt} = -G\frac{M}{r^2}\frac{\mathbf{r}}{r}, \tag{1}$$

where $\mathbf{r}$ is the distance to the other body.

Alternatively, one could work in the rest-frame of the test particle, in which the system consisting of the universe and the body moves with velocity $\mathbf{v}(t)$ and has acceleration $-d\mathbf{v}/dt$. In this reference frame, as in any other, the gravitational field on a particle is, on Sciama's assumption, generated[8] by the scalar and vector potentials of the universe, Φ_U and $\mathbf{A}_U$, and of the body, Φ_M and $\mathbf{A}_M$,

$$\mathbf{E} = -\nabla\Phi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}, \quad \mathbf{H} = \nabla\times\mathbf{A}, \tag{2}$$

where $\Phi = \Phi_U + \Phi_M$ and $\mathbf{A} = \mathbf{A}_U + \mathbf{A}_M$. Provided $v/c << 1$,

$$\Phi_U \approx -\int_{V_H}\frac{\rho}{|\mathbf{r}|}dV = -\frac{2\pi\rho c^2}{H^2}, \qquad \mathbf{A}_U \approx -\int_{V_H}\frac{\mathbf{v}\rho}{c|\mathbf{r}|}dV = -\frac{\Phi}{c}\mathbf{v}(t),$$

$$\Phi_M = -\frac{M}{r}, \qquad \mathbf{A}_M = -\frac{\Phi_M}{c}\mathbf{v}. \tag{3}$$

This gives

$$\mathbf{E} = -\frac{M}{r^3}\mathbf{r} - \frac{M}{rc^2}\frac{\partial \mathbf{v}}{\partial t} - \frac{\Phi}{c^2}\frac{\partial \mathbf{v}}{\partial t}, \qquad \mathbf{H} = 0. \tag{4}$$

The total field **E** induced by the system universe + body at the test particle should be zero in the particle's rest frame. This requirement, after some simplifications, is expressed thus:

$$\frac{M}{r^2} = -\frac{\Phi_U + \Phi_M}{c^2}\frac{\partial v}{\partial t}. \tag{5}$$

By the relationist assumption, the two descriptions of the situation, (1) and (5), must be equivalent. Hence, provided $\Phi_M << \Phi_U$,

$$\frac{2\pi G\rho}{H^2} = 1,$$

or better, given the approximate character of the above derivation of (4),

$$\frac{G\rho}{H^2} \approx 1. \tag{6}$$

In this relation, the "interaction" principle finds its manifestation: the gravitational constant *G*, which supposedly represents a *nomic* feature of the universe, is coupled to the density of matter in the universe (ρ) and its global velocity pattern (*H*), which are, presumably, of a purely "factual," non-nomic nature. It can be shown that the main contribution to *G* in Sciama's theory comes from very distant matter inaccessible to observation. In this sense, local measurements—in fact, the whole structure of local physics—give us information about the structure of the universe as a whole; the former indeed carry an "imprint" of the latter.

Another consequence of (6) that has a direct implication for steady-state cosmology is that, unless the universe is stationary on the large scale, the gravitational constant must be changing with cosmic time. Thus, because of the influence of the universe on the local nomic properties of matter, the latter would not survive unchanged in a changing universe.

Sciama has also shown that the case of uniform rotation can be treated similarly. His considerations outlined above do not, however, constitute a viable theory of gravity. On the one hand, they are limited to the simplest cases of uniform rotation and rectilinear accelerated motion and incapable of describing, in the same relational fashion, cases of arbitrary motion. For this purpose, a tensor rather than a vector potential is needed. Secondly, a theory should be relativistic. Sciama promised to develop a theory satisfying these desiderata in a subsequent paper, to which he referred as "paper II" throughout his (1953) article. "Paper II," however, was never published. One reason was probably empirical. Equation (6) relates three observable quantities, G, ρ, and H. Given the value of H, as it was estimated at that time, and even the value reduced more than thrice after the recalibration of extra-galactic distances in the late 1950s, the average density of matter in the universe should, according to (6), be of the order $\rho \approx 10^{-27}$ g/cm^3, which is too far off the mark (by a factor of 1000).

Nonetheless, Sciama's work on Mach's principle stimulated further developments of a similar kind,[9] and it was clearly supposed to be an exemplification of the philosophy of the steady-state project. Bondi and Gold, however, refer to Mach's principle as if it were just one manifestation of a *general interaction* principle, the latter equally pertaining to all local physical laws. It remains to be seen what such interaction could mean from a physical point of view and whether it could imply anything more than the existence of a more general law subsuming the hypothetical interaction under a more comprehensive principle that is itself unaffected by the state of the universe as a whole (see Balashov 1992). Here I put these questions aside and return to the exposition of SST-I.

7. The Perfect Cosmological Principle

The entire content of SST-I was expected to be deducible from the perfect cosmological principle (PCP) postulating the large-scale uniformity of the universe in space and time. Bondi and Gold considered it of crucial importance to stress that PCP and the cosmological principle (CP) of the big bang theory (assuming the universe to be uniform in space but changing in time) differed not only in their formulations but also in their status in the corresponding theories. According to Bondi and Gold, CP is no more than an auxiliary hypothesis needed to derive a particular empirically adequate cosmological model from the field equations of general relativity. Should a conflict arise between a model and the astronomical data, CP could well be replaced with a more complicated assumption without abandoning the framework of the big bang theory. In SST-I, on the contrary, PCP was supposed to be an essential element. SST-I and PCP stand or fall together, for, as Bondi and Gold invariably stressed, the scientific value of cosmology derives from the strong uniformitarian assumptions inherent in PCP.

On this view, the "rank" of PCP is higher than that of ordinary physical laws, for the very *raison d'être* of ordinary physical laws hinges on the validity of PCP. As Bondi and Gold noted in this connection,

> we regard the principle as of such fundamental importance that we shall be willing if necessary to reject theoretical extrapolations from experimental results if they conflict with the perfect cosmological principle even if the theories concerned are generally accepted. (Bondi and Gold 1948, p. 255)

The main target here was the principle of conservation of matter and energy. To satisfy PCP in an expanding universe, the creation-of-matter hypothesis must be introduced, in order to keep the density of cosmic matter constant. The rate of creation required for it[10] turns out to be too low to be discoverable by any observational effects. As the universe expands, new matter is created, leading thereby to local evolutionary phenomena, like the formation of new galaxies and stars. There is, however, no large-scale evolution in this picture. Any sufficiently large fragment of space contains objects at all stages of their development. No global feature of the universe, such as the mean density of matter, the integral luminosity or the spectral distribution of radiation, is subject to a systematic temporal change in SST. In other words, any large-scale process operative in the steady-state universe should be self-perpetuating.

This feature of the theory can be illustrated by the mechanism of galaxy formation elaborated by Sciama (1955) in the framework of SST. New galaxies were supposed to form permanently in the wake of the old ones. The latter moving through space served as attractors of intergalactic matter including its newly created fraction. The subsequent separation of the daughter and mother galaxies provided for the continuous rejuvenation of the cosmic population, keeping its average age constant. Unlike the big bang cosmology, SST allowed no unique "catastrophic" event associated with the *original* formation of galaxies in the remote past. Still more importantly, Sciama's mechanism was intended to account for "the *actual* distribution of matter in the universe entirely in terms of the general laws and constants of nature" (Sciama 1955, p. 3). The requirement that the properties of the self-perpetuating system of galaxies be independent of time determines, in Sciama's theory, these properties *uniquely*, without introducing any free parameters. The key point here is the following chain of relations: the mass of a parent galaxy determines the degree of compression of intergalactic matter (including its newly created fraction) which, in turn, determines (through appropriate considerations of gravitational instability) the characteristic mass of a stable daughter configuration. This chain is then closed by the requirement of self-consistency, namely, that the mass of a daughter galaxy determined in this way be equal to that of a parent galaxy. As Sciama claimed, in complete conformity with the philosophy of the steady-state project, "we have here the first example of an actual property of the universe being calculated from general principles, without the intervention of any arbitrary initial conditions" (Sciama 1959, p. 191).

Let us now return to the creation of matter hypothesis. To ensure the steady state of the universe, Bondi and Gold had thus sacrificed the conservation laws. From the cosmological point of view, which Bondi (1957, 1960) later expounded, this was not a deadly sin. Although creation events constitute anomalies contradicting the conservation principle, these anomalies are too small to be manifested in any observable effects. In actuality, the conflict is only between the creation hypothesis and the simplest theoretical generalization (viz., the laws of exact conservation of matter and energy) of multitudinous experimental facts testifying that energy is conserved with great accuracy. Inference from experience to theory should not, however, ignore the cosmological point of view. The cosmological case is not just one instance of local physical laws. The latter have their locus in the expanding universe. Any statement of their form is at the same time a statement of the global properties of the unique physical whole, the universe. The creation process required by PCP implies violation of the *exact* conservation principle thereby substantially reducing its simplicity, but this is "more than counterbalanced by the gain in simplicity" in the resulting cosmological model (Bondi 1957, p. 196).

> When observations indicated that matter was at least very nearly conserved it seemed simplest (and therefore most scientific) to assume that the conservation was absolute. But when a wider field is surveyed then it is seen that this apparently simple assumption leads to the great complications discussed in connexion with the formulation of the perfect cosmological principle. The

> principle resulting in greatest overall simplicity is then seen to be not the principle of conservation of matter but the perfect cosmological principle with its consequence of continual creation. From this point of view continual creation is the simplest and hence the most scientific extrapolation from the observations. (Bondi 1960, p. 144)

This argument suggests a highly inductivist interpretation of the fundamental conservation principles of physics. Such an inductivism occurs in a theory that places strong emphasis on the hypothetico-deductivist methodology. Whether or not one is willing to accept this argument, there is nothing impossible or even peculiar in this combination which is entirely consistent in its own right. One should certainly agree with John North (1965, p. 210) that it was naive to reject (as many physicists in fact did) an empirically successful theory (which SST was in the early 1950s) for this reason alone, that "some inviolable Principle of the Conservation of Energy" is violated in it.

8. The Perfect Cosmological Principle and General Relativity

Yet PCP is definitely in conflict with the field equations of general relativity, for the latter's mathematical formalism requires strict conservation of energy. Therefore, Bondi and Gold could not employ the available theory of gravity in deriving their model. Remarkably, no theory of gravity at all was needed for that. Bondi and Gold (1948, p. 260) proceeded from the generic Robertson–Walker metric for homogeneous and isotropic models, which was shown to be obtainable independently of any particular dynamical theory,

$$ds^2 = c^2dt^2 - R^2(t)(dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\ ^2)(1 + kr^2/4)^{-2}, \qquad (7)$$

where $(r,\theta,\ )$ are constant coordinates of a fundamental particle partaking in the cosmic expansion, $k = -1, 0, 1$ is the parameter defining the geometry of a particular model, and $R(t)$ is an arbitrary function of time usually called the scale factor in the relativistic models.

The steady-state model can be formally derived from (7) in the following way (see, e.g., Bondi 1960, pp. 145–146). The square of the radius of curvature of the $(r,\theta,\ )$ space, k/R^2, is responsible for certain observable effects (for example, the number of galaxies observable in the unit proper volume of space) and, hence, according to PCP, must be constant. Since obviously $R(t)$ is not constant (otherwise there would be no redshifts in the spectra of distant galaxies), this gives $k = 0$. The Hubble parameter H is also an observable quantity as it accounts for the receding of galaxies. From $H = \dot{R}/R = const.$ it follows that $R(t) = \exp(Ht)$. Thus the metric of the stationary universe is

$$ds^2 = c^2dt^2 - (dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\varphi^2)\exp(2Ht), \tag{8}$$

which formally reproduces one of the early de Sitter solutions, as expressed by Lemaître and Robertson (see North 1965, p. 112).

Whether this formal similarity has any physical meaning depends on SST's relation to the received field theory of gravitation. Bondi and Gold discuss this problem in detail. Because of the violation of conservation principles, it is not possible to incorporate the steady-state model into general relativity. It may, however, be possible to proceed the other way round and to derive the proper theory of gravity from SST-I, as a consequence of PCP (Bondi and Gold 1948, p. 270). From the cosmological point of view, this procedure may be legitimate. For PCP has priority over any particular physical law, and the methodology of SST-I assumes that implying laws from cosmological considerations is at least as fundamentally important as a general formulation of the laws.

In this sense, argued Bondi and Gold, the theory of gravity underlying the big bang cosmology is not entirely satisfactory. Locally, it proclaims an equality of all reference frames. At the cosmological level, however, the equality is violated owing to adoption of the *Weyl postulate*, which is nothing but a mathematical corollary of the cosmological principle. According to the Weyl postulate, the world lines of the fundamental cosmic units partaking in the general expansion of the universe are geodesics orthogonal to the spatial hypersurfaces $t = const$. The existence of such hypersurfaces and hence of t, the "cosmic time," is due to the uniformity of the universe in the smoothed-out model. Consequently, at each point of space-time there exists a time-like vector associated with the state of motion of a fundamental cosmic unit and an observer moving with it is privileged in the sense that she sees a strictly isotropic expansion picture.

The geometrical structure of the expanding universe thus naturally gives rise to a preferred vector field. This field, however, plays no role in the general formulation of the received gravitation theory. Because of this, wrote Bondi and Gold, the latter becomes too wide: "It covers a far greater range of possibilities than actually exist" (Bondi and Gold 1948, p. 268). An additional postulate (viz., that of Weyl) is then invoked to narrow down this range. "To us this narrowing-down of the theory in its final form seems to be utterly unsatisfactory, these restrictions should enter the theory at the beginning and not at the end" (Bondi and Gold 1948, pp. 268–269). There is, in other words, no reason to require a complete symmetry of the laws of nature while assuming that their most important application, corresponding to the unique structure of the universe, is signally asymmetrical.

SST, Bondi and Gold held (1948, p. 266), has an important advantage over relativistic cosmology in that it attributes a direct physical and not only a geometrical meaning to the field of privileged vectors, imposed by the uniform expansion of the universe, by identifying these vectors with velocities of the newly created particles of matter. Because of its universal significance, the vector field defined in this way should play as essential a role in the general formulation of the gravitation theory as the tensor field.

This idea, which can also be traced back to Bondi's "prolegomena" (1948), is most unusual and looks, at first sight, entirely opportunistic. A cosmological point of view, however, suggests a rationale for it. What Bondi and Gold seem to be implying is a certain *symmetry principle* requiring that the symmetric properties of the (smoothed-out) cosmological model match the dynamical symmetries of the underlying theory. In particular, the latter should not possess extra symmetries over and above those required to support the model of the actual universe. Such a requirement could be related to a somewhat similar principle operative in the methodology of local space-time theories. As stated by John Earman, this Symmetry Principle demands that every *dynamical* symmetry of such a theory be its *space-time* symmetry, and vice versa. Behind this principle "lies the realization that laws of motion cannot be written on thin air alone but require the support of various space-time structures. The symmetry principles then provide standards for judging when the laws and the space-time structure are appropriate to one another" (Earman 1989, p. 46). For example, the space-time appropriate to Newtonian mechanics should contain (Newton's own view notwithstanding) no less and no more symmetries than are needed to "bring out" the rotational and translational (i.e., Galilean) symmetries of the classical laws of motion.

Bondi and Gold's "cosmological symmetry principle" stems, in effect, from a further idea that the space-time at hand is not a generic space-time providing a suitable structure for the infinite class of local motions, but a very *particular* space-time of the cosmological model describing the global geometry of the *actual* universe. In other words, the space-time in which we live and do physics is the space-time associated with a single *model*, not with the general theory; hence its particular significance:

> While there is no logical argument against theories which are too wide, it is generally agreed that such a theory is unsatisfactory and likely to be mislead-

> ing in physics. If then we postulate that a theory of relativity should not be too wide, then any such theory makes certain demands on the structure of the universe. This is a most interesting point, in view of the distinction we had previously drawn between laws of motion and actual motion. While a theory of relativity as such only makes statements about the validity of the laws of motion, its cosmological implications will to some extent make statements about the actual motion of matter in the universe. (Bondi 1948, p. 106)

This disparity characteristic of generic relativistic models is, in Bondi's view, unsatisfactory precisely because the theory at hand (i.e., general relativity) turns out to possess a "superfluous symmetry" that is not manifest in the symmetries of the real universe: "although according to general relativity the laws of nature are immutable, it cannot in its current form provide a universe which is both homogeneous and stationary" (Bondi 1948, p. 107).

In order to deprive the existing theory of gravity of its "superfluity," this theory should be substantially modified. Bondi and Gold promised to present in another paper a formulation of a field theory immune from the above objections (Bondi and Gold 1948, p. 270). This idea, however, was eventually completely abandoned. Later on, Bondi gave reasons for that: "We feel that, as the assumption that the universe is in a steady state leads to observable consequences without any field theory formulation, no advantage is gained by tackling now the obscure and highly ambiguous problem such a formulation presents" (Bondi, in Stoops 1958, p. 78).

This later remark, however, looks more like a post factum rationalization than a real rationale for not pursuing the field theory project. As a matter of fact, a gravitation theory formulation satisfying, in many respects, the above requirements and leading to a steady-state model of the expanding universe already existed at the time Bondi and Gold's original paper came out, and awaited its appearance in the next issue of *Monthly Notices* (Hoyle 1948). Moreover, this theory had been criticized by Bondi and Gold in their paper before it was actually published.[11]

9. Hoyle's Theory

The author of SST-II was apparently less concerned with philosophical problems. He posed a physical question instead: where did the observable matter of the universe come from? There are two main alternatives: either it had been created all at once in the remote past, or it was, and now continues to be, created as the universe expands. The one-time "catastrophic" creation-in-the-past implicit in the big bang cosmology was, Hoyle maintained (1948, p. 372), “against the spirit of scientific inquiry,” for the theory, in fact, deals only with the already created matter and does not consider the process of creation itself.

Pushing the awkward question of creation of the material content of the universe back to the past is, one could say, quite similar to invoking suitable catastrophic events in the geological history of the Earth in order to account for its currently observable features. In geology this approach has been severely criticized and rejected by the uniformitarians. In cosmology, almost the same sort of criticism was presented by the authors of the steady-state theory, who suggested that severe constraints should be placed on cosmological speculation about the remote and inaccessible past of the universe by postulating that the processes that have occurred in the past are basically the same as those going on in the universe now. The most important process of this kind is the continuous creation of matter. Hoyle insisted furthermore that, because of its fundamental importance, this process should be explained and not simply postulated, as was done in SST-I. Contrary to the “philosophical” approach of the latter, he suggested a mathematical account of the creation process, by way of a modification of the field equations of general relativity.

This is reminiscent of the first steps taken in relativistic cosmology. In 1917 Einstein modified his field equations of gravitation, by introducing the famous Λ-term, in order to obtain the static model of the universe (Einstein 1917):

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu}. \tag{9}$$

Hoyle aimed to justify a stationary picture. By invoking the Einsteinian precedent, he too introduced an additional symmetrical tensor term into the equations of general relativity

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + C_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu}, \tag{10}$$

where

$$C_{\mu\nu} \equiv C_{\mu;\nu} = \frac{\partial C_\mu}{\partial x^\nu} - \Gamma^\alpha_{\mu\nu}C_\alpha \tag{11}$$

and

$$C_\mu = \frac{3c}{a}(1,0,0,0), \quad a = const. \tag{12}$$

The construction of $C_{\mu\nu}$ requires the introduction of a special reference frame as follows (Hoyle 1948, pp. 375–376). The universe is assumed to be uniform and satisfy the Weyl postulate. In such a universe, a family of geodesics always pass through a single point O in space-time. The choice of a particular geodesic passing through O is then fixed by providing three "space" coordinates x_1, x_2, x_3 of any other point P on it, whereas a suitable choice of the length along a geodesic from O to P gives the "time" coordinate. "Suitable" means that the measure of time is common to all geodesics; that is, the hypersurfaces $t = const.$ are, at each point, orthogonal to the geodesics. Given the postulated uniformity, together with the above assumptions, the generic metric of the model is

$$ds^2 = c^2dt^2 - R^2(t)h_{ij}dx_i dx_j, \quad i,j = 1,2,3,$$

where the curvature of space is constant. The additional assumption that this curvature be everywhere zero (suggested by the similarity of the implied stationary universe model with the de Sitter model) leads to further simplification

$$ds^2 = c^2dt^2 - R^2(t)(dx_1^2 + dx_2^2 + dx_3^2). \tag{13}$$

The vector $C_\mu = 3c/a(1,0,0,0)$ directed at each point along a geodesic gives rise, via (11), to the symmetrical tensor $C_{\mu\nu}$, which can be shown, given (10) and (13), to have the non-vanishing components

$$C_{ij} = -\frac{3R\dot{R}\delta_{ij}}{ac}, \quad i,j = 1,2,3.$$

In the modified field equations, $C_{\mu\nu}$ plays a role similar to that of the Λ-term in the de Sitter model, except that, unlike in the latter, where $\Lambda g_{00} \neq 0$, $C_{00} = 0$. It is precisely this difference that allows one to obtain the desired model of the steady-state universe, which is *both* de Sitter-like and non-empty.

The vector C_μ, which is parallel to a geodesic at each point of the homogeneous and isotropically expanding universe (thus satisfying the Weyl postulate), represents precisely the vector field that Bondi and Gold expected should play as fundamental a role in the general formulation of the gravitation theory as the tensor field.

Under the normal assumption that the only non-vanishing component of $T_{\mu\nu}$ is $T_{00} = \rho c^2$, a solution of (10)

$$ds^2 = c^2dt^2 - (dx_1^2 + dx_2^2 + dx_3^2)\exp(2ct/a) \tag{14}$$

is of a de Sitter type and gives the metric of the stationary universe (Hoyle 1948, pp. 375–377). Of course, the proper density of matter in SST-II, unlike that in the de Sitter model, is a constant non-zero quantity; it is given by

$$\rho = \frac{3c^2}{8\pi G a^2}. \tag{15}$$

It can be shown that the vector field C_μ is responsible for the creation of matter process. From Eq. (10) we have

$$(C^{\mu\nu})_{;\nu} = -\frac{8\pi G}{c^4}(T^{\mu\nu})_{;\nu}. \tag{16}$$

Since $(C^{0\nu})_{;\nu} \neq 0$, a continuous creation of matter and energy uniformly occurs.

The only free parameter in Hoyle's theory is *a*, and it can be adjusted to fit the actual redshift data. By (15), these data uniquely determine the value of the matter density, which makes SST-II more specific than SST-I, where no constraints are imposed on ρ. On the other hand, the steady-state metric (14) is not the only possible solution of (10). In this respect, Hoyle's 1948 theory is less stringent than SST-I.

Although Hoyle's approach was much less philosophical and more mathematical than Bondi and Gold's, the idea of cosmological uniqueness, which played so essential a role in deducing the model of the universe from the perfect cosmological principle in SST-I, had also found a very clear manifestation in Hoyle's theory. To appreciate this fact, one need only look at the modified field equations of gravity (10). These equations represent a *general* relation between physical quantities $g_{\mu\nu}$ and $T_{\mu\nu}$. Incorporated in this *nomic* relation, however, is another quantity, $C_{\mu\nu}$, having, it would seem, a purely *factual* significance, as it is constructed from the vector field C_μ, which has its origin in the features of a particular *model* of the universe. Thus, in order to derive this model from the modified field theory of gravity, one has first to ground the theory itself in the model at hand. What legitimizes creating such a "centaur," in which nomic and apparently non-nomic features are blended together in a single relation, is, again, the idea that for the universe as a whole, the distinction between the general and the particular fades away. Equation (10) describes the physics of the world in a general way. Such a description, one might think, should, by its very nature, be devoid of any *concrete* parameters. The concrete parameters of the whole universe, however, have a status different from that of the particular initial and boundary conditions attendant to a description of a local situation. General physics described by (10) has its locus in the *concrete* universe, not in some abstract set of possibilities, of which our universe is just one instance. In this view, the incorporation of the vector field C_μ into the structure of a general physical theory, which Hoyle's modified equations of gravity were supposed to represent, may be legitimate.

Nonetheless, neither Bondi and Gold nor Hoyle himself were entirely comfortable with the centaur-like equation (10). A major question looming in the background of this discontent was that of *violated covariance*. Indeed, the introduction of the "creation field" $C_{\mu\nu}$ presupposes the existence of the preferred vector C_μ at any point whose definition makes appeal to a particular coordinate system. As a result, the field equations of gravity (10) become non-covariant.

10. Covariance and Cosmological Expansion

Hoyle's discussion of this problem in his paper (1960) brings out, once again, the distinctive features of cosmological theorizing that played such an important role in the development of SST. Hoyle, in effect, makes two different points there. He argues, first, that the violation of general covariance manifested in (10) is not a defect but rather an advantage of his theory. The reasoning behind this claim can be reconstructed as follows. It is the phenomenon of global and uniform cosmological expansion that introduces a preferred direction at any space-time point. The question is whether this state of affairs should be written into the very structure of the general laws of nature. One might think that it shouldn't, for the state of affairs at hand constitutes an accidental characteristic of the universe and thus should be rooted not in the laws, but rather in the appropriate boundary conditions. This was the approach adopted in the big bang cosmology, an approach that, according to the steady-state advocates, does not seem to square properly with the "point of view of the whole."

The alternative is then to attribute more than merely factual significance to the existence of the preferred vector field in the expanding universe. In that view, the field of preferred directions in space-time should somehow originate in the laws of nature themselves. But—and this is the crucial point —"no theory working entirely in terms of covariant laws (i.e., without reference to a special coordinate system) could explain the development of preferred directions in space-time" (Hoyle 1960, p. 258). Indeed the ideal goal for a cosmologist who wishes to retain general covariance, or maximal symmetry, of the fundamental laws of nature, but, at the same time, aspires to explain the violation of this symmetry at the level of the cosmological application of such laws, would be to demonstrate the following result: “Given any arbitrary distribution of matter and motions, and arbitrary values of the metric tensor and its derivatives, on a space-like surface, prove that the universe must ultimately evolve to its present isotropic, homogeneous state” (Hoyle 1960, p. 258). But this is unattainable, for “it is difficult to see how this result could ever follow from covariant laws, since neither the laws nor the initial situation single out any particular coordinate system for especial preference” (Hoyle 1960, p. 258).

As is clear from these remarks, Hoyle’s purpose was to represent, in conformity with the philosophy of the steady-state project, the violation of covariance involved in Eq. (10) as a natural requirement of the cosmological point of view. If the existence of preferred directions possesses a nomic status, in virtue of being incorporated into the field equations (10), one may reasonably pursue the ideal of obtaining a homogeneous and isotropic universe from *arbitrary* initial and boundary conditions.

Having stated this much, by way of defending his approach in (1948), Hoyle, however, shifts emphasis rather sharply, by noting that the ideal specified above may in fact be futile and not worth pursuing, for “all that really needs proving is the stability of a large scale isotropic homogeneous distribution”:

> According to this second point of view, the notion of starting with an arbitrary distribution of matter could well be an invalid concept, because the [steady-state] universe need never have been in any state other than one of homogeneity and isotropy however far back in time we go. (Hoyle 1960, p. 258)

Relaxing the requirements on a viable cosmological theory in this way opens a possibility for the rehabilitation of general covariance. Hoyle then outlines a new and covariant formulation of the laws of creation of matter.

The key point in this formulation (Hoyle 1960, pp. 259ff) was to relate the creation field not to the structure of space-time of the universe, but to the already existing matter. The sought-for creation field φ is now assumed to be a scalar with a source proportional to the density of the existing mass:

$$\Box\varphi = \kappa\rho \,, \tag{17}$$

where $\Box$ is the operator of covariant differentiation (twice) and subsequent contraction by two indices, that is:

$$g^{\mu\nu}\varphi_{;\mu;\nu} = \kappa\rho \,. \tag{18}$$

The tensor $C_{\mu\nu}$ is now related to the material field rather than to the preferred direction in space-time:

$$C_{\mu\nu} = \frac{\partial^2\varphi}{\partial x^{\mu}\partial x^{\nu}} - \Gamma^{\alpha}_{\mu\nu}\frac{\partial\varphi}{\partial x^{\alpha}}. \tag{19}$$

Substituting (19) into (10) and assuming that φ is a function of time only (in virtue of the homogeneity and isotropy of the universe) gives the solution $R = \exp(Ht)$, similar to that obtained in (Hoyle 1948). The precise phenomenological law for the creation field follows from (14), (18), $T^{\mu\nu} = \rho v^{\mu}v^{\nu}$, and $v^{\mu} = c(1,0,0,0)$:

$$\varphi = \frac{3Hc^4}{8\pi G}t, \quad \kappa = 3c^2. \tag{20}$$

This law, Hoyle maintained, should eventually be explained by micro-physics.

Put in this form, Hoyle's theory confronts a serious empirical objection. According to (18), the rate of creation of new matter is proportional to the density of the already existing matter, which, in the real universe, is distributed rather non-uniformly. Hence most of the new matter must be created within the existing galaxies and in the interior of stars, which contradicts the available observational data. In the subsequent versions of the creation scalar field theory, the character of the creation of new matter was indeed determined by super-massive objects, such as galactic nuclei and quasars. In general, Hoyle's 1960 article marks a transition from the early SST-II to its later modifications in the work of Hoyle and Narlikar (1964, 1966). This program is still running (Hoyle 1989, 1990; Narlikar 1989, 1991, 1993), but it has become less and less adequate from the empirical point of view, especially after the detection of the microwave background radiation and in light of the progress of big bang cosmology in the recent two decades.[12]

I will not deal in this essay with these later developments of SST-II. Instead, I want to return to the formative years of steady-state cosmology and discuss another problem that gave a headache to all the steady-state defenders but was handled by them in rather different ways. This is the problem of conservation laws.

11. Steady-State Cosmology and Conservation Principles

As we saw in Section 7, Bondi and Gold argued that the simplicity of exact conservation principles could be traded off for the simplicity of the overall steady-state cosmological pattern. They also offered another argument to the same effect, by raising a question about the *meaning* of the notion of conservation of matter and energy in an *infinite* universe. It makes no sense, they argued, in dealing with an infinite universe, to speak of any conservation principle without specifying the type of volume in which the quantity at hand is supposed to be conserved. Relativistic models normally specify the coordinate volume of space partaking in the cosmic expansion and defined in terms of co-moving coordinates. The density of matter is assumed to be constant in this particular kind of volume. In the steady-state model, however, matter and energy are also conserved, but in a different type of volume, namely, "in the part of the universe observable with a telescope of given power, that is, in the part within any fixed distance from the observer. In this sense, matter is conserved in any constant proper volume of space" (Bondi 1960, p. 144).

Which type of volume, "co-moving" or "proper," is, then, more fundamental to cosmology? No obvious answer is available, according to Bondi and Gold. But certain empirical considerations could be brought up in favor of the "proper" volume: an observer keeping the resolution of her instrument constant will always see, in the stationary universe, a finite and constant amount of matter. Upon transcending the boundary defined by the power of resolution, matter becomes invisible. If this process were not compensated for by the continual creation of new matter within the limits of observation, the conservation principle would *not* hold for *observable* matter. The observable region of the universe can be taken to be more fundamental than any other type of volume in the infinite universe in the sense that "different observers might agree in ostensively defining it" (North 1965, p. 209). "It may well be considered more correct," Bondi concludes rather paradoxically, "to speak of conservation of mass in the steady-state model rather than in relativity, since proper volume is more fundamental than coordinate volume" (Bondi 1960, p. 144).

Hoyle took up this idea in his (1960) paper:

> For a universe of infinite volume (as in the steady-state theory) energy conservation for the whole universe is a meaningless notion. Conservation of energy must be considered in relation to a box of finite volume. Two important cases evidently arise: the box can have a fixed proper volume, or its walls can expand as the universe expands. When there is creation of matter, the

conservation equations require energy to be conserved in a box of fixed proper volume. When there is no creation of matter, the conservation equations require energy to be constant in a box that expands with the universe. (Hoyle 1960, p. 257)

This argument strikes one as unconvincing, at the very least, for it presupposes a purely operational definition of energy. Such a definition would carry no weight at all in local circumstances, where it is always possible to apply conservation principles to a system of objects or a configuration of fields, rather than to a particular volume of space. A cosmological perspective, however, suggests new ways of looking at familiar notions, and the steady-state theorists did not hesitate to exploit the potential inherent in this perspective.

In 1951, McCrea suggested another, in fact more inventive, way of dealing with conservation of energy in SST-II. Instead of looking at Hoyle's equations (10)

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + C_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu}$$

as a modification of Einstein's theory of gravity, McCrea proposed to view (10) as a *redefinition* of a conserved entity. If one takes

$$T'_{\mu\nu} = T_{\mu\nu} + \frac{c^4}{8\pi G}C_{\mu\nu} \tag{21}$$

to be the energy-momentum tensor in a new sense, all the cosmological results of Hoyle's theory are obtained "without any modification of Einstein's equations" (McCrea 1951, p. 563).

The legitimacy of such a redefinition of $T_{\mu\nu}$, according to McCrea, is due to the fact that Einstein's equations by themselves do not suffice to determine $g_{\mu\nu}$, for the general theory of relativity does not decide what form the energy-momentum tensor takes. A particular expression for $T_{\mu\nu}$ is normally borrowed from classical theory, or from special relativity, on the assumption that such expressions are the correct limits of the (general) relativistic case. In other words, the importation of a certain form of $T_{\mu\nu}$ into the framework of general relativity bears on the relation of correspondence between an old and a new theory. Since such relations are far from being clear and unambiguous, the classical limit of a sought-for relativistic expression may not determine the latter uniquely. "Relativistic investigations," McCrea observes, "may disclose phenomena in relativity theory that have no classical analogs" (McCrea 1951, p. 564). One particular phenomenon of this kind is the physical significance of the absolute value of pressure and its contribution to *gravitational mass*.

This notion was suggested in a work by Edmund Whittaker (1935) in which he offered an extension of Gauss's theorem to general relativity. He showed that the surface integral of what he termed the "gravitational force" over an arbitrary closed surface is equal to the volume integral

$$I = \frac{8\pi G}{c^2}\iiint (T_0^0 - \frac{1}{2}T)\sqrt{-g}\,dx^1 dx^2 dx^3,$$

which prompted Whittaker to interpret the quantity

$$\sigma = 2(T_0^0 - \frac{1}{2}T) = T_0^0 - T_1^1 - T_2^2 - T_3^3$$

as the density of "gravitational mass" in a distribution of matter and energy. In the case of

$$T^{\mu\nu} = \left(\frac{p}{c^2} + \rho\right)v^\mu v^\nu - \frac{p}{c^2}g^{\mu\nu},$$

this reduces to

$$\sigma = \rho - \frac{3p}{c^2}. \qquad (22)$$

Equation (22) shows that, in a general relativistic case, the absolute value of pressure p effectively contributes to "gravitational mass" σ.

Consequently, instead of modifying the field equations of gravity in order to get the steady-state model (as Hoyle did in his 1948 paper) with the consequence that energy is not conserved, one can assume that conservation equations $T^{\mu\nu}{}_{;\nu} = 0$ hold and then derive the form of $T_{\mu\nu}$ appropriate to the steady-state model (14),

$$ds^2 = c^2dt^2 - (dx_1^2 + dx_2^2 + dx_3^2)\exp(2ct/a), \qquad (23)$$

from the original Einstein equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu}. \qquad (24)$$

This being done, one has to provide a reasonable physical interpretation for $T_{\mu\nu}$ so obtained.

Substituting (23) into (24) and taking into account[13]

$$T^{\mu\nu} = \left(\frac{p}{c^2} + \rho\right) v^{\mu} v^{\nu} - \frac{p}{c^2} g^{\mu\nu} \qquad (25)$$

gives

$$\rho = \frac{3c^2}{8\pi G a^2}, \qquad p = -\frac{3c^4}{8\pi G a^2}. \qquad (26)$$

Thus, the steady-state model results from the Einstein equations (24) if one admits the existence of a uniform negative pressure (or "stress") $p = -3c^4/8\pi G a^2$ pervading the universe. Since the gradient of this stress is everywhere zero, it does not give rise to any directly observable mechanical effects. Its contribution to cosmology, however, is due to the fact that its absolute value contributes to the gravitational mass (22). The effect of the negative uniform pressure is, in a sense, similar to the effect of the Λ-term in the de Sitter model. The negative pressure performs a *positive* work on the expansion of the universe, which transforms into the mass-energy of newly created matter. The creation of matter proceeds, on this account, in conformity with conservation principles. Hoyle's tensor $C_{\mu\nu}$ represents a reservoir of *negative* energy (in the form of the negative pressure driving the exponential expansion of the universe) whose *rarefaction*, due to the universal expansion, supplies, in effect, *new* energy in the form of created matter, which, in turn, keeps the density of normal matter and of the energy reservoir constant.[14]

Hoyle later (1960) took McCrea's interpretation into account and represented the energy-momentum tensor in the form

$$T^{\mu\nu} = T^{\mu\nu}_{(g)} + T^{\mu\nu}_{(e)} + T^{\mu\nu}_{(c)} + T^{\mu\nu}_{(n)},$$

putting the "creation field" (c) on the same footing with more familiar physical fields: gravitational (g), electromagnetic (e), and "nuclear" (n). The gravitational and electromagnetic components of $T^{\mu\nu}$ were given by their standard expressions. The "nuclear" component was, of course, unavailable at the time, whereas the "creation component" was related to φ via (18), (19), and (10):

$$T^{\mu\nu}_{(c)} = \varphi_{;\,;}^{\mu\nu} = g^{\mu\lambda} g^{\nu\sigma}\left(\frac{\partial^2\varphi}{\partial x^{\lambda}\partial x^{\sigma}} - \Gamma^{\alpha}_{\lambda\sigma}\frac{\partial\varphi}{\partial x^{\alpha}}\right). \qquad (27)$$

Responding to George Lemaître's objection at the 1958 Solvay Congress, Hoyle said: "I would not agree that the steady-state theory violates conservation. It changes the nature of the quantity that is conserved, but the whole history of the conservation laws of physics shows repeated changes of the conserved quantities" (Hoyle 1958, p. 80).

It must be clear from the above that SST was not a single theory. Its two main versions were based on rather different foundations. Whereas SST-II was, in essence, a mathematical hypothesis, SST-I constituted a rare example of a scientific theory developed from explicitly philosophical arguments. Whereas SST-I, because of its logical inflexibility, was difficult to develop further, SST-II turned into a chain of modifications continuing up to the present. To be sure, most of the consequences of SST-I and SST-II were basically the same, and their authors, together with some other converts, formed a single front in their struggle with the common big bang rival in the 1950s. Hoyle, as mentioned earlier, never had any sympathy with Bondi and Gold's "philosophical" approach. Nonetheless, he fully shared with them the idea that cosmology imposes an unusual perspective on physical laws:

> I take the view that the laws of physics are not what people think they are. What we count as the laws are a combination of the true laws together with a cosmological influence. There are long-range interactions. When you look at a book on particle physics and look at the masses of the fundamental particles, if you believe in the canonical view of physics, then all that is a part of basic physics. I don't believe it. There *is* a basic physics. But in my way of looking at things, I don't have to assume that the various peculiar aspects of physics—particular masses, etc.—depend wholly on the basic laws. They are also a product of the way the universe actually is. What we actually see in the laboratory is a product of two things: long-range cosmological influence and the laws, which are very very much more elegant and symmetrical than particle physicists believe. (Hoyle, in Lightman and Brawer 1990, p. 65)

12. Steady-State Theory and Observations

Following the fate of SST is not my purpose here. (See note 4 for references to available historical accounts.) But a brief comment on the relationship between SST and the astronomical observations that finally overthrew it is in order. Much of the observational work in astronomy in the 1950s was stimulated by a desire to refute SST. The task, however, proved difficult. The theory was put to various tests including the redshift-magnitude data, counts of radio sources, and the theory's ability to explain the origin and abundance of the chemical elements in the universe. At first, none of these produced conclusive results, while some led to contradictory observational reports, much to the advantage of SST. Real problems for SST started to pile up in the early 1960s. First the discrepancy between different surveys of radio sources had been removed and their divergence from the prediction of SST had been firmly established. Then it was shown that the theory could not account for the considerable amount of helium actually observed in the universe and also for the perceptible presence of deuterium. At about the same time, a staunch steady-stater, Sciama, together with his student Martin Rees, performed a careful analysis of the number-redshift diagram for quasars discovered by that time and concluded that it "rules out the steady-state model of the universe" (Sciama and Rees 1966, p. 1283).

Formally, SST can be regarded as having been falsified by these observational data, if only barely so. Various modifications of SST-II were proposed in the early 1960s to explain away the mounting negative evidence. Retrospectively, they all look manifestly *ad hoc*.

Bondi and Gold took the failure of the uniformitarian cosmology at face value. They also seem to have remained true to their methodological principle that a non-uniformitarian "catastrophic" cosmology cannot be a science. Neither Bondi nor Gold joined the big bang mainstream. Their cosmological activity stopped in the early 1960s.

The final blow to SST was the discovery of the microwave background. It was, of course, no less a surprise to the steady-staters than to the rest of the cosmological community. Bondi recalls:

> I did not remain active in the field for long—the last paper I wrote on cosmology was a joint study on the radio number counts, published in 1955—but from early on I kept challenging adherents of evolving models. I told them that if the universe had ever been in a state very different from what it is today, they should please show me some fossils of that earlier age. At that time, there was no answer at all to this challenge. I began to suspect that the amount of helium might be very important as a potential fossil. . . . I must confess that the three degree radiation did not cross my mind. (Bondi 1982, pp. 60–61)

13. Conclusion

Uniformitarian cosmology lost the empirical and methodological battles. As in geology, its "developmental" rival proved its capacity to be a science. But what happened to the underlying philosophy of "cosmological uniqueness"? As we have seen, this philosophy gave rise to rather atypical views regarding the relations:

- between theory and model in the description of the physical universe;
- between laws and boundary (initial) conditions; and, in general,
- between the nomic and non-nomic features of the world.

It was the central claim of the philosophy of the steady-state project that a cleavage between these factors becomes the more problematic the more seriously one takes into account the cosmological point of view. In what sense are the accidental features of the universe *as a whole* different from the nomic characteristics of its content? What can prevent one from incorporating such "universal accidental" features into the formulation of general laws of nature, given that they both have the very same "jurisdiction"? If such incorporation is indeed possible and legitimate, what consequences may result from this procedure for both the accidental and the nomic properties? Can't the former somehow partake of the "nomicity" of the latter, and the latter of the "accidentality" of the former? Can't it be, in other words, that the allegedly accidental features of the universe are not really completely "accidental," whereas the nomic characteristics of its contents are not really that "necessary"?

Eugene Wigner once drew attention to the "three categories which physics used to describe the world and its events[:] . . . initial conditions, laws of nature, and symmetries."

> The initial conditions describe the structure as it now exists. And about this, physics does say virtually nothing. . . . There is one exception to that which I will admit; no, two exceptions: first, and this we often forget to mention, that all electrons have the same charge, that all electrons have the same mass. And the same applies for protons. In other words, there is some part of the structure of the world which has a high regularity. But these are about the only "initial conditions" regularities. Physics assumes, in fact, that the other initial conditions, the present structures of the world, are as irregular as conceivable except for what one can really view, and see, and experience. (Wigner 1980, p. 14)

The hybrid notion of "initial-conditions regularities" alludes to the sort of issues mentioned above. Although most of these issues were introduced into cosmological theorizing by the proponents of a failed theory, they have a more general significance. As was indicated earlier, they can be meaningfully posed and examined in the context of contemporary evolutionary cosmology. That the cosmic evolution of physical matter could, in principle, carry with it the evolution of its basic properties and, perhaps, even of natural laws grounded in them was regarded as a highly unpalatable consequence of a cosmological theory by the advocates of the steady-state cosmology. A desire to avoid it was a driving force behind the steady-state project. But what was viewed in the 1950s as an unacceptable implication of a cosmological point of view is now regarded by some as a real possibility.

It should not escape one's attention that although the steady state proponents raised an important problem of interaction between the nomic and the structural features of the universe, they had an easy and straightforward way of avoiding any serious discussion of the nature of the supposed interaction. To save the constancy and uniformity of laws, they postulated the steady state of the universe. The whole issue of how one should conceive of such an interaction was brought up only for a moment, in order to be immediately side-stepped, by ensuring that whatever interaction there might be between laws and objects thereby governed, one should not really be bothered by it inasmuch as one lives and does cosmology in a stationary universe.

To be sure, some of the steady state theorists came closer than others to an attempt at conceptualizing possible forms of "interaction." Sciama's work on Mach's principle, as we saw, was clearly stimulated by the methodology of steady-state cosmology. This work showed how the project of a purely relational dynamics in a cosmological setting naturally gives rise to the idea of the dependence of the gravitational "constant" (G) on the average density of matter in the universe (ρ) and its velocity distribution (H). Sciama concluded that making ρ and H constant (as in the steady-state model) allows one to avoid undesirable physical consequences of changing G. Hoyle's initial steady-state theory (1948) can be looked upon as a mathematically perspicuous way of expressing the idea of the supposed interdependence of the nomic and non-nomic properties of the universe by incorporating the features of a particular cosmological model (namely, the vector field defined by a family of geodesics in the homogeneous and isotropically expanding universe) into the modified field theory of gravitation. Later developments of Hoyle' theory, however, signal a retreat from this radical position through replacing the dependence of general features of a theory on properties of a single space-time model derived from it by a less contentious dependence of the former on the hypothetical properties of cosmic matter. In both cases, since the universe is supposed to be (and always to have been) in a steady state, the dependence of the relevant sort does not infringe upon the immutability of factors figuring in the equations of a theory.

The steady staters were in a fortunate position. On the one hand, they could be praised for drawing attention to a problem important both physically and philosophically, that of the status of physical laws from a cosmological point of view. On the other hand, they cannot be held responsible for not providing a detailed account that would render the idea of possible dependence of laws on the material structure of the universe intelligible. The authors of SST could pursue their goals without bothering to give such an account.

The contemporary big bang theory of cosmology gives rise to an entirely different situation. Here the idea of a global cosmological evolution is presupposed from the beginning and cannot be made an issue. All other ideas, including that of a possible dependence of laws on the properties of the universe as a whole, must square with this global evolutionary perspective. Anyone taking the possibility of such dependence seriously has to say much more about it than the steady staters did. Despite a growing enthusiasm with the idea of the evolution of laws, it is unclear if the idea is tenable or even coherent. But it is certainly an idea worthy of an analysis. Laws of nature are, after all, part and parcel of the universe. The steady staters were among the first to make this much clear.

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NOTES

[1] The idea of a natural selection of physical laws is explored, e.g., in Smolin 1997.

[2] Henri Poincaré was one of the first to offer such an analysis in one of his last philosophical essays (Poincaré 1911). He concluded that the essential immutability of the fundamental laws is a necessary precondition of the entire scientific enterprise: to deny the first is simply to undermine the second. For a critical examination of Poincaré’s arguments, see Balashov 1992.

[3] That is, the age of objects in the universe was estimated to be greater than the age of the universe as derived from the original Hubble constant in the most popular relativistic models.

[4] Historical accounts of the development of SST can be found in North 1965, Merleau-Ponty 1965; Brush 1992, 1993; Balashov 1994, 1998; Kragh 1996; Gale and Urani 1999. Personal recollections of the main protagonists are contained in Terzian and Bilson 1982. See also Bondi 1988, 1990, 1993.

[5] See Gale 1992; Gale and Urani 1993, 1999; Urani and Gale 1994; Gale and Shanks 1996.

[6] The best available account of the history of SST (Kragh 1996) downplays the significance of these questions. I hope to provide reasons for my disagreement with this stance below. See also Balashov 1994, 1998.

[7] This statement is somewhat misleading. One wonders what other cases can there be except existing and possible ones.

[8] In a way precisely the same in which the components of the electromagnetic field are generated by their vector and scalar potentials in the theory of electrodynamics. Hence the similarity of notation below, whose symbols, of course, should not be confused with the familiar electromagnetic quantities.

[9] In particular, the Brans–Dicke scalar-tensor theory of gravity (Brans and Dicke 1961).

[10] In SST-I, this rate corresponded to the emergence of 1 hydrogen atom per 1 m^3 every 3×10^5 years.

[11] Why did three physicists working together came up with two different theories? The story behind the publication of Bondi–Gold's and Hoyle's versions of SST is interesting in its own right. Slightly diverging recollections of Bondi, Gold, and Hoyle in Terzian and Bilson (1982) throw some light on it. Bondi and Gold had read Hoyle's work in manuscript. This prompted them to finish quickly their own paper which they submitted to the *Monthly Notices* two weeks earlier than Hoyle. As a result, it came out first containing, not surprisingly, a critique of Hoyle's views to be published four months later. For more detail, see Balashov 1994 and Kragh 1996, Ch. 4.

[12] The interested reader is referred to Ch. 7 of Kragh 1996.

[13] This form of $T_{\mu\nu}$, rather than the normal idealized expression $T^{\mu\nu} = \rho v^{\mu} v^{\nu}$, is needed precisely because, on McCrea's supposition, one may expect a cosmologically significant contribution from the absolute value of *p*.

[14] One can easily see, in retrospect, many features of modern inflationary scenarios in this picture. This fact prompted some steady-state defenders to view the inflationary theory as a revival of the steady-state cosmology. See Hoyle 1989, Narlikar 1988, pp. 221ff. One can even register, somewhat whiggishly, a further interesting anticipation of later discoveries in McCrea's comments that the origin of the negative pressure is to be found in the quantum theory of fields (McCrea 1951, pp. 573–74).

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