A Cognizable Universe: Transcendental Arguments in Physical Cosmology

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Abstract Cosmology deals with a unique object which comprises everything and yet is self-contained and singular. To describe this object in the language of physics, certain conditions must be in place. The increased role of such conditions finds its manifestation in distinct argument patterns. One popular case in point has to do with the anthropic arguments, some of which can be looked upon as varieties of transcendental reasoning, broadly construed. After reviewing this aspect of anthropic arguments, I show that the scope of transcendental inference at work in twentieth-century cosmology has been more extensive. Indeed, one important thread of such inference – the claim that, in order to be mathematically tractable, the Universe as a whole has to be a certain way – can be traced back to the first relativistic cosmological model proposed by Einstein in 1917. A somewhat different strategy of the same broad sort played a major role in shaping the steady-state theory, the main rival of big-bang cosmology in 1948–1965. Finally, the famous "no-boundary" condition for quantum cosmology would (if it could bear the weight of far-reaching interpretations put on it) be another example of grounding the mere possibility of the physical description of the Universe in its global properties.

1 Introduction

It has been a recurrent topic in philosophical discussions of physical cosmology, both by philosophers and physicists, to emphasize the special nature of its object, the Universe as a whole, which comprises all that exists and yet is manifestly singular. The fact that the object of cosmology combines these features naturally gives rise to a number of intriguing questions about the relationship between the general and the particular in the physical description of the Universe. Such questions

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have been framed in somewhat different ways,[1] emphasizing the unusual and often surprising connection, revealed or at least suggested by the cosmological perspective, between the members of traditional dichotomies: (1) laws of physics and boundary conditions, (2) necessity and contingency, (3) physics and geometry of the Universe as a whole. This, in turn, has been argued to have interesting methodological implications, by influencing explanatory standards and expectations, introducing novel inference patters or even imposing new Big Principles.[2]

I add my voice to those who think that modern physical cosmology embodies some of these distinctive features. But I believe one aspect of its methodology – one that it shares with other areas of contemporary physics, as evidenced by this volume – has so far been neglected. I argue below that *transcendental reasoning*, broadly construed, has been a recurrent topic in the development of relativistic cosmology since its beginning. The reasoning of this sort seeks to infer features of the entire Universe from conditions that make its physical description possible or coherent.

Two disclaimers are in order. First, while I borrow the term ‘transcendental’ from a venerable historical tradition, I make no attempt to relate my use it to any major representatives of that tradition. My objective is more modest: to show that a certain peculiar *pattern* of reasoning, roughly characterized as above, has been employed in modern cosmology on several occasions. Second, my consideration will, of necessity, be brief and abstract from many complexities of the historical cases at hand.

I begin by reviewing a recent instance of transcendental reasoning in cosmology, the anthropic reasoning, but only to set it aside. My real interest is to argue that *non*-anthropic transcendental arguments have been at play at some crucial junctures in the history of twentieth-century cosmology. In Sections 3–5 I focus on three important episodes: (1) Einstein’s first relativistic cosmological model, (2) the steady-state theory, and (3) Hartle-Hawking’s “no-boundary” condition for quantum cosmology. Different as these developments are, they have something in common; they attempt, in their distinct ways and with varying degree of success, to incorporate the idea that the mere possibility of a coherent physical description of the Universe as a whole poses constraints on what kind of entity it could be.

2 The Anthropic Reasoning

If certain physical properties of the Universe were even slightly different, it would not contain complex material structures. In particular, it would not contain observers capable of posing questions about the physical properties of the Universe. Importantly, the properties at hand comprise both *nomic* and *non-nomic* properties of the Universe as a whole (or at least of a large physically isolated and self-contained part of it): those

[1] See, in particular, Bondi (1960), Munitz (1962), North (1965), Merleau-Ponty (1965). For recent discussions, see Gale (1992, 1999), Gale and Urani (1993), McMullin (1993, 1994), Gale and Shanks (1996), Balashov (1994, 2002) and references therein.

[2] As was done by Edward Milne in his cosmological project (Milne, 1948). On Milne’s “rationalist program,” see, e.g., Gale (1992, 1999).

having to do with the fundamental physical *laws* operating across it as well as those having to do with its physical *state*. The first category includes the values of various physical constants (such as e, m_p, G, and α_e), while the second certain cosmological parameters (such as ρ, H, and Λ).[3] Why do we observe these particular values of such parameters and, hence, a particular physical makeup of the Universe, rather than some other? One answer is that we do it simply because a Universe with a different makeup would remain unobservable: there would be no one to observe it.

While certain interpretations of this situation may be questionable, one of them – involving the so-called *weak* anthropic reasoning – is valid. In order to perform its task, however, the reasoning needs to be supplemented with an additional assumption to the effect that an observable portion of the Universe is a small fragment of a larger portion, which, in turn, is a member of a huge ensemble of (lower-case) universes, each having a relevantly different physical makeup (where the latter may include both nomic and global non-nomic properties). If all relevantly different makeups are realized in such an ensemble the fact that we observe a very special one – that compatible with our existence – is not surprising. In order to be cognizable, the (lower-case) universe around us *must* be a certain way: it must allow cognizers. The real significance of this reasoning lies in modifying the antecedent likelihood of competing hypotheses about the universe (and the Universe). Suppose, on one such hypothesis, the actual value of a certain physical constant is antecedently unlikely, but the hypothesis is otherwise very successful.[4] One can support the hypothesis in the face of its initial implausibility by invoking a weak anthropic argument that the unlikely value of the constant is required for the observability of the universe (i.e., for the presence of observers in it) and, hence, the Universe must be structured accordingly, to allow for that value to be realized in one of its relatively isolated parts.

One can put this inference pattern in more formal terms and make its Bayesian pedigree more explicit (see Bostrom, 2002). However, the broadly transcendental nature of the inference is obvious: knowledge of the universe (and of the Universe) is constrained by the global physical conditions necessary for such knowledge to take place.[5] It would, however, be wrong to think that transcendental reasoning in physical cosmology is confined to occasional (and often problematic) applications of anthropic arguments. Even a cursory look at the history of twentieth-century cosmology suggests otherwise.

3 Einstein's "No-Boundary Proposal"

Soon after completion of his work on general relativity Einstein applied the new theory to the geometry of the Universe as a whole, thereby starting an entirely new chapter in the history of cosmology (Einstein, 1917). Einstein assumed that the large-scale

[3] See Barrow and Tipler (1986) for a useful survey of various "anthropic constraints."

[4] One good example is the vacuum-energy driven cosmological constant Λ. See Vilenkin (2004) for a recent discussion.

[5] On the transcendental nature of weak anthropic reasoning, see Balashov (1992) and Roush (2003).

structure of the Universe must be unchanging and was led to his first relativistic cosmological model by considerations having to do with the difficulty of formulating boundary conditions at infinity similar to those that would obtain in a static Newtonian Universe with no matter at infinity. The problem with boundary conditions was twofold. Part of it had to do with Mach's principle. At that time, Einstein thought that any viable theory of gravitation had to incorporate this principle, but a model with a flat spatial metric at matter-devoid infinity would violate it (for on Mach's principle, all metrical properties of space must be due to the influence of matter). Secondly, Einstein was worried that boundary conditions of this sort would bring with them a "definite choice of the system of reference, which is contrary to the spirit of the relativity principle" (Einstein [1917], 1923, p. 183).

Einstein's solution was, as we know, ingenious: to get around the problem of boundary conditions, he proposed that the Universe had *no* boundary. Rather, it must be a spatially closed spherical world. "[I]f it were possible to regard the universe as a continuum which is finite (closed) with respect to its spatial dimensions, we should have no need at all of any … boundary conditions [at spatial infinity]" (ibid., p. 183). The idealized geometry of such a world would be described by the following metric and stress-energy tensor:

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$$g_{14} = g_{24} = g_{34} = 0;\ g_{44} = 1$$

$$g_{mn} = -\left(\delta_{mn} + \frac{x_m x_n}{R^2 - (x_1^2 + x_2^2 + x_3^2)}\right) \tag{1}$$

$$T^{44} = \rho;\ T^{\mu\nu} = 0 \text{ unless } \mu = \nu = 4$$

Here *P* is the average density of matter in the Universe, *R* its radius of curvature, and *c* is set to 1. That was the model Einstein *wanted* to have. But it turned out to be inconsistent with his field equations of general relativity:

$$R_{\mu\nu} - \tfrac{1}{2}\mathrm{R}\mathrm{g}_{\mu\nu} = -\kappa T_{\mu\nu} \tag{2}$$

This prompted Einstein to modify his original equations by introducing the famous Λ-term:

$$R_{\mu\nu} - \tfrac{1}{2}\mathrm{R}\mathrm{g}_{\mu\nu} - \Lambda g_{\mu\nu} = -\kappa T_{\mu\nu} \tag{3}$$

Inserting the desired model (1) into the modified equations (3) yields the following relationships:

$$\Lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2} \tag{4}$$

$$M = 2\pi^2 R^3 \rho \tag{5}$$

where M is the mass of the closed Universe.

Certain aspects of this derivation are notable. First, Einstein's train of thought in deriving the model seems to have been the following:

1. In order to be mathematically tractable (i.e., to absolve one of the necessity to deal with boundary conditions at infinity) and physically consistent (to satisfy the demands of Mach's principle: no geometry – not even a flat geometry – without matter), the Universe must possess a certain global property: be spatially closed and thus have no boundary in space (Einstein's "no-boundary proposal").
2. In order for the Universe to possess this property and be static, Einstein's field equations (i.e. a law of nature) must be modified.

I submit that these two steps embody, in a very clear sense, transcendental reasoning: to be describable in the language of physics, the Universe has to be a certain way. Remarkably, the way the Universe has to be includes both its geometry and physics. Despite the fact that Einstein himself took the connection between the geometry and physics of the Universe, manifested in Eqs. (4) and (5), for granted, it is very striking. Equations (4) and (5) relate quantities of two rather different sorts: Λ and κ, figuring in the fundamental laws of physics, which describe all possible ways the Universe could have been, and the quantities R, M, and ρ, representing a unique way the Universe actually is. Both kinds of quantities, however, pertain to the Universe as a whole and this gives some reason to treat them on a par. And yet the correlation between them is unusual. Although Einstein did not find it particularly remarkable, Hermann Weyl, for example, wrote that the correlation between Λ and M, as expressed in Eqs. (4) and (5), "obviously makes great demands on our credulity" (quoted in North, 1965, p. 83). And Eddington noted that the correlation had a strange consequence that "the creation of a new stellar system in a distant part of the world would have to propagate to us, not merely a gravitational field, but a modification of the law of gravitation itself" (ibid., p. 85). Moreover, the propagation would have to be instantaneous.

These implications of Eqs. (4) and (5) should not detract from the significance of the main thread which led Einstein to his cosmological model. Upon reflection, the demand that reality has to be structured in a certain way in order to be describable in the language of physics should not strike one as outrageous: we see it at work in different quarters of physics. Cosmology, however, adds the grandeur of scale to it, and, in some cases, an interesting connection between the material structure of the Universe and its nomic structure. Einstein set a notable precedent for thinking along these lines.

4 Steady-State Cosmology

And the precedent was not without its followers. In 1948–1965, the big-bang cosmology had to fight a major rival, the steady-state theory (SST). 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.

The 1964–1965 discovery of the microwave background radiation, soon afterwards identified by the majority of cosmologists as a relic of the hot big bang, dealt a crushing blow to SST and vindicated the big-bang scenario. But the rivalry between the two competing theories of the Universe greatly stimulated theoretical and observational developments in the 1950s.

Both versions of SST (Bondi and Gold, 1948; Hoyle, 1948) were driven by methodological reflections on the nature of cosmology as a science,[6] in which transcendental motives played a major role. In the Bondi–Gold version, the guiding idea had to do with a possible influence the Universe at large may have on the local laws of physics. If the Universe changed radically in space or time, one could not, according to Bondi and Gold, apply physical principles discovered locally to other parts of the Universe. To guarantee the universal validity of physical laws, the Universe must be uniform in both space and time. The standard relativistic models fulfill this requirement only partially, in the form of the cosmological principle, which proclaims the large-scale homogeneity and isotropy of the Universe in space. But Bondi and Gold were convinced that one could not stop halfway here. The Universe must be constant on a large scale, not only in space, but also in time. Otherwise there would be no guarantee that the laws of physics discovered here and now could apply to the distant past of the Universe. In order to be describable by physical principles, discovered here and now, the past of the Universe must, in its gross features, be like its present. Bondi and Gold put these considerations in the form of the "perfect cosmological principle" (PCP). Their entire theory was then derived from this single principle, without relying on any particular field theory of gravitation.

The derivation proceeds as follows (see, e.g., Bondi, 1960, pp. 145–146). Bondi and Gold start with the generic Robertson-Walker metric:

$$ds^2 = c^2 dt^2 - R^2(t)(dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\varphi^2)(1 + \frac{kr^2}{4})^{-2} \tag{6}$$

The spatial curvature k/R^2 is responsible for certain observable effects (for example, the number of galaxies observable in the unit volume of space) and, therefore, according to PCP, must be constant. Since $R(t)$ is not constant (otherwise there would be no red shifts in the spectra of distant galaxies), this gives $k = 0$. The Hubble parameter H is also an observable quantity. From $H = \dot{R}/R = const.$, it follows that $R(t) = \exp(Ht)$. Thus the metric of the stationary Universe is

$$ds^2 = c^2 dt^2 - (dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\varphi^2) \exp(2Ht) \tag{7}$$

[6] See Balashov (1994) for a discussion of the methodological foundations of SST. For a detailed history of the big bang-steady state controversy, see Kragh (1996).

This model, which is formally similar to one of the early de Sitter solutions, represents the way the whole Universe has to be in order to secure the consistency of physics throughout its space–time volume. And just like in Einstein's model, the geometrical way the Universe has to be entails modifications in its basic physics. The Universe is expanding (here SST differs from Einstein's static model), but its density is constant and non-zero. Therefore there must be continuous creation of new matter, which should be incorporated into the basic laws of nature.

One way (due to Hoyle [1948]), in which this was done, takes a cue from Einstein's modification of the field equations of general relativity briefly discussed above (see Eq. 3). Like Einstein, Hoyle introduced into them an additional symmetrical tensor term $C_{\mu\nu}$:

$$R_{\mu\nu} - \tfrac{1}{2}\mathrm{R}g_{\mu\nu} - C_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu}, \tag{8}$$

where

$$C_{\mu\nu} = C_{\mu;\nu} = \frac{\partial C_\mu}{\partial x^\nu} - \Gamma^\alpha_{\mu\nu}C_\alpha \tag{9}$$

and

$$C_\mu = \frac{3c}{a}(1,0,0,0),\ a = const \tag{10}$$

Under the normal assumption that the only non-vanishing component of $T_{\mu\nu}$ is $T_{00} = \rho c^2$, a solution of Eq. (8):

$$ds^2 = c^2dt^2 - (dx_1^2 + dx_2^2 + dx_3^2)\exp(\frac{2ct}{a}) \tag{11}$$

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

$$\rho = \frac{3c^2}{8\pi G a^2} \tag{12}$$

It can be shown that the vector field C_∞ is responsible for the "creation-of-matter" process. From Eq. (8) we have:

$$(C^{\mu\nu})_{;\nu} = -\frac{8\pi G}{c^4}(T^{\mu\nu})_{;\nu} \tag{13}$$

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

The details of Hoyle's model are not of primary interest to us. But it is worth reflecting on the result. The modified field equations of gravitation (8) represent a *general* relation between physical quantities $g_{\mu\nu}$ and $T_{\mu\nu}$. Incorporated in this general 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 gravitation, one has first to ground the theory itself in the model at hand. What legitimizes creating such a “centaur,” in which the 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. Yet the particular “mixture” of them, which is represented by Eq. (8), must be in place to insure the consistency between the laws physics and the cosmological behavior of this very special Universe.

The two cases, Einstein’s static model and the steady-state model, thus have much in common in that both centrally involve transcendental arguments, in the sense noted in Section 1. Both cases present considerable historical interest. Both, however, represent dead ends in cosmological theory. It would be interesting to see what else, besides the anthropic arguments (briefly considered in Section 2), may illustrate the contemporary value of transcendental reasoning in cosmology. I would like to look at one rather controversial case and end on a cautious note.

5 Euclidean Quantum Cosmology

The case in question is the Euclidean, or Riemannian, quantum cosmology (Hartle and Hawking, 1983).[7] Its central idea is to use the path-integral approach to quantum gravity to calculate the wave function of the Universe. The propagator of quantum gravity, $K(\Sigma_i, \gamma_i, \phi_i; \Sigma_f, \gamma_f, \phi_f)$, is supposed to integrate over the set of all 4D Lorentzian manifolds interpolating between the initial and final 3D configurations $(\Sigma_i, \gamma_i, \phi_i)$ and $(\Sigma_f, \gamma_f, \phi_f)$, which include Riemannian metric fields γ_i and γ_f and matter field configurations ϕ_i and ϕ_f:

$$K(\Sigma_i,\gamma_i,\phi_i;\Sigma_f,\gamma_f,\phi_f) = \int_{\wp_{\mathrm{L}}} e^{iA/\hbar} d\mu \tag{14}$$

But Lorentzian integration is not well defined (one reason being the oscillatory nature of the complex exponent). Accordingly, one follows Hawking’s earlier proposal and replaces it with integration over the set of compact Riemannian 4-manifolds. The action A then becomes a “Euclidean” action A_E and is assigned a real-valued weight:

$$K(\Sigma_i,\gamma_i,\phi_i;\Sigma_f,\gamma_f,\phi_f) = \int_{\wp_{\mathrm{L}}} e^{-A_{\mathrm{E}}/\hbar} d\mu \tag{15}$$

Compact Riemannian geometries are geodesically complete, hence there are no singularities. This suggests the idea that one can avoid the initial cosmological singularity as well by eliminating the initial configuration (or replacing it, so to

[7] My account of the Hartle–Hawking proposal is based on an excellent critical review by Gordon McCabe (2005, pp. 74–81). His notation is used throughout.

speak, with an empty set) and integrating over the compact 4-manifolds with a single boundary[8]:

$$K(\varnothing;\Sigma_f,\gamma_f,\phi_f) = \int_{\wp_{\mathrm{L}}} e^{-A_{\mathrm{E}}/\hbar} d\mu \tag{16}$$

The Hartle–Hawking program builds on this framework by identifying the propagator of this sort with the "wave function of the Universe":

$$\Psi_0(\Sigma_f,\gamma_f,\phi_f) \equiv K(\varnothing;\Sigma_f,\gamma_f,\phi_f) \tag{17}$$

and claiming that it gives the probability amplitude of "creation of the Universe *ex nihilo*." To quote from Hartle and Hawking's seminal paper, "[t]his means that the Universe does not have any boundaries in space or time (at least in the Euclidean regime). There is thus no problem of boundary conditions" (Hartle and Hawking, 1983, p. 2961).

If this interpretation of Eq. (17) were plausible it would present another remarkable example of transcendental inference in cosmology. At the very least, one could say that, in order to be singularity-free and insensitive to boundary conditions, the Universe has to be a certain way: without a boundary, Euclidean in the past, and with a determinate probability of emerging from nothing.

Unfortunately, as noted by many critics (see, e.g., Butterfield and Isham, 1999, section 5.5; McCabe, 2005, pp. 79–81), Hartle and Hawking's result does not warrant the interpretation they put on it. First, it is doubtful that the features noted above – not having a past boundary and being Euclidean in the past – have anything to do with the Universe in which we live, for Eq. (17) describes a *wave function*, not a single classical manifold. Second, there is no clear sense in which "emergence from nothing" or even "from a Euclidean regime" could be viewed as itself a process in time. Finally, it is unclear whether the proposal actually gets rid of boundary conditions or, rather, provides a recipe *for* a boundary condition (of the wave function of the Universe); in other words, it is unclear in what sense it is a "no-boundary" proposal.

This prompts one to end on a cautious note. Transcendental arguments have been crucially involved in the history of modern physical cosmology. One also finds a different variety of them at work in weak anthropic arguments. Given the importance of transcendental reasoning, one should not be surprised to see other examples of its application – or at least *attempted* application – in contemporary cosmological theory.[9]

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[8] Even so, the "Euclidean" action is in general not positive definite, so the exponent diverges. To tame it, one needs to integrate over a select subset of four-geometries.

[9] A version of this paper was presented at the conference "Cosmology: Physics and Philosophical Perspectives" held at University of Notre Dame, Indiana, USA in April 2005. My thanks to the audience for a stimulating discussion.

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