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The Cosmos As Involving Local Laws and Inconceivable without Them

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ABSTRACT

Traditional debates, such as those regarding whether the universe is finite in spatial or temporal extent, exemplified, according to Kant, the inherent tendency of pure reason to lead us astray. Although various aspects of Kant's arguments fail to find a footing in modern cosmology, Kant's objections to the search for a complete objective description of the cosmos are related to three intertwined issues that are still of central importance: the applicability of universal laws, the status of distinctively cosmological laws, and the explanatory sufficiency of laws. We will advocate a broadly Kantian position on these three issues as part of a critical response to a prevalent strain of Leibnizian rationalism in contemporary cosmology.

1. INTRODUCTION

Attempts to grasp the world as a whole must confront difficult questions regarding modality. How can we make sense of the necessity or contingency of features of the universe? Can we attribute global properties to the universe as a whole, and what is their status? In his treatment of Newtonian natural philosophy, Immanuel Kant aimed to establish how physical knowledge is possible by treating its objects as constructed from the bare given by the activity of our understanding. This positive account sets limits on the scope of knowledge, excluding (among other things) the world as a whole as a viable object of knowledge. Traditional debates, such as those regarding whether the universe is finite in spatial or temporal extent, exemplified, according to Kant, the inherent tendency of pure reason to lead us astray, into transcendental illusion.[1] Kant's concerns may seem irrelevant to modern cosmology, given that various aspects of his arguments fail to find a footing in this new context. The questions of how we can have secure knowledge of the cosmos, and what are the limits to what we can hope to achieve, is, however, still pressing. On our view, Kant's objections to the search for a complete objective description of the cosmos are related to three intertwined issues that are still of central importance: the applicability of universal laws, the status of distinctively cosmological laws, and the explanatory sufficiency of laws. We will advocate a broadly Kantian position on these three

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issues as part of a critical response to a prevalent strain of Leibnizian rationalism in contemporary cosmology.

The universality of the laws governing natural phenomena is a central claim of the first *Critique* and the *Metaphysical Foundations of Natural Science* (MFNS). Yet demanding universality conflicts with the common practice of treating subsystems of the universe as if they were completely isolated. Treating a given subsystem of the universe as entirely closed, in the sense that the state of the system and its dynamics can be described fully without reference to the rest of the universe, is at best an approximation in theories with universal interactions, such as Newtonian gravitation. The first issue regards how to reconcile the universality of laws with their local applicability. The same underlying issue has been raised in cosmology repeatedly in the last century in the form of objections to formulating cosmological theories by extrapolating local physical laws. We cannot arrive at the universal cosmological laws, this objection holds, by extrapolating local laws that, by their very nature, leave out interactions among subsystems. We will articulate and defend a Kantian response to these debates, inspired by his treatment of space and time in MFNS: the application of laws to a particular subsystem is provisional, just as the description of motion in space and time depends upon the construction of a provisional center of mass frame. We will further defend this position as an effective response to a recent challenge to the applicability of laws in cosmology.

Cosmologists who have objected to extrapolating local laws have often proposed novel laws, or principles, that are intrinsically cosmological. The second issue concerns the status of such 'cosmological laws': how should such laws be characterized, and how can they be justified? From a Kantian perspective, empirical laws in various areas of science are grounded on a priori principles of the understanding in conjunction with the appropriate empirical concept(s). In the MFNS, roughly speaking, Kant treats the laws of mechanics as following from pure concepts of the understanding combined with the empirical concept of matter, and Kant grants that other areas of science may proceed autonomously, starting from distinctive empirical concepts. Yet Kant emphasizes in the Antinomies that the universe as a whole is not a possible object of experience. We consider the challenges of constructing such an empirical concept in contemporary cosmology, that is, to define empirically meaningful global properties of spacetime. Although such properties can be defined, they are empirically inaccessible in a clear sense. Since there is no empirical concept that could provide such a starting point for cosmology regarded as a special science, it should be instead treated as an application of local physics, as in Kant's own (pre-Critical) *Universal Natural History and Theory of the Heavens*. Even if there is a need for distinctive principles to ensure the viability of this approach to cosmology, we argue that these can be accommodated in the account of methodology described in the previous section.

Finally, cosmologists have often made remarkably strong demands regarding the kinds of explanations to be provided by cosmological laws. Some cosmologists have explicitly demanded that the laws should single out the actual universe as the only possibility; they see the existence of nonactual physical possibilities as raising an explanatory challenge. New cosmological laws have been proposed to meet this explanatory demand. We briefly criticize these demands as an example of the overreach of pure reason that was Kant's target in the Transcendental Dialectic.

Below we will take up each of these issues in turn, focusing on the broadly Kantian question of what principles are presupposed by contemporary cosmology. As our title emphasizes, we will make the case that physical cosmology can treat the cosmos by extrapolating local physical laws to ever larger regions, as well as criticizing the need for cosmology to adopt a distinctive methodology or novel conception of laws.

2. UNIVERSALITY AND APPLICABILITY

There is a puzzle regarding how to reconcile universality with the idea that the laws can be applied to subsystems of the universe (see Scheibe 1991). Although Kant did not discuss this issue, Brigitte Falkenburg (2004) characterizes the conflict between universality of laws and their local applicability as a pressing challenge to modern physics that is a natural extension of Kant's line of argument in the antinomies. If the laws are truly universal, treating a subsystem of the universe as if it were completely isolated will be, at best, an approximation; the universal laws apply exactly only to the whole universe. Consider, for example, a system of gravitationally interacting bodies described by Newtonian equations of motion, consisting of two stellar systems A and B separated by a very large distance. The equations of motion for A treated alone (entirely neglecting B) differ from the equations derived for A treated as a part of the whole system. The differences are negligible provided that the distance between A and B is much larger than the distances among the planets in either system, in which case either system can be treated to a very good approximation as an 'island universe'. It is also often possible to determine which conclusions about the system are sensitive to its degree of isolation.[2]

But does this provide sufficient justification for treating systems as isolated? Relational approaches to mechanics have held, for example, that no system is an island: interactions with the rest of the universe are necessary for grounding basic concepts such as inertia, even if practical calculations misleadingly appear not to take these into account. On this view treating a system as isolated would be a profound conceptual mistake, as it precludes the essential explanatory features.[3] In cosmology, this issue often arises from the other direction: the challenge is how to go from an island universe to the cosmos. Cosmologists routinely extrapolate from local physics, tested via applications to the solar system or terrestrial experiments, on the assumption that it captures the dynamics relevant at much larger scales, and in distant epochs of the universe's history. The example just mentioned raises the worry that straightforward extrapolation may fail, because, in general, an appropriate description of the combined system $A \cup B$ does not follow from combining those of the subsystems A and B. There are two obstacles to formulating a theory for the combined system. First, since the island universe description of A differs from the description of motions in A treated as a part of $A \cup B$ for universal interactions, we may be extrapolating from a misleading base case. Second, a full description of the combined system may include interactions between A and B that simply fail to register in the island universe descriptions, even though in principle there is no way to shield A from interactions with the rest of the universe. While the rapid progress of cosmology in the last few decades is largely based on extrapolating local physics, a vocal minority has long argued that this approach is based on a misconception regarding laws in cosmology.

Lee Smolin has recently given a clear formulation of this line of criticism, identifying a 'cosmological dilemma':[4]

> What we mean when we call something a 'law' is that it applies to many cases; if it applied to just one, it would simply be an observation. But any application of a law to any part of the universe involves an approximation [. . .], because we must neglect all the interactions between that part and the rest of the universe. So the many applications of a law of nature that are checkable are all approximations. To apply a law of nature without approximation, we must apply it to the whole universe. But there is only one universe—and one case does not yield sufficient evidence to justify the claim that a particular law of nature applies. (Smolin 2013, 99; 2015, ch. 1)

On the one hand, we routinely test local physical laws by treating them as exact descriptions of an island universe and assessing their consequences. Extrapolating these laws to cosmology overlooks the inherent approximation built into this approach. On the other hand, universal laws formulated exactly, entirely without approximations, apply only to the whole universe. Such laws no longer apply to multiple instances, and we cannot assess their consequences for multiple cases as we routinely do for other physical laws. On Smolin's analysis, this dilemma arises because cosmologists mistakenly rely on methods suitable for the study of local physics. The dilemma cannot be resolved, and cosmologists must adopt a different methodology.

There is an ambiguity regarding the 'application of the laws' in this argument. If the relevant laws are the field equations of general relativity (Einstein's field equations, EFE), there is a clear sense in which they do have multiple instantiations. For any cosmological model (a solution of EFE), an arbitrary open subset of that solution, treated as an entire spacetime, is also a solution.[5] In this sense, the laws apply to countless subregions. There are two ways of understanding 'application of the laws' so that the dilemma has some force. First, we could consider 'global' laws that lack this property of multiple instantiations in subregions (considered in §3). A second interpretation is more in line with Smolin's argument. What is at issue is not local dynamical laws such as EFE but their implications for a given system: the same laws yield *different* equations of motion for a system if it is regarded as isolated or as part of larger system. How then can we ever check the validity of the laws?

Our response to this form of the dilemma draws on a line of argument from the MFNS. Kant appeals to Newtonian physics to establish the spatial and temporal relations among coexisting substances. There are preferred ways of defining these relations such that accelerations match with the forces producing them; in modern terms, there is an equivalence class of inertial references frames in which Newton's laws hold.[6] Kant defines the true center of mass frame for a system of interacting bodies based on his formulation of the laws of mechanics. Yet the identification of a rest frame is provisional: considering more comprehensive collections of bodies—moving from (say) the interior of a ship's cabin, to the Earth as a whole, to system A, to $A \cup B$, and so on—leads to new frames.[7] Something like Newtonian absolute space only appears in this analysis as the endpoint of this process—that is, in Kant's terms, as an idea of reason. At any given stage in this analysis, the trajectories of bodies will be objects of experience in Kant's sense by virtue of their description as subject to the laws of mechanics. The acknowledgment that the reference frame is provisional is compatible with Kant's account of how the laws of mechanics constitute experience. There is on, this account, no need to appeal to absolute space:

> Absolute space is therefore necessary, not as a concept of an actual object, but rather as an idea, which is to serve as a rule for considering all motion therein merely as relative; and all motion and rest must be reduced to absolute space, if the appearance thereof is to be transformed into a determinate concept of experience (which unites all appearances). (Kant 2004, 4:560)

The process by which we represent bodies and their motions within a provisional reference frame, along with a procedure for refining this frame and unifying disparate descriptions of motion, suffices for turning motions from mere appearances into experience in Kant's sense.[8] This process of dynamically characterizing motions is what Kant refers to as "reduction to absolute space."[9] In place of an ontological commitment to absolute space, we have the commitment that there are no obstacles to the ongoing refinement of our descriptions of motion.

An analogous response to Smolin's dilemma acknowledges that cosmology depends upon extrapolating laws discovered for local systems treated as isolated, in the specific sense of being independent from properties of the universe at cosmological scales. The necessity of this idealization does not pose an insurmountable obstacle. In Kant's treatment of reducing motion to absolute space, there is a clear way to refine an initial frame to incorporate more bodies or further dynamical details. The analogous question in this case is whether it is possible to relax the initial idealization, and develop a richer dynamical description of ever larger systems. At any given stage of this analysis, the description will only be approximate, as Smolin rightly emphasizes. But, as with Kant's assessment of intermediate steps in the project of reducing appearances to absolute motion, we can at any given stage still synthesize appearances and represent the universe as subject to laws. Furthermore, this process of revision can be well controlled without assuming that it converges to a 'final cosmological theory'. The final cosmological theory Smolin aspires to should be regarded instead as an idea of reason in Kant's sense: a rule governing the process of refinement and generalization of the local descriptions, rather than a complete theoretical description.[10] The global description is not a competing theory that can be regarded as 'applied' to the entire cosmos directly. Stripped of the Kantian terminology, the point is that we should aspire to a theory that admits of ongoing refinements with a clear rationale, without expecting that these lead to a fully determinate description of the world or a 'final theory'.

Cosmologists who proceed by extrapolating local physics are, in effect, making a substantive empirical assumption: that the interplay between local and global physics can be handled via a series of controlled idealizations. Persistent failure to develop a satisfactory cosmological theory might lead us to doubt this assumption, and possible worlds in which such a methodology would not be fruitful are conceivable. For example, if gravity at solar-system scales depended directly upon a much larger-scale property, such as the average expansion rate at some specified cosmological scale, then it would be incorrect to apply general relativity to other regions of the universe with a different expansion rate. It would be challenging to pursue cosmology in such a world, given the difficulty of obtaining evidence regarding such functional relationships.[11] So far cosmology's track record of successful extrapolations arguably provides little reason to worry that we inhabit such a universe.

This point brings out a contrast with Kant's position, for we are forced to acknowledge that our ability to synthesize appearances into a coherent account of a law-governed cosmos depends upon contingent facts. Kant regarded the kinematics of Newtonian physics as following from the features of inner and outer intuition, in conjunction with the empirical concept of matter. But it would be a mistake to regard Newton's treatment of space and time as entirely based on the faculty of understanding; with the benefit of hindsight, we can see that it rests on a number of contingent empirical claims. This is also the case in cosmology: that the delicate interplay between local and global physics can be managed at all is not guaranteed a priori, but, if it in fact holds true, is a contingent piece of good fortune.

In sum, this Kantian response undercuts the terms in which the dilemma is posed, rather than leading us to grasp one horn. The modal force of the laws of mechanics is reflected in the process of revising descriptions of motion, and not just in constituting observed motions as legitimate objects of experience at any given stage. The focus on 'multiple instantiations' is misguided, since the ability of the laws to support successive refinements in the description of a single system constitutes an ongoing test of their validity. On the more sophisticated view of the application of laws this suggests, we can acknowledge that at any given stage the description of a subsystem as if it were an island universe is an approximation, without thereby abandoning hope of employing and assessing universal laws. This reflects one of the more appealing aspects of Kant's overall position: the step-by-step constructions of objects we undertake, while always partial and incomplete, can nonetheless yield stable objective knowledge. In the case of cosmology, as our title indicates, we can approach a description of the law-governed cosmos by extrapolating local laws. While we have argued against a dilemma meant to undermine this idea, there is another option that we have not yet addressed: could cosmology also be based on laws directly formulated in terms of global properties of the universe?

3. COSMOLOGICAL LAWS

Could the order of the cosmos be traced to distinctively cosmological laws? (That is, laws regarding the universe as a whole directly, in a sense to be made precise, by contrast with local physical laws that are extrapolated to apply universally.) And does cosmology require a distinctive methodology to uncover such laws? Or would such a conception of cosmology extend beyond the bounds of sense? Those who, like Smolin, hold that extrapolations of local physics do not suffice for cosmology need to provide an alternative positive account of the lawlike order of the cosmos, and how it can be investigated (or explain how we could accept a cosmos without order). Even for those who accept our response to the dilemma, it is interesting to assess whether local laws can be supplemented with distinctively cosmological laws. While Kant allows for the possibility of domain-specific empirical necessities, we will argue that there is no empirical concept appropriate to cosmology that could be used to generate distinctively cosmological laws in this fashion. But that does not undercut the very possibility of global laws. There are no obstacles to formulating well-defined global properties of the whole universe in relativistic cosmology, or laws invoking such properties. Such properties are, however, empirically inaccessible in a particularly strong sense. This raises a challenge of how to justify distinctively cosmological laws. Although we focus on a Kantian approach, any analysis of distinctively cosmological laws needs to address this challenge.

On our reading of Kant, the necessity of scientific laws can have two sources. The structure of our experience is due in part to the active role of our own intuition and understanding, which make it possible to represent objects as existing in space and time and governed by causal laws. Alongside this entirely general characterization of experience, Kant held that laws relevant to given empirical domains follow from specific concepts: “Particular laws, because they concern empirically determined appearances, cannot be completely derived from the categories, though they all stand under them. Experience must be added in order to know particular laws at all” (Kant 1998, B165). In the MFNS, the concept of matter is an empirical concept that provides the basis for the laws of mechanics. The real possibility of the concept of matter cannot be established *a priori*, but must be based on experience; the empirical necessities governing material bodies (Kant’s version of Newton’s laws) then follow as instantiations of the analogies of experience with respect to this concept. Taking the next step to establish the existence of attractive and repulsive forces requires finding experiences in which the actions of these forces are manifest. The empirical reality of forces is based, not on immediate sensations, but on their role in constructing our experience of bodies.

Although there is much more to be said to explore this position, for our purposes the significant point is that Kant treats scientific laws as the instantiations of general constitutive principles, given a specific empirical concept as the starting point. The MFNS, in a sense, follows the implications of taking a particular dynamical understanding of matter as the basic concept of substance. Breitenbach (2017) argues that these starting points are autonomous and irreducible, reflecting the specific features of different types of natural phenomena. This conception is open-ended, in that different domains of inquiry may begin from something other than the empirical concept of matter that provides the basis for mechanics. Scientific inquiry is further guided, according to Kant, by the regulative ideal of systematic unity, which brings together these diverse areas into a unified description of nature. There is a distinct sense of diversity in different areas of inquiry on Breitenbach’s (2017) reading: biology may require teleological principles, a distinctive form of regulative principle not necessary within physics, to provide a systematic account of organisms and guide biological research. This understanding of Kant raises the possibility that cosmology could also be established based on a distinctive concept, or regulative principle. Alongside this diversity, Kant still places high demands on what can count as 'proper science': he criticizes then current chemistry as merely a 'systematic art' rather than a science (Kant 2004, 4:468), on the grounds that it does not properly allow for the application of mathematics: ". . . in any special doctrine of nature there can be only as much *proper* science as there is *mathematics* therein" (2004, 4:470). A proper natural science must include a 'pure' part, on Kant's view, consisting of necessary and a priori laws, which may be supplemented by empirical necessities. Roughly put, chemistry fails to qualify as a proper science, because it is not able to give a constructive account of the forces of attraction and repulsion thought to underwrite chemical phenomena. By contrast, Kant does offer a reconstruction of the Newtonian argument for universal gravitation that is intended to show that the law of gravity should be regarded as an empirical necessity.[12] To make the case that the cosmos should be understood as governed by distinctively cosmological laws, pursuing this Kantian line of thought, we would need to identify an appropriate empirical concept as a starting point and establish how such a construction could proceed.

What distinctively cosmological concept could possibly play this role on the Kantian approach we are considering? Kant criticizes rational cosmology because no such concept is available; cosmology instead illustrates the *leitmotif* of the Transcendental Dialectic, that the application of the understanding, without contributions from sensibility, cannot yield knowledge. Kant's analysis of the antinomies holds that in forming concepts regarding the totality of possible objects of experience we fall into an irreconcilable conflict. For example, the first antinomy considers arguments for and against the finitude of space and time. According to Kant, the common problematic assumption in both arguments is that they apply spatiotemporal concepts appropriate to objects of experience to the world as a whole, regarded as a thing in itself, and the antinomies illustrate the errors and intractable debates to which this leads.[13] There are many details of Kant's argument that have not held up well to subsequent scrutiny, and in particular there is no obstacle to defining global properties of the universe in relativistic cosmology.

The study of models in general relativity (solutions of EFE) led to the introduction of various properties best thought of as attributed to spacetime as a whole. Could these properties serve the role of empirical concepts grounding distinctively cosmological laws? For example, the simplest cosmological solutions exhibit 'singularities': the spacetime curvature goes to infinity as $t \rightarrow 0$, where t is the cosmic time. Although these models suggest that singular behavior is a property of a localized region of a spacetime model (the 'big bang'), there is not a satisfactory local analysis of singularities—that is, as a property ascribed to some region.[14] Other types of singularities in physics can be assigned to a specific location, but in general relativity, infinities associated with the gravitational field cannot be used to 'locate' the singularity because the spacetime structure itself is ill defined.[15] A more sophisticated approach treats a singularity as a 'missing point' or 'tear' in spacetime, whose presence is indicated by an incomplete geodesic—a curve that 'runs out' abruptly. This can be made precise for some types of manifolds, but not for those used to represent relativistic spacetimes.[16] One might instead introduce boundary points as equivalence classes of incomplete geodesics. All the boundary constructions that have been proposed lead to counterintuitive consequences in some cases (see Curiel 1999). A review of some of these counterintuitive consequences led Geroch and collaborators (1982) to conclude that the idea might be rendered otiose: "Perhaps the localization of singular behavior will go the way of 'simultaneity' and 'gravitational force'."

The alternative to treating singularities as localized properties of specific regions is to construe 'singular' as an adjective characterizing the global structure of a spacetime (Earman 1995). On this view, various large-scale properties of the spacetime merit the label singular applied to the spacetime as a whole, even though there is no way to identify missing points or local regions as the bearers of pathological behavior. Conditions that have been introduced to characterize 'good causal behavior', in the sense of sharing structural similarities to a spacetime free of singularities or other causal pathologies (for example, Minkowski spacetime), should also be regarded as global properties. There is a hierarchy of causality conditions that classify global properties and the relations among them. One of the most demanding is the existence of a Cauchy surface.[17] The existence of a Cauchy surface is properly understood as a global property of the entire spacetime; although submanifolds of a given spacetime may be compatible or incompatible with the existence of such a surface, this property cannot be directly treated as a property of local regions which is then 'added up' to deliver a global property.

This line of work provides clear characterizations of global properties of spacetime. Although this addresses Kant's concerns about the consistency of descriptions of the entire universe, one can still ask about the status of global properties: in what sense can they be empirical concepts applied to the universe? To address this question we should distinguish, roughly, between three different types of global properties. First, several properties provide the background structure needed to formulate the field equations. Although Einstein dispensed with much of the spacetime structure used in Newtonian gravity, EFE are not written on thin air: cosmological models are assumed to be differentiable manifolds with various properties, such that the quantities appearing in EFE are well defined. Second, causality conditions such as the existence of a Cauchy surface are also sometimes take as preconditions for 'physically reasonable' models. This is more contentious, however, since these conditions seem more substantive than properties of the first type, which are regarded as mathematical preliminaries. Rather than stipulating that the causality conditions hold by fiat, many physicists prefer to prove, if possible, that they hold as a consequence of dynamics, perhaps in conjunction with weaker background assumptions.[18] Third, there are a number of global properties that appear to be contingent, at least by the lights of general relativity. The 'cosmological principle' (CP) holds if a cosmological model has a particular global symmetry, insuring that different locations are geometrically equivalent.[19] The CP is implicit when cosmologists make claims regarding the 'whole universe' and its fate in the far future, based on observations of our little corner of the world. The symmetry of these models supports inferences from local observations to global properties of the universe.[20]

Global properties are inaccessible in a particularly clear sense, and cannot be established directly by observations. Our observations are limited to regions of spacetime from which signals can reach us (called our past light cone). Recent work has clarified the epistemic situation of cosmologists with regard to global properties due to this restricted observational window on the universe. Manchak (2009) shows how one can, from an initial cosmological model with a global property *P*, construct a second cosmological model observationally indistinguishable from the first, lacking the property.[21] He proves that the construction can be carried out for several global properties, such as the existence of a Cauchy surface. This construction establishes the precise sense in which global properties are beyond empirical reach: the observers in the two models have access to all the same observations, yet they occupy models which differ on a wide range of global properties.

This last point establishes that global properties of the universe could not play a role similar to that of the empirical concept of matter in MFNS, even though they are mathematically well defined. But that is not the only possible role for global properties in a broadly Kantian understanding of contemporary cosmology. The first type of global property—and perhaps, more contentiously, the second type as well—can plausibly be regarded as constitutive principles that define the mathematical framework of relativistic cosmology. Furthermore, contingent global properties may insure the possibility of fulfilling the regulative ideal of a systematic account of nature. It is not clear that the CP has this status, as empirical cosmology can certainly proceed (albeit in less grandiose fashion) even if it does not hold. But other features of the universe support the practice of proceeding via extrapolation of local physics, possibly leading to a consistent unified account of cosmology, as discussed in §2 above.

The account of methodology described above also does not draw a sharp line between local and cosmological laws, as Smolin's does. The account of lawfulness is not based on the ability to observe multiple instantiations of the same kind of system. The modal force of cosmological laws may be reflected in the process of giving successively more accurate descriptions of subsystems of the universe, whether the laws are local field equations such as EFE or cosmological laws regarding global properties. This is not to deny that there may be challenges to assessing cosmological laws. It is difficult to draw a sharp contrast between 'initial conditions' and 'laws' in cosmology, as it is impossible to generate an ensemble of universes and observe what remains invariant. This is a challenge, but it is common to all areas of science that cannot directly manipulate their objects of study. More importantly, meeting the challenge does not demand a distinctive methodology.

4. SUFFICIENCY OF THE LAWS

Above we have argued that the lawlike structure of the cosmos follows from local laws extrapolated to the whole universe, with no need for distinctively cosmological laws formulated in terms of global properties. There is, however, a further contrast between the understanding of laws in cosmology and other areas. Cosmologists often demand far more of their laws than physicists in other areas. For most physical theories, the ability to describe accurately a wide variety of distinct situations is a virtue. Yet, according to many cosmologists, such flexibility is a vice: a *cosmological* theory that allows a wide variety of possible universes fails to explain why the universe is as it is.

This demand is reflected in responses to the apparent 'fine-tuning' of the initial state in the standard cosmological model, and in the values of fundamental parameters (in particle physics as well as cosmology). The early universe seems to be in a state of pre-established harmony: distant regions that are not in causal contact have uniform physical properties, and these properties appear to be 'improbable'.[22] Furthermore, the complexity of the observed universe seems to depend sensitively on the values of several of the fundamental parameters; had these parameters not fallen within narrow ranges of their observed values, the universe would not have complex, stable structures at a variety of length scales, and as a result it would not support the existence of life. (The fine-tuning of parameters in the Standard Model of particle physics falls within the purview of cosmology, insofar as these are thought to be fixed by dynamical processes in the early universe.) Dissatisfaction with accepting such finely tuned features has inspired the study of new theories, and the ability to explain fine-tuning is widely regarded as a criterion of viability for cosmological theories.

These explanatory aims are implicit in practice but rarely the focus of discussion. One notable exception is Smolin's recent advocacy of Leibniz's principle of sufficient reason (PSR), which he formulates as follows:

> [F]or every question of the form *Why does the universe have property* X*?* there must be a rational explanation. This implies that there should be rational explanations for the selection of the effective laws we see acting in our universe, as well as for any choices of initial conditions needed for that universe. (Smolin 2015, 367)

Conflicting research programs in physics should be judged, according to Smolin, on the basis of how many explanatory demands they satisfactorily answer, with spoils awarded to the program leaving the fewest open questions.[23]

Contemporary cosmology based on extrapolating local physical laws (the 'Newtonian paradigm') has arrived at a crisis, according to Smolin, because it cannot answer questions regarding why particular laws and initial conditions hold; these are treated, necessarily, as unexplained explainers (Smolin 2015, 373–75). Smolin's refusal of effective—necessarily approximate—laws in cosmology and his demand of explanatory closure result in unusually high expectations for cosmological theory: the theory should give a full account of the unique universe. The universe is the totality of events, which are treated as fully individuated, and comprehensively characterized, by their 'location in a network of relations'. This goes beyond the unobjectionable claim that there is a single 'way the world is', to the controversial idea that there must be a single comprehensive theory that provides an adequate representation. Smolin further argues for a new notion of law appropriate for cosmology that may 'evolve' with global time (cf. Unger 2015). Descriptions of subsystems of the universe follow as approximations of this underlying, unique description of the full universe. Due to the evolution of the fundamental cosmological laws, extrapolating approximate or partial local physics will fail to deliver a satisfactory cosmological theory (see §2).

We do not have space here to assess how far Smolin's own proposals (Smolin, 2015, ch. 6) go towards substantiating this aspiration. But it is striking how closely this position resembles the speculative cosmologies that inspired Kant's critique in the Transcendental Dialectic. As emphasized by Falkenburg (2004), the attempt to find such a complete, comprehensive description of the world is precisely what Kant decries as transcendental illusion. From the Kantian perspective, the further rationalist demands for an explanation of why the laws or initial conditions obtain simply does not find any purchase. We alluded above to the appeal of the constructive character of Kant's epistemology, which acknowledges our active role in constructing objects of knowledge and does not analyze truth of the resulting claims in terms of correspondence with elements of reality (see Torretti 2008). Instead, the Kantian approach focuses on elucidating the principles underlying the application of mathematics to phenomenal experience, such that the universe can be comprehensible. The adequacy of a particular set of principles is reflected in their ability to support an ongoing and open-ended process of refinement. Kant admittedly attributed some of these principles an a priori character, and provided arguments in their favor, which we would no longer accept. But in general it is not clear what more can be said in response to a demand to explain why certain laws obtain, other than to point to their success as foundational principles in a particular line of inquiry.

This suggests a direct response to concerns about fine-tuning, which holds independently of the Kantian line of argument. The many examples of fine-tuning discussed in the literature illustrate that the success of our physical theories in describing the world's rich complexity does not stem entirely from the laws of these theories. Their success also depends upon specific values of the fundamental parameters, and appropriate initial or boundary conditions. Rather than seeing this as an explanatory failure, to be remedied by a successor theory, this could be regarded instead as evidence for the limited scope of dynamical explanations.

5. CONCLUSION

Our approach to debates in contemporary cosmology has followed something akin to Kant's transcendental method to clarify the role of proposed laws as conditions for the possibility of relevant experience. We have argued against the cogency of proposals that principles formulated in terms of the universe as a whole can underwrite experience in this sense. Relativistic cosmology opens up the possibility of defining global properties properly attributed to spacetime as a whole, without falling into disputes like those Kant discusses in the Antinomies. Yet even in this context, Kant's concerns regarding the transcendental idea of the world-whole have some validity. The global properties of spacetime, well defined though they may be, are inaccessible to us, and as a consequence so are laws formulated in terms of global properties.

Along with this critical assessment of proposals for a distinctive type of cosmological law and associated methodology, we have defended the traditional way by which cosmology progresses by extrapolating local dynamical laws. On this account, cosmology requires starting with local dynamical laws that make the empirical reasoning pursued by cosmologists possible, in much the same way that the analysis of matter in MFNS is meant to underwrite Newton's argument for universal gravitation. We have defended this approach against two criticisms. First, we argued that concerns regarding how laws apply in cosmology overlook the possibility that laws may play a role in guiding a series of approximations. Second, some cosmologists would regard this approach as falling short of the explanatory aims of their field. We have criticized their demands as revealing a rationalist over-reach similar to that Kant diagnosed in Leibnizian metaphysics.

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NOTES

1. "Transcendental illusion" is reason's inherent tendency to incorrectly project subjective conceptual connections into claims regarding connections among things in themselves (Kant 1998, A 297/B 354).
2. For example, in an unpublished manuscript, Newton considered what kind of external force acting on the solar system would undercut his case for a form of Copernicanism. Newton's resolution of the cosmological controversy of his day depended upon treating the solar system as an isolated collection of interacting bodies, and inferring the forces responsible for their motions. But, as the manuscript indicates, he considered the consequences of dropping the assumption of isolation, and recognized that it is possible to embed the solar system within a larger system of bodies such that the Earth is at rest near the center of the solar system, as in the Tychonic system.
3. See Sklar (2000, 44–55) for an insightful, brief overview of several foundational debates regarding isolability.
4. This is a fairly common argument; see Ellis (2007); Smeenk (2013, §4).
5. A cosmological model is specified by a differentiable manifold M, metric field g_{ab}, and stress-energy tensor T_{ab}. For an open set $O \in M$, if $\langle M, g_{ab}, T_{ab}\rangle$ is a cosmological model then so is $\langle O, g_{ab}|O, T_{ab}|O\rangle$ (the model obtained by restricting the tensor fields to O). The point holds if the local dynamical laws governing the matter fields (e.g., the Standard Model of particle physics) are also included.
6. In noninertial frames there are accelerations that are not due to physical forces, such as the accelerated motion in rotating frames due to Coriolis forces. Here we are neglecting two more subtle points: first, Newton further recognized, in Corollary 6 to the Laws of Motion, that accelerations also match impressed forces locally in freely falling frames; and, second, Kant's position differs from Newton's in that he does not appear to grant the possibility of an equivalence class of frames.
7. Note that, from a modern point of view, there will be an equivalence class of such frames.
8. Kant's discussion in the Phenomenology classifies relative motion as merely "possible"; if the description of motion is augmented by including the forces responsible for the accelerations in a given rest frame they are then 'actual' motions, and in a rest frame in which all accelerations can be attributed to forces the motions are 'necessary' and satisfy empirically necessary laws such as the law of gravitation (see Friedman 2013, §34).
9. One of the themes running through Friedman's (2013) careful assessment of the MFNS is the contrast between Kant's "Copernican conception" of the relativity of motion and Newton's; see, in particular, §34 regarding how Kant 'reduces' motion and rest to absolute space.

10. Kant's discussion of the regulative principle of pure reason in the Antinomies clarifies this point. As he says there, "The principle of reason is thus properly only a *rule*, which prescribes a regress in the series of conditions of given appearances, according to which it is never permitted to stop with something absolutely unconditioned" (1998, A508/B536); and this rule "cannot say *what the object is* but only *how the empirical regress is to be undertaken*, in order to arrive at the complete concept of the object" (1998, A510/B538).
11. Advocates of the steady-state theory thought that this possibility, that the local laws vary with global structure, had to be ruled out *a priori*. While we agree that ruling out this possibility is, in a sense, a transcendental condition for pursuing cosmology through extrapolations of local physics, we regard this as reflecting an empirical fact about the universe. Scale separation (namely, that physics at short length scales is independent from physics at cosmological scales) is a plausible necessary condition for the viability of this approach.
12. For further discussion, see McNulty (2014); Friedman (2013, §20). The status of chemistry is a central problem in the "Transition from the MFNS to Physics" published in the *Opus Postumum* (see Massimi 2008).
13. See, in particular, Falkenburg (2004) for a more detailed assessment of the Antinomies, which we draw on here.
14. Here we follow Earman's (1995) overview of the difficulties with defining singularities in general relativity (in Chapter 2).
15. The metric g_{ab} is usually assumed to be defined and differentiable throughout the spacetime, and as a result there are no points within spacetime where g_{ab} 'blows up'.
16. A compact manifold includes all the points that it possibly can, in the sense that the manifold cannot be embedded as a proper subset of another manifold. For a space with a Riemannian metric there is a clear link between geodesic incompleteness and missing points; this nice correspondence between incomplete geodesics and 'missing points' breaks down for a pseudo-Riemannian metric (as in general relativity), and as a result the connection between geodesic completeness and compactness doesn't carry over to relativistic spacetimes.
17. A Cauchy surface is a null or spacelike surface Σ intersected exactly once by every inextendible timelike curve. In a spacetime with a Cauchy surface, EFE admit a well-posed initial value formulation: specifying appropriate initial data on Σ determines a unique solution to the field equations (up to diffeomorphism). A spacetime satisfying this condition is called globally hyperbolic, since it admits a well-posed initial value formulation for EFE; there are a number of conditions on global causal structure that are provably equivalent to the existence of Σ.
18. See Smeenk and Wüthrich (2011, §6) for further discussion of efforts to prove 'censorship' theorems.
19. Namely, that the spacetime is homogeneous and isotropic, implying that the models are foliated by spacelike surfaces Σ with respect to cosmic time $t \in R$. On the spatial surfaces Σ, there are no geometrically preferred points (homogeneity) or spatial directions from any given point (isotropy).
20. Here our analysis differs from that of Mittelstaedt and Strohmeyer (1990). They argue that the equations characterizing FLRW models should be taken as 'working hypotheses', and lack the necessity Kant attributes to the pure part of natural science. On our view, the more crucial point is that the FLRW models follow from the fundamental dynamics on the assumption that the CP holds. For further discussion of the CP, see Beisbart (2009).
21. Here a cosmological model is a solution of EFE, specified by $\langle M, g_{ab}, T_{ab} \rangle$. The definition of 'observationally indistinguishable' is, roughly, the requirement that for any observer in the first model, there is a point in the second model that is indistinguishable in the sense that it has all the same observable features; more precisely, the past light cone of $p' \in M'$ is isometric to that of $p \in M$ (there are 'identical copies' of the past light cones, in the second model, for all possible observers in the first model). Manchak proves this result for a variety of global properties, see Smeenk (2013); Butterfield (2014).
22. See, e.g., Smolin (2015, §3) for a discussion of these 'finely-tuned' features of the universe. How to justify assigning probabilities to these features is contentious. In the case of the early universe, the claim is that states with the observed uniform properties are 'measure zero' within the space of possible initial states allowed by general relativity, and are thus 'improbable'.
23. He formulates this as a separate principle, the 'differential' PSR, and acknowledges the aspirational character of PSR.

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