Epistemic Justification and Methodological Luck in Inflationary Cosmology

C.D. McCoy*†

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Abstract

I present a recent historical case from cosmology—the story of inflationary cosmology—and on its basis argue that solving explanatory problems can be a reliable method for making progress in science. In particular, I claim that the success of inflationary theory at solving its predecessor's explanatory problems justified the theory (epistemically), even in advance of the development of novel predictions from the theory and the later confirmation of those predictions.

1 Introduction

Much discussion over the epistemic relevance of explanatory considerations to scientific methodology has centered on general philosophical concerns, often at some remove from scientific practice and historical analysis. Especially prominent in the literature (due to their applicability to the scientific realism debate) are "in principle" underdetermination arguments (Stanford, 2016) and whether inference to the best explanation (IBE) (Lipton, 2004) is a generally valid form of reasoning. As the well-worn story goes, the underdetermination of theory by empirical evidence leads the realist to posit various theoretical virtues, such as explanatory power, to break this underdetermination or else to argue that an inference to the best explanation of the evidence suffices to infer the truth of the most explanatory of the lot of theories she considers. Her opponent rejoins the argument by pointing out that theoretical virtues are merely pragmatic (and hence non-epistemic), and that inference to the best explanation is insufficient to secure the truth of the most explanatory theory (insofar as "most explanatory theory" even makes sense) (van Fraassen, 1989).

Explanationism, as I will understand it, is the position that explanation is epistemically relevant, by which I mean, more precisely, that explanatory considerations can reliably justify beliefs (at least in some contexts) as knowledge. On the face of it, explanationism does not depend on the general validity of IBE, nor does it obviously depend on the truth of scientific realism. Indeed, attending to the roles that explanation actually plays and has played in scientific practice, such as the way it structures discourse

*School of Philosophy, Psychology, and Language Sciences, University of Edinburgh, Dugald Stewart Building, 3 Charles Street, Edinburgh EH8 9AD, United Kingdom. email: casey.mccoy@ed.ac.uk

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in a discipline and coordinates exemplars (Woody, 2015), suggests, upon analysis, that explanation is epistemically relevant in various respects and contexts quite independently of philosophical debates over realism.

Is there then aid to be found for the explanationist cause from scientific practice and historical cases that avoids a commitment one way or the other on the realism question?[1] I argue in this paper that there is. The case of inflationary cosmology, I claim, compellingly offers a concrete example of the crucial methodological role that explanatory considerations can and do play in science. It also makes for a strong case that explanatory considerations can provide an epistemological warrant for our scientific theories.

Opposition to explanationism is typically rooted in an empiricist stance towards science. My strategy in this paper is to argue that an empiricist interpretation of the case of inflationary cosmology is implausible, for it relies on evidential resources that are too limited to make rational sense of the success of the theory. Explanationism, by contrast, avails itself of broader evidential resources by allowing explanatory considerations to justify the acceptance of theories. By making use of these resources, the explanationist is able to supply a more satisfying interpretation of this historical episode.

It is convenient for my argument to bracket the anti-realism of the empiricist in order to focus on his epistemology. The empiricist-motivated understanding of the epistemic justification of scientific theories fundamentally rests on the agreement of theory with observation and experiment. An empiricist believes that empirical evidence alone grounds the acceptance of a theory. Explanatory considerations, however, arise from theory rather than just empirical evidence. If a theory explains some observation and that explanatory relation is taken to warrant the theory, then something other than empirical evidence is involved in the justification, a justification which the scrupulous empiricist would reject as extra-empirical.

In the remainder of the introduction I briefly sketch the main contours of my argument.

On empiricist accounts of epistemic justification inflationary cosmology was epistemically no better initially (if not much less justified) than the standard model of cosmology, the hot big bang (HBB) model, since it, for example, lacked distinctive observational support, made no novel predictions, and resolved no real empirical inadequacies with the HBB model (Earman and Mosterín, 1999). It was instead proposed and quickly accepted in the cosmological community on the basis of its putative solution to explanatory problems with the HBB model (Guth, 1981; Linde, 1982). According to empiricist epistemology solving such explanatory problems at best provides a non-epistemic justification for accepting inflationary theory (a pragmatic reason for pursuing the theory, for example). According to explanationist epistemology, however, solving explanatory problems can indeed provide an epistemic warrant for scientific theories.

A wealth of precise cosmological data has been acquired in the last 15 years, particularly by the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck space observatory. Cosmologists routinely claim that these data empirically support the simplest models of inflation—and strikingly so in terms of accuracy.[2] If this claim of confirmation is correct—and it surely is taken as such by most contemporary cosmologists—then inflationary theory should reasonably be considered an empirically successful theory whose predictive successes go beyond the HBB model.

Yet it is important to note that these predictions were not clearly foreseen at the time of inflation's proposal and initial acceptance by the community of theoretical cosmologists. How, then, can this widespread adoption of inflationary theory and its later empirical vindication be explained? While there are surely sociological, psychological, and other non-epistemic factors relevant for a complete historical understanding of this episode, I take it that the philosopher of science should be greatly interested in the question of whether there is a salient methodological, epistemological explanation as well.

[1] Readers interested in the status of scientific realism in cosmology are directed to the insightful discussion in (Azhar and Butterfield, forthcoming).

[2] See, for example, (Guth and Kaiser, 2005, 888). The chart found there (the same is found in many books, papers, presentations, etc.) depicts observational data from cosmic microwave background (CMB) anisotropies following the curve predicted by inflation almost exactly. This is the kind of correlation that cosmologists often have in mind when they claim that the data supports the inflationary model.

I argue that views of science rooted in an empiricist epistemology must admit that inflationary theory's empirical success was achieved by extraordinary methodological luck—roughly, epistemic success achieved through a method no more effective than guessing. Yet this degree of luck is quite implausible in the case at hand, for it seems evident that cosmologists were not guessing; rather, it appears as if they knew the theory was viable from the beginning (much like the similar case of the Higgs mechanism in particle physics). The alternative to the methodological skepticism that comes from attributing extraordinary luck to a scientific success is to consider that inflation's rapid and early acceptance among cosmologists was somehow epistemically justified prior to any observational support or provision of novel predictions.

I propose that the epistemic status of inflationary theory in cosmology in fact rests crucially on explanatory considerations, which arise from its approach to solving explanatory problems with the HBB model, viz. the fine-tuning problems known as the horizon and flatness problems. These problems center on explanations of certain presently observed cosmological conditions, namely the universe's spatial uniformity and flat spatial geometry. Inflationary theory's putative solution of these fine-tuning problems was largely responsible for the widespread acceptance of the theory, principally because inflation provided a better explanation for the uniformity and flatness of space than the HBB model's. I argue, borrowing the terminology of problem-solving and progress from (Laudan, 1977), that there is thus a salient and significant methodological story linking inflationary theory's putative success at solving the HBB model's fine-tuning problems with the later confirmation of its observational predictions. Although there is certainly no guarantee that its predictions would be borne out, cosmologists' confidence in the theory's viability is, I claim, reasonably justified by its past problem-solving success.[3]

Because my argument is based on a specific case, it is obviously sensitive to the details of the case. For example, the success of my explanationist account depends on whether inflation does in fact solve the HBB model's fine-tuning problems, which, despite cosmologists' sanguinity on the matter, is disputable. McCoy (2015), for example, has recently argued in fact that at present it cannot be said that inflationary theory does solve them. The trouble he raises is that it is not clear how to interpret the problems, since whether inflationary theory solves them or not depends on what precisely the problems are. Conventional interpretations, where fine-tuning is characterized in terms of likelihood or probability, clearly fail for philosophical and technical reasons (Schiffrin and Wald, 2012; Curiel, 2015). McCoy does, however, suggest various promising alternative interpretations deserving of investigation, such as characterizing fine-tuning as a case of over-idealization or a lack of robustness, which would ground the cosmologists' claim. Some solution, along these lines or otherwise, is clearly required to sustain the argument of this paper, i.e. the conclusion of the paper is conditional on a defensible account of what explanatory problems inflationary theory solves and how it solves them.

I begin with a brief history of recent cosmology, and inflationary theory in particular. It is to this history that I will subsequently apply an empiricist and an explanationist interpretation.

2 A Brief History of Inflationary Theory

Cosmology is the science of the universe. From our limited spatiotemporal perspective on it, the universe appears to be remarkably similar in every direction that we look—the universe is nearly isotropic about us. At cosmological distance scales and averaging out smaller scale features (such as galaxies, stars, planets, etc.) we observe a universe very close to uniform. Much of modern cosmology is based on the supposition that perspectives on the universe from elsewhere look much as ours does here and now in our own cosmological neighborhood. This assumption is known as the cosmological principle (CP) (Beisbart and Jung, 2006; Beisbart, 2009; Butterfield, 2014). The CP assumes that space is not only locally isotropic (roughly, the same in every direction from here) but also homogeneous (roughly, the

[3] As I do not want to presuppose realism, I will use "viability" as a generic epistemic term to represent the epistemic status of a theory rather than truth.

same in every place or, equivalently, isotropic about every point in space). Thus the universe as a whole is taken to be (nearly) spatially uniform.

The CP can be used to determine a subset of relativistic spacetimes permitted by the general theory of relativity (GTR), the theory of gravitation relevant for cosmological modeling. The spacetimes that respect the CP are known as Friedman-Robertson-Walker (FRW) spacetimes. Hubble's analysis of observations of receding galaxies in the 1920s suggested that space is expanding, so the appropriate subset of FRW models for modeling our universe is the set of FRW spacetimes that have an initial stage of expansion. These are the FRW spacetimes that may serve as possible hot big bang universes. In an HBB universe, the universe begins in a hot, dense state and then expands (at a decelerated rate) and cools, so that localized observers like ourselves observe every part of the universe (galaxies, for example) moving away from them (in what is known as the Hubble expansion). More accurately, an observer observes the wavelengths of light emitted or absorbed from distant objects shifted relative to what one would expect in local experiments, which lengthening of wavelengths is known as redshifting.[4]

The HBB model was remarkably successful as the standard cosmological model of the latter half of the 20th century (Kragh, 1996; Longair, 2006). Two theoretical problems, however, eventually led to its modification by the introduction of inflation (Earman, 1995; Earman and Mosterín, 1999; Smeenk, 2005, 2013). These problems are generally known as the horizon problem and the flatness problem (Dicke and Peebles, 1979; Linde, 1990). Both problems arise from the kind of explanation that the HBB model gives of certain cosmological conditions. The HBB explanation of these observationally-inferred cosmological conditions depends on the universe beginning with very special initial conditions, for which reason these are often called fine-tuning problems (McCoy, 2015).

The horizon problem begins with the observation of the (near) spatial isotropy of the universe, from which one infers (on the basis of the CP) its (near) spatial homogeneity as well. In order for the HBB universe to be as spatially uniform as it is now, it had to be extraordinarily uniform near in time to the big bang itself. If it had been the slightest bit less uniform initially, the universe would be nowhere near as uniform as it is now. This fine-tuning of initial conditions required to yield the presently observed uniformity is therefore perhaps better described as the "uniformity problem" (Earman and Mosterín, 1999, 18). A more robust explanation of uniformity than the HBB model's (which depends on special initial conditions) is, however, precluded by the presence of particle horizons in the model (this being the origin of the name of the problem). Particle horizons separate the observable universe into a large number of causally disconnected regions, i.e. regions of the universe that could never have physically interacted (in such a way so as to insure uniformity). These horizons thus represent an obstacle to devising a physical scenario to explain flatness and uniformity which would be less dependent on special initial conditions.

The flatness problem starts from the recognition that the universe's spatial geometry is very close to flat (or Euclidean). To be as nearly flat as we observe it to be today, the universe's spatial curvature had to be extraordinarily flat near in time to the big bang. If it had been any more curved, the universe would have never produced stars and galaxies or else would have quickly contracted back into a big bang. The fine-tuning of initial conditions required for this degree of flatness is known as the flatness problem. A more robust explanation of flatness than the HBB model's (which depends on special initial conditions) is, however, precluded by the presence of particle horizons as well (McCoy, 2015). Thus the presence of horizons represents a constraint on solving both problems.

Inflation is a cosmological scenario that was first proposed by Guth (1981) to solve the horizon and flatness problems.[5] Inflationary theory is based on the supposition that the very early universe underwent

[4]Further details on HBB cosmology can be found in standard cosmology textbooks (Dodelson, 2003; Mukhanov, 2005; Weinberg, 2008) and in some work aimed at philosophers (Smeenk, 2003; Ellis, 2007; McCoy, 2016). Precise mathematical details can be found in (McCabe, 2004; Malament, 2012).

[5]Guth (and other early adopters of inflation (Linde, 1982; Albrecht and Steinhardt, 1982)) was also somewhat concerned to solve a cosmological problem that arises in grand unified theories (GUTs) in particle physics. This problem, the monopole problem, is that in certain GUTs magnetic monopoles are created in sufficient numbers that they should be observable, but in fact no magnetic monopoles have ever been observed. As it is an external problem (Penrose, 1989) in the context of HBB cosmology (it only concerns

a brief period of accelerated and exponential spatial expansion. This expansion greatly increases the size of particle horizons—indeed, to such a degree that the entire observable universe fits within a single causally-connected region. Note that this accelerated expansion is in contrast to the decelerated Hubble expansion that figures in the HBB model (which in any case takes over after the end of inflation in order to maintain consistency with the empirically confirmed aspects of the HBB model). Proponents of the theory claim that the effect of inflation is to flatten the spatial geometry of the universe and make its contents more uniform. (One may usefully—if in some important respects disanalogously—picture the inflation of a balloon, which decreases the curvature of the balloon's surface and smooths small irregularities on the surface.) This mechanism is thought to operate for a brief period in the very early universe, giving rise to the conditions that eventuate in the presently observed spatial flatness and uniformity.[6]

The HBB model's fine-tuning problems are not problems concerning the model's consistency or empirical adequacy, since the model is certainly capable of explaining the present flatness and uniformity of the universe. Why does the universe have a flat geometry? Why is the universe so uniform? According to the HBB model it is because the universe was initially very uniform and close to flat; it then evolved (according the the dynamical laws of general relativity) to the present degree of uniformity and flatness. This is clearly an explanation of the kind that is paradigmatic of physics.

Instead the problems raise concerns over the kind of explanation given by the model (Earman and Mosterín, 1999). The essence of the problems is that only the explanatorily-deficient special initial conditions can give rise to certain currently-observed conditions within the context of the standard HBB model. The special initial conditions of the HBB model are explanatorily deficient because they are not robust. They make the explanations of which they are part *fragile*: if the conditions had been ever so slightly different, the explanation no longer would hold.

Since these conditions, uniformity and flatness, are supposed to be natural outcomes of inflation, cosmologists maintain that the previous paradigm's fine-tuning problems are solved by inflationary theory. Inflationary models explain our observations better than the HBB model, because inflationary theory is able to give more robust explanations of uniformity and flatness. The universe could have begun with a range of initial conditions which would eventuate in a present universe as flat and uniform as we observe it. This is certainly not to say that inflationary theory suffers from no fine-tuning of its own.[7] It is just to say that the inflationary explanation is better than the HBB one: it does not depend on special initial conditions to the degree that the HBB one does.

It is important to emphasize that at the time of its introduction inflationary theory could not be said to differ in its observable consequences from the HBB model. As already noted, this is because the inflationary stage must "smoothly splice" into some early stage of the hot big bang universe so that the latter's observationally confirmed content (the existence of the cosmic microwave background (CMB), light element abundances in accord with big bang nucleosynthesis, and the Hubble expansion) are not lost. The CMB is particularly important in cosmological research, for it provides observational evidence of the earliest times available to us. It is a remnant of the decoupling of light from matter, which light has since traveled freely throughout the universe with an imprint of the primordial perturbations from uniformity at the time of decoupling. Since inflation occurs well before the decoupling of light from matter responsible for the CMB, inflation itself is *in principle* observationally inaccessible (as are the initial conditions of the universe). Accordingly, basic inflationary models are observationally equivalent to HBB models.

Initially, inflationary theory also had no clear observational consequences which would differentiate it from the standard HBB model. Hence, cosmological theory in the early 80s is an actual case of transient

speculative theories in particle physics), it will not be discussed here.

[6]See (Smeenk, 2003, 2005, forthcoming; McCoy, 2015) for philosophical criticism and historical details concerning inflationary theory.

[7]Smeenk (2003, 182) remarks that there is a trade in fine-tuning of initial conditions for fine-tuning of other physical characteristics of inflation, e.g. its potential. McCoy (2015) also discusses fine-tuning in the context of inflation.

underdetermination (Sklar, 1975, 1981; Stanford, 2001, 2006) of theory by evidence.[8] The only clear difference between the two, then, is in how they explain observed cosmological conditions like uniformity and flatness. This circumstance is precisely what makes the case an important one, for it isolates explanatory considerations. In most familiar historical cases, by contrast, differences in explanatory considerations are accompanied by empirical differences, such that epistemological differences can always be easily attributed to the empirical ones.

Cosmologists were evidently not bothered by this lack of distinguishing empirical evidence and quickly adopted the inflationary framework for theorizing (Earman and Mosterín, 1999; Smeenk, forthcoming). The usual reason given then (and to a significant extent even to this day) was that inflationary theory solved the HBB fine-tuning problems (Lightman and Brawer, 1990). Although inflation was quickly accepted during inflationary theory's early history, at present the generally acknowledged best argument for inflationary theory is not that it (allegedly) solves these problems however; instead it rests on the striking observational confirmation of predictions later developed out of the inflationary framework, specifically of a very precise spectrum of small anisotropies in the cosmic microwave background.

It was soon realized after the introduction of inflation that quantum fluctuations in a hypothetical scalar field (the "inflaton") responsible for inflation could seed the primordial density perturbations of the hot big bang (Mukhanov and Chibisov, 1981; Guth and Pi, 1982; Hawking, 1982; Bardeen et al., 1983), which density perturbations are then later imprinted in the CMB (and eventually give rise to structure formation—galaxies, stars, etc.—in the universe as a whole). This development came quickly on the heels of the general acceptance of inflation (within one to two years). Nevertheless, it is clear from the cited papers that the motivation for this work was to build on the accepted success of inflationary theory at solving the HBB model's fine-tuning problems, not merely the realization that inflationary theory was capable of generating new predictions of CMB anisotropies.[9]

The existence of these anisotropies in the CMB was observed by NASA's Cosmic Background Explorer (COBE) in the early 90s, although the precision of the observations was limited. The inflationary predictions of a precise spectrum of anisotropies that are adiabatic, gaussian, and nearly scale-invariant were (arguably) confirmed in the early 2000s by WMAP (Mukhanov, 2005; Linde, 2007; Baumann, 2009). More recently they were (arguably) confirmed, and with even greater precision, by the Planck satellite (Linde, 2014; Guth et al., 2014).

To what degree inflationary theory is actually confirmed by these observations remains a matter of debate (Ijjas et al., 2013, 2014). It is striking, however, that a research program motivated by and widely accepted on the basis of its solution of mere explanatory problems should lead to specific, novel predictions that are then confirmed much later. It is a case from modern physics, like the Higgs mechanism (Dawid, 2013; Friederich et al., 2014), where it seems like theoretical physicists were right about a theory well in advance of its confirmation and seemingly *knew* they were right. It is a task for the philosophy of science to make sense of such episodes, so to this task I turn.

3 Empiricist Interpretations of Inflationary Case

In this section I consider how this historical episode would be understood from an empiricist point of view on scientific epistemology. Certainly there are a variety of views that could be considered empiricist in outlook. Nevertheless, I take it that a fundamental tenet of a broadly empiricist view of science is that scientific knowledge is empirical knowledge. Thus it is at bottom our empirical knowledge that must justify acceptance of scientific theories (accepting that scientific theories go beyond empirical knowledge).

[8] It is irrelevant to the decisions of actual scientists whether theories are "in principle" underdetermined given all possible evidence. What matters is if theories can be distinguished given presently available or expected future empirical tests.

[9] To be sure this work did not come out of a vacuum. The relevant pre-history to inflation, particularly the many contributions by Soviet physicists like Starobinsky, is presented in detail in (Smeenk, 2003).

If an empiricist holds that a scientific theory is epistemically justified, it is because our empirical knowledge in some sense warrants it. There are various more precise empiricist positions one could therefore take that differ on just what justifies this acceptance. I consider two—what I will call simple empiricism and predictivism—which illustrate the most salient empirically grounded features of scientific theories—empirical adequacy and empirical confirmation.

The simplest empiricist conception of epistemic justification of scientific theories requires only that a scientific theory is empirically adequate.[10] A theory is empirically adequate, roughly speaking, if the theory's observable consequences correctly describe the known phenomena within its purview.[11] The standard of warrant is therefore consistency. This is obviously an empiricist conception of epistemic justification, since theory acceptance is licensed solely by agreement with empirical knowledge. Thus, on this conception of epistemic justification if a theory is empirically adequate, then it is epistemically justified to accept the theory.

Empirical adequacy is a fairly weak standard on epistemic justification, i.e. it is permissive with respect to theory acceptance. Note that on the simple empiricist view no empirically adequate theory is better justified than its empirically adequate competitors. It therefore follows that theory choice (or acceptance) is, for the simple empiricist, necessarily based on non-empirical grounds when empirical evidence transiently underdetermines theory. These grounds may provide merely a pragmatic warrant to accept a theory (van Fraassen, 1980) or may be driven by social or contextual values (Longino, 2002). The strict kind of empiricist which I am describing here does not, however, allow for these grounds to *epistemically* justify the choice. Less strict empiricists may of course allow that some of these theoretical virtues or social values do so and continue to call themselves empiricists, but this is strictly speaking a significant departure from empiricism, in particular the fundamental epistemological tenet of empiricism noted above.[12]

Predictivism, the second empiricist position I introduce, maintains the doctrine that empirical knowledge is the ground for the epistemic justification of scientific theory, but also holds that the empirical confirmation of novel predictions confers greater credibility to the hypothesis that makes them than a hypothesis which merely accommodates the same empirical facts. Whether predictivism is correct has been vigorously debated in the past few decades (Worrall, 1985; Maher, 1988; Nickles, 1988; Lipton, 1990; Collins, 1994; White, 2003; Barnes, 2008; Harker, 2008; Douglas and Magnus, 2013). Regardless of the truth of the doctrine, we can at least state an appropriate conception of epistemic justification on the behalf of the predictivist: a scientific theory is epistemically justified to the extent that its novel predictions are empirically confirmed. A theory that does not offer novel predictions or whose predictions remain untested is accordingly unjustified.

Predictivism is especially noteworthy in the present context since there is a predictivist analysis of the case of inflationary theory (Earman and Mosterín, 1999). Earman and Mosterín's principal claim is that inflationary theory is epistemically unjustified. Thus they are clearly not simple empiricists (in the sense defined above), since the HBB model and the inflationary modification thereof were at the time of the latter's devising up until the 2000s equally empirically adequate to known observations. By the simple empiricist standard of epistemic justification the two theories were therefore equally epistemically justified. According to the predictivist interpretation of the story of inflation the HBB model was epistemically justified because it made novel predictions (the existence of the CMB and light element abundances in accord with big bang nucleosynthesis) which were observationally confirmed (Earman and Mosterín,

[10]van Fraassen (1980) holds something very much like this conception, although there are various particularities of his view, which, because they are not relevant to my overall argument, I will not add here.

[11]To avoid any confusion, I should emphasize that I restrict "observable" to a time contemporary to the assessment of adequacy, for this is the standard relevant to the decision making of actual scientists. It matters not for methodology what in principle could be or could have been observed by hypothetical, all-knowing scientists of the past and future.

[12]If all it takes to be an empiricist is to accept that empirical considerations are epistemically relevant, then almost nobody fails to be an empiricist. Hence empiricism would not be a position worth discussing. I take it that proper empiricists in fact exist and do accept the fundamental epistemological tenet presented above.

1999, 19); inflationary theory merely accommodates these predictive successes after the fact. Thus, according to the predictivist, the HBB model was better justified than inflationary theory at the time of the latter's proposal and acceptance in the community.

The post-2000 observation of a precise spectrum of anisotropies by the WMAP and Planck satellites which confirm novel predictions of inflationary theory should, according to the predictivist standard of epistemic justification, reverse the judgments of Earman and Mosterín's 1999 assessment, for at that time only the imprecise detection of some degree of CMB anisotropy had been obtained by the COBE satellite. The HBB model by itself suggests no novel predictions of the spectrum of inhomogeneities in the matter distribution of the universe, since it is by assumption spatially homogeneous. Lacking any motivation for a particular primordial spectrum of inhomogeneities, the HBB model becomes disfavored with respect to inflationary theory. For the predictivist this is entirely due to the successful confirmation of inflationary theory's predictions.

It is worth pointing out that the HBB model can in fact be easily modified (ad hoc) to accommodate the new data by introducing by fiat the correct primordial spectrum of spatial inhomogeneities that accounts for the observed anisotropies.[13] Thus, on a simple empiricist assessment the empirical adequacy (and justification) of both the HBB model and inflationary theory remains equivalent (although naturally the pragmatic assessment of these two theories by cosmologists may have changed).

Inflation has been widely accepted by theoretical cosmologists since shortly after its introduction and continues to be widely accepted at present as a core component of the contemporary standard model of cosmology (the so-called ΛCDM model). Since there was no epistemic reason for the initial acceptance according to the predictivist, he must explain the sociological fact of inflation's adoption by the community of theoretical cosmologists by non-epistemic factors. From the common empirical point of view of simple empiricism and predictivism such facts about theory choice can only be accounted for by pragmatic, sociological, or other contingent historical factors, since there is no rationally compelling epistemic reason to favor (for the simple empiricist) one empirically adequate theory over another or (for the predictivist) to adopt an untested speculative proposal. Indeed, Earman and Mosterín (1999, 6ff.) unsurprisingly offer precisely these kinds of factors to explain the quick adoption of inflationary theory in the early 80s.

In this section I have provided two interpretations of this scientific episode based on standards of epistemic justification motivated by prominent empiricist doctrines found in the philosophical literature. The predictivist account offers the following claims and explanations:

1. (<1980) The HBB model is epistemically justified because of the successful confirmation of its novel predictions.

2. (1980) Inflationary theory is epistemically unjustified because it does not offer any novel predictions.

3. (early 1980s) Inflationary theory remains epistemically unjustified because its novel predictions are unconfirmed.

4. (early 1980s) Inflationary theory's adoption by cosmologists is understood to be for pragmatic, social, or other non-epistemic reasons.

5. (2000s) Inflationary theory is epistemically justified because of the successful confirmation of its novel predictions.

The simple empiricist account offers these:

[13] As a referee puts it, the output spectrum of inhomogeneities of any early universe theory, e.g. inflationary theory, can be taken as an initial condition of the HBB model.

1. (<1980) The HBB model is epistemically justified because it is empirically adequate to all observed cosmological phenomena.

2. (1980) Inflationary theory is equally epistemically justified because it is empirically adequate to all observed cosmological phenomena.

3. (early 1980s) Inflationary theory's adoption by cosmologists is understood to be for pragmatic, social, or other non-epistemic reasons.

4. (2000s) Inflationary theory is epistemically justified because it is empirically adequate to WMAP observations, as is an ad hoc HBB model appropriately modified.

4 A Confutation of Empiricist Interpretations

Is the empiricist epistemology adequate to interpreting this historical episode? I argue in this section that it is not. The central claim of my argument is that empiricist explanations of inflationary theory's epistemic success must accept an implausible degree of luck in its attainment. A methodological view that attributes such luck to scientific successes evinces some degree skepticism toward the idea that the methodology of science is a reliable means of securing scientific knowledge. If such skepticism is severe in degree, then it should, like any philosophical skepticism, be held in abeyance where there are viable philosophical alternatives. I propose my explanationist alternative in the next section.

To begin, it is worth remarking that luck of various kinds certainly does play an ineliminable role in the sciences. It is surely the case that Guth, for example, was quite lucky to hit on the idea of inflation and its solution to the HBB model's fine-tuning problems. With respect to scientific methodology accepting some degree of luck is just to recognize that the methods of science offer no infallible means to scientific knowledge. There is, after all, no general logic of discovery (Nickles, 1990; Schickore, 2014).

The kind of luck relevant to my argument is what might be called "methodological" luck. By methodological luck (admittedly an oxymoron) I mean a case where epistemic success is achieved by means of a method no better (epistemically) than random guessing (Nickles, 1987).[14]

Attributing a sufficiently high degree of luck to scientific successes threatens the explanatory power of any epistemology that demands it. Either the methods of science are sufficiently reliable, economical means to epistemically justified theories, or, with Popper, we conclude that "the success of science is not based upon rules of induction, but depends upon luck, ingenuity, and the purely deductive rules of critical argument" (Popper, 2002, 70). A preponderance of clear cases of luck of this sort would either indicate that the methodology of science is indeed unreliable (if methodological at all) and hence could not explain many clear cases of progress, or else it would suggest that some economical methods have so far been overlooked within that conception of scientific methodology. In the latter case, examples thought to be matters of luck may in fact be rather sensible applications of legitimate methodology (Jantzen, 2016). Even a single case of significant putative methodological luck, however, may put pressure on the reliability of a conception of scientific methodology that accepts it, particularly if the case is a central development within some science.

I claim that the successes of inflationary theory represent just such a case. The case demonstrates that empiricism does lead to an undesirable methodological skepticism, for empiricist methods and standards of justification are inadequate to explaining these successes. To make the point clear, it is necessary to

[14]It is difficult to provide a precise rendering of the concept, since it depends on being able to specify a relevant set of possible theories over which one may guess. This depends on making assessments of transient underdetermination with respect to several things, such as the relevant criteria of epistemic appraisal, scientificality conditions (Dawid, 2013), etc. Due to such difficulties, the overcoming of which would contribute little to the present argument, the intuitive characterization I have given must suffice for this paper.

explain, following Nickles (1985), how discovery and progress (i.e. epistemic success) are connected to epistemic justification.

For methodology to be epistemically relevant to the progress of science, standards of epistemic justification should be appropriately related to the methods of theory generation. That is, "there must be some degree of coupling between the modes of generating theories and criteria of epistemic appraisal" (Nickles, 2000, 92). Otherwise our modes of generating theories are no better epistemically than blind guessing. This is because methods of discovery—the modes of generating theories in Nickles' terminology or positive heuristics in Lakatos's—furnish candidate theories which are subsequently subject to the relevant criteria of epistemic appraisal (e.g. the empiricist criteria of epistemic justification, etc.). Unless the modes of generating theories furnish candidates in a way that lends sufficient credence to their future viability (with respect to the appropriate criteria of epistemic appraisal), then there is no reason to expect methods of discovery to be epistemically relevant. Thus we see that discovery is epistemically relevant to justification if methodology is indeed economical in this way.

Consider how this functions in the context of empiricist epistemology. The empiricist view of science can certainly provide an acceptable account of those cases, so familiar from the history of science, where recalcitrant empirical data motivated the development of theories to save the phenomena responsible for them. It is no surprise that theories generated to save these phenomena should do so, as there is a strong coupling between the empiricist standard of justification and the heuristic that guides discovery based on it. Recall that empirical adequacy is the most basic empiricist conditions on epistemic justification. Recalcitrant data represents an empirical problem for science (Laudan, 1977), because a theory that cannot account for the associated phenomena is epistemically unjustified according to this basic condition. Such empirical problems obviously motivate the discovery of—in a sense, generate—theories which can account for the unaccounted for phenomena. Success in this endeavor—judged according to the basic empiricist condition on epistemic justification—represents progress over previous theories which could not. In this way solving scientific problems of empirical adequacy is motivated and success is judged by standards of epistemic justification.

Consider, for contrast, a methodology that privileges *simple* theories. There is evidently no coupling between a mode of generating simple theories and empiricist criteria of epistemic appraisal, since empiricism would only sanction simplicity as epistemically relevant when observations are in fact appropriately simple. A mode of generating simple theories is thus successful only as a matter of luck. It is therefore not epistemically relevant unless there is also an epistemic criterion of simplicity. There could seemingly only be such a criterion, however, if the world is in fact appropriately simple, which it is evidently not in any substantive sense. Therefore one is left to consider simplicity as at best only a pragmatic factor.

Returning to the case of inflation, it is crucial to recognize that inflation was motivated, i.e. generated, by the explanatory problems of the HBB model, not by empirical problems or its provision of novel predictions.[15] In other words, inflationary theory did not come about by the generative methods related to empiricist-sanctioned conditions on epistemic justification. Its acceptance in the community too was neither based on solving an empirical problem nor its promise of novel predictions, but on its putative solution to these explanatory problems. Thus its later epistemic success through the confirmation of its novel predictions cannot be wholly attributed to the empiricist's epistemologically-approved methodology.

From a methodological point of view, empiricists are therefore forced to attribute inflationary theory's adoption and later empirical success to luck. Of course some degree of methodological luck is surely acceptable, and the empiricist is happy to concede that there is much luck in science in order to preserve his epistemology. Still, there must be a point where the degree of luck becomes implausible. As I argued

[15] Although, as a referee points out, it should be noted that the HBB model in concert with certain grand unified theories is inconsistent with the absence of magnetic monopoles. This is indeed an empirical problem, but it is not one of the primary motivations for inflation, and definitely not a motivation in the context of cosmology (rather it is a motivation for certain speculative theories of high energy physics).

above, when the luck involved is significant enough, i.e. preponderant or acutely severe, the empiricist position must countenance a corresponding degree of methodological skepticism. I claim that attributing inflation's success to methodological luck is indeed implausible for the luck involved is acutely severe. I provide two supporting arguments.

First, several factors point to the significance of this historical episode in cosmology: the inclusion of inflation as one of the central pillars of the present standard model of cosmology; the fact that COBE, WMAP, and Planck, the primary missions of which were to measure anisotropies in the CMB, were among the most important experiments in cosmology in the past few decades; the centrality of inflationary model-building to contemporary theoretical practice. If one of the most significant episodes in the history of scientific cosmology can only be methodologically explained by luck, this alone casts some serious doubt on the efficacy of scientific methodology in cosmology.

Second, when one looks at the precise predictions from inflationary theory and compares them to the spectrum of CMB temperature anisotropies, one finds a strikingly precise agreement in essentially all respects (Guth and Kaiser, 2005, 888). Practically speaking, one could not have intuited the spectrum of spatial inhomogeneities responsible for these anisotropies from the theoretical point of view of the HBB model, which makes no assumptions at all about possible divergences from perfect homogeneity, whereas the observed spectrum is (ostensibly) a natural prediction of inflationary theory. If cosmologists were merely guessing at possible spectra or theories that predict them, they likely would have been wrong given all the overwhelming number of alternative possible spectra of inhomogeneities. Favoring simple spectra would have made it more likely to guess the actual spectra, but, as pointed out above, simplicity is not epistemically relevant and hence a matter of luck. Thus, from the empiricist point of view inflationary theory must be viewed as an extraordinarily lucky guess.[16]

The methodological luck involved in empiricist interpretations of the inflationary case is therefore severe. It follows, then, that empiricist epistemology is committed to a degree of methodological skepticism. It is thus far more plausible to suppose that cosmologists' acceptance of inflationary theory was epistemologically motivated—in other words, that their confidence in inflation's viability for future empirical test was epistemologically justified. Therefore epistemic justification should be more than empirical adequacy or a high degree of empirical confirmation, at least if one is to avoid a pronounced and implausible skepticism in the methodology of science.

5 Explanationist Interpretation of Inflationary Case

If there were no reasonable alternative interpretation of the inflationary case according to which inflationary theory was epistemically justified, then perhaps one should be willing to accept the methodological skepticism attendant to empiricist epistemology. There is, I suggest, a reasonable alternative, one manifestly suggested by the case itself: inflationary theory was epistemically justified well in advance of its empirical confirmation because of its solutions to the HBB model's explanatory problems. Indeed, cosmologists standardly argue in favor of inflation—even in contemporary textbooks, papers, and reviews—for exactly this reason. If its acceptance were only for non-epistemic reasons, then its later empirical success would be, as I argued in the previous section, a matter of luck—methodological skepticism would then be close at hand. So instead, we might consider that (at least in some cases or contexts)

[16] An important consideration when intuitively assessing underdetermination in this case is whether there are alternative theories of the early universe that could seed the initial perturbations which lead to the empirically confirmed spectrum of anisotropies in the CMB. If the nearly scale-free (flat) spectrum of perturbations is not really a distinctive prediction of inflation, then inflationary theory's success would not seem quite so lucky from an empiricist point of view. Smeenk (forthcoming), for example, has pointed out that in the early 70s, before the advent of inflation, Harrison (1970), Peebles and Yu (1970), and Zeldovich (1972) all gave various independent arguments for the initial spectrum of perturbations being scale-free. Whether their arguments are sufficient to establish the naturalness of the observed spectrum is an issue which clearly requires further careful analysis, not only to assess this aspect of inflationary theory's empirical consequences but also the degree to which inflationary theory is in fact confirmed, as cosmologists generally claim.

a method of discovery based on solving explanatory problems is economical, i.e. reliably leads to success by an explanationist standard of epistemic appraisal. The prominence of this case in the history of cosmology and the striking confirmation of inflationary predictions should, I think, lend this thought at least some plausibility.

One way to argue for such a standard is to give an account of why solving explanatory problems is epistemically relevant.[17] I do not have such an account and, in any case, am doubtful whether explanationism can bootstrap its way into epistemology. Another way, the one I take here, is to use the empiricist standards of justification to argue for the epistemic relevance of solving explanatory problems, since we know that these empiricist standards are reliable. In short, I argue that solving some explanatory problems, e.g. the HBB model's fine-tuning problems, is economical as judged by empiricist standards of appraisal, e.g. empirical adequacy. To the extent that solving explanatory problems is economical according to these standards one is licensed to introduce an independent explanationist standard of appraisal. In this way we ground an economy between a method of discovery based on solving explanatory problems and the assessment of solutions on the basis of an explanationist standard of appraisal—without having to moot an account of *why* it works.[18]

The explanationist interpretation of the inflationary case then provides the following assessments:

1. (<1980) The HBB model is empirically justified because it meets the empiricist conditions but explanatorily unjustified because it suffers from various salient fine-tuning problems.

2. (1980) Inflationary theory is explanatorily justified because it solves the HBB model's fine-tuning problems.

3. (early 1980s) Inflationary theory is partially empirically justified by its empirical adequacy, although its novel empirical predictions remain unconfirmed.

4. (early 1980s) Inflationary theory is adopted by cosmologists because it is sufficiently epistemically justified.

5. (2000s) Inflationary theory is epistemically justified because of its empirical adequacy (and the successful confirmation of its novel predictions).

Solving explanatory problems is surely not as reliable as empiricist-sanctioned methods, but so long as explanationist methods are better than guessing they will be sufficiently reliable to count as methodological. The inflationary case, I claim, strongly suggests that at least in some contexts solving explanatory problems is economical. The importance of such a method should be particularly salient in contexts, like cosmology and high-energy physics, where the more reliable standards of epistemic appraisal are inapplicable or unreliable due to experimental and observational limitations. Indeed, such situations have become increasingly common in the physics of the last century, although I suspect they may be found elsewhere in science, especially in other historical sciences besides cosmology. I have offered only one case here (although I think it is a strong case); the epistemological significance of explanationism ultimately depends on the degree to which explanatory considerations play an important role in science as a whole.

One would naturally like to have a clear account of why solving explanatory problems is methodologically reliable. My aim in the present paper is more modest. I wish to show only that some methodological account is desirable to make sense of the inflationary story and that the explanationist one fits well. More work is required to establish whether other cases fit and what it is, precisely, that explanation contributes to the viability of theories.

[17] A referee points out that a natural story to tell is that explanatory considerations are truth-tropic. However, in keeping with my remarks in the introduction, I do not wish to take a stand one way or the other on the realism question.

[18] I do not assume that success by this standard of appraisal licenses an inference to the truth of the theory, as I do not wish to presuppose realism or the validity of IBE. It is sufficient for my purposes that success by this standard only confirms the viability of the theory (where "viability" refers to some epistemic value weaker than truth).

6 Concluding Remarks

I have argued that explanatory considerations can epistemically justify theories on the basis of the case of inflationary cosmology. Inflationary theory was proposed and accepted in the cosmological community because of its solution of the hot big bang model's fine-tuning problems. These problems are explanatory problems, for the HBB model's explanations of certain cosmological conditions are fragile in a way compared to which inflationary theory's explanations are more robust. I claim that at this point inflationary theory was already adequately justified, such that the later observational confirmation of the theory only reinforced the epistemic justification that the theory already enjoyed.

Although my proposal is an explanationist one, I emphasize again that it does not necessarily presuppose that explanatory considerations can justify inferences to truth like inference to the best explanation purports to do. It is therefore not committed to scientific realism—although it is certainly compatible with it. For this reason my argument advances reasons to take seriously the methodological role of explanation independently of the considerations raised in the scientific realism debate. These reasons are based not on general philosophical arguments but rather on attention to scientific practice in an actual historical case.

I argued against broadly empiricist interpretations of this case in order to show that standards of epistemic justification that go beyond empiricist standards are required to account for the successes of inflationary theory. Empiricist interpretations cannot adequately explain the success of inflationary theory, essentially because the acceptance of the theory cannot be attributed to methods of theory generation sanctioned by empiricist standards of justification. This circumstance becomes problematic when one considers the likelihood of this success. I argued that the degree of luck involved (which the empiricist necessarily must accept) is severe in this case, such that the empiricist interpretation must countenance a significant and undesirable degree of methodological skepticism in science. To avoid this skepticism some "extra-empirical" standard of justification is required; the one that is naturally suggested by the case of inflation is the explanationist one I propose.

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