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THE COPERNICAN PRINCIPLE AND EVIDENCE IN MODERN COSMOLOGY

Abstract: Modern cosmology is not merely an empirical science but a domain deeply embedded in philosophical considerations. Various theoretical models of the universe that are underdetermined by evidence rest upon foundational principles, leading to epistemic and ontological debates about the status of these principles. The Copernican Principle is one example; it has played a crucial role, shaping the conceptual framework of cosmic structure and evolution. This preliminary critical examination of the Copernican Principle (Cosmological Principle) within the context of modern cosmological models explores its theoretical and evidential challenges and its indispensability. Although neither purely operational nor ontological, the principle has served as a key theoretical hinge to generate models and desired observational grounds within a field challenged by protracted underdetermination of models and theory by evidence.

Key words: cosmology; Copernican Principle; underdetermination; evidence

1. Cosmological Models

There is some controversy about when exactly cosmology was established as a modern scientific field (Kragh 1996). Some say it began with the 20^{th} century development of the first cosmological models to apply relativistic field equations (successfully tested in the Solar System by Edington) to the level of the universe. Others point to the discovery of the cosmic microwave background (CMB) in 1965 (Penezias and Wilson 1965) confirming these models. What cannot be debated is that modern cosmology was built in the first two decades after WWII (Kragh 1996) on a foundation of competing models that sought to explain the origin, structure, and evolution of the universe during the so-called Great Controversy.

These models were not developed as theoretical constructs only, simply seeking to align with the available observations or to predict observed properties. They also purported to have profound philosophical implications and inherent principles that properly belonged to the domain of philosophical study, particularly their treatment of initial conditions, physical laws, and the nature of reality (Kragh 2013). This contention, plus the glaring underdetermination of cosmological models by data (Perović and Ćirković 2024, Ch 8; Ellis 2014), underscores the need for a careful philosophical analysis of the assumptions and principles underlying them.

1.1 Big Bang Models

The so-called Big Bang model, the cosmological framework that has emerged as the winner in the protracted cosmological "wars", first appeared in the mid-20th century in the work of scientists like Georges Lemaître, George Gamow, and Robert Dicke. De Sitter (1916) and Friedmann (1922) applied relativistic field equations at the cosmological scale prior to WWII. Lemaître's (1931) proposal of an initial "particle" that expands according to relativistic field equations as the origin of the universe laid the groundwork for the concept of an initial singularity from which the universe expands. Then, in the 1940s and 1950s, Dicke (1961) and Gamow (1949) developed a detailed model, with all the basic stages of the expansion of the universe. The model predicted the key observable properties, in particular, the microwave background radiation as a remnant of the primordial fireball of matter and radiation and its properties (Figure 1).

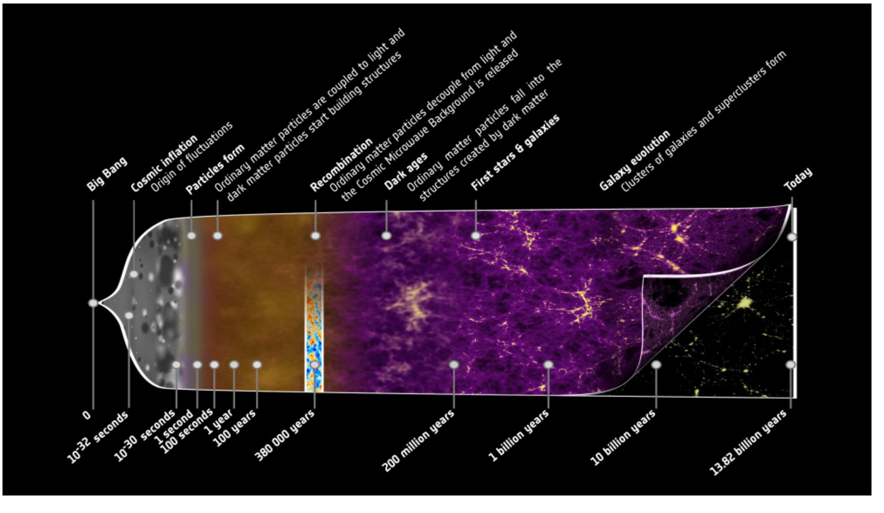

Figure 1: The basic stages of the evolution of the universe in the Big Bang model. (The diagram was originally posted as a Wiki-commons item.)

This predicted phenomenon – of seemingly strange 3K microwave radiation coming from all points on the sky, initially thought of by the discoverers as noise – was discovered in 1965, and after a protracted series of observations and arguments over its properties (temperature, isotropy, shape of the spectrum), it was finally confirmed as the remnant of the primordial fireball when detectors were placed on satellites in early 1990s (Perović and Ćirković 2024). We should note that this wasn't as easy as textbook accounts may suggest; various early Big Bang models, such as the Tepid Big Bang, Cold Big Bang, chaotic universe scenarios, and others also explored variations in initial conditions, each offering a different perspective on the universe's early state (Ibid).

It was also obvious from the start that the initial singularity raises deep epistemological questions as it does not imply the existence of space in any obvious way; rather, it seems to suggest a point where physical laws, particularly General Relativity, may break down. The epistemic status of this singularity triggers fundamental questions about whether it represents a genuine feature of reality or a limitation of current physical theories. The philosophical problem of why the universe began with particular initial conditions remains an open question, influencing contemporary debates on fine-tuning and multiverse theories (Ellis 2014).

1.2 Steady State Models

In contrast to the Big Bang model(s), the Steady State models of the universe, championed by figures like Fred Hoyle, Hermann Bondi, Thomas Gold, and others, posited an infinite and unchanging universe. These models, prominent from the 1930s to 1960s and remaining alive until the 1980s, argued for a constant density of matter over time, achieved through the continuous creation of matter, and the steady expansion of an infinite universe. They dealt with the continuous origination of matter in various ways. Most prominently, Fred Hoyle (1948) introduced a universal scalar creation field (C-field) as the mechanism providing the non-collapsing steadily expanding dynamics of the infinite universe that otherwise would eventually decelerate and collapse due to gravitational pull – as the Big Bang models initially predicted. The Steady State models' explanation of the spectral redshift (shift to the red region of the spectrum) of the receding galaxies was pretty much as convincing as that of the Big Bang models, so the multi-decade controversy was based, in part, on the interpretation of this key piece of evidence – at least until 1965 and the discovery of the CMB.

The Steady State framework for models explicitly relied on the assumption that physical laws are immutable, thereby avoiding the need to explain contingent initial conditions (as there were none) (Bondi and Gold 1948, Gregory 2005, Perović and Ćirković 2024, Ch 18). This assumption reflected a deeper epistemic commitment to the idea that the universe should not exhibit special initial conditions, and any principle underlying cosmological models should stick to epistemologically sound views.

1.3 Alternative Models

Unlike the Big Bang and Steady State models, other cosmological frameworks, such as Dirac's cosmologies (Dirac 1974; Perović and Ćirković 2024, Ch15), suggested physical constants might vary across time and space. Roger Penrose (1979) proposed the arrow of time arises from specific initial conditions rather than fundamental laws. These alternatives highlight the philosophical tension between necessity in physical laws and contingency in cosmological explanations, raising questions about the nature of physical laws themselves and their dependence on boundary conditions. But they do so in a rather different direction than the Steady State models.

2. The Copernican (Cosmological) Principle

In the foundational discussions of the models mentioned above, one principle stands out. The Copernican Principle, a cornerstone of modern cosmology, asserts that the universe is homogeneous and isotropic – in other words, it appears the same in all directions and all locations (Weinberg 1972). Thus, the density of radiation and matter cannot vary greatly, nor will it matter at which point one measures these values.

The principle has both strong and weak formulations, each with distinct philosophical and scientific implications relevant to the cosmological models at stake. The strong version, commonly known as Perfect Copernican (or Cosmological) Principle posits the universe is homogeneous and isotropic *at all times* and is thus characterized by constant density. This principle underpins all Steady State models, given their attempts to avoid the apparent contingency of the initial conditions of Big Bang cosmology. By assuming no cosmological feature escapes the laws of physics, the strong version of the Copernican Principle reflects an epistemological motivation to maintain regularity and predictability in the universe. (Bondi and Gold 1948, Hoyle 1955, Bondi 1960) Bondi and Gold provided a deduction into the cosmological models from the Perfect Cosmological Principle (i.e., the strong version of the principle).

The weaker version however, nowadays often simply equated with the label of 'Copernican Principle' without qualifiers due to the prevalence of the Big Bang model, allows for changes in density over time due to cosmic expansion. This version is compatible with Big Bang models describing a dynamic universe with evolving properties. Thus, the universe is homogeneous and isotropic *at any given tim*e, but not at all times, as it expands.

The Copernican Principle has been explicitly or implicitly challenged or rendered irrelevant by the alternative models, such as the models proposed by Dirac and Penrose suggesting homogeneity and isotropy may not hold universally. In Dirac's and Penrose's model, the Copernican Principle is treated as tenuous, if not dispensable, given that the physical laws themselves are either changeable or the result of arbitrary initial conditions.

The immediate philosophical challenge here is to identify what kind of principle the Copernican Principle actually is. Is it an empirical generalization to be tested, or some sort of necessary constraint on cosmological models? (Beisbart 2009) It is certainly treated as the former by astrophysicists (Camarena, Marra and Clarckson 2022), but its ontological status remains contested (Ellis 2014, Beisbart 2009, Besibart and Jung 2006). Does it have that sort of status at all? Is it a mere methodological assumption, or does it reflect an objective feature of reality?

Instead of going into discussion head-on I think we can set the stage for addressing and answering these questions by understanding the relationship between *the evidence and the principle*, both in practice and normatively. It is part of a more general question of how cosmologists treat principles such as the Copernican Principle in light of novel evidence, and what epistemic standards of the community ought to govern such a relationship. Examining this relationship will offer a unique perspective that may be more informative than simply looking at the relationship between the principles and the models.

3. Cosmological Models and Evidence

From the beginning of the 20th century and the development of relativistic cosmological models, the development of cosmological models has been shaped by ongoing efforts to reconcile theoretical predictions with observational evidence. The discovery of the CMB in 1965 provided strong support for the Big Bang theory, leading to the decline of Steady State models. However, the refinement of these models over four decades highlights the protracted scientific and epistemic battle between these competing frameworks and more than just transitory nature of underdetermination in the field (Perović and Ćirković 2024).

Cosmological evidence is primarily observational, not experimental, relying on signals from the deep past, such as the CMB. Unlike, for instance, an experimental field of particle physics, cosmology's evidential basis is observational and strongly model-dependent. This raises a question about the extent and space for interpretation of data and the role of theoretical principles in shaping scientific understanding across fields. The reliance on indirect evidence from the deep past – in fact as deep as naturally possible as far as we know – makes cosmology particularly susceptible to underdetermination of theories and models by evidence and to theory-ladenness (Perović and Ćirković, Ch. 8; Butterfield 2014; Ellis 2014). Even if underdetermination is transitory, it is protracted in cosmology in comparison to the fields where key parameters of interest can be controlled and varied in experimental conditions. In such a domain of available evidence, plausible and precise alternative models have been built, improved upon, and adjusted for decades. This applies to each key piece of evidence, be it redshift, CMB properties, or deceleration parameters. In a sense, the protracted proliferation and testing of various alternative models is a sign of a fruitful field if confined to observational, rather than predominantly experimental evidence.

4. The Copernican Principle and Evidence

4.1 The Copernican Principle as a theoretical hinge

The Copernican Principle's use as a guiding principle across cosmological models raises a philosophical dilemma. Is it a purely operational tool, and if so, how exactly does it "operate" within models? Or does it have unavoidable ontological features and implications indirectly connected to the models' parameters? Does any ontological feature go over and above the operational roles? Is this relevant to a particular model, and if so, how?

As I hinted in Section 3, instead of addressing the questions head-on here, I am taking a roundabout route. The goal is to determine what sort of role the Copernican Principle plays in the context of available or projected (by the model at stake) observational evidence. We can understand what the principle is if we understand how it functions in practice and how it ought to function given the nature of the scientific pursuit of cosmology as a scientific field.

First, undeniably, in cosmological work itself, the debates on the Copernican Principle have been couched as ontological (Perović and Ćirković 2024; Kragh 1996), and this, in turn, has defined the models' explanatory features. The debates and dilemmas stemming from them have been a staple of modern cosmological frameworks and debates among their proponents. This suggests the role of principles in cosmology extends beyond their operational utility, and that deductions concerning them have an impact on how models are created. But should we take the pronouncements and characterizations we find in the actual debates for granted? Are they perhaps only rhetorical devices?

Answering this question is a hefty task, with some sound philosophical analysis preceding the question concerning particular models (Beisbart 2009, Beisbart and Jung 2006), but if we stop using the usual philosophical labels for the moment, it seems clear that the Copernican Principle, as well as other similar principles, serves as a theoretical hinge for generating novel interpretations and models. It is initially formulated in a strong or weak fashion and then admitted into models as plausible by being connected with an operational parameter of some sort. Let me briefly state the case for this view.

The creators of both classes of early Steady State models argued vehemently for the strong version of the Copernican Principle (Bondi and Gold 1948; Gregory 2006; Kragh 2016; Kragh 2011). They not only thought it was plausible but they also either explicitly or implicitly pointed out what they argued were bad or even unacceptable implications of the alternatives. In this view, any principle that leads to the understanding of the laws of physics as immutable undercuts any attempt to understand the physical nature of the universe. The laws may be mutable, and if they are, we ought to give up attempts to understand the universe by means of physics. Thus, the weak version was not only judged as epistemically admissible and the preferred foundation of cosmological models, but was mostly regarded as the only viable option throughout the multi-decade development of various versions of Steady State models. Meanwhile, the key operational parameters of these models related to steady expansion and infinity, i.e., the properties of matter and radiation, were *aligned* with the strong version of the principle. Moreover, new parameters, such as the C-field, were introduced, and the observational parameters were interpreted along the lines of the models' key operational parameters aligned with the principle.

In fact, the proponents of the Steady State models (Bondi and Gold 1948) put weight on the restrictiveness of the Copernican Principle for ontological and epistemological reasons: to close what they regarded as the nonviable ontological possibility the weaker version opens up – the possibility of mutable physical laws – in light of the essential unknowability of the universe, that they thought contradicts our experience. The ontological concern and the formulation of the principle were thus pretty directly transferred through the red line of epistemic admissibility into the models' parameters. It's quite possible to speculate that the model could have been created without the deduction from the principle, but the fact is that the models were perfectly aligned with the Perfect Copernican Principle all along, and explicitly so. The speculation of that sort would be rather explanatorily vacuous.

The proponents of the Big Bang models followed somewhat different reasoning (Weinberg 1972). The weak version of the Copernican Principle was treated as an admissible foundation of the model, but its acceptance was more a consequence of weighing its plausibility against other features of cosmological models. The alternative, the strong version, was regarded as plausible but not inescapable. The operational parameters related to the expansion and density of matter and radiation over time were consistent with the weak principle but emphasis was put on the plausibility of the model's features and its increasing alignment with observations, rather than on the plausibility of the weak Copernican Principle *per se*. Yet this opened a can of worms: the status of initial singularity potentially fell out of the explanatory domain of the General Theory of Relativity, as I mentioned previously.

Moreover, after the 1980s, it turned out, precisely due to the shocking (to the Big Bang Proponents) observational result against which the principle was weighed, that the universe is accelerating, not decelerating as the proponents of the Big Bang models expected (simply due to the eventual gravitational pull of matter into itself – an implication that even Newton anticipated). The most convincing explanation of this result so far has resorted to the scalar inflationary field (Guth 1981, Linde 1990), a move not only reminiscent of, but inspired by, the scalar C-field introduction into the Steady State models (Gregory 2005, 324). The universe is not steadily expanding, as the proponents of the Steady State argued, but "something" makes it accelerate. And this "something" was conceptualized the way the C-field was. Thus, the observations eventually forced the Big Bang proponents to opt for the same kind of parameter (although of a different value), although most had previously argued this was an epistemically unsound if not entirely inadmissible move. This seems to suggest a rather hasty and more naïve epistemological attitude among Big Bang proponents than Steady State proponents, despite their triumph.

To make things even more complicated, the Dirac and Penrose cosmologies basically start with the open epistemic admissibility criterion as central and essentially treat the Copernican Principle as tenuous, to the point of making it only locally relevant. Dirac's model implies the mutability of physical laws is a plausible and preferable hypothesis that should be tested (Kragh 1982), while Penrose's model disposes of the notion that we are detecting universal physical laws at all, on cosmological grounds. Our universe is just a universe in the chain reaction of the creation of universes, the local boundary conditions of which determine what appear to us to be universal laws. Penrose suggested ways of testing his model, not just how existing observations aligned with it.

Thus, rather than characterizing it as purely operational, or ontological only in name, if we are true to the actual role the Copernican Principle has played in cosmological arguments, then we must accept that at least minimally, it has served as a theoretical hinge to justify or even generate operational parameters in novel models and interpretations and to generate novel sorts of observations or adjust models to novel observations (Figure 2). It has done so in different ways in terms of weighing various steps across models.

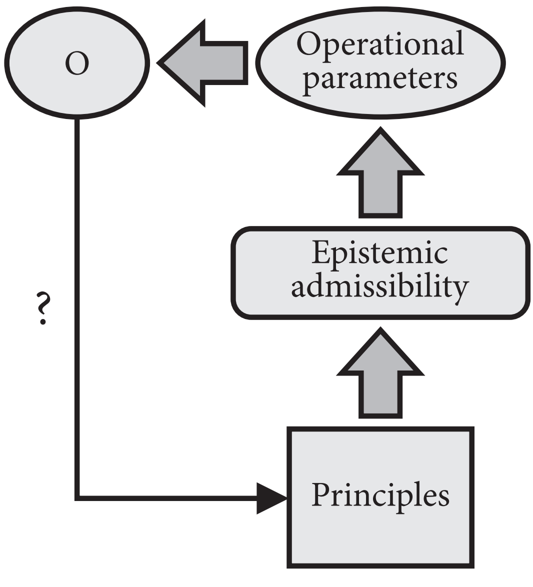

Figure 2: Various abstract principles are deemed as admissible or inadmissible into the cosmological models, on their own terms, then co-aligned with the operational parameters; finally, the latter are tested observationally. Whether the weight of the observational evidence suffices to give up the principles is the key question we consider.

4.2 Epistemological responsibility in cosmology, and theoretical hinges

This brings us to the second issue. When examining the status of a principle by looking at how it relates to observations, albeit indirectly via the operational parameters, in terms of epistemic responsibility when creating a model, at what point should a principle be abandoned in light of conflicting evidence? What strength of evidence is required to challenge a seemingly foundational principle, and thus the model it founds, via tested operational parameters?

The reasons for accepting or abandoning a principle in light of particular evidence offered by individual cosmologists can be analyzed on a case-by-case basis. But a more important general epistemological issue concerns the epistemological standards that ought to govern the community's treatment of models based on principles such as the Copernican Principle. When should they be accepted and when abandoned?

The return of ideas, such as the transition from the C-field in Steady State models to inflationary fields in Big Bang cosmology, is not an exception, although this particular case stands out. Generally speaking, in cosmology, models are underdetermined by evidence for protracted periods of time; thus, "fringe" alternatives that support or abandon established principles occupy a unique epistemic status. They have a special status compared to heavily experimental fields, where they are often justifiably treated as refuted and then abandoned (Perović 2021). The "tolerance" of an outlier that either holds on to a version of the Copernican Principle or abandons it wholesale should be a priority. Prolonged underdetermination requires diverse theoretical hinges and their application.

The interplay between principles and evidence in cosmology is obviously quite dynamic, but this evolution reflects broader questions in the philosophy of science about the persistence and transformation of theoretical commitments over time. Now, even in High Energy Physics, a heavy-handed experimental field, the situation is mixed, so to speak. During the first phase of experiments with colliding particles, the key parameters, such as energy, momentum, various charges, or angle of collision, can be manipulated at will. Yet after the collision, when the collided beams spray vast amounts of debris, sifting through the debris and analyzing it is very much in the domain of observational activity similar to astrophysicists scanning vast numbers of stars, clusters, and other celestial objects and inferring conclusions from their observations. The epistemological challenges in High Energy Physics may not be at the scale of cosmology due to underdetermination and observational uncertainties, but they are there nonetheless and worth thinking about for philosophical and pragmatic reasons.

5. Conclusion

The philosophical features of modern cosmology, as exemplified by the case of the Copernican Principle, reveal an intricate relationship between scientific principles, evidence, and philosophical inquiry. Cosmological models, from the Big Bang to Steady State theories, have reflected competing visions of the universe's nature and origins, while the underdetermination of cosmological theories by evidence and the evolving nature of observational data underscore the provisional status of even the most foundational principles. In such a context, the Copernican Principle, in its strong and weak forms, serves as a basis for models' construction and evaluation.

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