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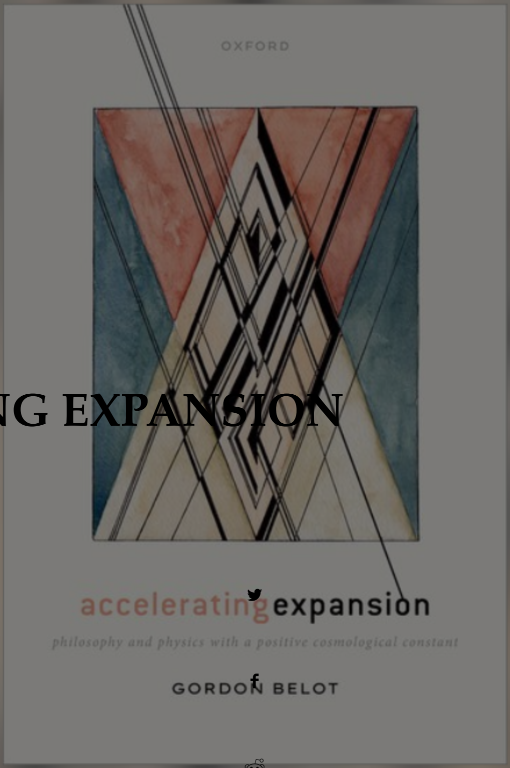

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Gordon Belot
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What would be the consequences of taking de Sitter spacetime as more fundamental to understanding physical geometry than Minkowski spacetime? De Sitter discovered his eponymous spacetime shortly after Einstein formulated general relativity, and it is the simplest—maximally symmetric—solution of the field equations with a positive cosmological constant (Λ). The standard model of cosmology attributes the majority of energy density in the universe to Λ. A cosmological constant remains (as the name suggests) constant as the universe evolves, and comes to dominate dynamically as other forms of matter and energy dilute with cosmic expansion—driving the large scale structure of spacetime towards de Sitter spacetime in the far future. Adding a non-zero Λ furthermore has a profound impact on the description of other domains, such as gravitational waves and black holes. As is familiar from the study of differential equations, adding a term to a set of equations, even if it is 'small', can radically change the structure of the space of solutions. In this case, the $\Lambda \to 0$ limit, to recover Minkowski spacetime, is not well behaved, undermining the use of mathematical techniques that exploit its structural features. There is now a substantial research literature devoted to the physics of de Sitter spacetime (and related spacetimes). It is hard to disagree with Belot's assessment that this is a 'field in which open problems extend as far as the eye can see' (p. x), and the literature abounds with ideas sure to provoke philosophers. *Accelerating Expansion* makes a compelling case that philosophers should get to work on these open problems—not only because they concern central questions regarding the applicability of physics and our epistemic situation, but because the provocations often stem from bizarre assumptions—and provides an orientation and training programme for those eager to join the effort.

Through several chapters, Belot takes the reader on a tour of de Sitter and related spacetimes. The first two chapters update the treatment given a half century ago in Schrödinger's ([1957]) wonderful *Expanding Universes*, using those figures along with new ones that Belot created in a similar style to effectively convey the geometry of de Sitter spacetime and the properties of various coordinate representations. The later chapters turn to related spacetimes: an alternative elliptical interpretation of de Sitter spacetime (chap. 4); anti-de Sitter spacetime, used to study black holes in string theory despite having a negative cosmological constant and bizarre causal structure (chap. 5); and asymptotically de Sitter spacetimes (chap. 6), which characterize the far future of cosmological models with positive Λ. Although the material is fairly standard within physics, Belot's treatment is systematic, lucid, and beautifully executed. (That is not to say easy; the exposition is terse, but repays careful reading.) This part of the book unfolds like a graduate-level textbook in mathematical physics, complete with exercises (and hints). Belot surveys several mathematical techniques routinely used in applying general relativity that are mostly unfamiliar to philosophers. Far from writing down the line element characterizing a solution and then studying its geometrical features, as Schrödinger did, modern relativists use conformal completions to study asymptotic behaviour, techniques from the study of partial differential equations to analyse the stability properties of specific solutions and systems of equations, and so on. Just as Earman's ([1995]) *Bangs, Crunches, Whimpers, and Shrieks* inspired philosophical research related to causal structure of relativistic spacetimes, *Accelerating Expansion* both introduces these techniques and identifies a number of foundational questions whose pursuit they enable.

Belot pauses at various points in the tour to elucidate and marvel at the oddities of de Sitter spacetime and to explore their foundational ramifications. Taking de Sitter spacetime seriously impacts many debates in foundations of spacetime theories, and I will highlight a few below. Belot's discussions of the more philosophical problems often start by giving a sharper reformulation to a line of argument from the physics literature (often from the early days of relativistic cosmology), but then leaves further analysis and assessment to the reader, guided by questions ranging in scope from puzzles resolvable in a few hours to viable dissertation topics. This approach leads to an initial survey of a wide range of issues, rather than a series of arguments for specific positions. Belot aims to conduct the survey in a 'non-judgmental fashion' (p. x), and indeed often leaves the reader with a rough map, a few landmarks (in the form of mathematical results), encouragement to find their own trail, and little or no idea what direction their guide would take.

Several of the striking features of de Sitter spacetime stem from its lack of a global time translation symmetry. When such a symmetry exists, as in Minkowski spacetime, it generates timelike orbits that correspond to observers who would see the local spacetime geometry as fixed. Although de Sitter spacetime is maximally symmetric, like Minkowski spacetime, its symmetries consist of rotations and boosts—which always have fixed points and hence do not generate (everywhere) timelike orbits. The consequences of this contrast are profound given the central role time translation symmetry plays in physics, from the definition of conserved quantities to the separation between positive and negative frequency modes used to define a Hilbert space inner-product in quantum field theory. In chapter 2, Belot draws out implications for simultaneity and the nature of temporal passage, developing a point Einstein made in 1918: 'time t cannot be defined in such a way that the three-dimensional slices $t = \text{const}$ do not intersect one another and so that these slices are equal to one another (metrically)' (quoted on p. 26). Far from providing grounds for rejecting de Sitter spacetime, as Einstein claimed, I agree with Belot's assessment that 'our inherited temporal concepts are not well-adapted' (p. 39) to life in de Sitter spacetime or, even more strikingly, in generic variably curved spacetimes of general relativity. Further reflections on general relativity are, characteristically, left to the reader: how much of a revision to our concept of temporal flow is required to accommodate gravitational time dilation is a 'smaller' question, whereas replying to Gödel's view that temporal flow involves modal claims rather than only features of a specific solution qualifies as 'larger'.

De Sitter spacetime further has an unusual status within the space of solutions of Einstein's field equations. Mathematical relativists have established a number of results regarding the global stability of specific solutions—roughly put, that 'small perturbations' decay away, generating a maximal solution that remains 'sufficiently similar' to the unperturbed background solution. Belot briskly summarizes several of these results (chap. 7), highlighting, among other things, questions raised by the expressions in quotation marks. A stronger type of result has been conjectured to hold for de Sitter spacetime, the 'cosmic no hair conjecture': that cosmological models with a positive Λ, satisfying various other conditions, asymptotically approach de Sitter spacetime. (The name derives from black hole uniqueness results, which aim to show that—like a bald head—a black hole can be simply characterized by a few parameters.) A proof of this conjecture would show that de Sitter spacetime acts as a dynamical attractor in the space of solutions. This is not necessarily good news, for the mathematical structures used to characterize asymptotic de Sitter spacetime turn out to lack features that have been essential to characterizing gravitational radiation and defining conserved quantities. Chapter 6 provides a conceptually oriented introduction to the techniques of conformal completion, nicely illustrating the balancing act involved in introducing mathematical structures appropriate to characterize 'isolated systems' in general relativity. The balancing act fails in de Sitter spacetime and its relatives. This is a further consequence of the lack of a timelike symmetry: de Sitter spacetime lacks an asymptotic timelike symmetry, by contrast with the asymptotic structure of Minkowski spacetime used to describe isolated systems.

The final two chapters turn to puzzles regarding the epistemic situation of observers in de Sitter spacetime. A Λ-dominated universe evolves into a cold and lonely place: all the galaxies we currently observe in the night sky will drift further away, leaving our descendants isolated in the galaxy that results from the merger of the Milky Way with Andromeda. The first puzzle arises in any cosmological model in which observers can see only a finite portion of the spacetime they inhabit. All of the observations that the observers can make, in principle, can be embedded in a second spacetime with quite different global structures. Glymour ([1977]), Malament ([1977]), and Manchak ([2009]) have distinguished relations of observational indistinguishability of varying strength and studied what global properties vary among observationally indistinguishable spacetimes. Belot raises some objections to this line of thought on epistemological grounds. In particular, weaker versions of the relation crucially do not require that 'typical' observers in one spacetime will 'see the same thing' as typical observers in an observationally indistinguishable counterpart. But Belot's main concern is to explore the implications of a line of argument developed (at great length) by Ringström ([2013]). There is a peculiar form of localization in a Λ-dominated universe: the physical state within a compact region (say, a 'ball' that is a subset of a Cauchy surface, Σ) determines the solution globally at arbitrarily late times. Observers at late times are then (as Ringström puts it) 'oblivious' to the topology of the full Cauchy surface, Σ; roughly speaking, for any standard cosmological model there is an approximately indistinguishable rival model with different global topology. A question running through this argument concerns how to characterize the epistemic predicament of cosmologists. While cosmologists have devoted some effort to assessing, for example, the impact of compact topologies on observable features of the cosmic microwave background radiation, to my mind results like Ringström's raise more pressing challenges to inferences cosmologists routinely make regarding local features of the observable universe. Cosmologists rely on the standard cosmological models to infer that there is a large Λ-like contribution to the energy–matter density of the universe (the primary reason for taking de Sitter spacetime seriously) from observations of accelerating expansion. Does this inference hold up to further scrutiny as relativists learn more about the full non-linear dynamics of general relativity? Belot classifies the assessment of a conjecture also discussed by Ringström, that the near-isotropy of the universe can be explained as a consequence of dynamics without requiring Λ, as a ('smaller?') exercise for the reader.

Suppose we follow the evolution of a Λ-dominated universe into the far future, to an era where stars have burned out and the physical state approaches equilibrium—a modern version of Kelvin's 'heat death'. Physicists have estimated the probability that fluctuations from the vacuum state in a patch of asymptotic de Sitter spacetime, treated as a closed quantum system, will yield 'Boltzmann brains' (brains complete with 'memories' of the observed universe, that fluctuate out of the vacuum and persist momentarily). In standard cosmological models with a positive Λ, the number of these Boltzmann brains far outnumbers the 'real observers' who exist during our epoch of cosmic history. This (allegedly) generates a novel sceptical paradox: if we take our selves to be 'randomly chosen' from among the physical states that are compatible with what we observe, we should expect to be a Boltzmann brain rather than a real observer. Within physics, this argument is taken to generate a new empirical constraint: we should reject theories that predict a high rate of Boltzmann brain production. But as soon as one tries to lay out the argument more carefully, as Belot does, a number of deeply problematic assumptions come to light. (What does it mean to assert that we are a 'typical' observer, and how would we justify this assumption?) While Belot provides ample background for assessing this argument—through tracing its historical roots and offering a primer on statistical physics—he characteristically plays his cards close to the chest, and ends with a longer than usual series of questions for the reader. It is clear that there is further work to be done: this literature is filled with open questions, but these often reflect deep confusion on foundational issues.

In sum, despite a topic that appears esoteric, *Accelerating Expansion* shows that taking de Sitter spacetime seriously generates remarkably interesting foundational questions that have been central to active discussions in mathematical physics. It introduces philosophers to some of the mathematical infrastructure designed to apply general relativity that has been developed over the last fifty years, in part through considering a case where it breaks break down. Although Belot aims primarily to elucidate rather than resolve the open questions and foundational confusions in this area, this text will inspire and enable philosophers of physics to make further progress.

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