Spacetime Substantivalism and Einstein's Cosmological Constant

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Abstract

I offer a novel argument for spacetime substantivalism: we should take the spacetime of general relativity to be a substance because of its active role in gravitational causation. As a clear example of this causal behavior I offer the cosmological constant, a term in the most general form of the Einstein field equations which causes free-floating objects to accelerate apart. This acceleration cannot, I claim, be causally explained except by reference to spacetime itself.

1 Introduction

Although the era of Newtonian physics is past, the controversy between substantivalist and relationist conceptions of space and time that began with Newton and Leibniz has not subsided. The three-dimensional Euclidean space of classical physics has been replaced with the four-dimensional, variably curved spacetime of general relativity (GR), but the question faced by the classical physicists and their philosophical contemporaries remains much the same today: What sort of entity is spacetime; indeed, is it any sort of entity at all? A relationist answers in the negative, holding that all spatial and temporal properties are reducible to properties of material objects, while

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a substantivalist maintains that spatiotemporal features are not so reducible, so that reference to these properties commits us to understanding spacetime as an entity existing separate from the objects contained within it. This is the ontological problem of space and time.

Today the ontological problem divides philosophers of physics into many camps. Some have suggested, and others (Rynasiewicz 1996) have explicitly argued, that the debate is outmoded in the context of GR, and that the relationist and substantivalist positions have become indistinguishable.[1] Those still concerned with the problem agree that GR is incompatible with relationist views on inertial motion (Sklar 1976, 216-221), but there is some controversy over whether inertial properties are really spatiotemporal properties (Earman and Norton 1987) or whether they can be explained as dispositions of objects instead of features of spacetime (Teller 1991). The correct answer to the ontological problem may seem to be a matter of “first philosophy,” a purely interpretive question. To the contrary, I offer here an argument from empirical physics to metaphysical conclusions, and hopefully a satisfactory resolution of the ontological problem.

At the time of GR’s inception, the most well-known and prominent objection to substantivalism was Mach’s principle of the relativity of inertia. In an attempt to vindicate the relationist ideas of Mach and make possible a static distribution of matter in the universe, Einstein introduced the cosmological constant (Λ) into the field equations of GR. Here I argue that because Λ manifests itself as a constant average curvature of empty spacetime, a built-in tendency of the universe to expand, it is an instance of nontrivial causal powers that we ought to ascribe to spacetime itself. Ironically, then, it seems that observations of a nonzero Λ provide evidence for the substantivalist position. For this reason, philosophers of physics should pay close attention to astronomical data that indicate a possible nonzero cosmological constant.

2 Einstein’s cosmological term

It is widely recognized that one of Einstein’s objectives in introducing Λ was to make possible static solutions to the field equations. Less well known is his early hope that Λ could help make GR compatible with Mach’s principle.

[1]For a refutation of these claims, see Hoefer (1998).

Without Λ, the field equations are

$$R_{ij} - \frac{1}{2}Rg_{ij} = \kappa T_{ij}. \tag{1}$$

It is easily established that Eq. (1) admits a solution with no matter content, i.e. $T_{ij} = 0$ – assuming standard boundary conditions, this is flat Minkowski spacetime. Einstein viewed the possibility of an empty universe as incompatible with Mach's claim that the inertial properties of any possible universe should be fully determined by its matter content. But he believed that his (1917) revision of the field equations to include the cosmological constant,

$$R_{ij} - \frac{1}{2}Rg_{ij} + \Lambda g_{ij} = \kappa T_{ij}, \tag{2}$$

had no solution for $T_{ij} = 0$, removing one obstacle to a Machian interpretation of GR (see Earman 2001, 193). This hope was foiled by the discovery of the De Sitter solution (cf. Eq. 5).

Machian or not, Λ's full significance to the broader substantivalist-relationist debate remains unaddressed, for the possibility of absolute motion in space itself is not the only point of disagreement between the two schools of thought. The relationist is committed to the claim that all supposed spatiotemporal properties are reducible to properties of objects. This ought to include not just motion, but also any additional properties that might be ascribed to spacetime. Does Λ represent such a property, and if so, is it reducible in a way that conforms to relationism? This question becomes more pressing in light of recent astronomical discoveries indicating a positive value for Λ (see Cohn 1998, 12).[2]

3 A causal argument for substantivalism

To see what sort of causal role Λ plays in GR, we must first examine the mechanism of gravitational causation in the theory. While Λ's repulsion may not be a gravitational force in the ordinary sense, the form of Eq. (2) does, I

[2]Other possible explanations for the cosmological repulsion include a contribution to the effective Λ from the energy density of the quantum vacuum, or a form of exotic matter with negative pressure, called "quintessence." Let us set these aside as beyond the scope of this paper, and concern ourselves from here on with a "bare" cosmological constant appearing in the field equations (2).

believe, justify the claim that Λ is the *same sort of thing* as gravitation. Its role in the field equations is to influence, by itself or in combination with other terms, the metric structure of spacetime, and thereby to affect the physical behavior of matter. This is exactly the sort of influence that accounts for gravitational forces in GR, the only difference being that Λ does not depend on matter as its source. Therefore, I shall begin my analysis of Λ's causal behavior with a study of gravitational causation.

Here I use the term 'causation' in a somewhat nonstandard way. As Sklar (1976, 75) notes, neither the spacetime structure nor the matter distribution precedes the other. Rather, GR tells us which distributions of matter are compatible with which spacetime structures, and vice versa. Nonetheless, this lawlike connection does allow for apparently causal relationships within spacetime, like the case of one object moving toward another under the influence of gravity. If the object had been alone in space, it would not have moved at all. I therefore suggest that causation in GR should be interpreted after the fashion of Mellor (1980, 287) who writes that cause-effect relationships mediated by spacetime structure should be expressed "by counterfactuals: had the action not occurred, the structure of spacetime would have been different."

Gravitational radiation is perhaps the starkest example of spacetime's seemingly independent causal behavior, and so I shall attempt to see if a good substantivalist argument can be built around it. Consider a binary star system, with two stars of equal mass rotating around their common center, forming a gravitational quadrupole (see Rindler 2001, 330-335). As time passes, the radius of their orbit will decrease and the speed of rotation will increase, reducing the total kinetic energy of the system. The missing energy is released in the form of a gravitational wave, consisting of a region of metric curvature that propagates at the speed of light. Suppose that a wave released in this way at time t_1 comes into contact at time t_2 with a simple detector, e.g. a pair of masses connected by a spring. The wave will induce tidal forces on each mass, causing the system to oscillate and thus to gain kinetic energy. An astrophysicist observing the binary star system and the detector might ask two questions: (a) what entity was the immediate cause of the oscillations in the detector, and (b) between t_1 and t_2, what entity possessed the energy that left the star system at t_1 and entered the detector at t_2?

The point of this example is that a substantivalist has a satisfactory answer to questions (a) and (b), while a relationist does not. From the perspective of substantivalism, it makes perfect sense to say that the moving region of metric curvature was the cause of the oscillations and the carrier of the energy. But there is no immediately obvious way for the relationist to explain what happened without compromising his position or departing in some significant way from the common-sense story about gravitational causation that I sketched previously.[3]

3.1 Spacetime: metric or manifold?

A promising route for the relationist may be to accept GR's description of gravitational waves, but deny that metrical structure should be construed as a property of spacetime. This amounts to arguing that the manifold – the set of spacetime points themselves, considered without reference to the metrical structure – is the only proper subject for substantivalism. This allows the relationist to claim that only the manifold counts as 'spacetime itself.' Since the energy of the gravitational wave is contained in the metric, which describes only the gravitational field, it is not a property of spacetime. The restriction of substantivalists to mere manifold substantivalism might be justified by appeal to Earman and Norton (1987).

Earman and Norton argue that the identification of spacetime with the manifold draws a clear distinction between spacetime and its contents. In GR, they write,

> ...geometric structures, such as the metric tensor, are clearly physical fields in spacetime... Consider, for example, a gravitational wave propagating through space. In principle its energy could be collected and converted into other types of energy, such as heat or light or even massive particles. If we do not classify such energy bearing structures as the wave as contained within spacetime, then we do not see how we can consistently divide between container and contained. (1987, 519)

But this is quite an impoverished conception of spacetime, as Maudlin (1988, 87) notes. Many structural properties which we normally take to be spatiotemporal – e.g., distances, intervals, volumes, past and future – are

[3]Further trouble for the relationist may arise from the possibility of sourceless plane wave solutions to the field equations, but it seems open to the relationist to reject these solutions as unphysical.

properties of the metric, not the manifold. The only such properties possessed by the manifold itself are its dimension and its topological and differential structure. Most glaring, perhaps, is the fact that the bare manifold does not distinguish the time dimension from the three spatial dimensions (Hoefer 1996, 11).

Of course, a consistent division between container and contained is the first step on the road to relationism. For substantivalism entails at least one significant similarity between spacetime and its contents: both exist. If we assume from the start that spacetime can have no effect upon (other) existing objects, it seems we have already conceded much to the relationist. Instead of being an *a priori* distinction underpinning the ontological debate, the container/contained distinction should be seen as a point of contention.

One might wonder what sort of ontology Earman and Norton have in mind for the metric. By their reckoning, it is a physical field, so perhaps we should take it to be a field of force. Instead of spacetime structure, perhaps the *gravitational field* is the dynamical medium described by GR's metric. But the metric is no mere force field. As mentioned above, it determines causal structure, distance, past, future, and so on. No other force plays such a broad role in defining the physical arena of discourse. In fact, other field theories depend explicitly upon many of these metrical properties; for example, the inverse-square law governing the attenuation of the electric field is meaningless without a measure of distance. So it seems that the metrical field is not a field of *force,* it is a field of *geometry.* If geometry is a material field, it is wildly different from all other forms of matter. It should be identified as such only under the pressing force of a compelling argument.

Earman and Norton's argument is not, I believe, compelling enough. I fail to see why the possibility of causal interaction between spacetime and its material contents prevents us from distinguishing between spacetime and ordinary matter. In fact, it is easy to do so: as Earman and Norton note, the stress-energy of the metric takes the form of a pseudo-tensor, while normal matter's stress-energy is specified by the tensor T_{ij}. In Eqs. (1) and (2) there is a simple way to discriminate between spacetime and its contents: the left-hand side of the equation describes the spacetime structure, and the right-hand side describes the contents.

This interpretation not only maintains the container/contained distinction insofar as possible, it also holds to the spirit of the historical dispute by identifying motion and inertia as spatiotemporal properties. Leibniz's original arguments for relationism rested on the indistinguishability of universes in distinct states of uniform motion, or universes in which every object is translated by a fixed distance. Newton's reply, the famous "bucket argument," appealed to the experimental consequences of absolute acceleration. To accept an interpretation (mere manifold substantivalism) which holds that states of motion are not spatiotemporal states would be to disregard the most basic assumptions of both Newton and Leibniz. If it were philosophically well-motivated, such an interpretation would call into question the very distinction between substantivalism and relationism, just as Rynasiewicz argues. But my main point is that in forming our concept of spacetime, we should try to hold onto as much of the classical concept of space and time as our new theories allow. Manifold substantivalism does not accomplish this.

3.2 "Radiation" without energy: Hoefer on gravitational energy and causation

There may still be hope for a "liberalized relationism" of the sort advocated by Teller (1991). This form of relationism recognizes possible as well as actual spatiotemporal relations as proper subjects for science. It is conceivable that a liberalized relationist could form an account of gravitational radiation that expresses its effects as constraints upon possible events. Such an account would hold that the (purely relational) distribution and motion of matter is connected in a lawlike way with the possible, as well as actual, motion of objects. Even in the case of gravitational radiation, spacetime plays an intermediary role in causation, and so this phenomenon might be reducible to a lawlike connection between the configuration of one matter system (the binary star system) and the possible spatiotemporal paths open to another system (the detector). I would be surprised to see a relationist explanation of this sort that does not also entail the reducibility of other (non-gravitational) fields and forces to merely relational constraints upon possible motion, but I do not unequivocally deny that this is possible. Perhaps relationists would welcome such reducibility.

A position like Teller's suffers from its disregard for the energetic nature of gravitational radiation. It is hard to deny the existence of a structure which can carry energy; if energy is not a mark of substance, one may be left with no reason to believe in the existence of matter. The best move for the relationist may be to deny that gravitational radiation is energetic. Hoefer (2000) makes exactly this argument.

GR obeys a limited sort of energy-momentum conservation law:

$$T_{ij;j} = 0 \tag{3}$$

Note that this law restricts only the covariant derivative of the stress-energy. A true conservation law would require a zero partial derivative, i.e, $T_{ij,j} = 0$. As it is, the matter field described by T_{ij} can gain or lose energy and momentum. In fact, this is exactly what happens in the example of gravitational radiation: the apparent transfer of energy from matter to the gravitational field.

There is a term that can be taken to describe the energy of the gravitational field: the gravitational stress-energy pseudo-tensor t_{ij}. The sum $T_{ij} + t_{ij}$ is conserved, but only for spacetimes satisfying very stringent conditions. In particular, this "total energy" is only conserved in asymptotically flat spacetimes, ones which approach flat Minkowski spacetime at infinity. The actual universe does not meet this condition. Also, because it is not a proper tensor, t_{ij} exhibits some strange properties. It does not possess well-defined values at particular points; at any point, there exists a coordinate transformation which will take t_{ij} to zero (Hoefer 2000, 193). Thus there is no clear way to localize gravitational energy.

On these grounds, Hoefer argues that we lack sufficient reason to accept that the metric can possess energy. From the lack of a conservation law, we know that GR can countenance a net gain or loss in the energy of an isolated system. We also know that the energy of a gravitational wave is not localizable, and so behaves quite differently from material energy. It is therefore possible to maintain that the only *genuine energy* (Hoefer's term) is localizable energy. On this picture, when a gravitational wave is "emitted" its source loses energy, and when the wave is "received" the receiver gains energy, and that's all there is to it. Energy disappears from the source upon emission, and energy appears in the receiver upon reception.

If Hoefer is right about this, there is nothing stopping the relationist from claiming that the causal behavior of a gravitational wave is no more than a primitive lawlike correlation between the source and the receiver. Thus construed, gravitational waves do not really exist at all, and so can provide no evidence for substantivalism. But Hoefer's account is not obviously the right way to understand gravitational energy. GR does represent the metrical field as causally efficacious – gravitational waves have the power to accelerate matter. If such powers are not a sure sign that an entity possesses energy, one might ask what basis we have for ascribing energy to material objects? In fact, one might credibly argue that energy is just an expression of an entity's potential to cause motion, and if the gravitational stress-energy pseudo-tensor describes such causal potential it should be accepted as genuine energy.

In the absence of a concrete proof, it may be best to interpret a theory conservatively. But which is more conservative: to accept that gravitational waves transmit energy which is nonlocal, or to maintain that one physical system can cause acceleration in another without the transmission of energy?

Hoefer is right in one regard: I cannot prove that the metric possesses energy as real as that of matter. The interpretation of gravitational energy that he outlines may be counterintuitive, but it has not been shown to be false, and so it remains an option for the relationist. Thus, although GR's description of gravitational causation seems to favor the substantivalist, it also admits a possible relationist interpretation. I will now reveal how Λ changes the rules in this regard by exerting causal influence over material objects while remaining unexplainable in terms of material causes, and by ascribing an undeniably real density of energy to empty space.

4 From Lambda to substantivalism

The form of the field equations (2) suggests a natural interpretation of Λ. Whatever influence Λ has on the motion of objects should, I submit, be seen as a gravitational effect. It affects which values of the metric are compatible with which matter distributions, and so helps to determine the value of the gravitational field.

Let us consider the qualitative features of a universe with nonzero Λ. In a region empty of matter, represented by $T_{ij} = 0$, Eq. (2) gives

$$R_{ij} = \Lambda g_{ij} \tag{4}$$

so for $\Lambda \neq 0$ we have $R_{ij} \neq 0$. Taking the trace of this Ricci tensor, we find that the scalar curvature is $R = 4\Lambda$. Thus we can immediately see that the new field equations entail constant average curvature of spacetime in the absence of matter. The basic, sourceless solution to the field equations is no longer flat Minkowski spacetime; instead, it is dictated by the value of Λ.

One might wonder whether Λ could be viewed as a field of its own, separate from the metric field, whose effects combine with those of gravity. In fact, this is not really possible. GR is a non-linear theory, and so contributions to the field from separate sources do not simply add together. Λ's contribution to the metric field cannot in general be isolated from the contribution of matter sources.

The cosmological constant is (or describes) a property of *something*. I submit that Λ describes a property of spacetime itself, specifically a basic, "unperturbed" amount of curvature that is altered, but not entirely created, by the presence of matter. In a universe with $\Lambda = 0$, this basic state is flat Minkowski spacetime, and gravitational causation between physical objects is mediated by variations in curvature due to matter. In a universe with nonzero Λ, on the other hand, spacetime does not merely mediate causation between objects. It is also quite capable of causing motion among the objects.

4.1 Lambda's causal powers

A nonzero value of Λ in the field equations (2) leads to considerable differences in the motion of material objects. To form an accurate model of Λ's effect on matter, we shall first consider its influence on a few isolated test objects in an otherwise empty universe. Consider the case of two test objects alone in otherwise empty space, separated by radius r. Choosing a frame with a test object O_1 (of trivial mass) at the center, we can predict the motion of another test object O_2 by solving the field equations (2) for the spacetime at a distance r away from a massless object. The solution is the de Sitter metric,

$$ds^2 = -(1 - \frac{1}{3}\Lambda r^2)dt^2 + \frac{dr^2}{1 - \frac{1}{3}\Lambda r^2} + r^2 d\theta^2 + r^2 \sin\theta d\phi^2. \tag{5}$$

The potential can be approximated as $\Phi = (-g_{00} - 1)/2$, which gives

$$\Phi(r) = -\frac{1}{6}\Lambda r^2. \tag{6}$$

This is the potential at the location of O_2, a distance r from O_1. O_2 will then move under the influence of a gravitational force given by $F = -m\nabla\Phi = -m(\frac{1}{3}\Lambda r)$, where m is O_2's (negligible, by assumption) mass. O_2 will move under this force with an acceleration $a = (\frac{1}{3}\Lambda r)$, where positive a signifies motion away from O_1. This repulsive (positive) force is not the result of any interaction between the two masses. This becomes clearer if we remove O_1;

$r = 0$ then signifies an unoccupied reference point. Even in this case, O_2 is influenced by a force – it is accelerated by $a = (\frac{1}{3}\Lambda r)$, a quantity that depends only on the values of r and Λ. No other object is causing O_2's motion. The only explanation for it is Λ, i.e. the constant average curvature of the spacetime.

I have no illusions that this model will satisfy a relationist. After all, with no objects in the test universe aside from O_2, the idea that O_2 is accelerating at all is unacceptable to a relationist. For one thing, there is no possible experiment in this empty universe that could discover O_2's motion – the Λ repulsion acts like a gravitational force, and so O_2 will feel no inertial forces as it accelerates under the influence of this force. Without any other objects to use as reference points, the relationist might argue, it is meaningless for me to say that O_2 is in motion. The apparent acceleration is just a misleading feature of the theory, and there is no need to causally explain this unobservable "acceleration" at all. So much for Λ's causal influence on O_2.

This objection is apt, and it correctly points out that by referring to an unobservable absolute acceleration, a feature which can exist only if substantivalism is correct, the above model begs the question. But this problem is easily fixed. Put O_1 back into the test universe, but place it very far from O_2, so that its worldline does not lie in O_2's past light cone.[4] This means that there can be no causal connection between O_1 and O_2 – they are far enough apart that no signals have had a chance to pass between them. Now we can use O_1 as a reference point to measure the motion of O_2, and sure enough, O_2 will accelerate away from O_1 at a rate proportional to r. This cannot be the result of any interaction between the two objects since, by assumption, they are too far apart for any signal moving at or below the speed of light to have gone between them. Nonetheless, any observer lying within the future light cones of both O_1 and O_2 can measure their motion.

It is hard to envisage something more substantival than spacetime which is curved in the absence of matter. To preserve relationism in spite of this, the relationist must demonstrate that the constant curvature can be explained only as properties of physical objects, without reference to spacetime except in terms of actual and possible relations between objects. Is a relationist reduction of this sort possible for Λ, and if so, how much is lost in the reduction? I do not doubt that a persistent relationist could describe Λ's

[4]This is possible in a De Sitter universe because of the De Sitter event horizon which manifests at $r = \sqrt{\frac{3}{\Lambda}}$.

effects as mere relational properties, but the price will be high. Considering my example of distant objects moving apart under the influence of Λ, the relationist would have to posit a brute fact that material objects possess a tendency to accelerate away from one another at a rate proportional only to the distance between them. But this could not be described as a causal relational property of material objects, since it has been established that objects in a Λ universe will move apart even when no causal connection between them is possible. So a relationist explanation of Λ would entail that spontaneous acceleration can occur without any cause, but in a lawlike way that can be described by the analysis of this section.

In Section 3 we saw that the metric of GR is capable of carrying causal signals between physical objects. Λ seems to be something more: a description of causal relationships that hold between curved spacetime and its material constituents. A relationist could deny the possibility of such relationships as a matter of principle, but this would oblige him to deny that the sort of motion described in the previous section is caused by anything at all. Relationism then becomes the doctrine that spacetime describes a set of spatiotemporal relations which spontaneously change without cause. This is not a very attractive position, even if we accept the notion that lawlike regularities might hold in the absence of causal connection.

4.2 Lambda's undeniable energy

We saw in Section 3.2 that the relationist can avoid the implications of the causal argument for substantivalism by denying that spacetime mediates causal relationships between physical objects, and by denying that it possesses energy. I have shown that in Λ universes the relationist cannot deny spacetime's causal powers without also abandoning causal talk about a broad set of common-sensically causal phenomena. I will now show that Λ's presence also prevents the relationist from denying, as Hoefer does, that empty space can possess energy.

We saw in Eq. (4) that Λ entails a nonzero average scalar curvature R in the absence of matter sources. This constant curvature entails an energy density of empty space, meaning that even empty regions will contain a certain amount of energy manifested in the curvature. To see why this is so, take Eq. (4) and insert it back into the *original* field equations (1):

$$\Lambda g_{ij} - \frac{1}{2}(4\Lambda)g_{ij} = -\Lambda g_{ij} = \kappa T_{ij}. \tag{7}$$

We see that Λ's influence is equivalent to a constant stress energy $T_{ij} = -(\frac{\Lambda}{\kappa})g_{ij}$. In a comoving frame, the first entry in the stress-energy tensor is $T_{00} = \rho c^2$, and in a weak field $g_{00} = -c^2$, so the energy density of empty space entailed by Λ is

$$\rho_\Lambda = \frac{\Lambda}{\kappa}. \tag{8}$$

This does not mean that Λ is caused by a density of matter fields; rather, its role in the field equations is *equivalent* to (or represents) a density of empty space.

This is, I think, another way of conceptualizing the point I made at the beginning of this section, that Λ represents the sourceless, unperturbed curvature of spacetime. We can see from Eq. (8) that in a Λ universe, space itself is a source for the gravitational field. Its contribution to the curvature of the metric combines with that of other (material) sources in the usual nonlinear way described by the field equations of GR. And this contribution can be seen as equivalent to a constant, nonzero energy density in the absence of matter sources.

Because this stress-energy takes the form of a tensor Λg_{ij}, it is just as localizable as the energy of matter fields described by T_{ij}. Hoefer's argument against the reality of gravitational energy therefore does not apply. Λ's energy meets all of the same criteria as "genuine" material energy, and so if we want to maintain that T_{ij} describes real energy, we had better accept the reality of ρ_Λ as well.

Besides the fact that Hoefer's argument has been bypassed, I can see no easy way for the relationist to explain the energy density of empty space. The density and total energy of the electric field (for example) depend only upon the distribution of charge, i.e. the distribution of matter. Not so for the repulsive gravitational field described by Λ. Its energy density does not depend upon matter at all, and its total energy within a region is purely a function of the volume of the region. It is possible for a liberalized relationist of Teller's sort to define the volume of empty space in terms of possible spatial relations, but to say that such possibilia help determine the actual total energy content of a region seems quite at odds with relationism.

I can conceive of a relationist theory of gravity incorporating all of the phenomena described by Λ, but I believe that such a theory would contain much needless complexity and require a considerable departure from our basic concepts of what causation is and what sort of behavior requires causal explanation. Therefore, a universe described by a cosmological constant of the sort conceived by Einstein is not a universe friendly to relationism. If the universe's expansion is found to be accelerating, and a cosmological constant introduced into the field equations is the best explanation, then relationism about space and time will become a far less defensible position.

References

[1] Cohn, J.D. 1998. "Living with Lambda," *Astrophysics and Space Science* 259: 213-234.

[2] Dainton, Barry. 2001. *Time and Space.* McGill-Queen's UP.

[3] Earman, John. 2001. "Lambda: The Constant That Refuses to Die," *Archive for History of the Exact Sciences* 55: 189-220.

[4] Earman, J. and Norton, J. 1987. "What Price Spacetime Substantivalism? The Hole Story," *British Journal for the Philosophy of Science* 38: 515-525.

[5] Einstein, Albert. 1917. "Cosmological Considerations on the General Theory of Relativity" (trans.), reprinted in J. Bernstein and G. Feinberg (eds.), *Cosmological Constants*. 1986. Columbia UP, 16-23.

[6] Hoefer, Carl. 1996. "The Metaphysics of Space-Time Substantivalism," *Journal of Philosophy* 93: 5-27.

[7] Hoefer, Carl. 1998. "Absolute Versus Relational Spacetime: For Better or Worse, the Debate Goes On," *British Journal for the Philosophy of Science* 49: 451-467.

[8] Hoefer, Carl. 2000. "Energy Conservation in GTR," *Studies in History and Philosophy of Modern Physics* 31: 187-199.

[9] Maudlin, Tim. 1988. "The Essence of Space and Time," in A. Fine and J. Leplin (eds.), *PSA 1988* 2: 82-91.

[10] Mellor, Hugh. 1980. "On Things and Causes in Spacetime," *British Journal for the Philosophy of Science* 31: 282-288.

[11] Penrose, Roger. 1991. "The Mass of the Classical Vacuum," in S. Saunders and H. Brown (eds.), *The Philosophy of Vacuum.* Clarendon.

[12] Rindler, Wolfgang. 2001. *Relativity: Special, General and Cosmological*. Oxford UP.

[13] Rynasiewicz, Robert. 1996. "Absolute Versus Relational Space-Time: An Outmoded Debate?" *Journal of Philosophy* 93: 279-306.

[14] Sklar, Lawrence. 1976. *Space, Time, and Spacetime*. University of California Press.

[15] Teller, Paul. 1991. "Substance, Relations, and Arguments About the Nature of Space-Time," *Philosophical Review* 100: 353-397.