Metaphysics of Causation and Physics of General Relativity[*]

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ABSTRACT

This paper aims to discuss two realist conceptions about causation in the light of the general theory of relativity (GTR). I first consider the conserved quantity of causation, which explicitly relies on the energy conservation principle. Such principle is however problematic within GTR, mainly because of the dynamical nature of the spacetime structure itself. I then turn to the causal theory of properties, according to which (fundamental physical) properties are such that insofar as they are certain qualities, they are powers to produce certain effects. In order to be compatible with GTR, such theory has to assume non-trivial global conditions on the spacetime structure; such assumptions seem to deprive the 'singularist' non-Humean feature of this theory of causation. The question of the possible causal nature of spacetime (metrical) properties is addressed in the conclusion.

1. INTRODUCTION

The question about the nature of causation is one of the most fundamental questions in philosophy of nature. In an analytical approach, this paper aims to discuss some aspects of this question in the light of one of our best fundamental physical theories, the general theory of relativity (GTR). If the possible link between causation, space and time is clearly not new (think about the standard Humean conception for instance), GTR might put some novel

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constraints on it (to the extent that it is relevant for such question). More specifically, I will discuss the constraints exerted by GTR on two realist conceptions of causation which have been widely discussed in the literature recently.

I will first consider the conception of causation in terms of conserved quantities, such as recently developed and discussed by Wesley Salmon (1998, 2002) and Phil Dowe (2000a) (section 2). This conception of causation considers the fundamental causal relations as physical relations whose nature relies on the physical principle of conservation of (mass-)energy. It seems clear that such physicalist and mechanistic conception of causation must come to terms with what our fundamental physical theories, such as GTR, say about our actual world. So the fact that within GTR there is in the general case no meaningful energy conservation (in a precise sense which is discussed below) might have important consequences for the conserved quantity theory of causation (section 3).

This conception of causation is a realist and non-Humean one in the sense that it considers fundamental causal relations as objective (mind-independent) and singularist (regularities-independent) relations in the physical world. However, such empirical conception does not say anything about necessity or about the irreducible causal feature of the relation between cause and effect – feature which is often hold as essential for any realist conception of causation.[1] Such aspect is taken into account within the causal conception of properties, or conception in terms of dispositions or powers, according to which fundamental physical properties are such that insofar as they are certain qualities, they are powers to produce certain effects: these effects can so be understood as the necessary consequence of the very nature of the considered properties (section 4). Within such realist conception of causation, developed and defended by Rom Harré and Edward Madden (1975), Sydney Shoemaker (1980), Stephen Mumford (1998) and Alexander Bird (2007) among others, the fundamental physical properties then have an irreducible causal nature; causation is then bound to the very nature of properties, reflecting its objective and fundamental nature. It seems clear that the existence of such irreducible causal nature of properties is not an empirical question that science and fundamental physics in particular could settle: indeed, a world where the fundamental physical

[1] See for instance Chakravartty 2005.

properties are categorical (non-causal) is not qualitatively distinct from a world where the fundamental physical properties are irreducibly dispositional (causal). This is a metaphysical distinction. However, insofar as we require that a conception about causation has to be compatible with what fundamental physics tells us, fundamental physics might provide relevant arguments in the debate. In particular, I will discuss some arguments from GTR (section 5). It should be made clear that this paper aims less to argue in favor or against these two conceptions of causation than to provide an interesting case of fruitful interaction between physics and metaphysics.

2. CONSERVED QUANTITY THEORY

In this section, I will briefly present the main elements of the theory of conserved quantity, as presented by Dowe (the differences with Salmon's version are not relevant here). Within this theory, causation is understood in terms of causal interactions and causal processes, which are themselves defined in physical terms.[2] A causal interaction is an intersection of worldlines that involves an exchange of a conserved quantity. A worldline is a (timelike or null[3]) curve in spacetime that represents the history of an object. The notion of exchange is understood here in a minimal way and only requires a change in the value of the conserved quantity for at least one incoming and one outgoing worldline involved in the interaction[4] and such that the corresponding conservation law holds. A conserved quantity is any physical quantity that satisfies a conservation law in any given spacetime region.[5] Our current best physical theories give us indications of what these conserved quantities might be; such conception of causation depends therefore strongly on what these fundamental physical theories have to say. One generally considers (mass-)

[2] I follow Dowe 2000a for most of the definitions of the conserved quantity theory.

[3] A curve in spacetime (M, g_{ab}) is said to be timelike or null if for all points p of the curve the tangent vector $t^a(p)$ to the curve is timelike, that is, such that $g_{ab}(t^a(p)t^b(p))<0$, or null, that is, such that $g_{ab}(t^a(p)t^b(p))=0$, with $(-, +, +, +)$ as the signature of g_{ab}.

[4] 'Incoming' and 'outgoing' are labels defined by the local light cone structure and are interchangeable, see Dowe 2000a, p. 92.

[5] As such, it does not need to be a law: what is required is only that the relevant conservation statements hold in the actual physical world, independently of the question about their possible lawlike nature (Dowe 2000a, p. 96; Salmon 1998, p. 259; Psillos 2002, p. 121). I will discuss below a mathematical representation of such conservation statement.

energy as the relevant conserved quantity within the analysis of causation. There are two main reasons for that. First, conservation of (mass-)energy is of fundamental importance for contemporary physics and seems to be an experimentally successful principle in our world. Second, there seems to be a close connection between (mass-)energy and causation, which has already been exploited by some philosophers in the past, such as Bertrand Russell and Hans Reichenbach for instance, and which is at the basis of the conserved quantity approach of causation[6]: the idea is roughly that two events are causally related if and only if they are in a certain relation with respect to their (mass-)energy.

The second fundamental element of the conserved quantity theory is the causal process, which is a worldline of an object that possesses a conserved quantity. The possession of a conserved quantity by an object is to be understood as the instantiation of this conserved quantity conceived as a property. The notion of object is conceived here in a very broad sense. To the extent that we are considering causation at the fundamental level, objects are the fundamental elements that constitute the ontology, like particles or fields for instance. The conserved quantity theory does not take position in the traditional debates in the metaphysics of objects and properties.[7] The main claim of the CQ theory is that there is a causal relation between two events if and only if they are linked by a set of causal processes and causal interactions such that any change of an object or any change of a conserved quantity occurs at a causal interaction and the changes in the conserved quantities are governed by the physical conservation laws.[8]

3. Conserved quantity theory and physics of general relativity

The notions of (total) energy of a physical system and of conservation of this energy constitute a difficult and tricky topic in GTR. The difficulties come

[6] See for instance Fair 1979 and Curiel 2000, §.2.

[7] However, this definition of a causal process requires that the object, whose world line is a causal process, has identity through time, sometimes called genidentity, in particular in order to distinguish a causal process from so-called pseudo-processes, such as a moving spot of light along a wall (Salmon 2002, p. 113-116).

[8] An event is understood here as the instantiation of properties in a given space-time region (ultimately a space-time point), the 'content' of a space-time region (without any commitment to a specific space-time ontology); in particular, a causal interaction is an event.

from the fundamental GTR property according to which the gravitational field and the spacetime structure are described as one and the same physical structure within GTR.[9] The spacetime structure is then fundamentally dynamical and there is (in the general case) no non-dynamical background with respect to which physical systems can be considered.[10] This property, often called 'background independence', is taken by many physicists and philosophers of physics to be the distinctive feature of GTR and one of the main difficulties towards a coherent view between GTR and quantum field theory (QFT), which relies on a non-dynamical spacetime background. As a consequence of this dynamical nature, there is in general no natural family of timelike curves representing observers all at rest with respect to each other; therefore, within GTR, a given observer cannot in general define the energy of a distant particle.[11] From a technical point of view, this comes in the general case from the lack of the symmetries that are required for such family of curves to exist (a general solution of the Einstein field equations does not possess timelike Killing fields). Without such symmetries it is not possible to express an energy conservation law in a given spacetime region: there is in general no integral (mass-)energy conservation law within GTR.[12] It should be clear that

[9] Spacetime is represented by an equivalence class of pairs (M, g_{ab}), where the Lorentz metric tensor field g_{ab} encodes the inertio-gravitational effects as well as the fundamental spacetime relations. Within GTR, spacetime and the gravitational field can be understood as a physical structure in the precise sense of a network of physical relations (spacetime and gravitational relations) among relata that do not possess any intrinsic identity (as made explicite by the invariance under active diffeomorphisms); see Esfeld and Lam 2008, and Lam 2010a.

[10] More precisely, the metric-gravitational field cannot be decomposed uniquely into an inertial (non-dynamical) part plus a gravitational (dynamical) part.

[11] See Wald 1984, p. 69.

[12] Within GR, we have the 'differential energy conservation' $\nabla^a T_{ab} = 0$, where T_{ab} is the stress-energy-momentum tensor representing the energy-momentum distribution and ∇ s the covariant derivative associated with the metric. But such differential expression does not represent a meaningful conservation statement valid on any (finite) spacetime region. Indeed, there is in general no unit timelike vector field v^a such that $\nabla_a v_b = 0$ or merely such that $\nabla_a v_b + \nabla_b v_a = 0$ (Killing's equation): this means that there is in general no family of observers all at rest with each other (with parallel 4-velocities). Therefore, there is no meaningful (integral) energy-momentum conservation law in the (integral) form of $\int_S J_a n^a \, dS = 0$ where $J_a = - T_{ab} v^b$ is the (mass-)energy current density 4-vector measured by the observers represented by v^a, S is a 3-dimensional boundary of any 4-dimensional space-time region and n^a is the unit normal (like in the flat Minkowski space-time of special relativity: see Wald 1984, pp. 69-70).

this fact is not an epistemological question but is a consequence of the very nature of spacetime and of the gravitational field.

From the point of view of the universally interacting gravitational field, the failure of integral (non-gravitational) energy conservation is an obvious consequence of not taking into account gravitational energy: strictly speaking, there cannot be non-gravitational energy-momentum conservation since any physical system interacts with the gravitational field and its energy can transform into gravitational energy and vice versa. So, it seems natural to think that one would just need to take into account the energy of the gravitational field in order to obtain an energy conservation law. Things are however a bit more complicated. Indeed, gravitational energy cannot be represented by a (unique) coordinate-free geometric object (that is, for instance, by a tensor field). It is always possible at any spacetime point to find a coordinate system in which (infinitesimally) there is no gravitational energy.[13] As a consequence, gravitational energy can be understood as non-local in the precise sense that the amount of gravitational energy in any given spacetime region cannot be defined in a unambiguous way.[14] In the general case, there cannot be energy conservation insofar as gravitational energy cannot be taken into account; gravitational energy can be transformed into non-gravitational energy and can therefore increase or decrease the amount of energy that is present in a given spacetime region.

Although not much debated in philosophy of physics yet, this conclusion and its consequences for the conserved quantity theory have been discussed by Alexander Rueger (1998) and Erik Curiel (2000). Due to the lack of a meaningful energy conservation law, the notions of exchange and of possession of energy as well as the notion itself of energy as a conserved quantity become problematic, so that the fundamental notions of causal interactions and of causal processes are undermined. GR tells us that, in general, there can be no genuine (mass-)energy conservation law and so no such conservation law can

[13] This is often understood as a consequence of Einstein's equivalence principle, see for instance Misner et al. 1973, p. 386; however, the meaning of the equivalence principle(s) is trickier, see Norton 1993, §.4.1.

[14] Hoefer (2000) argues that this non-local feature of gravitational energy precisely shows that it does not constitute a meaningful form of energy. Actually, there seems to be difficulties with the very notions of energy and mass (gravitational or not) within GTR, see for instance Jaramillo and Gourgoulhon 2010 as well as the discussion in Lam 2010b. These questions do not alter the point that in general there is no meaningful energy conservation law.

rule the exchange of (mass-)energy as a conserved quantity in a causal interaction. The characterization of 'causal' for an interaction then loses its fundamental meaning and one cannot say unambiguously whether two events are causally related or not.

Insofar as the energy conservation constitutes a fundamental principle within contemporary physics, it might still seem that the conserved quantity theory, in grounding causation on this principle, does well capture a fundamental aspect of the world. However, it seems that such a position would amount to dismiss the moral of one of our two most fundamental physical theories: the spacetime structure and the gravitational field are one and the same physical entity, which possesses energy and momentum and which is dynamically (and universally) related to the whole non-gravitational (mass-) energy. From the GTR point of view, the relevance of the energy conservation principle in most physical theories and in particular in quantum theory comes from the fact that these theories require a non-dynamical spacetime structure that possesses the high degree of symmetry needed to define an energy conservation law. Indeed, within GTR, there exists a well-defined notion of total energy for an isolated physical system, that is, a physical system in an asymptotically flat spacetime (without entering into the details, spacetime becomes Minkowskian 'very far' from the considered system). Although very useful and justified in many concrete cases, such idealizations cannot constitute the empirical basis for any account of causation that pretends to be fundamental.

Another possible position of the friend of the conserved quantity theory is first to explicitly consider this conception of causation as contingent, for instance on the existence of conservation laws in our actual world, and then to maintain that our actual world does possess the required properties, namely the high degree of spacetime symmetry necessary for conservation laws (in the case of energy conservation, the spacetime structure has to be invariant under temporal translations (such spacetime is called stationary). Such position is endorsed by Dowe (2000a, 2000b), who considers the conserved quantity theory as an empirical analysis of causation in our actual world in contrast to a metaphysics of causation valid in all possible worlds; according to him, such empirical analysis has to rely on the results of science – this is precisely the methodology here. The results from GTR applied to our actual world tend to show that, contrary to what Dowe (2000a, p. 97; 2000b, p. 24) says, our universe does not possess strictly speaking the required high degree of symmetry (Friedmann-Lemaître-Robertson-Walker solutions, which constitute the standard model of contemporary cosmology, are highly symmetric, in particular homogenous and isotropic, but it is clear that these physically relevant solutions only constitute approximations of our actual universe).[15]

That the conserved quantity theory requires such specific conditions (from a GTR point of view) seems to reflect the fact that this theory considers causation among material objects against a fixed, non-dynamical background.[16] But, as we have discussed above, GTR describes spacetime as a fundamentally dynamical physical entity that possesses energy and momentum and such that strictly speaking it is not possible to isolate a 'causal' process from 'causal' interactions with the spacetime structure or gravitational field.

The conserved quantity theory provides a good example of the fruitful relations between metaphysics of nature and physics: motivated by physical considerations, this realist conception of causation is put into question by even more fundamental physical considerations. In a similar way, any metaphysical position about nature should be discussed in the light of what fundamental physics tells us. It is clear that there is no direct implication between physics and metaphysics of nature; however, physics can bring some relevant light on certain metaphysical conceptions, such as in the case of the realist conceptions of causation. In the same move, I now discuss the realist conception of causation in terms of dispositions or powers.

4. Causal Theory of Properties

Within the conserved quantity theory, causation is considered as an objective feature of the world, but the more metaphysical question about the necessary (or irreducibly causal) nature of the causal relation is not addressed. On the one hand, despite their objective and singularist character, the causal processes and interactions of Salmon's and Dowe's theory can be understood

[15] Curiel (2000, pp. 47-48) underlines the fact that the slightest inhomogeneity breaks the required symmetry and that nothing so particular would correspond to our actual world.

[16] For instance, Curiel (2000, p. 47) underlines the fact that a timelike Killing field can be understood as a kind of privileged fixed temporal background against which conserved quantities can be considered.

as supervenient on a non-causal, Humean basis.[17] On the other hand, it seems possible to consider properties within the conserved quantity theory as irreducibly causal in the sense that their very nature is to produce certain effects.[18] From an empiricist point of view, one may wonder what would be the benefits of considering fundamental physical properties in terms of causal powers whose irreducible causal nature seems out of reach of empirical sciences (such consideration constitutes the crux of the Humean criticism). Within the contemporary debate, a more or less explicit motivation among the proponents of such conception comes from the way fundamental physics seems to work: indeed, it seems that we only gain knowledge about a fundamental physical property through the way it interacts, that is, through the causal relations in which it stands. If this epistemic specificity suggests that fundamental physical properties possess some dispositional nature, it does not constitutes a powerful enough argument against some underlying categorical basis for these properties. However, this epistemic specificity fits well with one of the main (purely metaphysical) arguments in favor of the causal theory of properties: insofar as we have access to the fundamental physical properties only through the causal relations in which they stand, their possible categorical nature is independent of their nomological and causal role. Such possible categorical nature is therefore a primitive and inaccessible qualitative feature (a 'quiddity') of the properties and forces us to some 'humility' in the sense that we cannot know what the properties are. From an empiricist point of view, it is not very satisfying to accept such inaccessible qualitative nature of properties. Two fundamental physical properties that are qualitatively distinct in virtue of their distinct categorical nature can therefore stand in exactly the same causal and nomological relations (corresponding to what we would consider to be the charge for instance). Such metaphysical underdetermination vanishes if one accepts a causal theory of properties according to which their nature is (the power, the disposition) to produce certain effects. So, two distinct properties in virtue of their very nature cannot produce exactly the same effects and cannot stand in exactly the same causal relations. These latter are then a consequence of the very nature of the relevant properties and have therefore an objective and necessary character: insofar as the nature of a fundamental physical property is to produce certain effects, these latter constitute the

[17] See for instance Psillos 2002, §.4.5.4.

[18] Chakravartty (2005, §.5) briefly discusses this possibility.

necessary consequence of the nature of the considered property. The fundamental physical properties are then conceived as possessing some irreducible dispositional essence or as irreducible causal powers, which do not require any external triggering condition (it is the very nature of properties to produce certain effects). The details and subtleties of the different versions of the causal theory of properties in terms of causal powers or irreducible dispositions are not relevant for the discussion here.[19] The main point is that there is an important purely metaphysical argument in favor of the causal theory of properties (although motivated by an empiricist stance, this metaphysical argument is independent from the above mentioned epistemic considerations), that is in favor of a strong causal realism, binding causation to the very nature of fundamental physical properties.[20]

As already mentioned, the main aim here is not to discuss this conception as such. Rather, the idea is to consider the interactions between this metaphysical conception about causation and the physics of GTR. More specifically, I consider the consequences of the fundamental dynamical nature of spacetime for the causal theory of properties. Some (non-trivial) global constraints have to be imposed on the spacetime structure in order to secure the coherence of the causal conception of properties. It then seems that an important aspect of this conception is affected by these constraints: the singularist character of the causal relation. If one considers two events *A* and *B* (instantiations of fundamental physical properties for instance) as related by a causal relation in the sense that the very nature of *A* is to produce the effect *B*, then the causal nature of the relation as well as the very existence of the event *B* rely entirely (in a local, singularist way) on the event *A*. On the contrary, according to the non-singularist, Humean conception of causation, the causal link between *A* and *B* depends on the regularities in the world between all events of type *A* and all events of type *B*; actually, it may supervene on the entire distribution of fundamental physical properties (as within David Lewis' thesis of Humean supervenience[21]).[22] Among the proponents of the causal

[19] See for instance Shoemaker 1980, Mumford 1998, Bird 2007, Chakravartty 2007.

[20] According to the proponents of the causal theory of properties, the main metaphysical argument about 'quiddity' is not the only one in favor of this conception; they also offer arguments from quantum physics (entangled quantum systems possessing irreducible dispositions to dissolve the entanglement for instance) and from GTR as well (spacetime properties as causal – see section 6); see recently Esfeld 2009 as well as references therein.

[21] See for instance Lewis 1986, pp. ix-x.

theory of properties, this singularist aspect of causation is not controversial and is considered as an advantage since only the nature of the relevant properties have to be considered in order to account for a causal relation. But the this singular character of the causal relation seems to be affected by the global constraints on the spacetime structure that have to be assumed: it seems that the causal nature of the relation does not only depend on the nature of the property that is considered as the cause any more, but also on global properties of the spacetime structure. Before discussing further this point, it is useful to consider in some more details the constraints that the proponents of the causal theory of properties have to assume.

5. CAUSAL THEORY OF PROPERTIES AND PHYSICS OF GENERAL RELATIVITY

One of the central points of GTR is that spacetime and the gravitational field constitute one and the same dynamical physical structure, which possesses (gravitational) energy and which universally interacts with gravitational and non-gravitational (mass-)energy – interaction that is encoded in the Einstein field equations. As a consequence of the dynamical nature of the spacetime structure, the spacetime topology can be non-trivial. Within special relativity, the inert Minkowski metric defines for all spacetime points a future and past light cone ('future' and 'past' are here interchangeable labels, modulo a certain consistency constraint called 'time orientability'). The future light cone of any spacetime point p determines the set of events that can be causally influenced by an event at p, that is for instance the set of spacetime points that can be reached by physical particle starting at p and travelling at a speed less or equal the speed of light (and similarly for the past light cone). This light cone structure exists only locally within GTR, that is, it is only valid for some

[22] It is possible that the relata of the causal relations may not be local and pointlike entities; for instance, within the framework of ontic structural realism, it has recently been suggested that the physical structures (defined in the precise sense of a network of concrete physical relations among concrete physical relata) are themselves causal (French 2006, Esfeld 2009); however, how structures and relations can possess causal powers remains obscure (French 2006, §.VI). In any case, the central feature of the singularist aspect of this conception of causation is that the cause (for instance the state of the world at a certain time) necessarily produces the effect (for instance the state of the world at a certain later time – this example is discussed in section 5) in virtue of its very nature and independently of the rest of the fundamental physical properties.

neighborhood (called 'normal') of any spacetime point *p*; things can be radically different at the global level. Indeed, in a dynamical (non-flat) spacetime, the set $I^{+}(p)$ of events that can be reached by a physical particle starting at *p* and following a (future oriented) timelike curve does not coincide with the interior of the future light cone at *p* (which is actually only defined locally for some neighborhood of *p* – strictly speaking, the light cone is on the tangent space at *p*). In particular, it is perfectly possible that $p \in I^{+}(p)$, which means that there exists a future oriented closed timelike curve through *p*. In such spacetime and within the framework of a realist conception of causation, an event can therefore causally influence events in its past and can causally interacts with itself; this latter aspect might be the most problematic one, in particular within the framework of the causal theory of properties. It seems indeed difficult to maintain that the nature of an instantiation of a property is to produce itself. Two attitudes are now possible. First, to accept the causally pathological behaviors as physically possible (in our actual world). Such attitude is motivated by the fact that many solutions to the Einstein field equations (among which some can apply to our actual world) possess closed timelike curves (for instance, the Kerr-Newman solution, which describes spacetime around a rotating charged mass, can contain such curves). In such cases, it seems that the causal theory of properties as presented in the last section is not compatible with GTR. Insofar as GTR provides an experimentally successful description of the world, this consequence constitutes an important drawback for the causal theory of properties. A second attitude is to dismiss solutions containing closed timelike curves as physically non relevant. Such attitude can be justified by the fact that many solutions of the Einstein field equations that contain closed timelike curves are artificial and do not correspond to physical situations in our actual world (for instance it is in general considered that the famous Gödel solution does not correspond to any region of our universe; in the above given example, the Kerr-Newman metric more specifically describing spacetime outside a charged rotating black hole does not contain closed timelike curves; moreover, global considerations on certain physical laws, such as Maxwell equations, can be invoked to exclude the existence of closed timelike curves). Such attitude is however controversial among philosophers of science as well as among physicists.[23] I will however

[23] See for example the discussion in Earman 1995, §.6.4 – for instance, the Kerr-Newman

adopt this attitude here in order to provide a physical framework in which the causal theory of properties can be discussed. It is therefore possible to impose a global constraint that excludes the solutions containing closed timelike curves ('chronology condition'). It is straightforward that such condition is not sufficient and that it is also necessary for our purpose here to exclude closed null curves as well ('simple causality condition'). It seems that this latter global condition provides the causal theory of properties with a safe (causally well-behaved) environment. But this is far from certain. Indeed, the 'simple causality condition' does not exclude timelike curves that are 'almost closed' in the sense that for some (possibly infinitesimal) neighborhood *U* of a spacetime point *p*, a timelke curve starting at *p* can cross *U* more than once. Such 'almost closed' curves can be excluded by the 'strong causality condition'. Moreover, it is likely (but not necessary) that the proponent of some strong causal realism may want to derive some temporal order out of the more fundamental causal order (this move allows her to ground the notion of change in the notion of causal production). The existence of a global time function[24] seems mandatory for such derivation to be possible (and maybe for the very notions of change and temporal evolution too).[25] The existence of such function is guaranteed by a stronger condition, called the 'stable causality condition'. Indeed, there exists a whole hierarchy of stronger and stronger causality conditions (a given condition implying the weaker ones) that one can impose on the Einstein field equations solutions. The strongest is the 'global hyperbolicity condition', according to which spacetime has the topology of a product $R \times \Sigma$, where R

solution that contains closed timelike curves can be understood as representing the spacetime generated by the gravitational collapse of a rotating star that does not lead to a black hole – physical possibility which cannot a priori be excluded)

[24] A global time function is a function t from the manifold M to the reals such that $t(p)<t(q)$ for all $p, q \in M$ that are linked by (future oriented) timelike curve from p to q. In general such function is not unique. It should be clear that the existence of such functions does not imply any notion of objective temporal distance between two events.

[25] The notions of temporal evolution and change are notoriously problematic within GTR ('problem of time'), in particular because of the (gauge-theoretic) diffeomorphism invariance of the theory; accordingly, the definition of meaningful observables (in the sense of Dirac or Bergmann) and the characterization of their 'evolution' are very difficult tasks within GTR. It is however possible to define gauge-invariant 'correlational' observables (or 'coincidence' observables as Earman 2002 dubs them with respect to Einstein's intuitions), such as Komar events, together with a meaningful notion of (not necessarily temporal) 'evolution'; the Global Positioning System (GPS) can be considered as a technological implementation of such 'correlational' observables (see Rovelli 2004, ch.2; about the problem of time, see Rickles 2006 and references therein).

represents the real line and Σ a *3*-dimensional hypersurface, called Cauchy surface, such that no (inextendible) timelike or null curve crosses Σ more than once (in some sense, Σ represents the universe 'at a certain time').[26] Such condition provides the possibility – very attractive for the proponent of the causal theory of properties – of an initial value formulation of the theory: without entering into the details, the set of initial data on a Cauchy surface completely determines (in a precise sense) the spatio-temporal (gravitational) and material structures on the rest of the spacetime. The causal realist can then be tempted to consider the relevant properties on the initial Cauchy surface as causally generating (producing) the entire (physical state of the) universe.[27]

The aim here is not to discuss to what extent the causal theory of properties requires this whole hierarchy of global conditions imposed on the spacetime structure. It is sufficient here to highlight the fact that such metaphysical conception about causation requires to impose (at least) some of these conditions; the 'simple causality condition' has to be at least required for the conception of causation as production to be make sense.[28] As already discussed, it might be the case that further conditions from the hierarchy might be needed for such conception about causation to be plausible. The important point is that these conditions are global constraints on the spacetime structure. Without entering into the technical details, it seems easy to see for instance that the 'global hyperbolicity condition' is a global condition in the sense that it constraints the global topology of the (whole) spacetime structure to be equivalent to $R\,x\,\Sigma$.

As a consequence, it seems that within this framework the causal relations depend on global spacetime properties (such as the global topology). As mentioned at the end of the last section, this fact seems to affect the singularist aspect of causation within the causal theory of properties. Considering again the example of the last section, it seems that the causal relation between the event A and the event B does not only depend on the nature of the cause A

[26] The spacetime foliation into Cauchy surfaces is not unique and no foliation is privileged. This fact constitutes one of the simplest formulations of the famous 'problem of time' within GTR as well as within the various attempts to quantize the theory.

[27] For instance, Maudlin (2007, ch. 6) defends such position, where the laws of nature, considered as primitive, rather than causation, underlie the notion of production.

[28] Maudlin (2007, ch. 6) underlines very clearly the fact that according to him the existence of closed timelike curves is incompatible with the notion of ontological production at the fundamental level.

(which is to produce *B* within the causal, dispositionalist conception of properties), but also on global properties of the whole spacetime (gravitational) structure. The nature of the causal relation between *A* and *B*, as well as the existence of *B* itself, cannot be ontologically grounded uniquely in the nature of *A*. Strictly speaking, the fact that *A* causes *B* cannot be uniquely in virtue of the nature of *A*, but also in virtue of the global spacetime (gravitational) structure. For instance, let us assume that *A* and *B* are located within a region *U* of the spacetime (M, g_{ab}), which satisfies the necessary global conditions such that it is meaningful to say that *A* causes *B* according to the causal theory of properties. Let us further consider a distinct spacetime (M', g'_{ab}), which does not satisfy these necessary global conditions but which possesses a region *U′* that is exactly similar (in a precise sense) to *U* (with the events *A′*, *B′* located in *U′* exactly similar to *A*, *B* in *U*). Now it seems that if *A* causes *B* in (M, g_{ab}) (by hypothesis), *A′* does not cause *B′* in (M', g'_{ab}) because for instance they might be related by closed timelike curve outside the region *U′*. So it seems that the nature of the causal relation between *A* and *B* depends not only on the nature of *A*, but also on the global properties of the spacetime structure in which they are.[29]

The reply from the proponent of the causal theory of properties is clear: she cannot consider (M', g'_{ab}) as metaphysically possible. It is the nature of properties to produce effects that globally satisfy the above discussed conditions; the global constraints are in some sense encoded in the very nature of properties and the singularist aspect of the causal relation remains unthreatened. If this reply may seem unsatisfying, there does not seem to be any definitive objection against such attitude. Besides the question of the relevance of this reply to the challenge of non-trivial topologies, the important point here is that this metaphysical conception about causation strongly constraints the solutions of the Einstein field equations. Indeed, it should be clear that the above discussed hierarchy of causality conditions is not a consequence of the theory; it is in general justified by some particular conception about causation. As already mentioned, the lack of certain global properties of the spacetime structure – a purely empirical question – would put the causal theory of properties into a difficult situation.

[29] *A* and *B* need not be local and pointlike for the argument; for instance, they can also represent states of the universe 'at some given time'.

6. CONCLUSION AND PERSPECTIVES

The main aim of this paper is not to provide a definitive argument against any specific metaphysical conception about causation. However, within the here adopted analytical approach, any metaphysical conception about nature can be strengthened or weakened by arguments from contemporary physics. So we have first considered the conserved quantity theory of causation; through its use of the (energy) conservation principle, such conception clearly relies on physics. However, we have seen that this it has to face certain difficulties from fundamental features of the spacetime (and gravitational) structure as described by GTR: the dynamical nature of the gravitational-spacetime structure, the lack of non-dynamical, background physical structure with respect to which physical entities as well as their (possibly causal) interactions can be considered ('background independence'). Indeed, the symmetries that are required by the conserved quantity theory constitute some fixed and privileged temporal structure with respect to which the conserved quantities can be considered. Strictly speaking, and contrary to what Dowe (2000b) argues, our actual world most probably does not possess such symmetries, even if these latter allow us to elaborate physically relevant and useful approximations, which are justified in many practical cases (see section 3). Another aspect of the problem is that, strictly speaking, one cannot isolate any physical system from the interactions with the gravitational field (even if, again, in many physically useful and justified approximations one does consider gravitationally isolated systems). Moreover, the non-local nature of gravitational energy (in the precise sense discussed in section 3) prevents the proponent of the conserved quantity theory to consider any gravitational interaction as a causal interaction (a gravitational wave destroying a rock would not be considered as a causal interaction within this account).

In a certain way, the case of the causal theory of properties is more complicated. We have seen that it requires that the world instantiates certain non-trivial global properties and it considers certain (many indeed) solutions of the Einstein field equations as metaphysically impossible. This conception can therefore clearly be challenged by the lack of such properties in our world. Insofar as it is a purely empirical question that remains debatable, this fact itself does not constitute a definitive objection against the causal theory of properties (section 5).

One can wonder how this conception accounts for the above mentioned fundamental aspects of spacetime and gravitation that cause so much trouble to the conserved quantity theory ('background independence', non-local nature of gravitational energy). This question belongs to the actual debate about this conception of causation and properties. Another aspect of the same question is about whether the causal theory of properties applies to spacetime (gravitational) properties. At first sight, it seems that the dynamical nature of the spacetime and gravitational structure within GTR provides an explicit argument in favor of a causal interpretation of the spacetime properties. The argument is that metrical properties within GTR (represented by the metric tensor field and its functionals such as the Riemann tensor field) can be considered as causal in the sense that they have a causal role that is manifested by the action of tidal forces.[30, 31] So the nature of the metrical (gravitational) properties is to produce tidal forces, which can be experienced by test particles for instance, via spacetime curvature. The presence of non-gravitational (mass-) energy is not necessary for such understanding, so that the causal understanding of metrical properties remains valid in the purely gravitational cases.

If such causal understanding of spacetime properties seems attractive at first sight, a closer look shows that it is not free of difficulties. According to this conception, the spacetime (gravitational) structure causally acts on non-gravitational (mass-)energy (via curvature and tidal forces) as well as on gravitational energy; this latter fact seems to imply that the spacetime (gravitational) structure causally interacts with itself. Moreover, the Einstein field equations do not privilege any 'direction' in the interaction between the spacetime (gravitational) structure and non-gravitational (mass-)energy; if one understands one side of the Einstein field equations as causally acting on the other ("matter tells space how to curve"), then it seems that the inverse is equally true ("space tells matter how to move"). The conception of causation as production of certain effects is far from being clear in this context. These questions actually deserve to be discussed in details in a separate paper.

[30] The argument is mainly defended by Bartels (1996, 2009) as well as Bird (2009); for a critical point of view, see Livianos 2008.

[31] Baker (2005) argues that the cosmological constant Λ within GTR also provides an argument in favor of a causal understanding of spacetime.

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