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Title: *Closed Timelike Curves, Singularities and Causality: A Survey from Gödel to Chronological Protection*

Author: Jean-Pierre Luminet

This is a well-written review paper about interrelated relevant issues (causality, singularity and chronological protection) that merits publication. Differently from somehow regular review articles, which deal with technical details of calculations, this one deals with the underlying ideas, interconnections between the subjects and possible implications. In spite of lacking fundamental references, it contains a good number of important ones. It is certainly not an article for those who need to go into the details of calculations of the subjects covered, but useful for those who wish to examine the underlying ideas and general context that permeates these timing issues. Nevertheless, I do have a few points that the author should deal appropriately with before my final recommendation.

1. Regarding the first paragraph of Sec.2 my comment/concern is the following: it is known that the geometry does not specify but in some instances it may restricts or constrains the topological possibilities. For example, the topology spatial section of Friedmann-Lemaître-Robertson-Walker spacetime is constrained by the geometry. So, it is known that for Euclidean spatial geometry we have only 17 possible flat topology. Clearly one may have trivial closed timelike curves (CTL) just by topological identification (multiply-connected topology) even in Minkowski spacetime. This is not the case of Gödel and other solutions with CTL curves. In Gödel universe gravity (geometry) inclines the local light cones in non-local spacetime regions. In doing so *gravity constrains topology* so as to allow for CTL curves. In this way the existence of CTL curves in Gödel model is not solely of geometrical origin, but it is of combined geometric-and-topological nature. Technically, Gödel gravity restricts the whole class of topological possibilities to a smaller family: the spacetimes whose topologies are not time-orientable. In my view, these resulting subset of spacetime topologies should contain Möbius strip, involving the time, as 2-D subspace. In other words, the topologies of the sub-family contain flip (inversion) in their discrete isometry group. In brief, CTL curves have a geometric-topological nature: matter specifies geometry, which in turn restricts the allowed class of underlying topology. Regardless of the way they were originally obtained this view ought to hold true for the other solutions of Einstein's equations (Gott, Taub-NUT, Misner, Kerr). In this regard, an important question is whether the underlying spacetime manifold is time orientable or not, a far-reaching point that should be tested either locally (experimentally) or at a cosmological scale (observationally).

2. In my view, the paper ought to point out that Gödel solution is not so unique in that it is just a particular member of a hyperbolic family of Gödel-type spacetimes. These spacetimes are

characterized by two physically relevant parameters: Ω (rotation) and another essential parameter m , which is used to divide Gödel spacetimes into 3 disjoint classes: $m^2 > 0$ defines the hyperbolic family which contains Gödel solution, for which $m^2 = 2\Omega^2$, as a particular case; The linear class with $m = 0$, which contains only Som-Raychaudhuri universe, whose CLT curves are discussed in ref.[21] of the review; and finally the trigonometric family, $m^2 < 0$, which contains solution with alternating causal non-causal regions discussed in ref.[20] of the paper. For details see, for example, the papers: Phys. Rev. D 28, 1251 (1983); J. Math. Phys. 28, 888 (1987), and more recently the clear summary given in Sec.3.1 of Eur. Phys. J. C (2018) 78:567.

3. In Section 3, although a due reference to the outstanding paper [Ann. Soc. Sci. Bruxelles A**53**, 51 (1933), reprinted in Gen. Relativ. Gravit. **29**, 641 (1997)] by Georges Lemaître is made, as well as to a general reference to Penrose and Hawking contribution along with a citation of Hawking-Ellis renowned book (Ref.[16]), this is certainly not satisfactory even for a brief review paper. There is no mention to Raychaudhuri's paper [A.K. Raychaudhuri, Phys. Rev. **98**, 1123 (1955)], which contains the first singularity theorem (physical singularity). In this important paper, he included the equation that is named after him, and which lies behind the singularity theorems due to its important consequences concerning geodesic focusing. Moreover, it is very old the absence of reference to the paper by Penrose [Gravitational collapse and spacetime singularities, Phys. Rev. Lett. **14**, 57 (1965), Nobel Prize in Physics 2020] in which he brought in the essential idea of geodesic incompleteness to describe singular spacetimes, and introduced the fundamental notion of closed trapped surface. These turn out to be fundamental ingredients in the proofs of the singularity theorems. A useful reference in this regards is the paper by Senovilla and Garfinkle [Class. Quantum Grav. **32**, 124008 (2015)] that contains technical details and important historical notes.

4. A point regarding Sec.4: my understanding of Novikov's self-consistency principle [I.D. Novikov, Phys. Rev. D **45**, 1989 (1992); A. Carlini et alii, Int. J. Mod. Phys. D **4**, 557 (1995)] is that it demands that the local solutions are admissible only when they are globally 'self-consistent', i.e. geometry consistent with a topology which does not allow for CTL curves. Thus, this principle is ad hoc global topological constraint on admissible local solutions. It is ultimately an assumption that forbids time-non-orientable spacetime manifolds. It adds just a topological restriction with no genuine physical motivation. It should be noted, however, that orientability of time is an open assumption (question), falsifiable in principle in order to have any physical value. It is not a physical law. For a recent way of locally access *spatial* orientability see, for example, arXiv:2009.04071 [hep-th].

5. Some additional comments regarding the final conclusion of the review article: Whether or not the physical laws permit the existence of stable time machines in the form of closed timelike curves is an active research field. Violation of causality, on the other hand, raises intriguing logical

paradoxes, and is generally seen as undesirable feature in physics. In this regard, despite chronology protection principle, Hawking himself and Penrose have also pointed out that severe causality assumptions could risk 'ruling out something that gravity is trying to tell us' [S.Hawking, R.Penrose, *The nature of space and time* (Princeton U.P., 1996)], thus, discouraging further investigations. The possible existence of closed timelike curves is also particularly interesting in the quantum realm, where, for example, the quantum systems traversing these curves have been studied [D. Deutsch, *Quantum mechanics near closed timelike lines*. Phys. Rev. D **44**, 3197 (1991)] and experimental simulation of closed timelike curves have been undertaken [M. Ringbauer et al., *Experimental simulation of closed timelike curves*, Nature Commun. **5**, 4145 (2014)].

6. Finally, besides the necessary addition to the list of references it does need a careful revision, because it contains a reasonable number of misprint/mistype/omission. Quick examples: lack of author's initials in ref.[19]–[21]; in ref.[30] mistake and also the addition of above-mentioned reprinted version of Gen. Relativ. Grav. ; and so fourth.