Closed Timelike Curves

Subjects: Others

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Closed timelike curves (CTCs) are space-time trajectories that return to their starting point without violating the laws of special relativity. A traveler along a CTC could journey into the future but arrive in its past, creating a possible violation of the principle of causality. Such CTCs occur in Gödel's rotating universe and many other general relativistic solutions of classical Einstein's field equations. The chronological protection conjecture suggests that Nature forbids this kind of situation.

Keywords: Closed Timelike Curves ; Gödel ; Chronological Protection

1. Introduction

In 1949, the mathematician and logician Kurt Gödel, who had previously demonstrated the incompleteness theorems that broke ground in logic, mathematics, and philosophy, became interested in the theory of general relativity of Albert Einstein, of which he became a close colleague at the Institute for Advanced Study at Princeton. He then discovered an exact solution of the gravitational field equations describing a rotating universe model [1].

Gödel's universe is infinite, non-expanding, and filled with an idealized, homogenous perfect fluid. It rotates to stay balanced against gravitational collapse, the angular velocity outward juxtaposed to the gravitational pull inward. Gödel explained that matter rotates relative to the compass of inertia with the angular velocity $2(\pi G\rho)^{1/2}$, where ρ is the mean density of matter, and G, Newton's gravitational constant. However, unlike a spinning top, Gödel's universe does not rotate about a privileged geometrical axis. The local inertial frames rotate with respect to a distant frame defined by faraway galaxies so that every observer sees himself at the center of rotation, hardly an unusual situation. More extraordinarily, in Gödel's rotating universe, there are space-time trajectories that return to their starting point, namely closed timelike curves (CTCs). Such curves remain confined locally to their future light cones, and an object traveling along a CTC never moves faster than the local speed of light, so that CTCs do not all violate the laws of special relativity, while representing possible paths for material objects. This is a very strange result because a traveler could journey into the future but arrive in the past, accompanied by all the paradoxes that arise from a possible violation of the principle of causality.

The Gödel's rotating universe is not expanding, which is in blatant contradiction to observations of the redshifts of distant galaxies and the cosmic background radiation. More and more drastic experimental constraints have been placed on the possible large-scale vorticity of the universe, starting with Stephen Hawking [2], such that the possibility of a cosmological model in global rotation, although it has been carefully studied, has been almost universally rejected [3].

It is fascinating to note that the philosophical option advocated by Gödel, namely the illusory nature of time, features prominently on the agenda of contemporary physics, with some approaches attempting to reconcile general relativity and quantum field theory. The fundamental equations of loop quantum gravity do not contain a time variable. The theory describes processes in which changes take place not under the action of an identifiable temporal variable but as the result of a non-commutative sequence of spatial operators whose ordered classification simulates an irreversible flow of time (for a topical review, see [4]). As in Gödel's view, but in a very different physico-mathematical context, the experience of passing time would then be relative to the particular conditions in which the observer finds himself. It would also depend on the structure of his cognitive system. Our own perception of time is certainly different from that of other animals. We should not look for a manifestation of our own experience of time in the realm of fundamental physics. On this view, time appears as an emergent quality, underpinned by strata mixing spatial transformations and cognitive processes [5].

2. How to Escape CTCs?

Geometries of this type offer fascinating possibilities, but they violate causality, a basic physical law which is believed to be fundamental. Proposals that allow for backwards time travel but prevent time paradoxes were first suggested by Novikov [6], then developed by collaborators [7]. Their so-called "self-consistency principle" asserted that if travel along a CTC exists and would cause a paradox or any change to the past whatsoever, then the probability of such travel is zero. In other words, it demands that local timeline curves are admissible only when they are globally "self-consistent", i.e., if geometry is consistent with a topology that does not allow for CTCs. Thus, this principle appears as an ad hoc global topological constraint on admissible local solutions, which ultimately forbids time-non-orientable spacetime manifolds. It just adds a topological restriction with no genuine physical motivation.

The orientability of time is not a physical law but an open question in principle falsifiable by experiments in order to gain physical consistency. Indications could come from quantum effects, which were not really taken into account in the precedent discussions. In quantum field theory without gravity, causality is closely related to the principle of locality, namely that an object is directly influenced only by its immediate surroundings, thus forbidding the possibility of instantaneous "action at a distance". However, the locality principle is disputed according to various interpretations of quantum mechanics, including when discussing quantum entanglement showing a violation of Bell's inequalities [8]. Lacking a full integration of general relativity and quantum mechanics in a theory of quantum gravity, semi-classical gravity provides an approximate method for modeling quantum fields in the curved spacetime of general relativity. Quantum systems traversing CTCs have been studied in this context [9], and experimental simulation of CTCs have been undertaken [10].

Using such a semi-classical approach, Hawking tried to counter the eventuality of a traversable wormhole by proposing, in 1992, a "chronological protection conjecture" [11]. There should exist, according to the conjecture, a physical mechanism capable of preventing CTCs from forming in any conceivable circumstances, whether natural or artificial. Hawking argued that the achronal regions of the Misner, Taub-NUT, and Kerr spaces are classically unstable; particles and fields falling into a Kerr black hole, or traveling at relativistic speed in Taub-NUT and Misner spaces, see their spectral shift diverge toward blue as the chronological horizon approaches. Thus, it seemed to him reasonable to think that the associated energy density, which is also divergent, had sufficient feedback over space-time to prevent the formation of CTCs.

One possible method for finding a universal protection mechanism can indeed be found in the quantum instability of time horizons. This can be described as a stacking of the quantum fluctuations of the vacuum in the vicinity of the chronological horizon, so that the fluctuations have a non-zero renormalized energy density that diverges as the horizon approaches. In turn, semi-classical Einstein equations suggest that this energy should distort the space-time geometry in order to protect the timeline. Such a feedback mechanism is the quantum analogue of the well-known Larsen effect in acoustics.

In a first study, when the calculation for a beam of radiation entering a wormhole mouth was done taking account of vacuum fluctuations, it was found that the beam would spontaneously refocus before reaching the other mouth, suggesting that the "pileup effect" becomes large enough to destroy the wormhole [12]. Uncertainty about this conclusion, however, remained because the semi-classical calculations indicate that the pileup would only drive the energy density to infinity for an infinitesimal moment of time, after which the energy density would die down [13]. But semi-classical gravity is considered unreliable for large energy densities or short time periods near the Planck scale, and a complete theory of quantum gravity is needed for accurate predictions. So, it remained uncertain whether quantum-gravitational effects might prevent the energy density from growing large enough to destroy the wormhole.

Indeed, subsequent works in semi-classical gravity provided examples of spacetimes with CTCs where the energy density due to vacuum fluctuations does not approach infinity in the region of spacetime outside the Cauchy horizon [14]. But in 1997, a general proof was given demonstrating that according to semi-classical gravity, the energy of the quantum field (more precisely, the expectation value of the quantum stress-energy tensor) must always be either infinite or undefined on the horizon itself [15]. Both cases indicate that semi-classical methods become unreliable at the horizon because quantum gravity effects would be important there; this is consistent with the possibility that such effects would always prevent time machines from forming. Nevertheless, the chronological protection conjecture remains unproven as no rigorous proof could be formulated in all the spaces that could conceivably host CTCs. It may be the case that chronology is not always protected at macroscopic scales, and even if it were, quantum gravity could give rise to nonzero probability amplitudes allowing CTC formation on a microscopic scale–for the latest developments, see [16][17]. Whether or not the chronology protection principle holds, Hawking and Penrose have pointed out that too severe causality assumptions, such as global hyperbolicity, could risk "ruling out something that gravity is trying to tell us" [18].

A definite theoretical decision on the status of the chronology protection conjecture would require a full theory of quantum gravity as opposed to semi-classical methods. So, what do presently available theories of quantum gravity say? Although none of the various approaches for quantizing gravity has proven to be fully consistent, the general tendency is that quantum effects should prevent the occurrence of timelike singularities, thus removing one of the restrictions to the physical existence of CTCs. In the general framework of string theory, geometries with CTCs have resurfaced as solutions to its low energy equations of motion and time travel appeared to be possible in these geometries. However, the situation is far from being clear as it was suggested that stringy effects should prohibit their construction. A (completely unrealistic) example is provided by the extremal supersymmetric five-dimensional charged spinning "BMPV" black hole [19], which contains causality violating regions. However, taking account of stringy effects, it was shown how the geometry in these achronal regions had to be corrected and that, once corrected, causality is preserved. More precisely, tracking the chronology protection conjecture in the dual conformal field theory reveals that the absence of CTCs in the geometry coincides with the preservation of unitarity in the conformal field theory [20]. There are more arguments that seem to support chronology protection in string theory [21][22]. Moreover, Gödel's universe seems to lose its closed timelike curves when modeled in string theory [23].

But string theory is not a complete theory of quantum gravity. Experimental observation of closed timelike curves would of course demonstrate the chronology protection conjecture to be false, but, short of that, if physicists had a theory of quantum gravity whose predictions had been well-confirmed in other areas, this would give them a significant degree of confidence about the possibility of time travel or not. None of the approaches to quantum gravity can do so. But the preservation of causality serves as a basic element of construction for two of them, namely the Causal Sets theory [24] and the Causal Dynamical Triangulations (CDT) theory [25]. I will end this review by commenting on CDT in a pedestrian approach [26].

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