The Cosmic Time Traveler's Dilemma

Bryan W. Roberts

2007-12-21

Abstract

1 Introduction

A general relativist preparing to take a ride on a time machine of the type envisioned by Morris and Thorne (1988) may want to weigh his options first. Like most general relativists, he will presumably have taken interest in the Cosmic Censorship Conjecture, and may even hope to participate in the search for its solution. However, in spite of recent developments in the physics of time machines, the most promising time machine results that have been presented so far do not adequately provide meaningful implications (positive or negative) toward this conjecture. As a result, from the perspective of the Cosmic Censorship Conjecture, the attempt to take a ride as it currently stands would seem to be fruitless.

This dilemma must be accompanied by two caveats. First, there are many other potentially fruitful reasons to study time machines. (Vague pronouncements about progress in the foundations of general relativity seem to be the most common justification for their study.) But as we shall see below, the motivation for studying time machines is an important factor in determining one's attitude toward their possibility. For this reason, I am suggesting the following clear and simple motivation: the study of time machines evidently can have and meaningful implications for the Cosmic Censorship Conjecture. Thus the second caveat: a solution to the cosmic time-traveler's dilemma is surely forthcoming, once an adequate relationship between the time machines and the Cosmic Censorship Conjecture is spelled out. The spelling out of this relationship is the topic of today's term paper.

After briefly reviewing Cosmic Censorship Conjecture and Thornian time machines, I will suggest an adequacy condition on any set of criteria used to define time machines, if they are to have a meaningful impact on the Cosmic Censorship Conjecture. Next, in light of this adequacy condition, I discuss all of the most popular criteria that I am aware of for the admissibility of a spacetime into physical study, and in particular into the definition of a time machine. (I will be referring to these as 'admissibility criteria.') Finally, I briefly review and draw conclusions for the two most promising and opposing results in the time machine literature: Krasnikov's (2002) no-go result and Ori's (2007) time machine.

1.1 The Cosmic Censorship Conjecture (CCC)

Almost forty years after Penrose (2002) suggested that there the Universe hides her nakedly singular regions, the Cosmic Censorship Conjecture is still recognized as one of the most important open problems in general relativity (for example, see the language of Virbhadra (1999)). Though an agreed upon statement of the CCC or even of the definition of a naked singularity is notoriously lacking, I follow Earman (1995) in taking the spirit of the CCC to lie in the prohibition of indeterminism proffered by global hyperbolicity[1]. This leads to the following definitions.

Definition 1. In a spacetime $(M, g_{\mu\nu})$, the open subset S with induced metric $g_{\mu\nu}|_S$ contains a *naked singularity* just in case S is neither i) globally hyperbolic nor ii) hidden behind an absolute event horizon.

The CCC concerns itself with local empirical phenomena, the canonical example being that of gravitational collapse. This suggests the following formulation of the CCC:

Definition 2. If a dynamical evolution of known matter fields evolves from generic initial conditions, then it cannot produce a naked singularity.

Note on Terminology: A popular alternative formulation of the CCC defines naked singularities in terms of some form of geodesic incompleteness.

[1]A set S is *globally hyperbolic* just in case S is strongly causal and the 'diamonds' are compact in S; i.e., for any two points $p, q \in S$, the set $J^+(p) \cap J^-(q)$ is compact and contained in S. See §6.6 of Hawking and Ellis (1973) for discussion.

If the reader dislikes my hijacking of these terms for a discussion of global hyperbolicity, he is free to substitute any alternative terms as he feels appropriate. [2]

The assumption of global hyperbolicity in the definition of a naked singularity means that, given the appropriate antecedent conditions, the evolution of closed timelike curves would immediately violate the CCC. Conversely, if it were shown that no generic initial conditions from known matter fields could ever lead to the evolution of closed timelike curves, then this feature of the CCC would be 'protected.' Thus, the recent time machine literature would seem like a natural place to find meaningful implications for the CCC. As we shall see below, matters are not as simple as that.

1.2 Thornian time machines

The intuitive notion of a Thornian time machine is just an admissible local region of spacetime that is responsible for the existence of closed timelike curves (CTCs) in its causal future. Two minimal requirements for a region to be a time machine are fairly well agreed upon in the literature (see reviews by Visser (2002) and Earman, Smeenk, and Wüthrich (2004)):

Definition 3. A future-extendible region S is a *Candidate time machine* if every maximal extension of S admits CTCs entirely contained in the causal future of S.

Although the Candidate time machine provides a first step toward making the intuitive notion of a time machine precise, is not sufficient. Two ambiguities prevent the further specification of time machines: when is a region *responsible* for the existence of CTCs, and when is a region *admissible*?

Answering the first question is one of the most difficult challenges in the

[2] As it turns out, global hyperbolicity is a much stronger property than geodesic completeness. Both diamond compactness and strong causality can be violated in a geodesically complete spacetime. An example of the former: delete the origin of Minkowski spacetime, and achieve geodesic completeness by funneling the singularity to infinity (just apply a conformal factor that causes the metric to blow up as the origin is approached). Global hyperbolicity fails, because there are points on the time axis (say, $p < 0$ and $q > 0$) that yield a diamond $J^+(p) \cap J^-(q)$ that is not compact. On the other hand, consider 'rolled up' Minkowski spacetime, in which the points $|t| > 1$ are deleted and the hypersurfaces $t = \pm 1$ identified. Here, global hyperbolicity fails because the existence of CTCs violates strong causality.

time machine literature, and we shall be considering the adequacy of various responses over the course of this paper. But answering the second question depends on one's goals. If one's aim is mere model-building in the sky, then there is little reason to provide further specifications on Time Machines at all; one need only provide Candidate time machine in any spacetime satisfying Einstein's field equations. The existence of time machines would be assured by the example of, say, Deutsch-Politzer spacetime. And this result would be completely trivial.[3]

On the other hand, if one's goal is to make progress toward the CCC, then some additional criteria must be applied to the family of admissible spacetimes. To avoid wild speculation about how this might be done, I propose the adoption of an adequacy condition.

1.3 Cosmically Ignominious Spacetimes

In order to guide the choice criteria for determining which spacetimes are admissible and which are inadmissible into our considerations, consider the following definition.

Definition 4. A set of criteria characterizing a family of admissible spacetime obeys the *cosmic adequacy condition* just in case it allows for meaningful results to be obtained toward the proof or refutation of the Cosmic Censorship Conjecture. Namely, such a set must at a minimum obey:

1. *Consistency.* The proposed criteria must not contradict the assumptions made going into the Cosmic Censorship Conjecture.

2. *Non-Triviality.* The proposed criteria must not trivially imply or negate the Cosmic Censorship Conjecture.

3. *Locality.* The proposed criteria must respect the Cosmic Censorship Conjecture's concern with local empirical phenomena.

Consistency and Non-Triviality demand that any putative proof or refutation of the CCC be a sensible one. Locality guarantees that each spacetime

[3]Indeed, it is well known that in the absence of additional constraints, any arbitrary geometry $(M, g_{\mu\nu})$ can be guaranteed to satisfy Einstein's field equations by the construction of a suitable energy-momentum tensor $T_{\mu\nu}$. Just use M and $g_{\mu\nu}$ to calculate the Einstein tensor $G_{\mu\nu}$, and then solve $G_{\mu\nu} = -(8\pi G/c^4)T_{\mu\nu}$ for $T_{\mu\nu}$.

admitted into the family is of a type that the CCC is ultimately concerned with. Given the stated formulation of the CCC, this last condition is perhaps a consequence of consistency, and thus redundant. However, its importance warrants its explicit statement. Although these three conditions may not be sufficient for meaningful results to be obtained toward the CCC, they are enough to substantially narrow the available time machine criteria in an interesting way. This will be the subject of the remainder of the paper.

The upshot of the cosmic adequacy condition is a clear strategy for selecting further criteria to add to our definition of a time machine, from among the murkey swamp of criteria adopted throughout the literature. The downside is that the condition might be too strong; that is, there might be no interesting time machine spacetimes that satisfy the cosmic adequacy condition. This would mean that the study of time machines cannot meaningfully contribute to the CCC. Such a result, though disappointing, would still be interesting in and of itself, although at this point I see no reason for believing it is true. The cosmic time-traveler's dilemma is that he has not yet found a cosmically adequate spacetime–but that just means that he ought to keep looking!

So let us begin the search. In the next section, we review the criteria that are candidates for the definition of a time machine.

2 Review of Admissibility Criteria

The proposed criteria for admissible time machine spacetimes can be organized into three categories: global geometric criteria, local geometric criteria, and local empirical criteria. We shall consider each of these categories in turn. At the end I provide a summary of which criteria seem reasonable, which are questionable, and which are downright ignominious.

2.1 Global Geometric Criteria

Global geometric criteria are imposed on the entirety of spacetime, and not just the region immediately surrounding a Candidate time machine. A few criteria that might be labeled under this heading are completely innocuous, and will barely enter into our consideration (such as the required satisfaction of the field equations). However, all three of the potential criteria that we review below are offensive from the perspective of the CCC.

Trivial Topology. Requiring three spacelike dimensions of spacetime to have the trivial topology topology $\mathbf{R^3}$ is suggested, for example, by Ori (2005). I can imagine little other motivation for such a criterion than some kind of requirement of cosmic simplicity. If this is the true motivation, then it not only smacks of platonism, but also fails to respect the CCC concern with local phenomena, thus violating Locality. Certainly, a no-go result for time machines that included this criterion could not be taken seriously, since the class of spacetimes under consideration would be unreasonably restrictive.

However, this is not to say that no topological criteria may be imposed on spacetime. In order to have a model that adequately represents our intuitive experience of the separation between points, for example, we almost always require that our manifold be Hausdorff, or at least $T1$. But these criteria are empricially well-motivated, in addition to being reformulable as local properties on demand.

The trivial topology condition is of questionable motivation in the first place, since among the spacetimes that admit a trivial spacelike topology, there are some that do contain CTCs (such as Taub-NUT spacetime) and some that don't (such as Minkowski spacetime). So let us move on to more interesting criteria.

Asymptotic Flatness. This is a very popular criterion for Candidate time machines (c.f. Ori (2005)). The idea is that any geometric effect that is really the result of a local dynamical evolution should have a diminishing effect on farther-out regions of spacetime. Unfortunately, this brings three unavoidable problems from the point of view of the CCC. First, asymptotic flatness violates Locality, by requiring that spacetime conform to a particular structure across the entire Universe. Second, we might very well imagine some scenario in which we would want to claim the CCC was violated *in spite of* the failure of this criterion, such as if some model of stellar evolution did not admit asymptotic flatness, while enjoying a great deal of experimental confirmation on a local scale. Finally, there are other conditions available to us that may do a better job of locating the responsibility for CTCs in the Candidate time machine, which we perhaps ought to consider first.

Still, would-be time travelers should be aware of the possible virtues of adopting this condition. In particular, if this condition is adopted, then Krasnikov's (2002) no-go result for Candidate time machines appears to be in grave danger of failure (see Section 3). However, adopting the asymptotic flatness criterion on this basis is *ad hoc*, and wouldn't give any hope to our cosmic time-traveler anyway.

Global hole-freeness. Hole-freeness is a criterion originally proposed by Geroch (1977). Intuitively, a spacetime is hole-free if the domain of dependence of an arbitrary partial Cauchy surface cannot be extended. More formally, a spacetime $(M, g_{\mu\nu})$ is *hole-free* just in case, for every extendible spacelike surface S and for every $(M', g'_{\mu\nu})$ that extends S, there is no isometry $\iota : (M, g_{\mu\nu}) \to (M', g'_{\mu\nu})$ such that $\iota(D^+(S))$ is properly contained in $D^+(\iota(S))$.

Hole-freeness offers a more convincing reason to believe that it is the Candidate time machine that produces the closed time-like curves, and not some indeterministic nonsense that might arise out of the non-uniqueness of a Cauchy development (see Earman (1995, 97-98) for discussion). Unfortunately, there are no visible grounds on which this criterion does not fail Non-Triviality. Hole freeness is a property that was designed to identify singularities in the manifold in the form of holes.[4] But global hyperbolicity immediately fails in spacetimes that fail to be hole-free, since the diamonds fail to be compact around the 'holes.' Thus, restricting one's attention to hole-free spacetimes risks trivializing the CCC.

Furthermore, when adopted on a global scale, hole-freeness violates Locality, just as the previous two potential criteria did. However, the easy response to this complaint is that all we are really interested in is that the local region immediately surrounding the Candidate time machine and the CTCs it is purported to produce. This leads us to the second category of admissibility criteria.

2.2 Local Geometric Criteria

Local geometric criteria are imposed on local regions spacetime, and are generally less objectionable from the perspective of the CCC. However, the criterion of hole freeness fares no better here.

Local hole-freeness. If we want a deterministic Cauchy development from the time machine region up through the chronology violating region in its causal future, then perhaps we can escape the Locality complaint by only requiring hole-freeness on the local scale of our Candidate time machine. (Of

[4] A comparable criterion had been previously suggested by Hawking and Ellis (1973, 58-59), called 'local inextendibility.' However, some replacement was needed when Beem (1980) discovered that local inextendibility fails for Minkowski spacetime! Geroch's definition has, so far, withstood as a more reliable condition for the exorcism of holes.

course, this will not escape the Non-Triviality complaint discussed above.) A condition like this is suggested by Earman et al. (2004) as well as Ori (2007).

Unfortunately, the maximal extension of a hole-free spacetime need not itself be hole free. Indeed, there are even spacetimes that have no maximal hole free extensions at all. To take an example due to Clarke (1976), start with $\mathbf{R^4}$ and a Lorentz metric:

$$ds^2 = A(r,t)(-dt^2 + dx^2 + dy^2 + dz^2). \tag{1}$$

Transform to polar coordinates by taking

$$r^2 = x^2 + y^2 + z^2 \tag{2}$$

$$x = r\cos\theta \tag{3}$$

$$y = r\sin\theta \tag{4}$$

$$A(r,t) = \begin{cases} 1 \ \text{ if } t < r \\ \sec\frac{\pi}{2}(\frac{t}{r-1}) \text{ if } r \leq t < 2r. \end{cases} \tag{5}$$

Finally, take the restriction of $\mathbf{R^4}$ to the region where $t < 2r$, $\frac{1}{2(\theta+\pi)^2} < r < \frac{1}{2\theta^2}$, $x = \cos\theta$, and $y = \sin\theta$, with $-\infty < \theta < \infty$. The result is a hole-free spacetime with no maximal, hole-free extensions.

Requiring local hole-freeness around our candidate time-machine doesn't banish indeterminism after all, but merely pushes it out to the level of the maximal extension. But this is precisely where the chronology violating region lies. So it seems that even the original motivation for adopting the hole-free criterion in our definition of time-machines is unwarranted.

Nevertheless, the interesting upshot to this criterion is that, like asymptotic flatness, its adoption seems to lead to the failure of Krasnikov's no-go result.

Locally evolved CTCs. If hole-freeness cannot adequately lead us to be confident that CTCs are being produced by the Candidate time machine, then what property can? It may still be possible to give a satisfactory answer to this question, but no such answer is forthcoming. For the moment we are left to fall back on the weaker requirement that the chronology violating region lie in some local neighborhood of the Candidate time machine, preferably in the immediate vicinity[5].

[5] Wald (1984, 305) formulates the field equations with energy conditions in such a way

Notably, a much stronger alternative was formulated by Hawking (1992), which counseled that the Cauchy horizon of a partial Cauchy surface in the candidate spacetime be compactly generated. Hawking used this result to prove that any such candidate spacetime must violate the weak energy condition. Anticipating our adoption of this energy condition below, we may take this as a *reductio ad absurdam* of the claim that this future Cauchy must be compactly generated. In most of the candidate spacetimes proposed after Hawking's result, this offending feature of future Cauchy Horizons was avoiding by assuming or constructing them so as not to be compactly generated.

Causality Conditions. Any criteria restricting the causal structure of the Universe that are not completely innocuous would risk violating Non-Triviality in a discussion of the CCC, and seem ironically out of place in the discussion of time machines. Recall that our stated definition of a naked singularity entails that strong causality holds in any non-nakedly singular spacetime. Thus we follow Earman (1995) in taking such criteria to have the disagreeable potential to be *ad hoc* in this context, so accordingly avoid them altogether.

Partial Cauchy Surface. The definition of a Candidate time machine as stated does not indicate a time when the machine was turned on, or even a finite spacelike region in which it can be said to exist. The former of these worries is satisfied by the requirement that a *partial Cauchy surface* exists in any Candidate time machine, that is, a surface that is not intersected more than once by any future-directed timelike curve. The latter worry is satisfied by requiring this surface be finite.

I see no problem with either of these two criteria. In fact, the requirement of partial Cauchy surfaces is positively supported by Locality, a necessary (if not sufficient) for a set of initial conditions to be 'generic'. So let us take this to be our first desirable admissibility criterion!

2.3 Local Empirical Criteria

These criteria are, in my view, the most desirable of the potential criteria for the admissibility of spacetimes. They are normally well-motivated by local

---

that uniqueness of the initial value problems are guaranteed. This can be taken as a particular setting in which the initial value problems are well-posed; however, they are not the general case. Any assumption of determinism that is too general risks rendering the CCC trivial.

empirical experience and epistemic modesty.

Energy conditions.

The satisfaction of the standard energy conditions (weak, dominant and strong) has for a long time been recognized as one of the most basic requirements on an admissible spacetime. To state each of them in rather informal terms: the weak energy condition implies that only non-negative energy densities can be observed; the dominant energy condition consists in the weak energy condition conjoined with the claim that local energy flow-vectors are non-spacelike; the strong energy generally requires that there be no negative energies or very large negative pressures (see Hawking and Ellis (1973, 89-95) for more discussion).

However, although the weak energy condition is satisfied for all known classical fields, its possible violation is well known in the context of quantum field theories, most notably as manifested in the Casimir effect (for a review, see Milton (1999)). Furthermore, the recent discovery that the Universe may be accelerating, together with the possible explanation of this phenomenon by means of a negative vacuum pressure, seems to have called off all bets on the strong energy condition as well.

Still, there is not yet a convincing evidence that the weak energy is violated on a cosmic scale, and the interpretations of the purported accelerated expansion are so wide-flung, it is in my view too early to draw any lasting conclusions about the strong energy condition. Furthermore, we can always retreat to the study of the Cosmic Censorship Hypothesis as a postulate of classical general relativity, in which 'generic conditions' necessarily imply that the standard energy conditions are satisfied.

Fields, equations of motion, and source constraints. Empirical and epistemic modesty has often counseled that we restrict our considerations to known fundamental fields (such as gravitation and electromagnetism) and known matter fields (composed of fundamental fermions). The requirement that our equations of motion be known and realistic nature has the potential to provide a fruitful and sophisticated admissibility criterion, if only on a case-by-case basis. And the requirement for realistic energy-momentum sources and on the equations of state are already at least partly entailed by the adoption of energy conditions.

These constraints will normally be applied on a case-by-case basis, through the careful examination of what physical phenomena are relevant to a given model. These conditions are also suggested by Consistency condition of adequacy, given that typical formulations of the Cosmic Censorship Hypothesis (including the one stated here) respect these criteria in some form or another.

Stability. No matter what result we find, we would like to know that the result is not artificial and fleeting. For example, imagine a claim that somehow hinged on whether or not a circular orbit of a particle beyond the inner-most stable could obtain. In the Schwarzschild metric, such a solution is readily available. However, since any orbiting body in this situation lies at the top of a gravitational potential hill, any perturbation of its state either sends the particle flying into the central mass or deflected off to infinity. In other words, such a solution is not stable.

From the perspective of the CCC, one would expect any naked singularity of interest to be stable in the same sense; otherwise, the singularity would not be nakedly visible, as it were, for all the Universe to see. An unstable naked singularity, like an unstable orbit, would have a kind of fleeting, theoretical existence that does not correspond to any empirical observations. At worst it is a potential violation of Locality; at best it is a violation of the spirit of the CCC. Thus, if for no other reason than to guarantee an interesting result, it seems advisable to test the stability of any time-machine (and correspondingly, of any no-go result) on a perturbative analysis.

Let us finally summarize the results of this section. *Inadequate criteria:* trivial topology, asymptotic flatness, global hole-freeness, causality conditions. *Questionable criteria:* local hole-freeness, locally evolved CTCs. *Desirable criteria:* admission of a partial Cauchy surface, energy conditions, field constraints, realistic equations of motion, and source constraints, stability constraints.

3 The Fate of the Cosmic Time-Traveler

Given the admissibility conditions suggested above, what is the fate of the cosmic time-traveler? Two answers have been given that at first blush appear very hard to reconcile. The first is a no-go result by S. Krasnikov (2002), which advertises: 'No time machines in classical general relativity'. The second is a construction by Ori (2007), which purports to be a time-machine satisfying most of the criteria given above. After reviewing each of these results in light of the previous discussion, we shall discuss the simple resolution of this apparent inconsistency, followed by the ultimate fate of the cosmic time traveler.

3.1 A No-Go Result

S. Krasnikov (2002) gives a constructive proof that any extendible spacetime, satisfying any local empirical conditions you like (such as the standard energy conditions), has a maximal extension satisfying those same local conditions, and which is free of closed timelike curves. In other words, there always exists a counterexample to the claim that every maximal extension of an extendible spacetime S contains closed timelike curves in the causal future of S. Therefore (as Krasnikov would have it), the definition of a Candidate time machine cannot be satisfied.

However, this is only a true no-go result for the existence of time-machines if Krasnikov's constructed counterexample counts as an admissible spacetime. Krasnikov has guaranteed that this construction can be made to satisfy the standard energy conditions; however, its respect for any further admissibility criteria requires further examination.

The crucial and most interesting part of Krasnikov's result is the construction of the (non-maximal) extension M_N from an arbitrary spacetime M, such that i) no closed timelike curves are properly contained causal future of M, and ii) this extension can be repeated such that there is an inductive ordering on the resulting family of extensions. It is then a simple consequence of Zorn's lemma that M admits a maximal extension with the desired property (as discussed in Earman (1995, 61 n.15)).

From the point of view of the CCC, the extension M_N is immediately disastrous, because it contains a singularity. (In the language of S. Krasnikov (2002), the points Θ are removed in the construction and, as proved in Proposition 27, cannot be glued back into M_N.) So the assumption that Krasnikov's maximal extension is an admissible spacetime immediately entails the failure of global hyperbolicity (in fact, countably times over). Thus, the construction violates the Non-Triviality condition of adequacy, since by this assumption the CCC is trivially contradicted.

One could perhaps try to smooth out the singularities in Krasnikov's extension by multiplying the metric by a conformal factor that funnels the singularities off to infinity. The encouragement for this is that Krasnikov's original extension M_N is homeomorphic to the Deutsch-Politzer topology, which Chamblin, Gibbons, and Steif (1994) suggested can be smoothed out in just the desired way, to obtain the topology of $S^1 \times S^3 - (point)$. S. V. Krasnikov (1998) even showed how this could be done while still preserving the weak energy condition. However, finding a suitable conformal factor, if one exists, is a highly non-trivial matter. Krasnikov only constructs a conformal factor for the simpler, two-dimensional version of Deutsch-Politzer spacetime, and then shows how to extend four-dimensional Deutsch-Politzer. But it is far from clear whether or not there is even such a lovely simplification of M_N.

Worse, there is still no guarantee that the resulting doctored extension would be globally hyperbolic (and thus non-trivial), even if it were forced to be geodesically complete. And neither Krasnikov's original extension nor its potential conformally-doctored cousin is likely to satisfy the desirable empirical criteria for admissible spacetimes. In particular, the extreme cut-and-paste nature Krasnikov's extension makes it very unlikely that it could evolve from known matter fields with realistic sources and equations of motion. These shortcomings, in my view, pose the most significant threat to Krasnikov's construction independent of the question of Cosmic Censorship. As a result, the most fruitful way to approach the construction of a time machine would seem to be through the insistance that these 'empirical' admissibility criteria be satisfied.

However, there are two other admissibility criteria which, though deemed inadequate in the above discussion, have interesting consequences for Krasnikov's result. By either requiring admissible spacetimes to be hole free or else that they be asymptically flat, it seems that Krasnikov's result can be foiled. Krasnikov's construction is evidentally not hole-free due to the singularity discussed above; thus, adopting the requirement of hole-freeness effectively disbars the construction and hence his prohibition of time machines. I conjecture that Krasnikov's construction would also fail to be asymptotically flat, although this claim remains to be verified. The motivation for this conjecture is the following. In order to satisfy the Non-Triviality condition, Krasnikov's construction must be modified so as to be non-singular. Such a modification would seemingly have to follow the strategy outlined above, following the example of the related Deutsch-Politzer spacetime. But by a result of Chamblin et al. (1994), the singularities in Deutsch-Politzer spacetime cannot be smoothed out while obeying the requirement of asymptotic flatness. Therefore, it is unlikely that Krasnikov's construction could achieve such a result either.

Although only the insistence on empirical constraints is a reasonable way out of Krasnikov's no-go result from the perspective of the CCC, it now seems that both the restriction to asymptotic flatness and to hole-free spacetimes are also plausible ways out as well. This will allow us to make some sense out of the following, apparently diametrically opposed result.

3.2 A Yes-Go Result

It has recently come to my attention that Ori (2007) has given an intriguing new proposal for a candidate time-machine. This construction consists in concentric regions of vacuum, then dust, then vacuum. The interior region is causally similar to the Taub-NUT geometry, while the exterior region is similar to the Schwarzschild geometry. An initial hypersurface of a time machine is described in the internal vacuum region, in which the evolution of CTCs is then shown to occur.

The most intriguing feature of Ori's construction is the laundry-list of admissibility criteria that it claims to satisfy. The model is found to satisfy known matter-fields and realistic energy-momentum sources and equations of motion, satisfying the Einstein-dust model $G^{\mu\nu} = 8\pi\epsilon u^{\mu}u^{\nu}$. It is said to satisfy the weak, dominant, and strong energy conditions. Closed timelike curves are shown to evolve from (apparently) generic initial conditions, in every hole-free extension of a particular partial Cauchy surface. Finally, it admits the trivial topology of $\mathbf{R^4}$, and is asymptotically flat.

However, before celebrating the final discovery of an admissible Candidate time machine, there are two reservations that we ought to consider. First: a truly admissible Candidate time machine would have to remain stable under perturbations of state. Otherwise, we should treat them with no more interest than possibility of unstable orbits in the Schwarzschild geometry; such solutions could never be realistically said to occur, let alone have an impact on the CCC. Nevertheless, this worry might very well turn out to be unwarranted; the perturbative behavior of this solution is simply not yet known.

Second, and more importantly: it is not necessarily a virtue that Ori's time machine satisfies more admissibility conditions that are desirable. In many of these cases, the satisfaction of such conditions is a harmless bonus. For example, Ori does not *restrict* his attention to asymptotically flat spacetimes, but rather works very hard to design a model that has this feature. In contrast, one criterion that is overly restrictive is the fact that he only considers the formation of CTCs in the *hole-free* extensions of the partial Cauchy surface.

As a reminder, this restriction is worrisome because 1) it means Ori's construction risks trivializing the CCC; 2) it doesn't seem to accomplish what it was designed for, in that we still cannot be confident about where the CTCs are coming from and what might prevent them from forming; and 3) it is therefore overly restrictive, leading to the possibility that legitimate evolutions from the partial Cauchy surface might escape our attention.

If any one of these legitimate evolutions fails to produce a closed timelike curve, then Ori's construction will no longer function as a Candidate time machine. The importance of this warning is further indicated by the fact that the restriction to hole-free spacetimes is the only obvious feature of Ori's construction that prevents it from falling prey to Krasnikov's no-go result. Krasnikov's maximal extension of an arbitrary extendible spacetime (with no CTCs in the causal future of that spacetime) fails to be hole-free. So avoiding holey spacetimes altogether is a guaranteed way to avoid this result.

These constructions of Krasnikov and Ori are the most promising results that I am aware of toward an evaluation of the existence of time-machines might meaningfully impact the Cosmic Censorship Conjecture. Unfortunately, neither of them are adequate from the perspective of the CCC, and thus our cosmic time-traveler is for the moment left wanting. However, through the careful analysis and extension of these results and their assumptions, it is clear that an adequate result can soon be obtained. Until then, it is the continued work of physicists and philosophers that will bring the cosmic time traveler's dilemma closer to an end.

References

Beem, J. K. (1980). Minkowski space-time is locally extendible. *Communications in Mathematical Physics*, *72*(3), 273-275.

Chamblin, A., Gibbons, G. W., & Steif, A. R. (1994). Kinks and time machines. *Physical Review D*, *50*(4), R2353-R2355.

Clarke, C. J. S. (1976, February). Space-time singularities. *Communications in Mathematical Physics*, *49*(1), 17-23.

Earman, J. (1995). *Bangs, crunches, whimpers, and shrieks: Singularities and acausalities in relativistic spacetime.* New York: Oxford University Press.

Earman, J., Smeenk, C., & Wüthrich, C. (2004). *Take a ride on a time machine.* (Forthcoming)

Geroch, R. P. (1977). Prediction in general relativity. In J. Earman, C. Glymour, & J. Stachel (Eds.), *Foundations of space-time theories, minnesota studies in the philosophy of science* (Vol. VIII, p. 81-93). Minneapolis: University of Minnesota Press.

Hawking, S. W. (1992). The chronology protection conjecture. In H. Sato & T. Nakamura (Eds.), *The sixth marcel grossmann meeting* (Vol. A, p. 3-13).

Hawking, S. W., & Ellis, G. F. R. (1973). *The large scale structure of space-time.* New York: Cambridge University Press.

Krasnikov, S. (2002). No time machines in classical general relativity. *Classical and Quantum Gravity*, *19*(15), 4109-4129.

Krasnikov, S. V. (1998). A singularity-free wec-respecting time machine. *Classical and Quantum Gravity*, *15*(4), 997-1003.

Milton, K. A. (1999). *The casimir effect: Physical manifestations of zero point energy.*

Morris, M. S., & Thorne, K. S. (1988, May). Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity. *American Journal of Physics*, *56*(5), 395-412.

Ori, A. (2005). A class of time-machine solutions with a compact vacuum core. *Physical Review Letters*, *95*(2), 021101.

Ori, A. (2007). Formation of closed timelike curves in a composite vacuum/dust asymptotically flat spacetime. *Physical Review D (Particles, Fields, Gravitation, and Cosmology)*, *76*(4), 044002.

Penrose, R. (2002, July). "golden oldie": Gravitational collapse: The role of general relativity. *General Relativity and Gravitation*, *34*(7), 1141-1165.

Virbhadra, K. S. (1999, Oct). Naked singularities and seifert's conjecture. *Physics Review D*, *60*(10), 104041.

Visser, M. (2002). *The quantum physics of chronology protection.*

Wald, R. M. (1984). *General relativity.* Chicago: University of Chicago Press.