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Do transient white holes have a place in Nature?

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Abstract. The white-hole sector of Kruskal's solution is almost never used in physical applications. However, it can provide a radically different take on the gravitational collapse process, avoiding the problems appearing within the standard paradigm. In this contribution we will try to draw attention to some bouncing geometries that make a democratic usage of the black and white sectors of Kruskal's solution. We will argue that this type of behaviour could be perfectly natural in some approaches to the next physical level beyond classical General Relativity.

1. Theoretical vs astrophysical views on black holes

In general informative publications as well as in the scientific literature the term black hole is used with no distinction nor qualification to represent both, characteristic configurations of theoretical General Relativity and astrophysical objects possessing certain features. However, these two notions need not coincide. Strictly speaking, a General Relativity black hole is a geometry with a region causally disconnected from infinity: the region inside the event horizon. At present we dare saying that most specialists think that an event horizon is a too-idealized notion and that it will have no place in a next-level theory replacing General Relativity, *e.g.* when quantum effects are taken into account. It is largely believed that these strict black holes will be substituted by regularly evaporating black holes and, correspondingly, event horizons substituted by long-lived trapping horizons [1].

On the other side, an astrophysical black hole is nothing but a very dark and compact region containing such a large amount of mass, measured by its gravitational influence in the surrounding matter, that standard General Relativity does not offer other possibility for it than being a black hole. However, one has to take into account that the very notion of event horizon makes it impossible that any astrophysical observation could verify their existence in any of the candidate dark and compact regions. For this reason, before entering into wild philosophical speculations about the implications of the existence of event horizons, it appears more reasonable to propose alternative and verifiable (at some level) hypothesis regarding the nature of the objects hidden in this dark and compact regions.

As already mentioned, the most common hypothesis is that these objects are regularly evaporating black holes. However, although this hypothesis is in principle verifiable, in practice it seems out of reach for the human kind in any foreseeable future. This is what constitutes the lifetime problem of evaporating black holes [2].

2. The lifetime problem of evaporating black holes

Hawking's original calculation [3] concluded that black holes should evaporate quantum mechanically, but at an extremely slow rate if only they contain any realistic initial mass: a stellar-mass black hole would evaporate completely in 10^{67} years! Hawking initially believed that the final evaporation would be accompanied by a loss of information [4]. At present there are several scenarios showing that the evaporation can proceed in a perfectly regular way with no final loss of information (see *e.g.* [5, 6, 1]). However, these scenarios maintain the slowly-evaporating-(now trapping instead of event)-horizon characteristic.

The gigantic lifetime of the trapping horizon makes it difficult to believe on the verifiability of the actual presence of a trapping horizon in any reasonable time expand. This is seldom presented in the literature as a problem, more as a "such is life" fact. However, in our view it constitutes a strong motivation to seek for the viability of an alternative scenario devoided of the lifetime problem.

3. Newtonian gravity vs General Relativity

General Relativity can be thought of as a theory that corrects Newtonian gravity with new effects. Till the sixties of the previous century General Relativity was considered, mostly, a post-Newtonian theory. In most physical situations General Relativity predicts small deviations from the Newtonian behaviour. Even today, there are not direct experimental evidences of the working of General Relativity in regimes far apart from their Newtonian counterparts. However, the similarity between Newtonian gravity and General Relativity breaks up when event horizons are at stake.

Let us compare how one would describe what happen in the head-on collision of two equal balls of matter in Newtonian Gravity and General Relativity. Initially we put the two balls very far apart and with certain initial velocity towards each other. Then, we set them free subject to the rules of gravity. First of all in Newtonian gravity one can imagine the balls of matter to be as small as desired, even as point particles. In the approaching phase their relative velocity increases at the expense of the gravitational potential. Then at some point they collide with each other. In this colliding phase one naturally invokes other physics, the collision itself cannot be understood with gravitational physics alone, that is without further hypothesis. The simplest situations one can imagine is one in which the collision is elastic as if they were hard-balls, or one in which they are transparent to each other, meaning that while traversing each other they do not feel their respective gravity fields. In both cases the colliding phase will be followed by an escaping phase in which the balls will be climbing the gravitational potential. This escaping phase will be the perfectly time-symmetric version of the approaching phase.

The first new feature of General Relativity is that when the two balls start approaching each other there is some dissipation in the form of gravitational-waves emission. Leaving aside this issue (of crucial importance, but not for the point we want to make in this article) the collision process proceeds in a similar way to that in Newtonian gravity ... *except if the collision is so energetic that a horizon forms.* If the initial kinetic energy of the balls is sufficiently high, the collision will generate an event horizon so that the approaching phase will not be followed by a time-symmetric escaping phase: once the event horizon is formed there is no possible escaping phase, the very collision will end up with the formation of a singularity. This time asymmetry [7] separates definitively General Relativity from Newtonian gravity.

Is this separation inescapable? It is puzzling to realize that the time-symmetric version of the approaching phase exists as a classical General Relativity solution even in the cases that involve horizons. These configurations represent lumps of matter emerging from a singularity and escaping from each other, or using the standard terminology, they represent white holes. If only the regularization of the classical singularity allowed to connect the two time-symmetric branches this final separation would not happen.

Given the lifetime problem and the time asymmetry of classical General Relativity, and of most of the scenarios incorporating some quantum effects, it is interesting to seek whether there is space for an alternative scenario devoided of these two characteristics.

4. An alternative scenario

In a series of works [8, 9, 2] the authors have proposed an alternative scenario to the gravitational collapse process and the evaporating black hole paradigm. The alternative scenario has been worked out only for the simplest situation of a spherically symmetric collapse. However, we believe that this situation displays in the clearest possible way the new conceptual notions involved.

The logic of our works is the following. First, we realize that it is possible to imagine a regularization of the classical singularity that would appear in a spherically symmetric collapse so that it gives place to a time symmetric configuration. In geometrical terms the resulting geometry is nothing but the smooth continuation of a black hole spacetime, through its future singularity, to a white hole spacetime, both integrated in a single universe (a single asymptotic region). Then, on the one hand, we reflect about what would be the most salient consequences of this scenario in case it was actually at work in Nature. Most importantly, we argue that the scenario should leave distinct observable traces. On the other hand, we reflect about what characteristics should have a next level gravitational theory (beyond classical General Relativity) to be able to accommodate a regularization of the proposed type.

4.1. The geometries: Two salient features

In [2] we present a family of geometries representing the time-symmetric continuation of the spherically symmetric collapse of a homogeneous ball of dust initially at rest in a finite radius r_i (Oppenheimer-Snyner collapse [10]). The geometries are composed of i) a past region corresponding exactly to the Oppenheimer-Snyner spacetime, *i.e.* an external Schwarzschild region and an internal collapsing Friedman-Roberson-Walker region; ii) a future region corresponding exactly to the time reversal of the previous geometry; and iii) an intermediate region smoothly interpolating between the past and future regions. The precise interpolating function will depend on details of the underlying theory, which we do not know at this stage. However, here we are concerned with the generic and robust features of these geometries, independent of those details. The main features of these geometries can be read directly from their representation in Figure 1 (for more detailed arguments and an algebraic description of the geometries see [2]).

Two salient features of these geometries are:

- The total time inverted in the collapse and reestablishment of the initial configuration is extremely short as seen by external observers. Essentially this time is twice the proper time to form the classical singularity in the Oppenheimer-Snyder collapse. For figures taken from a initial neutron-star-like object this bouncing time will be of the order of 10ths of millisecond.
- The central grey triangular region in Figure 1 represents the transient region that is not a solution of standard General Relativity. Below and above this triangle the geometry is perfectly Einsteinian. What is remarkable is that in these geometries the non-standard

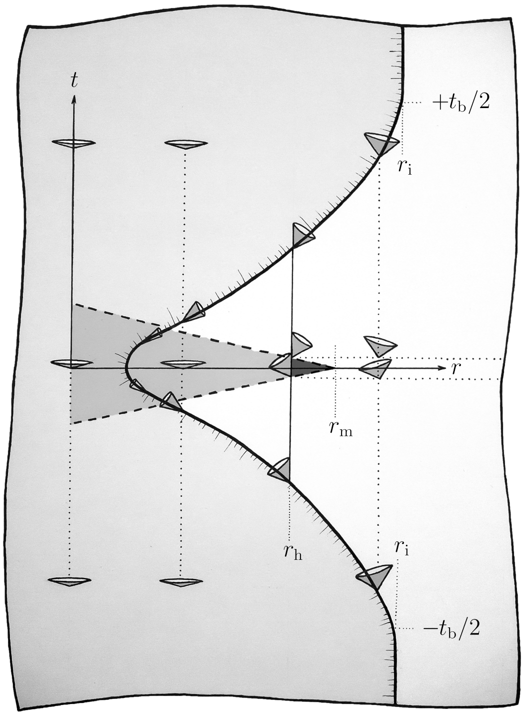

Figure 1. The figure represents the collapse and time-symmetric bounce of a stellar object in our proposal (the thick line). The past thick dashed line from $r = 0$ to $r_{\rm m}$ marks the boundary where the non-standard gravitational effects start to occur. In all the external white region the metric is Schwarzschild. In the region between the two thick dashed lines (which extends outside the stellar matter itself) the metric is not Schwarzschild, including the small dark grey triangle outside the Schwarzschild radius $r_{\rm h}$. The drawing tries to capture the general features of any interpolating geometry. The slope of the almost Minkowskian cones close to the origin has been taken larger than the usual 45 degrees to cope with a convenient and explicit time-symmetric drawing.

region always extends beyond the classical gravitational radius (represented by the small dark-grey triangle in Figure 1). An observer sufficiently close to the gravitational radius will realize that something strange (in General Relativity terms) is going on even before the matter starts to reappear from beyond this radius. Obviously, this radius will not longer act as an event horizon.

The conformal diagram of these geometries is presented in Figure 2. Here you can see that the spacetime associated with this time-symmetric bounce is causally equivalent to Minkowski spacetime. However, the geometries posses transient regions containing outer trapped surfaces and inner trapped surfaces (respectively, the bottom and top down-gray regions in Figure 2). There are no long-lived trapping horizons of any sort.

A geometry causally equivalent to this one has also been presented in [11]. However, as opposed to our proposal, the geometry in that paper is such that the total duration of the bounce as seen by external observers is extremely long, so it does not solve the lifetime problem.

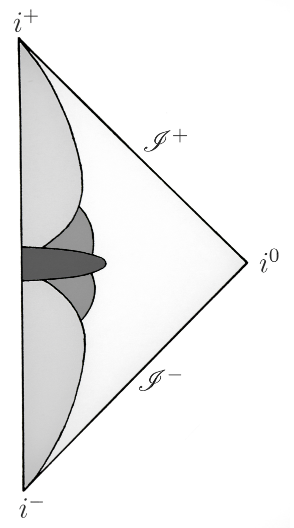

Figure 2. The figure represents the Penrose diagram of the proposed geometry. Globally it has the same causality as Minkowski spacetime. Locally it has some peculiarities. The dark grey region represents a non-standard gravitational field, while the up and down grey regions are respectively regions with inner and outer trapped surfaces. The light grey regions on the left-hand side are those filled by matter.

4.2. A verifiable scenario

If there exists a regularization of the classical standard General Relativity behaviour of the form we have described, the collapse process itself would not constitute the final stage of collapse in stellar physics. One would immediately be impelled to wonder about what would happen after the bounce. The search for new states of equilibrium, on the one hand, and the understanding of the transient collapse process itself, on the other, become entirely distinct issues.

In an ideal situation, perfectly spherically symmetric and without dissipation, the collapsing body would enter into a never-ending cycle of contracting and expanding phases. In a realistic situation though, one expects that the system will dissipate at least quantum mechanically while searching for new equilibrium configurations. However, now these new equilibrium configurations need not conform with the standard image of an evaporating black hole. For instance they could be objects close to their gravitational radius but with no long-lived horizons whatsoever (what we call generically black stars [12]).

The observable features of our scenario must be separated into two categories, those associated with the transient phase (the collapse and relaxation period) and those associated with possible new states of equilibrium different from evaporating black holes.

The transient phase should leave some traces, for instance, in the physics of Gamma Ray Bursts (GRBs) and its coincident gravitational-waves emission. One would expect some signatures associated with a reverberant collapse. In the collapsar model of GRBs however (see *e.g.* [13]) the emission zone is supposed to be very far from the collapsed core. This means that the connection between the processes at the core and those at the external wind shells could be very far from direct. The signatures should be clearer in the Gravitational Waves band. The last part of the gravitational-waves signal should clearly distinguish between the standard direct relaxation towards a black hole and the presence of some bounces.

Regarding the possible existence of black stars in place of evaporating black holes, here let us just say that these objects, having no trapping horizons, would be at least susceptible to complete astrophysical exploration.

4.3. A necessary underlying hypothesis

The past thick dashed line in Fig. 1 marks the boundary where non-standard gravitational effects start to happen. It is born at $r = 0$ and travels outwards even though the light cones are pointing inwards. This signal, should it exist, cannot follow the causality associated with the gravitational light cones. Rather it must follow an underlying causality that is explored only when Planck energies are at stake. This background causality should be trivial in the sense of containing no horizons whatsoever, the simplest example one can think of being a Minkowskian structure. This is the only hypothesis we need for our proposal to make sense. Otherwise general-relativistic light cones could not suffer such a dramatic turn.

The underlying causality we talk about could be nothing but the causality produced by the rest of the matter in the universe (*i.e* not considering the very matter undergoing the high-energy collision). This causality will be naturally (almost) Minkowskian in what concerns a localized process of gravitational collapse. Therefore, we are far from claiming that there need existing a background geometry unrelated to the matter content of the universe.

The previous hypothesis finds natural connections with some conceptualizations of gravity coming from particle physics and condensed matter physics. On the one hand, our proposal resonates with Rosen's reformulation of General Relativity as a nonlinear theory on a flat Minkowski background [14]. This reformulation indeed goes further than the standard formulation of General Relativity in the sense that it is a convenient effective framework to describe the switching-off of gravity at high energies. Rosen's reformulation can be understood as the long-wavelength limit of a nonlinear theory of gravitons (see [15] and references therein). It is still an open possibility that an ultraviolet completion of such a theory would exhibit asymptotic freedom (as its QCD cousin). On the other hand, similar ideas also appear when thinking of gravity as an emergent notion in a condensed matter framework [8] (see also [16]). The nonlinear theory of gravity describes in that case the behaviour of collective degrees of freedom. There, it is reasonable to think that the first quantum gravitational effect is that, above some Planckian energy scale, the collective degrees of freedom corresponding to gravity are diluted, leaving a Minkowskian background for the matter excitations.

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