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Transition to light-like trajectories in thin shell dynamics

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Abstract

It was recently shown that a massive thin shell that is sandwiched between a flat interior and an exterior geometry given by the outgoing Vaidya metric becomes null in a finite proper time. We investigate this transition for a general spherically-symmetric metric outside the shell and find that it occurs generically. Once the shell is null its persistence on a null trajectory can be ensured by several mechanisms that we describe. Using the outgoing Vaidya metric as an example we show that if a dust shell acquires surface pressure on its transition to a null trajectory it can evade the Schwarzschild radius through its collapse. Alternatively, the pressureless collapse may continue if the exterior geometry acquires a more general form.

1. Introduction

Hypersurfaces of discontinuity are idealizations of narrow transitional regions between space-time domains with different physical properties. The thin shell formalism [1–3] makes this idealization consistent by prescribing joining rules for the solutions of the Einstein equations on both sides of the hypersurface. These rules — junction conditions — determine dynamics of

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the shell. The resulting joined geometry is a solution of the Einstein equations with an additional distributional stress-energy tensor that is concentrated on the hypersurface.

The thin shell formalism plays a role in studies of cosmological phase transitions [4], impulsive gravitational waves [5], gravastars and other non-singular substitutes of black holes [6], traversable wormholes [7], and gravitationally-induced decoherence [8]. A massive thin shell separating a flat interior from a curved exterior spacetime region provides the simplest model of collapse. Classically the exterior spherical geometry is described by a Schwarzschild metric and the shell collapses into a black hole in finite proper time.

Such models has also been used in investigations of collapse-induced radiation [9,10] anticipated before formation of the event horizon. The basic idea is that the process of gravitational collapse excites fields in the spacetime, giving rise to asymptotically thermal radiation [9]. We shall refer to this as pre-Hawking radiation [11–13]. The consequences it might have for black hole formation and the information paradox have been a subject of interest in recent years [9,10,14–22]. While it has been argued that such effects are too small to prevent the formation of an event horizon [10,22], others contend that such approximations are not reliable and that horizons may not form if pre-Hawking radiation is properly taken into account [16,19]. Indeed, it has been posited that this should be a generic feature of quantum gravity, with the black hole interior and accompanying singularity replaced with a genuine quantum geometry where the notion of event horizon ceases to be useful [23].

A number of researchers have argued [15–18] that there are two options for the evolution of a thin shell in a spacetime with pre-Hawking radiation. One possibility is that an event horizon never forms: either the shell does not cross its Schwarzschild radius r_g before complete evaporation or a manifest breakdown of semiclassical dynamics, such as violation of the adiabatic condition [26], or formation of some quantum geometry [23] occurs. The other alternative is that evaporation stops producing a macroscopic or a Planck-scale remnant [25], forever preventing a distant observer at late times from detecting Hawking radiation. An outgoing Vaidya metric [27] is often used as an example of the exterior geometry of this process despite its known limitations [28].

This result applies to a broad class of possible exterior geometries. It is based on an implicit assumption that through their evolution a massive shell remains timelike and a massless shell remains null. However, it was recently demonstrated by Chen, Unruh, Wu and Yeom (CUWY) [29] that this assumption is unwarranted. Via an explicitly regular coordinate system, while CUWY confirmed horizon avoidance for an exterior geometry described by the outgoing Vaidya metric, they also demonstrated that it comes with a price.

Indeed, it was shown that if the exterior metric outside is outgoing Vaidya, a massive dust shell sheds its rest mass in finite proper time (while still outside its Schwarzschild radius), becoming null. It was further argued that if the evaporation continues the shell becomes superluminal. The choice is evidently between eventual tachyonic behavior or switching off the radiation. In the latter case the subsequent development is classical and the shell crosses r_g at a finite value of a suitable affine parameter [29].

Our goal is to understand in this context the limits of the thin shell formalism in various geometries and validity of the semiclassical approximation taking pre-Hawking radiation into account. The detailed description of the basic assumptions of this approximation and their application to thin shells is given in [17]. In practical terms, the standard curvature terms of the left hand side of the Einstein equations are equated to the expectation value of the renormalized stress-energy tensor. We assume its existence and consistency, but make no assumptions beyond that of spherical symmetry and certain regularity conditions that are described below. We leave