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Singularity Avoidance During Gravitational Collapse

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Abstract. The singularity theorems depend on reasonableness assumptions concerning the properties of the matter source in Einstein gravity. Known quantum effects in general relativity indicate that such assumptions are violated, specifically in the strong field regions surrounding black holes and perhaps other highly condensed objects such as neutron stars. On the other hand, alternative quantum effects lead to the hypothesis of Hawking radiation, raising questions about information loss and the prospect that black holes may evaporate. Although not well localized, this radiation would nevertheless tend to have strong support in regions where reasonable assumptions about singularity formation break down. We discuss the outlook for gravitational "collapse" processes which avoid singularity formation while, at the same time, preserving the conditions necessary for the development of Hawking radiation. It is found that the existence of this radiation subtly changes the spacetime geometry in the neighbourhood of the "horizon", partly clarifying the emission process, giving rise to conditions compatible with the singularity avoidance, and indicating specific conditions which must prevail in order to ensure the absence of singularities. Further questions about particular aspects of the evaporation are also discussed, although open questions remain.

1 Introduction

In this talk I shall do three things: i) argue that, at present, we have little grounds for considering that spacetimes embodying gravitational collapse inevitably contain singularities, ii) discuss consequences of considering collapse spacetimes which do not result in singularities, and iii) examine what rôle a theory of quantum gravity may play in illuminating these consequences.

2 Collapse and Singularities

The strongest arguments for the development of spacetime singularities during the process of gravitational collapse come from the singularity theorems of Penrose and Hawking.[1] The fairly generic applicability of these results[2] means that they have played a central rôle in most thinking on gravitational collapse within General Relativity for the past several decades. However, Hawking's acclaimed work[3] on quantum effects during gravitational collapse essentially changes the foundations upon which this thinking has been based.

The realization for this comes in two steps. First, Hawking[3] and others[4] have shown that, in the context of classical collapse, an initially pure quantum state would evolve to a mixed, outgoing, thermal state in the region exterior to an event horizon. As should be evident, this flux of quantum matter must itself have an effect on the evolution of the spacetime in which it occurs - energy conservation ensuring that the black hole must shrink. Second, it has been shown[5] that the surface which locally forms the boundary between inside and outside of the black hole must locally have negative energy densities in its neighbourhood, in conjunction with the positive energy flux at future null infinity. It is this outcome - that a quantum flux at infinity leads to local, negative energy densities within the spacetime - which must completely alter our perspective on the singularity theorems, dependent for their existence on an assumption that all local energy densities are positive. Quantum effects are seem to violate this condition, even for states which are not initially pure.[6]

An important consequence of this realization is a subtle separation between spacetime properties associated with the presence of an horizon, and those associated with the occurrence of a singularity.[1] The local existence of an horizon is determined by the marginally non-divergence properties of outgoing null rays, whereas the emergence of a singularity is established by, say, whether or not curvature becomes unbounded - not immediately related to the properties of null surfaces.[2] What, then, if an outward flux of quantum radiation does arise, but no singularity forms?

3 Collapse without Singularities

For a singularity to be avoided, the horizon cannot shrink to zero area. From a geometrical perspective, we can see that the horizon must eventually close on itself, to avoid running out of somewhere else to go. A similar conclusion has also been reached by other authors,[5, 7]

[1]Not enough is yet known about singularities resulting from the collapse of a rotating body for angular momentum to be fully included here. Thus, our attention will be confined to spherically symmetric, uncharged matter in which singularities resulting from classical collapse are known to be spacelike. Charge appears to be of no astrophysical relevance, though it may have an influence on the virtual physics of the early universe. But, as Hawking radiation can carry charge and angular momentum, so eventually should our collapsing matter.

[2]Actually, in spherically symmetric collapse, the singularity does arise precisely where the centre of the collapsing object becomes momentarily null.[5] We thank Greg Burnett for discussing concerning the generality of this observation.

even when motivated by different matter configurations, and requiring a general argument[8] will lead us, too, to consider the quantization of the gravitational field.

If the avoidance of a singularity rested upon particulars of each independent field theory, it would be difficult to argue in complete generality that a spacetime singularity must never form. For a general argument, it would seem that we must depend on the agent which we would otherwise expect to cause the singularity - namely, gravitation - and so it is to the quantum theory of gravity that we must make appeal. The effect should then be universal, and the "halting" of the shrinking of the horizon can always be expected to occur at Planckian dimensions - the scale governed by such a theory.

4 Rôle of Quantum Gravity

It is clear that there is a "generalized" (apparent) horizon which shrinks to zero area inside classically collapsing matter. In the traditional evaporation scenario, the horizon which emerges from the matter also shrinks, as a result of Hawking radiation carrying off energy to infinity. If quantum gravity is to prevent singularity formation, then it must arrest both these shrinking processes. Indeed, examples of spacetimes portraying this effect have been discussed in the past.[5, 7] Moreover, in his series of papers,[7] Vilkovisky has argued that local quantum effects already halt singularity formation during collapse, but that non-local effects are necessary to determine the evolution of the horizon at sufficiently late time.

Something is remarkable in these examples. At only one point does the horizon attain its minimal area, a point that is the same coming from early or late times, whether the horizon resides entirely inside[5] or outside[7] the matter. Clearly, in these examples, non-local effects must corroborate the influence of local effects - if not, then local effects would be in contradiction. Yet, for both "early" and "late" times the horizon shrinks from its maximal area by being partly spacelike and partly timelike. So, a real question for which we must await an answer is: How do "non-local" effects influence the horizon as it passes from timelike to spacelike evolution during evaporation? This, along with a similar understanding of "local" field effects at the spacelike to timelike transition for the horizon inside the collapsing matter, would seem to be the key to a full reconciliation of how separate - local and non-local - quantum gravity effects may truly lead to singularity avoidance, if indeed they do.

5 Conclusion

What we have seen is that classical theory tells the gravitational field how to respond to the presence of matter in a spacetime, even to the point of creating horizon conditions. On the other hand, quantum theory tells matter how to respond to those conditions, apparently by radiating away energy to infinity. We understand that classical gravity further responds to this energy flux, causing the horizon to shrink, but very slowly to begin with for astrophysical sources. In the formation of the horizon and in initiating evaporation, quantum gravity would appear to play no major part. We expect that quantum gravity becomes effective once the horizon has shrunk to Planckian proportions. Thus, quantum effects at the horizon and at a potential singularity have been distinguished by their separate dependence on matter and gravitation respectively. For the moment, there is some difficulty defining the domain where the local and non-local effects of quantum gravity can and must meet.[3]

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[4] Talk also given at the Second International Sakharov Conference on Physics, Moscow, May 20-24, 1996.