Horned Particles as the Endpoint of Hawking Evaporation

Thomas Banks

Department of Physics and Astronomy
Rutgers University
Piscataway, NJ 08855-0849

This essay reviews recent developments in the theory of Hawking evaporation of black holes. Study of near extremal magnetically charged black holes using a two plus four dimensional effective field theory has led to the concept of horned particles or *cornucopions* as the endpoint of Hawking evaporation. Horned particles are geometries containing two large asymptotic regions connected by microscopic necks. They look like point particles to an observer in any given asymptotic region, but in many ways behave like macroscopic objects. In particular, it is very difficult to pair produce them in external fields and their contribution to virtual loops is highly suppressed. They can serve as the remnants necessary to account for the information apparently lost in Hawking evaporation. The information simply goes into the new asymptotic region formed when the black hole collapses and evaporates.

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The paradoxes posed by Hawking's[1] demonstration that black holes emit apparently thermal radiation have resisted resolution for almost eighteen years. Hawking's suggestion that the endpoint of black hole evaporation is the vacuum, and its consequent requirement that quantum mechanics be replaced by a new theory of density matrix evolution in which states do not remain pure, seems to be inconsistent with the simultaneous preservation of Poincare invariance (conservation of energy momentum and angular momentum) and locality.[2] The apparently conservative suggestion that quantum phase information is returned to the external observer in subtle phase correlations not visible in Hawking's approximate calculation, seems to lead to macroscopic violation of causality[3]. The remaining alternative, that black hole evaporation terminates in stable or quasi-stable remnants, appears to be in gross disagreement with experiment. The "phenomenology" of Hawking radiation requires us to envisage an essentially infinite number of distinct remnants which are almost degenerate in Arnowitt-Deser-Misner[4] (ADM) energy. It is then difficult to understand why these remnants do not produce infinite contributions in virtual loops to ordinary low energy processes, and why they are not produced with infinite cross sections in slowly varying fields. The prescient early paper [5], which advocated the remnant scenario, ascribed the resolution of these difficulties to rapidly falling form factors for remnant production, but did not provide a physical picture of where the infinite number of remnants could come from or of the mechanism which suppressed their production.

The study of extremal charged black holes, which are the natural candidates for the final states of black holes which manage to retain their charge in the process of Hawking radiation, has shed a great deal of light on the remnant scenario. In particular, in the version of dilaton gravity which follows from string theory, the geometry of the extremal magnetically charged hole [6] is geodesically complete and has a global timelike Killing vector. Its cross section at fixed polar angle is shown in Fig. 1. Light charged fermions in the background of this configuration have an infinite number of modes which propagate as massless fields in the effectively one dimensional horn of the geometry. These are candidates for the infinite number of states required by the remnant scenario. In a seminal paper Callan *et. al.*[7] made the plausible suggestion that the last stages of Hawking evaporation for charged black holes in string theory could be described by a two dimensional quantum field theory concentrated in the horn. They conjectured that infalling massless fermion states would be bleached of their energy by quantum corrections, and would smoothly asymptote to the ADM-degenerate states of the remnant scenario. In this picture[8] remnants would look like pointlike "particles" to an external observer, but would really be states moving at the speed of light down an infinite horn hidden from the external observer by the throat of the black hole. These peculiar states were dubbed *horned particles* or *cornucopions*[8].

The strong coupling singularity of the extremal dilaton black hole has so far prevented us from verifying the conjecture of Callan *et. al.* [9][8]. Nonetheless, progress has been made in understanding how cornucopions evade the paradox of infinite production cross sections. The most dangerous process is pair production in an external magnetic field. An adaptation of the Affleck-Manton[10] discussion of pair production of 'tHooft Polyakov monopoles, would lead one to believe that the solution of the field equations which describes a cornucopion accelerating in a weak magnetic field, consisted of a sequence of static infinite horns strung out along the accelerating world line of the cornucopion mouth. Analytic continuation of this solution to Euclidean space gives an instanton describing pair production of cornucopions. For weak fields it has an action equal to that for a point monopole of the same mass and charge, and the production probability is given approximately by Schwinger's formula[11]. This is true for all of the degenerate cornucopion states and the total production cross section appears to be infinite.

In fact, naively copying the Affleck Manton prescription leads to a paradox with causality[12]. If the Affleck-Manton picture were correct we could study the difference between cornucopion states that differed only by an excitation millions of miles down the horn, via laboratory scattering experiments carried out near the mouths of the cornucopions. The paradox is resolved by noting that the correct solution for a cornucopion accelerating in a weak constant background field has a horizon a finite distance[1] down the horn, just like the exact solution utilized by Garfinkle and Strominger to describe pair production of Wheeler wormholes[13] in Einstein-Maxwell theory. The geometry beyond the horizon is time dependent and cannot be analytically continued. The exterior of the horizon continues to a compact Euclidean geometry[12]describing production of a Wheeler wormhole of finite size[2]. The number of states that can be created in this way is finite, and the spectre of infinite production cross sections has been laid to rest.

It should be emphasized that the rules for Euclidean quantum gravity are far from being understood, and that much more work needs to be done to justify the calculation of

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[1] which goes to infinity logarithmically as the field goes to zero.

[2] Perhaps in a theory with real magnetic monopoles, one would instead create a pair of finite length cornucopions with monopoles at their tips.

[12]. Nonetheless, the "naive" answer now gives a finite rather than an infinite cross section and the cornucopion scenario must consequently be viewed as a good working hypothesis for resolving the puzzles of Hawking radiation.

Rather than dwell on the (important) technical details of the effective two dimensional theory[14] from which these results have been derived, I would like to describe the general physical picture which emerges. I believe that it is equally applicable to the case of neutral black holes, where no two dimensional simplification occurs, and our prospects of analytical control over the problem are much more dim. The fundamental tenet of the cornucopion hypothesis is that gravitational collapse followed by Hawking evaporation leads to the creation of a new asymptotic region of spacetime. The formation of a black hole is, in this view, *always* "the creation of a universe in the laboratory" [15] . The information lost to the original asymptotic observer in Hawking evaporation, goes into another large part of space which is connected to the original region by a small throat. The resulting spacetime manifold can be foliated by spacelike hypersurfaces and quantum fields propagating on it will evolve unitarily from one spacelike surface to another. However, if we insist on discussing asymptotic properties, and the S-matrix, we find that the S matrix for the initial asymptotic observer is not unitary. The full unitary S-matrix relates the initial connected asymptotic region to two disconnected pieces of spacetime. For the charged cornucopions which have been the subject of recent study, the second final region is "down the horn".

This result may have profound implications. It implies that scattering theory for quantum gravity can only be formulated in the "Fock space of disconnected Universes" which has been introduced in wormhole theory [16]. Perhaps, by requiring both unitarity and locality of the gravitational S-matrix we will be led to derive the necessity for topology changing virtual processes (wormholes), and the resulting probabilistic restrictions on our knowledge of the fundamental coupling constants. It is important however to remember that wormholes do not lead to time dependent loss of information or to a violation of the microscopic laws of quantum mechanics for observers with a distance resolution coarser than the size of a typical wormhole throat. This is consistent with the cornucopion scenario, in which small virtual fluctuations of geometry do not lead to a violation of unitarity, and the local rules of quantum mechanics are preserved.

The most exciting prospect suggested by the remnant scenario for black hole evaporation is that of actually finding the remnants. Typically, stable particles with masses of order the Planck mass are produced copiously enough to overclose the universe. A consistent theory containing such particles can be formulated if a period of inflation intervenes between their production and the present stage of cosmological expansion. In that case there are typically only a small number of relics in our present horizon volume. We have emphasized however, that cornucopions often behave quite differently from elementary particles. Perhaps the same is true when it comes to the theory of their abundance in the present stage of the universe. If indeed they are present in relatively large numbers they might contribute to the dark matter in the universe. If they are sufficiently common we might be able to capture large numbers of them and study their unusual behavior in the laboratory. Most strikingly, we should find that, though apparently pointlike and indistinguishable, they do not obey the laws of Bose or Fermi statistics [12]. Indeed, they should behave essentially like classical objects, and would not, for example, form interference patterns in double slit experiments. I do not underestimate the difficulty of working with objects that may interact only gravitationally[3] but the possibly unique insights about quantum gravity that an experimental study of black hole remnants would provide make the search well worthwhile. The development of a theory of cornucopion production in both inflationary and Robertson-Walker universes seems to be the appropriate next step in research on black holes.

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[3] I assume here that charged cornucopions are even more rare than neutral ones.

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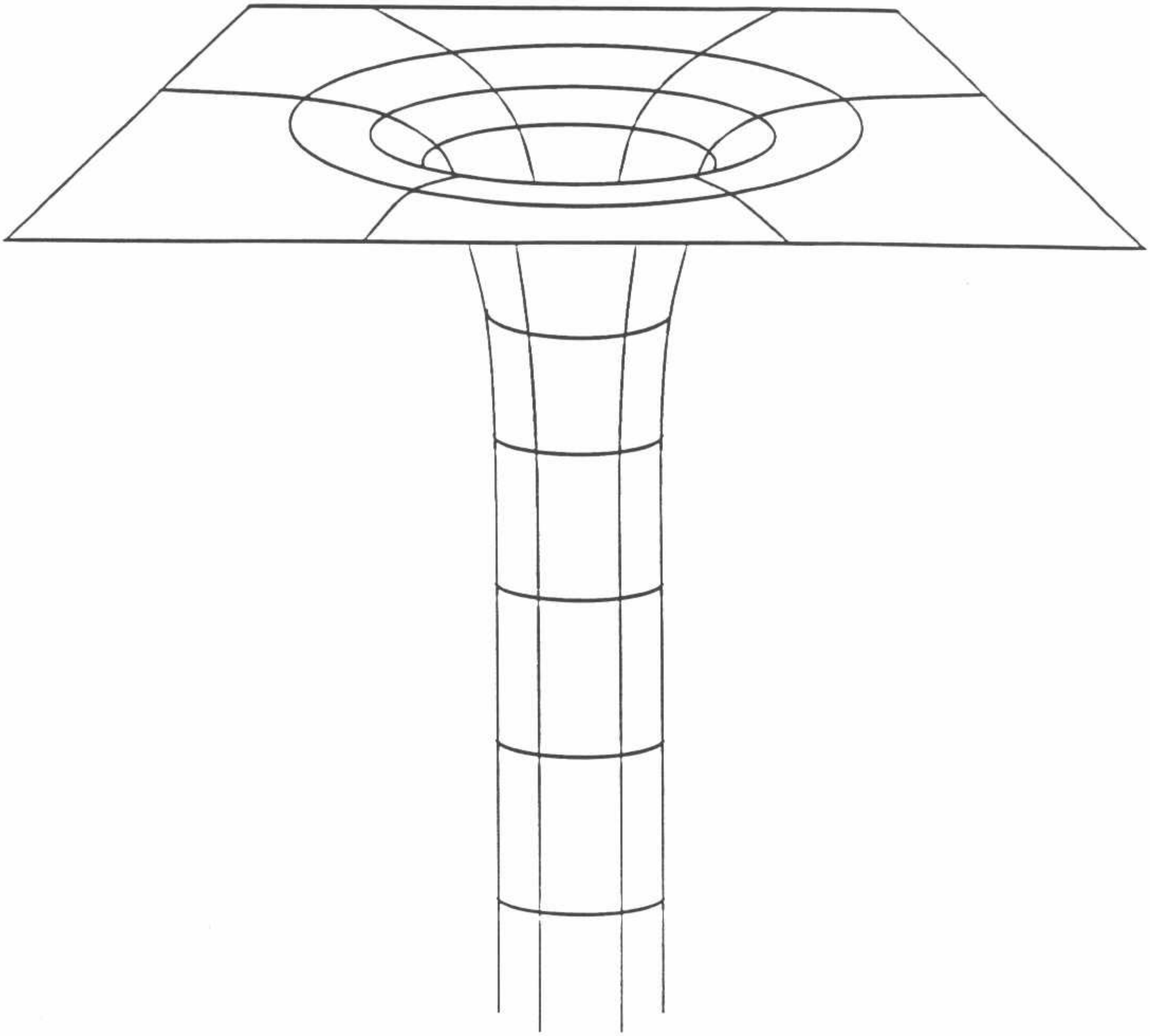

Figure 1

The Static Cornucopion Geometry At Fixed Polar Angle