Physics

VIEWPOINT

Black Holes Have Soft Quantum Hair

A black hole may carry "soft hair," low-energy quantum excitations that release information when the black hole evaporates.

by Gary T. Horowitz*

Four decades ago, Stephen Hawking proposed that black holes could destroy information—a conclusion that is incompatible with standard laws of quantum physics. This idea started a controversy known as the "black hole information problem" that even now has not been resolved. A new study by Hawking himself and Malcolm Perry, both at the University of Cambridge, and by Andrew Strominger at Harvard University shows that some of the assumptions that led to the information problem might be wrong [1]. Their results do not completely solve the problem, but point to a promising research direction that might lead to its long-awaited solution.

According to Einstein's general theory of relativity, stationary black holes are completely determined by just three observable parameters: their mass, charge, and angular momentum. Almost none of the information about what fell into the black hole is visible from the outside. Physicist John Wheeler described this idea by saying that "black holes have no hair."

In 1975, Hawking studied the behavior of quantum matter in the vicinity of a black hole and showed that black holes are not really black [2]. They emit nearly thermal radiation, just like a hot object radiates away heat. If no matter falls in, the energy lost through such "Hawking radiation" will cause the black hole to reduce its mass and eventually evaporate. This raises the question of what happens to all the information stored inside the black hole. Since the Hawking radiation comes from the surface of the black hole, which is determined by only a few parameters, Hawking argued that the information would be lost [3].

By the late 1990s, other developments in physics, most notably in string theory, convinced most researchers that all the information that falls into a black hole must come out when the black hole evaporates. How this might happen is still unclear. But one can start with a simpler question: What is wrong in Hawking's original argument that information must be lost? The paper by Hawking, Perry, and Strominger provides a possible answer. They point out problems with two underlying assumptions that originally led Hawking to his conclusion. The first is that the vacuum in quantum gravity (the quantum state with the lowest possible energy) is unique, and the second is that black holes have no hair. Instead, they argue that there is an infinite family of degenerate vacua in the quantum theory, and that black holes can carry what the authors call "soft hair"—quantum hair associated with very-low-energy quanta.

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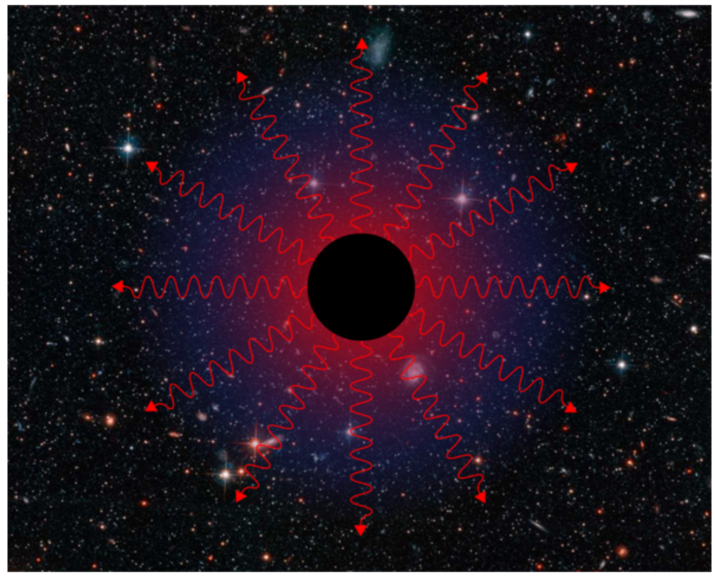

Figure 1: Hawking, Perry, and Strominger suggest that black holes might have "soft hair," low-energy quantum excitations that release information when the black hole evaporates. (APS/Alan Stonebraker)

Strominger had an important insight in 2014 [4] while investigating a different problem. He realized that there are an infinite number of conservation laws that govern the scattering of gravitons—the elementary excitations in a quantum theory of gravity. Working with his students, Strominger realized soon thereafter that a similar result holds for electromagnetism [5]. Currently, he is collaborating with Hawking and Perry to apply this insight to black holes. In the new paper, the authors illustrate their ideas by considering electromagnetism in the presence of a black hole.

The key to their argument about black hole hair is provided by new conservation laws that generalize the usual notion of conservation of electric charge. The total charge in a region can be obtained by integrating the radial component of the electric field around a sphere surrounding the region. If no charge enters or leaves the region, its value is independent of time. Strominger's generalization is based on integrating, over a sphere of infinite radius, the radial electric field weighted by an arbitrary function. It turns out [5] that this integral is still conserved. This provides an infinite number of new conserved quantities.

This observation connects to black hole hair in the following way. Using Gauss' theorem, one can convert the surface integral describing the new conserved charge to a volume integral over all space. In the absence of black holes, the new conservation law simply means that this volume integral in the past is equal to the integral in the future. However, if black holes are present, the integral in the future must include a contribution over the black hole horizon.

If both gravity and electromagnetism are described classically, the contribution to the new charges coming from the black hole horizon must vanish. But Hawking, Perry, and Strominger argue that the situation is very different when electromagnetism is described quantum mechanically. To understand the difference, first consider the vacuum state and then add one photon. The result is a new quantum state with energy equal to the energy of the photon. As Strominger showed [5], if one takes the limit as the photon energy goes to zero (that is, the photon becomes "soft," with vanishing energy), the result is a new state, which can be called a new vacuum because it has essentially the same energy as the original vacuum state. The first vacuum is turned into the second by acting with an operator that is just the quantum version of the new conserved charge.

The authors' work now shows that acting with this same operator on a black hole horizon adds photons with essentially zero energy. These photons make up what they call the "soft hair" on a black hole. Since there are an infinite number of new charges, there are an infinite number of soft hairs that a black hole can support. Furthermore, the researchers demonstrate that when a charged particle falls into the black hole, it excites some of this soft hair. The exact conservation of the new charges implies that when a black hole evaporates, the information about the hair on the horizon must come out in the Hawking radiation (see Fig. 1).

It is important to note that this paper does not solve the black hole information problem. First, the analysis must be repeated for gravity, rather than just electromagnetic fields. The authors are currently pursuing this task, and their preliminary calculations indicate that the purely gravitational case will be similar. More importantly, the soft hair they introduce is probably not enough to capture all the information about what falls into a black hole. By itself, it will likely not explain how all the information is recovered when a black hole evaporates, since it is unclear whether all the information can be transferred to the soft hair. However, it is certainly possible that, following the path indicated by this work, further investigation will uncover more hair of this type, and perhaps eventually lead to a resolution of the black hole information problem.

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