indeed eaten, before it could withdraw its drilling equipment). In either case, Smith *et al.* argue that the two 'failures' of the naticid-like shell-drilling habit in the Devonian and the Triassic were the result of poor adaptation. Only in the Cretaceous did the naticids evolve the necessary drilling techniques and the means of self-protection.

Many older examples of predatory bore holes in shells are known — for example from the late Cambrian of the United States (about 510 Myr ago)[10], from the Silurian of Sweden (about 420 Myr ago)[11,12] and from the early Devonian of Canada (about 400 Myr ago)[13]. The predators could have been gastropods in some of these cases[12,13] but the holes are either much smaller than those produced by living naticids[10,11] or they lack the central boss and the inwards taper[12,13]. The holes could have been produced by cephalopods[3,11,12], or by unknown forms[3,11]. Whatever the answer, these studies offer much scope for further work on the history of marine predation, on the modelling of predator–prey interactions[5] and on establishing the role of predation in macroevolution. □

*Michael J. Benton is in the Department of Biology, The Queen's University of Belfast, Belfast BT7 1NN, Northern Ireland.*

## Astrophysics

# Unravelling fates of black holes

*from Don N. Page*

EVER since S.W. Hawking's remarkable theoretical discovery of thermal radiation emitted from black holes[1,2], it has been clear that these objects cannot be the stable final states of gravitational collapse they were once believed to be. But what happens during the last stages of black-hole evaporation has remained uncertain, leaving unanswered several important conceptual issues such as the fundamental predictability of the ensuing state[3-5]. Now M.J. Bowick, L. Smolin and L.C.R. Wijewardhana argue[6] that superstring theories[7,8] can help unravel the answer.

Black holes allow nothing to escape, according to classical (that is, non-quantum) physics in which each particle has a definite position and a definite velocity, which must not exceed $c$, the speed of light. However, in quantum physics the uncertainty principle prevents a particle from definitely being confined to the space inside the hole and simultaneously definitely having a velocity $\leqslant c$. In this way quantum mechanics allows a particle to tunnel out from a black hole. Hawking[1,2] calculated this black-hole emission process in a semiclassical approximation in which quantum mechanics was applied to the particles being emitted, but not to the black hole itself, which was instead assumed to have a definite classical gravitational field.

Conservation of energy requires the black hole to lose mass, and hence shrink, as particles carry away its energy. Eventually it evaporates to such a small size that the semiclassical approximation becomes invalid, and quantum mechanics must be applied to the gravitational field of the black hole itself. It is not known how to do this in a completely consistent manner, hence the uncertainty of what happens in the last stages of black-hole evaporation. It has been variously suggested that a black hole stops radiating and shrinking when it reaches a positive-mass stable remnant; that it continues radiating until its mass becomes negative; or that it completely disappears.

There is also the question of whether the quantum evolution of the state is deterministic, or whether there is a new breakdown of predictability beyond the ordinary limitations of the uncertainty principle[3-5]. If the black-hole emission is precisely thermal, with no correlations between different modes (as is predicted by the semiclassical approximation), then its evaporation results in a loss of information or an increase in entropy even without any coarse graining of the final state. Furthermore, in a classical description of the gravitational field, the disappearance of a black hole would be accompanied by a so-called naked singularity (a visible edge to space-time), at which unpredictable information might enter the Universe.

Bowick, Smolin and Wijewardhana[6] now offer a preliminary analysis of these questions in the context of superstring theories[7,8], exciting new candidates for a consistent quantum 'theory of everything' (unification of the fundamental forces, including gravity; see ref. 9 for review). If one of these theories is indeed correct, it should in principle be able to explain what happens when a black hole evaporates. Unfortunately for our curiosity (but perhaps fortunately for the continuation of our careers), our understanding of superstring theories is still far too meagre to say definitely what they imply about black-hole evaporation. Bowick *et al.* readily admit this limitation, but investigate what can be said from our present knowledge of superstring theories.

By a thermodynamic analysis of perturbative (linearized) string modes, Bowick *et al.* conclude that it is statistically probable for a black hole to turn into a massive string when it gets sufficiently small. The string itself then decays into ordinary radiation (massless particles). The authors suggest that this allows the black hole to disappear completely (yet without the accompaniment of a naked singularity) because the gravitational field is only part of the superstring field.

This conclusion is eminently reasonable, although it must be admitted that the paper of Bowick *et al.*[6] is hardly a rigorous derivation of the result. Even before superstring theories, one could have postulated that a sufficiently small black hole turns into a suitable spectrum of massive particles without having a classical gravitational field that would lead to a naked singularity. Superstring theories give hints as to how this could conceivably happen, but so far they are just hints.

On the question of whether there is a breakdown of predictability in black-hole evaporation, Bowick *et al.* admit that they do not see how superstring theory will resolve the problem. Indeed, one would need a method for correctly calculating the enormous number of multi-particle correlations between the different black-hole emission modes. Each one of these correlations is likely to be very small and hence individually close to the semiclassical approximation that it is zero, but cumulatively it is conceivable that the correlations could gradually restore to the exterior all the information that enters the hole during its formation and evaporation process. It is still too early to say whether or not superstring theory will show this possibility to be the case. □

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*Don N. Page is Associate Professor of Physics at The Pennsylvania State University, University Park, Pennsylvania 16802, USA.*

## Erratum

| | |
|---|---|
| Consensus sequence | Lys–Gly–fob–Gly–Thr–Asp–Glu–var–var–Leu–Ilu–fil – Ilu–Leu–Ala – fil–Arg |
| Lipocortin residues 56-72 | Met–Val–Lys–Gly–Val–Asp–Glu–Ala–Thr – Ilu – Ilu–Asp-Ilu–Leu–Thr–Lys-Arg |
| Lipocortin residues 128-144 | Lys–Gly–Leu–Gly–Thr–Asp–Glu–Asp-Thr–Leu–Ilu-Glu– Ilu–Leu–Ala–Ser-Arg |
| Lipocortin residues 287-303 | Lys–Gly–Val –Gly–Thr–Arg –His–Lys–Ala-Leu–Ilu–Arg–Ilu–Met–Val–Ser-Arg |

In the article by Robert H. Kretsinger and Carl E. Creutz "Consensus in exocytosis" (*Nature News and Views* 17 April, page 573), two of the amino-acid residues that should have been included in the figure were omitted. The correct figure is shown above.