The Hawking Effect, Its Desiderata and Its Discontents

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Outline

Coming to Grips with a Verbal Tic

Desiderata

Discontents

Looking for Inner Peace in the Face of a Hot Mess of Theory

The Virtues of Pragmatism

it may seem a mannerism on my part by this point to do so, or even a verbal tic, but I must say again (and again and again. . .):

> How did a theoretically predicted phenomenon (Hawking radiation), derived by combining seemingly incompatible theories in a novel way so as to extend their reach into regimes that we have no way of empirically accessing in the foreseeable future, constrained only by principles based on physical intuition not honed in those regimes, become one of the most important touchstones for testing novel ideas in theoretical physics? Can it play that role? What epistemic warrant do we or can we have for it in the end?

$\Longrightarrow$ absolutely no experimental or observational evidence for any of it – why do we trust it?

a common answer:

> *[T]he Hawking temperature and the Bekenstein-Hawking entropy have been derived in so many independent ways, in different settings and with different assumptions, that it seems extraordinarily unlikely that they are not real.*
>
> Carlip (2014, p. 2)

consilience!

that most puissant of all epistemic tools from a foundational point of view: one of the most fascinating aspects is multiplicity and multifariousness of derivations, differing radically in:

- mathematical rigor of the chosen matter + spacetime framework
- mathematical and physical character of its structures
- physical principles assumed or required
- types of physical system treated
- approximations and idealizations required
- form of conclusion
- physical origin of that form
- regime of propriety and adequacy of conclusion
- physical perspecuity and intuitiveness of them all

$\Rightarrow$ all suggest different physical interpretations we are spoiled for choice

let's sketch a picture of Hawking radiation

not describe any particular derivation: the rough, intuitive ones tend to be badly misleading; the precise, rigorous ones too technically demanding for this talk

rather: sketch basic form of ingredients any derivation requires; lay out the choices one must make and assumptions they require

what is wanted radiation, in some way or other

what is needed necessary assumptions

choices to be made how do we get there

conclusion the validation of what is wanted

interpretation what is its physical significance?

spacetime (GR) choices:

1. shape and character of spacetime:
   - **1.1** exact solution: Schwarzschild, Kerr, Reissner-Nordström, Kerr-Newman, dS, AdS, dS-Schwarzschild, AdS-Schwarzschild, . . .
   - **1.2** abstract characterization:
     - **1.2.1** type of horizon: event, isolated, trapping, cosmological, general causal, . . .
     - **1.2.2** eternal, past horizon, stationary, quasi-static, dynamic
     - **1.2.3** topology: form of domain of outer communication (if a black hole); . . .
     - **1.2.4** symmetries
     - **1.2.5** other asymptotic structure, *e.g.*, some form of flatness or predictability
2. local or global region
3. near-horizon or asymptotic region

spacetime (GR) necessities:

1. some form of cosmic censorship: complete future null infinity; non-singular event horizon; . . .
2. topological assumptions (*e.g.*, topological censorship)
3. causality conditions (*e.g.*, chronology)
4. stability assumptions ("small perturbations do not destroy the event horizon")
5. assumptions about asymptotic behavior and structure (*e.g.*, asymptotic symmetries)

matter (QFT) choices:

1. QFT formulation (S-matrix, algebraic, canonical based on a Lagrangian, holographic, low-energy quantum gravity, . . .)
2. flavor of QFT (scalar, vector, bosonic, fermionic, . . .)
3. choice of eigenbasis needed? if so, which? or generic conditions imposed?
4. choice of state needed? if so, which? or generic conditions imposed?
5. boundary conditions

matter (QFT) necessities:

1. constructibility of stress-energy tensor operator
2. niceness of state (*e.g.*, "Hadamard")
3. eikonal approximation
4. adiabaticity conditions
5. insensitivity to trans-Planckian phenomena
6. various forms of locality and causality
7. cluster decomposition

joint (GR and QFT) choices:

1. backreaction or no?
2. stationary, quasi-static or dynamic
3. entropy conditions (*e.g.*, satisfaction of the GSL)

joint (GR and QFT) necessities:

1. assumptions about asymptotic behavior and structure ("almost-conserved" quantities, energy fluxes that don't contribute to curvature)
2. "energy conservation": subtle balancing of often ill-defined local inward energy fluxes at horizon and local outward fluxes at $\mathscr{I}^+$ with changes in global quantities at $\imath^0$ (*e.g.*, ADM mass)

what is wanted: radiation

1. in some regime (energetic, spatiotemporal, . . .)
2. in some region (local, global, interior, asymptotic)
3. characterized by some set of quantities, properties or behaviors:
   - 3.1 expectation values
   - 3.2 occupied modes
   - 3.3 a local or a global state of a particular sort
   - 3.4 energy flux with characteristic spectrum
   - 3.5 behavior of detectors
   - 3.6 . . .

common interpretation:

1. thermalized radiation is generated by the interaction of a black hole and a scalar quantum field, with a temperature proportional to the black hole's surface gravity
2. we are warranted in thinking of the radiation as being related to the black hole itself in the same (or, at least, a relevantly similar) way as ordinary blackbody radiation is related to the ordinary hot matter that generates it
3. thus, when quantum effects are taken into account, black holes can and should be attributed a physical temperature, and thence a physical entropy
4. thus, such black holes are truly thermodynamical systems

there are now, at a conservative estimate,

2,069,547,534

possible derivations (with a tip of the hat to I. J. Good) most popular forms:

1. S-matrix *à la* Hawking's (1975) original
2. past-boundary *à la* Unruh's (1976) original
3. algebraic
4. canonical, based on Lagrangian
5. canonical, based on Cauchy evolution
6. tunneling
7. anomaly-canceling
8. more general stress-energy tensor
9. near-horizon symmetries
10. thermal atmosphere
11. renormalization group
12. analytic continuation
13. Euclidean path-integral
14. Lorentzian path-integral
15. low-energy quantum gravity (EFT)
16. perturbative canonical QG
17. perturbative LQG
18. perturbative string theory
19. holographic

this all leaves us with (at least) 2 problems to consider:

1. is this really consilience in any appropriate sense?
2. how do all the radically different possible choices, necessities, conclusions and interpretations square with each other?

I fear the issue may be more that we are spoiled, than that we have many equally desirable choices this is not traditional, standard consilience, in at least three ways:

1. the different derivations are all purely theoretical, not deriving from empirical support
2. this is not a case in which the same equations or relations or model, or values of quantities, are being derived for a given phenomenon based on different types of interactions among different types of physical systems, as in the classic case of Perrin's derivation of Avogadro's number
3. rather a case in which different physical assumptions are made about (what we want to conceive of as) the very same (or relevantly similar) class of physical systems and interactions among them, and then calculations and arguments run in very different conceptual and mathematical frameworks
4. all leading to conclusions with varying physical interpretations not always straightforwardly consonant with each other

1. in historical sciences, consilience is sometimes characterized as convergence of results derived by independent methods or arguments (Elder 2020, ch. 3)
2. but that does not suffice in physics, even in those fields, such as astrophysics and cosmology, which have much in common evidentiarily with the overtly historical sciences such as evolutionary biology and archaeology
3. the methods and arguments must be based on streams of empirical evidence derived from dynamically independent processes—where, presumably, to characterize "dynamical independence" in this case will be non-trivial, if possible at all
4. note how *none* of this is the case with regard to the derivations of Hawking radiation
5. for similar reasons, one cannot view this as a kind of Wimsattian robustness (Wimsatt 1981)

so let's try a different tack to drum up epistemic warrant if both

$$A \wedge B \Rightarrow H$$

and

$$\neg A \wedge C \Rightarrow H$$

are true, then there are only 3 possibilities:

1. H is a tautology
2. B and C are both false
3. exactly one of $A \wedge B$ and $\neg A \wedge C$ is true

none, in this context, are appealing (even assuming that we settle on a unique H!)

what is rather wanted is a way to try to construe 'A' and '$\neg A$' not as strict logical contradictories, but as something like:

- loose ways of expressing similar facts as they appear represented in different regimes
- or one as representing an approximation or idealization of the other
- or something like that

the idea:

- all the different derivations are disparate in ways that make it difficult to see what if anything they share in common
- nonetheless, they do in fact share a common core
- and that common core, moreover, is captured by a set of minimally stringent physical conditions
- and they all seem difficult to doubt, in so far as they individually seem to be supported by entrenched empirical knowledge we have, respectively, from GR and QFT

- Visser (2003) showed one can get by with:
    1. basic quantum physics (essentially, that different observers see different vacua)
    2. plus a slowly evolving future apparent horizon (not even an event horizon)

  $\Rightarrow$ "Hawking radiation is kinematical, not dynamical"

- even more strongly, Barceló et al. (2011) showed all that's needed is:
    1. "exponential affine-peeling" between null affine coordinates on future and past null infinities ("something non-trivial in the interior for ingoing modes to scatter off of in the right way")
    2. and an adiabaticity condition: "the width of generic wave packets has to be much smaller than the frequencies at the peak of the Planck spectrum"

  $\Rightarrow$ not even a horizon! any adiabatic process or structure that gets the peeling right is assured of the result, and that follows just from the geometry of the spacetime upshot:

- the many different kinds of derivations consistent with the pictures of Visser (2003) and Barceló et al. (2011), using so many different kinds of methods, all just gild the lily in different ways, a lot of fancy bells and whistles on the same very basic wheel that's doing all the work
- in light of that, it would be astonishing if all those derivations didn't derive Hawking radiation, and that for no reason having to do with anything like empirical entrenchment of the effect

- flat-footed derivations rely essentially on the same machinery as Hawking's original one (mostly consistent with both Visser 2003 and Barceló et al. 2011), albeit gussied up and made more precise in their manners
- fancier ones are all in frameworks that were developed specifically to recover BHT, so it would frankly be surprising if they didn't deliver the result

- but, how can we know that the *recherché* phenomena of QFT-CST, SCG and perturbative QG don't have confounders that spoil the affine-peeling or the other stuff needed?
- or that make it so that the conceptual machinery required for formulating and applying the idea of "peeling" is even available?

so, I suggest, we should rather try to understand what we do when we derive Hawking radiation as

- trying to capture a minimal, schematically articulated *mechanism* shared by all, or almost all, derivations, or perhaps a small set of such schematic mechanisms
- based on the minimal prerequisites and witnessing the fact that they can be cogently formulated and appropriately applied
- each mechanism capturing a wide class of derivations jointly covering almost all possibilities
- first, to see whether that or those can be argued to have more support or plausibility than the detailed derivations themselves
- and second, if there is more than one, to try to determine what the relations among the different schematic mechanisms may be, how they may or may not be consonant with each other

this should trouble realists

A possible reply:

- SCG is only an approximative framework: don't take putative metaphysical or ontological lessons seriously
- a better, deeper theory will come along, to which SCG is an approximation
- and that will tell us how to draw metaphysical and ontological lessons about Hawking radiation

That, however, is a pious hope, and a pious hope only.

- not grounds for dismissing what our best current physics—even if having itself only weak epistemic warrant—tells us
- and that physics tells us there are many incompatible ways to make a realist want to begin drawing ontological and metaphysical lessons
- none privileged over the others *sub specie æternitatis*, or even privileged merely empirically.

- in any event, no reason to expect any better, deeper theory coming alone will have a canonical, privileged formulation to support univocal, unambiguous ontological and metaphysical lessons
- no other physical theory has ever had one, and there are many reasons to expect that no theory ever will

I suggest, therefore, that, in our current epistemic state, in so far as we want to take seriously the idea that there is something in the world corresponding to our idea of Hawking radiation and that all these radically different derivations are latching on to it in some way or other, we should not construe the mathematics of SCG as a picture of the world in the sense that a realist traditionally attempts to, as standing in a depictive or designative or verisimilar relation of representation to the world

we should rather take a pragmatic attitude: the mathematics of our physical theories is not a picture of the world, but rather serves as only one subset among many conceptual tools we use to get a grip on the world, and different bits of the math, and often even the same bits in different contexts, are used in many different ways, some appearing to instantiate relations superficially similar to traditional representational ones, others not

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