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Black Hole Complementarity in Terms of the Outsider and Insider Perspectives

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Abstract

A complementarity hypothesis concerning outsider and insider perspectives of a gargantuan black hole is proposed. The two thought experiments presented herein are followed by a brief discussion of a new interpretation of black hole interior "space-and-time-reversal." Specifically, it is proposed that the "singularity" space of the black hole interior is time-like and the expansion time of the black hole interior is space-like. The resemblance of this new insider interpretation to our own expanding and redshifting big bang universe is compelling.

Keywords

Black Holes, Complementarity, Cosmological Models, $R_h = ct$ Models, Flat Space Cosmology, Schwarzschild Cosmology, Thought Experiment, Dark Energy, Quantum Vacuum

1. Introduction and Background

Stephen Hawking pointed out that quantum information passing through a black hole horizon into its interior should be permanently lost at the singularity, thus apparently violating a bedrock principle of quantum physics, that quantum information cannot be destroyed [1]. This has become known as the "black hole information paradox." A hypothesis of "black hole complementarity" was subsequently introduced by Susskind [2], as a means of solving Hawking's paradox. He treated quantum information as interacting with a black hole in two different and complementary ways, only one of which could be observed from any given outside or inside perspective. Susskind's follow-up book, entitled *The Black Hole War* [3], provides a nice historical summary of his philosophical battle and apparent victory over Hawking with respect to this paradox.

The concept of complementarity in physics goes at least as far back as Emmy

Noether's strict and limiting mathematical definition in 1918. In a broader sense, differing but valid wave-and-particle interpretations of observations of double slit experiments, including Bohr's Copenhagen interpretation of quantum physics, are examples of physical complementarity. The Copenhagen interpretation withstood a barrage of challenges by Einstein, Podolsky, and Rosen (EPR) [4] and others [5]. There have since been a number of other examples of complementarity in modern physics, now including Susskind's important contribution concerning black holes.

This paper is not intended as a comprehensive review of complementarity in modern physics. Rather, the above brief summary is merely offered in order to show that the concept of physical complementarity is now over one hundred years old, pre-dating any specific applications to black holes. *In its broadest sense, a complementarity in physics can be defined as two different, but equally valid, perspectives concerning the same physical object or event.* Such complementarities rely upon underlying conservation laws of great importance. Proving this was Noether's greatest contribution to physics. As an extension of her logic, this author proposes that a deeper understanding of black hole complementarities could well be an important key to uniting general relativity with quantum physics. Thus, we would have a useful and accurate quantum cosmology.

It is the purpose of the present paper to present a somewhat different (with respect to Susskind) complementarity hypothesis concerning black holes. By means of thought experiments and a new interpretation of black hole interior "space-and-time-reversal," the reader can perhaps gain a foothold on understanding how black hole cosmological models, a distinct category of $R_h = ct$ models, can potentially resolve some cosmological conundrums [6] [7] [8] [9] [10].

2. The Outsider Perspective of a Black Hole (Thought Experiment)

Most readers are already familiar with the outsider perspective of a black hole. Such a perspective is all that is available to us, whether we are Earth-bound or space satellite telescope observers. We see a black hole as a finite and circumscribed spherical object emitting no visible light or other detectable electromagnetic radiation. If it does, in fact, emit Hawking radiation, as believed by nearly all black hole experts, such radiation is predicted to be so faint as to be forever beyond our means of detecting and measuring it. Furthermore, our Earth-based telescopes, as part of a planet-wide array, have revealed that selected nearby supermassive black holes (SMBHs) are bending light rays around them in exactly the way predicted by general relativity. Black holes have, so far, been highly predictable in terms of their relatively few measurable parameters. In this context, it is often said that "black holes have no hair." They are viewed, from our outside perspective, as remarkably simple spinning objects surrounded by an accretion disk of hot gases emitting x-rays and/or gamma rays. Their powerful polar magnetic fields can spin with great rapidity and eject concentrated beams of photons and charged particles (at nearly the speed of light) in "jets" many light-years in length. Quasars and blazars are almost-certainly some of the largest and most powerful SMBHs of the early universe, which just happen to be pointed in our general direction (as for quasars) or directly, or nearly so, at us (as for blazars).

In the present paper, we offer a thought experiment of highly-reasonable assumptions about the experience of spacecraft observers outside, but close to, a SMBH, in a somewhat similar manner to that offered by Kip Thorne in his excellent book entitled *Black Holes & Time Warps—Einstein's Outrageous Legacy* (see pages 38-48) [11]. Let us imagine that we are observers on a large spacecraft ("mother ship") hovering relatively close to the event horizon of a *truly gargantuan* supermassive black hole of 14.62 billion light-years in Schwarzschild radius. We have done our measurements and calculations and determined that our black hole, which doesn't appear to rotate or have a net charge, has an average density of approximately 8.4×10^{-27} $kg \cdot m^{-3}$. Thus, it appears to be a real Schwarzschild black hole! From our safe distance of observation, our black hole is so large that we and our mother ship do not experience any significant tidal effects of its gravitational field. We wish to send down a spacecraft probe to hover above the spherical horizon at various fixed distances, while returning a powerful laser pulse signal of predetermined frequency to our mother ship observers. These pulses are sent at regular time intervals according to a clock on the probe. What will we observe at the mother ship with respect to these probe signals?

The answers to such a question are a near-certainty, given our knowledge of, and extremely high confidence in, special and general relativity. At each hovering distance above the SMBH horizon we can observe frequency, wavelength, energy and timing interval of the pulses coming from the probe. At first, when the probe is nearly at the orbital height of our mother ship, we notice little, if any, change of signal properties with respect to the pre-programmed pulse signals. Frequency, wavelength, energy and timing intervals of the pulses are in-line with our on-ship calibrations prior to release of the probe. However, we gradually and then more rapidly notice, as the probe decreases its hovering distance and moves closer and closer to the horizon, the following things: the pulse frequency continuously decreases; pulse energy continuously decreases, in-line with decreasing frequency; the pulse wavelength continuously redshifts, getting longer and longer; and the pulses are more prolonged and separated by increasingly-long time intervals. If we were to plot such signal features on a graph as a function of increasing probe proximity to the horizon (or increasing hover distance from the mother ship), we would notice that frequency and pulse energy asymptote towards zero, while wavelength and timing intervals asymptote towards infinity. Although we would not be able to observe directly, due to infinite time dilation, we would expect that our probe, when embedded exactly in the horizon, would become completely undetectable to us, either by signal reception or by powerful optical, infrared or radio telescopes on the mother ship. From our outside perspective, we mother ship observers can readily extrapolate that the clock on a horizon probe (were it possible to have an infinite quantity of fuel and infinite energy thrusters in order to maintain its position at the horizon) would be *frozen in time*! In our outside observer thought experiment, these very predictable observational phenomena would all be the result of gravitational redshift and time dilation, in exact agreement with special and general relativity.

3. The Insider Perspective of a Black Hole (Thought Experiment)

Now we introduce the reader to an equally valid and complementary perspective of our truly gargantuan black hole, which is the perspective of a *free-falling* (*i.e.*, not hovering) astronaut passing through the horizon and into the black hole interior. Our free-falling astronaut would have a markedly different experience in comparison to that of the hovering mother ship and probe. Let us consider this new perspective in a thought experiment.

From our astronaut's perspective, time is moving along at its usual pace, as she remembers it when she was last on the mother ship during calibrations of her watch and laser pulser with that of the aforementioned probe. She notices nothing unusual as she passes through the event horizon (according to her watch) and into the black hole. She also does not notice any frequency, wavelength or energy change in the activity of her pulser or the activity of her watch. After passing through the horizon, which now becomes her future event horizon, she puts the ticking watch up to a microphone in her helmet and hears it ticking just as loud and clear as it did back on the mother ship. She notices that, in all directions, objects more distant from her, but still inside the horizon, are more redshifted than nearby objects. She also notices, by leaning back and returning her gaze in the specific direction of where the mother ship was, that it has disappeared, and that the stars which were behind the mother ship have been replaced by an impenetrable blackness. The light of the outside universe has long ago (in comparison to her new time frame) stopped pouring into the black hole, due to the extreme time differences between her new universe (the black hole) and her old universe (the parent of the black hole in which she now finds herself). This is also a predictable time dilation effect.

Before we finish the story of our free-falling astronaut, we should take note of the following: black hole experts have shown mathematically how the interior of a black hole should have a very peculiar feature. Judging from signage changes in their mathematical formulae in the Schwarzschild metric, these experts are generally in agreement that a sudden switch takes place as one crosses the black hole event horizon into the interior:

Space becomes time-like and time becomes space-like.

The particular formula of interest for the Schwarzschild solution of the Einstein field equations (leaving out rotational terms because we are referring to a Schwarzschild black hole) is commonly expressed as follows [12]:

$$\Delta s^2 = \left[1/\left(1 - r_s/r\right)\right]\Delta r^2 - \left[1 - r_s/r\right]c^2\Delta t^2 \quad (1)$$

wherein the Schwarzschild metric term is on the left, the space-like term is in the middle and the time-like term is on the right. The symbol r_s represents the Schwarzschild radius of the black hole. Notably, when Equation (1) applies to the interior of the black hole, both bracket terms switch to a negative signage, because r_s suddenly becomes greater than radius *r*. General relativists interpret this signage change in terms of the space-and-time-reversal description above.

We can maybe best understand this new interior perspective by comparing it to what we observe or imagine about a black hole as outsiders. We first imagine a "singularity" of infinite properties at the geometric center of *space* within the black hole interior. This is presumably, from the outsider perspective, where all matter and information of any kind ends up. For a Schwarzschild (*i.e.*, non-rotating) black hole, this "singularity" is a point-like *spatial* object. For a Kerr-type rotating black hole, the "singularity" is ring-like and surrounding the geometric center of the black hole. Without confusing the matter further, or updating the reader on Kerr's new view on singularities of any kind, suffice it to say that a *space-like* object of "infinite" properties (*i.e.*, smallness, density and temperature) exists in the perspective of the outsider in, or very near, the geometric center of a black hole. Obviously, these properties cannot *actually* be infinite, but the fully valid outsider perspective of such a "singularity" must be left to a final theory of quantum gravity in the future.

However, according to a reasonable interpretation of the "space-and-time-reversal" math of black hole relativists described above, insiders should perceive a "singularity" of their black hole as no longer an object in space, but rather an *object in time*; this perspective resembles how we imagine our own cosmic singularity! In our own universe, there is no residual singularity within a localized point of absolute space; there is only a singularity in our most remote past. From her new "space-and-time-reversal" perspective, our free-falling astronaut might have no existing singularity to fall into. Rather, she may have fallen into an *expanding* time-like structure with an average density of approximately 8.4×10^{-27} $\text{kg}\cdot\text{m}^{-3}$, very much like our own universe. As in our own expanding (*i.e.*, redshifting) universe, every point in her new space, because she can perceive it as expanding by her redshift observations, also represents a point in time; in other words, her continually expanding new environment is now time-like! Her new horizon is no longer acting as a time-less and fixed invisible spatial object, but rather acting as a dynamic, expanding, entropy-driven, time clock. The "ticking" of her new universal clock is the regular increase in horizon surface area (*i.e.*, Bekenstein-Hawking's entropy-as-time definition). Our imaginary astronaut is no longer falling towards a geographic center any more than an intergalactic astronaut in our own universe falls towards a particular absolute center of space. In an expanding universe such as ours, there is no residual center. Likewise, one can perhaps imagine in this thought experiment that her new gargantuan SMBH environment could be perceived by her in a similar way. To put it in more modern cosmological terms, the center of our free-falling astronaut's new universe is not localized, but now everywhere. She is truly free to fall wherever the new gravitation field in her new universe takes her.

4. Discussion

As presented, our outsider perspective of a black hole is highly-dependent upon our very limited human time perspective. Rather than perceiving a black hole as a dynamic and changing object once born, we tend to see and describe a black hole as an object almost frozen in time, other than when it ingests new matter or merges with another black hole. Although we tend to believe that, between such ingestions and mergers, a black hole continually radiates away a tiny amount of energy, complete evaporation would only occur at many times the current age of our universe. For all practical purposes, we can safely ignore the theoretical Hawking radiation and black hole evaporation.

One of the most surprising findings from recent deep telescopic observations of our past early universe is that early SMBHs have grown even faster than we could have imagined. We have even had to consider new ways in which SMBHs could have initially formed, such as "direct collapse" from gargantuan primordial gas clouds. Furthermore, the recent discovery by Farrah *et al.* [13] that the rapid growth of SMBHs appears to be *coupled* with the expansion of our own universe is astonishing. Their results and interpretations are understandingly preliminary, but they appear to imply that SMBHs could be a source of universal expansion dark energy. The present author has recently offered a quantum hypothesis on how black holes might actually *continually* grow in size and produce such dark energy [14]. A follow-up paper on likely gravitational field effects on the quantum vacuum was also published [15], and now appears to have additional theoretical support [16].

Our second thought experiment introduces the mathematical discovery by black hole experts that, within the interior of a black hole, there is a switch in space and time perspective in comparison to our own outsider perspective. Space within the black hole interior is interpreted to be time-like and time is interpreted to be space-like. This is a conclusion based upon signage changes in the terms of relativistic Schwarzschild metric equations for crossing over from outside to inside a black hole horizon.

What is still open for interpretation is the exact meaning of such a mathematical signage change. Those theorists who apply light cone analysis to the inside of a black hole take the conventional point of view that anything inside a black hole rapidly gets stretched and then crushed at the singularity; this is really no different from the outsider perspective and perhaps shows a bias in this respect. For the sake of argument, a new complementarity interpretation of black hole interior "space-and-time-reversal" is offered in the present paper, largely based upon the perspective that a SMBH is a *dynamic* object *coupled* with the expansion of our universe (see the Farrah *et al.* reference). The present author interprets the insider perspective as follows:

The 'singularity' space becomes time-like and the expansion time becomes space-like.

What is meant by this is that the insider perspective of a truly gargantuan black hole the size and average density (8.4×10^{-27} kg·m^{-3}) of our own universe could be that the singularity is only in the past, and that past epochs of such a black hole could perhaps be observed (by redshifting light within the SMBH) as past events of an *expanding* interior space, much like our own perceived expanding universe. In summary, in a sufficiently large black hole, there might be conditions suitable for life, rather than lethal tidal forces ending in an infinitely small, infinitely dense and hot point.

While such an insider interpretation might seem to be completely outlandish, no one can yet know *exactly* what the mathematical signage change means. Understandably, we may have been biased by our outsider perspective. It may also be that the Schwarzschild metric is not the correct metric to use for the *inside* of a black hole. The only thing which we can say for certain is that the inside of a black hole will always have some mystery about it. An inside observer will never be able to report back to us.

A subject of debate among cosmologists is whether our universe is as spatially flat as recently observed in the Planck satellite survey, or is curved in some way [17]. If our expanding universe is ultimately observed to be at its Friedmann critical density for a flat universe (*i.e.*, $k = 0$), we can call it spatially flat according to the cosmological definition of "critical density." In a similar fashion, if it turns out to be true that a supermassive or gargantuan black hole expands over the great extent of cosmic time (see the Farrah *et al.* reference), a black hole interior might also qualify for a critical density definition of spatial flatness. Obviously, this would be a radically different perspective in comparison to the outsider perspective of spatial collapse to infinite spatial curvature occurring at a geometric center "singularity." Lacking any possibility of observing a gargantuan black hole interior as an insider, one can only speculate about the true insider perspective.

One could say that such an insider interpretation cannot be considered to be within the realm of scientific interest, because it can never be verified or falsified. This is a valid point of view. Nevertheless, as discussed in other publications within this Special Issue, the meaning of recently-discovered mathematical relationships between our universe and black holes and black hole-like objects is gaining in scientific interest among reputable physicists and cosmologists [18] [19] [20] [21]. For readers with a scientific interest but an open mind, one should perhaps begin with physicist Ethan Siegel's article entitled "Are We Living in a Baby Universe that Looks Like a Black Hole to Outsiders?"

5. Summary and Conclusions

Following in the footsteps of Leonard Susskind, a new black hole complementarity is offered in the present paper. After first detailing the well-known outsider perspective of a black hole, using a thought experiment, a plausible speculation on the free-falling insider perspective is offered in a second thought experiment. This second experiment incorporates a new interpretation of the meaning of black hole interior "space-and-time-reversal," owing to signage changes in the Schwarzschild metric mathematical formula, when one passes through a black hole event horizon. We can summarize this new interpretation as follows: The "singularity" space of the black hole interior is time-like and the expansion time of the black hole interior is space-like.

While the Schwarzschild metric mathematical formula of Equation (1) is generally agreed upon, the precise *meaning* of the signage change for the interior perspective of a black hole can still be subject to different interpretations. We can never observe, and can only *speculate*, what the inside of a particularly gargantuan black hole might be like. Perhaps the "singularity" of the outsider perspective is no longer an impossibly small, dense, and hot object in space when one becomes an insider, but rather an object in time only, much as many believe to be true for our own universe.

The resemblance of this new black hole insider interpretation to our own expanding and redshifting universe is intriguing. It is particularly interesting in the context of the recent Farrah *et al.* observations and physicist Ethan Siegel's article entitled "Are We Living in a Baby Universe that Looks Like a Black Hole to Outsiders?"

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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