Cosmic solipsism

Amanda Gefter

Abstract

Cosmology is the study of the origin and evolution of *the* universe – the one we all love and inhabit. In this essay, however, I argue that the basic assumption of a single universe shared by multiple observers is wrong. Synthesizing the implications of black hole radiation, horizon complementarity, dark energy, observations of the cosmic microwave background and quantum logic, I argue that moving toward a true theory of quantum gravity will require us to give up the notion that we all share the same universe. Instead, each observer has their own universe, which constitutes a complete and singular reality.

Introduction

The standard view of cosmology suggests that we all live in a single universe born in a Big Bang some 13.7 billion years ago. Our shared universe is a volume of spacetime whose boundary lies approximately 45 billion light years away, a product of the time that has passed since the Big Bang and the expansion of space that has occurred all the while. The theory of eternal inflation as well as the mathematical existence of the string theory landscape suggest that our universe may be just one of an infinite number of causally disconnected universes. Nonetheless, even this multiverse cosmology assumes that all observers here on Earth live in one and the same universe.

I believe that advances in both foundational and observational physics have conspired to show us that this assumption is wrong: that each observer lives in their own unique universe, that nothing beyond its boundary is real and that we must never speak of more than one observer or universe at a time. If true, this implies a radical rethink not only of cosmology and fundamental physics but also of the nature of reality and of each observer's place in the grand scheme of existence. It may well be the case that abandoning this deeply ingrained assumption will be the key step toward a full theory of quantum gravity.

The first clue

Physicists are hard at work in search of a theory of quantum gravity that would unite Einstein's theory of general relativity with the strange world wrought by quantum mechanics. One of the most illuminating clues discovered so far is Stephen Hawking's 1975 discovery that particles are produced at the event horizon of a black hole[1]. The discovery was profound. It brought the formerly disparate theories of general relativity, quantum mechanics and thermodynamics crashing together and the philosophical implications that emerged from the collision continue to resonate loudly today.

Hawking radiation is born of the observer-dependence of the vacuum, which seems to be an inherent feature of quantum gravity. In the flat Minkowski spacetime of a world without gravity, symmetries ensure that all observers will agree on the definition of the lowest energy state, the vacuum, and on the definition of observables, like particles. However, when an event horizon is introduced, the (accelerated) observers outside the horizon and the (inertial) observers who fall through the horizon will no longer agree on such things. By restructuring the field modes of the vacuum, the horizon produces particles – according to the accelerated observer, that is. As far as the inertial observer is concerned, the horizon doesn't even exist. He falls right through and measures no radiation in the process. These two observers live in incommensurable worlds, neither one more "real" than the other.

Horizons break global symmetries and reduce physics to local descriptions. Particles, for instance, are defined by the global symmetry of spacetime, namely, as invariant representations of the Poincaré symmetry group. In breaking Poincaré symmetry, the black hole's event horizon undermines the very definition of a particle – which is why Hawking particles objectively exist according to observers outside the black hole and objectively do not exist according to the unlucky observers who fall in. Hawking's relativity of the vacuum state went beyond Einstein's relativity, providing the first hints that quantum gravity will radically change the way we think about the role of observers and the notion of a mutually shared spacetime.

Paradox and resolution

The discovery of Hawking radiation led to a now-infamous paradox. The production of Hawking radiation reduces the area of the event horizon and in turn the mass of the black hole. In other words, the black hole evaporates and eventually blinks out of existence, presumably taking all internal information with it. This, as initially emphasized by Leonard Susskind and Gerard 't Hooft, violated the inviolable: the unitarity of quantum mechanics. Indeed, all of quantum theory is based on the conservation of information; without it, the theory would fall apart.

Physicists found themselves at an impasse: relativity's unbreakable speed limit meant that no information could escape the black hole while quantum unitarity meant that it had to. As far as the external observer was concerned, all would be well if the information never passed through the horizon in the first place—and indeed, from his perspective, it does not; relativistic redshifting and time dilation halt the information at the brink of the black hole. However, the equivalence principle mandates that, according to the infalling observer, the horizon doesn't even exist, thus the information must fall right through. The best solution, it seemed, was that the information be duplicated at the horizon, one copy radiating back out to the accelerated observer and one copy falling in toward the singularity. But again the laws of physics conspired against it – the quantum no-cloning theorem forbids the duplication of information.

Susskind discovered a way out of the convoluted mess. His key insight was that no single observer can ever see inside and outside a black hole at the same time. It is acceptable, he argued, to claim that the accelerated observer sees the information radiated out while the inertial observer sees the information fall in because the two observers can never compare notes, nor can any third observer see both copies of the information. There is simply no reference frame in which the quantum no-cloning theorem is violated. The lesson was shocking: when horizons are involved, we can speak of the accelerated observer's world or the inertial observer's world, but never both. We must restrict to a single, local point of view; in doing otherwise, we violate the laws of physics. Susskind gave this radical limitation on our description of reality a name: horizon complementarity[2].

Alone in de Sitter space

Horizon complementarity may have remained a mere curiosity had it applied only to black holes. It didn't. Einstein's equivalence principle put gravity and acceleration on equal footing: if gravity can form a horizon and in turn render the vacuum observer-dependent, so can acceleration. One such case occurs when an observer is accelerating through Minkowski spacetime – his acceleration induces an event horizon that prevents light from a far region of the universe from ever catching up with him, so long as he continues to accelerate. Known as a Rindler horizon, it too produces radiation at the Hawking temperature. A second case is when spacetime itself is doing the accelerating. If the expansion of space accelerates, an inertial observer inside the spacetime will find himself surrounded by an event horizon and by a thermal bath of radiation. It's an important point, since we happen to be such observers.

The 1998 discovery[3] that the expansion of the universe is accelerating, driven by the negative pressure of dark energy, revealed that an event horizon lurks in our future and that spacetime is asymptotically de Sitter. The location of the de Sitter horizon, however, is relative to the location of the observer. In other words, every observer[1] has his or her own unique de Sitter horizon.

Hawking along with Gary Gibbons calculated the properties of the de Sitter horizon[4] and found them to be identical to those of a black hole, suggesting that horizon complementarity should apply. As Raphael Bousso writes, "Gibbons and Hawking (1977) showed that the de Sitter horizon is endowed with the same quantum properties as a black hole horizon: a temperature and an entropy. They noted that the de Sitter horizon…is observer dependent. They interpreted their result as an indication that quantum gravity may not admit a single, objective and complete description of the universe. Rather, its laws may have to be formulated with reference to an observer – no more than one at a time."[5]

Updating a flawed assumption

Compared to the distances involved in cosmology, which are measured in millions or billions of light years, the distance between any two observers on Earth is

[1] By "observer" I am not referring to a person or a conscious creature but merely to a reference frame.

obviously negligible. There may seem to be little harm in proceeding with cosmology *as if* we all share a single de Sitter spacetime. After all, save the tiniest region, our spacetimes almost entirely overlap. I would argue, however, that this assumption, while practical enough, blinds us to the fundamental nature of reality and can get us into trouble when we find ourselves deep in the trenches of quantum gravity. After all, for practical purposes it may be reasonable to operate *as if* the speed of light were infinite or *as if* Planck's constant were zero, but doing so would clearly veil the true nature of the world.

Just as no observer can be inside and outside a black hole simultaneously, no observer can straddle a de Sitter horizon and view both sides. In speaking of "our" de Sitter universe, then, we are taking an impossible point of view. More importantly, *we are violating the laws of physics*. We "clone" or over-count information, introducing subtle but dangerous redundancies in our description of the universe. Respecting horizon complementarity in de Sitter space means replacing the incoherent global description with a local description accessible to a single observer. The existence of dark energy renders every reference frame a universe unto itself, the end-all and be-all of reality.

The fate of the multiverse

The notion of an infinite multiverse produced by eternal inflation and populated by the vacua of string theory's landscape is now a widely accepted view in cosmology. The multiverse, however, suffers a potentially fatal flaw. The infinity of all possible universes makes it impossible to define probabilities or make predictions of any kind – a worrisome state of affairs known as the measure problem. Some physicists, including Susskind[6] and Bousso[7], have suggested that these problematic infinities may be the result of the over-counting of information that occurs when we cut across horizons. If you violate the laws of physics when you cut across a single black hole horizon, imagine how badly you obliterate them when cutting across infinite cosmic horizons!

Horizon complementarity reveals the multiverse to be an impossible object, and as we come to grips with the flaw in our assumption of a single, shared universe, I don't see how it can survive. Susskind and Bousso have suggested[8] that we may be able to patch together a global multiverse out of fundamentally local frames, thereby retaining the benefits of the multiverse, such as the ability to use anthropic reasoning to explain the otherwise inexplicable value of dark energy. Personally, however, I think horizon complementarity is too deep a concept to be a mere add-on to the standard view and instead believe that multiverse cosmology will have to give way to a new kind of cosmology, one that is radically frame-dependent.

On glance, one might think that this one-universe-per-observer paradigm produces its own kind of multiverse, but it's crucial to see why this isn't the case. It was Einstein who drove home the importance of a democracy of reference frames, insisting that no observer has a "truer" view of reality than the next. The same applies here. There is no such thing as a preferred observer, which means it is equally valid to describe reality from any one of an infinite number of possible reference frames. Does this infinity of frames form a multiverse? No. The key rule of horizon complementarity is that, in order to uphold the laws of physics, we can never speak of more than one frame at a time. We can use the frame of any observer, and yet, fundamentally, there is only one.

Experimental evidence of solipsism?

While the standard model of cosmology has been largely confirmed by experiment, a few curious anomalies have resisted explanation. One, first seen by NASA's COBE satellite and more recently confirmed by WMAP[9], is the so-called "low quadrupole". The WMAP satellite has mapped in great detail temperature fluctuations in the cosmic microwave background (CMB) radiation that pervades the sky. Standard cosmology predicts that we should see such temperature fluctuations at every scale. Both COBE and WMAP, however, discovered that there are virtually no fluctuations at angular scales larger than 60 degrees. One possible interpretation of this perplexing anomaly is that spacetime simply isn't large enough to support such large-scale fluctuations. If true, this result would set the upper bound on the size of the universe at almost precisely the size of the observable universe. In other words, the boundary of spacetime – the edge of reality – would coincide with the boundary of a single observer's reference frame. According to the standard view, this is quite a coincidence!

Perhaps cosmologists will find a way to reconcile the low quadrupole with standard theory, but I can't help but see it as a provocative hint that reality is more solipsistic than it seems.

The future of cosmology

Taken together, I believe that these clues – Hawking radiation, horizon complementarity, dark energy, the measure problem, possibly even the CMB low quadrupole — make a powerful case that our intuitive belief that there is a single universe shared by multiple observers is wrong. Instead, each observer has their own universe. This cosmic solipsism turns on all of our common sense notions about the world; then again, fundamental physics has a long history of disregarding our common sense notions.

It remains unclear how cosmology should be altered to rid itself of its central assumption. Cosmology is the study of *the* universe and yet I have argued there is no such thing. What's more, inflation – now the bedrock of the Big Bang – is very much a theory about what happens outside our horizon, while the preceding pages have suggested that the horizon marks the very edge of reality.

One way forward is suggested by Tom Banks and Willy Fischler's theory of holographic spacetime[10], according to which each observer's reference frame defines a complete universe, and anything outside the frame is considered merely a redundant description. Holographic spacetime respects Einstein's democracy of observers by insisting on consistency conditions that hold from one observer's universe to the next, while remaining true to horizon complementarity by restricting to a single observer's viewpoint. It remains to be seen, however, if holographic spacetime or something similar can account for the many observational successes of the standard model.

Why the quantum?

Recent physics makes a powerful case for the abandonment of our assumption of a shared reality, but I suspect that this is exactly what quantum mechanics has been trying to tell us all along. The infuriating strangeness of the quantum world is rooted in the notion of superposition. Our minds reel at the fact that a photon can travel through two slits simultaneously or that an electron can be both "spin up" and "spin down" at the same time, scenarios clearly evidenced by the well-documented phenomenon of quantum interference. Even more confusingly, when we actually measure the photon's path or the electron's spin, we find it in only one of its two states – as if the very act of measurement somehow affected reality.

It helps, I believe, to look at this bizarre situation in the light of quantum logic. Any single observer's reference frame can be described by a Boolean logic – that is, ordinary two-valued logic according to which a proposition is either true or false, a photon took one path or the other. However, when we *compare* the reference frames of two different observers, the truth values of propositions don't always line up. In other words, I have a Boolean algebra in which the electron is *only* spin up, and you have a Boolean algebra in which the electron is *only* spin down, but when we try to put them together we find our shared world to be described by a non-Boolean algebra in which the electron is somehow both spin up *and* spin down. It is precisely this non-Boolean logic – logic in which a proposition can be both true *and* false—that lies at the heart of quantum weirdness.

Carlo Rovelli has proposed an interpretation known as relational quantum mechanics[11], according to which quantum measurements – and hence, the supposed "collapse of the wavefunction" – can only be defined relative to a given observer. While I whole-heartedly agree, I suggest we take the conclusion a step further: the "quantum" of quantum mechanics results from the mistaken assumption that two observers share the same universe. Just as we end up over-counting information when we cut across horizons, we end up describing the world with non-Boolean logic when we cut across reference frames. In the case of the electron spin, our faulty assumption lies in the belief that we can view the electron's spin from two frames simultaneously. John Wheeler famously asked, "Why the quantum?" I suspect that the answer is something like this: because each observer has their own universe, and we can never speak about more than one at a time.

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