Cosmological Constant Problem, Holography, de Broglie Waves, and Dark Energy: The Relevance of Information

Willard Mittelman

Abstract: The role of information is explored in a cosmological context. It is argued that this role is indeed a fundamental one, though not more fundamental than that of material entities. Beginning with the cosmological model of Barrow and Shaw, in which there are vestiges of Wheeler's "it from bit" idea, we move on to consider information's relevance to both the holographic entropy bound in cosmology and the current accelerated expansion of our universe.

A "Wheeler-like" Cosmological Model

One way to assess Wheeler's "it from bit" proposal, and his related idea of delayed-choice experiments – according to which quantum measurements made *today* can determine the *past* history of the universe (at least for measurements of certain appropriate cosmological parameters) – is to examine specific physical models that have some degree of affinity with Wheeler's proposal. As it turns out, an interesting and noteworthy example of such a model is available: namely, the cosmological theory recently proposed by John Barrow and Douglas Shaw (B&S), which proposes "a testable solution to the cosmological constant and coincidence problems" [1].

B&S start from the Wheeler-inspired idea that there exists a wave function Ψ of the universe that represents a superposition of a wide range of cosmological "histories." They then promote the "bare" cosmological constant λ of Einstein's field equations from a fixed parameter to a (scalar) field that is constant in time and space; this ensures that λ itself varies from history to history and hence has a wide range of possible values. As a result, the effective cosmological constant Λ can also take a wide range of values, since Λ's value is just the difference between λ's value and the value of the vacuum energy density calculated from quantum field theory.

Now, B&S do not go so far as to say that quantities such as Λ only acquire a definite value when we measure them. Instead, they argue that: (i) at any given cosmological time and location, there is a particular (classical) history that dominates the universal wave function Ψ, thereby determining the Λ-value obtained by measuring Λ at the time and location in question; and (ii) the particular history that dominates at a given time and location is not, in general, dominant at other times and locations – in other words, the dominant history varies over time and space, a variation that represents Ψ's evolution. (From a quantum perspective, a "dominant classical history" is actually a superposition of histories with a small spread in Λ's value.) In order to make such an argument convincing – or at least plausible – it is necessary to provide a way of calculating Λ's value in any given dominant history; and B&S accomplish this by the above-mentioned promotion of λ to a field. This promotion makes it possible to extremize the total action of the universe with respect to Λ, as a result of which we obtain an additional field equation that determines Λ in terms of other properties of the observed universe; and with Λ's value thus determined, we can then assign a definite Λ-value to each dominant history.

(As an aside, we note that B&S' making Λ determinable in this way enables them to obtain a specific prediction for the curvature parameter Ω_{k0} of the present universe; hence, their model is testable. As it turns out, the model's prediction that Ω_{k0} = -0.0055 is consistent with the latest PLANCK satellite data, though for some of the data combinations this value of Ω_{k0} is rather far from the center of the relevant confidence contours (see [2], p. 37, Table 10).)

Yet even though the value of Λ that we measure today is, according to B&S, determined by the currently dominant classical history, the fact remains that the wave function Ψ of the universe is a quantum entity, and therefore it is *possible*, even from the standpoint of B&S' model – and however small the probability may be – that some of our Λ-measurements will yield a value that clashes with the dominant history. Thus, something of the spirit of Wheeler's "it from bit" view of current quantum-cosmological measurements as informational queries that can determine past cosmological history is still present in B&S' model after all. This fact allows us to pose a query of our own: if we were to discover that B&S' model is correct, would this show that information is, in some sense, *more* "fundamental" than the objects (including spacetime itself) that constitute our universe? The answer to this question, I believe, is negative – the reason being that in order to associate particular values of Λ with particular histories in the first place, thereby making it possible for our Λ-measurements to "select" a given cosmological history, it is necessary, as indicated above, to promote the bare λ to a (constant-valued) field. In other words, our queries for information regarding Λ *can't* be more fundamental than this λ-field itself – even if they "create" a particular value for Λ – for the simple reason that the very ability of such queries to yield particular Λ-values *presupposes* the existence of λ as a field that is constant in time and space.

Nonetheless, even if information does not have complete primacy in relation to the physical universe, we can still ask whether it plays a role that is, more or less, equally as fundamental as that of physical objects. In order to address this question, we begin by noting a prominent feature of B&S' model: namely, its nonlocality. For, B&S are saying that our present measurements of Λ not only determine its present value, but also give it a past value. Thus, for B&S, Λ-information is not constrained by, or subordinate to, the causal structure of spacetime, which suggests that it is no less fundamental than spacetime itself. Note also that, given the fundamentally quantum character of B&S' model, Λ-information for B&S is quantized. And given the conjugate relation between Λ and spacetime volume V – a relation that is not only a feature of unimodular gravity, but is also derivable from time-energy uncertainty [3] – this suggests that spacetime itself is fundamentally quantum, or discrete, a discreteness that may reasonably be associated with the Planck scale. In addition, it suggests that spacetime at the Planck scale is subject to fluctuations that reflect quantum uncertainty. Thus, the quantum character of certain information – specifically, information about Λ – can be viewed as imposing a constraint on the very nature of spacetime, again suggesting that information is at least as fundamental as spacetime.

The above remarks assume the validity of B&S' model; but the basic idea that they express, namely that information has a certain independence of space and time, can be supported without assuming B&S' model. This is just as well, since this model is by no means problem-free. In particular, the fact that the cosmological constant λ gets promoted to a field suggests there should be a multiplicity of scalar fields, since λ is not promoted because of some special feature that it alone possesses. Indeed, B&S themselves support λ's promotion by noting that something similar occurs in the case of string theory and its vacua; and in this very case there is, as is well-known, a large number of scalar fields. The crucial point here is that if λ exists in an "environment" in which there are many fields, one would expect the λ-field to quickly decohere as a result of interaction with its environment. In the case of string theory, it has in fact been argued that the string-theoretic dark energy (DE) field acquires a definite (tiny) value because it decoheres due to interaction with its environment, with such decoherence being natural in this context [4]. Hence, there is no reason to regard B&S' λ-field as immune from decoherence; and once this field does decohere, there is no longer an evolution of dominant histories that determines Λ 's measured value in the sort of way that B&S describe, which clearly undermines B&S' model.

Despite this, there are significant commonalities between this string-theory-inspired account of DE and B&S' model, and these are relevant to the present discussion. For one thing, both treat the energy density of the DE field as a quantum value, which, as noted, constrains spacetime itself to be discrete. Furthermore, the fact that the ground state of the string-theoretic DE field is delocalized over the various local minima of this field's potential ([4], p. 1) indicates that nonlocality is significant in the string-theoretic case as well as in B&S' theory. And so, as remarked above, the idea of information's independence of spacetime can find support outside of B&S' theory, e.g. in string theory.

Holography, Cosmology, Information, Entropy

Rather than focusing on string theory per se, however, let us consider some other ideas which, though of great relevance to string theory, are applicable to other contexts as well: namely, the ideas associated with holography, or the holographic principle. These ideas, like those of string theory, combine strong nonlocality and fundamental discreteness, with information playing a central role. In particular, (i) holographic relations between horizon and interior are manifestly nonlocal, whether we are dealing with black holes or with cosmological horizons, and (ii) information on a holographic screen is stored in discrete bits. As a further tie-in with B&S' account of Λ, holographic models of dark energy have attracted considerable attention (not all of it favorable, admittedly). In particular, the implications of such models for accounts of cosmological entropy and thermodynamics have been explored in numerous books and papers. And so, in considering the question of whether information is on a par with physical objects as far as its "fundamentalness" is concerned, the topics of holography, cosmology and entropy are certainly worth pursuing.

A good place to begin is with Jae-Weon Lee's point [5] that the holographic principle entails the presence of entanglement in the bulk degrees of freedom (dof's), since such entanglement is crucial to eliminating redundant dof's that would otherwise lead to a violation of the holographic entropy bound (HEB), which limits the magnitude of the universe's entropy to (roughly) the area of the relevant cosmological horizon. This leads us to ask a crucial question: how should the entanglement here be described, and what are its physical effects or manifestations?

One interesting proposal, motivated in part by the goal of incorporating holographic dark energy into a general account of gravity, is that there are on the order of 10^{123} bulk dof's, each of which is an entangled system that is delocalized on a cosmological scale [6][7][8][9][10]. This number of dof's satisfies the HEB, giving an entropy value roughly equal to the area of the horizon of the observable universe (more specifically, we may take this horizon to be the apparent horizon). It has been argued [8] that such delocalization strongly suggests that these dof's are quon fields, i.e. particle species that obey infinite statistics ([7] gives a somewhat different, thermodynamically inspired argument for the "quonic" character of these dof's). The problem with this proposal, however, is that various considerations, some of which are independent of holography altogether strongly indicate that the bound on the number of species is in fact much lower (by over fifty orders of magnitude) than this [11]. This “species problem” indicates a need to re-think the nature of the fundamental dof’s and their entanglement.

To that end, let us begin with de Broglie’s characterization of a given particle, such as an electron, as something that “occupies all space” (quoted in [12]). This (nonlocal) “pervasiveness” of particles is connected, as one might suspect, with their “wave aspect”; specifically, it reflects the infinite phase velocity of the de Broglie wave in the particle’s rest frame ([13]; see also references 16 and 17 there, on waves with infinite velocity). One manifestation of such pervasiveness is the tendency of localized wave packets to “spread” [13]. Such spreading is not, in general, accompanied by a tendency of the spreading wave to become entangled with other waves that are present in the regions into which the wave in question spreads. In the case of discrete, Planck-sized elements of spacetime, however, if we think of these elements as “particles” each of which has an associated wave, then “spreading” here has a fundamentally different character: specifically, since the particles here just *are* spacetime regions, the spreading of a wave into a given region is, quite literally, the spreading of the wave into particles themselves (and into the waves associated with these particles). The way to understand this, we suggest, is to say that such spreading inevitably and inherently produces entanglement between elements of spacetime. Since this is true of all such elements alike, the end result is an entanglement of spacetime elements that extends (at least) throughout the entire universe or four-volume enclosed within a suitable cosmological horizon (such as the apparent horizon [14] of our universe). In other words, the universe’s spacetime forms a single entangled system and has a single (cosmic) rest frame, which we may equate with the CMB rest frame. The entanglement here gives rise to nonlocal correlations between the spacetime elements; and, following the account of de Broglie waves given in [13], we propose that it is the phase wave of the entangled system – which, as noted, has an infinite velocity in the system’s rest frame (making it essentially a standing wave) – that enables and enforces these correlations. The wave’s infinite velocity means that the correlations here can be present on a cosmological scale. And, returning to our initial concern, no “multiplicity of species” problem arises here, since there is only a *single* fundamental entity or system in the case we are considering.

It is natural to suppose, of course, that each of the N constituent elements of this “universal” spacetime entity fluctuates (randomly) *on its own*, i.e. independently of all the other elements, and more or less continually. Consequently, one might think that each such Planck-sized element should be counted as a (bulk) dof, which would violate the HEB. We avoid this conclusion here by proposing that the pervasive entanglement that characterizes the spacetime entity or system leads to a general suppression of such independent fluctuations. In that case, it is not obvious that the HEB is violated; but it is still necessary to make sure the HEB is actually respected here. For convenience and simplicity, as well as definiteness, we stipulate that: (i) the expectation value $\langle v \rangle$ of the volume v of a single spacetime element, or “bit,” is equal to 2, in Planck units; and (ii) *if* the fluctuations of each bit were completely independent of those of other bits – i.e., if there were no entanglement here – *then* the magnitude of a single bit’s fluctuation at a given time, i.e. the amount by which the bit’s volume deviates from $\langle v \rangle$, would be equal to ±1, with equal probability, and in Planck units of volume. (These stipulations are idealized assumptions, of course; in particular, they ignore dimensional reduction at the Planck scale, the occurrence of which suggests that we should work with Planckian bits of *area* rather than volume. Yet doing so would significantly complicate the present discussion because of the need to explain the relation between Planck-scale area and large-scale volume; and a more realistic physical model, including one that takes account of dimensional reduction, would not affect the order of magnitude of the cosmological quantities that concern us here.) We propose that these would-be fluctuations, at any given time, are suppressed nearly everywhere; i.e., they are effectively subject to nonlocal (instantaneous) mutual cancellation, so that at any moment of time – and taking into account the fact that N is an extremely large number – the number of (randomly "selected") uncanceled fluctuations in the entire universe is on the order of $N^{1/2}$ (with the magnitude of each such fluctuation having a Planckian value of 1). We also suggest that this universal spacetime system be regarded as a kind of "particle," both because it has a de Broglie wave and because, arguably, it has a definite (Planckian) mass derived from time-energy uncertainty (though the argument for this latter claim is beyond the scope of the present paper).

Next, we say that the total magnitude of these uncanceled fluctuations, at a given time t, represents global information I concerning the universal spacetime particle. The value of I at t is the amount $|\Delta V|$ by which the universe's volume V, at t, fluctuates or deviates from its expected value $\langle V \rangle$, where this latter value is the result of multiplying (a) the number N of discrete spacetime bits at t by (b) the expectation value $\langle v \rangle$ of a single bit's volume v. The reason for regarding the quantity $|\Delta V|$ as *information* is that it provides "input" for determining other quantities of cosmological importance (in particular, as suggested below, its input helps determine the dark energy density). And it is clear from the preceding paragraph that at a given time t the value of I, or $|\Delta V|$, is on the order of $N^{1/2}$.

The relation $I \sim N^{1/2}$ can hold (mathematically) even if each spacetime bit has its own independent, random, and unsuppressed fluctuations. In that case, however, there are N dof's of the system (the vast majority of which are redundant), so that the HEB is greatly exceeded, as already noted; and as also noted, pervasive intra-system entanglement and the resulting general suppression of fluctuations can eliminate these redundant dof's. But since the fluctuations that are uncanceled at a given time are not, in general, uncanceled at other times, they themselves are not true, enduring dof's of the system; hence, the entropy S of the system cannot be determined by simply counting them. We therefore propose instead that S is an entropy of entanglement and is induced by a cosmological horizon. One source of motivation for this view is that a de Broglie phase wave, with its infinite velocity, can be expected to manifest entanglement on a scale even larger than that of a single universe enclosed within a horizon. Thus, such a wave can "know" the value of $|\Delta V|$ in a neighboring universe U that is similar to our own. The separation between us and U, however, entails that this $|\Delta V|$-information is "erased" at the horizon; and since U is similar to our universe, the number of erased information-bits should be on the order of $N^{1/2}$. By Landauer's principle [15], the entropy s per bit is at least k ln 2, where k is Boltzmann's constant; for Planckian bits such as our spacetime elements, the value of s is on the order of 1 ([16], pp. 17-18), giving us $S \sim (N^{1/2} \cdot s) \sim N^{1/2}$. And so, by taking the entropy S of the spacetime system or "particle" to be entanglement entropy, we see that the HEB is indeed respected, as desired; and we can write $I \sim S \sim N^{1/2}$.

Taking another step, let us equate the volume $v = \langle v \rangle$ with a "bit-density" ρ such that $\rho = 1$. In other words, for a bit b of volume v', b's density ρ is just the number of bits of volume v' that are needed to fill a $\langle v \rangle$-sized region; and $|\Delta\rho|$ is the amount by which a given bit's density deviates or fluctuates from the value $\rho = 1$. From what has been said so far, it is clear that at a given time t, the number N' of bits such that $|\Delta\rho|$ is nonzero is on the order of $N^{1/2}$; and the sum of the density-fluctuations $\Delta\rho$ at t, i.e. $\sum |\Delta\rho_i|$, where i runs from 1 to N', represents global information that depends on, but is nonetheless distinct from, $|\Delta V|$.

It can be argued ([17], Part III) that the global distribution of fluctuating bit-densities at a given t is such that it gives rise to a "quantum potential of spacetime" Q, and that Q's value, which reflects in part the total magnitude $\sum |\Delta\rho_i|$ of these density-fluctuations, is on the order of $N^{1/2} \sim I \sim S$. The energy density associated with Q is comparable to the observed dark energy density; and the quantum force or pressure ∇Q equals $-Q$, giving us a suitable dark energy equation of state as well. Thus, in the presence of a cosmological horizon, information not only yields a quantity of entropy that satisfies the HEB; it can also determine the current accelerated expansion of the universe. (Since a particle's quantum potential is inversely proportional to its mass, the existence of a coupling between the spacetime particle and other matter, a coupling that scales with this matter's cosmological energy density and increases the spacetime particle's effective mass, makes it possible for Q's value to be significantly weakened in early cosmological eras, in accordance with BBN and structure-formation constraints ([17], Part IV).) One could, alternatively, regard dark energy as the entanglement energy associated with the entanglement entropy S [8][15]. However, since the horizon represents the surface of inducement of this entanglement energy, it is necessary for this energy to delocalize in order to fill up the volume within the horizon [8]; and in order to ensure such delocalization, one needs to assume the existence of a vast number of delocalized degrees of freedom, or particles, with the number of these particles being on the order of $N^{1/2}$ [8]. Yet as noted earlier, the existence of that many dof's violates various theoretical and observational constraints [11]. Hence, we prefer to view dark energy as the quantum potential of spacetime. (As for the question of what happens to the entanglement energy if it does not act as dark energy, the answer may be that it simply replaces the energy consumed in erasing information at the horizon.)

Conclusion

We have seen that a combination of entanglement, information, and a cosmological horizon can lead both to satisfaction of the HEB and to the production of dark energy. Thus, information is clearly a factor to be reckoned with. We have also suggested a close relation between (some) information and the superluminal de Broglie phase wave, a wave that has generally been viewed as having zero energy – and hence as being "unphysical" – in order to avoid conflict with relativity. In the present context, this wave's close association with information suggests a different possibility: namely, the wave's energy is purely "information energy," which means [18] that it is not available for doing work – or more specifically, it is not able to affect anything other than the spacetime elements with which the phase wave itself is inseparably connected. This would seem to rule out the phase wave's having any observable, relativity-violating effects; but it does not support the idea that this wave is unphysical. (It should be noted that information energy's being unavailable for doing work is *not* tantamount to its being effectively "dark," *pace* [18], and hence it does not provide a basis for viewing information energy itself as dark energy.)

Regarding the issue of conflict with relativity, a bimetric structure that associates a separate metric with the phase wave can also help alleviate such conflict [19]. Admittedly, if the phase wave's velocity is truly infinite, then the metric associated with this wave would appear to be degenerate, so that the distance between arbitrary "points" or elements of spacetime would be zero, or perhaps infinitesimal. This would take us beyond typical accounts of bimetricity such as [19]. Examples of degenerate metrics are available, however, such as the "zero-space" metric of [20] or the 8D complex Minkowski space metric of [21], which suggests that such an extension of bimetricity is indeed possible – though it may require delocalizing the zero-space metric so that our 4D pseudo-Riemannian spacetime becomes “stuffed” with zero-space ([20], p. 42).

References

[1] D.J. Shaw, J.D. Barrow, “A testable solution to the cosmological constant and coincidence problems” arXiv.1010.4262; Phys. Rev. D83:043518, 2011.

J.D. Barrow, D.J. Shaw, “A new solution of the cosmological constant problems” arXiv.1007.3086; Phys. Rev. Lett. 106:1013082, 2011.

J.D. Barrow, D.J. Shaw, “The value of the cosmological constant” arXiv:1105.3105; Gen. Rel. Grav. 43, 2555-2560, 2011.

[2] “Planck 2013 results. XVI. Cosmological parameters” arXiv:1303.5076

[3] A.E. Shalyt-Margolin, “Some comments on dynamical character of cosmological constant and GUP” arXiv:0807.3485

[4] C. Kiefer, F. Queisser, A.A. Starobinsky, “Cosmological constant from decoherence” arXiv:1010.5331; Class. Quantum Grav. 28 (2011), 125022.

[5] J.-W. Lee, “Quantum entanglement from the holographic principle” arXiv:1109.3542

[6] S. Thomas, “Holographic vacuum energy” arXiv:hep-th/00010145

[7] Y. Jack Ng, “Holographic foam, dark energy and infinite statistics” arXiv:gr-qc/0703096; Phys. Lett. B657:10-14, 2007.

[8] A.J.M. Medved, “A comment or two on holographic dark energy” arXiv:0802.1753; Gen. Rel. Grav. 41:287-303, 2009.

[9] M. Li, X.-D. Li, C. Lin, Y. Wang, “Holographic gas as dark energy” arXiv:0811.3332; Commun. Theor. Phys. 51:181-186, 2009.

[10] S. Gao, “A conjecture on the origin of dark energy” arXiv:1001.4567; Chinese Phys. Lett. 22, 783, 2005.

[11] R. Horvat, “Effective field theory, large number of particle species, and holography” arXiv:0812.2768; Phys. Lett. B674:1-3, 2009.

R. Horvat, “Entanglement in holographic dark energy models” arXiv:1003.4363; Phys. Lett. B693:596-599, 2010.

R. Horvat, “Holographic constraint and effective field theories with N-species” arXiv:0911.5045

[12] R.E. Kastner, “de Broglie waves as a ‘bridge of becoming’ between quantum theory and relativity” arXiv:1107.1678

[13] R. K. Pradhan, L.P. Singh, “On reality of tachyonic de Broglie waves” arXiv:0908.1365

[14] V. Faraoni, “Cosmological apparent and trapping horizons” arXiv:1106.4427; Phys. Rev. D84:024003, 2011.

[15] J.-W. Lee, H.-C. Kim, J. Lee, “Gravity from quantum information” arXiv:1001.5445

[16] J.R. Buczyna, C.S. Unnikrishnan, G.T. Gillies, “Standard and derived Planck quantities: selected analysis and derivations” arXiv:1006.3241

[17] W. Mittelman, “Ever-present Lambda and the quantum potential of spacetime” viXra:1010.0028; Prespacetime Journal 1, no.7, 2010.

[18] M.P. Gough, T.D. Carozzi, A.M. Buckley, “On the similarity of information energy to dark energy” arXiv:astro-ph/0603084

[19] V. Garber, “A proposed superluminal S-field mediating quantum entanglement” arXiv:quant-ph/0702208

[20] D.D. Rabounski, L.B. Borissova, “Particles here and beyond the mirror” arXiv:gr-qc/0304018; viXra:1002.0014
[21] R.L. Amoroso, E.A. Tauscher, “Relativistic physics in complex Minkowski space, nonlocality, aether model and quantum physics” viXra:1305.0055