The Causet Mechanism for the Creation of Energy$^1$

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$^1$This paper is dedicated to Rafael Sorkin and will appear in the volume published to honor him on his 60$^{th}$ birthday.
1. Introduction

Perhaps the most urgent and most vexing problem that confronts modern physics is the elucidation of the nature of space-time, otherwise put, the reconciliation of quantum mechanics with gravity. How does the expected quantum graininess at the planckian scale give way to the successful continuum theory of general relativity at much larger scales?

At present, systematic efforts, notably string theory and/or loop quantum gravity, remain incomplete in this quest. Therefore, for the nonce, we must rely on our "physical intuition" acquired from experience in dealing with situations more amenable to our human limitations. In this, we resort to phenomenology, a priori hypotheses designed to handle problems which, by their nature, force us into physics at the planckian scale. The most dramatic of these is encountered in the backward extrapolation of cosmology towards inflation in the quest for a causal universe and thence, presumably, to creation itself. Less dramatic, but also fascinating, is the nature of black hole evaporation, once more concerned with the creation of matter accompanied by an increase of volume of observable space, in this case the Schwarzschild space exterior to the black hole horizon which is occasioned by the reduction of the black hole mass.

The present contribution, in honor of Rafael Sorkin, is based on Sorkin's causet phenomenology. Section 2 contains a brief review of the causet mechanism for the creation of dark energy, Ref. [1]. Then in Section 3, it is argued that causets could apply to inflation as well as to dark energy in the adiabatic era, Ref. [1], whereupon one is led to speculate that this latter is the fluctuating remnant of the vacuum energy responsible for inflation. The last section indicates how causets may be applicable to black hole evaporation.

We close this introduction with a question. When space expands, as in cosmology, generally speaking there are two options. Is there an underlying metric manifold which metric encodes the expansion? Or does one create space as in the causet phenomenology? The latter motivates loop quantum gravity; the former is the more traditional point of view of general relativity. We shall here follow the second alternative. In this, it is well to point out that even if one pursues the more traditional point of view, one still cannot avoid something of the causet idea, related to the so called space-time foam, necessitated by the need for a reservoir of modes of quantum fields since elsewise the density of modes would decrease during the expansion. So whichever way, one is forced to speculate in terms of a priori hypotheses.

Let imagination roam fancy free
To speculate what the world might be.

2. The Causet Scenario of Dark Energy in the Adiabatic Era

It is postulated that as the universe expands, space is delivered as discrete lumps of planckian dimensions in space-time. These are distributed at random with a mean density which is planckian in space-time. The word causet is used because only the causet elements situated within the backward light cone of a given event can influence happenings around that event. The happenings of interest are those which cause variations of energy near the event (near
and around are presumed to mean within a planckian space-time interval). To this end, one postulates that the causet elements are the sites wherein vacuum energy is given to or taken from those degrees of freedom within the universe whose energy causes the expansion, as dictated by the condition of energy constraint. This energy is created or annihilated as space is created. One may suppose that there are “hidden” degrees of freedom within the causet element whose energy content does not affect the expansion. In Section 3 we shall draw upon an analogy in matter physics which may help one to visualize this process. For the moment, following Ref. [1], we sketch how this scenario can deliver the requisite dark energy density. In particular, it explains why the energy density of vacuum ($\rho_{\Lambda} = \text{dark energy density}$) is the same order of magnitude as the energy density of matter ($= \rho_M$) during the adiabatic era.

We now present the beautiful argument of Ref.1. One introduces the energy density ($\rho_{\Lambda}(t)$) coupled to the macroscopic expansion through the energy constraint: $H^2(t) = \rho_{\Lambda}(t) + \rho_M(t) = \rho_{\text{Tot}}(t)$. We have set $m_{\text{pl}} = 1$ and all constants of $O(1)$ are set equal to 1. $H(t)$ is the Hubble constant at time $t$. We repeat: any energy associated to possible degrees of freedom within the causet is not contained in $\rho_{\Lambda}(t)$. Rather, consider $\rho_{\Lambda}$ to be a conventional type of zero point field energy (including gravitational and other interactions) which is born or annihilated through interactions between conventional cisplanckian configurations of fields and degrees of freedom in the causet elements.

The space-time volume of the backward light cone of an observer at proper time $t$, during the adiabatic era, is easily shown to be $O(H^{-4}(t))$. For that observer, one must compute the effective vacuum energy that is due to the causets within that zone. Since the causet density is $O(1)$ the number of such elements ($= N(t)$) is $O(H^{-4}(t))$. Each element is the site of a random exchange with vacuum; hence the net accumulated vacuum energy density, in the sense of the preceding paragraph, is $\pm O(\sqrt{N(t)/H^{-4}(t)}) = O(H^2(t))$. Since $H^2 = \rho_{\text{Tot}}$, one sees $\rho_{\Lambda}(t) = O(\rho_{\text{Tot}})$ and it is presumed that $\rho_{\text{Tot}}$ has a significant portion which is $\rho_M(t)$ in the adiabatic area.

This scenario has been put into more quantitative form as a stochastic equation which gives $\rho_{\Lambda}(t_{i+1})$ in the $(i + 1)^{\text{th}}$ time slice in terms of $\rho_{\Lambda}(t_i)$ in the $i^{\text{th}}$ slice of the backward light cone. Some runs duplicate phenomenology remarkably well, Ref. [1].

In this, only the energy constraint is used. Since $\rho_{\Lambda}$ varies with $t$ (in fact in both space and time, but space is taken to be sufficiently homogenous to ignore spatial variation), one should include the acceleration equation of cosmology as well, along with an equation of state. To assimilate $\rho_{\Lambda}$ to a cosmological constant is an approximation that will require justification in future work. In what follows, we assume its legitimacy.

An essential assumption in Ref.1, which is truly profound, is the characterization of the “target” value of $\rho_{\Lambda}$ in the adiabatic era, to wit: as $\rho_M \to 0$, it is assumed that $\rho_{\Lambda} \to 0$. Thus the asymptotic universe is empty and quiescent ($H = 0$).

But quantum mechanics cannot tolerate such tranquility. Fields fluctuate and gravity has an unbounded spectrum from below as is manifested in the energy constraint where $-H^2$ is an average negative energy density associated with gravity when applied to the cosmological expansion. Thus, this empty quiescent universe should be considered a metastable state. A fluctuation from it can seed a new universe. An example of such a seeding is in Ref.2, Ch.8. Another is the concept of chaotic inflation conceived in Ref.3 and later in Ref.4. In fact the very idea of inflation and a causally created universe was so conceived, Ref. [2].

Therefore, the causet phenomenology of dark energy, taken together with the assumption
that $\rho_\Lambda \to 0$ as $\rho_M \to 0$ on the average, forces one to speculate on the physics of vacuum, creation and inflation. These speculations are presented in Section 3 where we shall argue that the causet mechanism of dark energy creation in the adiabatic era is the fluctuating remnant of the causet energy creation process of the inflationary era.

3. Inflation and Creation

It would be nice if one could extend the causet-mode exchange idea to the earliest times. The inflationary era was introduced into physics to be able to conceive the universe as a causal response to a seed which is a vacuum fluctuation. If we retain this view of inflation, and in the following paragraphs this shall be our point of view, the causet scenario of the adiabatic era must be modified; for if the seed arises from vacuum there is no possibility for the causet element to remove energy, but rather only to give energy to the nascent universe. A further consideration which prompts us to modify the causet scenario when applied to inflation is the vast difference in magnitude of $\rho_\Lambda$ between the adiabatic epoch where $\rho_\Lambda^{\text{Now}} = O(10^{-100})$ and inflation where $\rho_\Lambda = O(10^{-10})$. The ratio of Hubble constants for example is $H^{\text{Now}} / H^{\text{inflation}} = O(10^{-50})$.

To come to grips with this question it is useful to inquire into the possibility of modeling a mechanism for causet-vacuum energy exchange. To this end there is a useful analogy which may serve as a guide, the tight binding mechanism for the generation of electron bands in metals from atoms.

An isolated atom has all its electrons localized in the vicinity of its nucleus. But when the atoms approach each other the wave functions of the outer (valence) electrons overlap and the wave functions develop into delocalized bands which, by translational symmetry, are classified by momenta rather than localized orbitals. The inner or core electrons, in very good approximation, remain localized. Thus we have a simple model in which degrees of freedom of the same type of stuff are classified into two widely different types of configurations. Let us now return to field theory.

In usual quantum field theory, the fields are developed in terms of modes characterized by their momenta. This approach ceases to be valid when the momentum becomes planckian for then the field coupling to gravity induces strong coupling among the modes and the momentum of a planckian mode is a concept that loses its usefulness. It makes no more sense to describe configurations of fields at the planckian scale in terms of modes and their momenta than it does to describe a liquid in terms of the momenta of its constituent atoms. Modes at the planckian scale are strongly coupled as are the molecules of a liquid and one must seek an alternative way to describe field configurations at that scale. Degrees of freedom of fields at the planckian scale could well fold up into localized structures. These could be the causet elements. They can also be called elements of space-time foam, sometimes envisaged as black hole in character.

In a quantum theory of gravity where space-time can be conceived as field variables as well, these causet elements of planckian dimensions then could correspond to Sorkin’s conception of how space is created to describe the cosmological expansion.

Long wavelength modes still exist since their mutual interactions are weak. So the same kind of stuff, at the small length scale, can be causets, and at long length scale, are describable in terms of the conventional modes of field theory on a background.

This picture accommodates well to the problem posed by the dilution of modes induced
by the cosmological expansion. The problem, as usually stated, is that modes must be cut off at planckian momenta, because they are then strongly coupled. But the cut-off decreases as the inverse of the scale factor. So they must be replenished from a reservoir. In the causet scenario this is automatic. The causets remain at constant density and the modes cut off at the length scale that separates the causet elements. No dilution! The visualization offered by the tight binding mechanism of bands helps in this conception. One just makes larger and larger crystals, more and more atoms, as well as more and more electrons in the modes (bands). Their number is $(\text{Volume}) \times (\text{cut-off momentum})^3$, Ref.\[3\], where the cut-off momentum stays fixed during the expansion.

This image also could give some notion of how it is that the degrees of freedom sequestered in a causet element have no influence on the macroscopic dynamics such as the Hubble constant that figures in the energy constraint. In the tight binding analogy, the pressure exerted by the electron gas in many metals comes from the electrons in the bands. The core electrons have no role. (For metals where the cores are far one from the other, such as the alkalis, the bulk modulus is well approximated by that of the free electron gas formed from the valence electrons). So it is that field degrees of freedom within the causet elements can have no impact at the macroscopic level. It is only through the microscopic processes of the energy exchange with the mode system that indirectly they have influence. That is the substance of the causet explanation of dark energy, an energy that is transferred to the mode system in vacuum, exchanged in and out of the causet elements.

Unfortunately, these concepts are not sufficient to rationalize the existence of a quiescent metastable vacuum. But since in the following paragraphs we shall build a scenario of cosmogenesis and subsequent inflation from such an initial state, it behooves us to make some remarks in its defense.

There is some element of self consistency in the state $\rho_M = 0$, $\rho_\Lambda = 0$, hence $H = 0$. No net temporal variation of the average metric is consistent with no net creation of quanta, hence $\rho_M = 0$ thence, $\rho_\Lambda = 0$ since $H = 0$. In the causet phenomenology we envision causet elements whose population fluctuates leaving no net expansion of space and no net exchange of energy to the cisplanckian world. Perhaps this occurs in a mathematical framework which at present, at least, is beyond our ken, such as the elements of spin foam or the $SU_2$ matrices of Kodoma or the high energy configurations of strings which are black hole in character or, or, . . . . Whatever these fluctuating bits of space-time may be, when taken together with the ephemeral configurations of matter fields which they carry, in this metastable state they transfer no energy to our universe in the macroscopic sense.

To seed a universe we must appeal to a collective type of phenomenon wherein a number of causet elements act coherently to give a macroscopic sense of expansion, hence a gravitational average energy due to the expansion which is $-H^2$.

Then the causet can start to deliver energy to the cisplanckian sector in that part of space where a sufficient number have agglomerated to make a seed. Modes form and at the same time pick up vacuum energy. At this early stage we expect $\rho = O(1)$ since the causets deliver their energy as well as space to the seed. The seed causes space to expand rapidly with $H = O(1)$ and a macroscopic universe composed of causets and the modes which develop from them comes into being. One may imagine that this rapid expansion does not allow time enough for a significant amount of vacuum energy to be reabsorbed onto the causets as they do in the quasi stationary situation of the adiabatic era, i.e., $\rho_\Lambda = O(N/N) = O(1)$
in the early universe rather than $\rho_\Lambda = O(1/\sqrt{N})$ as in the adiabatic era.

Our present knowledge of the early universe is well accounted for by the inflationary scenario. And the implementation of the inflation through the inflaton scenario has been highly successful in accounting quantitatively for the CMBR fluctuations. Furthermore the inflaton has the advantage that it has its own demise built into the formulation of the concept and its equation of motion. Is it possible to rationalize the existence of an inflaton from the seed? And is it possible to offer some explanation for its mass, $\mu(=10^{-5})$ in terms of the causet concept? To answer these questions is extremely difficult and these next paragraphs are speculative in the extreme.

We postulate that the inflaton comes into existence as a collective mode of fluctuation once the initial seed has become well organized to justify the use of the macroscopic notions of cosmology, a homogeneous space as a viable zeroth order approximation which expands through a Hubble constant that depends on time only throughout the patch that contains this small universe. This macroscopic system is now endowed with modes and causet elements which interact. Having emerged from a planckian seed with $H = O(1)$, it will take a while for that initial expansion to slow down and then turn over to the adiabatic stage. This period between the formation of the seed and the adiabatic expansion is the inflationary epoch. Phenomenology indicates that its expansion rate is slower than planckian, say $H = O(10^{-5})$ and the inflaton mass follows suit $\mu = O(10^{-5})$ if the mean value of the inflaton amplitude, $\phi$, is taken to be $O(1)$.

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It is less simple to rationalize $\mu = O(10^{-5})$. We sketch below a speculation given in Ref.\[7\], now taken over for causets.

Within the inflating patch there is the planckian graininess at the smallest scales. It is proposed that there exists a local equilibrium between the degrees of freedom sequestered within the causet and the modes just as is there is during the adiabatic epoch and ultimately in the metastable vacuum. It is maintained by the cis-trans exchanges to and from the causets, but now in the background $\phi = \text{const.} = O(1)$ during the greater part of the inflationary epoch. This is taken to be a rapid process whose characteristics are in good approximation background independent. Rapid means on the scale of the inflaton decay from $\phi = O(1)$ towards the reheating era and the subsequent adiabatic expansion.

It was proposed in Ref.\[7\] that the fluctuations about this effective two fluid quasi-equilibrium were those of a massy acoustic degree of freedom, massy because neither the density of modes nor of causet elements is conserved. It was argued that $\mu^2 = M^2 p$ where
$M$ is the mass scale of the matrix element for the cis-trans exchange and $p$ the dimensionless probability encoded in that matrix element. One may try to estimate $p$ by making use of the parameter $\alpha$ introduced in the stochastic process of Ref. 1. There it was found that $\alpha$ was tightly constrained to be $O(10^{-2})$. With $p = O(10^{-2})$ and $\mu = O(10^{-5})$ one finds $M = O(10^{-4})$. It is difficult to interpret these parameters save that one might expect $M = O(1)$. In Ref.[7], black hole processes taking place in vacuum were speculated upon as a possible interpretation.

In summary, the creation -inflation scenario proposed from the causet phenomenology is: 1) formation of an initial seed from causet elements which function to create both space and vacuum energy with $\rho_\Lambda = O(1)$; 2) the subsequent inflation driven by a massy acoustic fluctuation identified with the inflaton. The energy that drives the inflationary expansion is essentially that of the inertia of the inflaton ($= 1/2\mu^2\phi^2$) which decays from $\phi = O(1)$ to the adiabatic era. This mean energy within the patch is accompanied by small rapid fluctuations. How these might be related to CMBR observed fluctuations is an interesting question which remains to be elucidated in terms of the causet model.

As mentioned, the advantage of the inflaton scenario is that inflation stops naturally and passes over to adiabatic expansion. As this happens, the exchange between the causets and modes continues and the mechanism of Ref.1 to explain $\rho_\Lambda$ takes over.

A problem that arises in Ref.1 is that in the adiabatic epoch there exist runs in which $\rho_{\text{Tot}}$ goes negative since the fluctuations are about mean situations for which $\rho_{\text{Tot}}$ is close to zero, $\rho_M$ being so small. If the above concepts have any validity, when this happens the exchange equilibrium breaks down and the causets will pump out more than they absorb, keeping $\rho_{\text{Tot}} \geq 0$ and $H^2 \geq 0$. Presumably such runs do not represent the cosmic environment in which we live. But the main point to stress is that their existence does not seem to pose a conceptual problem. They simply give rise to situations too far from equilibrium to permit the applicability of the pure random exchange process.

A far deeper problem is the target state with $\rho_\Lambda \to 0$ as $\rho_M \to 0$, the quiescent metastable vacuum. This is the problem of the existence of a (metastable) vacuum with zero cosmological constant, a highly controversial issue.

In terms of the above concepts, there is little one can say to justify this ansatz save, as we have mentioned, its consistency which bears repetition. One goes to the limit $\rho_M \to 0$, then it must be supposed that $H \to 0$, for if $H \neq 0$ the temporal variations of the metric will induce the excitation of modes to make quanta, hence $\rho_M \neq 0$. But if $H = 0$ then $\rho_\Lambda = 0$ since $H^2 = \rho_{\text{Tot}}$.

$\rho_\Lambda = 0$ means that the vacuum energy in the mode sector must vanish on the average. This can be rationalized in that the conventional zero point energy of modes must be combined with the gravitational energy of the modes, both their mutual interactions and their interactions with causet elements. It is easy to make models to shown how in, say a Hartree-Fock approximation, one can choose a cut-off to make $\rho_\Lambda = 0$. But the question is, why is this cut-off so chosen, or in other words, why does the cut-off take on a value which yields a universe at absolute rest? There is something missing in our formulation of physics which would make this ansatz compelling.

Of course this target space is metastable and from it new universes can develop from fluctuating seeds. We exist within one of those.
4. Black Hole Evaporation

Hawking’s seminal paper on black hole evaporation was based on free field theory, Ref.[5]. The modes of a quantum field propagating in a background Schwarzschild metric manifest themselves as conversion from vacuum fluctuations of the past to on-mass-shell quanta in the future.

One of the principal problems that one encounters is that the field configurations which give rise to this radiation adhere exponentially closely to the horizon of the black hole all the way into the past before they break away to become quanta with some finite probability. Concomitantly their proper energy is exponentially large, i.e. one is dealing with field configurations in vacuum whose momenta are $>> 1$. This is the transplanckian problem. Clearly the idealization for using modes and free field theory breaks down.

This does not mean that Hawking evaporation does not take place. Its origin can be argued almost on thermodynamic grounds. If the matter that makes up the black hole is placed within a cavity then one is dealing with an eternal black hole. Green’s functions of fields far from the horizon are periodic in imaginary time as if there was a temperature there. And this temperature is the same as that obtained using Hawking’s free field scenario for the production of radiation. See, for example, Ref.[9].

The use of the eternal black hole and the induced temperature does not rely on free field theory, but only on very general properties of quantum field theory. It also implies radiation since one can imagine punching some holes in the boundary of the cavity to let some radiation escape. It escapes at the Hawking temperature. It is Hawking radiation and free field theory is not necessary to get it.

Therefore we must inquire: how does one get around the transplanckian problem in the Hawking process, the process that is applicable to the situation of the dynamical collapse resulting in black hole formation? One way is suggested by the causet scenario. Within a distance of $O(1)$ from the horizon, space-time exists as causet elements and field configurations cannot be described in terms of modes. Successively, the field configurations locked into the causets pick up the cispplanckian components which get converted into modes. This happens when the wave functions of the fields begin to overlap with the grainy structure of the space that had been lain down in the prior history of the collapsing matter that made the black hole. Then the Hawking mechanism takes over.

Parentani, Ref.[10], has shown how in the backward extrapolation of a wave packet that is constructed to be an evaporated quantum the interaction of that packet with incoming vacuum fluctuations causes the packet to dissipate in the backward direction. We presume that it is in the space-time region of this dissipation that the field configuration has emerged from its sequestration within a causet element.

Parentani’s demonstration shows that this rate of emergence into modes and subsequent conversion to quanta is a steady state process whose rate is that calculated by Hawking. So in the causet picture there is a steady conversion of field from their configurations in causet elements into modes.

At the same time the volume of space-time around the horizon increases due to the reduction of the black hole mass i.e. that portion of space-time that is within the horizon decreases according to Hawking’s result $dM/dt = M^{-2}$. This increase of the exterior Schwarzschild space may be attributed to the increase in the number of causet elements which have exchanged their field energy with the modes that have been converted to quanta. Once more,
as in inflation, a wake of causet is suggested by the dynamics of energy creation. The slow roll of inflation is replaced by the slow decrease of $M$.

It is a pleasure and an honor for me to have had the occasion to contribute these speculations, which were stimulated by the causet mechanism of dark energy generation, to the 60th birthday anniversary volume dedicated to Rafael Sorkin. This is to express my gratitude to Rafael for his patient explanations and moreover to express my admiration for this highly original and astute scientist. These pages were written during my stay at the Perimeter Institute to which I express my gratitude for its support.
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