Simplicity of the Universe

This article briefly describes a fundamentally new paradigm for analyzing what we have learnt about the Universe over the last three hundred years. While it is clear that gravity is the dominant force (of the four fundamental forces) that shapes the Universe as we observe it today, the precise nature of the way gravity determines the structure of the Universe has been rather obscure.

Gravity as a force (post Newton), usually described by the General Relativity theory and its derivatives or variants, produces the coupling between space-time and matter (energy). This is needed to describe most of the finite systems that we originally encountered historically in the theories of gravity (apple, moon, mercury, solar system, stars, galaxies etc.). This description assumes the a-priori existence of space and time and matter. However the extension of these theories to describe the dynamics of the Universe as a whole, requires that we understand the genesis of space time and matter, and then use this to describe the rest of the structure - a top down description that would involve the emergence of space time and then matter and then the description of how the smaller scale structures such as stars and planets came to be.

In order to arrive at a consistent understanding of this top down model, we must keep in mind that the broad picture which is usually simple and elegant (Occam's Razor) is often obscured by details, making the scenarios intractably complex. This has, in the past, confounded us considerably and a simpler theory is a must to make progress.

Let us assume that the Universe can be described by a scale factor *a(t)* and a Hubble Constant, *H(t)* (which is a function of the scale factor). (FLRW model equations?)

In a simplified sense, the current observational data indicates that the Universe consists of three phases – **an initial exponential expansion** (with the Hubble radius remaining constant and the scale factor of the universe expanding exponentially), **a radiation and matter dominated phase** and **a third exponential expansion phase**. The galaxies and stars and planets are formed in the second phase of the Universe's history. (Figure needed?)

Traditionally we have studied gravitation as a force experienced on the surface of our planet and have extended it to describe solar systems and galaxies and clusters of galaxies etc. Further extension allowed us to model the Universe as a product of gravity (as a solution to the equations describing gravity) namely the equations of General Relativity.

If you turn this argument on its head, it is possible to envisage a model where gravity is a cosmic force and the finite gravity observed in smaller systems such as super clusters, clusters, galaxies etc. in scales which are very small in

comparison with the scale of the Universe is to be treated differently with respect to Gravity at the Cosmological scale.
Modern Gravitational theory is a geometric theory dealing with gravity as the curvature of space-time (in a manner that gives equal importance to space and time). However at the cosmological scale it is possible to envisage gravity as being 'pre-geometric' with a **preferred time**, thus enabling us to describe the emergence of cosmic space as a function of **'cosmic time'** – the time associated with a class of preferred observers co-expanding with the Universe.

These pre-geometric variables would thus be the 'atoms of spacetime'. And like any other atomic theory it is possible to use a statistical description leading to a macroscopic thermodynamic description of gravity. It is quite natural to presume that quantum mechanical description of these 'atoms' would lead to the much sought after 'quantum gravity'.

The thermodynamic description of gravity has already elicited much insight into the structure of gravity as described by Einstein equations or higher dimensional theories such as Lanczos-Lovelock theories (Similar to Einstein's theory of 4 dimensional space time gravity but with higher space time dimensions). An 'emergent' picture of gravity has been arrived at through this approach. In this approach we have seen that gravity can be described as 'emergent' a la elasticity or fluid mechanics. The similarities are mathematically rigorous and can be derived with a very small set of assumptions. (Links to the appropriate pages here)

Given that gravity is emergent at the level of current descriptions of finite or small scale gravitational fields, it is a logical next step to inquire about the emergent properties of space time itself.

To describe space-time as 'emergent', the most consistent and simple approach is to use the preferred time of the co-moving observers and describe the emergence of space itself, like ice emerging from water when the conditions are appropriate. The length scale of relevance that is to be used is obviously the natural length scale of the universe itself, the Hubble scale.

However there is another natural length-scale, which is obtained from the combination of the fundamental constants – gravitational constant (Gravity), Planck's constant (Quantum mechanics) and light speed (maximum speed of signal propagation according to theory of relativity). This is the small length scale corresponding to Planck scale. Thus all that the Universe is, lies between the Ultraviolet scale (as in small wavelength of light) of the Planck scale and Infra Red (as in the large wavelength of light) of the Hubble scale.

Our mathematical description of such a universe utilizes a well-known model called the De Sitter model (Named afted Willem De Sitter), which is an exponentially expanding model. (**Advanced comment: This model has the interesting property that it is time translation invariant which means that it could have existed since eternity – a sort of steady state which takes care**

of the question of initial singularity or what happened at the beginning of the universe)

The first de sitter model is associated with Hubble scale equal to the Planck scale, namely when the Universe is very small.

This small (or ultra violet) scale is deeply entrenched in quantum gravity regime and is unstable to quantum fluctuations. These instabilities can cause the universe to make a transition from exponential expansion of inflation to radiation dominated phase. With the transition comes creation of particles and universe become filled with normal matter. In other words both space and matter emerge simultaneously from the small scale state due to an instability.

The radiation dominated phase will continue until the second length-scale (the infra red length-scale or the present day Hubble Scale) starts to dominate. Why does this happen? We believe it is because the dark energy component of the Universe, the one which looks like the 'cosmological constant', becomes more dominant than the matter and radiation energy combination. Once this happens the universe will make a transition to a second de sitter phase in which the Hubble radius remains constant at the large-scale value. Observations suggest that this happened rather recently in the expansion history for our universe and can continue to eternity!

How do we describe the precise dynamics? One can count the number of degrees of freedom on a surface with radius equal to the Hubble radius as well as the number of degrees of freedom contained in the bulk volume. The two de-sitter phases correspond to states of "**holographic equipartition**" in which the **number of degrees of frame in the bulk is equal to that on the surface**. The transition stage can then be described as **an evolution towards equipartition driven by the holographic discrepancy between the degrees of freedom on the surface and the bulk**. (This is similar to systems evolving in response to discrepancy in current and extremal energy or entropy states in other dynamical systems in physics).

In Planck units, this is just a combinatorial evolution with the Hubble volume at the n^{th} time step being given by the recurrence relation:

$$V_n=V_{n-1}+(N_{sur}-N_{bulk})$$

Which connects the volumes at time steps n and n-1 to the difference in the number of degrees of freedom of the surface N_{sur} and the bulk of the volume N_{bulk}. (Figure needed?)

Remarkably enough, this description leads to an equation for the expansion of the Universe, which is identical to the standard description in terms of General Relativity.

The above observation allows us to posit a completely new way of looking at cosmic evolution. We concentrate on the Hubble radius and think of it as describing the emergence of space. **Its dynamics is governed by an equation which describes evolution towards holographic equipartition.** The two equilibrium states of the universe are described by two de-Sitter or exponential expansion phases – one at the small Planck scale and the other at the large dark energy related scale (or present Hubble scale).

The conventional cosmology, which deals with the existence of humans on Earth finally, in many senses, becomes a rather insignificant part [lasting for a tiny fraction of time] sandwiched between the two eternal de-Sitter phases! More to the point, the above description remains very simple and elegant if we ignore a small interval when the Universe was matter dominated rather than radiation dominated.

Scientific methodology requires testability. Hence the question - how can we test such a paradigm? In addition to theoretical consistency, there are the following possible ways of testing.

(i) **Boundary conditions** - It is possible that when we think of the Universe with two scales we need some non-trivial boundary condition at the transition point from radiation and matter dominated scale to dark energy dominated scale. This in turn will lead to a discreet [though very closely spaced] spectrum for radiation modes. Such a discreet spectrum must violate statistical isotropy of CMBR; possibly at a small level but in principle these **holographic equipartition** ideas should leave a trace in the cosmic microwave background radiation (CMBR). Which means that as we look at the background in all directions we should find traces of this 'edge' or 'boundary'.

(ii) **Mathematical and observational concordance -**

- A mathematical analysis indicates that the three phases of the Universe (two de-Sitter phases and a radiation dominated phase sandwiched in between) must expand by nearly equal factor, say, e^N where N is the number of e-foldings of the Universe (Given that e = 2.718 one can think of this as approximate number of times the Universe tripled in size) during the expansion phase. This allows us to link the ratio between the large and small length-scales to the number of e-foldings of the initial Planck scale inflation. Putting in the numbers based on our current understanding of Inflationary phase, we arrive at a quantitative measure for the dark energy component, which is in accord with present day observations. (Figure needed?)

- The density perturbations in the energy that seed the later formation of large observed structures like super clusters and voids, cross the Hubble radius three times during the evolution of the Universe in this model. Theoretical consistency requires **equal number of modes** of perturbations to cross during all the three phases, which is borne out in this model.

Will this description allow us to incorporate Planck scale corrections in a simpler way into cosmology and study the earliest phases of the evolution of the universe with clearer observational signatures for the model? This is the question that is driving the theory forward. And the answer appears to be strongly positive.