

Cosmic Microwave Background Fluctuation Amplitude from Dark Energy De-Coherence*

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Standard cosmology connects the scale generated at late times by the cosmological constant with that generated in early times by the energy dynamics. Assuming dark energy de-coherence occurs during early times when the scale parameter expansion rate is no longer supra-luminal specifies a class of cosmological models in which the cosmic microwave background fluctuation amplitude at last scattering is approximately 10^{-5} .

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The luminosities of distant Type Ia supernovae show that the rate of expansion of the universe has been accelerating for several giga-years[1]. This conclusion is independently confirmed by analysis of the Cosmic Microwave Background radiation[2, 3]. Both results are in quantitative agreement with a (positive) cosmological constant fit to the data. The existence of a cosmological constant / dark energy density defines a length scale that must be incorporated in any description of the evolution of our universe. When the dynamics of the cosmology is made consistent with this scale, we expect that the usual microscopic interactions of relativistic quantum mechanics (QED, QCD, etc) cannot contribute to cosmological (gravitational) equilibrations when the Friedmann-Robertson-Walker (FRW) scale expansion rate is supra-luminal, $\dot{R} > c$. The cosmological dark energy density is expected to decouple from the energy density in the Friedmann-Lemaitre(FL) equations when the FRW scale expansion is

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no longer supra-luminal, at which time the microscopic interactions open new degrees of freedom.

Prior to de-coherence, the coherence which preserves the uniform density needed to make the FL dynamical equations meaningful must be maintained by *supra-luminal* (eg. gravitational) correlations and not by the luminal or sub-luminal microscopic exchanges that are available after de-coherence. In this sense the energy which de-coheres *must be "dark"*. In what follows it is called *dark energy*. If the usual backward extrapolations from the present to *de-coherence time* are accepted, the decoupling of the evolution of the dark energy from that of the microscopic degrees of freedom must occur during a time when the mass density which drives the FL dynamical equations is dominated by radiation, and at a finite time *earlier* than big-bang nucleosynthesis. The basic assumption in this paper is that the dark energy which is fixed during de-coherence is to be identified with the cosmological constant. It is shown that the expected amplitude of fluctuations driven by the dark energy de-coherence process is of the order needed to evolve into the fluctuations observed in cosmic microwave background radiation and in galactic clustering. From the time of dark energy de-coherence until the scale factor expansion rate again becomes supra-luminal due to the cosmological constant, the usual expansion rate evolution predicted by the FL dynamics is expected to hold.

The horizon problem for present day cosmology arises from the large scale homogeneity and isotropy of the observed universe. The present age of the universe can be estimated from the Hubble scale using $H_0 t_0 \cong 0.96$ to be about $13\frac{1}{2}$ Gyr. If the size of the observable universe today is taken to be of the order of the Hubble scale $\frac{c}{H_0} \approx 10^{28} cm$, then its size at the Planck scale would have been of the order $\sim 10^{-4} cm$. Since the Planck length is of the order $L_P \sim 10^{-33} cm$, then there are expected to be about $(10^{29})^3 \sim 10^{87}$ (luminal) causally disconnected regions in the sky. Further, examining the ratio of the present conformal time η_0 with that during recombination $\frac{\eta_0}{\eta_*} \sim 100$, the subsequent expansion is expected to imply that light from the cosmic microwave background would come from about $100^3 = 10^6$ disconnected regions. Yet, angular correlations of the fluctuations have been accurately measured by several experiments[3]. This homogeneity and correlation is indicative

of some form of cosmological coherence in earlier times.

The general approach used here is to start from well understood macrophysics, assume that the physics of de-coherence defines a cosmological scale parameter, and end the examination of the backward extrapolation of cosmological physics at the time when the rate of expansion of that scale parameter is the velocity of light. For times after that *boundary* there is general confidence that well understood micro- and macro-physics are valid at the cosmological level. The process that takes the cosmology from the very early universe (i.e. prior to de-coherence) through this boundary will be called *gravitational dark energy de-coherence*. The FRW scale parameter is used to compare cosmological scales to those scales relevant for microscopic physics, which define the lengths of rulers, ticks of clocks, mass of particles, and temperatures of thermodynamic systems. The calculations presented here will not depend on the present horizon scale, which is an accident of history. Global gravitational coherence prior to de-coherence (i.e. the assumption that the FL equations still apply in the very early universe) solves the horizon problem because the gravitational correlations implied by the FL equations are supra-luminal; it is hypothesized that the same will be true of any type of dark energy to be considered. A preliminary discussion of why *quantum coherence* in the very early universe might also provide the requisite dark energy scale has been presented elsewhere[4].

The existence of a cosmological constant Λ introduces a natural length scale for the late time FRW metric. If we express the FRW scale parameter $R(t)$ which results from the physics of de-coherence in units consistent with those of the dark energy density $\rho_\Lambda = \frac{\Lambda c^4}{8\pi G_N}$ and the FL energy density ρ which drive the expansion in the FL equations, then the expansion rate \dot{R} is expected to have physical significance with respect to the cosmological dark energy. In particular, for very late times, the De Sitter horizon $R_{DeSitter} = \sqrt{\frac{3}{\Lambda}} \equiv R_\Lambda \approx 1.5 \times 10^{28} cm \approx 1.6 \times 10^{10} ly$ scales the exponential expansion rate of the scale parameter. For regions beyond this horizon, no luminal signals can reach $r = 0$, and information from those inaccessible regions is limited to what can be ascertained from the temperature of this horizon $k_B T_{DeSitter} = \frac{\hbar c}{2\pi R_{DeSitter}} \sim 2 \times 10^{-30} \text{ }^\circ K$. For a cosmology primarily driven by a positive cosmological constant, *any* FRW scale parameter has a value equal to the De Sitter horizon scale when the

late time expansion rate is that of light, $\dot{R} = c$. An understanding of the physics of de-coherence allows one to use the known value of the cosmological constant (dark energy) to determine the behavior of the scale parameter during early times. It is therefore meaningful to use this scale parameter to describe the subsequent dynamics of the cosmology. If this is the scale parameter to be used in the FL equations, an “open” cosmology is excluded, since (as will be shown) at no time in such a cosmology is $\dot{R} \leq c$. Likewise, a “closed” cosmology can be shown to never expand to an extent that would allow structure formation[4]. The only cosmology consistent with the observed phenomenology is then exactly spatially flat. In the development that follows, the evolution of a spatially flat cosmology using the natural scale factor determined by the physics of dark energy de-coherence will be examined.

Prior to the de-coherence scale condition $\dot{R}_{DC} = c$, gravitational influences on scales $R < R_{DC}$ must propagate (at least) at the rate of the gravitational scale expansion, and microscopic interactions (which are assumed to propagate no faster than c) cannot contribute to cosmological scale equilibrations. If the expansion rate is supra-luminal $\dot{R} > c$, scattering states cannot form decomposed (de-coherent) clusters of the type described in references [5, 6] on cosmological scales, i.e. incoherent decomposed clusters cannot be cosmologically formulated. Since the development of the large number statistics needed to define a cosmologically significant temperature requires an equilibration of interacting “microstates”, any mechanism for the cosmological redistribution of those microstates on time scales more rapid than the cosmological expansion rate can only be through gravitational interactions.

The question now arises as to whether dark energy is geometric or dynamical in origin. From the form of Einstein’s equation

$$\mathcal{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathcal{R} = \frac{8\pi G_N}{c^4}T_{\mu\nu} + \Lambda g_{\mu\nu}, \quad (0.1)$$

if the term involving the cosmological constant should most naturally appear on the left hand side of the equation, dark energy would be considered geometric in origin. If this term is geometric in origin, one would expect Λ to be a fundamental constant which scales with the FRW/FL cosmology consistently with the vanishing divergence of the Einstein tensor. However, if it arises from the process of de-coherence at $\dot{R} = c$,

this means that it is fixed by a physical condition being met, and thus would not be a purely geometric constant.

During de-coherence, the Friedmann-Lemaitre(FL)/Hubble equations which relate the rate and acceleration of the expansion to the densities, are given by

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N}{3c^2}(\rho + \rho_\Lambda) - \frac{kc^2}{R^2} \quad (0.2)$$

$$\frac{\ddot{R}}{R} = -\frac{4\pi G_N}{3c^2}(\rho + 3P - 2\rho_\Lambda), \quad (0.3)$$

where the dark energy density is given by $\rho_\Lambda = \frac{\Lambda c^4}{8\pi G_N}$, ρ represents the FL matter-energy density, and P is the pressure. The term which involves the spatial curvature k has explicit scale dependence on the FRW parameter R . The dark energy density is assumed to make a negligible contribution to the FL expansion during de-coherence, but will become significant as the FL energy density decreases due to the expansion of the universe.

The energy density during dark energy de-coherence ρ_{DC} can be directly determined from the Hubble equation to satisfy

$$H_{DC}^2 = \left(\frac{c}{R_{DC}}\right)^2 = \frac{8\pi G_N}{3c^2}(\rho_{DC} + \rho_\Lambda) - \frac{kc^2}{R_{DC}^2}. \quad (0.4)$$

A so called ‘‘open’’ universe ($k = -1$) is excluded from undergoing this transition, since the positive dark energy density term ρ_Λ already excludes a solution with $\dot{R} \leq c$. Likewise, for a ‘‘closed’’ universe that is initially radiation dominated, the scale factors corresponding to de-coherence $\dot{R}_{DC} = c$ and maximal expansion $\dot{R}_{max} = 0$ can be directly compared. From the Hubble equation

$$\frac{c^2}{R_{max}^2} = \frac{8\pi G_N}{3c^2}[\rho(R_{max}) + \rho_\Lambda] \cong \frac{8\pi G_N}{3c^2}\rho_{DC} \frac{R_{DC}^4}{R_{max}^4} \Rightarrow R_{max}^2 \cong 2R_{DC}^2. \quad (0.5)$$

Clearly, this closed system never expands much beyond the transition scale. Quite generally, the assumption of dark energy de-coherence due to sub-luminal expansion at early times *requires* that all such cosmologies are spatially flat.

Setting the expansion rate to c in the Hubble equation 0.2 with $k = 0$, the energy density during dark energy de-coherence is given by

$$\rho_{DC} = \frac{3c^2}{8\pi G_N} \left(\frac{c}{R_{DC}}\right)^2 - \rho_\Lambda. \quad (0.6)$$

Since the FL density at de-coherence is specified in terms of the single parameter given by the scale at de-coherence R_{DC} , all results which follow depend only on this single parameter.

As is often assumed, if the cosmology remains radiation dominated in the standard way down to $t = 0$, then the scale parameter satisfies

$$R(t) = R_{DC} \left(\frac{t}{t_{DC}} \right)^{1/2}, \quad (0.7)$$

which gives the time at de-coherence as

$$t_{DC} = \frac{R_{DC}}{2c}. \quad (0.8)$$

The assumption of radiation dominance during de-coherence corresponds to a thermal temperature of

$$g(T_{DC}) (k_B T_{DC})^4 = \frac{90}{8\pi^3} (M_{PC}^2)^2 \left(\frac{\hbar c}{R_{DC}} \right)^2, \quad (0.9)$$

where $g(T_{DC})$ counts the number of degrees of freedom associated with particles of mass $mc^2 \ll k_B T_{DC}$, and $M_P = \sqrt{\hbar c/G_N}$ is the Planck mass.

Using the FL densities at radiation-matter (dust) equality $\rho_M(z_{eq}) = \rho_{rad}(z_{eq})$, one can extrapolate back to the de-coherence period to determine the redshift at that time. Ignoring threshold effects (which give small corrections near particle thresholds while they are non-relativistic), this gives

$$1 + z_{DC} = \left[\frac{\rho_{DC}}{\rho_{Mo}} (1 + z_{eq}) \right]^{1/4} \cong \left(\frac{c}{H_o R_{DC}} \right)^{1/2} \left(\frac{1 + z_{eq}}{\Omega_{Mo}} \right)^{1/4}, \quad (0.10)$$

where equation 0.6 has been used to explicitly exhibit the R_{DC} dependence. The scale parameter at the present time is then expressed in terms of this redshift using the usual definition $R_o = (1 + z_{DC})R_{DC}$.

The evolution of the cosmology during the period for which the dark energy density is constant and de-coupled from the FL energy density is expected to be accurately modeled using the FL equations. There is a period of deceleration, followed by acceleration towards an approximately De Sitter expansion. The rate of scale parameter expansion is sub-luminal during the finite period of this evolution, as shown in Figure 1. The particular value for the scale at de-coherence chosen for the graphs is not

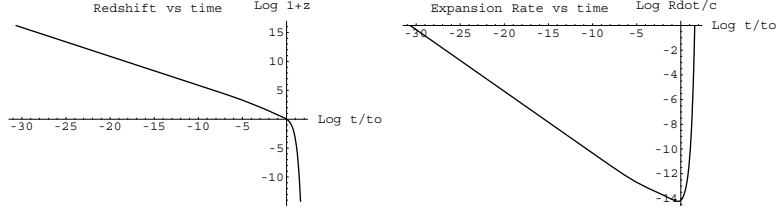


Figure 1: *Graphs of redshift and expansion rate vs time*

important for the present discussion, and generally is determined by the microscopic makeup of the dark energy. The present time since the “beginning” of the expansion $H_0 t_0 \cong \frac{2}{3\sqrt{\Omega_\Lambda}} \log\left(\frac{1+\sqrt{\Omega_\Lambda}}{\sqrt{1-\Omega_\Lambda}}\right)$ (see reference [2], page 193, Eq. 19.30) corresponds to the origin on both graphs. The value of the expansion rate is seen to equal the speed of light for any particular value chosen for R_{DC} , as well as when the expansion scale reaches the De Sitter radius R_Λ .

Adiabatic perturbations are those that fractionally perturb the number densities of photons and matter equally. For adiabatic perturbations, the matter density fluctuations grow according to [2]

$$\Delta = \begin{cases} \Delta_{DC} \left(\frac{R(t)}{R_{DC}}\right)^2 & \text{radiation - dominated} \\ \Delta_{eq} \left(\frac{R(t)}{R_{eq}}\right) & \text{matter - dominated} \end{cases} \quad (0.11)$$

This allows an accurate estimation for the scale of fluctuations at last scattering in terms of those during de-coherence given by

$$\Delta_{LS} = \left(\frac{R_{LS}}{R_{eq}}\right) \left(\frac{R_{eq}}{R_{DC}}\right)^2 \Delta_{DC} = \frac{(1+z_{DC})^2}{(1+z_{eq})(1+z_{LS})} \Delta_{DC}. \quad (0.12)$$

The energy available for fluctuations in the two point correlation function is expected to be given by the cosmological dark energy, in a manner similar to the background thermal energy $k_B T$ driving the fluctuations of thermal systems. This means that the amplitude Δ of the fluctuations is expected to be of the order

$$\Delta_{DC} \equiv \left(\frac{\rho_\Lambda}{\rho_{DC}}\right)^{1/2} = \frac{R_{DC}}{R_\Lambda}, \quad (0.13)$$

where $\Lambda = 3/R_\Lambda^2$. Using equations 0.10, 0.12, and 0.13, this amplitude at last scat-

tering is given by

$$\Delta_{LS} = \frac{(1 + z_{DC})^2}{(1 + z_{eq})(1 + z_{LS})} \frac{R_{DC}}{R_{\Lambda}} \cong \frac{1}{1 + z_{LS}} \sqrt{\frac{\Omega_{\Lambda_0}}{(1 - \Omega_{\Lambda_0})(1 + z_{eq})}} \cong 2.6 \times 10^{-5}, \quad (0.14)$$

where a spatially flat cosmology has been assumed. This estimate is independent of the scale parameter during de-coherence R_{DC} , and is of the order observed for the fluctuations in the CMB (see [2] section 23.2 page 221). It is also in line with those argued by other authors[7]. Fluctuations in the CMB at last scattering of this order are consistent with the currently observed clustering of galaxies.

Cosmological dark energy de-coherence has been assumed to occur when the rate of expansion of the cosmological scale parameter in the Friedmann-Lemaitre equations becomes sub-luminal. The choice of a cosmological scale parameter in the FL equations directly relates the scale of dark energy de-coherence to the De Sitter scale associated with the cosmological constant. Such a scale necessarily requires a spatially flat cosmology in order to be consistent with structure formation.

When the cosmology has global coherence, the dark energy is expected to evolve with the contents of the universe. When global gravitational coherence of the dark energy is lost, only local coherence of microscopic degrees of freedom within independent clusters is expected to remain, and the dark energy scale coherence with the clusters is lost as the new degrees of freedom become available. The dark energy density at de-coherence is frozen out as a positive cosmological constant. The cosmological constant is not viewed as the *same* as dark energy density. In this interpretation, cosmological dark energy could change during pre-coherence and post-coherence.

The dark energy de-coherence hypothesis defines a class of cosmological models all of which give an amplitude of density fluctuations in the CMB expected to be of the order 10^{-5} . Work in progress involves specific models of the de-coherence process. For these models, the form of the power spectrum of the fluctuations expected to be generated by de-coherence will be calculated.

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