Cosmological Constant Decaying with CMB Temperature

Tomohide Sonoda

Graduate School of Natural Sciences, International Christian University, Tokyo, Japan

Abstract: Recent observations of the dark energy density demonstrates the fine-tuning problem and challenges in theoretical modelling. In this study, we apply the self-similar symmetry (SSS) model, describing the hierarchical structure of the universe based on the Dirac large numbers hypothesis, to Einstein’s cosmological term. We introduce a new similarity dimension, $D_B$, in the SSS model. Using the $D_B$ SSS model, the cosmological constant $\Lambda$ is simply expressed as a function of the cosmic microwave background (CMB) temperature. The result gives a natural interpretation of the cosmological scenario and helps understanding the extreme smallness of the present value of $\Lambda$ without fine-tuning.

Keywords: cosmological constant; cosmic microwave background; large numbers hypothesis; self-similarity; symmetry

1. Introduction

The cosmological constant problem, i.e., the dark energy problem, poses a formidable challenge in physics. In 1998, observations of distant supernovae provided evidence for the acceleration of the expansion of the universe [1,2]. Einstein’s cosmological term emerged as the simplest candidate to explain the mechanism of the accelerating universe. However, the inconsistencies between theoretical expectations and observations are extremely problematic, despite many attempts to provide a proper explanation [3–8]. In order to provide insights into this issue, the axiomatic approach has been proposed by Beck [9]. Beck formulated a description of the cosmological constant, $\Lambda$, using four statistical axioms: fundamentality ($\Lambda$ depends only on the fundamental constants of the nature), boundedness ($\Lambda$ has a lower bound, $0 < \Lambda$), simplicity ($\Lambda$ is given by the simplest possible formula, consistent with the other axioms), and invariance ($\Lambda$ values obtained using potentially different values of the fundamental parameters preserve the scale-invariance of the large-scale physics of the universe). Using the four axioms, Beck showed that $\Lambda$ is given by:

$$ \Lambda = \frac{G^2}{\hbar^4} \left( \frac{m_e}{\alpha_f} \right)^6, $$

where $G$ is the gravitational constant, $\hbar$ is the reduced Planck constant, $\alpha_f$ is the fine structure constant, and $m_e$ is the electron mass. The same formula has been proposed using different approaches [10,11], and recently discussed in several reports [12–15].

In this study, we applied the self-similar symmetry (SSS) model [16], that explains the hierarchical structure of the universe based on the Dirac large numbers hypothesis (LNH) [17,18], to Beck’s formula. We show that the values of the cosmological constant can be simply expressed as a function of the cosmic microwave background (CMB) temperature. A dynamically decaying cosmological constant with cosmic expansion has been proposed in several reports [19–28]. The result of decaying cosmological constant based on the SSS model gives a natural interpretation that the cosmological constant is small because of the low CMB temperature at present epoch.
2. D_B SSS model

The SSS model [16] describes the CMB with a symmetrical self-similar structure. The model consists of dimensionless values because a physical constant with a dimension would not have universality. Therefore, we define the fundamental dimensionless mass ratios of the proton mass $m_{pr}$, electron mass $m_e$, and Planck mass $m_{Pl}$ as follows:

$$A = \log \alpha = \log \left( \frac{m_{Pl}}{m_{pr}} \right), \quad B = \log \beta = \log \left( \frac{m_e}{m_{pr}} \right).$$  \hspace{1cm} (2)

We also defined the fundamental dimensionless time and length ratios as follows:

$$T = \log \left( \frac{t}{t_{Pl}} \right), \quad L = \log \left( \frac{l}{l_{Pl}} \right),$$  \hspace{1cm} (3)

where $t$ and $l$ are the time and length scales of the objects, respectively, and $t_{Pl}$ and $l_{Pl}$ are the Planck time and length, respectively. Using these dimensionless values, we define the similarity dimension $D_A$ as:

$$D_A = \left( \frac{T}{L} \right)^3 = \frac{A}{A + B} \approx 1.20592.$$  \hspace{1cm} (4)

A new similarity dimension, $D_B$, is then introduced:

$$D_B = \frac{A - B}{A + B} \approx 1.41184.$$  \hspace{1cm} (5)

The hierarchical structures of the $D_B$ SSS model are constructed according to the following sequences:

$$L_0 = 2(A + B) \approx 31.70089,$$  \hspace{1cm} (6)

$$L_n = D_B^n L_0 \quad \text{for} \quad L > L_0,$$  \hspace{1cm} (7)

$$L_m = (2 - D_B^m) L_0 \quad \text{for} \quad L < L_0,$$  \hspace{1cm} (8)

where $n$ and $m$ are the natural numbers that represent the hierarchical levels. The time scales of each hierarchy are also calculated using Eq. (4). Eqs. (7) and (8) indicate that $L_n$ and $L_m$ are self-similar to $L_0$, which corresponds to the CMB temperature [16].

3. Verification of the $D_B$ SSS model

In order to verify the proposed $D_B$ SSS model, we compared the model values with reference values. Table 1 and 2 summarize the length and time scales of the Planck, weak, solar, and universe hierarchies. The values obtained using the $D_B$ SSS model agree well with the reference values. Figure 1 shows the hierarchy time scale as a function of length scale. The coincidences seen in the figure confirm the validity of the SSS model.

4. Discussion

Using the gravitational coupling constant $\alpha_G = Gm_{pr}^2/\hbar c$ and Eq. (2), $2A = -\log \alpha_G$ is obtained. The following relations are satisfied:

$$L_{n+1} + L_0 = 3L_0 - L_{m+1} = 4A,$$  \hspace{1cm} (9)

$$L_{m-1} - L_0 = L_0 - L_{n-1} = 4B.$$  \hspace{1cm} (10)

Therefore, $\alpha_G$ and $\beta$ are important in forming the hierarchical structure of the universe. Regarding the similarity dimension, $D_A = (r_a - r_b)/(1 - r_b)$, (where $r_a = (D_A^3 + D_A^2 - 2)/D_A$ and $r_b = (2 -$
Table 1. Length scales of the hierarchies of the universe.

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>$l$ (m)</th>
<th>$L$</th>
<th>$D_B$ SSS model</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck scale</td>
<td>$1.6 \times 10^{-35}$</td>
<td>0</td>
<td>0.21 ($m = 2$)</td>
<td>-</td>
</tr>
<tr>
<td>Weak scale</td>
<td>$10^{-16}$</td>
<td>18.79</td>
<td>18.65 ($m = 1$)</td>
<td>-0.8</td>
</tr>
<tr>
<td>Solar scale</td>
<td>$1.4 \times 10^9$</td>
<td>43.93</td>
<td>44.76 ($n = 1$)</td>
<td>1.8</td>
</tr>
<tr>
<td>Universe scale</td>
<td>$4.1 \times 10^{28}$</td>
<td>63.40</td>
<td>63.19 ($n = 2$)</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

- Planck length $l_{Pl} = \sqrt{\hbar G/c^3}$, where $c$ is the speed of light in vacuum.
- Experimental results show that the range of the weak interaction is $r_w \leq 10^{-16}$ m [29].
- Diameter of the sun, based on the nominal solar radius defined by the International Astronomical Union [30].
- Upper bound of the universe derived from the $D_A$ SSS model [16].

Table 2. Time scales of the hierarchies of the universe.

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>$t$ (s)</th>
<th>$T$</th>
<th>$D_B$ SSS model</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck scale</td>
<td>$5.4 \times 10^{-44}$</td>
<td>0</td>
<td>0.23 ($m = 2$)</td>
<td>-</td>
</tr>
<tr>
<td>Weak scale</td>
<td>$6.6 \times 10^{-27}$</td>
<td>17.09</td>
<td>19.85 ($m = 1$)</td>
<td>13.9</td>
</tr>
<tr>
<td>Solar scale</td>
<td>$2.3 \times 10^5$</td>
<td>48.63</td>
<td>47.64 ($n = 1$)</td>
<td>-2.1</td>
</tr>
<tr>
<td>Universe scale</td>
<td>$1.7 \times 10^{24}$</td>
<td>67.49</td>
<td>67.26 ($n = 2$)</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

- Planck time $t_{Pl} = \sqrt{\hbar G/c^5}$.
- The electromagnetic and weak forces unify at 100 GeV; [31] $t = h/10^{11}$ s.
- Sun’s rotational period; [32] $t = 2.32 \times 10^5$ s.
- Time scale of the universe derived from the $D_A$ SSS model [16].

$D_A^3/(D_A^2 - D_A)$ are the ratios of the length scales of the hierarchies [16]) can be used to obtain a simple relation between $r_a$ and $r_b$:

\[
(a\beta)^{r_a} = a\beta^{r_b}. \tag{11}
\]

Equation (11) can be interpreted as the basic formula for the similarity dimension and indicates the correlation between the cosmic structure and fundamental dimensionless mass ratios. Using Eq. (11), we obtain:

\[
D_B = \frac{2r_a - r_b - 1}{1 - r_b}. \tag{12}
\]

However, the numerical relation between $D_B$ and $r_a$ is:

\[
\frac{r_a D_B}{\sqrt{2}} \approx 1.000009. \tag{13}
\]

Equation (13) indicates the validity of $D_B$; if the $D_B$ value is substituted into Eq. (8), $L_{m=2}$ is consistent with the Planck length.

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1 Using Eq. (11), we can derive another similarity dimension, $D_C = -B/(A + B) \approx 0.20592$. 
Figure 1. Time scale as a function of length scale for the SSS model and reference values. The reference values for the DA SSS model are taken from Ref. [16]. The lower and upper bounds of the universe are interpolated in the DB SSS model. Note the symmetry of the first term $L_0$, which corresponds to the CMB temperature. This symmetry indicates that each hierarchy is self-similar to the CMB temperature.

Regarding $\Lambda$, Eq. (1) can be written in an equivalent dimensionless form using $G = \hbar c / m_{\text{Pl}}^2$:

$$l_{\text{Pl}}^2 \Lambda = \alpha_f^{-6} \left( \frac{m_e}{m_{\text{Pl}}} \right)^6.$$  \hspace{1cm} (14)

We employed the following formulas derived from the DA SSS model [16] in Eq. (14):

$$\alpha_G \simeq \tau_{\text{CMB}}^{D_A},$$

$$\beta^2 \simeq \tau_{\text{CMB}}^{D_A-1},$$  \hspace{1cm} (15)

where $\tau_{\text{CMB}} = T_{\text{CMB}} / T_{\text{Pl}}$; $T_{\text{CMB}}$ is the CMB temperature and $T_{\text{Pl}}$ is the Planck temperature. Then, we obtain:

$$\lambda(\xi) \simeq \xi^3$$  \hspace{1cm} (17)

where $\lambda$ is the cosmological constant in reduced Planck units, $\lambda = l_{\text{Pl}}^2 \Lambda$, and we defined $\xi = \alpha_f^{-2} \tau_{\text{CMB}}^{D_A}$. Equation (17) is based on the LNH and indicates that the CMB temperature can be considered as a cosmological scalar field.

If we employ $T_{\text{CMB}} = 2.725$K as the current parameters in Eq. (17), we obtain $\lambda T_{\text{CMB}} = 2.725K \approx 3.07 \times 10^{-122}$, consistent with the latest observational data [33].

If we employ $T_{\text{CMB}} = T_{\text{Pl}}$ for the universe initial condition and substitute it into Eqs. (15), (16) and (17), we obtain $\alpha = \beta = 1$ and $\lambda T_{\text{CMB}} = T_{\text{Pl}} = \alpha_f^{-6}$, which implies that the entire hierarchy was contained in a single point and that a large $\lambda$ can trigger the cosmic inflation. The value of $\lambda$ decreases with the
Assuming that $T_{\text{CMB}} \rightarrow 0$ is the ultimate fate of the universe, $L \rightarrow \infty$ and $\lambda \rightarrow 0$. This indicates that the universe falls into an inactive state as it expands to infinity.

5. Conclusions

We showed that the similarity dimension $D_B$ based on the SSS model is valid to describe the hierarchy structure of the universe. Using $D_B$, $\lambda$ is expressed as a function of the CMB temperature. The cosmological scenario of the dynamically decaying $\lambda$ gives natural interpretation for the sufficiently small $\lambda$ at the present epoch without fine-tuning. We need to apply the result to the Einstein field equation to analyze more details in the future.

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