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TIME, IRREVERSIBILITY AND COSMOLOGICAL THROTTLING

UMBERTO LUCIA *

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ABSTRACT. In 2011 Perlmutter, Schmidt, and Reiss discovered that the expansion of the Universe is accelerating. This finding is contrary to the expectation that gravity should slow this expansion. This discovery raises fundamental questions about dark energy, which constitutes about three-fourths of the Universe's mass-energy and is responsible for driving this acceleration. In this paper, we propose a thermodynamic perspective based on a possible cosmological Joule-Thomson effect, supported by the significant entropy content of the Universe, primarily from black-body radiation. The evolution of entropy in an open system involves exchanges with the environment and is characterised by two components: entropy flow and internal entropy production. Understanding irreversible processes is essential to grasping these dynamics, as they link order and disorder. This approach shifts our understanding of thermodynamics, revealing that the creation of order is associated with non-equilibrium conditions, while disorder often corresponds to stable equilibrium. This perspective calls for a revaluation of how systems in Nature are analysed, emphasising the intricate relationship between order, disorder and the definition of time.

1. Introduction

In 2011 Saul Perlmutter, Brian Schmidt and Adam Reiss were awarded the Nobel Prize in Physics for their discovery of the accelerating expansion of the Universe (Riess *et al.* 1998; Perlmutter *et al.* 1999; Schmidt 2012). Their finding is that the Universe is not only expanding but also accelerating. The surprising consequence is that the Universe would end not with a bang, but a whimper. Indeed, physicists and astronomers expected that gravity should slow the expansion. In cosmology, it is known that, around 13.7 billion years ago, the Universe was being flung apart due to the Big Bang (Weinberg 1972). But these findings have pointed out a Universe that was unknown to science. Today the fundamental question concerns how it happens and why the force of dark energy, which accounts for about three-fourths of the mass-energy of the entire Universe (Brout, Englert, and Gunzig 1978; Brout *et al.* 1980), doesn't decelerate the expansion. Here we propose a thermodynamic approach to this topic based on the 'cosmological Joule–Thomson effect' or 'cosmological throttling process', related to a thermodynamic definition of time (Lucia and Grisolia 2019a, 2020).

The thermodynamic approach is justified because the Universe exhibits a significant entropy content, predominantly in the form of black-body radiation (Prigogine *et al.* 1988). The evolution of entropy in an open system can be understood as a dynamic interplay involving exchanges with the surrounding environment and the internal mechanisms of the system itself. This exchange is characterised by entropy flow, d_eS, which can take on positive, negative, or null values; it represents the entropy related to heat and mass inflow and outflow of the system. On the other hand, internal entropy production, d_iS arises from irreversible processes that occur within the system and is positive or at least zero. It's crucial to highlight the significance of these irreversible processes. They are the fundamental building blocks of all physical, chemical and biological processes in Nature, emphasising the transformative nature of these processes. Moreover, it is important to recognise that the concept of irreversibility extends beyond the mere destruction of organised structures, being intricately linked to the notion of disorder. Entropy production points out a complex relationship between order and disorder within a system. This brings us to a pivotal evolution in our understanding of thermodynamic principles: the traditional view has been altered to reveal that the creation of order is inherently linked to non-equilibrium conditions, whereas disorder can often be associated with stable equilibrium states. This shift in perspective requires reconsideration of how we interpret the behaviour of systems in nature, highlighting the complexity and interdependence of order and disorder in natural processes (Prigogine 1983).

In this context, we highlight the strict relation between the systems' evolution and the definition of time, which remains one of the unresolved problems in physics (Prigogine and Petrosky 1987; Petrosky and Prigogine 1988; Prigogine and Petrosky 1988). In Galileo's approach to motion, time is viewed as an absolute and fundamental quantity (Galilei 1998). Isaac Newton, on the other hand, considers time merely a mathematical construct without any real or physical essence; in his framework, simultaneity and the durations of phenomena are absolute (Newton 1726; Borghi 2016). Albert Einstein derived the concept of time from the postulate that the speed of light is invariant (Einstein 1920). This leads to the conclusion that duration is a quantity dependent on the observer, making it a local quantity (Weinberg 1972). Einstein also introduced the idea of an isoentropic Universe (Madsen 1995), but understanding entropy within the Universe's context is crucial for comprehending its evolution (Prigogine 1989). As the universe expands, the distributions of energy and matter undergo transformations that affect entropy (Prigogine *et al.* 1988; Kox, Klein, and Schulmann 1996). Across these various approaches, time has been defined operationally based on the concept of duration. However, a precise analytical definition of time was not provided until 2009, when an analytical mechanics approach, based on the mechanical Lagrangian, was suggested (Barbour 1982). However, this earlier approach did not take into account the aspect of irreversibility (Lucia and Grisolia 2024).

Therefore, while the initial considerations may be related to the findings of Prigogine, this study proposes an alternative approach grounded in our prior research regarding non-equilibrium thermodynamics, particularly focusing on the analysis of irreversibility and fluxes. Indeed, recently, we proposed an analytical definition of time that arises from the Second Law of Thermodynamics (Lucia and Grisolia 2019a,b, 2020; Lucia, Grisolia, and Kuzemsky 2020; Lucia and Grisolia 2022). In this framework, time is viewed as a manifestation of irreversibility associated with all possible electromagnetic interactions, in agreement with Einstein's conjecture (Einstein 1920; Borghi 2016). We have evaluated the atomic footprint of irreversibility by considering atoms as open finite-size systems (Lucia 2015, 2016, 2018, 2023) and taking into account Condon's experimental results (Condon 1928). Consequently, our findings agree with fundamental principles from physics (Bellemans and Orban 1966; Mareschal and Kestemont 1987): time is a local quantity, measurable in any laboratory, and is intricately related to the evolution of the universe, consistent with the General Theory of Relativity. Thus, we consider that irreversibility in the Universe arises from the continue interaction between electromagnetic waves and matter.

This manuscript proposes an engineering thermodynamic approach to the expansion of the Universe, caused by the increase in local pressure generated by entropy production related to the time arrow.

2. Material and methods

In this section, we consider the second law of thermodynamics. Thus, we can define a state function, S, i.e., the entropy of a macroscopic system, whose change during a physical process can be expressed as the sum of two components (de Groot and Mazur 1984):

$$dS = d_eS + d_iS \tag{1}$$

where, d_eS represents the entropy added to the system from its surroundings, while d_iS refers to the entropy produced within the system itself. The second law of thermodynamics states that dS must be zero for reversible transformations or at stationary state and must be positive for irreversible transformations of the system (de Groot and Mazur 1984), i.e.,

$$d_iS = dt \int_V \sigma \, dV \geq 0 \tag{2}$$

where t is the time, V is the system's volume, σ is the entropy production, i.e., entropy rate per unit volume due to irreversibility. The entropy supplied, d_eS, can be positive, zero, or negative, depending on the interactions between the system and its surroundings (de Groot and Mazur 1984):

$$d_eS = \frac{\delta Q}{T} = -dt \int_A \mathbf{J}_s \cdot \hat{\mathbf{n}} \, dA \tag{3}$$

where Q is the heat exchanged between the system and its environment, T is the temperature, $\mathbf{J}_s$ the total entropy flow per unit area and unit time, A is the area of the system's boundary (de Groot and Mazur 1984), and $\hat{\mathbf{n}}$ is the surface versor. In the case of an adiabatically insulated system, this last quantity is null (de Groot and Mazur 1984). Assuming that the Universe is adiabatic (Tolman 1950) the entropy supplied d_eS result null, so for our approach the Universe entropy variation results in:

$$dS = d_eS + d_iS = d_iS \geq 0 \tag{4}$$

that per unit volume becomes:

$$s = s_i \tag{5}$$

where $s = S/V$ is the entropy density, i.e., the entropy per unit volume, and s_i the entropy density due to irreversibility with $ds_i = d_is = \sigma \, dt$ its variation due to irreversibility. This relation highlights that the Universe's entropy variation is caused by irreversibility.

Now we consider the first law of thermodynamics (Prigogine *et al.* 1988; Bejan 2006):

$$dH = \delta Q + V\,dp \tag{6}$$

where H is the enthalpy and p is the pressure. Per unit volume, considering that in this analysis the heat exchange is null, it follows:

$$dh = dp \tag{7}$$

where $h = H/V$ is the enthalpy density, i.e., the enthalpy per unit volume. But, remembering the definition of enthalpy density (Kondepudi and Prigogine 2015):

$$h = u + p \tag{8}$$

it follows:

$$\begin{cases} dh = dp \\ dh = du + dp \end{cases} \Rightarrow du = 0 \tag{9}$$

Here we consider the Gibb's fundamental equation (Bejan 2006; Kondepudi and Prigogine 2015) in the absence of chemical reactions:

$$dU = T\,dS - p\,dV \tag{10}$$

that per unit volume becomes:

$$u = T\,s_i - p \tag{11}$$

thus it follows:

$$\begin{cases} du = T\,d_i s - dp \\ du = 0 \\ d_i s \geq 0 \end{cases} \Rightarrow dp = T\,d_i s \geq 0 \tag{12}$$

which means that the increase in entropy implies an increase of pressure.

Now, we consider the concept of time. To do so, some considerations are proposed. At the atomic level, photons can be absorbed by the electrons of atoms or molecules, leading to electronic energy transitions between two stationary states of the atom. When the excited electrons return to their original, lower-energy state, they emit photons. This process appears to follow a reversible energetic path, as the electrons revert to their original stationary state (Condon 1926; Franck and Dymond 1926; Born and Oppenheimer 1927; Slater 1951; Alonso and Finn 1968). In examining a single atom or molecule, the energy perturbation of the center of mass is approximately 10^{-13} J, while the energy associated with electron transitions between atomic or molecular levels is typically around 10^{-8} J, with excited states having a lifetime (Alonso and Finn 1968) on the order of 10^{-15} s. Consequently, it is usual to neglect the effect of the atomic nucleus in these calculations. However, it is important to consider that this is an approximation (Condon 1926; Franck and Dymond 1926; Born and Oppenheimer 1927; Slater 1951; Alonso and Finn 1968), and it cannot be overlooked when analysing irreversibility. Such analysis requires a focus on the role of the nucleus during the photon-electron interaction (Lucia 2015, 2016, 2018; Lucia, Grisolia, and Kuzemsky 2020), as indicated by recent experimental results (Kukk *et al.* 2005). As a result of the interaction between the atomic or molecular electrons and photons, a measurable effect, or footprint, occurs in the atom or molecule (Lucia 2016). The interaction between a photon and an atomic electron influences both the energy levels of the electron and the center of mass of the atom (Lucia 2016; Lucia and Grisolia 2019a, 2020), in agreement with theoretical and experimental results summarized by Condon (1928), Slater (1951), and Doyle (1968, 2014, 2016). Thus, macroscopic irreversibility arises from microscopic irreversibility, which is attributed to the photon-electron interaction, i.e., the interaction between environmental electromagnetic waves and matter. Following the insights gained from thermodynamic analyses of electromagnetic fields (Beretta and Gyftopoulos 2015), this interaction can be expressed in terms of entropy production and the entropy production rate, and also of their densities. Notably, the ratio between entropy production and entropy production rate can represent a time. Drawing an analogy with analytical mechanics, where position and velocity serve as independent variables for state space (Landau and Lifshitz 1976), we introduce entropy production per unit volume s_i and entropy production rate density σ as independent variables within the state space $\Omega = \{(s_i, \sigma)\}$. We have used this space to study the behaviour of the photon-atomic electron interaction. So, following the dimensional analysis in thermodynamics (Langhaar 1951), we have proposed the definition of time, τ, as follows (Lucia and Grisolia 2019a; Lucia, Grisolia, and Kuzemsky 2020):

$$\tau = \frac{s_i}{\sigma} \tag{13}$$

Then, the entropy production rate density was written in relation to the electromagnetic waves in the Universe, by considering the Gouy-Stodola theorem (Bejan 2006), as follows (Beretta and Gyftopoulos 2015):

$$T\sigma = \frac{A}{2V}\varepsilon_0 c E_{el}^2 + \frac{A}{2\mu_0 V} c B_m^2 \tag{14}$$

where E_{el} is the mean value of the electric field, B_m is the mean value of the magnetic field, $c = 299,792,458$ m s^{-1} is the speed of light, $\varepsilon_0 = 8.8541878128(13) \times 10^{-12}$ F m^{-1} is the electric permittivity in vacuum and $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1} is the magnetic permeability in vacuum. Using the definition of time into the previous Eq. (12) it follows:

$$dp = T\, d_i s = T\,\sigma\, d\tau \geq 0 \tag{15}$$

which links the pressure increase to time and irreversibility.

3. Results

In this study, we have obtained various interrelated results.

The first finding is that the variation in the entropy density of the Universe is driven by irreversibility, which we assess through entropy production, i.e., the entropy variation is the consequence of irreversibility. We propose that this irreversibility arises from electromagnetic interactions with matter, as discussed in our previous papers (Lucia and Grisolia 2019a, 2020; Lucia, Grisolia, and Kuzemsky 2020; Lucia and Grisolia 2022; Lucia 2023) on the concept of time. The fundamental conjectures introduced can be summarised as follows:

- Time may be considered as a discrete quantity (Lucia and Grisolia 2019a), as pointed out also by Riek (2017);
- Time is in a way the result of the irreversibility in the Universe, thus reversible clocks cannot be realised (Lucia and Grisolia 2020);

- While entropy can locally decrease, the overall entropy production (i.e., entropy variation due to irreversibility) must always be positive. Consequently, time can only progress in one direction, aligning with the concept of the arrow of time;
- Our findings are completely consistent with those of Briggs; in fact, only macroscopic classical clocks can be created (Briggs 2015);
- Time may be regarded as a manifestation of cyclic processes with ν frequency of the electromagnetic radiation from a black body or, in an equivalent way, of the interaction of the electromagnetic wave and the ‘normal matter’ (Kuzemsky 2020);
- We have considered a constant value of the entropy production rate related to the mean value of the electromagnetic wave power in the Universe, following the usual engineering thermodynamic approach to thermodynamic systems;
- The Second Law of Thermodynamics cannot be fully considered only from a mechanical perspective, because some irreversible phenomena may influence or manifest in interaction processes (Lucia, Grisolia, and Kuzemsky 2020).

Consequently, we can highlight that the flow of time leads to variations in pressure (Eq. (15)). Indeed, in Eq. (15), pressure and time variation are directly proportional and present the same sign. Consequently, An increase in time results in an increase in pressure, which we suggest is a consequence of irreversibility. This rise in pressure can be related to the discoveries of Perlmutter, Schmidt, and Riess when considering the Joule-Thomson effect. This effect, also known as a throttling process, refers to the cooling of fluid during expansion (Bejan 2006). In our case, the Universe expands into nothingness. The throttling caused by flow resistance in thermal systems results in energy losses (Borgnakke and Sonntag 2009; Balmer 2011); thus, it is fundamentally an irreversible process.

Following Prigogine *et al.* (1988) and Kox, Klein, and Schulmann (1996), we can consider the Universe as an ideal fluid under an adiabatic expansion without any shaft work. Thus, its expansion can occur only if there is a pressure drop in the direction of its expansion (Weinberg 1972; Bejan 2006; Borgnakke and Sonntag 2009; Balmer 2011). During the expansion the specific enthalpy h of the universe remains constant (Weinberg 1972), as it occurs also in the Joule–Thomson process (Borgnakke and Sonntag 2009; Balmer 2011). Considering two different positions A and B on the radius $a(t)$ of the expansion of the universe, corresponding to two different time of expansion t_A and t_B. The thermodynamic control volume considered is the volume of the universe between these two positions. During the expansion a mass volume flows between these two positions. By considering the work-energy theorem for the fluid under the process considered, it follows that (Bejan 2006; Borgnakke and Sonntag 2009; Balmer 2011):

$$p_\mathrm{A}\rho_\mathrm{A}^{-1} - p_\mathrm{B}\rho_\mathrm{B}^{-1} = \frac{1}{2}\left(v_\mathrm{B}^2 - v_\mathrm{A}^2\right) \tag{16}$$

where ρ is the local density and p is the local pressure of the fluid, v is the local velocity at the positions considered. The expansion is possible only if $p_\mathrm{A}\rho_\mathrm{A}^{-1} - p_\mathrm{B}\rho_\mathrm{B}^{-1} > 0$; consequently, Eq. (16) holds:

$$v_\mathrm{B}^2 > v_\mathrm{A}^2 \tag{17}$$

which proves that during its expansion the universe increases its velocity, because the expansion is a process similar to the throttling transformation for an ideal fluid.

The temperature change during a Joule–Thomson expansion can be quantified by the Joule-Thomson coefficient μ_{JT}, which may be either positive or negative. The positive values of this coefficient correspond to cooling, while the negative ones correspond to heating. The sign of the coefficient may change due to different conditions during the expansion, in relation to pressure, temperature and velocity of fluid (Bejan 2006):

$$\mu_{JT} = \frac{1}{c_p}\left[T\left(\frac{\partial\rho^{-1}}{\partial T}\right)_p - \rho^{-1}\right] \tag{18}$$

where c is the specific heat of the fluid, and the subscript p means at constant pressure. The fluid can change its behaviour as a consequence of the change in the sign of the Joule-Thomson coefficient; it happens if the coefficient becomes null in a certain time, a condition which holds the following differential equation:

$$\frac{d\rho^{-1}}{\rho^{-1}} = \frac{dT}{T} \tag{19}$$

The solution of this equation, considering the isoenthalpic condition for the real fluid throttling effect holds:

$$\rho_{\mathrm{B}} = \frac{\rho_{\mathrm{A}} T_{\mathrm{A}}}{T_{\mathrm{B}}} \tag{20}$$

where ρ and T are respectively the local density and local temperature of the Universe at the two position A and B. This last equation, considering the throttling effect and the Bernoulli equation, becomes:

$$\rho_{\mathrm{B}} = \frac{2c_v\rho_{\mathrm{A}}T_{\mathrm{A}}}{\left(v_{\mathrm{B}}^2 - v_{\mathrm{A}}^2\right) + 2c_vT_{\mathrm{A}}} \tag{21}$$

where v is the local expansion velocity, c is the specific heat of the fluid, and the subscript v means at constant volume. But, if we consider the position A as the point at which the expansion started, and B the position corresponding to the possible critical condition, then ρ_{B} will be the critical density, which is well known to be (Einstein 1917; Lemaître 1927; Weinberg 1972):

$$\rho_c = \frac{3H^2}{8\pi G} \tag{22}$$

where G is Newton's constant, and H is the present expansion rate of the universe, named the Hubble parameter, or the Hubble constant. Consequently, from these two last equations, considering that $-1 \leq \left(v_{\mathrm{B}}^2 - v_{\mathrm{A}}^2\right)/2c_vT_{\mathrm{A}} \leq 1$ it follows that the universe could change its behaviour if the initial density was:

$$1 \leq \frac{\rho_{\mathrm{A}}}{\rho_c} \leq 2 \tag{23}$$

Now, we introduce the hypothesis that the expansion began when the universe was composed by only photons, with density ρ_γ it follows that the condition for the universe to change its behaviour, i.e., decreasing its velocity is:

$$\rho_c \leq \rho_\gamma \leq 2\rho_c \tag{24}$$

in accordance with the conditions for slow-roll parameters and the measures deviations from the perfect de Sitter limit (Kolb and Turner 1994; Dodelson 2003; Peter and Uzan 2013).

Our result introduces a classical thermodynamic approach, based on the throttling effect, to explain the results obtained by Perlmutter, Schmidt, and Reiss (Wright 2011). Moreover, it allows us to obtain some conditions useful to evaluate the evolution of the universe, by studying the initial condition of the universe, its Joule-Thomson coefficient, and its density variation during the expansion. Moreover,

$$p_{\mathrm{A}}\rho_{\mathrm{A}}^{-1} - p_{\mathrm{B}}\rho_{\mathrm{B}}^{-1} > 0 \Rightarrow d(p\rho^{-1}) = v\,dv > 0 \tag{25}$$

considering that expansion implies

$$d(p\rho^{-1}) = p\,d\rho^{-1} + \rho^{-1}dp = p\,d\rho^{-1} + \rho^{-1}T\,\sigma\,d\tau > 0 \Rightarrow d\tau > \frac{p\,d\rho}{T\,\sigma\,\rho} = \frac{p}{T\,\sigma}\,d\ln(\rho) \tag{26}$$

we can argue that Universe could end its expansion if the time flow becomes null and could also decreases if:

$$d\tau < \frac{p}{T\,\sigma}\,d\ln(\rho) \tag{27}$$

This last relation opens to two considerations:

- Which is the relation between time variation, and more general space-time curvature, and expansion;
- Which is the behaviour of the mass density of the Universe over time but also the conversion of energy to mass.

These two considerations are outside this papers' aim, but emerge from the thermodynamic approach proposed.

4. Discussion and conclusions

This study develops a well known topic, the thermodynamics of cosmology, but the results obtained are based on non-equilibrium thermodynamics and not on hydrodynamics. Non-equilibrium thermodynamics approach, as shown by Eq. (15), suggests that the variations in pressure and time are directly proportional and share the same sign. Consequently, an increase in time results in a corresponding increase in pressure. Furthermore, the increase in time is inherently linked to irreversibility within the continuous electromagnetic interactions that occur in the Universe (Eqs. (13) and (14)). Thus, the primary conclusion emphasises that the expansion of the Universe is fundamentally driven by the concept of irreversibility.

Our findings prompt a discussion about the mass density distribution in our Universe: is it homogeneous or inhomogeneous? In this paper, we propose that inhomogeneity, meaning varying mass density in different regions of the Universe, or a transition from homogeneity to inhomogeneity, could be a factor in halting both the acceleration and the expansion of the Universe.

In terms of matter, all modern cosmologies are founded on the cosmological principle, which states that whichever direction we look from Earth, the universe is basically the same: homogeneous and isotropic (Einstein 1939). This principle grew out of Copernicus's result that there were no special observers in the universe and nothing special about the

Earth's location in the Universe. Since the formulation of General Relativity in 1915, this homogeneity and isotropy have greatly simplified the process of devising cosmological models (Einstein 1939).

To study mass distribution the mollweide map of the cosmic microwave background (CMB), created from nine years of data collected by the Wilkinson Microwave Anisotropy Probe (WMAP), plays a fundamental role, obtaining the following data: in the Lambda-CDM model of the Universe, its age results in 13.772 ± 0.056 billion years with more than 1% precision. The current expansion rate of the universe results in 69.32 ± 0.80 km s^{-1} Mpc^{-1}. The matter content of the universe currently consists of $(4.628 \pm 0.093)\%$ ordinary baryonic matter, $(24.02 + 0.88/-0.87)\%$ cold dark matter that neither emits nor absorbs light, and $(71.35 + 0.95/-0.96)\%$ of dark energy in the form of a cosmological constant that accelerates the expansion of the universe, less than 1% is in neutrinos. Moreover, the map reveals tiny residual variations that display a specific pattern, consistent with the presence of hot gas that is mostly uniformly distributed. Initially, the Universe began with matter arranged in a homogeneous distribution. Over billions of years, however, massive structures have emerged, including hundreds of billions of stars within galaxies, clusters of galaxies, superclusters, and vast filaments of matter. According to general relativity, these denser regions and the voids between them affect the curvature of space-time because matter influences how space-time bends. The additional mass of galaxies and galaxy clusters should create a more positive curvature in the nearby space-time, while the voids should have the opposite effect, imparting negative curvature around them. The critical question is whether these effects, known as backreactions, are negligible or significant enough to alter the geometry of the Universe.

Our results do not directly answer fundamental questions about homogeneity and inhomogeneity. However, they provide a thermodynamic perspective on the expansion of the Universe. This perspective highlights the potential effects of the transition from homogeneity to inhomogeneity, as a result of shifting from order to disorder and *vice versa*, as introduced in non-equilibrium thermodynamics.

Lastly, the findings presented here are consistent with various theoretical frameworks that point out the role of viscous phenomena (Pavon, Bafaluy, and Jou 1991; Zimdahl 1996; Li and Barrow 2009; Casado 2020; Kolekar, Shankaranarayanan, and Chitre 2020). In this context, the interactions between electromagnetic waves and "normal matter" may contribute to an effective mass viscosity within the cosmological model. Specifically, these models express pressure into two components: a thermodynamic pressure associated with energy density and an irreversible dynamic contribution related to the interplay of energy density and the rate of expansion. Should the expansion rate reach sufficiently high levels, the resultant negative contribution to pressure could induce an acceleration of expansion independently of dark energy considerations. Consequently, such acceleration and expansion would primarily stem from irreversibility. In this context, we have not addressed the role of dark matter, due to the need to develop a macroscopic model utilising a non-equilibrium engineering thermodynamic approach. Future research may consider the assertion made in the bullets regarding time in the Results section, which states, "Time may be considered as a discrete variable." This assertion highlights the connection between dark matter and Planck lengths, a topic not encompassed in the current analysis but recognised as an open question for prospective advancements in a non-equilibrium thermodynamic model of the Universe's expansion.

Conflicts of Interest

The author declares that he has no conflict of interest.

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* Politecnico di Torino,
Dipartimento Energia "Galileo Ferraris",
Corso Duca degli Abruzzi 24, 10129 Turin, Italy

and

Istituto Nazionale di Fisica Nucleare, Sezione di Torino,
Turin, Italy

Email: umberto.lucia@polito.it

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