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On the appropriateness of applying the First and Second Law of Thermodynamics to the universe as a whole

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Abstract. The 1st and the 2nd laws of thermodynamics are among the principles with the most serious approaches in science, especially due to the overwhelming implications they have, both in the elaboration and development of theoretical concepts in the most diverse fields, as well as in the technical applications that have revolutionized industrial production. One of the questions related to these laws is whether or not they can be applied to the scale of the entire universe. The implications resulting from this approach are very diverse as they underpin concepts such as the continuous accelerated expansion of the universe, the thermal death of the universe, the entropy of the universe and the evolution of the universe as a cyclical process, energy as a property of the space-time relationship, dark energy and matter, black holes, white holes etc. This paper is an attempt to provide some answers to the challenge of discussing the applicability or inapplicability of the First and Second Laws of Thermodynamics on the scale of the entire universe, with arguments for and against, generated by well-defined or only incipient theoretical developments that treat cosmogony and cosmology through the prism of thermodynamics.

Keywords: 1st and 2nd laws of thermodynamics, universe, applicability of thermodynamic concepts.

1. Introduction

We always expect scientific theories and principles developed on theoretical or empirical bases to be valid on the widest possible scale. Isaac Newton was

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convinced that the laws of gravity he developed in the 17th century apply to the scale of the entire universe, as time and space were considered absolute [1]. For more than two centuries, physicists believed that Newton's laws were immutable and universally valid, because they were supported by the intuition of the human brain - which often deceives us - but then came Einstein, at the beginning of the 20th century, who, based on the theory of general relativity, demonstrated that they represent only a particular case and cannot be applied in gravitational fields much more intense than those in our planetary system [2].

A scientific theory is not accepted by the academic community unless it is validated by observations or experimental results. In this sense, the most conclusive case is that of the atomic theory, developed by Dalton in 1807 [3], certainly inspired by predecessors, starting with Leucippus and Democritus from Abdera [4], which was accepted by chemists at that time because it allowed stoichiometric calculations to be made on the basis of relative atomic masses. Physicists, with the exception of those dealing with crystallography, for whom the atomic theory allowed them to explain some structural data, did not believe in the atomic theory until after the publication of the results of the experiments of Ernst Rutherford (1911) at the University of Manchester [5].

Among the principles with the most serious approaches in science are the I and II laws of thermodynamics, especially due to the technical applications that have revolutionized industrial production. They were developed in the 19th century, following the study of heat engines in which the transformation of heat into mechanical work was investigated. It should be noted that the laws were developed without taking into account the atomic structure of substances, therefore they apply to macroscopic systems, and the phenomena studied were approached under conditions in which the influence of gravitational and electromagnetic fields is insignificant [6]. But the most important thing is that they are based on experimental results verified even at the industrial level [7].

2. The First Law of Thermodynamics

It is well known that the first principle of thermodynamics was formulated starting from the demonstration of the equivalence between mechanical work and heat. For an isolated system, which does not exchange substance or energy with the outside, the total energy is not lost, nor created, it is only transformed from one form to another, regardless of the physical or chemical processes that take place. In other words, in a closed system, the total energy is conserved [8].

There are other conservation laws relating to mass, momentum, angular momentum, electric charge and others [7]. For example, the law of mass conservation was developed as early as the 17th century and formulated by Antoine de Lavoisier in the 18th century in the famous form: “In nature, nothing is lost, nothing is created, everything is transformed” (1789) [9]. Similarly, M. V. Lomonosov, in a letter to Euler (1784) stated: “All changes that occur in nature are states in which whatever is taken from one body is added to another” [10]. Such conservation laws were perceived since Antiquity, without being based on certain experimental facts. Based on Democritus’ atomism, Epicurus launched the idea that “Nothing comes into being from nothing” [11].

Moreover, over two centuries later, Lucretius wrote in his De Rerum Natura [12]:

> „But since, as proved, nothing from nothing comes,
> And naught to naught returns, primordials, strong
> In their simplicity, eternal are,
> And at their final hour things but dissolve,
> Materials to afford for recreating things;
> Not else could Nature through all time endure.”

Even in the 17th century, mass and energy were treated as two distinct entities, without a clear one-to-one correspondence relationship. For René Descartes, the essence of things was the substance, while for Gottfied Wilhelm Leibniz, what was paramountly important for things was the energy [13]. As in the case of Newton's theories, the laws of conservation of energy and mass are valid under non-relativistic conditions. In order for these laws to be applied on an astronomical scale, one must take into account Einstein's special theory of relativity, which established the equivalence between mass and energy, according to the famous relationship given by equation (1) [14]:

$$E = mc^2 \tag{1}$$

where E is the energy in J, m – mass, kg, c – speed of light, m s^{-1}.

Therefore, Einstein refers to the conservation of the mass-energy ensemble in the four-dimensional space-time system, in which mutual transformations between mass and energy take place. There are numerous examples in this sense. Among the cases in which Einstein's relationship is verified is the particle-antiparticle interaction. Richard Feynmann [15] treated the case of the interaction between an electron (e^-) and a positron (e^+) through a diagram that bears his name (figure 1). As a result of the interaction of e^-/e^+, particles that possess mass, two photons γ, are formed, which possess energy but have no mass.

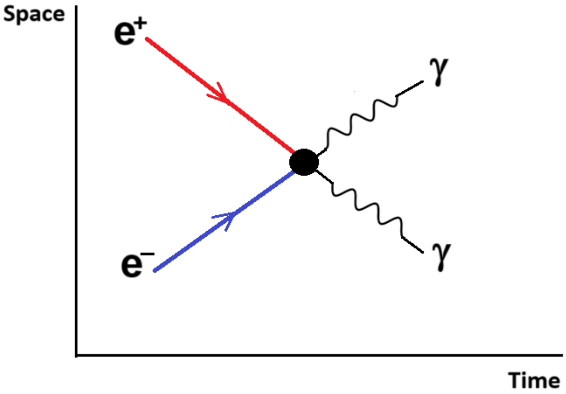

Fig. 1. Feynmann diagram for electron-positron interaction [16].

In this transformation, the entire mass of the electron and positron is converted into energy. This transformation is a fundamental phenomenon of quantum physics, known as annihilation and is used to illustrate and to better understand the conservation of energy, the mass of the initial particles being completely converted into electromagnetic energy.

Returning to equation (1), we ask ourselves the question, why in chemical reactions, in which the thermal effect is appreciable, does Einstein's theory not apply? Let's take as an example, the combustion reaction of acetone, given by chemical equation (2):

$$CH_3COCH_3(l) + 4O_2 \rightarrow 3CO_2(g) + 3H_2O(l). \qquad (2)$$

The thermal effect of the reaction of this exothermic reaction, which we assimilate with the standard enthalpy of reaction, is -1789.79 kJ mol^{-1} [17]. Therefore, the energy released in reaction (2) is 1789.79 kJ mol^{-1}. In technical calculations, we consider that the mass of the reactants is equal to the mass of the reaction products, according to the law of conservation of mass, but contrary to the special theory of relativity. But, according to Einstein's equation (1), the release of energy following the development of reaction (1), will lead to a decrease in the mass of the reaction products.

We can calculate the mass m transformed into energy due to the combustion of acetone, according to reaction (2), using relation (1), from which the mass m transformed into energy is calculated.

$$m = \frac{E}{c^2} \qquad (3)$$

where: E is the energy associated with the chemical reaction (2), in J, c – speed of light, m s^{-1}.

It is obtained:

$$m = \frac{1789.79 \times 1000}{299\,792\,458^2} = 1.99140994 \times 10^{-11} \text{ kg}.$$

Therefore, the generation of energy obtained by burning 1 mol of acetone (58 g) with 4 mol of oxygen (128 g) leads to a decrease in the mass of the reaction products by approximately $2 \cdot 10^{-11}$ kg or $2 \cdot 10^{-8}$ g, i.e. an insignificant amount compared to the mass of the reactants, which is why stoichiometric calculations can still be made without taking into account relativity.

In general, chemical energy is stored in the chemical bonds that are established between the atoms of substances, their values being much smaller than those between the component particles of atomic nuclei. In the case of nuclear reactions, it has been demonstrated that, for example, in nuclear fission reactions, this energy increases significantly, a mass defect appears associated with the release of these enormous amounts of energy, demonstrated in practice in nuclear reactors for producing electricity and in the case of nuclear explosions.

The mass defect is the difference between the total mass of the individual nucleons (protons and neutrons) that make up an atomic nucleus and the mass of the nucleus itself, according to relation (4). This difference arises because some of the mass is converted into nuclear binding energy, which holds the nucleons together in the nucleus.

Mathematically, it can be expressed as follows:

$$\Delta m = Z \times m_p + N \times m_n - M_n \qquad (4)$$

where: Δm is the mass defect, Z - the number of protons, N - the number of neutrons, m_p - is the proton mass, m - is the neutron mass, M_n - the mass of the nucleus.

The nuclear binding energy associated with the mass defect is given by Einstein's equation (1). The total mass of the resulting nuclei and the emitted neutrons is less than the mass of the original nucleus and the absorbed neutron, the difference in mass being converted into energy in the form of radiation and the kinetic energy of the fission products.

This energy is responsible for the stability of the nucleus and for the release of enormous amounts of energy in nuclear reactions. In a nuclear fission reaction, a heavy nucleus (such as uranium-235 or plutonium-239) absorbs a neutron and splits into two smaller nuclei (fission products), releasing several neutrons and a significant amount of energy.

Let us consider the concrete example of the fission of the uranium-235 isotope. When a nucleus of the uranium isotope (235) absorbs a neutron, it can fission into products such as barium (141) and krypton (92), according to relationship (5):

$$^{235}_{92}U + n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3n + energy. \qquad (5)$$

For this reaction, the calculated mass defect is about 0.2 atomic mass units, the energy released is about 200 MeV per fission reaction or $3.2 \cdot 10^{-11}$ J, leading to a total of 82 TJ/kg fissile uranium. Calculations for the Pu-239 isotope lead to an even higher value of 210 MeV/reaction [18].

Similarly, in hydrogen fusion reactions – reactions in stars or in the H-bomb, the mass defect is also present here. However, in these cases, unlike the fission reaction that can occur naturally, upon reaching a critical mass or induced by neutron beams, a high energy initiation is needed. The nuclei participating in the fusion are electrically charged, with strong repulsive forces between them, so that for the nuclear fusion reaction to take place, an energy input is necessary to provide the two nuclei with sufficient kinetic energy to overcome the electric potential (electric repulsion forces) and therefore to come close enough, up to a distance of the order of 10^{-15} m, for the nuclear forces (which have a limited range) to rearrange the nucleons. This condition requires extremely high temperatures (the reaction occurs in plasma, naturally in stars, by accelerating nuclei in powerful particle accelerators, in isolated plasma in magnetically suspended/isolated reactors such as Tokamak, MCF, LHD, JET, NIF or by initiation using the detonation of a mini-atomic bomb for the H-bomb). The processes taking place here are similar to those that occur naturally in stellar fusion. Once the reaction has been initiated, it is self-sustaining, due to the excess energy, until the fusible material is exhausted.

We present below a few nuclear fusion reactions that take place in stars [19], with the mention that they are not the only fusion reactions, many other elements fuse in stars, forming new elements with higher atomic numbers.

$$\mathrm{H} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} \qquad + 19.8\ \mathrm{MeV} \qquad (6)$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T} + \mathrm{H} \qquad + 4.04\ \mathrm{MeV} \qquad (7)$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} \qquad + 3.27\ \mathrm{MeV} \tag{8}$$
$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} \qquad + 17.58\ \mathrm{MeV} \tag{9}$$
$$\mathrm{D} + 3\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \mathrm{p} \qquad + 18.7\ \mathrm{MeV} \tag{10}$$
$$\mathrm{T} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + 2\mathrm{n} \qquad + 11.3\ \mathrm{MeV} \tag{11}$$
$$\mathrm{H} + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + 3\mathrm{He} \qquad + 3.9\ \mathrm{MeV} \tag{12}$$
$$\mathrm{H} + {}^{11}\mathrm{B} \rightarrow 3({}^{4}\mathrm{He}) \qquad + 8.68\ \mathrm{MeV} \tag{13}$$
$$\mathrm{D} + {}^{6}\mathrm{Li} \rightarrow 2({}^{4}\mathrm{He}) \qquad + 22.3\ \mathrm{MeV} \tag{14}$$

where: H = ${}_{1}^{1}H$; D = ${}_{1}^{2}H$; T = ${}_{1}^{3}H$; p – proton; n – neutron.

The mass defect demonstrates that the total energy of a system is conserved. This can ultimately take different forms:

- The "lost" mass is converted into energy in the form of radiation and heat, which is a perfect example of the first law of thermodynamics;
- The energy released in the fission process increases the disorder (entropy) of the system, either in the form of emitted radiation or by heating the surrounding environment, and this is in full agreement with the second law of thermodynamics.

From the perspective of cosmology, the mass defect and the conversion of mass into energy are essential for processes such as:

- the formation of elements in stars (the process of nuclear fusion and fission contributes to the nucleosynthesis of elements);
- the formation of supernovae (the energy released through the mass defect of nuclear processes leads to the explosion of massive stars and the dispersion of heavy elements in the universe);
- the thermodynamic evolution of the universe: the energy released through these processes contributes to the thermal equilibrium of the universe and, eventually, to the final state of "heat death".

We ask ourselves the question: *can the First Law of Thermodynamics be applied on the scale of the entire universe?*

The image of the universe has undergone a series of metamorphoses over time, starting from the infinite, unchanging, indivisible and immobile universe promoted by the school of Parmenides [11]. According to the latest assessments, *the universe can be considered a finite and isolated system, since it does not gain/loose mass or energy, even though it is infinite* [20,21]. But, taking into account special relativity, the conservation law must be formulated in the form of the equivalent mass constancy (15) or the equivalent energy constancy (16).

$$m + \frac{E}{c^2} = \text{constant} \tag{15}$$
$$mc^2 + E = \text{constant} \tag{16}$$

where: *m* is the mass of matter present in the universe at a certain moment, *E* – the energy associated with the universe at the same moment.

Acceptance of the conservation laws (15) and (16) can have important consequences for theories in astrophysics. First of all, one can admit the idea of a universe independent of the eventual existence of other forms of universes. In fact, we will never be able to discover the existence of another universe that is absolutely independent of our universe. Because the moment another universe becomes visible to an observer in our universe, it means that the two universes have collided. Only Niels Bohr can object that, however, information can be transmitted by the wave associated with the entire universe [22], but let us admit that the distance between the two universes is sufficiently large (on a cosmic scale obviously), so that the wave of the universe cannot bathe the shore of the neighboring universe.

Also in the category of theories that contradict the First Law of Thermodynamics can be included Fred Hoyle's idea of an eternal Universe, without beginning and without end. Since the general theory of relativity did not allow this, in the late 1940s, Hoyle modified the equations so as to allow for a creation field - a mysterious force that continuously creates matter from nothing [23]. Hoyle's collaborators, Hermann Bondi and Thomas Golad, were somewhat more reserved, stating that "*The Universe was not born and will never die. It simply is*" [23]. On the other hand, theories that predict the creation of mass and energy from nothing or from quanta of space can be rejected [24, 25, 26, 27].

The accelerated expansion of the universe, attributed to the existence of dark energy and dark matter, is a fascinating phenomenon that, at first glance, seems to contradict the First Law of Thermodynamics. However, a closer look shows that not only is this principle not violated, but it is actually supported and extended in a cosmological context.

In general relativity, the total energy includes contributions from ordinary matter, radiation, dark matter, and dark energy, and the conservation of energy is expressed by the cosmological continuity equation:

$$\dot{\rho} + 3H(\rho + p) = 0 \qquad (17)$$

where: ρ is the energy density of the universe, $\dot{\rho}^{\cdot}$ - the time derivative of the energy density, H - the Hubble parameter, $km \cdot s^{-1} \cdot Mpc^{-1}$ (Mpc - megaparasec), p - the pressure associated with each component, bar.

The Hubble parameter - improperly called the Hubble constant - is time-varying parameter and describes the expansion rate of the universe at a given time: H = 100h, h - expansion rate, $km \cdot s^{-1}$ [28].

The accelerated expansion does not involve the spontaneous destruction or creation of energy, but rather a distribution of energy consistent with the dynamics of the universe. The expansion of the universe involves changes in the density of matter, radiation, and dark energy, but these changes are governed by the field equations of general relativity. In essence, energy does not spontaneously disappear or appear but will be redistributed among the components of the universe (matter, radiation, and space-time). Dark energy is usually described as a cosmological constant, Λ, or as a form of energy with constant density ρ_Λ and negative pressure $p_\Lambda = -k_\rho \Lambda$. As the universe expands, its volume V increases, and the total energy of dark energy ($E = \rho_\Lambda V$) increases proportionally. This apparent increase in energy does not contradict the First Principle, since dark energy is not "created" from nothing but is a fundamental property of the space-time connection. The negative pressure associated with dark energy does work on the space-time relation, accelerating the expansion. This can be understood as a conversion of the energy associated with the dark energy density into kinetic energy (mechanical work), so the continuity equation mentioned above is equivalent to a cosmological version of the first law of thermodynamics, which also includes space-time terms [29].

Unlike dark energy, dark matter is a form of matter that interacts gravitationally, but not electromagnetically. It obeys the classical laws of conservation of energy and momentum. Its density decreases proportionally to the volume of the universe ($\rho m \sim a^{-3}$), according to the laws of thermodynamics applied to an expanding space. In other words, in the accelerating expansion the apparent increase in energy associated with dark energy is balanced by the interactions of negative pressure with the expansion of space-time. This is fully compatible with the First Principle. As the density of matter and radiation decreases due to expansion, dark energy takes over the dynamics of the universe, a process that fully respects the conservation of energy through transfers between available energy forms.

The implications of these phenomena are remarkable, as they support the heat death of the universe. As the accelerated expansion continues, dark energy will completely dominate the energy content of the universe. In such a scenario, matter and radiation become increasingly dilute and the universe approaches a state of thermodynamic equilibrium in which dark energy becomes the only dominant component. This scenario argues that the total energy of the universe is conserved, but redistributed towards the form associated with dark energy. The accelerated expansion of the universe does not contradict the first law of thermodynamics; dark energy, as a property of the space-time relation, respects the conservation of energy by redistributing it among the component forms of the universe. Experimental observations and the theoretical framework of general relativity support this reconciliation between thermodynamics and cosmology.

Although it seems hard to believe, there are a number of observations and experimental data that support this interpretation. For the accelerated expansion of the universe, Perlmutter, S., et al. and Riess, A. G., et al. A, referring to observations of type I supernovae a demonstrate that the universe is in a phase of accelerated expansion. These observations support the existence of dark energy, which contributes about 68% of the energy density of the universe [30, 31].

For the cosmic microwave background radiation, data from the WMAP and Planck satellites confirm that the total energy density of the universe is consistent with a model that includes dark energy and dark matter.

For the large-scale structure of the universe, models of galaxy formation and the structure of the universe support the existence of dark matter, which explains the observed gravitational mass distribution.

The big bang theory is compatible with the first law of thermodynamics, even if at the zero moment of the explosion, there was only energy. Also, relations (15) and (16) applied to the big crunch theory allow that during the final collapse, elementary particles, including gravitons, can be transformed into energy. Under such conditions, the big bang can no longer be slowed down by gravity, and inflation can proceed at maximum speed until the reappearance of mass (gravitons), in accordance with the model of a pulsating universe. Simon Singh said that “the big bang model offers an elegant explanation of the origin of everything we see in the night sky, being one of the greatest achievements of human intelligence and spirit [27].

The white holes are the generic name for theoretical solutions to Einstein's equations (time-symmetric solutions of the field equations of general relativity, associated with black holes). If a black hole attracts matter and energy from the surrounding universe, a white hole does the exact opposite: it ejects matter and energy into space. In a mathematical sense, white holes are the "time inverse" of black holes. This means that a white hole could appear as a region of the space-time relationship into which nothing can enter, but matter and energy could only be expelled. They can be considered as the inverse functions of black holes or as their complementary part, in the sense that when a black hole appears, a white hole is necessarily generated, so that all the "lost" matter and energy, actually entering the black hole, will find their counterpart in the expelled matter and energy, leaving the white hole [32, 33].

In general relativity, the Schwarzschild solution describes the space-time around a non-rotating black hole. This solution can be theoretically extended to include a white hole, connected to a black hole by an Einstein–Rosen bridge (a type of "wormhole") [32, 34, 35].

In this theoretical framework, white holes could "spit" matter into the universe, forming new stars, but this matter could come from another region of space-time on the principle or rather respecting the principle of quantum entanglement or an equally plausible hypothesis that a white hole would represent the "death" or end of the cycle of a "black hole" that "dies" through Hawking evaporation, becoming a white hole, releasing the accumulated matter and energy when they reached critical values that prevent additional accumulations.

Although, apparently, white holes seem to violate the second law of thermodynamics, which states that the total entropy of an isolated system must increase, with theorists suggesting that white holes could appear in the universe as transient or rare phenomena, in which large amounts of energy and matter are suddenly expelled into space, leading to the formation of new stars or even galaxies or the "creation out of nothing" of stars, in reality they do not violate the principle of conservation of energy, since energy could be transferred from another region of space-time, on the principle of quantum inseparability stated above, so that the creation of matter and energy by white holes is fully compatible with the conservation of energy and with the laws of thermodynamics, the matter and energy created in one part of the universe in a white hole disappearing in equivalent amounts in a black hole in another part of the universe, the connection between the two holes being made through a "wormhole", thus white holes do not create matter "out of nothing". nothing", but redistributes energy from an extremely compressed initial state.

Such an interpretation supports the hypothesis that the Big Bang itself could be seen as a singularity of a white hole, in which all the matter and energy in our universe was "expelled" from a singularity of a wormhole in another universe.

The theory of cosmic inflation is a central pillar of modern cosmology, providing an explanation for the extremely rapid expansion of the Universe in the first moments after the Big Bang. Alan Guth formulated this theory in 1981 to solve fundamental problems with the standard cosmological model. Andrei Linde later extended and refined the idea, proposing the concept of eternal inflation and involving the notion of a multiverse [36, 37, 38].

The standard Big Bang cosmological hypothesis, at the time of its proposal, faced three major problems before the introduction of inflation:

1. The horizon problem:

Why is the temperature of the Universe so uniform in all directions, even though opposite regions of the sky have not had time to causally interact?

2. The platitude problem:

Why is the density of the Universe so close to the critical value, suggesting a nearly flat geometry?

3. The magnetic monopole problem:

Why don't we see dense relics, such as magnetic monopoles, that should have been created in large quantities by phase transitions in the early Universe?

The theory of inflation attempted to solve these problems by postulating a phase of exponential expansion of the Universe at an extremely early time scale (around 10^{-36} seconds after the Big Bang). During this time, the size of the Universe would have increased by a huge factor (of the order of 10^{26}).

3. Mechanisms

3.1. Guth's mechanism

Guth proposed the idea that inflation is driven by a scalar field called the inflation field and associated with a large potential energy. The energy stored in this scalar field would have produced a strong gravitational repulsion, causing the accelerated expansion. In a process called spontaneous symmetry breaking, the scalar field would have passed to its minimum energy state, and the energy accumulated in the field would have been transformed into particles and radiation, marking the end of inflation.

3.2. Andrei Linde's Developments: Eternal Inflation and the Multiverse, Chaotic Inflation

Andrei Linde proposed in 1983 an improved variant called chaotic inflation, which removes some of the constraints of Guth's original model. In this theory, no extremely precisely defined initial energy state is required and inflation can start naturally, from quantum fluctuations of the scalar field.

Linde extended the idea to the concept of eternal inflation, in which inflation does not completely stop everywhere in the Universe. Due to quantum fluctuations of the scalar field, inflation continues in some regions of space-time, generating new "bubbles" of universes. Each of these bubbles can have different physical properties (for example, different values for the fundamental constants of nature). This process leads to the idea of a multiverse: an infinite set of universes, each with different laws of physics and initial conditions.

However, this concept presents a number of problems, the solution of which has been attempted later. These are, as follows:

- Horizon problem:

Rapid expansion "pushes" causally connected regions of the past beyond the visible horizon, explaining the uniformity of the temperature of the cosmic microwave background.

- Platitude problem:

Inflation "flattens" the geometry of space-time, bringing the density of the Universe close to the critical value.

- Magnetic monopole problem:

Monopoles are drastically diluted by exponential expansion.

3.3. Existence of the multiverse

Eternal inflation provides a framework for understanding why our universe seems to be "fine-tuned" to allow the existence of life. In a multiverse, universes with unfavorable physical conditions could not support complex structures such as galaxies and life. Our universe is just one of many possible universes, and its favorable conditions are the result of anthropogenic selection. The concept of energy associated with the scalar field of inflation has similarities to the dark energy that drives the accelerated expansion of the Universe today. These two phenomena could be related, although they manifest on different time scales. In this context, the question arises: Is there eternal inflation?

The theory of inflation, developed by Alan Guth and expanded by Andrei Linde, revolutionized cosmology by providing a robust explanation for the uniformity and structure of the Universe. The idea of eternal inflation opens up fascinating insights into the existence of a multiverse and the fundamental laws of physics. Although the hypothesis remains partly speculative, indirect evidence from the cosmic microwave background and the large-scale structure of the Universe gives it a solid foundation. Although the inflation theory has been remarkably successful in explaining observations and is largely accepted, the idea of eternal inflation coupled with the multiverse raises serious questions, especially the problem of verifiability. If other universes cannot be directly observed, it is difficult to scientifically test these hypotheses [39].

4. Second Law of Thermodynamics

The Second Law of Thermodynamics was developed following research on steam engines by Sadi Carnot (1824), who concluded that a heat engine cannot produce mechanical work unless there is a temperature difference between the heat input and output points. Carnot also determined the expression for the maximum efficiency of heat engines, according to relation (19) [40]:

$$\eta = 1 - \frac{T_2}{T_1} = \frac{T_1 - T_2}{T_1} \tag{18}$$

where T_1 is the temperature of the hot source, T_2 – the temperature of the cold source.

It should be noted that the second law of thermodynamics is a statistical concept, which can be considered only for systems composed of a very large number of component particles and cannot be applied to individual particles at the atomic or subatomic level[40].

An interesting formulation was given by Clausius [40]: *Spontaneously, heat can only pass from higher temperatures to lower temperatures; the reverse passage is possible only with the absorption of external mechanical work.*

William Thomson (Lord Kelvin) gave another statement of the second principle, equivalent to that given by Clausius [41, p. 203]:

It is impossible by means of a lifeless material agent to continuously develop a mechanical effect from any portion of matter, by cooling it below the temperature of the coldest object in the environment.

William Thomson also noted that a thermal machine cannot operate with a single source of heat, giving another formulation of the second principle:

The construction of a perpetual motion machine of the second kind, which operates with a single source of heat, is impossible [40].

The efficiency of a heat engine is given by equation (19):

$$\eta = 1 - \frac{Q_2}{Q_1} = \frac{Q_1 - Q_2}{Q_1} \tag{19}$$

where Q_1 is the heat received by the heat engine, Q_2 – the heat given off to the environment.

Carathéodory's approach in 1909 gave a new definition of the II principle [41]:

In the vicinity of any state of a system in thermodynamic equilibrium there are states that cannot be reached by reversible adiabatic processes.

Theoretical and experimental studies related to the second law of thermodynamics led to the introduction of both thermodynamic temperature and the notion of entropy - a criterion for evaluating the spontaneous nature of processes.

The concept of entropy was introduced by Clausius in 1865, based on the observation that, for reversible thermodynamic processes, the differential defined by the relation (20) is a total and exact differential [42], unlike dQ.

$$\mathrm{d}S = \frac{\mathrm{d}Q}{T} \tag{20}$$

Therefore, for a cyclic reversible process the entropy variation will be zero (21) [43].

$$\oint \frac{\mathrm{d}Q}{T} = 0 \tag{21}$$

If the initial state is not identical to the final one, then the entropy variation is given by relation (22) [4, p. 58].

$$\int_i^f \frac{\mathrm{d}Q}{T} = S_f - S_i = \Delta S \tag{22}$$

For irreversible (spontaneous) processes the entropy change is positive. This is a central consequence of the second law of thermodynamics (6). Bolzmann specified that natural *phenomena are irreversible* [40].

$$\Delta S > 0. \qquad (23)$$

There are numerous spontaneous irreversible processes: heat production by friction, expansion of a gas, diffusion phenomena, numerous chemical reactions, etc. For non-spontaneous processes, the entropy change is negative (24).

$$\Delta S < 0. \qquad (4)$$

Entropy has proven its applicability not only in the field of thermal machines, but also in the thermodynamics of chemical processes, in which the driving force is the existence of a chemical potential difference. A series of methods for determining entropy associated with physicochemical processes have been developed, so that E. Schrödinger said, obviously exaggerating: “it is a measurable quantity like the length of a stick, the temperature of a body at a certain point, the heat required to melt a crystal or the specific heat of a substance” [44].

Like Newton’s laws, the Second Principle of Thermodynamics was developed within the limits of the conditions existing on Earth. On the one hand, the processes were studied in the absence of a very strong gravitational field, which would decisively influence thermochemical processes, on the other hand, the working temperatures were limited to those that could be achieved on an industrial scale, far from the temperatures that exist in stars, quasars, neutron stars, black holes, etc.

Therefore, the application of the II principle to the scale of the entire universe, viewed as an isolated material system, raises extremely complicated problems. The first problem that arose was the heat death of the universe – a pessimistic hypothesis on the evolution of the universe developed by Lord Kelvin in 1852 [41]. According to this theory, the universe will reach a state of equilibrium in which matter and energy will be uniformly distributed and no process will take place, since the entropy of the Universe will reach its maximum value [45]. The apocalyptic scenarios of this theory developed at a time when knowledge about the universe was still precarious are well known. Moreover, entropy has been given the label of the arrow of time: time flows in the direction in which entropy increases. Of course, there are also spontaneous anti-entropic or anti-thermodynamic processes, as Lee Smolin plastically calls them, such as those related to gravity [45].

The evolution of the universe must be seen as a cyclical process, in which we choose as a starting point the singularity, when the universe could be considered an infinite small, of minimal entropy. The first stage of the cycle consists of the period of expansion - big bang - with all the stages known and described by astrophysicists - until the maximum size of the universe is reached, obviously also the maximum entropy is reached, after which the big crunch follows - the second stage of the cycle, in which we reach, of course not by the same path, again the singularity, a process in which the entropy decreases again to the minimum value. We can accept the variant of the pulsating universe because it does not contradict the second principle of thermodynamics [46].

We can choose as a starting point the state of maximum inflation of the universe (figure 2) [46]. It is possible that at the moment of maximum expansion of the Universe, it will be almost dead: enormous distance between solar systems, extinguished stars, planets - as many as there are - lifeless, enormously many solar systems swallowed by black holes, and the dominant force under these conditions will be gravity. Metaphorically, we can say that the Universe is in thermal death. It is the starting moment of the big crunch. Consequently, the entropy of the Universe, as an isolated system, will begin to decrease, the gravitational effects being of an anti-entropic nature. However, it does not mean that the arrow of time is reversed.

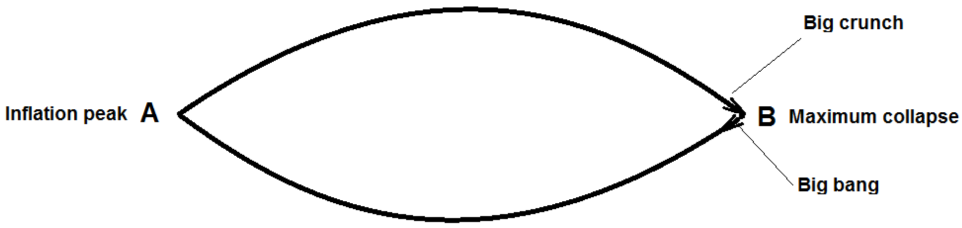

Fig. 2. The cyclic model of evolution of the universe [46].

The idea of a universe with cyclic development was imagined more than two millennia ago in Stoic philosophy: “Once upon a time there was nothing but fire; the other elements and furniture of the universe, to which we are accustomed, gradually appeared. Later, the world will return to fire again, in a universal conflagration, and the whole cycle of history will be repeated again and again” [11]. The modern model of the evolving universe belongs to Roger Penrose (Conformal cyclic cosmology) [47].

5. Conclusions

In a finite yet unbounded Universe, we can assert that the First Law of Thermodynamics remains applicable - specifically in the form of mass-energy conservation, as represented by equations (15) or (16) - even if the Universe is expanding. The potential existence of dark matter and dark energy does not contradict this principle. Furthermore, the Big Bang Theory and its derivatives are compatible with the First Law, despite many of these models being accepted primarily because they "save the world". Under these circumstances, cosmological theories positing the creation of the Universe from nothing / ex nihilo - such as those proposed by Hoyle or Volekin - are rendered untenable. On the other hand, theories involving the emergence of universes from space quanta, however appealing, are inadmissible under the First Law of Thermodynamics.

Unlike the First Law, the Second Law of Thermodynamics faces significant challenges when applied to the Universe as a whole, owing to the specific conditions under which it was formulated. It is well-established that the Second Law arose from empirical studies of internal combustion engines, where the influence of external gravitational and electromagnetic fields was negligible. Theoretical and experimental research on the Second Law led to the concept of entropy - a criterion for determining the spontaneous direction of processes.

For irreversible processes, entropy increases, implying a progression toward greater disorder. This principle underpinned Lord Kelvin's proposal of the Universe's "heat death." However, in cyclic processes, as demonstrated by Clausius, the net change in entropy is zero. Given that gravitational processes exhibit anti-entropic behavior, cyclic models of cosmic evolution have been proposed, the most sophisticated being Penrose's Conformal Cyclic Cosmology. If a cyclic Universe is assumed, the Second Law of Thermodynamics can indeed be extended to the cosmos as a whole.

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