INFORMATION AND THERMODYNAMIC ENTROPY FROM THE STANDPOINT OF LOCAL OBSERVERS IN AN EXPANDING UNIVERSE

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We describe cosmic expansion from the standpoint of an observer's comoving horizon. When the Universe is small, the observer detects a large amount of the total cosmic bits, which number is fixed. Indeed, information, such as energy, cannot be created or destroyed in our Universe, i.e., the total number of cosmic bits must be kept constant, despite the black hole paradox. When the Universe expands, the information gets ergodically "diluted" in our isotopic and homogeneous Cosmos. This means that the observer can perceive just a lower number of the total bits, due the decreased density of information in the cosmic volume (or its surrounding surface, according to the holographic principle) in which she is trapped by speed light's constraints. Here we ask: how does the second law of thermodynamics enter in this framework? Could it be correlated with cosmic expansion? The correlation is at least partially feasible, because the decrease in the information detected by a local observer in an expanding Universe leads to an increase in detected cosmic thermodynamic entropy, via the Bekenstein bound and the Laudauer principle. Reversing the classical scheme from thermodynamic entropy to information entropy, we suggest that the quantum vacuum's cosmological constant, that causes cosmic expansion, could be one of the sources of the increases in thermodynamic entropy detected by local observers.

THE PARADIGM OF INFORMATION

Information is a measurable physical quantity that, according to some scholars, might stand for the most general paradigm able to investigate cosmological, physical and biological systems. Indeed, it has been claimed that the physical world is made up of information itself (Bekenstein 2003), so that our Universe is assessable in pure terms of information. The idea that information is the fundamental physical quantity dates back to F.W. Kantor (1977). By then, different information-related perspectives have been developed, from the hypothesis that the Universe is a giant digital computer (Schmidhuber 2000; Zenil 2012), to the suggested link among information theory, statistical thermodynamics and the probabilistic nature of quantum mechanics (Jaynes 1957;Lloyd 2000; Marzuoli and Rasetti, 2005; Fuentes-Guridi et al., 2005), from computational loop quantum gravity (Zizzi, 2001) to connections between information and the Bekenstein and Hawking entropy (Görnitz, 1988; von Weizsäcker, 2006). Therefore, information sits at the core of physics, so that an "it from bit" dogma has been proposed (Wheeler 1990): every field or particle exists because of its observation. In our Universe, information cannot be created or destroyed. The conservation of information is derived from quantum field theory, via the quantum Liouville theorem (Zeidler 2011). Indeed, quantum field theory works both forward and backward in time, and the same does information's conservation. The probabilistic combination of pure states keeps the same set of probabilities. In other words, because time evolution is unitary, this means that it's reversible, i.e., no information can ever get lost because one is theoretically allowed, starting from any time-like slice, to run time backwards and compute what happened earlier. Therefore, the amount of information is invariant in our cosmos: the number of bits encompassed in the whole Universe cannot modify, even if the theory of "the world as hologram" holds true ('t Hooft 1993; Susskind 1994). Also, the "black hole information paradox" related to the hypothetical loss of information in the black holes has been solved: the latter might release the "trapped" information through the Hawking radiation, until they evaporate (Hawking 1975; Hawking 2005; Gyongyosi 2014). Here we will show how this simple statement related to the conservation of cosmic information leads to unexpected consequences for a local observer embedded in her own cosmic horizon.

THE ROLE OF THERMODYNAMIC ENTROPY

In the previous paragraph, we stated that information is constant in our Universe. This may sound weird to anyone familiar with the second law of thermodynamics, which says that "*every process occurring in nature proceeds in the sense in which the sum of the entropies of all bodies taking part in the process is increased" (*Planck's formulation). How can these opposite claims be consistent? The microscopic laws of physics are reversible: despite irreversibility comes out due to coarse graining to a larger effective scale, the microscopic information does not get lost. Indeed, the entropy described by the second law is the sum of the entropies of many macroscopic local objects. Macroscopic physical systems, like the observable Universe, are not just regulated by stochastic variables and random fluctuations, but also by constraints given by the arrow of time. Despite the large number of different scenarios, the processes governing time constraints of physical and biological systems may be generalized, taking into account the universal principle of the second law of thermodynamics (Bryngelson and Wolynes, 1987; Ferreiro et al., 2011; Tozzi et al., 2016). Therefore, the positive arrow of time observed in the macroscopic Universe (due to the time-reversal symmetry violation) is strictly correlated with the second law of thermodynamics. In thermodynamics, information I can be defined as the negation of thermodynamic entropy S (Beck, 2009):

$$I \,\underline{=}\, -S$$

Therefore, a bit of thermodynamic entropy stands for the distinction between two alternative states in a physical system. As a result, thermodynamic entropy of the Universe is proportional to the total number of distinguishable states encompassed in the cosmos: the higher the number of states, the higher the entropy. We will see in the sequel how the two apparently not comparable quantities, i.e., thermodynamic entropy and information, can be correlated.

COSMIC EXPANSION COMES INTO PLAY

The Universe is expanding. It has been hypothesized that it arose from a perturbation in the quantum vacuum, when an inflationary mechanism, correlated with a false vacuum state, led to the production of cosmic matter and to the huge expansion that took place 1^{-35} seconds after the Big Bang (Veneziano, 1998). Indeed, vacuum quantum fluctuations (dictated by the Heisenberg energy-time uncertainty principle) could have been able to cause, through an inflaton-based mechanism, the occurrence of the Big Bang and our Universe (Mandelstam and Tamm, 1945; Vaidman 1992; Uffink 1993). Our Universe started with the Big Bang, characterized by very high density and temperature state (Penrose, 2011). At the very beginning, 1^{-43} seconds after the Big Bang, our Universe was equipped with an energy $=10^{19}$ GeV and a temperature of 10^{32} K, while its horizon was 10^{-25} cm and the density 10^{96} kg/m^3. By then, the temperature halved every double expansion. At 10^{-36} seconds after the Big Bang, the energy lowered at 10^{16} GeV, while at 10^{-32} seconds the temperature decreased at 10^{28} K. The cosmic inflationary expansion at 10^{-35} sec is the current explanation for cosmic features such as isotropicity, homogeneity, symmetry and zero curvature. It is noteworthy that the Universe underwent a rapid expansion so that, from the above-mentioned horizon diameter of 10^{-25} at 10^{-43} after the Big Bang, it reached the size of about one-meter diameter at 10^{-32} seconds. Another gentler inflationary period started approximately 4.5 billion years ago (Ellwanger, 2012). Currently, 13.79 billion years after its birth, our Universe is still accelerating, slowly proceeding towards thermal death (Bars and Terning, 2009). In our cosmic era, from our standpoint of local observers, the visible cosmic horizon is 10^{29} cm, the cosmic density is 10^{-29} gr/cm^3, the matter corresponds to one atom/m^2 and the space is expanding at a speed of $74{,}3\pm2{,}1$ km/sec per megaparsec.
How did (and still does) cosmic expansion occur? It is possibly linked with the quantum vacuum, a material medium capable of polarization and equipped with its own electric permittivity, permeability and dielectric constant. The quantum vacuum is believed to display a negative pressure (an anti-gravitational force) that equals its energy density and causes the accelerated expansion of the current Universe. One of the possible explanations of the anti-gravitational strength of the quantum vacuum is the repulsive dark energy, correlated with the cosmological constant. The cosmological constant gives rise to a negative pressure: indeed, the amount of energy in a container full of vacuum increases when the volume increases. The dark energy amount stands for the 73% of the whole Universe: in sum, due to the increase in cosmic expansion, the density of "visible" matter and radiation is diluting. What about information? In the next paragraphs, we will elucidate how it is feasible to correlate cosmic expansion with information and thermodynamic entropy.

LINKING COSMIC EXPANSION, INFORMATION AND THERMODYNAMIC ENTROPY

The cosmic expansion leads to an unexpected consequence: for a local observer enclosed in a given cosmic horizon that is constrained by the light speed, the information density (bits/ cosmic volume unity) is decreasing with time passing (**Figure**). This means also that the observer perceives the thermodynamic entropy as increasing around her. How is it possible? Here we illustrate the procedure that allows the correlation in a common theoretical framework of the relationships between thermodynamic entropy and thermodynamic information. The entropy must be finite in the sphere delimited by the observer's cosmic horizon, i.e., the space assessable by the local observer. Therefore, the total entropy embedded inside the cosmic horizon can be quantified through the Bekenstein bound. The Bekenstein bound is an upper limit on the thermodynamic entropy S (or the information I, according to Shannon (1948)) endowed in a space region equipped with a given amount of energy. In other words, the Bekenstein bound stands for the maximum quantity of information required to describe a physical system down to the quantum level. The universal form of the bound can be described as follows (Bekenstein 1973; Bekenstein 1974):

$S_{sys} = \zeta \frac{AEK}{\hbar c}$

Where S_{sys} is the cosmic thermodynamic entropy detectable by the observer, A is the area of the local observer's cosmic horizon, E is the Energy including matter (the total mass-energy of the Universe consists of about 10^{69} Joule), $\hbar$ is the reduced Planck constant, c is the speed of light, k is the Boltzmann constant, ζ is a factor such that $0 \leq \zeta < 1$.
Setting ζ to one in case of the total S_{sys}, we are allowed to quantify the thermodynamic information, by partitioning the factor into a relative information component ($\zeta_I = 1- \zeta_S$) and a relative entropy ($\zeta_S = 1- \zeta_I$) (Street 2016):

$I_{sys} = \zeta_I \frac{AEK}{\hbar c} = (1- \zeta_S) \frac{AEK}{\hbar c}$

In case of cosmic expansion, we are in front of decrease of information density in the space inside the observer's cosmic horizon. In other words, the bits available for our observer decrease. This means that information exits from the observer's cosmic horizon, according to the formula:

$\Delta I_{sys} = \frac{\Delta Esurr}{kT} = \Delta \zeta_S$

Where T is the temperature. Note that temperatures decrease with cosmic expansion, and it contributes to the thermodynamic entropy's cosmic budget.
Here the Landauer principle comes in to play too: any logically irreversible manipulation of information, such as the erasure of a bit, must be accompanied by a corresponding entropy increase of the information-processing apparatus or its environment (Landauer, 1961). Therefore, there is a minimum possible amount of energy required to erase one bit of information, the so-called "Landauer limit":

$kT \ln 2$

When one bit of logical information is lost, the amount of entropy generated is at least k ln 2, so that the energy that must eventually be emitted to the environment is $E \geq kT \ln 2$. At 20°C (293.15 K), the Landauer limit represents an energy of approximately 0.0172 eV, or 2.75 zJ. (Bérut et al., 2012).
We cannot state that system formed by the local observer's cosmic horizon is a physically closed system; nevertheless, our general framework holds the same. Indeed, an increase in the number of physical states corresponding to each logical state means that, for an observer (a human "observer" embedded in its limited cosmic horizon) who is keeping track of the logical state of the system but not of its the physical state, the number of possible physical states has increased; in other words, entropy has increased from the standpoint of our observer.
In the whole Universe, the total expansion leaves the thermodynamic entropy of relativistic particles (such as photons, gravitons and neutrinos unchanged). This occurs because the entropy of a gas of relativistic particles is proportional to the number of particles, which does not change as the cosmos expands (Lineweaver and Egan, 2008). Therefore, if we follow the thermodynamic entropy of a cosmic comoving volume, the number of photons in that volume does not change. This means that, if thermodynamic entropy increases in the whole Universe, the cause is not the cosmic expansion. However, we, local observers embedded in our cosmic horizon constrained by the light speed, perceive a decrease in information (more diluted), and therefore an increase in thermodynamic entropy. In sum, it is feasible that the cosmic expansion dictated by the cosmological constant of the quantum vacuum leads to a local decrease in information, and to the increases in thermodynamic entropy detected by local observers. Because in the Universe an observer sees always the same macro-cosmic features and different observers see the same macro-cosmic features (the Universe is homogeneous and isotropic), it is feasible to extend the framework to every observer in the entire Universe.

CONCLUSIONS

Here we partially explain the occurrence of the second law of thermodynamics through the issue of the cosmic expansion, that leads to a diluted information for a local observer, and, consequently, to her detection of increases in thermodynamic entropy. The classical scheme is reverted: here we start from information, and reach the entropy, and not vice versa as generally assumed. It is noteworthy that information is also linked with the Shannon entropy, that holds for ergodic systems: the Universe is ergodic too, because it has been demonstrated that it is homogeneous and isotropic, at least at its macroscales (Clifton et al., 2012).
Therefore, (at least a part of) the increase in thermodynamic entropy might be correlated with cosmic expansion. Our hypothesis leads to (theoretically) testable previsions. To make an example, when (and if) the universe expansion decreases or relapses, the entropy perceived by a local observer embedded in her cosmic horizon must decrease, or even relapse. Furthermore, we predict that, in the current cosmic era, due to the increased cosmic expansion, the thermodynamic entropy detectable by a local observer is increased, compared with previous periods.

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