Quantum Gravity and the Second Law of Thermodynamics

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ABSTRACT

According to the present-day cosmological standard model, whatever physical state constituted the beginning of the current cosmic expansion lies an effective 13.8 Gyr in our past and differed in essentially every respect from the Universe's current state. In particular, there is strong evidence that all matter known to be present in the Universe today either directly or indirectly owes its existence to reasonably well understood physical processes, e.g., "Big Bang Nucleosynthesis", that occurred during (or shortly afterwards) this "initial" phase. Moreover, there is even stronger evidence that some 380.000 years after *this "initial" phase (essentially still 13.8 Gyr ago), i.e., when matter and radiation effectively decoupled and the Cosmic Microwave Background (CMB) was formed, the matter degrees of freedom were to a very high degree of precision thermally distributed, i.e., were essentially in a state of maximum entropy. This immediately gives rise to a paradox, since the matter degrees of freedom characterizing the current Universe are obviously nowhere near thermal equilibrium. Although a priori different possible scenarios can be contemplated for resolving this paradox, the correct answer must at least partially take into account the prima facie anti-thermodynamic behaviour of gravity. Indeed, formation of the kind of structures characteristic of the Universe at its present stage from an essentially thermal distribution of matter through gravitational clumping, is an entropy-increasing process and this thus means - in complete accordance with usual expectations based on the Second Law of Thermodynamics - that the totality of* all *physical degrees of freedom at the time the CMB formed were distributed in a highly non-thermal fashion, i.e., the Universe at that time was in an ultra-low entropy state. A fundamental problem with this picture however is that although it seems clear that proper gravitational degrees of freedom must somehow be assigned a physical entropy, whereas the laws of black hole mechanics even constitute ample evidence for the existence of a deep link between gravity and thermodynamics, there is at present no well defined measure of gravitational entropy. After reviewing this situation in some depth and incorporating it into a wider perspective on explaining the origins of the Second Law of Thermodynamics in terms of a cosmological boundary condition, while also taking note of some well-known theoretical and conceptual caveats that such an account runs into, I will argue that a future theory of "quantum gravity" is exactly what is needed to properly address these difficulties. But this cuts both ways and arguably the search for a theory of quantum gravity should be strongly constrained by the aim to properly account for the Second Law.*