

Universe runs on G

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From our everyday life observations we can draw some bold conclusions such that the working class in the US runs on coffee and donuts, and that they have a tendency of dunking donuts in their coffee. It is not as simple as that when it comes to more fundamental questions, though. What does the universe run on? What makes the universe evolve into its current phase? Why are there stars, galaxies and other complex structures like us? What were the initial conditions for that to happen? Such questions arise from our observations of the universe and we believe that we have good answers to most of them, but not to all of them.

The assumptions one often makes when constructing a standard model of the universe include constancy of constants of nature such as the speed of light, c , Planck's constant \hbar , the fine structure constant, α , the weak coupling constant, α_w , the strong interaction coupling constant, α_s , the Newton's constant, G , and the cosmological constant, Λ . I will separate these constants into two groups, namely, the fundamental constants, c and \hbar , and the rest. In what follows, I will argue that the former are true constants and the latter are not.

Let me start with the easiest part that is known to everyone in physics. As we know from the renormalization group calculations in quantum field theories, e.g., in quantum electrodynamics (QED), electroweak theory (EW) and quantum chromodynamics (QCD), the coupling constants do run with energy, hence it is not fair to call them as constants anymore. This effect can be understood as follows. You want to go to a concert of your favorite band, say Radiohead, but you also want to be as close as possible to the stage to see how awesome they are. The problem is the tickets are almost sold out, and you ended up getting a ticket for a seat where you cannot even see them. Let us assume for the sake of the analogy that if you can pass all the crowd, and stand in the very front row at the end of the day, you are allowed to give Thom Yorke a high five. As per common sense, it would have been a lot easier to penetrate through the crowd and give Thom a high five, say, 15 years ago when not many people know them that well. However, as they got better and had more fame, your high five ritual seems to get harder and harder. The vacuum in quantum field theory looks similar to this situation except you should replace fame with energy, crowd with virtual particle pairs and easiness of giving a high five with the coupling constant. Quantizing the electron and electromagnetic fields lead to the phenomena of virtual particles: An electron-positron pair emerging out of the nowhere from the vacuum, and then annihilating immediately. This is the so called pair creation/annihilation in QED. The guiding principle for this effect is the Heisenberg's uncertainty relation, $\Delta E \Delta t \geq \hbar/2$. For the time scales of order $\Delta t \sim \hbar/(4m_e) \sim 10^{-22}$ s, where m_e is the electron mass, an electron-positron pair pops in and out of vacuum. Therefore, as you try to take a closer look to an electron, namely, using smaller and smaller wavelength photons to see it closely, more pairs will screen the actual electron, hence the coupling constant does run to larger values. On the other hand, in the so called asymptotically free theories such as QCD, due to the nice cancellations of the contributions of gluons and quarks to the β function –the function determining how the coupling constant changes with energy–, the coupling constant goes to zero at high energies, hence, it becomes easier to give quarks a high five at higher energies. How about Newton's constant G ? Since we do not have a final quantum theory of gravity, we can speculate about the running of G , but as I will argue at the end, in my opinion, there are good reasons to think that gravity is asymptotically safe, i.e., gravity gets weaker at extremely high energies that is relevant for the very early universe [1].

I will switch gears and elaborate on the constancy of the “true” constants of nature, c and \hbar , before I discuss the running of G and Λ , and its possible consequences. Although there are some claims about varying speed of light to explain the current accelerated expansion of the universe, this idea seems in conflict with the very basic concepts that we use to describe physics at the very fundamental level. The speed of light is nothing but the ratio between a space coordinate and the time coordinate, hence it is fixed when the local physics is fixed, i.e., when we use a Minkowski (flat) metric tensor to describe the nature of the spacetime locally. In general relativity, the universe is a certain solution to the Einstein's equations. No matter what this solution is, we know that locally it is described by the same Minkowski metric to a perfect accuracy, which implicitly fixes the speed of light everywhere in the universe provided that the equivalence principle holds (equivalence principle is basically the ultimate democracy for the observers where every observer is equal to the other no matter what frame of reference he/she uses to describe physics).

Now let us see what would happen if we vary Planck's constant, \hbar . The Planck's constant appears as a measure of the non commutativity of the position operator, x , and the momentum operator, p , in quantum mechanics, and there is a difference if one is to operate with x and then p or vice versa. To quantify this we use the so called commutator which measures the difference between the two operations, $xp - px$ and denoted as $[x, p]$. The value of this quantity

turns to be given in terms of Planck's constant as $[x, p] = i\hbar$, where $i = \sqrt{-1}$. Now, let us first assume that the value of \hbar can change in space and time, and see what kind of inconsistencies we would encounter. When we apply quantum mechanics to particles and atoms, we would immediately realize that the energy of photons with frequency ω , $E = \hbar\omega$, would have to change unless the frequency also changes exactly the same way \hbar changes if we want to keep the conservation of energy intact. Similar problem arises when we consider the energy levels of atoms. For simplicity let us take an electron in the ground state of a hydrogen atom whose binding energy is $E = -m_e e^4 / (2\hbar^2)$, where m_e is the electron mass and e is the electron charge. Decreasing \hbar would lead to a more negative binding energy, hence, atoms would release this energy difference by emitting photons. Increasing \hbar would require energy since this time the binding energy would be smaller, hence, the electron would need to absorb energy to get to its ground state. Similarly, the blackbody spectrum of the cosmic microwave background would be different than what we observe if \hbar were not constant. Therefore, assuming conservation of energy and equivalence principle, such effects are not consistent with what we observe, hence I argue that speed of light, c , and the Planck's constant, \hbar , are the "true" constants of the universe.

Now comes the interesting question: Are the Newton's constant, G , and the cosmological constant, Λ , really constant? We know from quantum field theory that the vacuum has non-zero energy which is 10^{120} orders of magnitude larger than what we observe today. This embarrassing result clearly suggests that the way we calculate the contribution of matter to the vacuum energy is not the end of the story, and further suggests that the yet unknown quantum gravity effects might cancel the big number. Even there is such a nice cancellation, then, we have to explain why there is such a finely tuned cancellation that left us with a tiny Λ today [2]. In late 1970s Steven Weinberg asked what if gravity is asymptotically safe, i.e., G runs towards smaller values at high energies relevant to the very early universe [1]. The situation could be such that there is an attractor solution for the value of G and Λ at small energies that approaches to their current values. Of course there has been a lot of progress made in a technical sense by checking whether such a scenario can be realized. Rather than discussing the technical issues, I will just try to see what would be the phenomenological implications of running G and Λ . First of all, as we go to higher and higher energies, gravity would get weaker and weaker, and eventually would decouple from matter. What I mean by decoupling is that at sufficiently early times geometry of the spacetime is no longer determined by the matter content of it, hence it would be fixed no matter what kind of matter there is. This picture also suggests that the cosmological constant Λ would reach to some very large constant value at high energies [3]. It is well known that the universe filled with matter has a singularity in its past if G is constant, i.e., the density of matter increases as we go back in time, and it would be so big that it leads to a singularity eventually. On the other hand, if G and Λ are running the way that was just described, the universe will be dominated by Λ before the matter decouples, and then reach to an asymptotic de Sitter universe. I will further speculate that this picture suggests a some kind of topological quantum gravity theory. In other words, whatever the final quantum gravity theory is, it will be background independent and the spacetime emerges as a solution of this topological theory that is independent of the matter content and gravity. In other words, there would be no gravity in the quantum theory gravity!

Now let us watch the film forward in this scenario to see whether it makes sense at all. First, the de Sitter spacetime emerges as a solution of the quantum gravity theory. Due to the running of G and Λ , eventually matter fields begin coupling to gravity, and particles are produced gravitationally [4]. As Λ keeps running towards smaller values, the universe enters to a radiation dominated phase as in the case of standard inflationary scenarios. Therefore, we can get the required initial conditions to end up in the universe we observe today if these speculations turn out to be right. Hence, there is no chance to give gravity a high five since there would be no gravity in this theory of quantum gravity, and the universe indeed would run on G .

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