Fundamental constants – To change or not to change?

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Fundamental Constants – To change or not to change?

Modern metrology and cosmology rely on the fact that the fundamental constants of the universe are actually constant. However, a look into the world of fundamental constants reveals that things are not that simple, and some theories and experiments challenge our idea of a universe ruled by unchangeable constants. Evidence of variable fundamental constants would open the door for new, exciting physics and revolutionise our view on the universe.

Physicists like to describe the universe in terms of models, theories and laws. A closer look at those structures reveals that most of them involve undetermined free parameters: parameters that play a crucial role in how physical laws manifest themselves in the universe, but whose value cannot be deduced by any current theory. These parameters are known as fundamental constants. Usually eight such parameters are considered truly fundamental, namely the gravitational constant *G*, the mass of the electron and the mass of the proton m_e and m_p, the speed of light in vacuum *c*, the reduced Planck constant *ħ*, the electron charge *e*, the Boltzmann constant k_B and the Avogadro constant N_A (Fig. 1) [1].

Although every free parameter of a theory is a fundamental constant, they are not all equal. One common way of classifying them is the one introduced by Levy-Leblond. In his system every constant is put into one of three classes: A, B and C. Type A constants are constants that describe the physical properties of particular objects. Obvious examples of type A constants are the masses of elementary particles such as quarks and leptons. Type B constants are characteristics of classes of physical phenomena, such as coupling constants of fundamental forces. *G* is one of those coupling constants and famously shows up in Newton's law of gravitations. An alternative interpretation of *G* is provided by the concepts of inertial and gravitational mass. By requiring that the gravitational mass of a body be equal to its inertial mass times some constant of proportionality $M_G = \Gamma m_I$ and using Newtons law in the form $F = \frac{M_G^1 M_G^2}{r^2}$, the square root of *G* turns out to be the constant of proportionality linking both masses to each other. Finally, Type C constants are universal constants, which enter directly into universal physical laws. Examples for type C constants include *ħ* and *c*. These constants are also special in the sense that new physical phenomena emerge, when a physical quantity becomes of the same order of magnitude as the constants [2].

How a constant is classified can change over the course of history. The constant *c* used to describe a property of one particular phenomenon, namely light, and thus was a type A constant. With the discovery of electromagnetic theory and Maxwell's equations, *c* became characteristic of all electromagnetic phenomena and hence turned into a type B constant. Finally, with the advent of special relativity in the early 20th century, *c* was promoted to a type C constant, being a constant in a universal law [1][2].

Now that we have established what fundamental constants are, let's look at their structure. Every fundamental constant is written as a numerical

Quantity	Symbol	Value	Units
Gravitational Constant	G	$6.674\ 08(31) \times 10^{-11}$	$m^3\ kg^{-1}\ s^{-2}$
Proton Mass	m_p	$1.672\ 621\ 898(21) \times 10^{-27}$	kg
Electron Mass	m_e	$9.109\ 383\ 56(11) \times 10^{-31}$	kg
Speed of Light in Vacuum	c	299 792 458	$m\ s^{-1}$
Reduced Planck Constant	$\hbar$	$1.054\ 571\ 800(13) \times 10^{-34}$	Js
Electron Charge	e	$1.602\ 176\ 6208(98) \times 10^{-19}$	C
Boltzmann Constant	k_B	$1.380\ 648\ 52(79) \times 10^{-23}$	$J\ K^{-1}$
Avogadro Constant	N_A	$6.022\ 140\ 857(74) \times 10^{23}$	mol^{-1}
Fine Structure Constant	α	$7.297\ 352\ 5664(17) \times 10^{-3}$	
Proton g-Factor	g_p	5.585 694 702(17)	
Proton/ Electron Mass Ratio	μ	1836.152 673 89(17)	

Fig 1: The values of some of the most important fundamental constants as given by NIST [5].

value multiplied by relevant units. This means that constants are not only defined by their numerical value, but are *always* intertwined with a set of defined units. This has important implications: It is experimentally impossible to determine whether a dimensionful constant changes in space or time, because there is no way of ascertaining whether an observed change in the value of a constant corresponds to an actual change in the numerical value, a change in the physical representation of the relevant units or, even worse, a change in both. In other words, whenever a measurement of a dimensionful quantity is conducted, this quantity is compared to the physical representation of its units. This is best illustrated as follows: Before the meter was defined through c, which imposes its constancy, it was defined by the International Prototype Meter. If somebody were to travel to Paris, where the Meter is located, every year and file off some of the metal from one side of the bar every time, then measurements of c would yield different values every year. Of course, this is not evidence that c is a function of time, it simply means that some joker has been tempering with the physical representation of our definition of the meter as a unit. Does that mean that all hope is lost and that we will never be able to find out whether fundamental constants are spacetime dependent or not? Not exactly [1][3].

Dimensionless constants to the rescue

Although it is a hopeless task to try to pin down the variation of constants with dimensions, there is a class of constants, whose measurements do not require any dimensional input. These dimensionless constants are just as fundamental as their dimensionful siblings and come up all across physics. The standard model of particle physics, for example, contains 19 dimensionless constants and only three dimensionful constants [4]. However, among the experimentally most commonly considered dimensionless constants are the fine structure constant α, the ratio of the electron and proton mass μ and the proton g-factor g_p. α can be written as $\frac{e^2}{4\pi\varepsilon_0\hbar c}$ and determines the splitting of electron energy levels in atoms. In quantum electrodynamics α governs the interaction between photons and electrons and is hence related to the fundamental coupling constants of the standard model. The proton g-factor is the constant of proportionality that links the intrinsic magnetic moment of the proton to its spin combined with some unit of the magnetic moment, usually the Bohr magneton. The fact that the value of the proton g-factor is around 5.5 tells us that the spin of a proton is 5.5 times as effective in creating a magnetic moment as an electron whizzing around in a wire loop [1][6].

Since the second is currently defined by electronic transitions in caesium atoms and these transitions depend on α, it is crucial to ensure that α really is constant. A varying value of α would not only make metrology, the science of measurement, observer dependent, it would also cause changes in $\hbar$, G and other fundamental constants. At this point we can see why measurements that for example claim to examine the constancy of $\hbar$, are so problematic: they implicitly assume the constancy of both α and e. All this shows that there is a deep interconnection between fundamental constants and metrology. Since the definition of all SI units are at some point supposed to be based on fundamental constants, it is crucial to ensure their constancy. But it is not only metrology that is affected by varying constants. Many cosmological models suggest that a range of dimensionless constants could vary with space and time [1][3].

Let's listen to the theorists for a second

In 1921 Theodor Kaluza proposed a theory that promised two unite two fundamental theories of physics: general relativity and classical electromagnetism. The only twist was that his theory suggested the existence of 4 + 1 dimensions, the usual four dimensions of spacetime plus one extra spatial dimension. Five years later Oskar Klein interpreted Kaluza's theory in the light of the newly developed theory of quantum mechanics. Since its discovery Kaluza-Klein (KK) theories have been enhanced and generalized to 4 + N dimensions. In KK theories the additional N dimensions are compactified and coiled up curls of spacetime. Each extra dimension is characterised by a mean radius, which changes with time. This change is thought to be connected to changes in the value of α and other constants in four dimensions. Thus, observing variations in α could be a hint that there are more than four dimensions in the universe [1][7].

Before KK theories were found to predict a change in fundamental constants, Paul Dirac in 1937 suggested a cosmological model known as the Large Number Hypothesis (LNH), in which some of the fundamental constants varied with time. He formed five dimensionless ratios between cosmological and atomic constants each corresponding to one of the quantities: force, length, mass, energy and time. Four of those numbers were either roughly equal to 10^{39}, like the ratio of the Coulomb and the gravitational force between an electron and a proton, or roughly equal to 10^{78}, like the total number of nucleons in the universe [3]. Dirac noticed that the age of the universe, expressed in atomic units of time, is also around 10^{39}. Since dimensionless constants are independent of human definitions and because Dirac believed that there must be an explanation for the values of dimensionless numbers, he hypothesised that all of the four ratios must either be proportional to t or to t^2, with t being the age of the universe. In Dirac's

	Property	Expression	Value
FORCE	$\frac{\text{Coulomb}}{\text{Gravitational}}$	$\frac{\mu_0 c^2 e^2}{4\pi G m_p m_e}$	$\sim 10^{39}$
LENGTH	$\frac{\text{characteristic scale in the universe}}{\text{classical radius of electron}}$	$\frac{c t_{age}}{(\mu_0 c^2/4\pi) e^2/m_e c^2}$	$\sim 10^{39}$
MASS	$\frac{\text{mass visible universe}}{\text{mass per particle}}$	$\frac{\rho_0 c^3 {t_{age}}^3}{m_p}$	$\sim 10^{78}$
ENERGY	$\frac{\text{gravitational potential energy of the rest of the universe in the field of a nucleon}}{\text{rest mass energy of a nucleon}}$	$\frac{G m_p \rho_0 c^3 {t_{age}}^3 / c t_{age}}{m_p c^2}$	$\sim$ unity
TIME	$\frac{\text{age of the universe}}{\text{characteristic atomic time}}$	$\frac{t_{age}}{(\mu_0/4\pi)(e^2/m_e)}$	$\sim 10^{39}$

Fig. 2: Dirac's big numbers *- Paul Dirac proposed the idea that the above five dimensionless ratios of atomic and cosmological constants ($\rho_0 \sim 7 \times 10^{-28}$ kgm^{-3} is the density of the universe) could vary with time. He expressed the age of the universe t_{age} in term of the atomic time unit e^2/mc^3 yielding $t_{age} \sim 7 \times 10^{38}$, which is of the same order of magnitude as four of his big numbers [3].*

Large Number Hypothesis, fundamental constants are no longer basic, unchangeable characteristics of the universe, but dynamic variables characterising its state. Because ε_0 is *defined* to be constant in SI units, it follows from the time dependence of the ratio of the Coulomb and the gravitational force between an electron and a proton that either G or α is a function of time. Another important consequence is that the number of nucleons in the visible universe increases with t^2, implying the continuous creation of matter. Although both KK-theories and Dirac's LNH are very exotic ideas, a range of experiments has been conducted in recent years to test their predictions [3][8].

Laboratory Measurements

Seeing evidence for the variation of any fundamental constant would be a clear hint at new physics. To this day the most compelling constraints on changes in α and μ come from the analysis of atomic spectra. All the electronic energy levels in atoms depend to some order on α. A close look at the spectra emitted by hydrogen-like atoms, for example, reveals that the energy levels defined by the principal quantum number n are really split up into several energy levels. This fine-structure splitting of the principal n energy levels, from which the fine-structure constant gets its name, arises from relativistic corrections and from interactions between the spins and the orbital angular momentum of the electrons, the former being proportional to $(Z\alpha)^2$, where Z is the nuclear charge. An even closer look shows, that the fine-structure levels are again split up into even finer energy levels: the hyperfine-structure. The hyperfine-structure of the atom depends not only on α, but also on μ and g_p. By comparing different fine-structure and hyperfine transitions, it is possible to determine the value of all three of these constants and combinations of them. As the laboratory, in which the experiment is conducted,

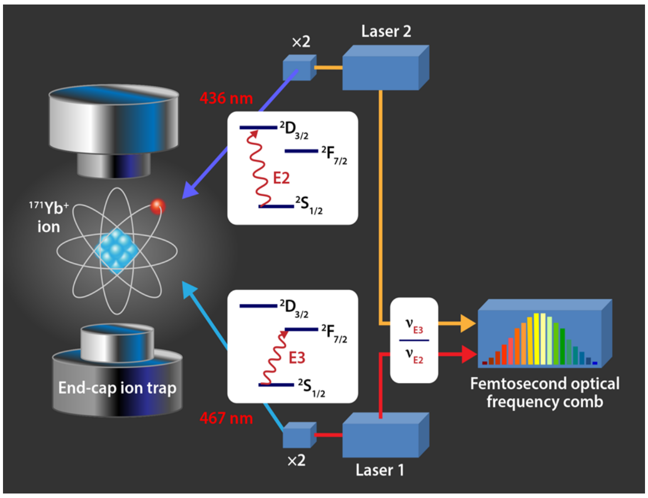

Fig 3: Experiment used to measure the values of α and μ [1].

orbits around the sun, changes in the transitions would indicate that those constants are functions of space and time [1][6].

The latest constraints on the variation of α and μ were reported by two independent teams around Patrick Gill at the National Physics Laboratory (NPL) in the UK [9] and Ekkehard Peik [10] at the Physikalisch-Technische Bundesanstalt (PTB) in Germany. Both teams studied transitions in singly charged ytterbium ions, which were found to have two highly stable excited energy states. By stabilizing a laser to the energy of the transition from the ground state to the first excited state and another laser to the energy of the transition from the ground state to the second excited state, the researchers were able to very accurately measure the transition frequencies. A comparison of those frequencies with the caesium frequency standard yielded constraints on the relative variation of α and μ of $-0.20 \pm 20 \times 10^{-16}$ and $-0.5 \pm 1.6 \times 10^{-16}$ per year (PTB) and $-0.7 \pm 2.1 \times 10^{-17}$ and $0.2 \pm 1.1 \times 10^{-16}$ per year (NPL). It was also the first time that two different transitions of the *same identical* ion were compared, a technique which in the future should enable scientist to put even lower limits on the variability of fundamental constants, because systematic errors resulting from the comparison with the caesium frequency standard will be eliminated (Fig. 3). Although at the moment the tightest constraints come from such atomic clock measurements, there are limits to the technique. Atomic clock measurements run on time scales of one month to one year, depending on the stability of the frequency standard. There are, however, ways that enable physicist to probe the constancy of constants nearly all the way back to the beginning of the universe [11].

Peering into the universe's past

If you want to study an object that is terribly far away, that object must be terribly bright. Quasars are ancient galaxies with extremely bright galactic centres and because they are such bright objects, they are the ideal candidates for light sources that allow astronomers to study the outermost edges of the visible universe. As the light from those quasars takes time to reach the earth, looking at quasars far away also means looking into the past. On its way through the universe the light from these distant objects passes through gas clouds, where certain wavelengths of the light are absorbed, depending on the material contained in the clouds. This leaves behind a characteristic spectrum with dark absorption lines in it (Fig. 4). On Earth astronomers are then able to deduce what the values of α, μ and g_p were billions of years ago, by comparing those absorption lines with each other and with present day laboratory results [1][12].

In 1998 a team of astronomers led by John Webb from the University of New South Wales in Australia reported that they had observed

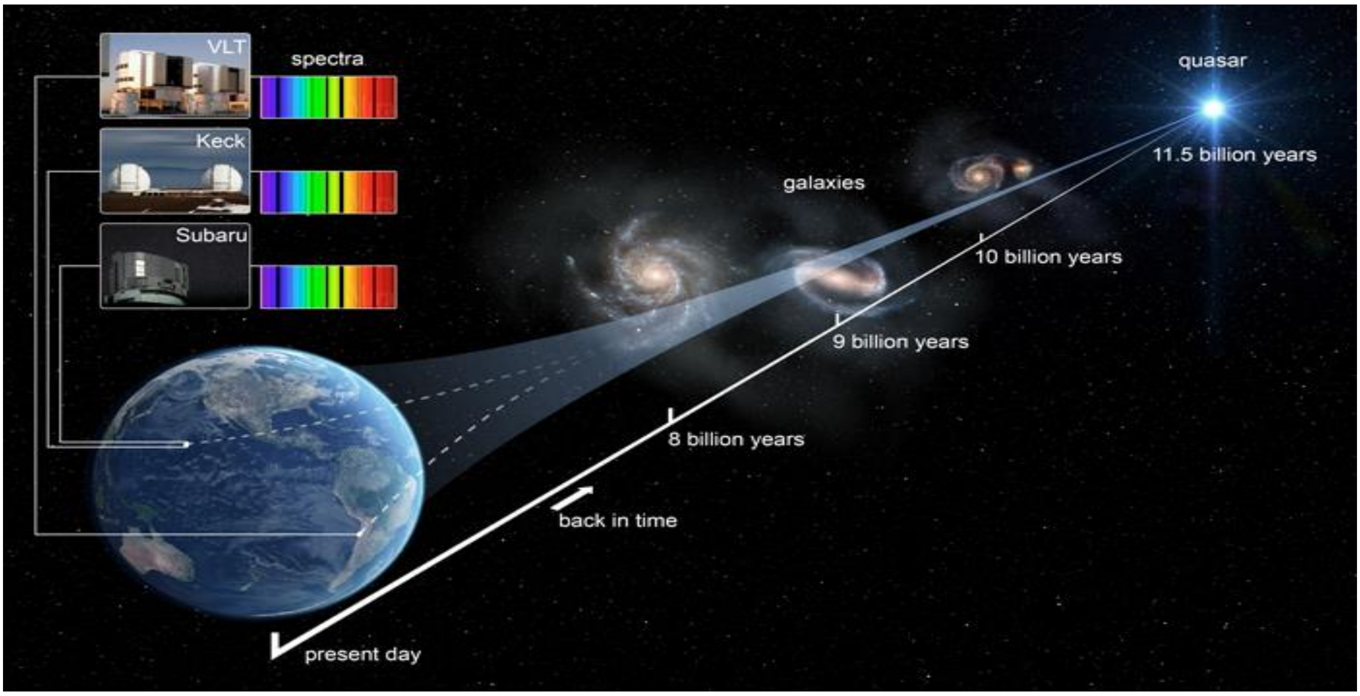

Fig 4: Looking at far away quasars enables astronomers to measure the value of fundamental constants billions of years ago [2].

changes in the fine-structure constant α [13]. They used the 10-meter W. M. Keck Observatory on Mauna Kea, Hawaii to look at light coming from quasars in the northern hemisphere. Their result: α has undergone a percentage change of -10^{-5} in the last 12 billion years. In 2011 Webb repeated these measurements, this time using the Very Large Telescope in Chile to survey the southern hemisphere [14]. The conclusion was thrilling. The researchers once more observed a relative change in α, just this time an increase of $\sim 10^{-5}$. These results are consistent with a spatial dipole model, which assumes that α varies along a line across the sky. Nevertheless, the study by Webb has not been widely accepted. The authors themselves point out that the results are prone to systematic error and that the effect observed in the 2011 study has a 1/34 chance of being caused by unknown systematics. Apart from that, other studies, such as the one by Patrick Petitjean have found no change in the fine-structure constant [15]. This could be explained by the fact that he did not look at quasars along the line of change that Webb identified and hence was not supposed to see any variation. As for now, the two studies by Webb remain the only observed, albeit highly disputed, hints at variations in α. No hard evidence for variations in fundamental constants has been found yet, but that does not stop an open mind to ponder the question, what such variations would mean for life, the universe and everything.

Are we all going to fall apart tomorrow?

The famous astronomer Fred Hoyle once said: “One must at least have a modicum of curiosity about the strange dimensionless numbers that appear in physics [4].” It is indeed the case, that why the dimensionless constants of the universe take exactly the value they take, longs for an explanation. A universe with variable dimensionless constants would be one way to tackle this issue. Of course, in such a universe the physics associated with the constants would also change. An interesting question to ask is which values of fundamental constants permit life as we know it to exist in the universe.

One of the main ingrediences necessary for life are oxygen and carbon. Carbon is created inside of red-giant stars by a mechanism called the triple alpha process. Initially two alpha particles collide and form a highly unstable beryllium atom with an average lifetime of 10^{-16} seconds. Then the beryllium atom absorbs a third alpha particle, resulting in a carbon atom, which is further synthesised into an oxygen atom. This process depends on resonances in carbon, which are sensitive to changes in the Coulomb and strong forces. In fact, changes of only 4% and 0.5% in the those forces respectively could reduce the carbon production rate in stars by a factor of 1000. Since the fine-structure constant determines the strength of the electromagnetic force, a big enough change in the value of the fine-structure constant could bring the triple alpha process out of resonance, reduce the carbon production rate and render life, as we know it essentially impossible [1] [16].

Gravity is another force that influences the outlook on life in the universe. It determines the future of the universe, it determines which kind of stars are stable and which are not, and it determines which structures can form and which cannot. Large scale structures in the universe such as galaxies are known only to be stable if $\alpha_G < 10^4$. The dimensionless constant $\alpha_G = Gm_p^2/\hbar c$ is the gravitational counterpart of the fine-structure constant α and hence describes the strength of the gravitational force. Those are only two examples to show how variations in fundamental constants would create vastly different universes from the one we live in. We inhabit a universe that appears to be fine-tuned for the existence of life, with all its fundamental laws, interactions and constants exactly right for us to exist [1][4]. A range of theories have been devised to explain this coincidence, but for now we are left with more questions than answers as to why the fundamental constant of nature are the way they are.

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Figures

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Science Article Plan

Fundamental Constants – To change or not to change?

Aims:

Many people think about fundamental constant as plain numbers, without considering their meaning more closely. In this article I aim to develop a more sophisticated view on fundamental constants. After reading this article, the reader should have a better understanding of the properties of fundamental constants and how they are connected to measurements. I will introduce the idea of time variability of constants and what that means for physics. Finally, I will present an overview of the status quo of the experimental research concerning the time variability of fundamental constants.

Introduction – Welcome to the world and wonders of fundamental constants! (~ 700 w)

- Motivate why it is relevant to talk about fundamental constants and whether they are constant or not
- Present some of the fundamental constants in a bit more detail, specifically G, charge/mass ratio of the electron, fine structure constant
- Explain how fundamental constants are classified (Levy-Leblond), the difference between dimensionless and dimensional constants

Section 1 – Let's listen to the theorists for a second! (~ 600 w)

- Introduce some of the theories that predict changes in fundamental constants (Dirac's "Large Number Hypothesis", Kaluza-Klein Theories)
- This section is not meant to go into too much detail, but rather to give a short overview over the theoretical situation

Section 2 – Measure what is measurable and make measurable what is not so! (~ 900 w)

- Establish how fundamental constants are connected to the definition of units and how they affect measurements
- Present experiments that have been done so far, especially concerning G, charge/mass ratio of the electron, alpha (quasar spectra, atomic clocks measurements, geological constraints)

Conclusion – Are we all going to fall apart tomorrow? (~ 400 w)

- In this section I'd like to explore what consequences potential changes of fundamental constants could have on physical models and the future of the universe, especially how we would have to account for such changes in cosmological models

Selection of References:

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Feedback:

This is great ! Get it? Well – maybe – there are a few too many exclamation marks. Before discussing why fundamental constants are important, be sure to introduce what they are. I like the part on listening to theorists. You could also include when they were predicted so that we get a sense how well established they have been in history. There was some discussion about fundamental constants varying by location in universe (http://www.sciencemag.org/news/2011/11/fundamental-constant-may-depend-where-universe-you-are) and about potential updates (https://phys.org/news/2017-10-scientists-key-fundamental-constants.html). As the introduction and section 1 are likely to be light on diagrams, I would make sure to include figures for each of the experiments in section 2 to make it a more enjoyable read. Be sure to cite predictions for the impact of changes to fundamental constants.

Comment:

I tried to give a general introduction to fundamental constants in the beginning. My idea was to lead the reader down the wrong path by first introducing widely known dimensionful 'fundamental' constants and then explaining why dimensionless constant can be considered as or even more fundamental than dimensionful ones and why the bulk of the research focuses on finding variations is dimensionless constants. That's also why, in contrast to the plan, I split up the first section into two: to make the distinction between dimensionful/dimensionless constants clearer. I also did this by incorporating some theories to give a reader a sense of the history of the subject. As for the experiments, I found that there were too many to explain all of them, so I choose the two of them, which I considered the most interesting and current experiments. Once again, I spit this section up into two, so as to explain each type of experiment on its own. I did not mention geological (Oklo-phenomenon) or paleontological constraints to stay under the word limit. The same is true for the last section. I restricted myself to two concrete examples, I tried not to get to much into fine-tuning/anthropic principle.