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The stability of fundamental constants

La stabilité des constantes fondamentales

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ABSTRACT

The tests of the constancy of fundamental constants are tests of the local position invariance and thus of the equivalence principle, at the heart of general relativity. After summarising the links between fundamental constants, gravity, cosmology and metrology, a brief overview of the observational and experimental constraints on their variation is proposed.

RÉSUMÉ

Les tests de la variation des constantes fondamentales sont des tests de l'invariance de position locale et donc du principe d'équivalence, au cœur de la relativité générale. Après un résumé des liens entre constantes fondamentales, gravitation, cosmologie et métrologie, ce texte propose un état des lieux des contraintes expérimentales et observationnelles sur leur variation.

1. Introduction

Fundamental constants are not determined by the theories in which they appear. They can only be measured, which is actually their most important property. This explains why metrology has engaged in the quest of measuring physical constants, fundamental or not, to the highest precision that is deeply entangled with the improvement of the definition and realisation of the standards of units [1].

These constants play an important role in physics since they set the order of magnitude of phenomena, allow one to forge new concepts and characterise the domain of validity of the theories in which they appear. They also play a central role in cosmology and astrophysics. Their value fixes the rate of local clocks (e.g., radioactive decay rates, atomic transitions, etc.) that allow one to perform datation of geophysical and astrophysical phenomena. There are a key to the reconstruction of the history of our Universe. The phenomena that can be observed in our local Universe, from big-bang nucleosynthesis time to now, rely mostly on general relativity, electromagnetism, and nuclear physics. The fact that we can understand the Universe

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and its laws has an important implication in the structure of physical theories. At each step of their construction, we have been dealing with phenomena below a typical energy scale, for technological constraints, and it turned out (experimentally) that we have always been able to design a consistent theory valid in such a restricted regime. This is not expected a priori and is deeply rooted in the mathematical structure of the theories that describe nature. This property, called *scale decoupling principle*, refers to the fact that there exist energy scales below which effective theories are sufficient to understand a set of physical phenomena. *Effective theories* are the most fundamental concepts in the scientific approach to the understanding of nature and they always come with a domain of validity inside which they are efficient to describe all related phenomena. They are a successful explanation at a given level of complexity based on concepts of that particular level. For instance, we do not need to understand and formulate string theory to develop nuclear physics and we do not need to know anything about nuclear physics to develop chemistry or biology.

The set of theories that describe the world around us can then be split into a hierarchy of modular levels in interaction. The relation between the different levels have the following properties [2,3]. (1) Higher-level behaviours are constrained by the lower level laws from which they emerge. This is the usual bottom-up causation in which microscopic forces determine what happens at the higher levels. The more fundamental gives the space of possibilities in which a higher level can develop, by constraining, e.g., causality, the type of interactions or structures that can exist. (2) Scale separation implies that at each level of complexity, one can define fundamental concepts that are not affected by the fact that they may not be fundamental at a lower level. In that sense, much of the higher level phenomena remain quite independent of the microscopic structures, fields, and interactions. (3) At least for the lowest level, the fact that physical theories are renormalisable implies that they influence higher levels mostly through some numbers. This in particular the case of the fundamental constants of a given effective theory. While they cannot be explained within the framework of this particular level, they can however be replaced by more fundamental constants of an underlying level. For instance, the mass or the gyromagnetic factor of the proton are fundamental constants of nuclear physics. They can however be "explained", even if the actual computation maybe difficult (see [4]), in terms of constants of the lower level (such as the quark mass, binding energies). This explanation of the constants of an effective theory may reveal new phenomena that could not be dealt with before (e.g., the fundamental parameters of the effective theory may now be varying), but these phenomena have to be at the margin (or below the error bars) of the experiences that have validated this effective theory. (4) Not all the concepts of a higher level can be explained in terms of lower-level concepts. Each level may require its own concepts that do not exist, or even are not related, to lower-level concepts. These are emergent properties so that the whole may not be understood in terms of its parts. (5) The fact that there exists a lower level of complexity and thus microscopic degrees of freedom implies that these degrees of freedom can be heated up so that we expect to see entropy and dissipation arising. (6) The higher levels of complexity can back-react on the lower levels. This is the notion of top–down causation. (7) Historically, various disciplines have developed independently in almost quasi-autonomous domains, each of them having its own ontology. Sometimes two such theories collide and show inconsistency that will need, in order to be resolved, the introduction of new concepts, more fundamental, from which the concepts of each one of the theories can be derived in a limiting behaviour. For example, Maxwell electromagnetism and Galilean kinematics are incompatible, which is at the origin of special relativity with the new concept of spacetime; or in quantum mechanics, the concept of wave function has to be coined from the preexisting concepts of particle and wave. This implies that concepts that were thought to be incommensurable (such as space and time, or momentum and wave number) need to be unified, which is usually achieved by the introduction of new fundamental constants (speed of light, or Planck constant, in the two examples above) that were not considered as fundamental (or even existed) in the previous theories; see, e.g., [5].

I shall thus define a *fundamental constant* as "any parameter not determined by the theories in which it appears", which emphasises that constants and theories cannot be considered separately. Indeed, this parameters have to be assumed constant for two reasons. First, from a theoretical point of view, we have no evolution equation for them (since otherwise they would be fields) and they cannot be expressed in terms of other more fundamental quantities. Second, from an experimental point of view, in the regimes in which these theories have been validated, their constants should be constant at the accuracy of the experiments, to ensure their reproducibility. This means that testing for the constancy of these parameters is a test of the theories in which they appear and allow us to extend the knowledge of their domain of validity.

These constants raise a number of questions. First, are they really constant during the evolution of the Universe? Then, can we explained their value? The first question is related to the validity of Einstein's equivalence principle, while the second is related to the apparent fine tuning of our Universe. In the following, I will summarise in Section 1 some theoretical aspects about fundamental constants, in particular their relation to general relativity and cosmology. Section 2 will provide an overview of the constraints on their variation, focusing on the latest developments. More details can be found in reviews [5,6], as this text focuses on more recent developments.

2. Theoretical considerations

This section briefly summarises some theoretical considerations about the constants, in particular their nature (Section 2.1), their link with the equivalence principle (Section 2.2), and cosmology (Section 2.3)