The Equivalence Principle and the Constants of Nature

Thibault Damour

Received: 29 April 2009 / Accepted: 11 May 2009 / Published online: 30 May 2009
© Springer Science+Business Media B.V. 2009

Abstract  We briefly review the various contexts within which one might address the issue of “why” the dimensionless constants of Nature have the particular values that they are observed to have. Both the general historical trend, in physics, of replacing a-priori-given, absolute structures by dynamical entities, and anthropic considerations, suggest that coupling “constants” have a dynamical nature. This hints at the existence of observable violations of the Equivalence Principle at some level, and motivates the need for improved tests of the Equivalence Principle.

Keywords  Gravitation · Equivalence Principle · Constants

1 Introduction

The currently known laws of physics contain about twenty independent dimensionless “constants”. For instance, some of the most important ones, for determining the world around us, are:

$$\alpha_{\text{EM}} = \frac{e^2}{\hbar c} \simeq \frac{1}{137.0359997},$$  \hspace{1cm} (1)

$$\frac{m_p}{m_e} \simeq 1836.152672,$$ \hspace{1cm} (2)

$$\frac{G m_e m_p}{\hbar c} \simeq 3.216 \times 10^{-42}.$$ \hspace{1cm} (3)

An important question is: What determines the values of these constants? According to Leibniz, one of the basic principles of rational thinking is the Principle of Reason: “Nihil est sine ratione” (“Nothing is without a reason”). What could be the “reasons” behind the very specific numbers quoted in (1)–(3) above? We do not have any firm answer to this
question. The aim of this note is to recall the various contexts and scenarios within which this question might be addressed. The main conclusion of our discussion will be that it is important to perform improved tests of the Equivalence Principle because these tests are one of our few windows on the physics which is possibly at work for selecting the constants of Nature.

2 Are the Constants Constant?

Einstein’s theory of General Relativity has deeply transformed one aspect of the general framework of physics. Before 1915, both the structure of spacetime and the laws of local matter interactions were supposed to be “rigid”, i.e., given once for all, as absolute structures, independently of the material content of the world. General Relativity introduced the idea that the structure of spacetime might be “soft”, i.e., influenced by its material content. On the other hand, one of the basic principles of General Relativity, the Equivalence Principle (EP), postulates that the laws of local physics, and notably the values of all the dimensionless coupling constants, such as $\alpha_{\text{EM}}$ or $m_p/m_e$, must be kept “rigidly fixed”. General Relativity thereby introduces an asymmetry between a soft, dynamical spacetime structure and a rigid, non-dynamical set of coupling constants.

This asymmetry was questioned by Dirac (1937) and Jordan (1937, 1939). Dirac phenomenologically assumed that the small dimensionless coupling $G m_e m_p/\hbar c$ of (3) varied proportionally to the inverse of the age of the universe, while Jordan (reviving generalizations of General Relativity à la Kaluza-Klein) essentially assumed that both $\alpha_{\text{EM}}$ and $G$ could become spacetime fields $\varphi(t, x)$. Actually, the first author to clearly realize that Jordan’s original theory implied that the fine-structure constant $\alpha_{\text{EM}}$ had become replaced by a field $\varphi(t, x)$ was Fierz (1956). Fierz then pointed out that astronomical data (line spectra of galaxies) were putting rather strong constraints on the spacetime variability of $\alpha_{\text{EM}}$, and suggested to restrict the original, two-parameter class of Jordan’s “varying constant” theories to the special one-parameter class where the fine-structure constant $\alpha_{\text{EM}}$ remains constant, but where the gravitational coupling $G$ is allowed to become a spacetime field. [This EP-respecting one-parameter Jordan-Fierz theory coincides with the tensor-scalar theory later studied by Brans and Dicke.]

3 Varying Constants and Equivalence Principle Violations

The considerations of Jordan and Fierz on field-theory models of varying constants attracted the attention of Dicke. In particular, Dicke realized the important fact that any theory in which the local coupling constants are spatially dependent will entail some violation of the (weak) Equivalence Principle (EP), namely some non-universality in the free-fall acceleration of bodies embedded in an external gravitational field. Dicke’s general argument (Dicke 1964) is that the mass $m_i$ of a body, which is made (in view of $m c^2 = E_{\text{tot}} = \sum E_\alpha$) of many contributions, related to various interaction energies (strong, weak, electromagnetic; to which we can now add the Higgs interactions, responsible for the “rest masses” of the quarks and the leptons), is a certain, complicated function of various coupling constants, notably the gauge and Yukawa coupling constants: $m_i = m_i[\alpha_{\text{EM}}, \ldots]$. If the coupling constants are spatially dependent, the free-fall acceleration deduced from the action of a point particle embedded in a (general relativistic) gravitational field $g_{\mu\nu}(x)$,

$$S_{m_i} = -\int m_i[\alpha_{\text{EM}}(x), \ldots]\sqrt{-g_{\mu\nu}(x)}\, dx^\mu\, dx^\nu,$$

(4)